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A very warm welcome to all of you. I am Rajan Choudhary, Professor in the Department of Civil Engineering at the Indian Institute of Technology, and Course Instructor for the NPTEL MOOC Course Pavement Construction and Technology, funded by the Ministry of Education, Government of India. Today's lecture will discuss the skid resistance or friction resistance of pavement surfaces and their measurement. So, at the very beginning, I would like to acknowledge the use of text, information, graphs, and images sourced from various textbooks, codal standards, journal articles, reports, newsletters, and public domain searches. Now, skid resistance or friction resistance forms a very important aspect of a pavement surface because it is related to the safety of the users. If I mention skid resistance, as per the NCHRP report, it represents the force developed when a tire that is prevented from rotating slides along the pavement surface.

Whenever a vehicle tire that is moving on the surface is prevented from rotating and slides, the force developed between the tire and the road surface is your frictional resistance, or we can call it skid resistance. So, the friction force normally requires two surfaces. So, the friction force is defined as the resistance encountered when one body is in contact with the other. So, here we have the vehicle tyre that is in contact with our road surface, which is moved or tends to move, depending on the interaction between the tyre and the pavement surface.

So, this will highly depend on the interaction between the tire and the pavement. So, from this particular aspect, we can get an idea; it will depend upon the characteristics of the tyre and the characteristics of the road surface. Therefore, any factor influencing either the macro texture or micro texture of the surface. Now, when we talk about the pavement, the surface can usually be classified in terms of its texture. So, the texture is further classified into macro texture and micro texture, which we will discuss in detail in the coming slides.

This will depend on the pavement surface characteristics, I will say, and texture forms part of the pavement surface characteristics. So, this plays an important role when it comes to the coefficient of friction; many times it is referred to while we do various computations with regard to the stopping sight distance or the design of the super elevation in the case of the design of horizontal curves. The coefficient that is used is the coefficient of friction, which you might have encountered in some other courses; it is the ratio of the frictional force to the normal force. This is what we have. Where F is the frictional resistance to

motion in the plane of the interface and L is the load that is normal to the interface, this is what your coefficient of friction is.

Now, specifically when it is related to road surfaces, the safety of the motoring vehicles or the users is highly dependent upon the skid resistance or the frictional resistance of the surface, and this becomes more challenging, specifically when the pavement surface is wet, because this friction resistance gets significantly reduced in the presence of water. So, the friction in general, as well as skid resistance and friction resistance, plays an important role in the safety and safe maneuvering of these vehicles over the surface, and this specifically becomes more important when the surface is under wet conditions. So, the friction resistance, or what I will call the skid resistance, offered by the pavement surface under various driving and surface conditions specifically refers to the various speeds at which the vehicles are traveling. So, whether that also plays a role in the friction resistance of the surface is unclear. So, the pavement surface under various driving conditions and surface conditions will have characteristics, and in addition, we now have one parameter, which is water.

So, it is quite important with reference to safety. The term tyre pavement friction suggests that friction developed in any situation involves two primary components, as I mentioned: one is the tyre and the other is the pavement. Now, this combination, along with the third one, makes another critical combination when water is present; you can see that when water is on the surface, this combination becomes more critical. So, whenever water is present, we generally want this surface not to be slippery; the vehicle should be able to control its maneuverability when moving on a wet surface as well. So, the friction between the vehicle tyre and the pavement surface is one of the factors determining the operating speed.

If this is challenging, you need to move out at lower speeds; you can see this particular vehicle is traversing a horizontal curve. So, definitely depending on the radius, there will be some centrifugal force exerted on this vehicle, and this centrifugal force has to be balanced out by what, one, is the superelevation, which should be there in the surface; second, is the lateral friction that is present on the surface. So, these two factors will help ensure a safe transition over this particular horizontal curve. So, if we are not able to have a good amount of lateral friction or there is always a limitation with the amount of superelevation that is what portion you have raised, these outer edges with respect to the inner edges, there is a limitation; if that is not able to counteract the centrifugal force, what will happen is that you have already gone to the limits of your superelevation and the lateral friction has its own limitations. So, in that case, you need to bring down your speed.

