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A very warm welcome to all of you. I am Rajan Choudhary, a professor in the Department of Civil Engineering at the Indian Institute of Technology, Guwahati, and the instructor for the NPTEL MOOC course, Pavement Construction and Technology, funded by the Ministry of Education, Government of India. Today's lecture under module 12 will focus on full-depth reclamation, as well as the discussions on cold-in-place recycling and cold-in-plant recycling, and we will also discuss some aspects related to cold mix design. At the outset, 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, as we discussed in our previous lectures about the recycling of bituminous pavements, we specifically discussed hot in-plant recycling and hot in-place recycling. In today's lecture, I will be covering three more aspects related to recycling.

And where we will discuss cold in-plant recycling, we will also discuss the equipment that is involved in all three of these processes. So, cold in-plant recycling, cold in-place recycling, and full-depth reclamation. In addition to this particular one, we will briefly discuss the design of the cold asphalt recycled mixes as well. So, as the word itself says, "cold," that means there is no heating involved in this particular one.

So, cold recycling involves the reuse of the existing pavement materials without the application of heat, and as in the case of hot mix recycling, when we talk about cold in-plant, that means the recycled mix is produced at the plant; when it is in the field or in situ, it is cold in-place recycling. Now, there is no small difference that exists between full depth reclamation. It is also similar to in-situ cold recycling, but with some specific considerations that we will discuss; both full-depth reclamation and cold in-place recycling are recycling methods that are done in situ. So the cold recycling is mainly attempted in three ways: cold in-plant recycling, cold in-place recycling, and full-depth reclamation. Both cold in-place recycling and full-depth reclamation are in-situ recycling.

As the term itself says, cold mix asphalt recycling is the process of reuse, as in the case of hot mix recycling, of reusing the reclaimed asphalt pavement by blending it with new binder recycling agents, specifically, or virgin aggregates, if required, to produce cold mix. And it says that, most of the time, the recycled mix, which is produced through cold mix recycling, is preferred to be used as base courses. So, that means after the construction of the base course, one may definitely need to go with a bituminous overlay as a wearing course over it. So, the process can be carried out either in place, in situ, which is your cold

in-place recycling and full-depth reclamation, or at a central mixing plant, which is your cold in-plant recycling. So, first, cold mix asphalt recycling is usually applied to what kind of distresses?

The wonderful part is that a significant number of distresses can be addressed specifically with cold mix asphalt recycling. So, it is usually applied to address pavement distress affecting both surface and base courses. So, you can go for a greater depth, specifically the bituminous wearing course, surface course, or the bituminous binder, and any issues related to these bound courses can be addressed in this one. Though its use has been more prevalent for base course rehabilitation, mainly because if there is an issue specifically with the bound bituminous courses, then it can be addressed with cold mix asphalt recycling. The process typically stabilizes the reclaimed materials, your reclaimed materials, and since it is a cold mix technology, the recycling agents that are going to be used are either foamed bitumen or emulsified bitumen, and may include, in certain cases, certain additives as well.

The additives may be, or many times they are called, active fillers as well. So, the additives are lime, fly ash, or cement. These are the common additives that are specifically used, and the purpose of using these additives is to improve the strength and durability of the coat for recycled mixes. These cold-mix asphalt recycling methods are quite effective in addressing surface distress, which may be in the form of cracking, rutting, and poor ride quality. So, they can be addressed with the help of cold mix asphalt recycling while offering the key advantages of enhancing the pavement structure without altering its existing geometry.

This is the conventional advantage that comes with the recycling of asphalt pavements. Now, let us first go over the cold in plant recycling (CIP). In cold in-place recycling, the reclaimed bituminous material is transported to a mobile cold mixing plant. So the amount of RAP that is generated when there is currently no facility for an in-situ one, or the amount of reclaimed material, is more than what can be used. So a good amount of reclaimed material will be stockpiled at the plants and some nearby plants.

