Analysis and Design of Bituminous Pavements

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Lecture – 38
Rutting and Low-Temperature Cracking

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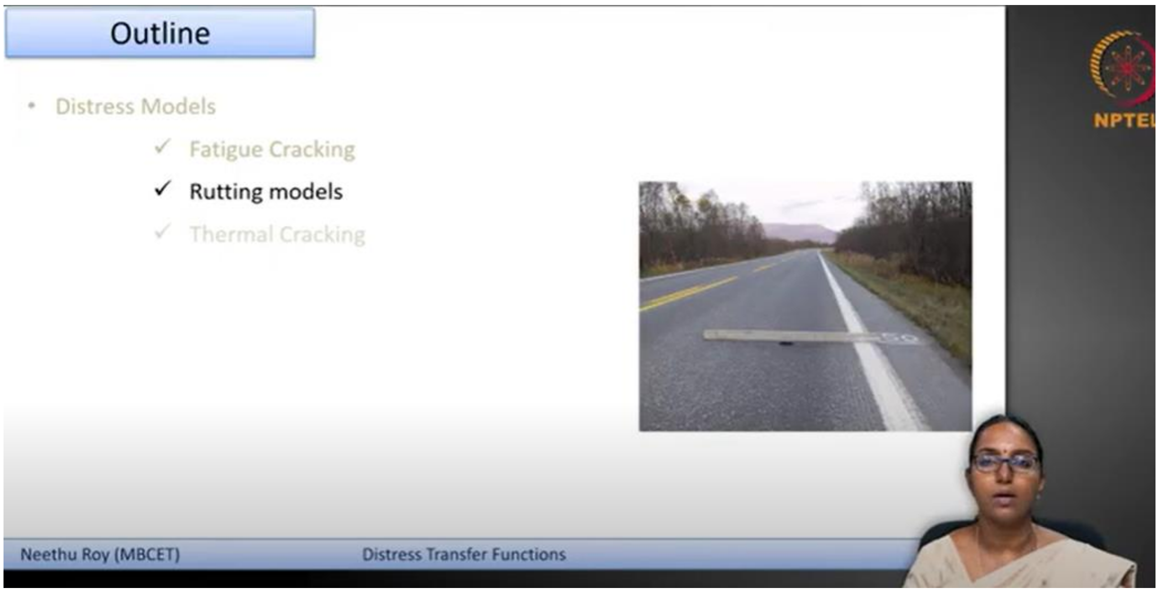

Now, we will discuss about the rutting prediction models or the rutting transfer functions. Now, what is rutting? It is the deformation that you see along the wheel path in the transverse direction. So, this is a distress that we observe in the pavement surface, which could happen due to many reasons. And we need to predict this rutting so that you can design the pavement structure without this rutting being exceeded beyond a particular value. Now, when I say rutting, as I said, this is the deformation that you see on the top pavement surface. Now, there are two ways in which this rutting is considered or two ways in which this rutting is modeled.

The first one is that you will consider the vertical compressive strain on top of the subgrade alone, which is called as a subgrade rutting. So, the assumption is that you see rutting on the top of the subgrade and this rutting will get transferred and you see that as a rutting on the top of the pavement surface. So, this is called as a subgrade rutting. Essentially, the rutting in all other pavement layers is not considered when you talk about the subgrade rutting. Whereas, the second approach is that you find out what is the permanent deformation or the rutting that happens in every layer of the pavement structure. And then, that is accumulated to see what is the total accumulated rutting on the top surface. So, when I say rutting, it is essentially what you see on the surface of the pavement or when I say permanent deformation, it is the deformations that happens in each one of the layers. Now, as in the case of fatigue damage, here also there has been certain rutting models.

A general form of rutting model has been developed by Asphalt Institute and Shell considering the subgrade rutting. So, for subgrade rutting, the expression is given as,

$$N_d = f_4 \varepsilon_c^{-f5}$$

Here, N_d is the number of repetitions of failure due to rutting on this pavement surface, whereas ε_c represents the critical vertical or the maximum vertical strain on the top of the subgrade. So, this is a critical strain that is considered in this rutting transfer function.

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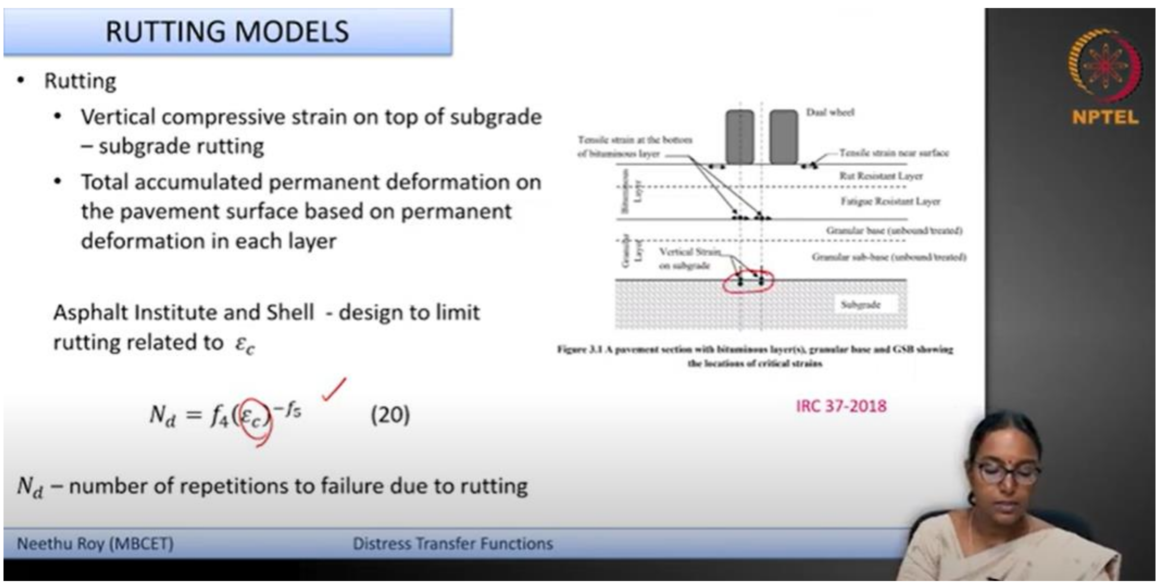

Now, various studies have tried to correlate the pavement surface rutting with this ε_c that is, the critical strain that we observe on the top of the subgrade while doing a layered elastic analysis. And then, the factors f_4 and f_5 has been estimated. So, as you can see here, Asphalt Institute has given the factors of f_4 as 1.3×10^{-9} and f_5 as 4.477. And, the failure criteria that was adopted is for rut depth of 0.5 inch, whereas Shell has given these parameters at various reliability levels of 50%, 85%, 95% and so on.

And then, UK TRRL has given the parameters or the coefficients f_4 and f_5 at 85% reliability level and for a rut depth of 0.4 inch as failure. Also, you can see some values given by the Belgium Road Resource Centre. So, you see that these parameters, the f_4

values as well as f_5 values vary among the various agencies, but mostly the changes is more in the case of f_4 as compared to f_5.