So, operating speeds have to be low. Another is when you want to stop a vehicle that has a stopping sight distance, so in those design aspects, you also need good information about the skid resistance or friction resistance of a road surface. Now, if important key factors that can be considered with respect to the frictional resistance or strict resistance of a

surface, one is pavement surface and material characteristics. So, pavement surface characteristics, as I specifically mentioned, are in terms of surface texture, which is defined in terms of surface asperities. So, ranging from the fine roughness of individual aggregate particles here, this is an exaggerated view; you can see these are the fine roughnesses of individual particles which can form a part of your microtexture.

To larger surface deviations, these are specifically larger surface deviations, which are from your gradation. So, deviations spanning several feet form your macro texture on this particular large surface. So, this specifically comes under your macro texture. Now, pavement surface material characteristics also play an important role in what type of aggregates you are using. If those aggregates get polished easily, then it will definitely make your surface more slippery in that case.

Mix characteristics; it will look into your binder, which is present, your gradation, which is there, and texturing patterns, because normally you create a texture through your mix gradation also. So, define surface texture and influence its long-term durability by determining resistance to polishing, because aggregate should not get polished, and how it experiences abrasion and wear under traffic and environmental conditions, as well as how this surface texture is affected in the presence of different environmental factors. You have two important factors related to the pavement surface: the road surface characteristics and the material characteristics. Then you have, as I mentioned, the vehicle operating characteristics because it also depends on your maneuvering speed, which we also call the slip speed. Third are tyre properties.

Now, you know very well that if you are driving on a wet surface, you will prefer to have a new tyre because there are treads in the tyres. So that tread pattern is there that allows the water to skip; whenever a vehicle moves over a wet surface, the water is moved in the form of a splash, and it gets removed with the help of this texture as well as the treads that are in the vehicle tire. So, you always prefer to have a new tire when you are traveling on a wet surface. So, it depends on the tyre properties, specifically tyre tread design and its condition, because worn-out tyres may be present later on when these treads are reduced. So, those may be worn-out tyres, and tire inflation pressure is usually affected if under-inflated tires are present; in such cases, the depths of your treads get reduced.

So, they again become challenging when you are traveling over a wet surface. So, another characteristic is with respect to the tire properties, and the last one is the environment, as I mentioned. It is quite safe compared to when you are making a movement over a dry surface versus a wet pavement surface. And in addition to thermal properties, your tire rubber expands because it is a viscoelastic material; it changes with the change in the temperature of the surroundings. Water, snow, and ice, if present, definitely further reduce

vehicle friction when the tire contact face reaches the pavement surface due to any ice or snow buildup on the surface.

Contaminants may be present due to dirt, sand, or any oil spillages that further reduce your tire pavement friction. So, in addition, these are the important contributing factors: your surface characteristics, vehicle operating characteristics, your tyre properties, and the environment. These are some of the main properties. Now, when this interaction comes into the picture, two components are specifically important for the development of the friction between a tyre and a pavement surface. So, we say tire pavement friction mainly arises from two components: one is an additional component, which is molecular bonding or interlocking between the rubber and the pavement surface.

So, this is one component that builds up the friction or skid resistance, and we put this particular one under the heading of adhesion. The second is the hysteresis component, which accounts for energy losses from repeated compression and recovery of the tyre rubber. When it passes over the surface irregularities, it regularly experiences compressions and expansions, also when it passes over these surface irregularities. So, this particular one normally dissipates in the form of heat and is a component of your friction resistance. So, these adhesion and hysteresis form two important components that contribute to your pavement tyre friction.

Now, specifically, when does adhesion dominate and when does hysteresis dominate? So, specifically, if a non-slippery surface is there, basically in that particular case, you have a good amount of friction, which is available from your adhesion. So, on skid-resistant surfaces, initially fresh new surfaces are where adhesion dominates, where the interlocking is good enough, and the bonding with the binder, the road surface, and the tyre rubber is good. Whereas the hysteresis in that particular case plays a little role compared to when on slippery surfaces, hysteresis occurs because the tyre gets deformed due to surface irregularity, and then, in this scenario, adhesion does not play a role, specifically when the surface is slippery. So, at that particular one, your hysteresis dominates. And hysteresis is normally not affected by the speeds that are usually encountered on the surfaces.

