Analysis and Design of Bituminous Pavements

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Lecture - 33

Reliability in pavement design – Part 03

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Hello everyone, welcome back. In this lecture, we are going to look into the reliability aspects and its considerations in the AASHTO 1993 design procedure. So, let us get into the design procedure straight away.

So, this is the AASHTO guide for design of pavement structures. In fact, it is the older version of the AASHTO guideline. It is succeeded by the MEPDG in 2004. Still this standard introduces the concept of reliability and it starts with designing a pavement by assuming a reliability level. So, it is more relevant to look into the reliability perspective from this standard as well.

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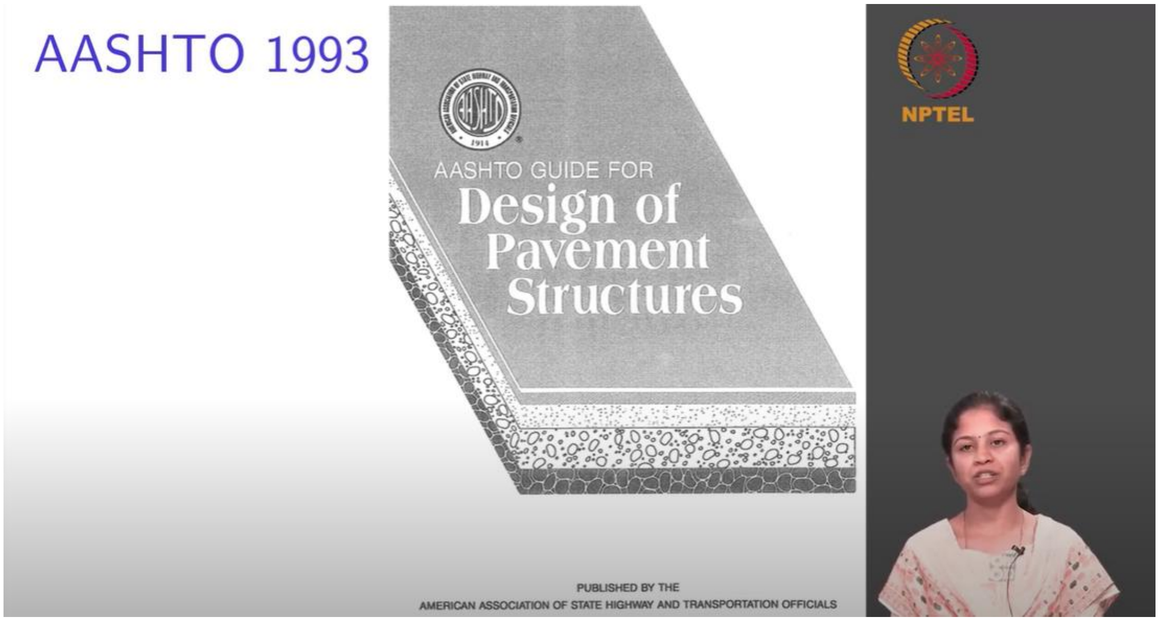

So, now this is the equation which is given in AASHTO 1993 to predict the number of load applications. This W_{18} is the expected number of load applications. So, it is defined as predicted number of 18 kip, which is nothing but equivalent to 80 kN equivalent single axle load repetitions. So, you calculate the expected number of load repetitions through this equation. It has a lot of parameters. Let me introduce a few of these parameters one by one. The first one is Z_R, which is nothing but the standard normal deviate for a given reliability level. We will look into the details of each of these parameters. Then the next one is S_0, which is combined standard error of the traffic prediction and pavement performance prediction. So, we have a standard error based on the standard deviation, which could be calculated for the traffic parameters. Again, we have the same variability associated with the performance prediction. So, combining all of it, we get an S_0 value. Then the third parameter is structural number. This structural number gives the relative strength of a pavement. So, a pavement with a higher structural number is said to have a higher load carrying capacity. So, again, we will see about this. Then we have a lot of constants. We have ΔPSI which is the difference between the initial design serviceability index P_0 and the design terminal serviceability index P_t. So, hold on to all these things for a while. Then we have structural number and we have M_R, which is nothing but the resilient modulus of the granular layer. So, using all these parameters, we are going to calculate the predicted number of load repetitions. We have a similar equation with to compute the allowable number or the maximum number of load repetitions. So, obviously, a ratio of these two is going to tell us how whether the pavement has sufficient load carrying capacity.

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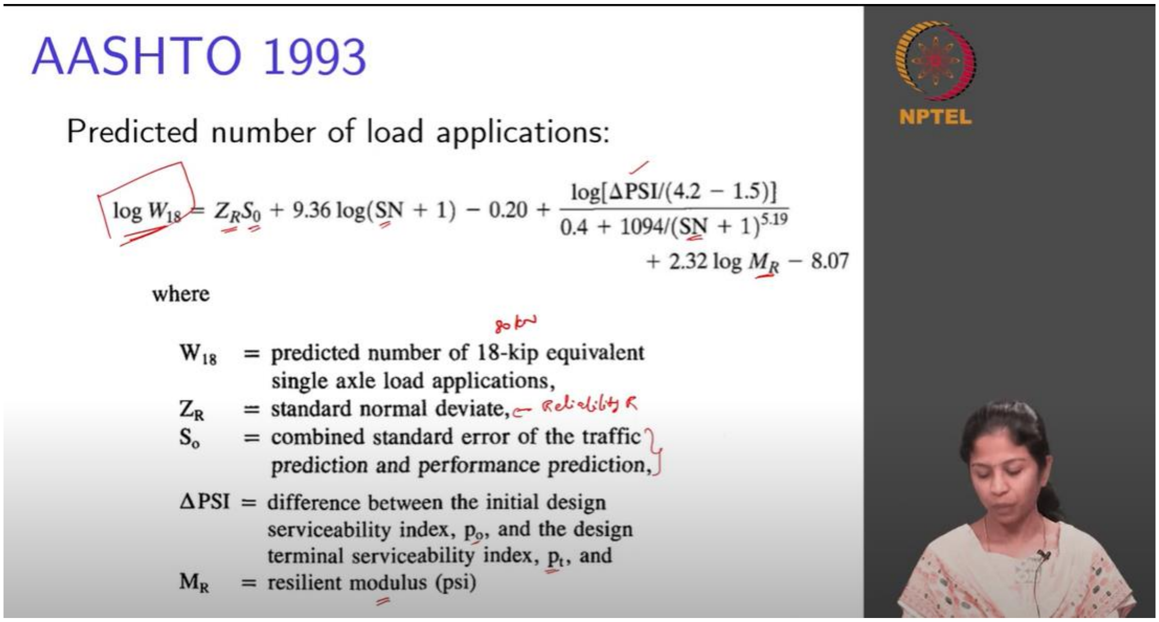