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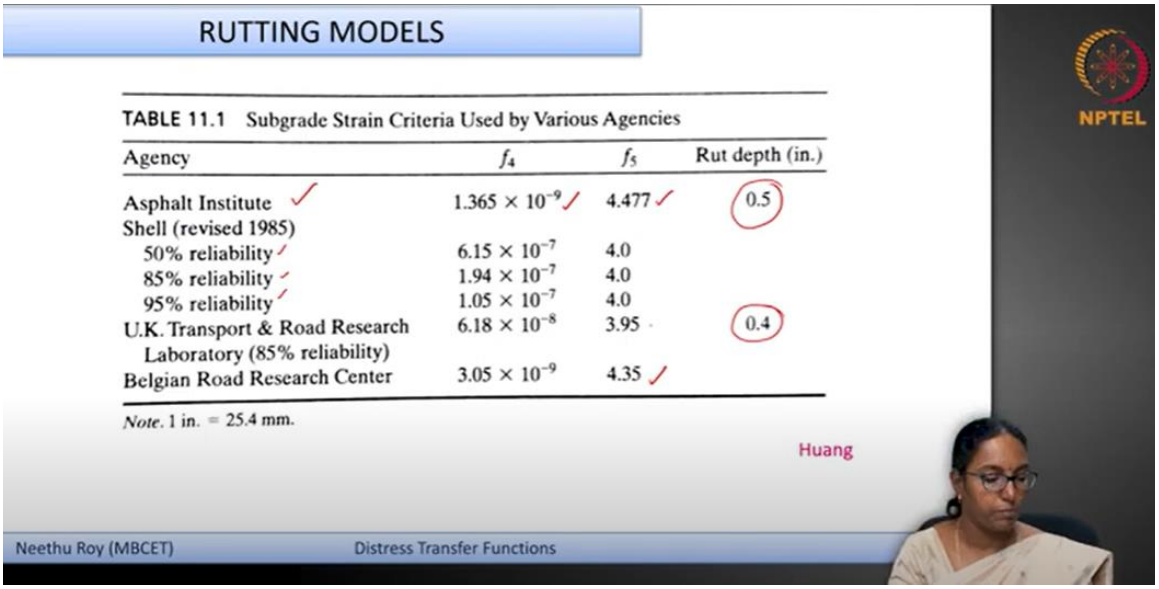

Now, let us see how this rutting is considered in IRC 37, 2018. So, in IRC also, you consider the subgrade rutting as the rutting criteria. So, the failure condition that is considered is an average rut depth of 20 mm along the wheel path. The distress transfer functions are given correlating the equivalent number of 80 kN standard load repetitions that can be served by the pavement before a critical rutting failure of 20 mm occurs. Now, as I said, it is given for two reliability levels in IRC 37. One is N_R is for 80% reliability level and the second one is for 90% reliability level. N_R is given as

$$N_R = 4.1656 \times 10^{-8} \left(\frac{1}{\varepsilon_v}\right)^{4.5337} \qquad \text{80\% reliability}$$

$$N_R = 1.41 \times 10^{-8} \left(\frac{1}{\varepsilon_v}\right)^{4.5337} \qquad \text{90\% reliability}$$

Here, ε_v denotes the vertical compressive strain at the top of the subgrade which can be obtained by the layered elastic analysis of the pavement structure. And N_R here represents the subgrade rutting life or the cumulative equivalent number of 80 kN standard axle loads that can be served by the pavement before this 20 mm rutting happens.

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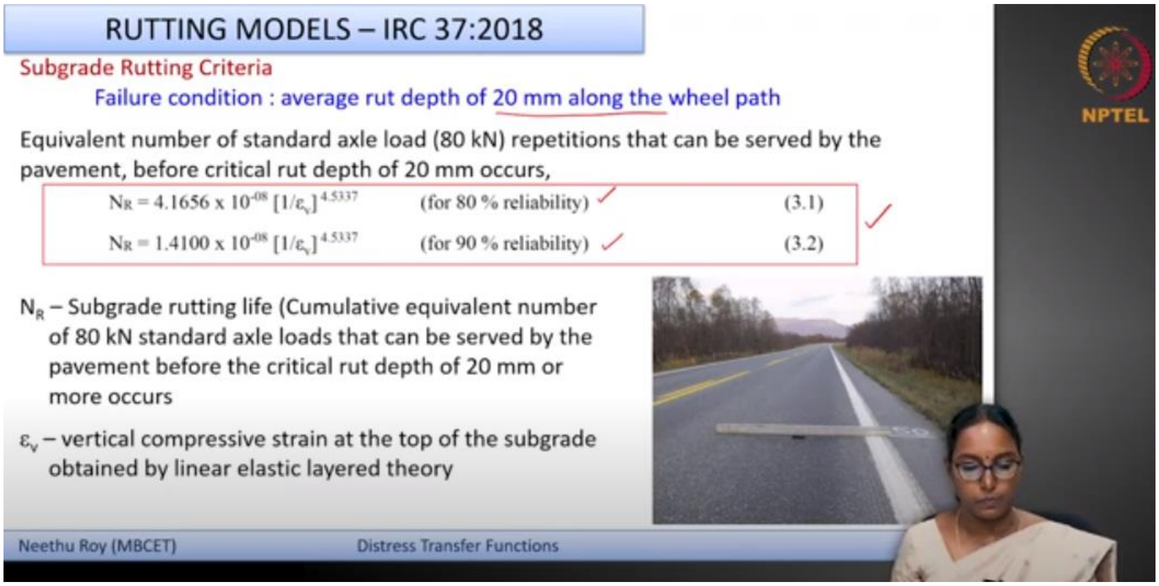

Now, what we have discussed is the rutting expression as far as the subgrade rutting is concerned. So, essentially all other layers are not considered in that equation. You see what is the strain that happens on top of the subgrade and it is related to the pavement surface rutting. Now, there are not many distress functions which are commonly used for rutting of HMA and other granular materials. But essentially the approach that is adopted is a rutting rate concept that can be used for HMA, granular and as well as fine grain soils or the various layers of the pavement structure. So, this is generally represented as a permanent strain that is happening in the pavement material or any type of material which is given as,

$$\varepsilon_p = AN^b$$

So, this was adopted in the NCHRP, National Cooperative Highway Research Project and this expression is derived from a experimental study of a material and from the $\log \varepsilon_p - \log N$ data, where N is the number of load repetitions. So, this expression actually represents what is the permanent strain that is accumulated in a material when loaded with N cycles.

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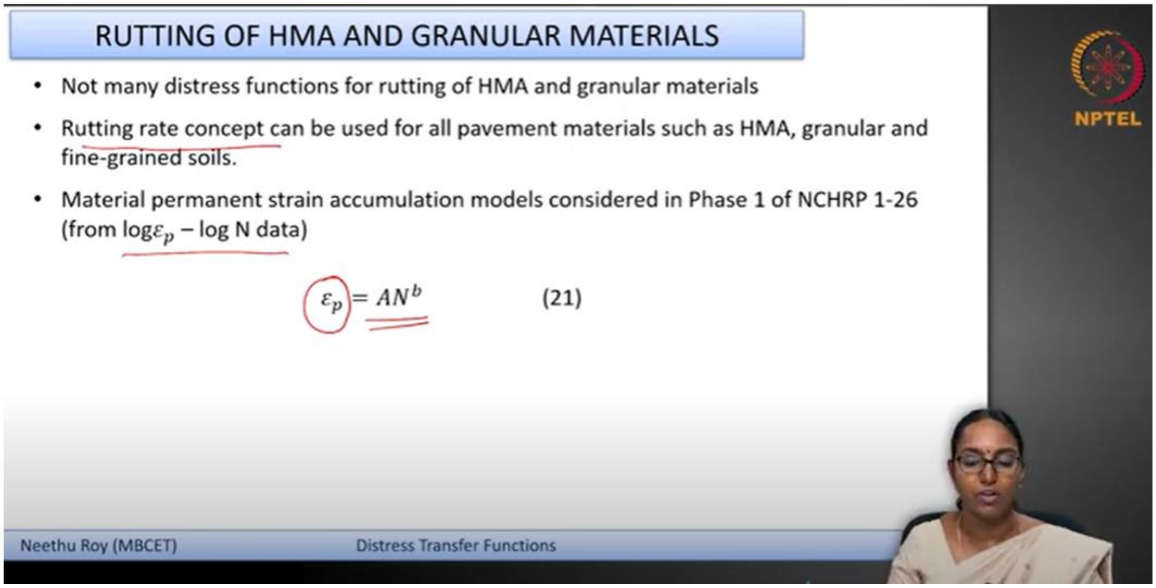

Now, there has been many models which are developed in line with this expression. So, I will discuss about this Ohio State model, which essentially assume a linear relationship between this permanent strain ε_p and the number of load repetitions in a log-log scale. So, you can see a similar picture drawn here which shows a relationship between ε_p by N. See, rather than taking the permanent strain ε_p, the rate of permanent strain which is ε_p/N is noted here and N is the number of load repetitions and the plots are made for different stress levels and at different temperatures. You can see the stress application of 29.76 psi, then application of 40 psi and so on and also at different temperature levels. See, till here the temperature 100 °F and beyond that this is like 120 and so on. So, a series of experiments are conducted on materials at different temperature levels and the accumulated permanent strains are captured and then it is plotted here. So, from this, a linear relation can be developed and the rutting rate is indicated as

$$\frac{\varepsilon_p}{N} = AN^{-m}$$

where A and m are the constants which essentially depend upon what is the material type and what is the state of stress which is used for testing the material.

