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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 IIT Guwahati and the instructor for the NPTEL MOOC course, Pavement Construction and Technology, funded by the Ministry of Education, Government of India. Today's talk will be an extension of the discussion from lecture 30 of module 12, where we specifically discussed full-depth reclamation along with cold in-place recycling and cold in-plant recycling. So, today, this is a discussion in addition to this particular one, where we will discuss some of the key aspects related to the design of cold recycled asphalt mixes. 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. So now coming to the design of cold recycled mixes, there are certain key features that make them different from the design of hot recycled mixes.

And what are those key features? One important key feature is moisture adjustment. As in the case of hot mixes or hot recycled mixes, we do not want to have moisture content specifically as low as in the case of RAP. But in the case of cold recycled mixes, there is a requirement for a particular amount of moisture content. And that is why water is added to the reclaimed asphalt pavement and added aggregates; virgin aggregates may also be included if necessary to achieve the desired gradation for optimum moisture content, which provides the desired amount of workability to attain the required density.

So, in the case of reclaimed asphalt material, you need to determine your optimum moisture content and maximum dry density to obtain the required amount of water that is needed. So, some amount of water may already be there in the RAP, and some additional amount of water may be required, too. Usually, this water content goes in the range of about 2 to 6 percent, which gives you a maximum density with the reclaimed asphalt pavement. Then, in addition to this one, specifically in cold recycled mixes, you prefer to use additives like cement and hydrated lime because they are present; you produce these stabilized base courses to enhance their strength and durability. These two additives are referred to as active fillers because they produce compounds that add to the stability; they react with water and help in better dispersion of your bitumen immersion and impart greater strength and durability to your cold recycled asphalt mixes as well.

The third important thing is that the main focus is usually on the density. Instead of air void content, we will prefer to focus more specifically on density. We also go for the

measurement of the stability, the indirect tensile strength, and the measurement of your tensile strength ratio. So, wet the dry unconditioned samples and the conditioned samples; the strength of the unconditioned and conditioned samples is compared as we did in the case of the hot mixes as well. But here, you will find that more concentration will be given specifically to the density because we are producing it as a stabilized base course.

So, more focus will be on density compared to the air void content because air void content may show high variability with the change in your reclaimed materials, specifically because you are involving a greater depth of layers in it. Curing is another aspect that is usually not required in the case of hot mix asphalt. After an overnight, the surface can be opened for traffic, but here curing is an important aspect in the design of cold asphalt recycled mixes. The material is allowed to cure before placing the wearing course, either after the reduction in moisture content or as specified. So, either you go for what was mentioned in the earlier talk in the case of, say, foam-bitumen stabilized base courses, or you will see how much the water content has gone down.

So, once the surface has reached that particular level of dryness, only then can the varying course be applied over it, or it has undergone a given period of curing, which I say may be 3 days or 7 days, after which you can go for the application of the wearing course. So, these are some main differences that exist in the design of cold asphalt recycled mixes compared to what you have in the case of hot mix asphalt. Now, let us look at what the important steps are that are involved in the design of cold recycled asphalt mixes. One is the gradation of RAP. Here, another important aspect is that we are not going to consider the binder that is available with the reclaimed asphalt pavement.

They are treated as black rocks. So, it is treated as a black aggregate particle. The binder that is present over it will not be taken into consideration. This is one important difference that exists. So, you are going to go for the graduation of the RAP as it is specifically.

So, the cold recycled asphalt mix is designed to utilize the black rock gradation of treated RAP particles as aggregate rather than using extracted aggregate gradation. So, this is another difference that specifically applies to what you have in the case of hot mix recycled mixes as well. So, RAP samples for gradation analysis can be prepared, and where do you get them? You can get it from your milling operations. So, small milling jobs can be taken from the existing payments. They may differ from that of a full-size recycler because, in reality, there may be a larger recycler that can be used.