So, this is usually the case where cold in-plant recycling will be preferred, either if you do not have facilities in place for recycling or if the amount of bituminous-bound materials produced is large and of good quality; they are stockpiled at a mixing plant. And then this code in plant recycling attempts the recycling using specifically either the formed bitumen or emulsified bitumen as a recycling agent. And here, as we know, it is a plant production. So, the plant precisely measures and feeds the reclaimed bituminous material and fresh aggregates, usually in the twin shaft pug mill mixer, which you can see is specifically at a cold mix plant. So, a metered amount is the important aspect in this one; also, a metered amount of either bitumen immersion or formed bitumen, which are the two common recycling agents, is then injected in this particular one.

After being mixed for a specific duration to achieve a homogeneous blend, the material is then transported to the work site, paved, and compacted, as we do in the case of hot mix asphalt as well. Mixing processes for cold mix recycling can be carried out at either a batch plant, drum plant, or a continuous stabilizing type plant, which is highly preferred specifically for the production of these cold recycled asphalt mixes. Now, the key steps, if we can put those key steps in sequence, are as follows: the first is the removal of the existing pavement. So, this is your ripping, or your milling is there; ripping is there, then crushing has to be there, or milling or pulverization has to be there, or milling has to be there. So, the removal of the existing pavement has to be done.

Crushing and stockpiling are necessary because the sizes are larger than what can be accommodated; usually, we go for sizes up to 2 inches. So, if the sizes are more of your reclaimed bituminous material, then it needs to be crushed, and finally, you stockpile it at a mix plant. Then the mixing is done using your different recycling agents: emulsified bitumen or foam bitumen. Lay down, since it is an emulsion, there may be a requirement for aeration. So, the compaction and curing requirements will be there.

So, these are some specific requirements; we will discuss these requirements in the upcoming slides as well. And finally, since it is laid as a base course, you need to go for a bituminous wearing course on top of it. So, if we look into the aspects specifically cold in plant recycling about the mixing part, then in cold in plant recycling, precise control of mixing time is important because what happens if I am using, say, the emulsified bitumen is that if it is mixed for a longer period of time, then the breaking of the emulsion may take place. So, this may again make your mix very stiff, and if the time given is less than proper, coating may not take place. So, the control time is very important at the plant also because, as it is mentioned, overmixing can cause premature breaking of emulsified bitumen.

So, then your mix will become stiff enough and very difficult, or it may not be feasible to compact it in the field, while under mixing may lead to inadequate coating of the aggregate. So, you will not have good cohesion of the mix. For foamed bitumen, the foaming is done at the plant. So, you have, we will also discuss the foaming aspects when we discuss the mixed design aspects. So, foaming is done at the plant itself, and it can also be done in situ, where you have a bitumen tanker and water.

And then hot bitumen is injected into the bitumen foamer, along with cold water, which leads to the foaming of the bitumen. Now, the important thing here is the injection rates of the hot bitumen. So, it may be the grade of the bitumen, the temperature of the bitumen, and the source of the bitumen that have to be there, and much percentage of water to be injected is an important aspect which will control how much amount of foaming occurs, as this foaming exercise increases the volume of your bitumen. Now, as the volume increases,

the viscosity decreases, which helps us coat your aggregates in a better manner; along with that, this volume will fall over time. So, we need to know that another aspect is the half-life by the time this volume, whatever the volume that has been expanded, gets reduced to half of its initial volume.

So, these are some important characteristics that need to be understood when we are using foamed bitumen in the case of cold in-place recycling as well. So, the injection rates of hot bitumen and water must be carefully regulated to ensure uniform coating of the aggregates. Laydown, aeration, and compaction, as I mentioned, aeration of the recycled mix is essential to reduce excess moisture because even when we are using this reclaimed bituminous material, many times you need to add, when you are producing these cold implant recycled mixes with your emulsified bitumen, some initial water to the RAP to improve its workability. So, there may be some initial moisture content already existing in the RAP. So, the moisture content of the RAP needs to be determined first and then monitored at the hot mix plant.