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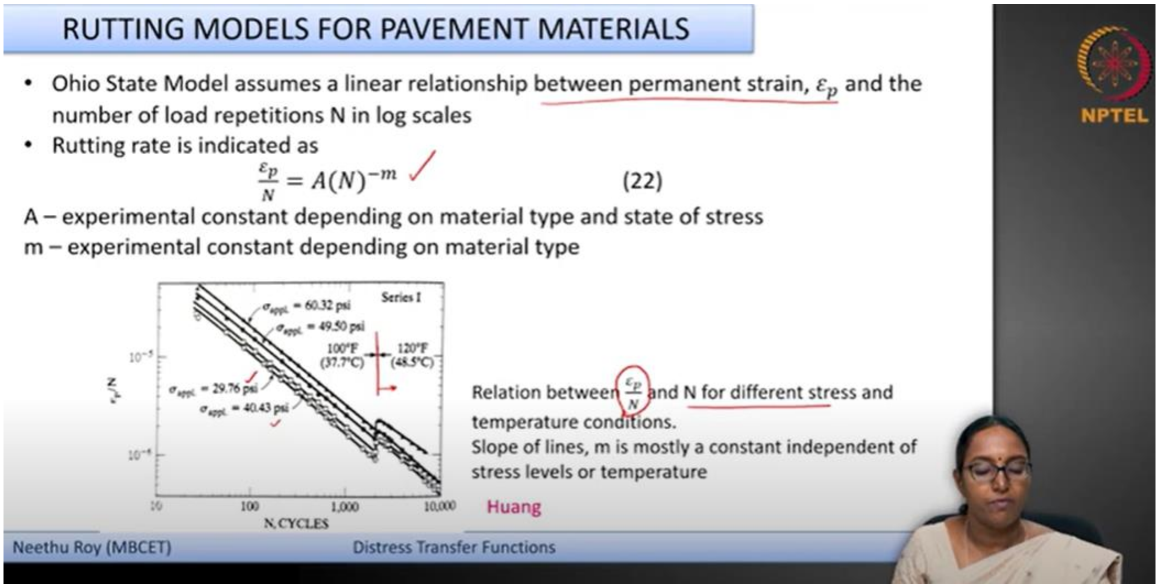

Now, if this relation is written in terms of ε_p, it becomes

$$\varepsilon_p = AN^{1-m}$$

Now, many other studies have been conducted to arrive at or see how these constants of A and m vary. So, they have conducted a large number of repeated load test on HMA specimens and they found that they have tried to find out what is this A parameter with the modulus of the material or the elastic strain of the material. So, as you can see here, there is a plot being made with M_R/σ_d. So, M_R actually represents the resilient modulus of the material and σ_d represents the applied stress. So, you do a repeated loading test on the specimen having a modulus of M_R and with a deviator stress level of σ_d and M_R/σ_d essentially represents the elastic strain. The elastic strain versus this parameter A from this expression shows that there is a linear variation. So, A itself can be written in terms of $a\varepsilon^b$, where the a and b are the material constants.

So, you have conducted a number of tests on various bituminous mixes to find out these experimental constants a and b or to get this relation between the parameter a and the elastic strain of the material. Now, substituting this in the ε_p equation you can see that the final form of the Ohio State model becomes

$$\varepsilon_p = a\varepsilon^b N^{1-m}$$

As I said m is the experimental constant which depends upon the material type, a and b are again material constant and ε is essentially M_R/σ_d which is the resilient modulus by the applied stress or it is elastic strain of the material and ε_p represents the permanent strain. So, what is interesting here is that your permanent strain that happens in the material is represented as a function of the elastic strain in the material or the recoverable strain in the material.

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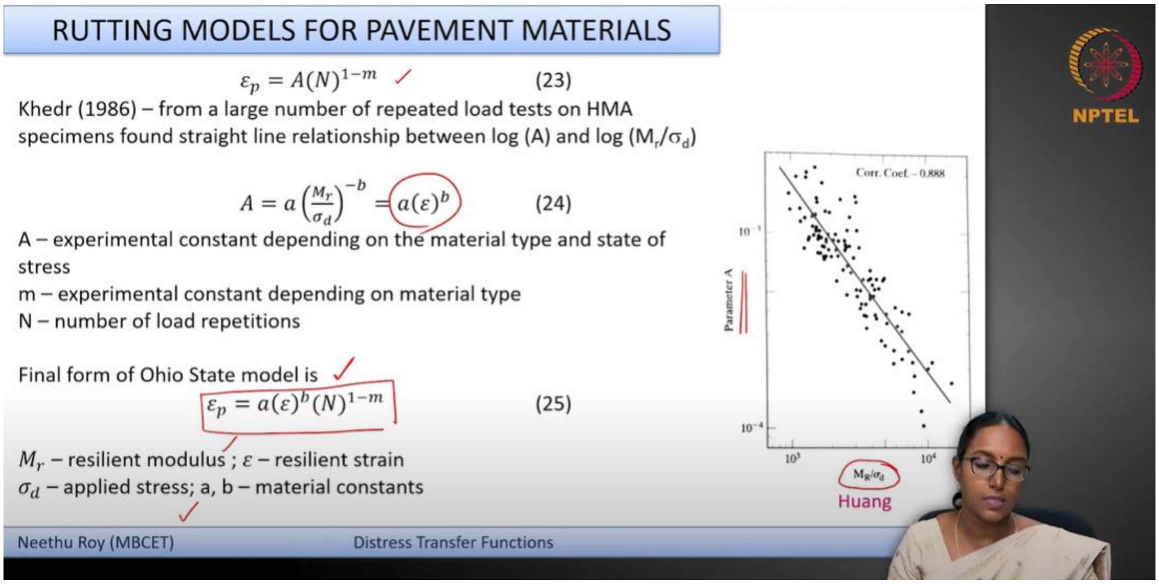

Now, how we can predict the rut depth of different layers of a pavement structure? Suppose you have different layers and for each of these layers, you can divide it into a number of sub layers if you want and for each of these layers you can do a stress analysis and see what are the stresses and strains at different heights of each layer. Now, for convenience you will consider the mid layer of each of these layers and you see what is the radial stresses as well as the vertical stresses that happens at the mid layer of this pavement structure and then use those stress conditions, that is the normal stresses and the radial stresses. You use those as the deviatoric stress and the confinement pressure on the material specimens and conduct laboratory investigations with the material that you are going to use in the field. So, identical material can be taken and specimens can be casted and tested with these stress states that are going to happen in the material and ε_p that is the permanent strain in the material due to a large number of load applications can be determined. Now, in the field actually the structure may be subjected to a large number of deviatoric stresses as well as radius stresses. So, it may not be possible to find the ε_p corresponding to all these stress levels. So, what you do is that you have a number of stress levels at which this will be tested and then you can estimate the coefficients *a*, *b* and *m*. Now, once you know this *a*, *b* and *m* for the pavement material or for each one of these layers then ε_p that is the permanent strain of these layers due to the applied axial loads can be determined and once you know this, the strain then multiplied with the thickness of the pavement layers will essentially give you the total deformation in each one of these layers. Now, if you get the permanent deformations in each one of these layers you can add them together to get what is the total rutting on the top. So, essentially using the material parameter of ε_p that has been determined from the laboratory you can use it to see how the material deforms or how the pavement structure deforms and sum up the total deformations on each one of these layers to get what is the total deformation on the surface.