So, that is why hysteresis specifically plays a very important role in wet conditions. So, adhesion decreases whereas adhesion decreases with the speed on wet surfaces, making hysteresis relatively more important because it does not usually get impacted by the usual speeds encountered on the surfaces. Now, this hysteresis is because we are experiencing the compression and recovery of the tyre rubber over the surface irregularities, and surface irregularities are more importantly related to the texture of the surface. So, surface texture enhances hysteresis; this is, but more importantly, it provides channels. Now, the surface

texture, because you have the vehicle tread, tires' treads also provide the channels, and your surface texture also provides the channel.

So, provide channels for water escape, enabling the tyre pavement contact. So, this again plays an important role. On flooded pavements, water is partly splashed away, but primarily drained through tire tread grooves or pavement voids and textures. So, this surface texture and the condition of the tyre play a very important role, specifically under wet conditions, and hysteresis is the component that plays a more important role, specifically under wet conditions when you have slippery surfaces, which means the chances are higher when some water is present on the surface. Now, how do we make these measurements? If you want to make the measurements at the actual speeds at which a vehicle is moving, there is one quite popular method for measuring the pavement skid resistance, which is high-speed skid resistance friction measurement using full-scale test tires.

So, this is one of the locked wheel tests that are included in the ASTM guidelines, specifically ASTM 274, where there is a skid trailer that is towed and moved at a speed of around 64 to 96 kilometers per hour to evaluate the skid resistance under actual service conditions. So, it moves on the actual pavements in these particular speed ranges. So, at this particular speed range, this is the ASTM E274 skid resistance of paved surfaces using a full-scale tire. So, it is an actual field test that is there, and it is highly preferred. So, at this speed, water is sprayed ahead of the tyre; one or both wheels may be locked, and the resulting resistance is measured as the torque on the trailer axles.

This particular measurement is converted into a skid number, or we call it a frictional number, and if this value is high, we say that the surface has higher friction resistance. So, the friction number, or the skid number, is a factor that is usually represented through these locked wheel testers. So, the result of these locked wheel tests is reported as a friction number or skid number, which corresponds to this particular expression of friction number at a given velocity, usually conducted at, say, 60 kilometers per hour. Then, this is how we use your velocity of the test tire because usually they go in miles, so 40 to 60 miles per hour is there. Coefficient of friction, tractive horizontal force applied to the tire, and vertical load applied to the tire.

So, this is if we need to work it out when we have different units, as we look for the measurements in kilometers per hour. So, speed, as I mentioned, typically ranges from 40 to 60 miles per hour, which is otherwise 64 kilometers per hour, as per ASTM this description. So, lower skid numbers invite safety hazards and would require immediate action based on the skid numbers. Our manual, which is there for the construction and supervision of bituminous works, says we can decide about the maintenance levels on the basis of the skid number or the friction number as well. So, the minimum desirable values of the skid number for three levels of maintenance are given below.

So you can see level 1, which provides the highest level of comfort, convenience, and safety when the skid number is a minimum of 50. In that case, level 2 is the level to which the road deteriorates from level 1 after 2 to 3 years of use before fresh maintenance is implemented. So, this is for skid number 20; if it is less than that, the minimum level necessary to protect the investment and provide reasonable levels is 35. So, this is the minimum level of skid number that is required on a surface.

So, this is given in the manual. So, on the basis of these skid numbers, we can look into the maintenance part. And as I also mentioned, this plays important roles in other aspects, including frictional resistance and skid resistance. So, it plays a key role in highway geometric design. And where do we play a role? It plays a role in determining minimum stopping sight distance, minimum horizontal curve radius, minimum curvature, vertical curve radius, and maximum superelevation on horizontal curves, where all these factors are considered. So, the only one I will discuss here is the braking distance.

