Analysis and Design of Bituminous Pavements

Dr. MR Nivitha

Department of Civil Engineering

Indian Institute of Technology, Madras

Lecture – 26

Environmental Effect - Part 03

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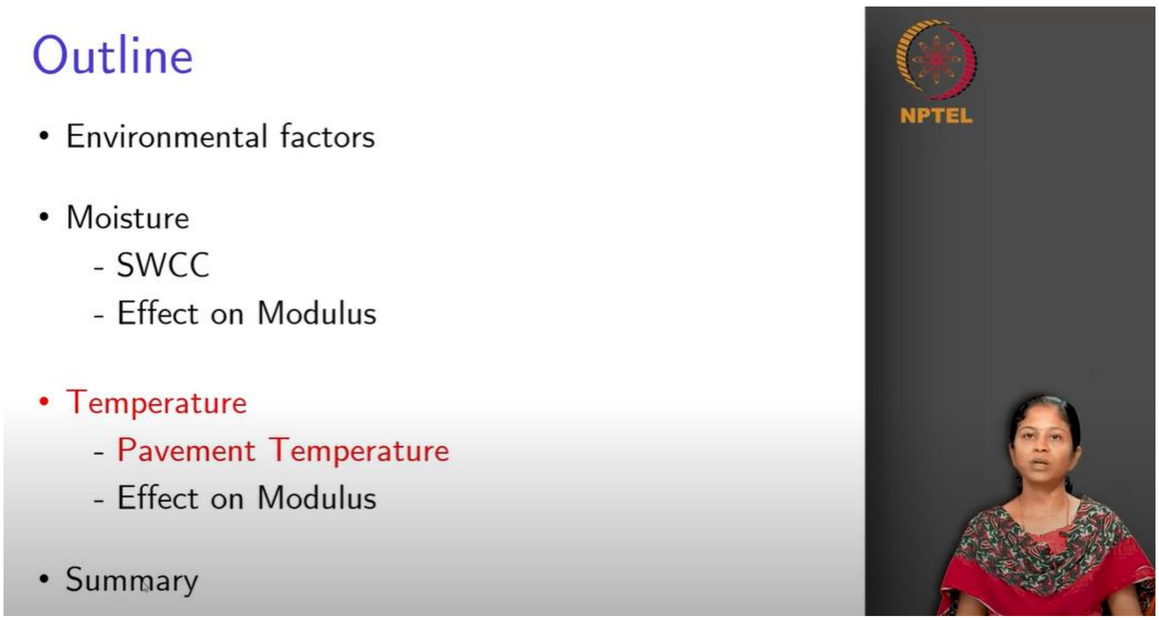

In this lecture, we are going to talk about the influence of temperature on the modulus aspects of pavement. So, we had already said that the influence of temperature is significant in the pavement layers as it influences the modulus directly. For the granular layers, it is significant only when the temperature falls subzero and we have the ice formation. So, considering the absence of such kind of ice formation phenomena in most locations in India, we will be only focusing on the effect of temperature on the modulus of the bituminous layers. So, here the air temperature would be something that we will be able to measure, but the pavement temperature is what is going to influence the modulus. So, there is a specific relation that is defined between the air temperature and the pavement temperature. So, the first aspect we will focus on is this relation between air temperature and pavement temperature, how to determine the pavement temperature. So, once we get the pavement temperature, we will see how the modulus depends on this pavement temperature.

So, we will start with defining the influence of temperature on bituminous layers, we can see asphalt bound materials exhibit varying modulus depending on the temperature. So, this modulus parameter can vary from 13 to 20 MPa or more. So, in this range or more during the cold winter months, compared to the normal value, when the temperature drops, it can vary from 13 to 20 MPa to about 700 MPa or less during the hot summer months. So, from the nominal value it can go on this side which is like 13 to 20 times or as the temperature increases to about a value of plus or minus 700 MPa. So, this is the influence of temperature on the modulus of bituminous layer. So, how does temperature vary? We know that the air temperature has different variations throughout the year. So, if we take a particular day, there is going to be variation in temperature. So, let us say if this is a given day, maybe this is at midnight, the temperature might be different, then it will increase throughout the day and then maybe it will reduce something like this. So, the temperature will vary in a given day. Similarly, in a year also there, will be variation in temperature. During winter, the temperature will be the lowest and during peak summer, the temperature will be highest. So, over this period, there is a gradual variation in temperature. Also, a third dimension is the variation in temperature along the depth of the pavement. So, we usually get information related to air temperature. So, that is based on the solar radiation, we will be measuring air temperature. This air temperature has to be converted to pavement temperature that is usually done at the surface or at a location which is closer to the surface. Now, we have to see how this temperature varies along the depth. So, if we take a conventional pavement system, so we have about 40 mm as the BC layer. So, let us say that we have 120 mm DBM, let us say for example, so in total we have 160 mm as the bituminous layer. So, over this 160 mm, it is important that we quantify the influence of temperature. Again, it is more approximate if we consider one temperature value across the whole depth of this 160 mm, because the temperature at the surface might be different and at this bottom most point at 160 mm will be different. So, it is ideal that we consider at least 2 or we divide this 160 mm into 2 or 3 segments and take different temperature value for each of this segment. So, these are the temperature variations in a pavement.

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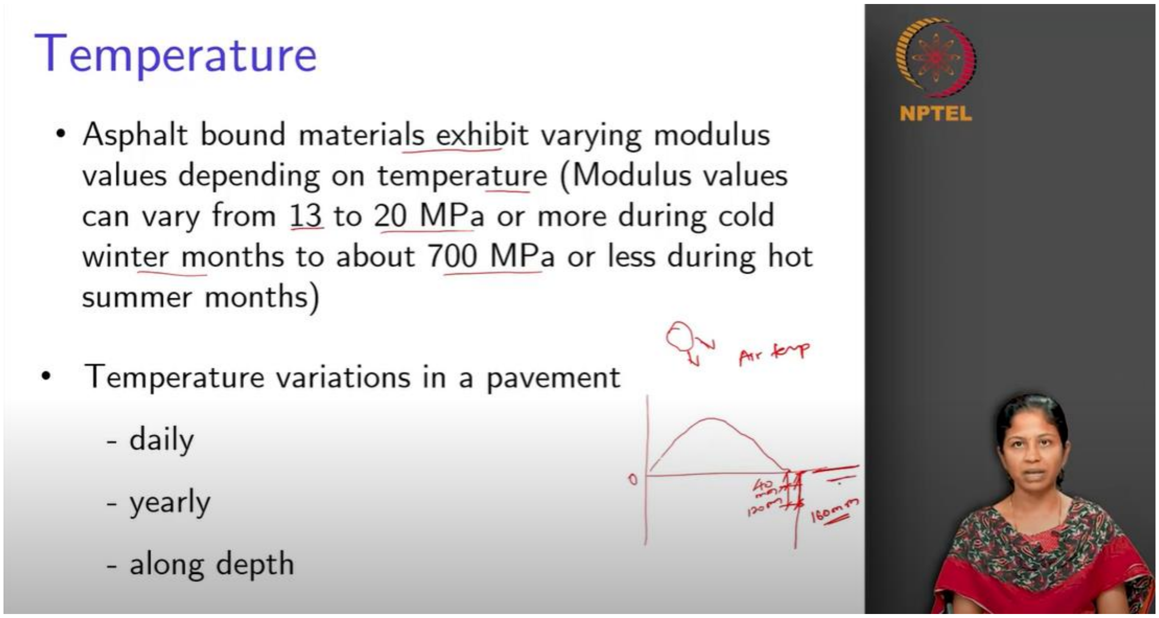