But, before moving on to such comparisons, let us define all these parameters which are given in this equation one by one. So, these are the key terminologies that I am going to discuss. So, we are going to discuss the time period, performance period, analysis period and so on. What is serviceability? How it is taken into account? What is reliability from AASHTO 1993 perspective? How is structural number quantified? Traffic, most of these in terms of EALF and the truck factor which you should have seen earlier. EALF is used to convert any given axle to equivalent number of repetitions of standard axle and mixed traffic is used to take into account of different types of vehicles into one parameter. These things, we will see subsequently and the environmental effects and how they are considered and finally, how to arrive at this standard normal deviate. So, at the end of all these topics, we will go back and revisit the same equation and see how to use it for the design procedure.

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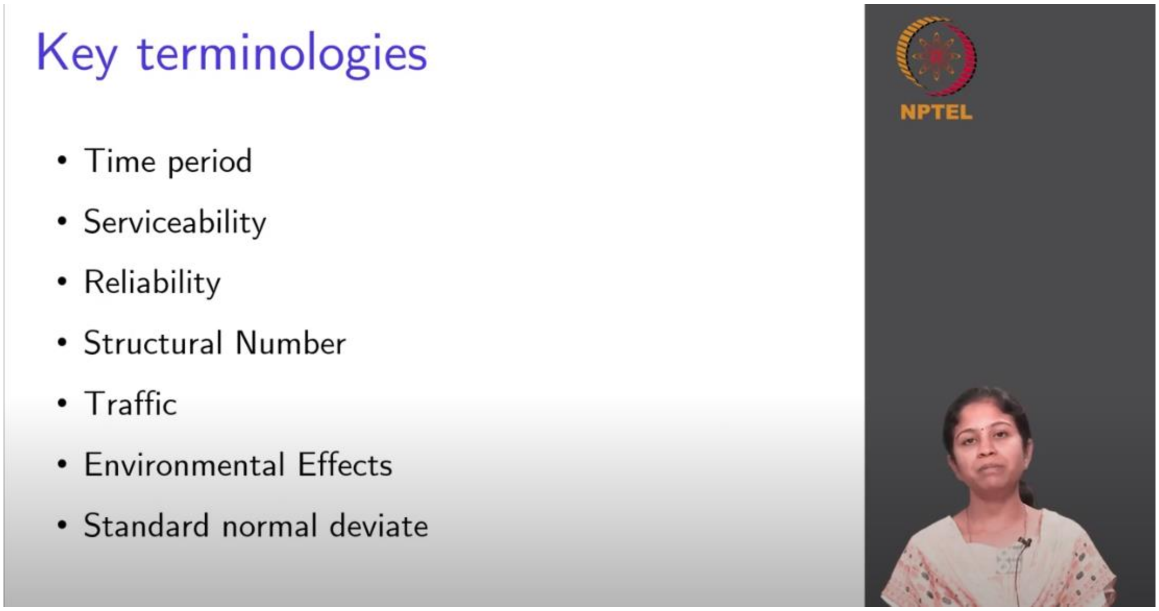

So, what is the time period aspect here? AASHTO 1993 defines two parameters with respect to time period. One is called as an analysis period and the other one is called as a performance period. So, what is the analysis period? It is the period of time that any design strategy must cover. Let us say I am interested in keeping this pavement in a good condition or I am interested in the performance of this pavement over some period. Let us say 20 years is my period of interest. This is my analysis period. In this analysis period, I can do a stage construction, maybe I can lay 75% of the thickness initially and because the traffic would have projected will be for the design period, we initially we will not be experiencing those many traffic repetitions. So, I can keep a lower layer thickness and as and when the number of repetitions increases, as and when the traffic increases, maybe I can add one more layer and increase the thickness. So, that we call as a staged construction. So, it could be a staged construction or it could be a planned rehabilitation. I can do multiple things over the analysis period. So, basically it is a time period for which I am interested in monitoring and maintaining the pavement. So, AASHTO defines a range for analysis period. If it is a high volume urban road, it could be between 30 and 50 years, high volume rural road 20 to 50 years, low volume paved road maybe 10 to 20, 15 to 25 and low volume if it is an aggregate surface 10 to 20 years. So, this is the analysis period.