So, if a vehicle needs to stop over a particular surface, how much time or how much distance does it travel before it safely stops and protects itself from, say, an obstruction that is on the surface? So, on a level road, just for an example, braking distance is usually derived by equating. So, initially, it is moving at a speed of V , so it has kinetic energy. So, it has to apply the brakes and bring it down with the help of friction resistance. So, what is being done? The work done by the frictional force in stopping the vehicle is to be equated with its initial kinetic energy. So, if F is the maximum frictional force that can be developed over the surface, L is the distance over which it can stop; if this is the distance, I will say it is the distance over which it can stop.

So then, the work done against the friction equals the vehicle's kinetic energy. So, this is your frictional force; this is the distance it takes before it stops in this particular case. So, what this particular one is your coefficient of friction, which is F equals F into W , where W is the total weight of the vehicle. Now, what we are going to equate here is the kinetic energy, $\frac{1}{2}mv^2$, which is w by gv^2 divided by 2, and we are going to equate it with the work required by the friction, the work done by the frictional force. So, kinetic energy is equated to this frictional force multiplied by the length, so fwl .

Here we have the kinetic energy and the work done. So, this is what they are equated to, and when they are equated, we get the braking distance as V^2 upon $2gf$, where V is in meters per second. Now, on the basis of this particular expression, we can work out the various design speeds and determine how much length is required for the safe stopping of a vehicle. Now, in addition to this one, you can see there is a lag distance mentioned; what this lag distance means is that, as soon as any vehicle user finds an obstacle, there is sometimes a lapse of time before it applies a brake. So, he needs a certain amount of time to come into action.

So, this is normally a peep theory that is there. So, how much reaction time is normally required? So, during the time when I first saw that particular object and by the time I applied the brakes, some amount of time had lapsed. So, at that particular moment in time, I am traveling at the same speed. So, that time is usually 2 to 2.5 seconds, and I will travel at the same speed. So, that will form my lag distance, and then I will apply the brake. So, after applying the brake, which is known as my braking distance. I need this much length to safely stop my vehicle before encountering any damage from any obstacle on the road surface. So, this is what is given here: stopping sight distance is usually when V is in kilometers per hour; it mentions that it is the distance traveled at the standard speed for the initial time, and this is the distance traveled during the braking action. So, on the basis of it, I can work out this particular breaking distance.

Now, this braking distance, as I have seen, is highly dependent upon my coefficient of friction. On the basis of this, our caudal guidelines specifically like I am giving just one example, how this friction is involved in the geometric design aspects also. So, we have IRC 73, 2023, which is the geometric design standards for non-urban roads, where it says that when one is traveling, this expression is already there: L_v squared upon $2gf$. So, it says, "How much distance is required?" So, we have, as I mentioned, perception time. The lag distance, which is with respect to the perception time, indicates how much time it takes to analyze the situation and apply the brakes.

So, a standard perception time of 2.5 seconds is used. And on the basis of that particular one, it takes a certain amount, at whatever speed it is traveling, as your lag distance. And this is what the braking distance is. So, this breaking distance will take into consideration your lateral coefficient of friction. Now, here you can see the lateral coefficient of friction at a smaller speed because it is traveling in the longitudinal direction.

So, you can see it is the longitudinal coefficient of friction. So, this is 0.4 and 0.38. So, while computing specifically my braking distance, I need to work out the coefficient of friction, F .

So, here you can see in this particular case they have assumed that the coefficient of friction, specifically the longitudinal coefficient of friction, decreases with the increase in speed, and on that basis. So, this much distance is required for a vehicle to apply the brakes and finally stop. So, as you have a good coefficient of friction, you can stop the vehicle in a shorter distance. So, the surface resistance of any pavement surface is very important from this particular perspective. Now, there are various pieces of equipment that are used for measuring pavement surface resistance or skid resistance; some are used at a laboratory scale, while others can be used in the field, such as the log wheel tester, which we discussed before, and is preferably used in the field where you can move at the same speeds as actual vehicles.