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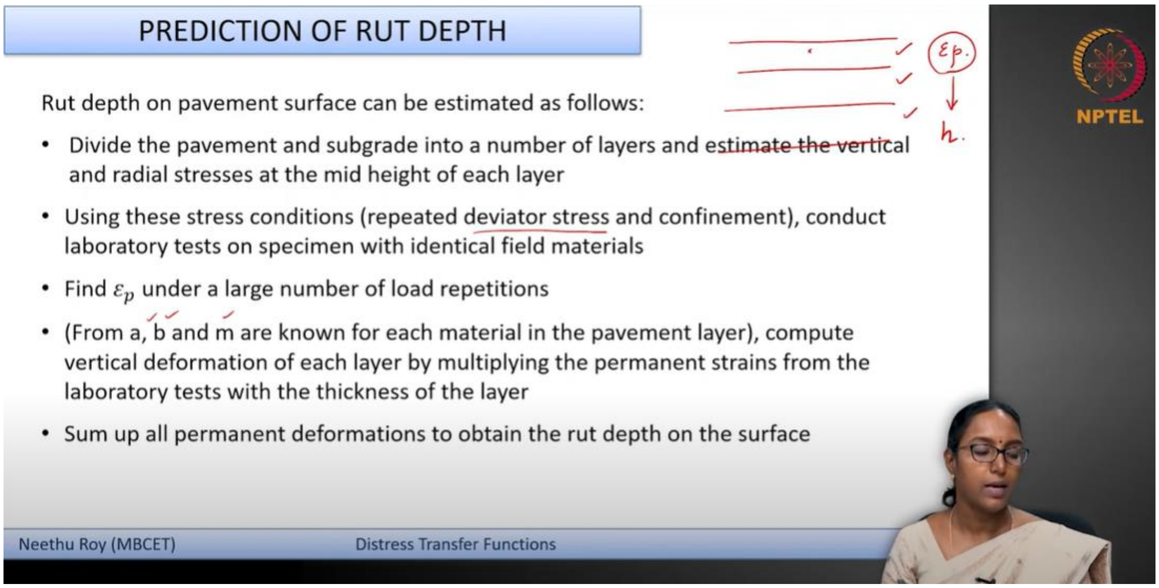

Now, what I have discussed just now is you do a repeated axial load kind of a testing on the specimen to get the ε_p values or the ε_p expressions. Whereas, there are other studies also wherein rather than using a repeated load test you go for a creep test that is a constant loading test given by the modified Shell procedure for the bituminous concrete. Permanent deformation is given by $\varepsilon_{vp} = at^b$ where t represents the time for which the creep test is done. a and b again are the regression constants from the creep testing.

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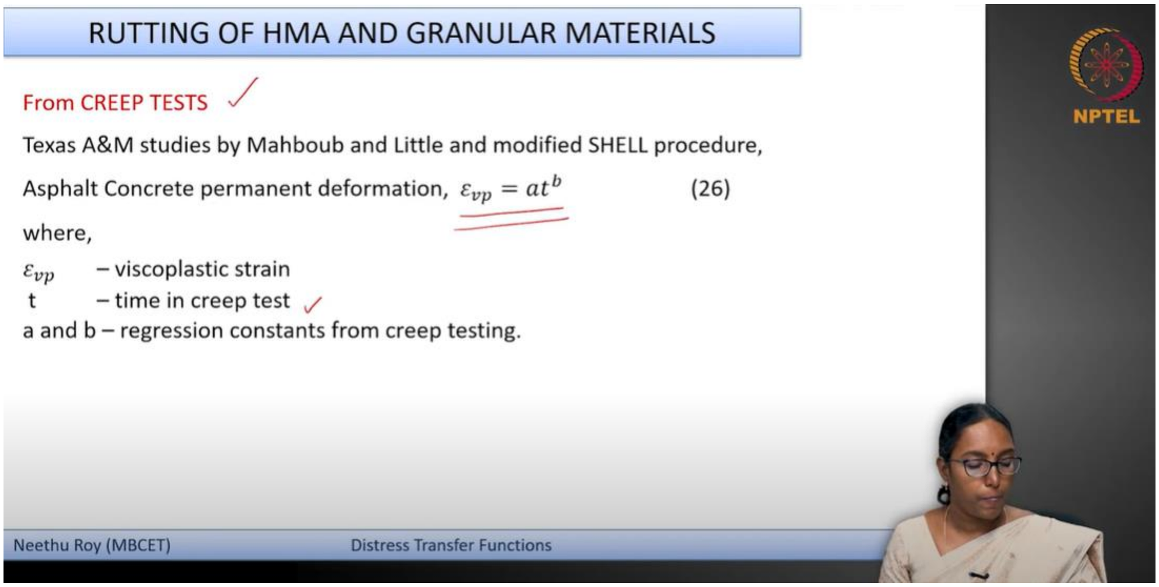

So, all the different pavement layers follow the relation between ε_p and N model that we have just discussed. Then, the surface rutting of the pavement can also follow a similar trend if we have data that correlates the number of repetitions of loading and what is the rutting that is observed in the field. So, this model has been developed in terms of the rutting rate or rut depth by the number of load applications which are developed from the field data. So, it takes a form,

$$RR = \frac{RD}{N} = \frac{A}{N^B}$$

Here, RR is the rutting rate, RD is the rutting depth in inch and A and B are the terms which are developed from the field calibration data.

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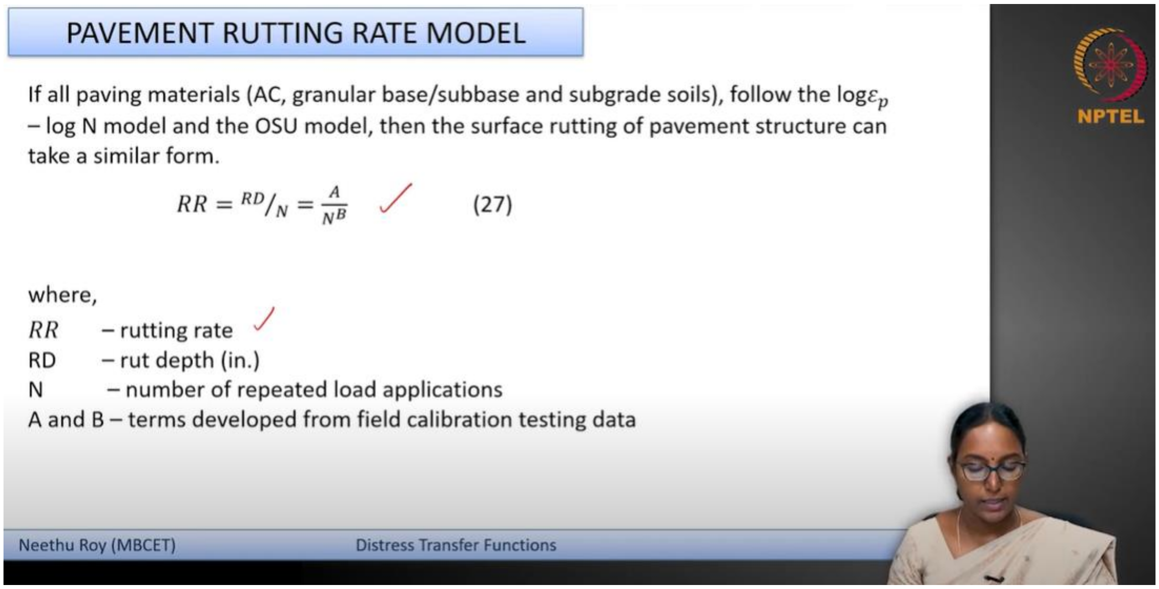

So, this is some data that has been used for the development of such models. The AASHO road test data, the American Association of State Highway Officials Road test data is given for certain road test stretch and then you can know in a log scale you can plot the rutting rate versus the number of applications. So, you can know form a relation between them, a straight-line relation can be formed. So, you see that RR $= 2.65 \times \frac{10^{-3}}{N^{0.623}}$

So, such relationship can be directly obtained or such distress functions can be obtained if you have sufficient amount of field data which correlates the rutting rate and the number of load repetitions in the field.