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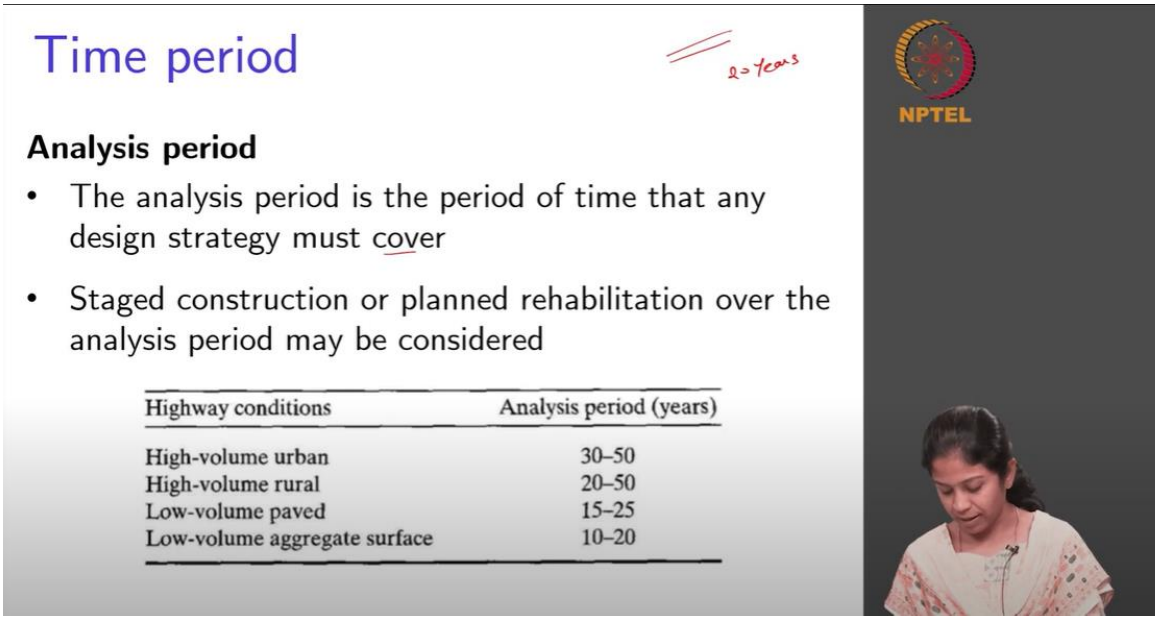

The performance period is slightly different. It is the time that an initial pavement structure, I have constructed a pavement, so that I call as an initial pavement structure will last before it needs rehabilitation or the performance time between two rehabilitation options. That is, once I lay a pavement, how long can it provide the desired performance. What is the time period between one treatment given to a pavement and another major rehabilitation operation I am carrying on the pavement? So, once I put a pavement for how long is it going to serve, right? That is what is called as the performance period. It is equivalent to the time elapsed as a new constructed or rehabilitated structure deteriorates from its initial serviceability to its terminal serviceability. So, we have something called a serviceability which we will be defining next. So, what is the time period over which it deteriorates from the initial serviceability condition to the final serviceability condition. That we call as the performance period. So, I might construct a pavement during the analysis period, let us say my analysis is for 20 years as we have said earlier. This is the initial condition of the pavement. It might deteriorate, right? So, this has reached a minimum level. So, it has reached this minimum level, right? So, it needs another rehabilitation. So, this is my performance period. So, I can do another rehabilitation operation, improve it, so it will again deteriorate and so on. So, maybe I can have 3 rehabilitation routines in my total analysis period of 20 years, right? So, this is my analysis period over which I am interested in monitoring the pavement and this is the performance period, one single treatment, how much time it takes to reach the minimum serviceability level. So, this is the difference between these two terminologies.

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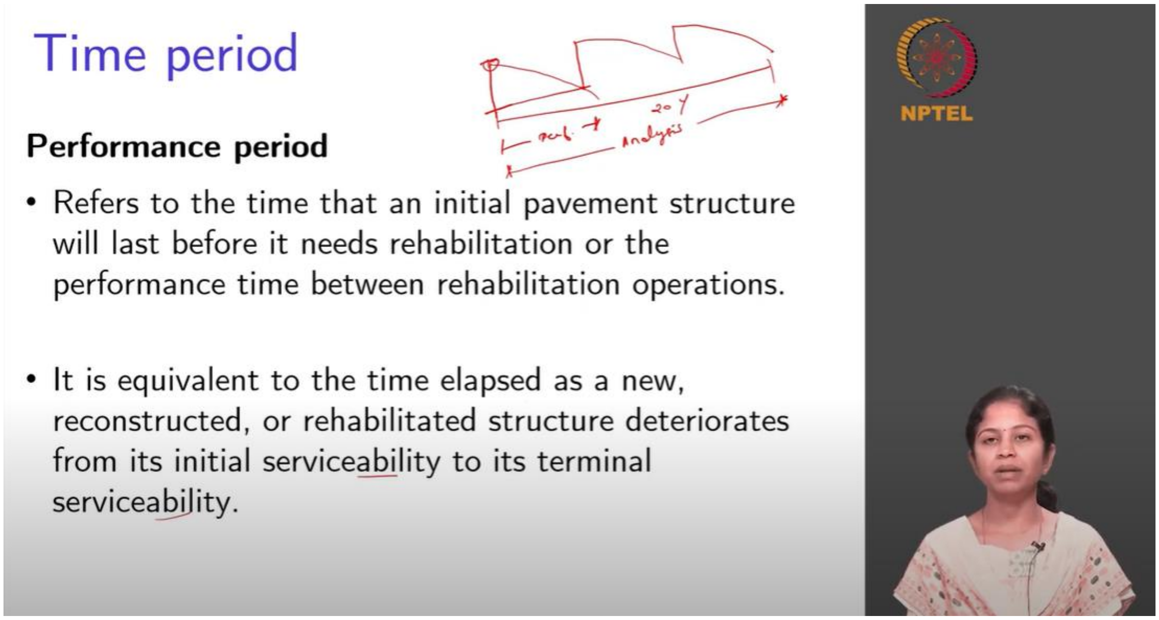