Now, let us see for a given case, how the air temperature varies in a given day, what is the corresponding variation in pavement temperature at the surface and at different depth in a pavement. So, if you look at this again, it is not for a location in India, so you will see very low temperatures. If you look at this, this is midnight. Let us talk about air temperature first, which is this dotted line. So, this is at midnight, the air temperature is -5 degrees or so. So, it keeps dropping in the night and then during the day, it increases, reaches a maximum at about 3 pm and then it keeps reducing like this. So, this is the variation in air temperature throughout the day. We have already seen that the solar radiation is one important parameter, which is going to influence this air temperature variation. Now, if you look at this solar radiation, which is also plotted here, during the night when the sun is not present, the solar radiation is almost 0, you can see this y-axis which quantifies the solar radiation, the solar radiation value is almost 0, then the solar radiation increases. So, during the midday, the solar radiation is the maximum and then it reduces. So, we can see that the air temperature also reaches a maximum, but there is a small offset between the time at which the solar radiation value reaches the maximum and air temperature reaches the maximum. But there are many studies which have shown that solar radiation is proportional to air temperature. In a few slides down, I will also be showing one of one such relation.

Now, let us come to the pavement temperature. What we are seeing here, let us now ignore this effect of solar radiation, remove this effect. We will now focus on the surface temperature of the pavement. So, you can see here. So, as when this is the air temperature, the pavement temperature is slightly higher. So, during nights when the temperature is subzero, compared to the air temperature, the pavement is warm. So, you can see here, this is the surface temperature of the pavement. So, then as the temperature keeps increasing, the surface temperature increases, it reaches a maximum and then it reduces. So, again, we can see here, this is the point at which air temperature reaches the maximum, but we can see here, the surface temperature reaches a maximum at some other point at some instance, even before the air temperature reaches the maximum. So, this is with regard to the surface.

Now, let us take another point, which is at 5 cm depth, which is 5 cm below the surface. So, you can see here, this is the line corresponding to that. You can see this particular point, let us now compare this 5 cm depth with the surface. So, this point is warmer than the surface. So, at a depth of 5 cm, this point is warmer than the surface up to a particular point. And then you can see here that it is less warm than the surface, the surface temperature seems to be higher. And then again, this begins to increase. So, during the time when the pavement is exposed to the solar radiation, the surface temperature is higher. But at some other instance, you can see that other depth values seem to have higher temperatures. If you see this is a 20 cm depth, if you look at this line here, which corresponds to 20 cm depth, you can see it is warmer most of the time except during the day when there is solar radiation, and then it continues to be higher. So, that is why we have to capture the effect of pavement temperature along the depth because it does not have a similar trend at each of the depth values. So, this is with regard to the temperature variation in a given day.

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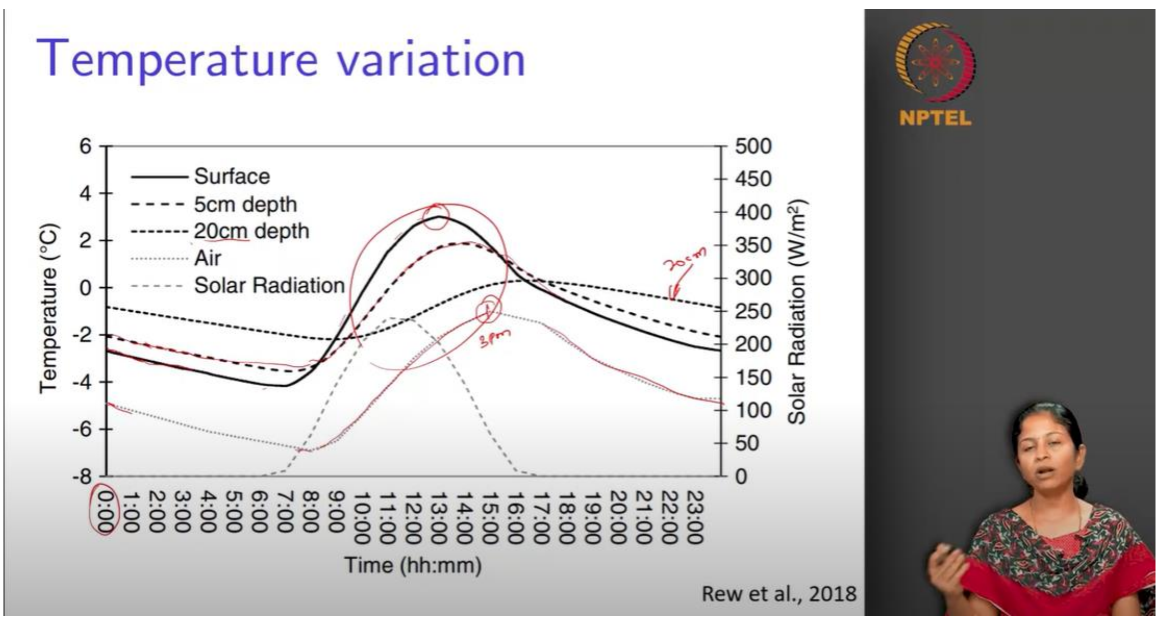

Now, if I plot the average temperature which I measure over a year, we will get something like this. This is the yearly maximum temperature which is plotted for a longer duration from 1970 to 2019. So, this is yearly maximum air temperature in a given year considering all the 365 days, what is the maximum temperature that has been recorded. So, that is plotted, we can see here it has a nice cyclic trend. So, this is the yearly maximum air temperature. Most of these studies use artificial neural network kind of a technique to predict the air temperature. Let us say we are now in 2022, we want to design a pavement whose design life is 15 years. So, I want to know the air temperature up to 2037. I have pavement, I know the pavement temperature previously, I know the pavement temperature history. So, using that, I can use one representative value for the subsequent years. Alternatively, we can predict air temperature for the subsequent years from 2020 to 2037, we can predict the air temperature and from the air temperature, we can calculate the pavement temperature and use it also. So, different approaches are followed.