Specifically, here, it is a cold implant because no heating is involved to reduce excess moisture and volatile content, thereby improving stability before compaction. So, this is what you need to know: here you can see the mix is placed in windrows and has been leveled with the help of a motor grader. So, it has been, and it is going to be brought to the chamber by using this or the cross profile with this motor grader. So, the mix may be placed in a windrow and leveled to the required cross slope with the help of a motor grader, and this process also helps us to do some aeration to a certain extent. This process helps to reduce the fluid content, making the mix stable enough to support the compaction equipment, including standard compaction equipment such as vibratory rollers or specifically the sheep foot or pad foot rollers, which are used for the compaction of these stabilized courses.

Now, at the central plant, the cold recycled mix is produced using either bitumen immersion or foam bitumen, followed by laying and compaction. But there are a few typical advantages that are specifically available within plant recycling. There are certain cost aspects as well because you can understand that the reclaimed material has to be brought to the plant, and then the mix has to be produced at the plant and again needs to be transported to the site. So, these are some certain cost-related aspects that get introduced when you are doing cold in-plant recycling. But some important aspects are that through this particular one, you can go for a large amount of production, specifically when you are producing cold in-plant recycled mixes.

Quality control is important because, at a plant, you have good control over the injection of your emulsified bitumen, foamed bitumen, or other additives, which may include cement or lime. And at the plant, when you are mixing it, the control over the mixing is also better compared to what can be there in the case of the field. So, it allows for precise control over

input materials and mixing, ensuring consistent quality. This is one key advantage of cold in-plant recycling. Stockpiling treated materials, specifically in the case of foam bitumen, can be done for some time for use at a later period.

Settled plant recycling is preferred when stockpiles are already present. So, if you already have some RAP available, which is lying unutilized, then definitely cold in-plant recycling will be a good option. And when the existing pavement must be removed from the site, in-place recycling is not a viable option. So, that is because if, say, all your bituminous courses have shown some amount of distress, then the entire one has to be removed, and that may not be possible with your in-situ cold in-situ recycling or in-place recycling. So, that has to be brought to the plant, and then you produce it to come up with the cold in-plant recycled mixes.

The second, the word itself says, is cold in-place recycling when you do the recycling at the institute itself, at the site itself. So, cold in-place recycling is a pavement rehabilitation technique that reuses existing materials directly on the site. So, you do not have to bring your reclaimed asphalt material to the plant. It is directly used at the site, so you may have one single piece of equipment, or there may be a train of sets of equipment that may be used, as was the case with the hot in-place recycling as well. But there is no heating involved here.

So, the process involves milling and mixing simultaneously. You are milling, removing the existing surface, mixing it with a recycling agent, mixing it with some other aggregates, and virgin aggregates if the gradation is falling short at certain sizes. And in addition to the stabilizing additives carried out using either a single machine or a train of equipment, as I mentioned, since it is carried out at the site, it may be a single machine or a set of equipment forming a train of equipment. So, the milled material is conveyed to a pug mill; whatever is milled is conveyed, and if required, it needs to be brought down to be sieved. So, as to ensure that the sizes are within acceptable ranges, which also receive fresh aggregates through a parallel supply.

In addition, as I mentioned, if some aggregates are also required, then a parallel supply line is available to provide you with fresh aggregates and separate feeds for your recycling agent. Now, when it comes to foamed bitumen specifically, dedicated lines supply hot bitumen and water, as I mentioned, because foaming is to be done in situ. So, there will definitely be separate supply lines for your hot bitumen. The hot bitumen is typically in the range of 160 degrees centigrade to 200 degrees centigrade. And then the water needs to be injected to generate foam before it is introduced into the pug mill.

So, first, the foaming has to be done, and then this foam glutamine is to be introduced to the pug mill. The prepared cold-recycled mix is discharged directly into the paver hopper. So, finally, it comes out through the paver hopper. So, we have the vibratory screeds,

followed by paving and compaction, and then it is spread to the desired cross-profile and compacted. Coal-in-place recycling efficiently restores old pavements by correcting the profile.

This also helps us to correct the profile. It also helps to address the wheel ruts when these wheel ruts are caused by your bound base courses. Re-establishing the crown and cross slope, eliminating the potholes, unevenness, and roughness, it also addresses transverse, reflective, and longitudinal cracking. So, it is cold in place because we are going up to the recycling, and specifically when it is cold in place, recycling typically will go for a thickness in the range of 75 mm to 100 mm. So, this cold in-place recycling, many times called partial depth recycling, falls under the category of cold in place when the depth is more than that; specifically, if the depth is around 75 to 100 mm, then it is called partial depth cold in-place recycling.