So, initially, for some samples, you used a small milling machine. So, there may be a slight difference in the samples or the gradation of the RAP. Or it can be seen by extracting the pavement course from the project site and then crushing it using jaw crushers at laboratory scale to achieve the desired maximum particle size, which I mentioned may typically be around, say, 40 mm, because, considering the laboratory mix design, the maximum sizes

are typically restricted to around 40 mm in that case. If the RAP gradation falls outside the recommended range, virgin aggregates must be added to adjust the overall gradation. This is another important requirement.

This virgin aggregate is typically spread. Now, how this particular one is specifically added in the case of cold in-place recycling or in the case of full-depth reclamation is that whatever additional virgin aggregates or stabilizing additives are required are spread on the existing pavement surface in front of your recycler. So, this is another important consideration that is to be there. Determination, now in the laboratory, you will definitely be using your pygmy mixers, where you can incorporate it directly, but simultaneously, how it is done in the field is mentioned. So, the determination of optimum water content for mixing.

So, the optimum moisture content of rap is similar to that of soils and aggregates, as we discussed earlier in our talks when we determined the optimum moisture content and maximum dry density of granular materials, as well as for subgrade soil. So, using IS 2720, specifically part 8, which is there for heavy compaction. So, this can be attempted whether we are using rap alone or if a combination of rap and virgin aggregates is present; both have to be combined together in the desired proportion, and then the moisture content is to be worked out, which gives you the maximum density. So, the moisture content corresponding to the maximum dry density is selected as optimum, as it ensures effective compaction and uniform distribution of the recycling agents. So, this is what it is because if you have this much of it, then whatever your recycling agent is, it gets better distributed, and you get a good density as well.

Then, another feature that should be taken care of specifically is the use of some active fillers. Active fillers, specifically your lime and your cement, are the two most commonly used active fillers. Bitumen stabilization is typically carried out with a small percentage of active fillers. The percentages of hydrated lime may be around 1.5 percent, and the cement may be around 1 percent to enhance the dispersion of the bitumen within the mix.

This is an additional advantage that is present, and along with it, it gives you higher soaked strengths and durability values when these active fillers are used because they add to the strength and durability of your mix. So, we need to look for the incorporation of active fillers along with this particular part of the water content. As I mentioned, the typical percentages that are used depend on the rap gradation; they may vary. The typical contents of hydrated lime are 1.5 percent, and if we go for higher contents of cement, it usually makes your mix harsher, or you can say it makes your mix more brittle.

So, you normally do not prefer to go for higher percentages; these are the typical percentages of cement that are used for these cold asphalt recycled mixes. And what are the key advantages? Some of them have already been discussed. Enhancers foam bubble

distribution in foamed bitumen mixtures. This is one advantage. It distributes, leading to a uniform or better distribution of foamed bitumen in cold asphalt recycled mixes.

Improves wet as well as dry strength, so whether you measure by any test specifically in terms of material stability, retained material stability, or indirect tensile strength, both conditioned and unconditioned. It helps us improve the strength of these cold recycled mixes, and this is quite useful if they are showing marginal performance without these additives. Promotes early strength gain because, as we have seen, the curing periods may range from 3 days to 7 days. So, in that case, early gain in strength is required to reduce it in that particular case, so that it can be allowed for the traffic. So, these are again active fillers, and this hydrated lime and cement play an important role in contributing to the long-term strength and durability of the stabilized material.

So, that is why these are quite popular, specifically in the design of cold asphalt recycled mixes. Two recycling agents are used. One is your bitumen immersion, emulsified bitumen, and the second is your foamed bitumen. In cold recycled asphalt mixes, a recycling agent, which is a binder, is used to bind the reclaimed materials. The two commonly used types are foamed bitumen and emulsified bitumen.

So, we just need to look at the key characteristics of the foamed bitumen, specifically the one that is very popular in producing these cold-stabilized base courses. So, the important parameters that need to be ensured when you are using foamed bitumen to produce these stabilized courses are the expansion ratio. As I mentioned, the foaming of the bitumen is done by adding water to hot bitumen. Hot bitumen means the temperature of the bitumen is in the range of around 160 to 200 degrees centigrade, and we usually add water, which may range from 2 percent to 6 percent of the mass of your bitumen. So, that particular one is injected; it leads to the foaming of the bitumen, and the expansion in volume may be 8 times to 10 times. Your desired range is around 8 to 10 times; the volume expansion should take place.