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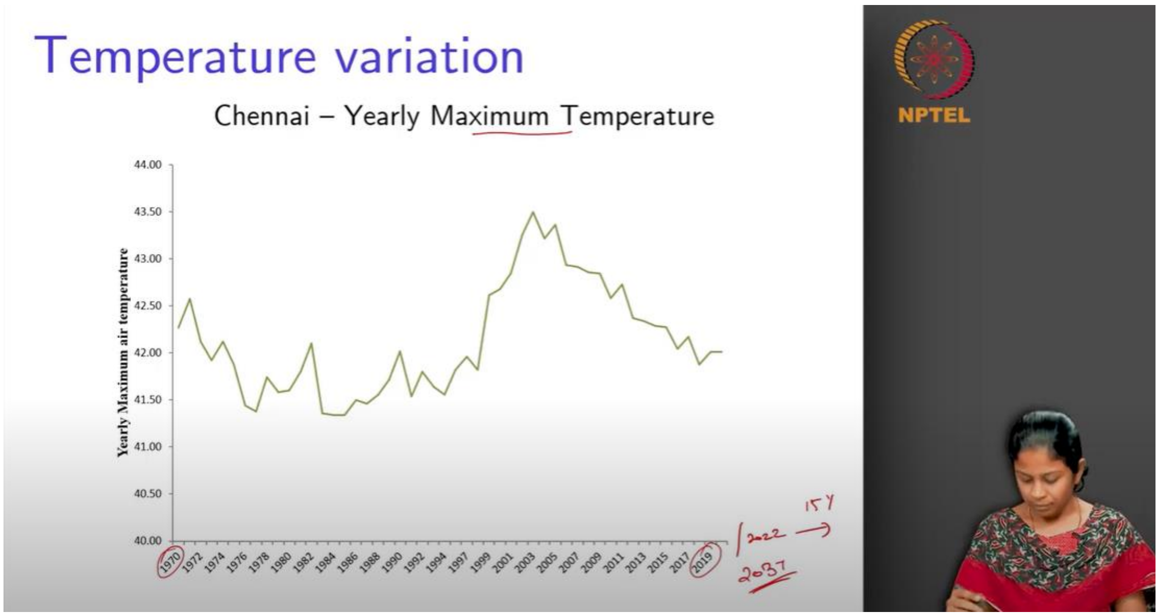

You can see here, this is a case wherein the temperature was predicted, we actually tried to use artificial neural network and predict the air temperature for a particular year. So, this is for year 2009, you can see here. So, this is the actual maximum, the square ones are the actual maximum and the star ones are the predicted maximum. This is the daily maximum and minimum value for a given year, actual minimum values are given in circle and the predicted values are given here as triangles. So, for a given year, we were able to closely predict the actual maximum and minimum values for a given year. So, similar techniques can be used to predict the temperatures for the design period and representative value or history data can also be used, which is an easy and convenient option. So, in either case, we need information about pavement temperature. But currently in India, we have very limited temperature, very limited information on pavement temperatures. If you look at locations in US, they have a program called LTPP, Long Term Pavement Performance. So, as part of this long term pavement performance, they have specific locations, wherein they collect lot of data with regard to the traffic, with regard to the environmental factors, with regard to pavement temperature, with regard to the moisture content, many parameters are collected. So, based on that, we will be able to get some representative value for a given location. But in India, we do not have such kind of data so far. So, the ideal thing would be to establish an air temperature-pavement temperature correlation, because the air temperature information is widely available. So, we can use that and predict the pavement temperature.

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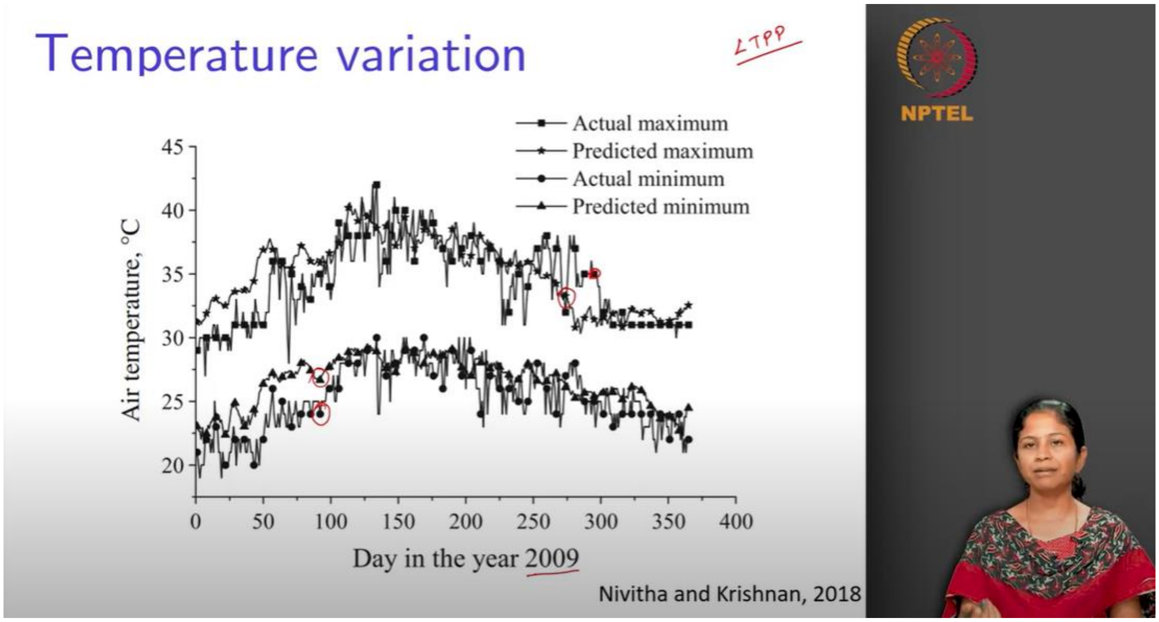

So, this pavement temperature basically depends on air temperature. So, this air temperature is a primary parameter which determines the pavement temperature, but it does not solely depend on air temperature. The relation between pavement temperature and air temperature depends on other factors also. The first one is solar radiation, the amount of solar radiation that is received by a pavement influences the relation between air and pavement temperature. Similarly, the amount of sunshine, wind speed. So, when I was talking about the environmental factors, we said wind speed does not have a separate effect on the pavement, but it influences the manner in which the other parameters interact with pavement. And for convenience in many cases, latitude is used as a representative parameter to determine the solar radiation. If you look at literatures, they specify that for all the locations which fall on a similar latitude, the solar radiation intensity would be more or less identical. So, using that concept, many of the pavement temperature calculations are made using latitude instead of using solar radiation which has to be actually measured or collected from a third source, whereas information on latitude is easy to obtain. So, this parameter is used in calculation of pavement temperature.