Now, what is this serviceability level? So, the serviceability is usually expressed in terms of PSI. This is nothing but a present serviceability index. Let us first define what serviceability index is, then we will move on to this picture here. This serviceability index is a measure of overall section of a highway based on visual observation. So, I look at the highway, right? And then I observe what is the condition of the highway. So, by mere visual observation, I give a number to the condition of highway. So, that number is called present serviceability index. So, it is a measure of the overall condition of a highway. So, if I construct, for a newly constructed pavement, the PSI usually varies from the range of 5 to 0. So, 0 is basically there is nothing there and 5 is a perfect newly constructed surface, but usually construction quality will vary, so we will not assume a value of 5, but somewhere around 4.5 or slightly less or slightly more. So, this is the initial condition, let us say, but theoretically it varies from 5 to 0, 5 is the maximum limit and 0 is the minimum value. Let us take section A here. Once I construct a pavement, this value of PSI is going to be high here, okay? So, as time progresses because of repeated applications of load, environmental effects, the condition of the pavement keeps deteriorating. So, it deteriorates in this manner and reaches a terminal value. So, what is this terminal value P_t? It is minimum allowable serviceability. So, beyond this, this pavement is no more traversable, right? I cannot ride a vehicle on this pavement, that I call as the terminal serviceability level. So, this is my initial value P_0, initial serviceability level and this P_t is allowable, minimum allowable serviceability level below which I cannot use the pavement any longer. So, it deteriorates from P_0 to P_t over these many axle load repetitions. You can see x axis is accumulated ESAL. So, the condition deteriorates from P_0 to P_t over these many number of axle load repetitions. So, this I call it as N_t which is the maximum allowable load repetition for this particular section. Similarly, I can take section B. This is the initial value P_0 and this is the P_t value. So, I can see here that my section B is able to sustain more number of load repetitions before it reaches the terminal serviceability level. But the design period is T years. And the number of axle load repetitions, standard axle load repetitions expected over this period is N_T. So, this is what I have designed for, but I have two pavements or two sections, one which has failed in lesser number of repetitions and another which is able to take more number of repetitions. So, this N_t is defined as the number of load repetitions it can take before it fails. So, what we are going to calculate is for a given pavement, what is my expected number of load repetitions N(A) and then I can calculate what is the serviceability level. Alternatively, I can visit a pavement, identify what is the PSI value. So, if let us say I am having a PSI value of this, I need this curve. So, I have consumed N number of axle load repetitions. So, these many axle load repetitions are yet to be consumed by this pavement before it reaches the condition P_t . So, that is how we use these curves to make interpretations about the serviceability index.

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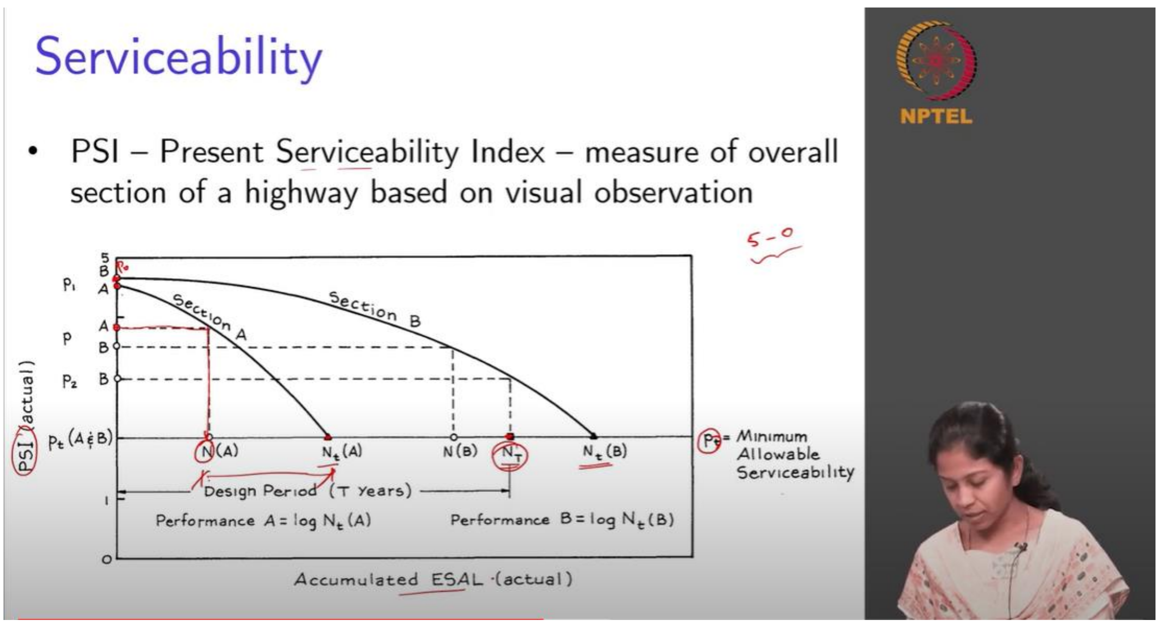

Now, AASHTO gives some guidelines regarding what are the initial and final serviceability indices. So, the initial serviceability index is a function of pavement type and construction quality. So, we have different values for flexible pavements and we have different values for rigid pavements. So, for a flexible pavement, this value is suggested to be 4.2. Terminal serviceability level is lowest index that will be tolerated before rehabilitation, resurfacing and reconstruction that is necessary for that particular pavement and this value is 2.5 or higher for major highways and 2 for highways with lower traffic level. So, this is the P_0 value and P_t value. So, initial and terminal serviceability index has to be established to compute change in serviceability. So, how much is the variation in serviceability from the initial to a given particular stage, that we call as ΔPSI. So, this we have, let us say this is 4.2, this is 2.5. So, at any given point in time somewhere between this, I can compute the serviceability index and based on that I can say what is the number of load repetitions that is yet to be consumed by this pavement. So, this is with regard to the serviceability value. Then we will move on to reliability.

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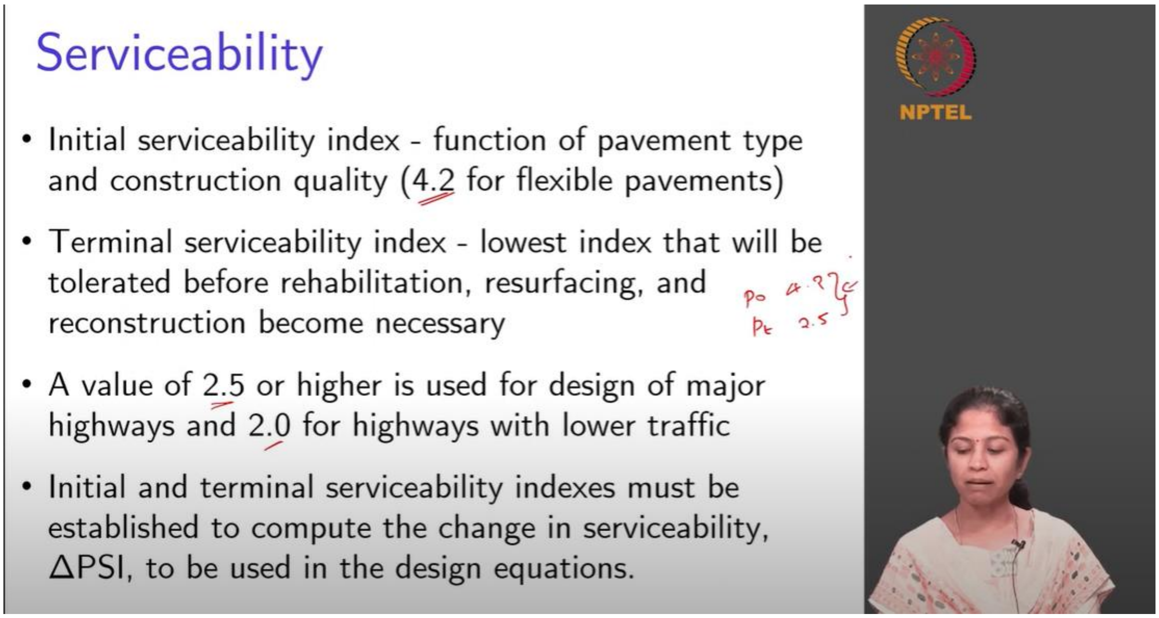