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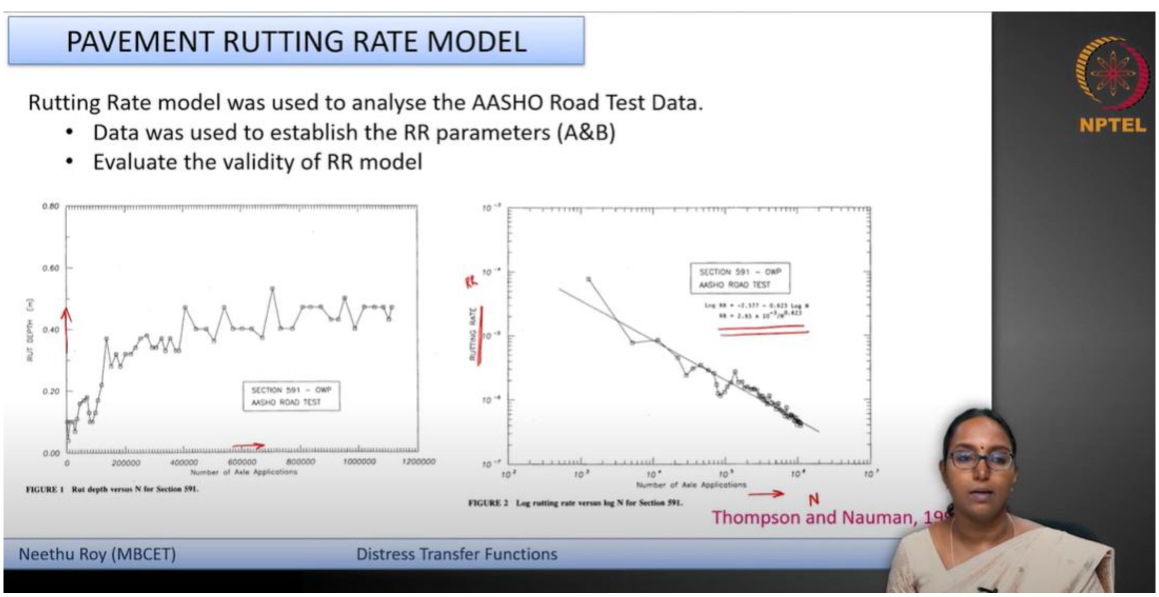

Now, let me go back to the IRC design again. So, as I said in the IRC method of design you consider the subgrade rutting. As per IRC 37, rutting within bituminous layers caused by accumulated plastic or permanent deformation in these layers due to repeated application of traffic load is another major distress occurs in the bituminous pavements. But this distress are considered by integrating the mix design into the structural design by incorporating the mix volumetric parameters into the performance models and by making suitable recommendations about the choice of the binder and the mix to be used in the different layers. So, it is suggested that you can use rut resistant mixtures in the layers and these mix parameters can be so adjusted so as to have rut resistant mixture so that you may not have to consider this rutting of individual layers in the bituminous layers in the overall rutting of the pavement structure. So, this is what is recommended in the IRC code.

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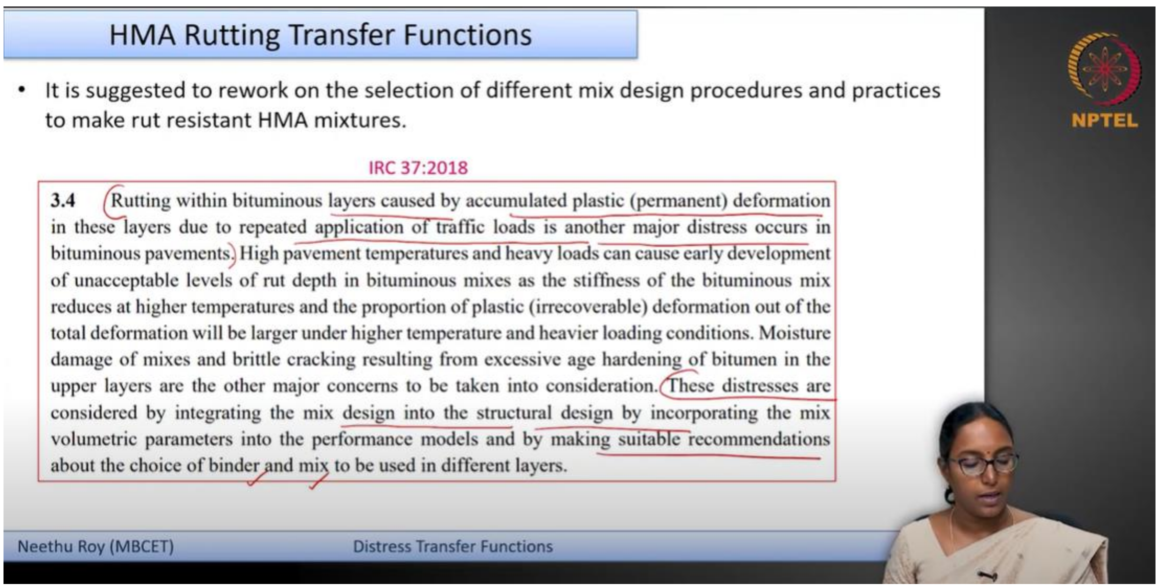

Now, the current mechanistic empirical pavement design model. So, I will just quickly mention what is the model being used in MEP-DG. So, MEP-DG considers the spatial as well as the temporal variation in rutting for bituminous layers as well as granular layers, you can see models here. Say $\Delta_{p(HMA)}$ is actually the accumulated vertical deformation in the HMA layer (that layer alone) is represented as this expression which has parameters such as ε_r. So, $\varepsilon_{r(HMA)}$ which is actually the elastic strain that is calculated by the structural response model. So, you do a structural analysis or the layered elastic analysis and you can represent what is the elastic strain in the HMA. So, this is similar to what we have already discussed, that is, the elastic strain is something proportional to the plastic strain. And n is the number of load application and T, the payment temperature is also a major factor which is incorporated in this model. And then k_z is something called the depth confinement factor. So, that it will take into account the confinement pressure that is acting on the material.

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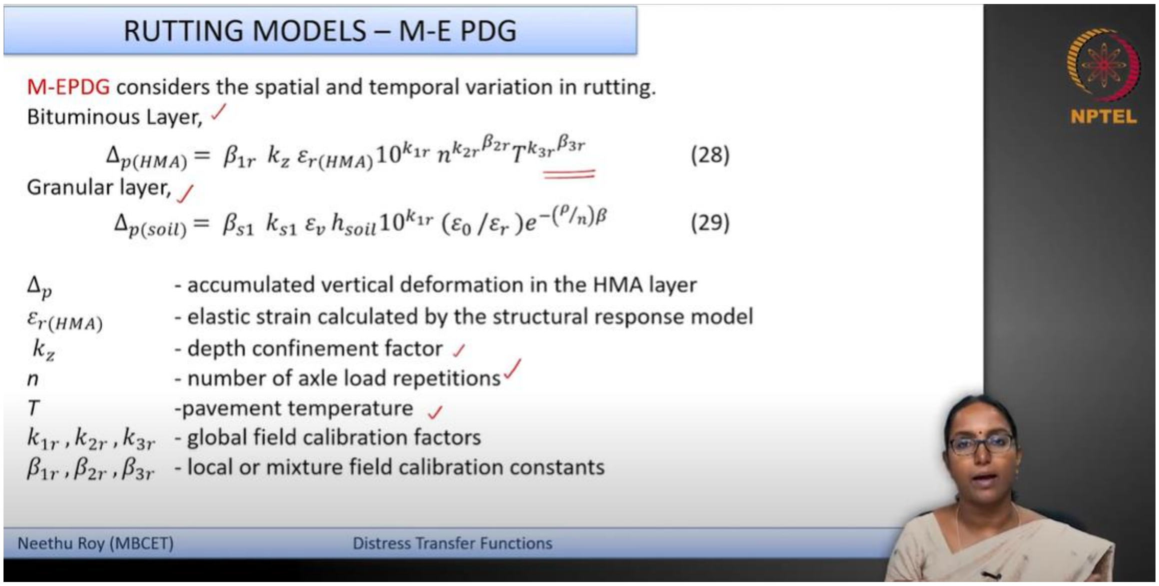

And then you have another expression for the granular layer which is Δ_p for soil which has parameters like ε_v, which is the average vertical elastic strain in the layer, which is again calculated by the structural response model. And ε_r here is the resilient strain which is imposed in the laboratory test to maintain the material to obtain the material properties. And then h_{soil} is the thickness of the unbound layer. And also, there are constants like ρ and β in here. So, these ρ, β and all some of the constants have individual equations to capture all this. So, I am not discussing all that in detail but just wanted you to highlight the fact that MEPDG has given a similar approach.