When the depth typically ranges from 100 to 300 mm. That means we are going deep, we are going up to the unbound courses also, which may be your say granular base courses, wet mix mechanism may be there, or the granular subbase courses are there. When we go deep into those layers up to a depth of 100 to 300 mm, this becomes your full depth reclamation, which we are going to discuss later. So, both are code-in-place recycling, but the one attempted at depths ranging from 75 to 100 mm comes under the category of code-in-place recycling, and when the depth goes lower, specifically to the unbound courses of your unbound base courses or sub-base courses, we call it full-depth reclamation. Now, typical components that are involved in a cold in-place recycling plant or a recycler are components you can see in this particular example; we can try to understand this particular one.

This is a recycler, so you have the milling drum, which is going, so this one is showing where you can go for greater depths. Also, this one is a typical one where you can see it is written as unbound pavement and bound pavement, so it can mill to a greater depth. However, when we are going for cold in-place recycling, definitely the depth will not be more than 100 mm. So, typically, it will be restricted to your bituminous-bound courses. So, I can say this is a bituminous wearing course; there may be a bituminous base course, or a binder course may be there.

So, these two milling drums are going to remove this particular one. Finally, in this milled material, you will have the injection of immersion or the injection of the formed bitumen, along with any additives, and this is the mixer. So, it mixes a definite period of time, and then it comes out. Here, you have the tamping screed, and then there is vibration. So, finally, this is your stabilized material, which is there, compacted to a certain extent by your vibrating screed, and then it is ready for your rolling or compaction operations.

So, similarly, here you can see that this is a train of this particular one, where water is required when you are using emulsified bitumen. You have the milling machine there. So, then you have the recycling unit where the conveyor belt is. This is the one that conveys the reclaimed material, and then there is a screening and a crusher. If there is oversized material present, it will be removed, or the larger pieces can be reduced, and finally, it will be mixed, and here you can see this is an immersion tanker.

So, you can have one piece of equipment, one big piece of equipment, or a set of equipment running like a train. So, what are the main components or the main steps specifically in cold in-place recycling? First, the cold milling unit removes the existing pavement surface. Then, the material transfers, as you can see, this is a conveyor belt in the conveyor system to carry milled material, and if required, the fresh aggregates will be simultaneously added. So, precise weighing and proportioning of different aggregate sizes, as I mentioned, typically go for sizes up to 2 inches (40 mm to 50 mm). So, whatever oversizes are there, they are discarded.

Mixing a pug mill equipped with separate feed lines for aggregates and recycling agents, as the recycling agent can be emulsified bitumen. In the case of emulsified bitumen, you need to ensure that the RAP has a particular amount of moisture content because that is required for good workability of the RAP. This is when you are using emulsified bitumen as your recycling agent. Then, finally, once this is mixed with foamed bitumen or emulsified bitumen, it comes out with the help of these vibrating screeds. These are tamped and profiled with the recycled mix to the desired profile using the set of equipment; it is compacted, and in this particular train, you need to have proper control, specifically of the dust emissions, which are present because during the reclaiming of the existing pavement a lot of dust is generated, and there should also be control for the noise.

Now comes the other part, which is full-depth reclamation. As I mentioned, this is the one where you go for greater depths, in the ranges of 100 to 300 mm. So, if there are certain distresses taking place because of underlying courses that may be your bound base course, unbound base courses are showing some distress, or unbound granule sub-base courses are showing some distress. So, in that case, we can go for a greater depth, and this particular one can be recycled to produce the stabilized base course. So, this is an advantage here in this full-depth reclamation that, in addition to the bound courses, we are going to address any issues with the unbound courses, and then these unbound and bound courses together will be with or without a requirement for virgin aggregates, and the recycling agents will be used to produce a stabilized base course.