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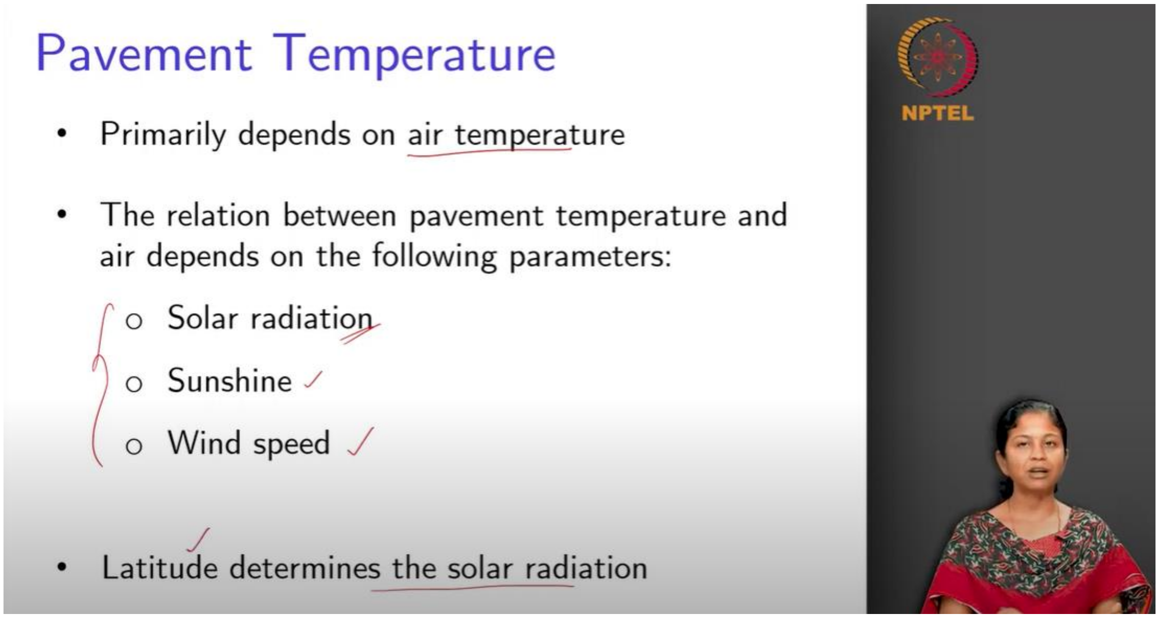

Now, if you look at the correlations, you can see here, this is the minimum air temperature and this is the minimum surface pavement temperature. So, for different days for a given location, if I try to plot the air temperature versus the surface temperature I measure for a bituminous pavement, you can see here they correlate very well. There is much higher degree of correlation between these two parameters. And this correlation is not valid only for bituminous pavements, even for concrete pavements they have seen that this correlation holds true. So, you can look at this plot, wherein air temperature is plotted on the x-axis and the pavement surface temperature is plotted on the y-axis. So, these red dots here given here are for a bituminous pavement and the blue dots given here are for a concrete pavement. So, if you plot a trend line for both the pavements, we see that the pavement surface temperature and air temperature correlations are more or less identical. So, for this particular case, they were able to see that irrespective of the type of pavement we use, the surface temperature of the pavement is dependent on the air temperature to a large extent.

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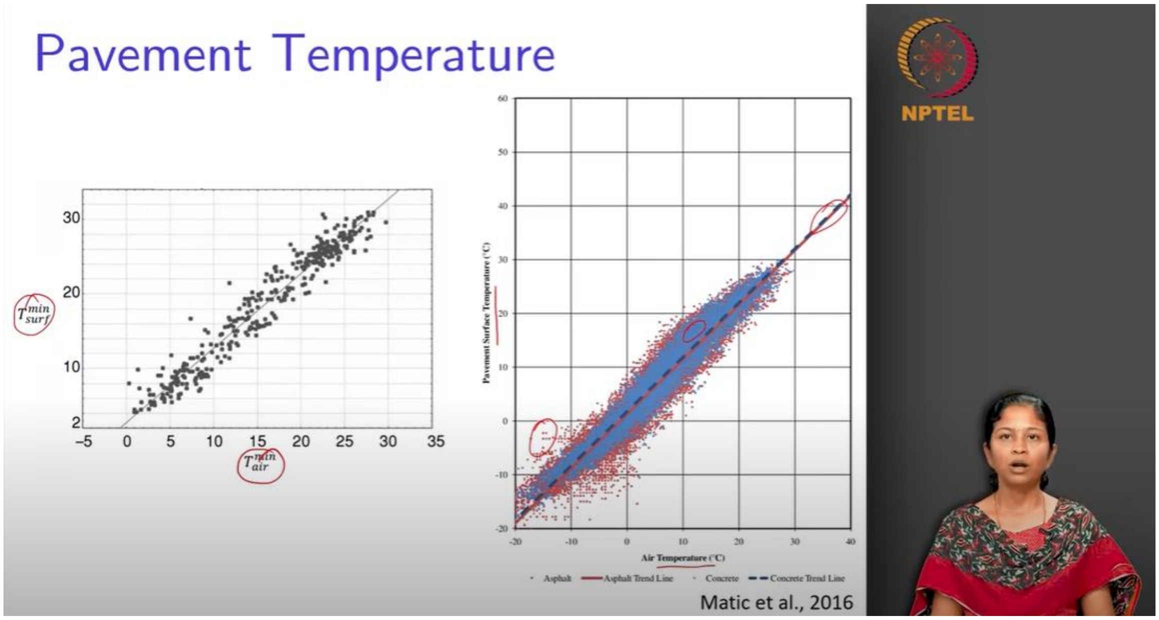