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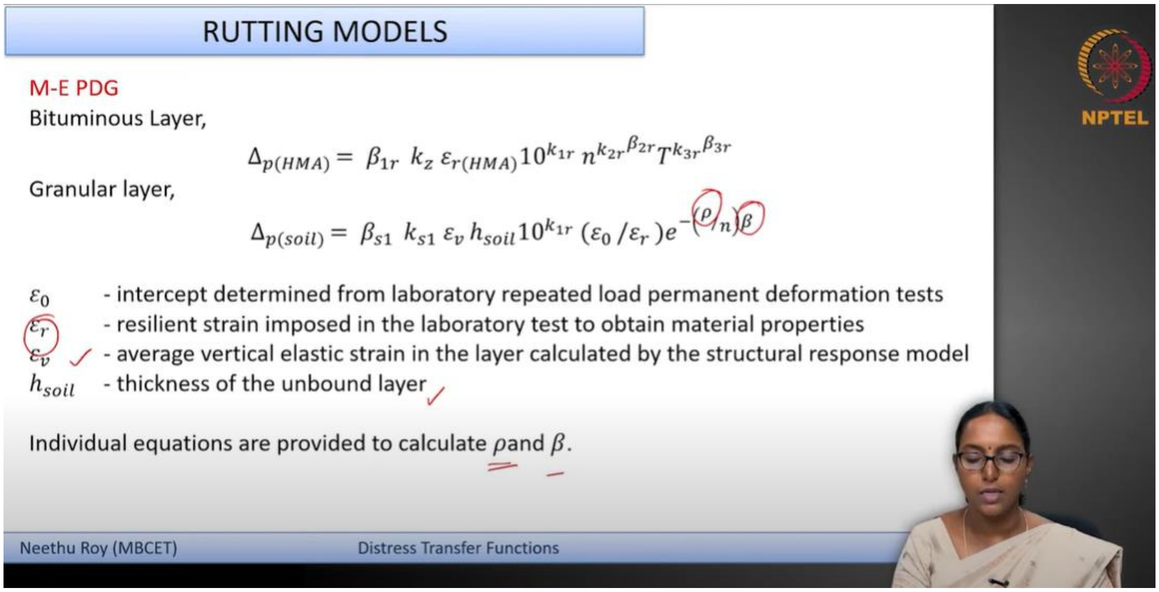

This approach here is to find out what is the accumulated vertical deformation in each one of the layers which essentially is given as a factor proportional to the resilient or the elastic strain in the material. And then, there are various calibration factors like you have k_{1r}, k_{2r}, k_{3r} and so on which are the global field calibration factors and there are the local or the mixture field calibration factors. So, for the performance of the pavement and the performance of the mixture, you have calibration factors which can be utilized to convert this model to be used in your local conditions.

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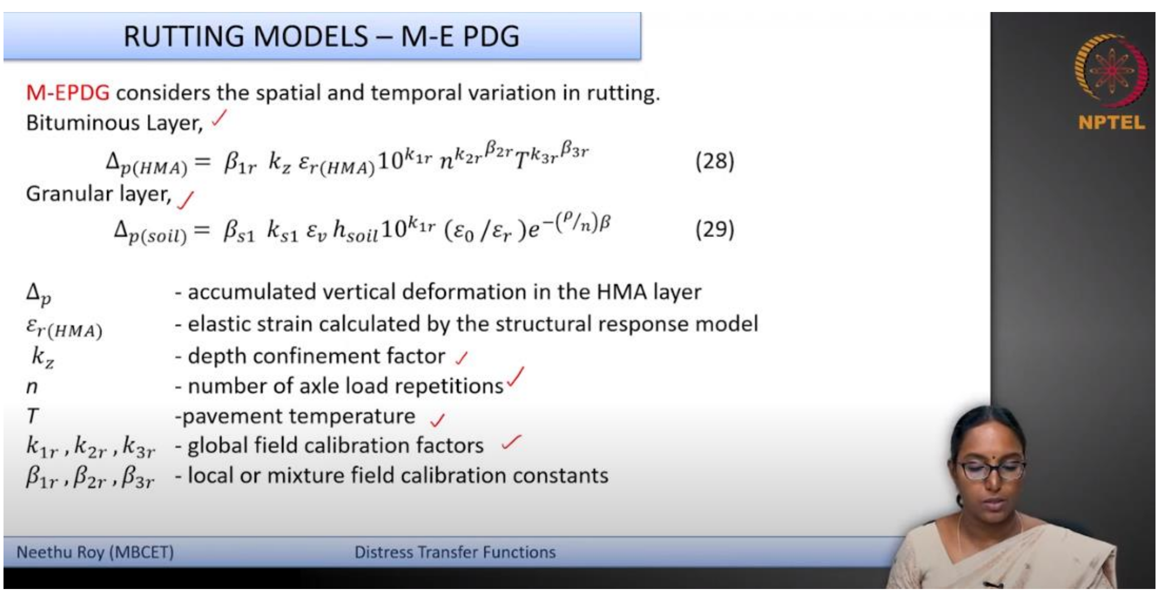

So, what we have discussed so far is the rutting transfer functions. We have seen that in IRC 37, rutting is a subgrade rutting that is being considered whereas there are other approaches wherein you can use the rutting in each one of the layers and the permanent deformations in each one of the layers that can be added together to get what is the rutting that happens on the pavement structure. So, such distress equations can be again developed based on the studies that are conducted on the HMA mixes in the laboratory and the extensive field studies that relates the number of load applications to the permanent deformations that you see in the field.

Now, let us move on to the third mode of failure or the third type of distress transfer function that are normally used in many of the design approaches though this is not used in the IRC approach. Now, what is this thermal cracking or low temperature cracking? Low temperature is divided into two types basically. One is the low temperature thermal cracking and the second one is a thermal fatigue cracking.

Let us see what are these. See, as the pavement temperature decreases, we know that the tensile strength of the material can increase. So, you can see a picture here by McLeod. So, from your right to left you see that the temperature decreases and this graph here shows the tensile strength of the material and the other one shows the thermal stresses that are there in the material. So, we see that as the temperature increases, your strength of the material can keep on increasing but only up to a certain level thereafter the strength decreases. Whereas, if the temperature keeps on decreasing, the thermal stresses that are coming on the structure will keep on increasing. Now, a stage will reach when the thermal tensile stresses that are there on the material exceeds that of the tensile strength of the material, then in that case there will be cracking. So, that is called the thermal cracking.

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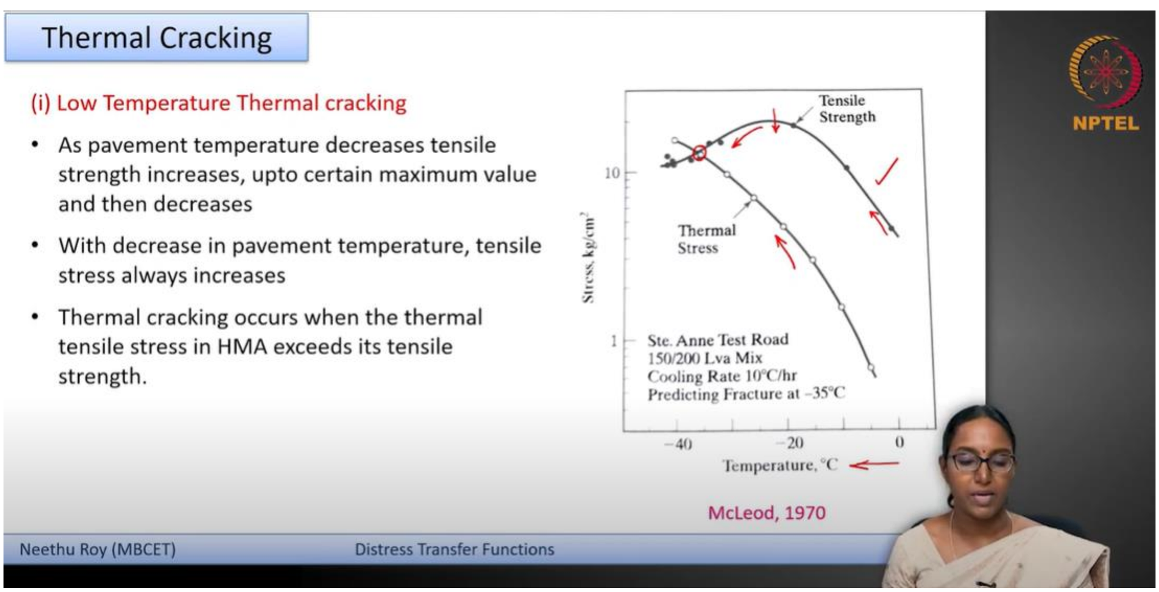

Now, the second aspect is that suppose this tensile stress that is coming on the material is less than the tensile strength of the material, still there is a possibility of cracking if these low stresses are being applied for a continuously for a number of times. So, the pavement will not crack under the single daily application of this thermal stress due to that one temperature stress cycle. But it may crack over a period of time when large such temperature stress cycles are applied on the material. So, this is called a thermal fatigue cracking. Now, when I say the thermal cracking, it is a combination of this thermal cracking plus the thermal fatigue cracking.