We have already seen in detail about reliability, what it means and the definitions. AASHTO also gives a set of definitions for reliability. We will anyway look into what AASHTO says. There are about 5 definitions for reliability. The first one is the probability that serviceability (we have defined what serviceability will be maintained at adequate levels from a user's point of view throughout the design life of the facility) condition should be between P_0 and P_t will be maintained at adequate level from a user perspective because this PSI value is given by a user who is traversing on the pavement, throughout the design life of the facility.

The second definition is reliability is the probability that load applications a pavement can withstand reaching a specified minimum reliability level, serviceability level is not exceeded by the number of applications that are actually applied to the pavement. So, there are a specified number of repetitions within which I reach from P_0 to P_t that we have defined as N_t. So, this the actual number of load repetitions I observe in the pavement. N_t should be greater than the actual number of repetitions that I observe on the pavement. So, this is the second definition.

Third one is reliability is the probability that pavement system will perform its intended function over its design life and under the conditions encountered during operation. So, this has another term related to the environmental conditions. So, it says it should deliver the required performance over the design life and under the environmental conditions to which it is subjected to.

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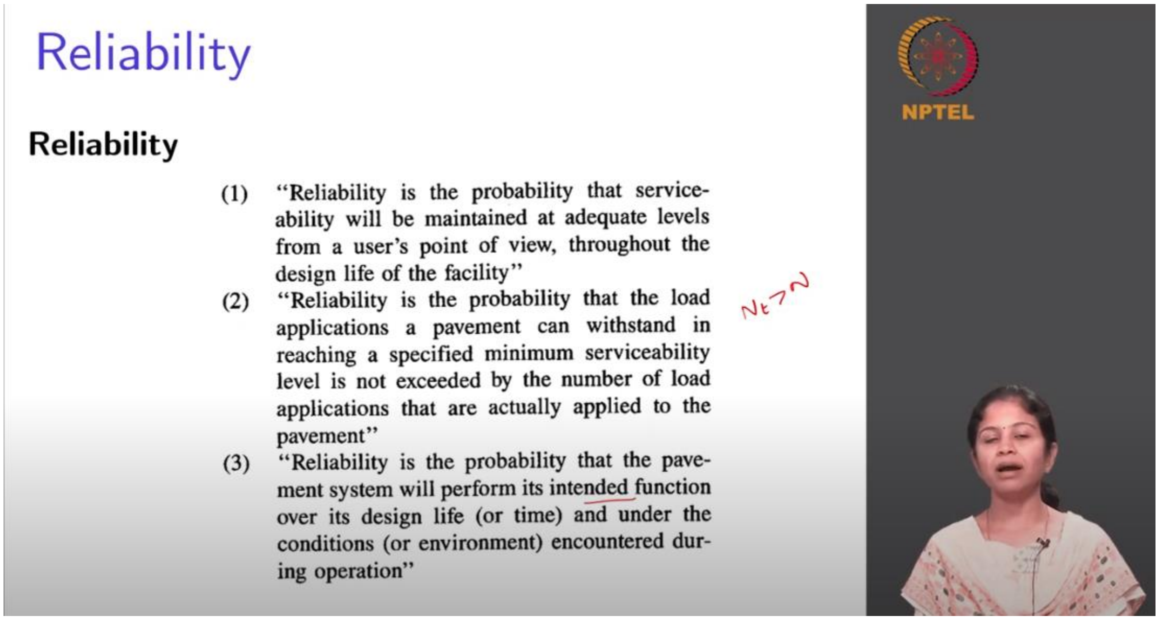

And we have two other definitions. It is the probability that any particular type of distress or combination of distress manifestations will remain below or within the permissible level. So, this definition says that the distress could be one distress or it could be multiple distresses, but this should remain less than the limiting value. That they call as permissible level during the design life.

And the final definition is the reliability of a pavement design performance process is the probability that a pavement section designed using the process will perform satisfactorily over traffic and environmental conditions for the design period. This is what we had seen initially in the first or second slide. So, this is a comprehensive definition which takes into account of the performance, says that it is a probability, says it is designed using a process satisfactory under these conditions for this period. So, it kind of encompasses all the factors. Now if you look at all the five definitions, you can see it has slowly evolved from a generic term to a more specific definition in the case of the last definition.