And there are a few more that are quite often used to capture some of the other characteristics related to pavement skid resistance. One is the sand patch method, which is there; the second is the British pendulum tester, which we briefly discussed when we talked about the aggregate characteristics and the polished stone value. The dynamic friction tester is there, and the circular track meter is often referred to as the circular texture meter. We will briefly discuss it. Now, the sand patch method, as I mentioned, plays an important role specifically in the micro texture and macro texture.

Now, the macro texture is specifically the one where the surface irregularities are present because it is specifically derived from the gradation. So, this test is suitable for researching the specific sand patch method and determining the average macro texture depth of a surface. Because, as I mentioned, this is an important aspect; macro texture plays an important role in the hysteresis part and in having good contact with the tyre rubber, specifically under wet conditions as well. So, the macro texture depth values derived from this test method can be used to compare the pavement skid resistance capability of different surfaces with this particular one. And what is done is a simple volumetric test; it involves spreading a known volume of a material, specifically sand, on a clean and dry pavement surface, and for this given volume, we are going to measure the area that is covered.

And subsequently calculating the average depth between them, so once the area is known to us and the volume is known to us, we can work out the average depth. So, that is how your mean texture depth can be worked out. So, the average pavement macro texture depth is calculated using the following expression, where this is the volume of the material that is spread out, and this is the diameter indicating how much it has been spread out. So, you can see this is the standard sand volume which has been spread, and then we measure this diameter, and when we get the mean texture depth. So, this is quite simple, and with this particular one, we can work out which one has a higher mean texture depth, which is going to have a higher macro texture and is expected to give a higher friction resistance.

Now, the other one is a British pendulum tester we discussed previously, also under aggregates. So, it is a dynamic pendulum impact tester that is used in the field as well as in the laboratory, and it typically captures the microtexture because the individual aggregate characteristics or the rugosity of these aggregate particles are captured. This test involves measuring the frictional property microtexture of surfaces; specifically, it can be done on, say, specimens prepared in the laboratory subjected to different polishing levels, or it can be done using this particular one on actual surfaces as well. So, the British pendulum tester measures the friction values; you can see this is a pendulum, and this pendulum is allowed to move over that particular surface, which is prepared in the laboratory or in the field, and when it slides over this particular one, there is a graduated scale present.

Which is starting from 0. So, if it has a higher friction, it will rise to a lower height. So you will have higher graduation numbers. So, when do you prefer to have it so you can compare

it with this particular one? So, if it rises to a lower height, that means the surface here where it has finally interacted is rougher. So, this is how it can be compared. So, the British pendulum tester measured friction values in terms of the British pendulum number (BPN), or BPT as it is sometimes called, or polished stone value in the case of laboratory-prepared samples, which represent the frictional properties for flat surfaces and polished accelerated polishing wheel specimens that are prepared in the laboratory.

The higher BPN value, as I mentioned, indicates the higher friction between the slider and the surface because it will rise to a lower height, and it starts from a reading of 0. So, that means if this higher number is there, it indicates that there was more friction between your rubber slider and the test surface. Generally, a 5-degree swing of the pendulum for any particular surface will yield consistent determinations of this specific number. Now, as I mentioned, you can have these samples that are prepared in the laboratory when you are checking and ensuring the polished stone value of aggregates to see how susceptible your aggregates are to polishing. So, they are prepared in the laboratory in this matrix, and then they are subjected to this accelerated polishing action.

And then finally, these are the ones that are already tested; this particular one is the one that is without being subjected to the accelerated polishing machine, and the one that is subjected to these two accelerated polishing machines. So, you can work out the difference between these two. So, the polishing of aggregates is carried out for hours using an accelerated polishing machine, and what we arrive at is a polished stone value that is usually required for aggregates. If you recall, we mentioned that for aggregates to be used in wearing courses, we want the polished stone values of the aggregate to be greater than 55. So, this is again one test; the British pendulum can be used for measuring the frictional characteristics of specimens in the laboratory as well as in the field on actual surfaces with the different slider arrangements that are available.