Now, what is the degree of influence of the other parameters that we said the solar radiation and other parameters. So, if you look at this plot, this is pavement temperature you have to mind the unit it is in Fahrenheit and this is air temperature again in Fahrenheit. So, this relation between air temperature and pavement temperature, again, we get a linear correlation, but this correlation is offset depending upon the solar radiation. So, we can see we have 3 different solar radiations, 400 British Thermal Unit, BTU is British Thermal Unit, which is used as a quantification measure of solar radiation. So, it is 4000 BTU per square feet per day, again 3500 and 3000. So, when the solar radiation is higher, for a given air temperature, the pavement temperature is higher. Similarly, when the solar radiation is less for the same given air temperature, the pavement temperature is lesser and so on. This correlation is calculated for a specific wind speed which is 10 miles per hour and a specific sunshine which is 80% of sunshine. So, this actually determines the cloud cover, the solar radiation will remain constant for a given day, but depending on the cloud cover, the amount of solar radiation that reaches the pavement will vary. So, this is the influence of solar radiation we can see, it varies linearly with the pavement temperature, air temperature correlation varies with the amount of solar radiation. The next parameter is sunshine. So, this relation is computed for a given wind speed again 10 miles per hour and for a given radiation, which is 4000 BTU per square feet per day. So, if you see here, this is for 90% sunshine, this is for 70% and this is 45%. So, it is obvious that when we have a cloud cover, the amount of solar radiation that reaches the pavement is lesser, so the pavement temperature will be relatively lower. So, for 45% sunshine, when there is more cloud cover, the pavement temperature is lower for a given air temperature, whereas it is higher for a case with 90% of sunshine. And also, we said this wind speed is going to influence this relation. If you vary the wind speed, again this relation will be different. So, this is the impact of these two parameters.

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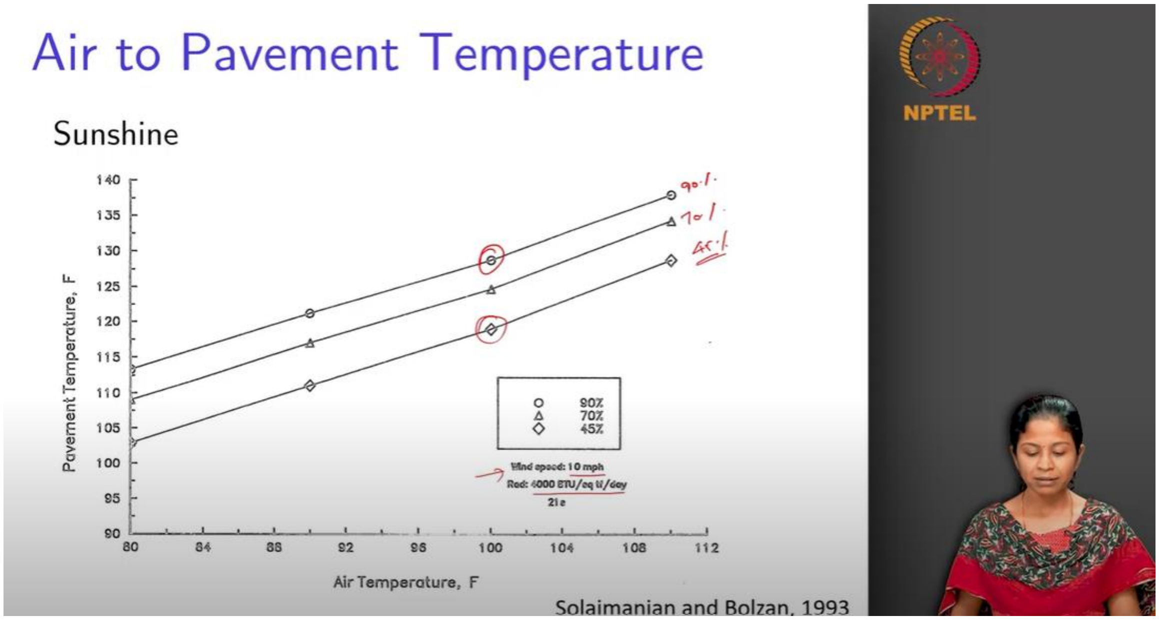

Now, there are a number of models which have been used to calculate pavement temperature from air temperature. There are models which calculate the surface pavement temperature, but there are some studies which have observed that the maximum pavement temperature is observed at a depth of 20 mm from the surface. So, this will be kind of lower here, it will increase marginally here, if this is my temperature, it will increase marginally here and then it will reduce like this along the depth. So, the maximum value is observed is observed at a depth of 20 mm from the surface. So, most of the models use air surface temperature, while some models specify explicitly at 20 mm depth, while some models specify it at the depth at which the maximum temperature is observed.

Now, if you look at these models, we have the model which is specified in SHRP A410. So, there, air temperature and latitude are used as the independent variables to compute the pavement temperature. So, this model is basically computed from the heat flow model. There are two kinds of theories based on which the pavement temperature can be calculated. One is the heat flow equation. So, you have certain amount of heat falling in entering into the pavement system, certain mechanisms through which this heat is dissipated from the pavement system. So, both these, the heat inflow and the heat outflow are equated and based on that the temperatures are arrived. This is based on the heat flow model.

Alternatively, regression models are used wherein information on air temperature is measured, the pavement temperature is also measured and then a regression is established between the two to compute pavement temperature from air temperature. So, you can see here, the temperature at a depth of 20 mm which is the maximum temperature is computed from the surface maximum temperature and a constant. As far as the surface temperature is concerned, there are two equations to compute. I have just shown you the minimum equation. The minimum surface temperature is nothing but the minimum air temperature. There is one more equation available which gives you the surface temperature, which gives you the maximum temperature at the surface. So, both these equations can be used to compute the minimum surface temperature or maximum surface temperature. It could be input here to compute it at the depth of 20 mm.

Similarly, there is another equation which is given, which is called as HANS model. Again, this equation uses air temperature and latitude as the input parameters. This is based on the data collected from seasonal monitoring program which is through LTPP. So, here also they have an equation, this 5 is latitude, this $T_{a(max)}$ is the maximum air temperature and this is the depth at which the temperature is required to be measured. So, here they give a generic equation wherein depending upon the desired depth, we can calculate the temperature. So, this is for maximum temperature and this is for minimum temperature.

And then there is another model which is called as Moseni's model. You can see here this is again maximum air temperature, latitude and depth. So, most of these models have a similar form. They all use air temperature and they use latitude to compute pavement temperatures. There are few other studies which have used these heat flow equations, few studies have used finite element analysis to compute the temperature variation along the depth. So, a wide variety of models are available in this regard.