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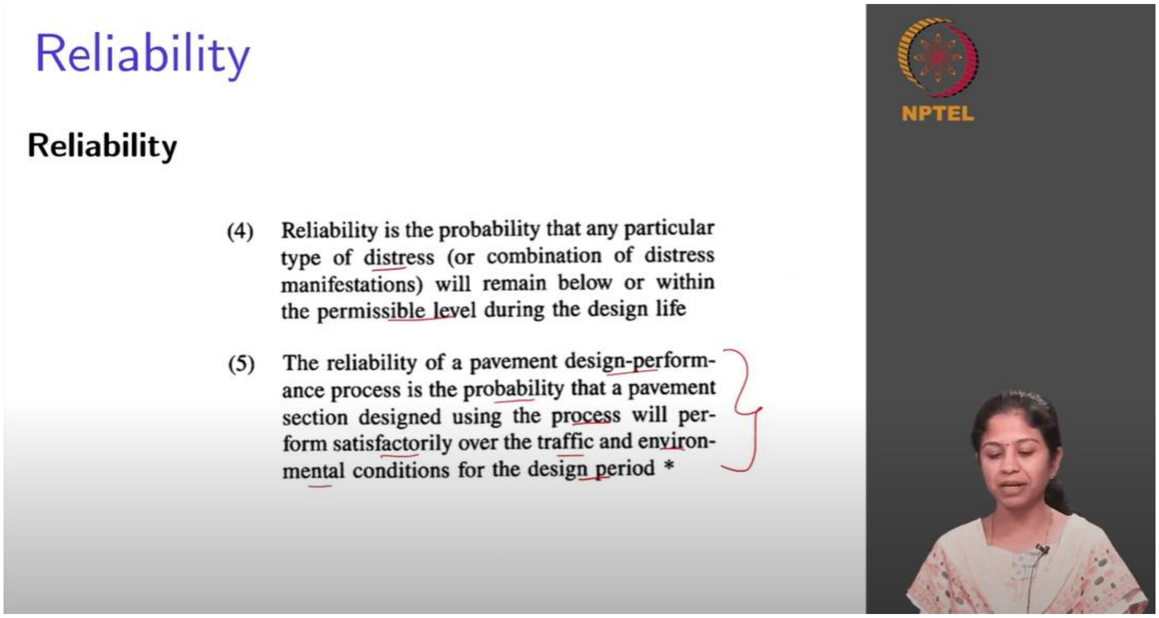

There are different reliability levels which are suggested based on the type of highway. If it is interstate or other freeways, you can consider it to be like our national highways. Something like equivalent to that. The recommended level of reliability will be 85 to 99 in an urban scenario and 80 to 99 in a rural scenario. Say if it is a rural road, we can have slightly lower level of reliability because the number of traffic repetitions are going to be lesser in that case. Even if you take principal arterials, the next major level of highways 80 to 99 and 75 to 95. Similarly for collector roads and local roads also, the recommended level of reliability is specified. So, depending upon the type of highway, the importance of the highway, we can choose appropriate reliability levels. Higher reliability levels are usually given for roads of importance or those carry higher traffic volume and higher loads. So, in that case, we use a higher reliability level. For other cases, we can go in for a lower value.

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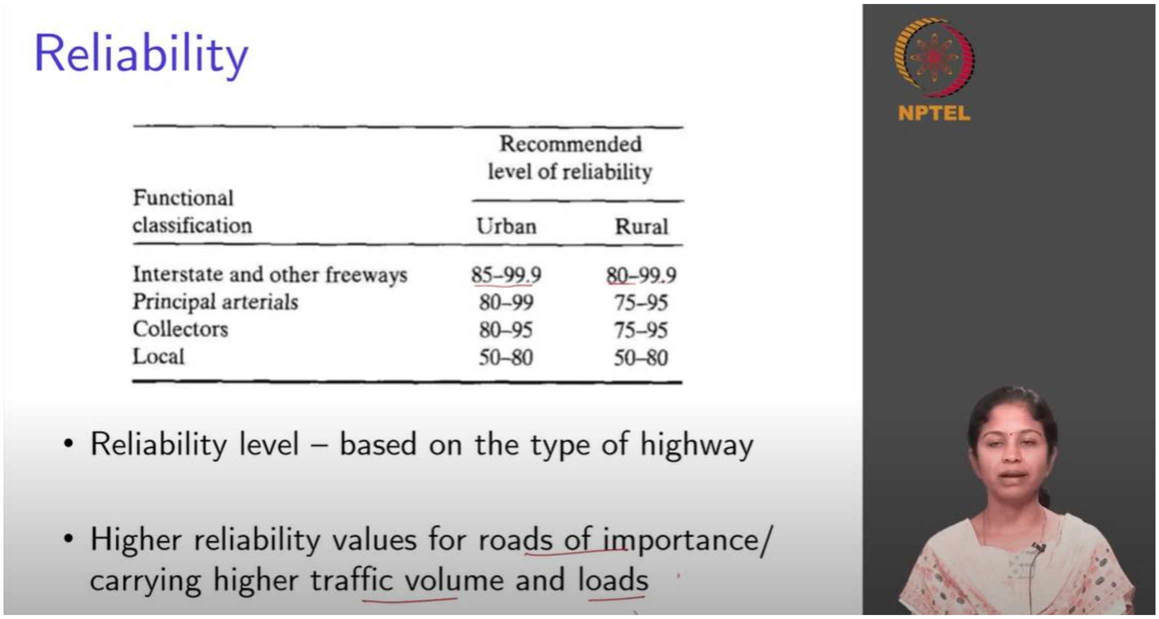

The next one is a structural number. As I said, this structural number is a parameter which considers the strength aspect of all individual layers in a given pavement. If we look at a pavement, let us say we have 3 layers. So, this is the subgrade, this is the base course and this is the bituminous course. So, each of these layers are going to have different thickness, let me call h_1, h_2. Similarly, each of them are going to have different modulus, E_1, E_2, E_3. Now if you look at the load carrying capacity, it is a function of the thickness of a layer and modulus of the layer. This, let us say the bituminous layer will have a higher modulus. So, even for a lower thickness, it is going to have a higher load carrying capacity. So, if I have to combine all of them into one single number, that we call a structural number, then I have to give appropriate weightages to the difference in modulus of each of these layers because the same thickness let us say 100 mm thickness of bituminous layer is not same as the 100 mm thickness of the base layer. So, they are going to be different. So, to consider all this variability, we are using some coefficients. So, let us see how the structural number is defined. So, this structural number is a function of 3 parameters, one is a, another is D and the third one is m. So, what are these coefficients a_1, a_2, a_3? They are layer coefficients for the surface, base and sub-base course. So, this coefficient converts the difference in modulus value of each layer into a uniform value so that all of them can be combined together into one number.