So, expansion ratio, what is the expansion ratio of foamed bitumen? The ratio of the maximum volume of the formed bitumen with respect to the original volume of hot bitumen. So, it reflects the degree of expansion; the greater the degree of expansion, the lower the viscosity, making it easier to coat your aggregates or reclaimed materials.

Half-life: This is another important aspect, which is that once this is established, the expansion is present. After this particular phase, in due course of time, the volume will start reducing. So, it says the time it takes for the foam to collapse to half of its maximum volume, specifically that is given in seconds, is again an indication of the stability of the foam.

So, this particular one is basically, we usually recommend having a value of around 8 to 10 seconds; at least 8 to 10 seconds should be there by the time it collapses and comes

down to half its volume. So, since this foaming is done at the site itself. So, usually we need to check for different percentages of water with respect to the two parameters: one is the expansion ratio, and the second is the half-life, as we can see; this is the expansion ratio. So, the more water is injected, we can vary it, say, from a percentage ranging from 2 to 5 percent or 2 to 6 percent; as the water injection increases, the expansion increases. Here, it can be said that the expansion ratio is the volume of the formed bitumen with respect to the volume of the original bitumen.

So, our target may be around 8 or 10. So, here I am showing a target of around a 10 percent expansion in volume. Simultaneously, this half-life goes down as the percentage of water injection increases. So, this white one shows the half-life and what my target half-life is: around 10 seconds. If I am keeping my target, the half-life is 10 seconds.

So, I get the two water injection percentages, and I can pick a middle one of this particular one, which I can select; this is the combination on-site. I will require around 3 percent of water injection to get my desired foamed bitumen. So, these parameters are essential for evaluating the quality, workability, and effectiveness of foamed bitumen in the recycling process. So, these are two important parameters. Parameters are specifically taken care of during the lab-produced stabilized courses, as well as in plant and in situ, as both these parameters specifically refer to the expansion ratio and the half-life, which depend upon the amount of water, the bitumen type, specifically the grade of bitumen used, the source of the bitumen, and the temperature.

So, the temperatures may be in the range of 160 to 200 degrees Celsius. So, you can work this particular one out at different temperatures to get suitable water injection percentages, water pressure, and additives. So, these are some of the parameters on which this expansion ratio and half-life depend. Now, when we are using an emulsified bitumen specifically as a recycling agent, the most commonly used are cationic slow-setting emulsions. And even in this case, many times it has been observed that if the RAP already has some softer grade of binder coated over it, then we can prefer to use a cationic slow-setting emulsion that has a base binder of a harder grade.

So, you can choose to use a cationic slow-setting one, which is about 1 inch, where an inch represents the harder base binder. So, this can be used specifically if you are finding that whatever binder is on the RAP is a softer one; then emulsified bitumen, having a stiffer base binder, can be used. And the most preferred grade is cationic slow-setting emulsions, which are used. And the other thing is, whenever we are using these active fillers, specifically with the emulsified bitumen, we need to ensure that it does not cause the emulsified bitumen to break too quickly; otherwise, it will be difficult to produce the mix, and it will be more difficult to compact that particular mix. So, that is why this foam bitumen is more popular, specifically in the production of stabilized base courses, which

means in your code, in-place recycling or full-depth reclamation, because the foaming is done on site; this is one additional advantage.

Foam bitumen-treated material can usually be placed, compacted, and open to traffic much earlier compared to what we have with the emulsified bitumen-treated cold mixes. The treated material remains workable for a longer period. So, you can stockpile it for later use. So, these are some specific reasons why this foam bitumen is more popular in the production of cold asphalt recycled mixes. Now, while doing the laboratory mix design, you need to work out the optimum binder content for which the samples have to be prepared, the specimens have to be prepared, and we can use a mechanical bucket mixer or a laboratory-sized pug mill mixer with the pedals that are there.