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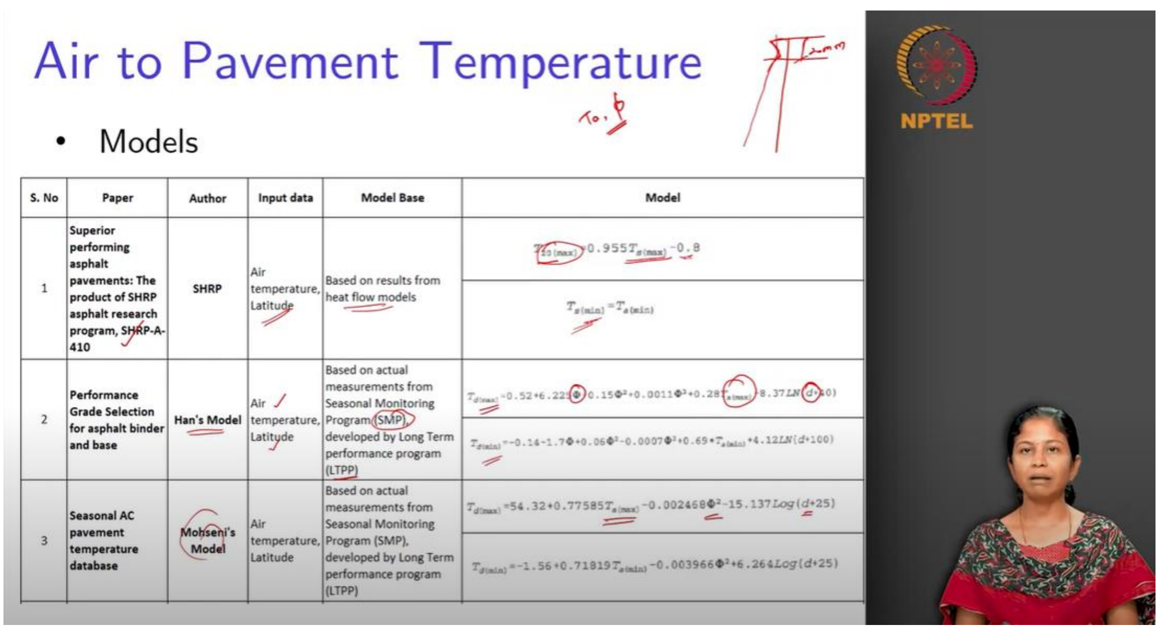

Again, few other sets of models exist by Leukanen that use similar parameters except the variation in the constants. And there is also another equation given by Wisconsin DOT. So, this also depends on maximum air temperature. They have used the solar radiation-daily total solar radiation intensity. And then they have also given at 6.4 mm depth to compute the temperature at 6.4 mm depth, two different equations for air temperature less than 0 and for air temperature greater than 0. So, like this there are wide variety of models available and then there is another equation given by Barber which was one of the primary equations in this regard to compute the relation between air temperature and pavement temperature. So, this is based on solar diffusion theory. You can see here they have given an equation to compute the temperature based on a specific set of parameters.

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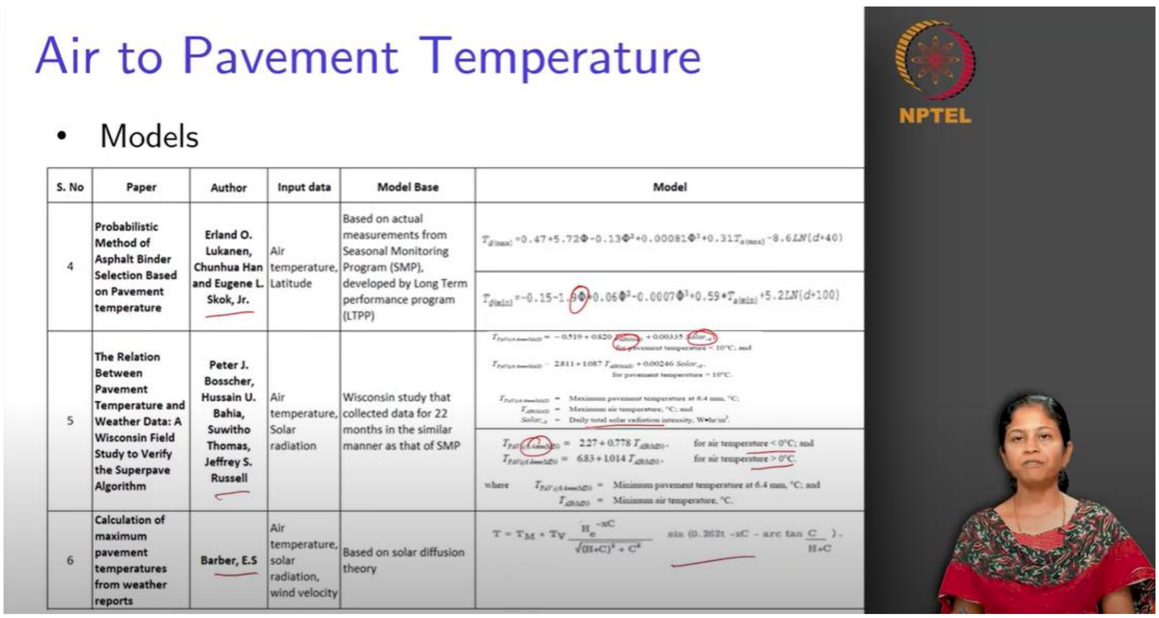

Similarly, some standard nomographs like this are given, wherein the temperature between the relation between solar radiation and air temperature is specified and based on this we will be able to obtain the pavement temperature. Similarly, there are other equations by other authors like this. We have *n* number of equations which are reported in literature. The one important aspect that we should note here is if it is a regression model, the constants that are used in the regression model are valid only for the conditions in which the data is collected. So, let us say that we collect data in US or Canada in some location where it is relatively cold. Can I use and we develop a regression model between air temperature and pavement temperature? Can I use that in a model for Indian conditions? It may not be valid because the temperature conditions in India are totally different. Even if you look at these models you will see that they have given two different equations, one for minimum temperature and one for maximum temperature. So, even in a given location, one single equation is not able to predict the minimum and maximum, the mean and the correlation between air and pavement temperature over the range in which the temperature varies. So, that is why it is highly necessary to have a customized model which will give us the air temperature and pavement temperature correlation for a specific location.