Now this is another test, a test setup that is used to obtain the frictional measurements with the variation in speed. A dynamic friction tester measures surface frictional properties as a function of speed, and it can be conducted on laboratory-prepared specimens or preferably in the field; this test can be conducted in the presence of water as well as in its absence. So, it is used to determine the relative effects of various polishing techniques on materials or material combinations because I can do some accelerated polishing over these laboratory-prepared mixed samples. And I can take this particular one in the field and measure this variation in the friction with the speed of the field samples also. So, here you can see that there is a particular horizontal disc lower down; this is a bottom view of this dynamic friction tester.

This is how it looks from the bottom; you can see that there are three rubber sliders. So, the dynamic friction tester consists of a horizontal spinning disc fitted with three spring-loaded rubber sliders, and when it is brought down, it is rotated to the desired speed and

then lowered so these rubber sliders touch your surface. And then with the torque, you get the variation of your friction with the revolution speed. So, as the disc rotates, the rotational speed decreases due to the friction generated between the slider and the surface. So, the torque generated by the slider forces measured during spin-down is then used to calculate the friction as a function of speed.

So, this provides a maximum tangential velocity of 90 kilometers per hour. So, this can give you information. So, you can compare the different surfaces with the help of this dynamic friction tester. And you can have fresh samples if you prepare laboratory samples; you can subject them again by some means of polishing, and then you can use this dynamic friction tester again to get information about the friction values. Now, the other one is a circular track meter, specifically the texture, which we are comparing through the sand patch method; we can better obtain this particular information from the circular track meter as well. And this particular one is specifically because we want to correlate this particular one with the dynamic friction test measurements.

So, we will prefer to move it over the same track that is used for the dynamic friction test. So, because then we will get an idea, we got the friction with respect to speed, and we want to get information about the texture of the surface as well. So, it is run mainly on the same track where we have run the dynamic friction tester. So, it consists of a charge-coupled device, specifically a laser displacement sensor, which is mounted on an arm that rotates clockwise at 80 mm above the surface, such that the displacement system follows a circular track with a diameter specific to this particular one, and what it captures is a sensor that captures the macro texture depth. So this is an important part, and as I mentioned, it can be used for both laboratory investigations and field investigations, and importantly, it captures the macro texture profiles in terms of the mean profile depth.

So overall, you will have the lowest and highest peaks, which will help you to determine the mean profile depth with this particular one, and this mean profile depth is well correlated with your mean texture depth. So, I can say that this particular one, specifically your mean profile depth, is a 2D measurement compared to the 3D measurement you have in the volumetric sand patch method. So, it has been found that the average of the mean profile depth, which you get from the circular track meter for the 8 segments, because it is divided into 8 segments using the circular track meter, is extremely highly correlated with the mean texture depth and can replace the volumetric measurements. So, then you get more accurate measurements, and it can replace what you have gotten from your mean texture depth. So, the recommended relationship for the estimate of mean texture depth from the mean profile depth by the circular track meter is a standard expression used for converting your mean profile depth, obtained from the circular track meter, to the mean texture depth, which we get from the sand patch method.

So, the mean profile depth is mainly a 2D estimate of the 3D mean texture depth and is defined as the average of the highest profile peaks across 8 segments, as it is divided into 8 segments over which this particular one is measured. Along with it, the root mean square, a statistical measure, is also computed with this circular track meter. And which gives you how much the measured profiles deviate from their best-fitted model profile. So, this is additional information that you get from the circular track meter. So, we have discussed some of the important features that are related to the skid resistance or the frictional resistance of pavement surfaces, including the key properties on which it depends, such as the pavement surface, the vehicle, the tyre, the environment, and how the measurements can be done in the field using the locked wheel tester.

And there are certain other setups that can be used in the field as well as in the laboratory. We have the British pendulum tester, the dynamic friction tester, the circular track meter, and the sand patch method, which can be used in the laboratory as well as in the field. And then we briefly discussed the usefulness of these frictional factors, where we discussed the coefficient of friction in terms of the braking distance. So, this is all about today's lecture. Thank you so much.