So, full-depth reclamation is a cold recycling technique in which all asphalt layers and part of the underlying unbound layer are reclaimed and stabilized to form a new base course. This is what this specific thing is for. It is usually recommended for pavements with severe distresses when you have deep ruts that are caused by the lower layers contributing to these

distresses. If the distress is because of your unbound courses, then deep rutting is present, load cracking is present, reflection cracking is present, extensive patching is present, and we need to go down in that case, as base and subgrade deficiencies are present. So, you will prepare a good stabilized base course to strengthen your pavement structure.

So, the key advantages usually associated with full-depth reclamation are improving pavement structure without altering its geometry because you are treating that particular unbound and bound course to produce a more stabilized or stronger base course. So, overall, your pavement structure is not being disturbed much; only on the top of it will you require a wearing course. Restores, profiles, crowns, slopes, and eliminates ruts, potholes, and irregularities. So, most of the distress can be addressed through this full-depth reclamation. Accommodating payment widening is another concern because when you widen it, you will match the existing one with the widened one.

So, you may have to require that your base course is in profile, and your unbound or bound base courses are in profile with the widening and the existing one. So, in that case, you need to strengthen the existing one. So, full-depth reclamation can be a good option that provides a uniform and durable pavement structure because it is a controlled process. So, you get good uniform strength and a base course, which eliminates major cracking, improves ride quality, and reduces frost susceptibility with suitable additives, because if some of the materials are present specifically in your unbound courses, granular course materials may be more susceptible, specifically those that are highly clayey with high plasticity index values. So, those kinds of materials in that case can be stabilized using additives like slime, which can be used to stabilize those weaker materials.

Low production costs usually need only a thin wearing course because this gives you a very strong base course. So, on top of it, you usually go for a thin-wearing course. So, what are the typical components that are involved specifically in full-depth reclamation, such as pulverization? So, it is breaking now because you are going to a greater depth; you can see here that this particular depth is there. So, you are going for a greater depth; you are going for a depth where these are the asphalt courses and these are your unbound courses.

So, you may be going for greater depth in that case. So, pulverization to break down this material to the required sizes, addition of recycling additives, shaping of the mixed material, bringing it to the profile and the camber, compaction, and finally, adding an asphalt wearing course are necessary steps. This is the usual process: you can see a set of equipment working, and finally, you come up with this stabilized base course. So, in full-depth reclamation, recycling is typically carried out to a depth ranging from 100 to 300 m. And what we usually have in this particular one is a self-propelled high-horsepower recliner because you are going for a depth of around 300 mm. So, a high-power recliner is required, a motor grader is needed to spread it to the desired camber, and then heavy rollers are required because the thickness is high enough in that case.

So, going through these individual steps, pulverization is the process usually performed with a cutting drum, and the specific motion that is used is the up-cut method. You can see in this particular one that whenever this one is going, this drum moves in this manner. So, it goes from your unbound courses and then removes your bound courses. This is a typical way in which this existing road material is removed. And why it helps to cool down the tool when it goes into the unbound courses minimizes wear and enables effective milling through the moist layers, like wet mix macadam or the granular subbase course.

So, when it goes into these underlying layers, it cools down. So, and then it removes this bituminous material. So, this is the up-cut method, which is usually used in the removal of the existing pavement or the pulverization that occurs while breaking the asphalt layers from the bottom upwards. So, this is one way you can use rippers, and there are also hammer mills. These reapers can be attached to your gridders as well as dozers. It can break the existing pavement structure, and then, through the hammer mills and crushers, you need to reduce them to usable sizes.

The application of a stabilizing or recycling additive is present. Additives like specifically emulsified bitumen, foamed bitumen, cement, and lime are incorporated into the reclaimed material to improve the strength and durability, producing a uniform base for construction. So, in this one, we typically prefer to use foam bitumen because, again, foam bitumen can be produced in situ. So, here is a generating system with heated bitumen and binder to adjust the doses of applications and whatever the virgin aggregates or any other additives specifically to treat the unbound materials, if required in terms of lime or in terms of the two most common materials that are used, which are lime and cement. So, whatever virgin aggregates, lime, or cement that are required to be added to this particular one are spread in front of this reclaimer. So, when it picks up, the desired quantity is spread on the surface in front of these reclaimers.