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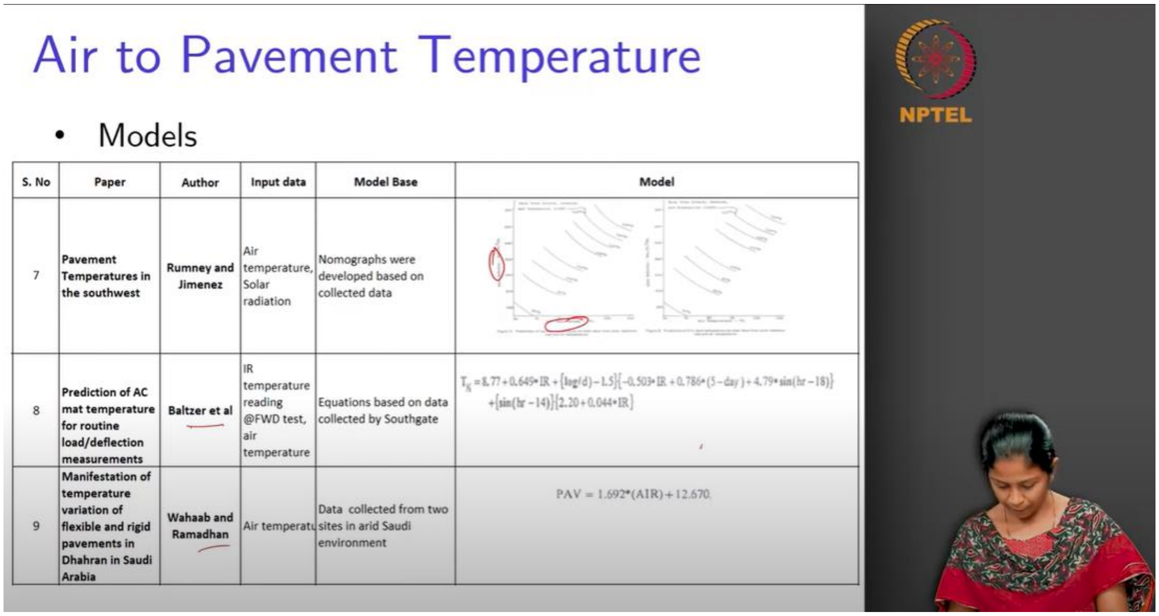

So, in this regard in one of our studies, we have attempted to develop such kind of a correlation between air and pavement temperature. So, we used a form, a generic form like this, constant, another constant multiplied by the air temperature and another constant multiplied by the latitude. So, here also we chose air temperature and latitude as the independent variables to predict the pavement temperature. And this was the regression model that we developed to predict the pavement temperature. Now, we compared the relation, we validated the relation with the data that was collected in Chennai by highway research station. It was in 1970 or so. So, that was one data which was available which had information on both air temperature and pavement temperature. So, we wanted to check the validity of this particular model. Again, this model was not developed for temperatures collected in India because officially there is no such temperature information that is available and only if one collects this information, we will be able to develop an in-house model. But using the concept that for locations lying on a given latitude, the solar radiation is the same, we chose locations in the southernmost part of US which had similar latitude as that of India. So, for those locations, the air temperature and pavement temperature were obtained from this LTPP program which is long term pavement performance. Locations were selected such that they have similar latitude as that of India. Then, that particular data was used to develop this regression model and it was validated with the data that was collected from highway research station. So, if you now look at this, this blue line is the actual pavement temperature which was collected by highway research station and how other models were able to predict this pavement temperature. So, you can see here, this was HANS model which is one of the popularly used models to predict the pavement temperature. Now, you can see here this is SHRP model, this is Lukanen model and other models.

So, you can see this regression model which was developed as part of this study by choosing locations which have similar temperature conditions as that of India. So, we were able to get a better correlation between the air and pavement temperature and it corresponded well with the temperature that was measured in field. So, this black line is the regression model, this is the result of this particular regression model. So, it is necessary that we predict the pavement temperature precisely because the modulus value is going to depend on this pavement temperature. So, unless we get this parameter correctly, there is going to be a lot of approximations associated with calculation of modulus. So, the first part is to identify a correct model to calculate the pavement temperature for a given air temperature.

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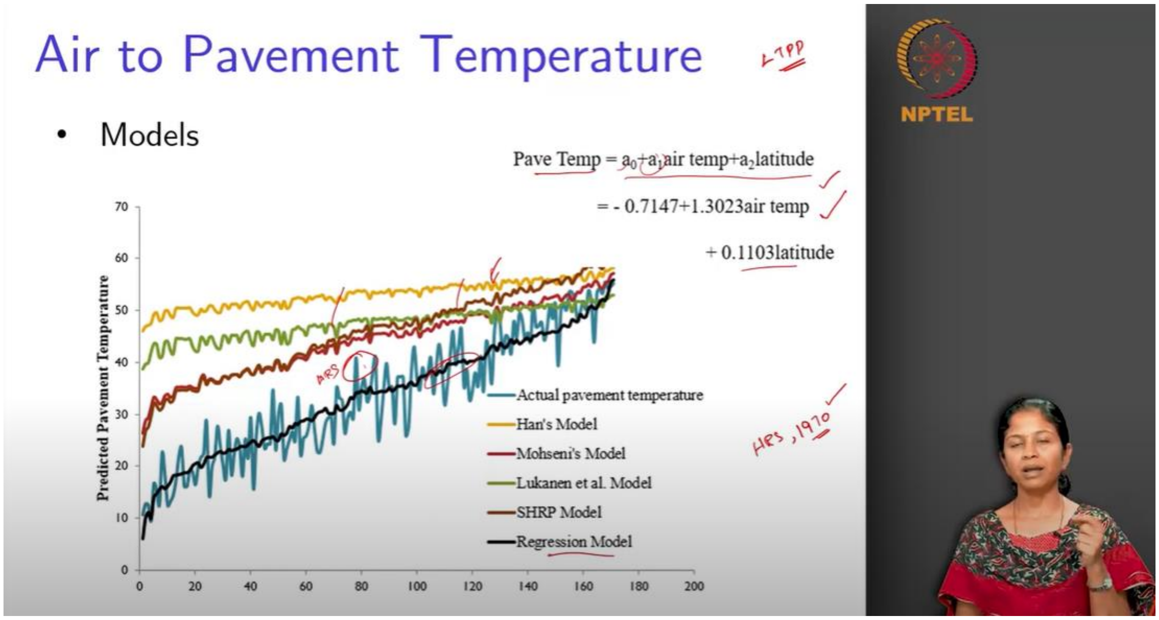

Now, we can see how the temperature varies along the depth. So, if you see here, this is an asphalt concrete, base, subbase and subgrade kind of a system. So, let us compare the variation along the depth for different time durations in a given day. So, this is at midnight, at 00 hours, you can see here surface is less warm. So, somewhere at 20 to 30 cm, the maximum temperature is observed and then it reduces and then reduces. Similarly, if I take at 4 am in the morning, I get a similar trend like this, this is this pink line here you see here, this is at 4 am in the morning. Now, if I take 8 am in the morning, once we start receiving solar radiations, the trend reverses. You can see the temperature at the surface begins to increase, reduces and then increases because the bottom part of the pavement is still warm. So, it again begins to increase at this particular portion. So, as time progresses, let us say that it is about midday, you see surface temperature is much higher or it is the highest and then it begins to reduce at depth. Similar thing is seen at 16 hours also. So, once the solar radiation stops or once the sun sets, you see that again, the surface temperature reduces. So, this is a trend that is very commonly observed in most of these studies. So, if we have to establish the correlation, again the point at which the maximum temperature is observed is also a variable here, depending upon the time of the day. So, this should also be kept in mind.