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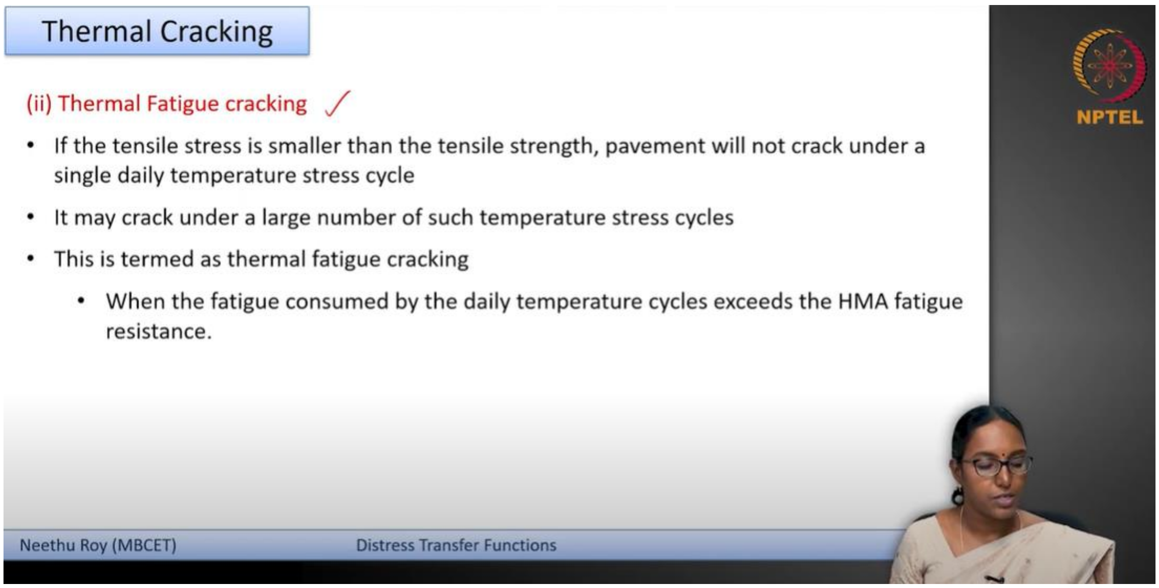

Again, there are various approaches which are used to consider thermal cracking in the design. So, the one which is very common and which considers both the thermal cracking that is a low temperature cracking and the thermal fatigue cracking is given by Shahin and McCullough. And the sequence of steps that are to be followed to do this design procedure or to do this analysis for thermal cracking is given here in this flow chart.

So, I will quickly discuss what this process is. First of all, you have to give the input data. So, input data includes weather data, the material properties, the HMA properties and the design period. Now, when I say the weather data, so any data that actually contributes to the thermal behavior of the material is needed for this analysis which includes the mean annual air temperature, the annual temperature range, solar radiation, wind, surface absorptivity, how the weather changes or how the temperature changes. The second one is the bituminous material. So, again it is the bituminous material that undergoes this thermal cracking phenomena. So, in the bituminous material you need to give all the physical properties of the material, then the aging that happens because of the exposure to temperature conditions or environmental conditions, then thermal conductivity, specific heat, density, the mix composition, what is the coefficient of thermal expansion of the material, what are the fatigue characteristics and the maximum tensile strength of the material. So, all these comes under the material characterization part which is related to the low temperature cracking. So, this information has to be given as an input.

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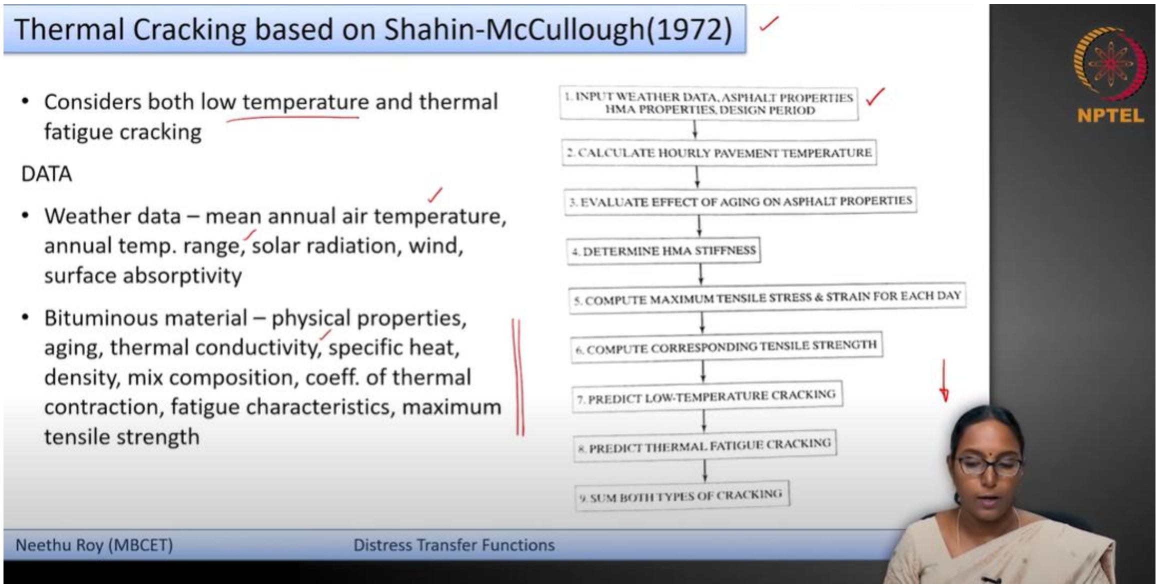

Now, next what we do is that you will calculate what is the hourly pavement temperature because you have to essentially accumulate this damage and see how the damage accumulates over a period of time. So, as you know that the temperature varies on a daily and as well as an hourly range and based on these variations in temperature, the response of the material changes. So, you estimate the hourly temperature at the surface of the pavement, you can use various models for that. Now you estimate the asphalt and the HMA stiffness as a function of time. So, again from the material characterization data you can see that at various temperatures and with aging, the material modulus and the material stiffness changes. So, evaluate the effect of this aging and other characteristics on the asphalt properties and you have to determine what is the stiffness of the material over this period of time. Now, you can use various nomograms which are available, and also predictive regression equations are available to estimate what is HMA stiffness and so on.

So, I am not going into the details of each one of this because you can always refer to the mechanical material characterization course to find out how the stiffness or the material modulus values are estimated.

Now, the next step is to compute the thermal stresses. So, once you compute the thermal stresses, the extent of low temperature cracking can be evaluated by comparing what is the maximum tensile stresses with the tensile strength of the HMA at the corresponding temperature.