So, it picks up, and then the new materials, along with this particular one, are mixed together. So, additional required aggregates can be placed ahead of the recycling train to modify the layer thickness or RAP gradation, and dry agents such as lime and cement are also pre-applied. So, this is what is done. Then the shaping of the material is necessary because many of them have screeds that can lay down to the desired profile, or we can use motor graders to bring those materials in windrows to the desired shape and cross slope.

So, shaping the mixed material. When emulsified bitumen is used, a bitumen tanker is included because the emulsion tanker, along with the water tanker, as I mentioned in the case of emulsions, needs to have some pre-moisture content over the RAP for better workability. So, that is taken care of during the mix design of cold recycle mixes, which we will discuss in the next lecture. So, in the FBR train, is there a bitumen tanker along with a water tanker to premix, and if the already existing RAP has the required amount of water content, then you do not need to have this additional tanker? If the reclaimed material

exceeds the optimum moisture content, there may be a situation where it has a moisture content greater than what is required. So, in that particular case, the motor grader may have to aerate that one also. It helps to aerate it through its blade and finally to reach the desired consistency, where it can be compacted.

So, this is how it can aerate; it can also bring it to the desired profile. And then, large heavy rollers are typically used for compaction to achieve the required density of the reclaimed material, and as mentioned earlier, we typically go for depths of 100 to 300 mm. So, heavy rollers are required depending on site conditions. Pneumatic vibratory rollers and vibratory pad foot rollers can be employed for effective compaction of the stabilized courses. And you can see this is how it looks when you have reclaimed the existing surface to produce the stabilized base course. So, this is what we discussed specifically for the cold implant recycling, and the other one is cold in-situ recycling, where when the depth is less, we specifically call it cold in-place recycling, and when the depths are more than 100 mm, it can go up to approximately 300 mm, then we call it full-depth reclamation.

So, compaction, as mentioned, has to be done just after the immersion and during the compaction part, specifically when immersions are there. One important concern that needs to be taken care of is that the compaction has to be completed by the time immersion starts breaking; otherwise, the mix will become stiff and difficult to compact. Whereas, when you are using foamed bitumen specifically, we prefer that the compaction be completed when the mix becomes dry enough, because you have the time when this particular one will become stiff. So, we prefer foamed bitumen by the time the mix becomes dry, and in the case of emulsified bitumen, we prefer to complete it when the emulsion starts breaking. So, the curing and application of the bituminous wearing course may involve various additives, such as lime or cement.

So, these additives may require some additional curing time. So, that needs to be ensured before it can be opened up to traffic. So, proper curing of these stabilized reclaimed materials is essential to achieve the desired strength and prevent ravelling. If the traffic is opened before curing, then raveling will take place. Therefore, we finally allow the traffic once the wearing course is over. So, traffic is allowed on the foamed bitumen stabilized layer until it has dried up, and specifically when the moisture content of the top 10 centimeters of the layer has reduced to 50 percent.

So, these are certain estimates through which we try to work it out. Now, this particular one, your moisture content of the surface has become dry enough. So, when the moisture content of the surface has reduced to a certain level, it has to be allowed to dry up, and during this time, specifically during the daytime, it is always preferred to have light watering over the surface, which is typically done for at least 3 days. So, depending on what type of stabilizing additive you have used—lime, cement, and the content—we may have to go for a curing period of a longer duration, possibly for one week. So, the final

curing process may take up to a week before the wearing course can be applied. This is very important; otherwise, if the proper curing is not done and the wearing course is applied, then the wearing course will get damaged and will also get stripped.

So, if your base course did not achieve the required strength and traffic is allowed on the wearing course, then this will immediately lead to premature distress in these stabilized base courses as well. So, the choice of wearing course will depend on the anticipated traffic load. This is what type of wearing course it may be: a bituminous concrete or a stone matrix, depending on your traffic load. So this is all for this particular talk, where we discussed the cold in-place recycling, cold in-plant recycling, and full-depth reclamation. In the next talk, we will discuss the mixed design aspects of cold mix and cold asphalt recycling. Thank you so much.