So, it takes into account of the relative difference in load carrying capacity of unit thickness of individual layers. So, now if you look at it, we have a constant a_1 for the surface layer, a_2 for the base layer and a_3 for the sub-base. And what are D_1, D_2, D_3? They are thicknesses of each of these layers, surface, base and sub-base. So, if I multiply thickness into load carrying capacity per unit thickness, I will get the load carrying capacity of that particular layer for the specified thickness. So, now I have all these three, but we also have one more parameter called m. This m is nothing but the drainage coefficient. Since we are dealing with granular layers, the more the soil becomes saturated, the lesser will be the load carrying capacity. So, we might have two values for these constants, one is in a wet state and another is in a dry state, right. So, we should use different constants. Instead of that, this parameter m_2 and m_3 are defined. This takes into account of the drainage conditions of that particular layer, right. So, m_2 and m_3 are the drainage coefficient of base and sub-base cores. Now, let us see how these coefficients are calculated.

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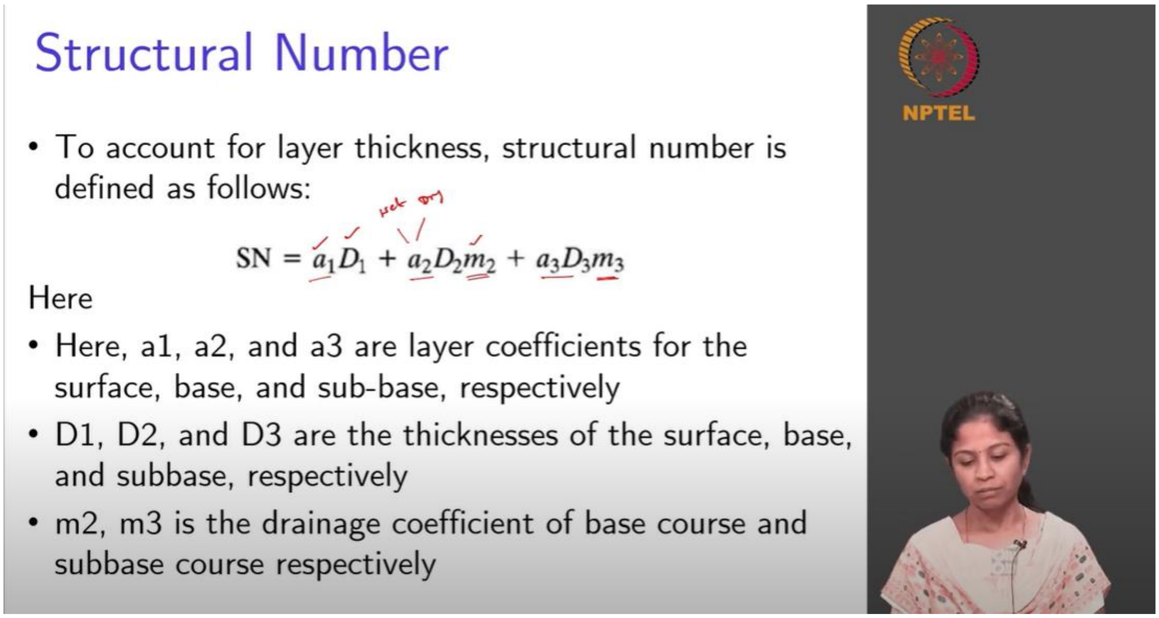

For a layer, for the layer coefficient a_1, which is for the bituminous layer, graph is specified, right. So, this is the structural coefficient a_1 and this is nothing but the resilient modulus of the bituminous layer. We should see it is at 70 °F and at 10^5psi. So, if I have a resilient modulus, let us say 2×10^5 psi, if this is my resilient modulus, 0.3 is going to be my structural coefficient. So, this value can be directly taken from this graph.

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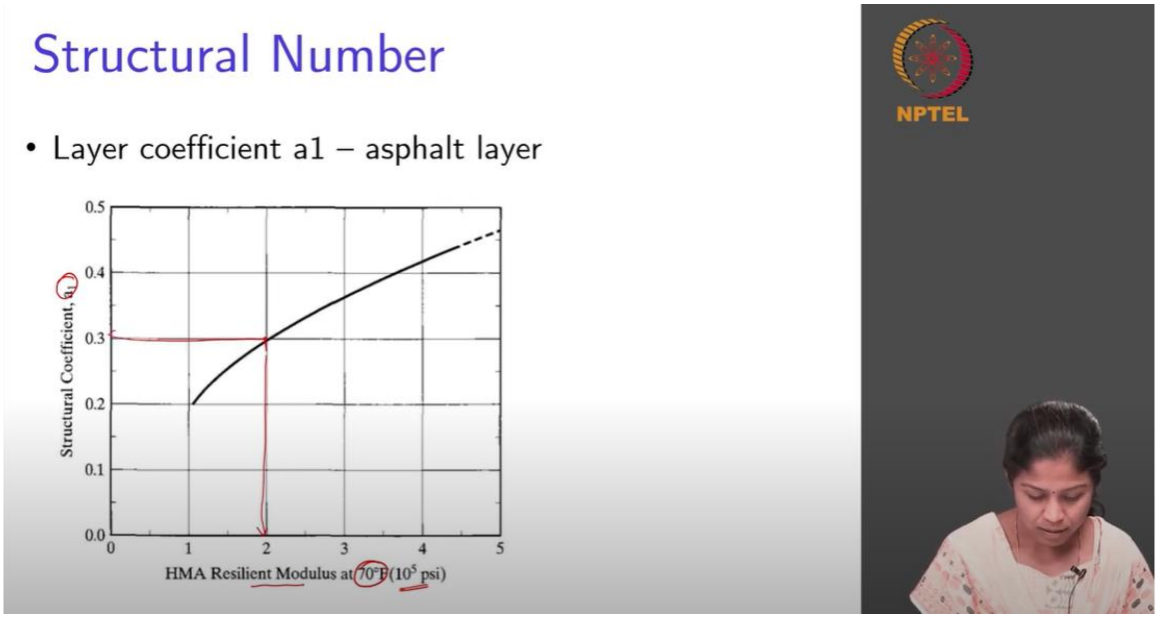