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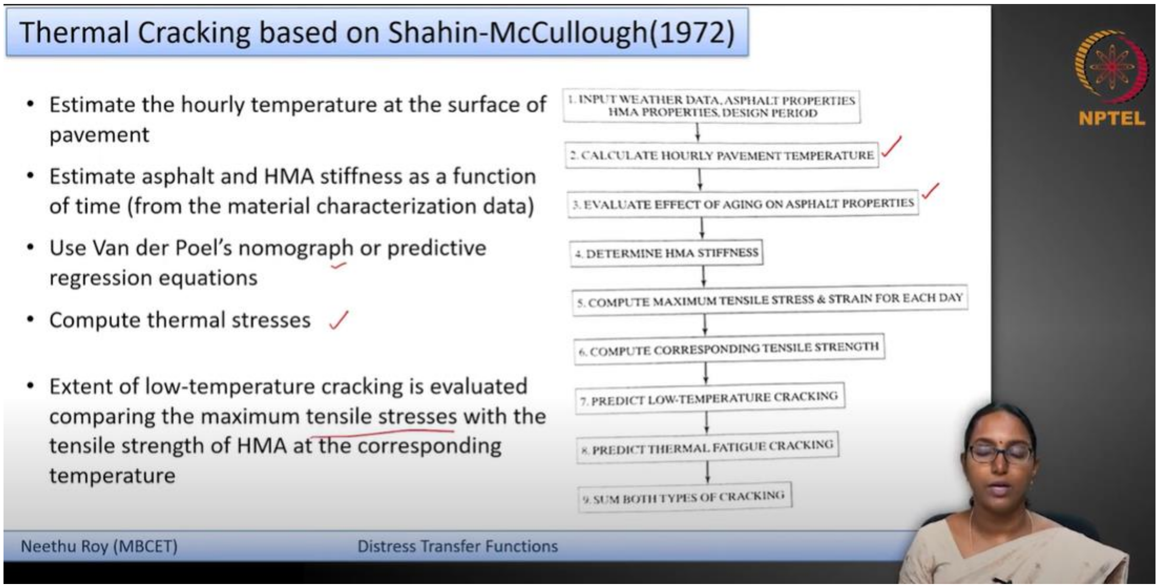

Then, we have to see whether there is a failure probability or not. Now, the probability of failure is given as $P(\sigma - H) > 0$. Now what is the σ? σ is the maximum tensile stress that is coming and H is a tensile strength of the HMA material. So, at that particular temperature if the stress exceeds the strength of the material, there is a possibility of failure. Now, this is the first aspect wherein you determine the thermal cracking possibility or the thermal cracking is being predicted based on this approach.

Now the next comes the thermal fatigue cracking approach. Now, this aspect has to be done in a similar way as you find the fatigue cracking due to repeated loading. So, here, a similar model can be used but it is for a low temperature. For low temperature, the material moduli and the material relationships can be developed and then based on that you can predict the fatigue life and you can use a similar approach as the Miner's approach to find what is the damage ratio. Now, for each thermal cycle, what you are trying to find out is that in the thermal cycle how much is the damage that has occurred. Since it is one cycle, your damage ratio becomes $1/N_i$ where N_i represents the total number of repetitions for the i^{th} day for a similar pavement. n is the number of days, so over a number of days you can see how the damage gets accumulated and then you can fit a normal distribution for this N_i that is the cumulative damage that can happen due to the various temperature differences.

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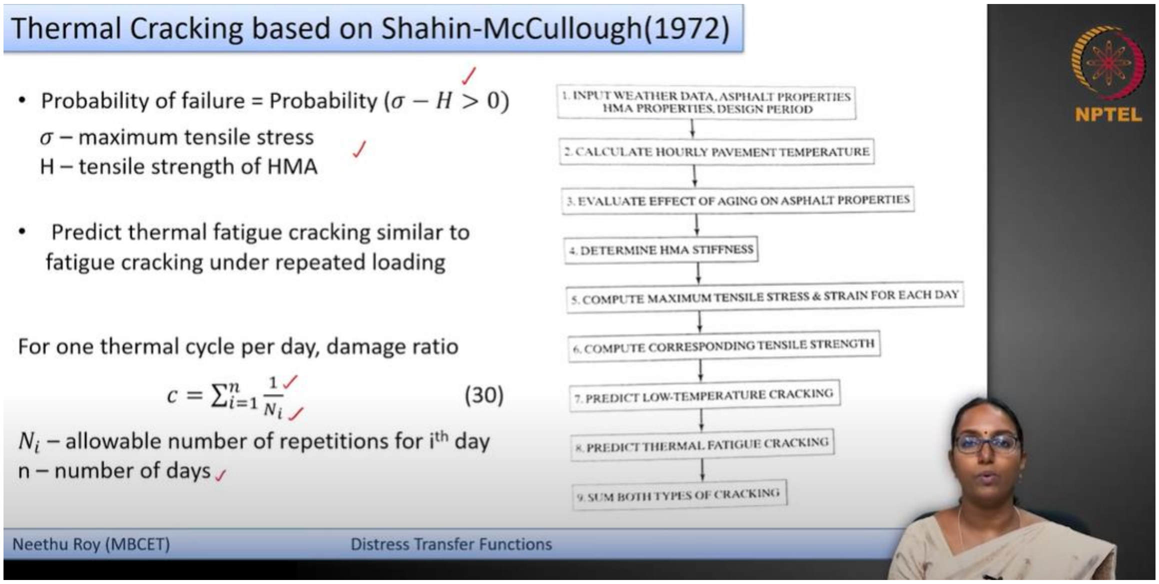

Then, the probability of failure is when the probability of log c > 0. Now, what is c, this is the damage ratio for one thermal cycle when log c > 0, it means that c is always less than 1, that is c has not crossed 1. So, then when the damage ratio is less than 1, you see that the pavement is safe.

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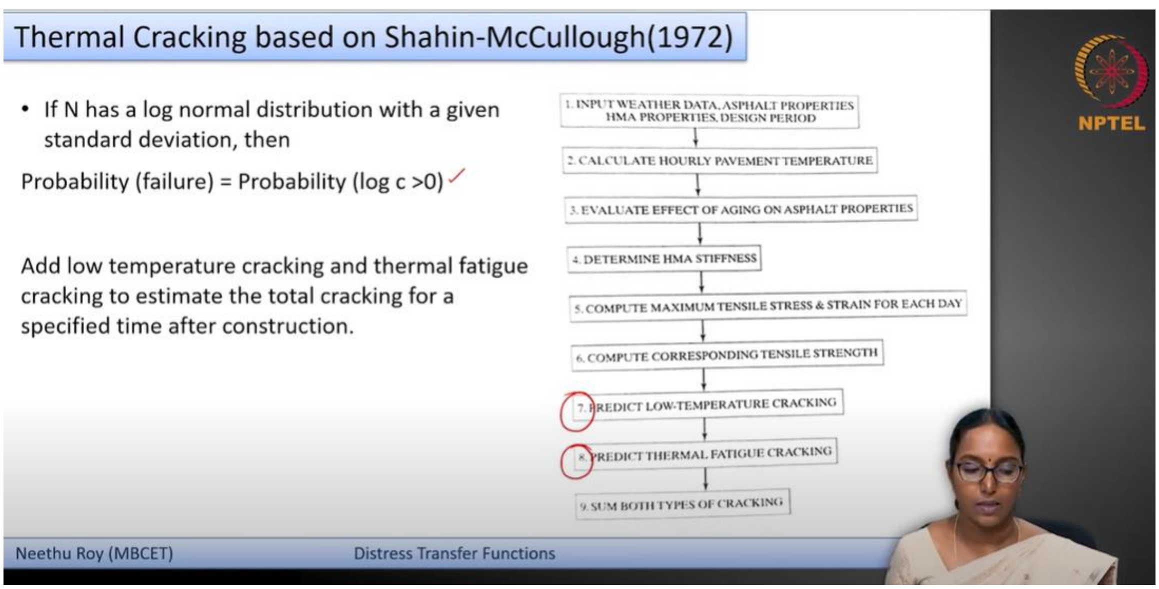

So, what we have done is that, in this we have predicted the low temperature cracking and we have also predicted the thermal fatigue cracking using the various approaches. Now, you can add these two low temperature cracking and the thermal fatigue cracking to estimate what is the total cracking in a specified time after construction and see whether this is within the allowable limit or not and whether the design is safe or not. So, this is the overall approach in which you consider thermal cracking which includes both the thermal cracking and the thermal fatigue cracking and how you use it in the design.