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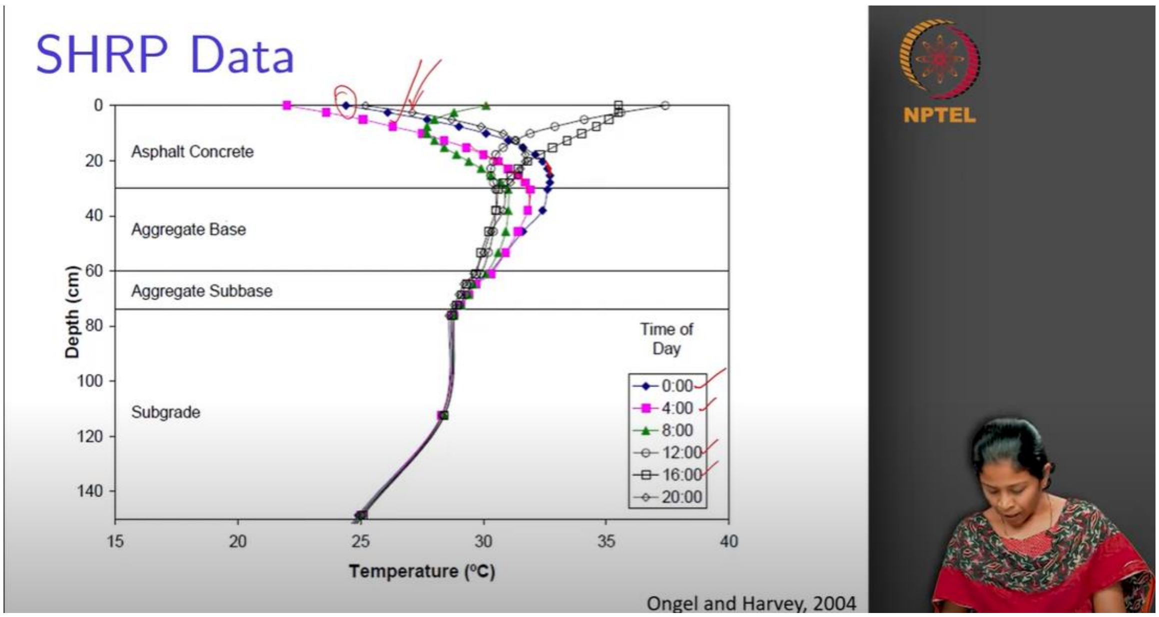

There is also another study which shows data collected for Sweden. This is again at different time periods, you can see here 10th February, 15th, 20th, 25th and all that, but more or less at a specific, at a fixed time. So, you can see depending upon the air temperature variations prevalent in that particular day, the temperature variations are observed along the depth of the pavement. On some days, it is observed to be maximum at this particular point, while on some days, surface is observed to have a maximum value. The other thing that we should remember here is beyond a particular depth, so, here we can see beyond a particular depth, the temperature starts converging or irrespective of the duration, the surface temperature, the time of the day, all the temperatures narrowed down on a closer range.

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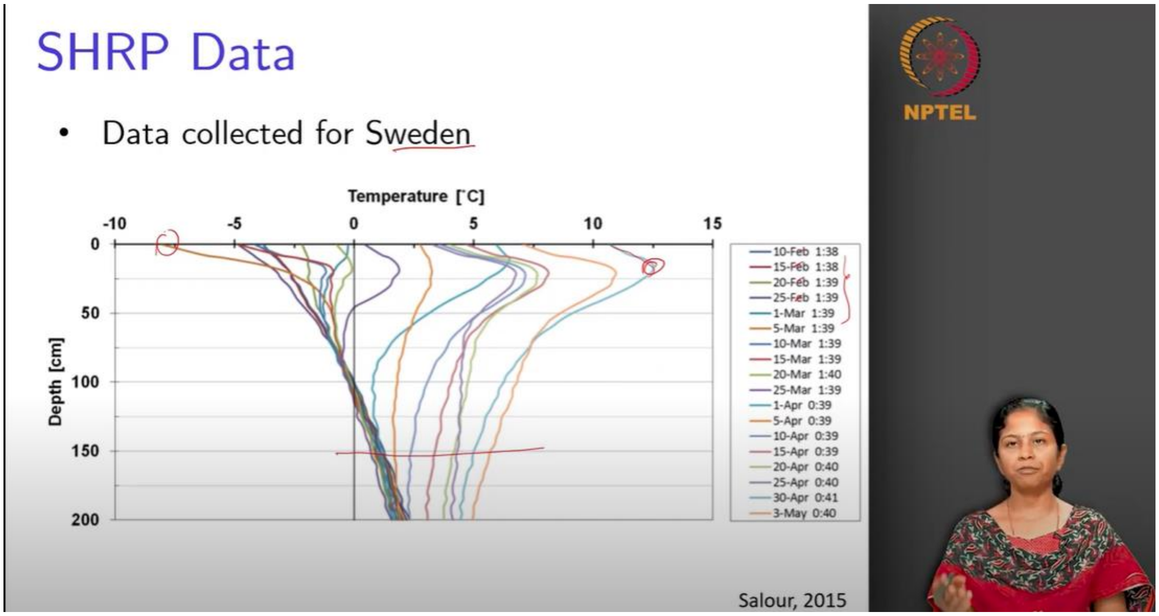

So, this is also observed in the previous study also, you can see here, this is for the subbase layer again, which is for the depth, but you can see here, once we reach this particular layer or so, the temperature almost like converges to a specific case and beyond this point, you can see there is barely any effect of temperature. So, this like we discussed for the moisture content, here also we see that the effect of temperature is observed only up to a certain depth and beyond that there is very little variation of temperature.