For the other two layers, equations are specified to compute the layer coefficients and we have already said that it is the relative variation in load carrying capacity. So, obviously, it is going to depend upon the modulus value. So, this coefficient a_2 is specified in terms of E_2, which is modulus of the base layer and this modulus of the base layer is defined in terms of the constants K_1 and K_2. So, these values K_1 and K_2 are specified for different states in which the material is present. So, K_1 for dry, damp and wet condition is specified and similarly K_2 for these three moisture conditions are specified. And what is this theta? This theta is nothing but the stress state of the material. The modulus that is experienced by a given layer depends upon the stress state of that layer. So, basically what is the load that is coming onto that layer because of the above lying layers. So, if I am required to calculate the stress state of the base layer, I need to know what is the thickness of the above lying layer and it also depends upon the resilient modulus of the underlying layer. So, that is why this theta depends upon the roadbed soil resilient modulus or nothing but the resilient modulus of the base layer and the thickness of the asphalt layer which is lying on top of it. So, based on these two values, we will be able to compute the stress state for the material. Let us say we have a case wherein the thickness of asphalt layer is between 2 to 4 inches and my roadbed resilient modulus is 3000 psi. So, this is going to be the stress state value and we can use K_1, K_2 get E_2 value, use it here and get the corresponding a_2 value.

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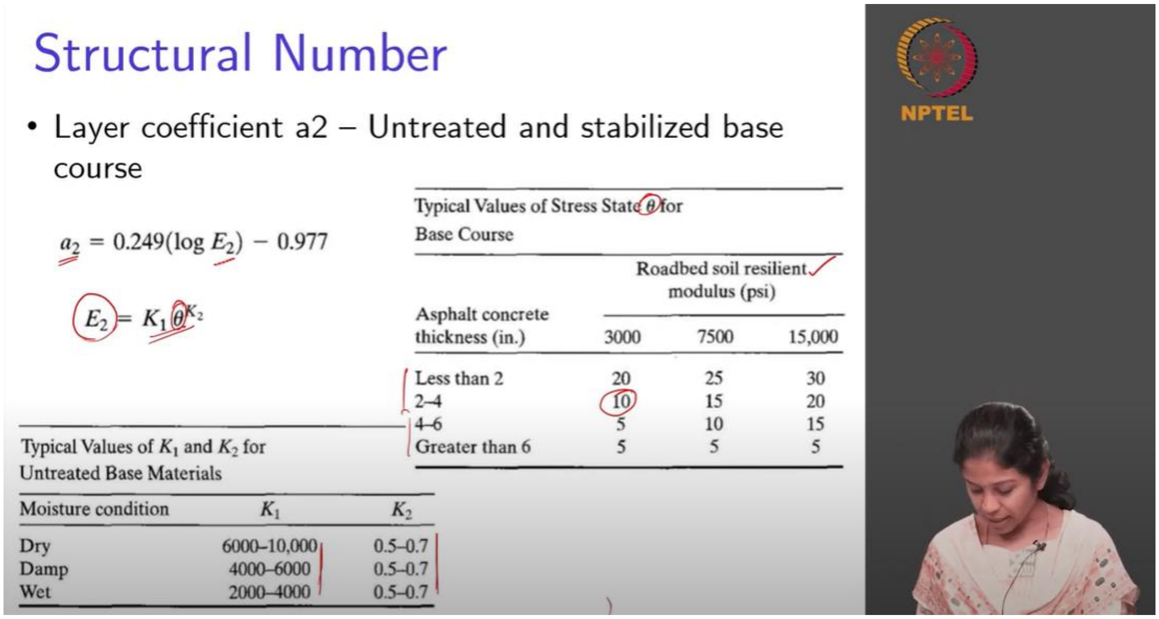

We have similar values for the sub base layer also. So, if you look at the granular sub base layer, we have a similar form of equation. So, you can see here and this depends on again two constants K_1, K_2 and this depends upon the stress state. The values of K_1, K_2 for different conditions are also specified here. In fact, these are the values of K_1 and K_2 for the granular sub base materials. This is specifically from the AASHO road test. So, there was an AASHO road test which was connected on a particular test section. Based on the observations from those test section, all the empirical parameters in the AASHTO 1993 design procedure have been arrived. So, this is the value of K_1, K_2 obtained from that particular AASHO road test. Then we also have drainage coefficients m_1 and m_2. So, this is selected based on the water retention capacity of a given layer. So, it is defined in terms of the length of time for water to be removed from base and sub base. So, if the layer is drained quickly, if it is excellent quality of drainage and water is removed within 2 hours, then this coefficient is higher. These quick draining layers will most of the times will not become saturated, will not reach a fully saturated state. So, these layers have a higher coefficient and this also is specified in terms of percentage of time the pavement structure is exposed to moisture levels approaching saturation.
So, when it is for how much amount of time is it like nearing the saturation state. So, if it is less than 1 or between 1 to 5 percent, 5 to 25, greater than 25. Depending upon that also the drainage coefficients vary. So, basically this drainage coefficient depends upon two parameters. One is the moisture condition at a given instant and how much percentage of time it is nearing that condition.

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Drainage coefficients

- Selected based on the length of time for water to be removed from bases and subbases
- Quick draining layers that almost never become saturated have higher coefficient value

Recommended Drainage Coefficients for Untreated Bases and Subbases in Flexible Pavements

Quality of drainage		Percentage of time pavement structure is exposed to moisture levels approaching saturation			
Rating	Water removed within	Less than 1%	1–5%	5–25%	Greater than 25%
Excellent	2 hours	1.40–1.35	1.35–1.30	1.30–1.20	1.20
Good	1 day	1.35–1.25	1.25–1.15	1.15–1.00	1.00
Fair	1 week	1.25–1.15	1.15–1.05	1.00–0.80	0.80
Poor	1 month	1.15–1.05	1.05–0.80	0.80–0.60	0.60
Very poor	Never drain	1.05–0.95	0.95–0.75	0.75–0.40	0.40