Whatever the required amount of active fillers, different percentages can be tried along with a virgin aggregate that is to be added and mixed in the pug mill to get a uniform blend, and usually around 30 seconds are required to achieve that uniform blend. Then the water is added again. For this particular one, you need to ensure what the existing water content in the RAP is. So, whatever additional water content is to be added to reach the optimum moisture content, it is to be mixed again. Finally, after that particular one, the recycling agent, which is either emulsified bitumen or foamed bitumen, is added to the mix, ensuring that the cold recycled asphalt mixes are uniformly coated at room temperature.

So, there is no heating involved here. So, whatever the required doses of your emulsified bitumen or your foamed bitumen are, they are added. Now, this particular one for working out the optimum doses, we usually try at least three to four contents of your foamed bitumen or your emulsified bitumen. And, for example, typically the optimum binder content is in the range of 2 to 2.5 percent, but may be as low as 1.8 percent for a mix with foamed medium in cold recycled asphalt mixes.

So, different from the various combinations of virgin aggregates and RAP. We need to work out at least three to four different trial binder contents for the preparation of these specimens to determine your optimum binder content. Now, when we are doing the second step, there should be at least three different trial binder contents; then these cold asphalt recycled mixes are to be compacted. As we go with the Marshall method of mix design, they can be compacted by giving 75 blows on both sides. If a gyratory compactor is available, 30 gyrations are usually used for compacting these specimens.

Now, thereafter comes the curing. The curing conditions, which are typically mentioned, may differ in specification from region to region. So, these are some of the most commonly preferred combinations. So, for foam bitumen as a recycling agent, compacted specimens are typically cured at 40 degrees centigrade in a forced draft oven for 72 hours, as in this particular one. So, first, it is cured at 40 degrees centigrade for 72 hours and then cooled to room temperature at 25 degrees centigrade for 24 hours. So, this is how this particular

curing is done specifically for foam destabilized mixes, and then these can be tested for indirect tensile strength.

For indirect tensile strength, as the test is to be done at 25 degrees centigrade, we keep these specimens for 2 hours at 25 degrees centigrade, and then we go for the indirect tensile strength. Similarly, we can go for this, which is unconditioned, or I can say the dry ITS value. Many times, many specifications require putting up a requirement for your tensile strength ratio, which is your ITS, which is your wet upon ITS, and which is your dry. And it says that many specifications say that this value should be at least 70 percent or 70 to 80 percent; depending on the different codal guidelines, this range may be 70 to 80 percent. So, the tensile strength ratio for most of the cold asphalt recycled mixes, as per our IRC 120:2015, usually states that a tensile strength ratio of 70 percent is preferred for evaluating these mixes.

So, we can have the dry ITS value and the one after conditioning it at 25 degrees centigrade in a water bath for 24 hours, and then we determine the wet or soaked ITS value, and thereafter we get the tensile strength ratio. When it is there for the emulsified bituminous specifically, the specimens are first cured to a constant mass at 60 degrees centigrade in the forced draft oven. So, this is to ensure it is first cured in a forced draft oven at 60 degrees centigrade. These are some of the typical conditions that are recommended, and after curing, the specimens are cooled to 25 degrees Celsius and then brought down to ambient temperatures of 25 degrees Celsius. And then the strength of these specimens can be measured either in terms of Marshall stability or ITS testing.

Usually, for Marshall stability, the testing is done at 40 degrees centigrade, and for ITS, the testing is done at 25 degrees centigrade. Now, for this particular one, even many times for cold asphalt recycled mixes, they go for retained Marshall stability. So, the conditioning will involve the dry Marshall stability value, which will be determined at 40 degrees centigrade; the second will be the stability, which will be determined after it is subjected to soaking conditions. In soaking conditions, it is often referred to that you should go for a saturation of these samples to a particular degree, and thereafter, the stability is measured. Whereas, when the ITS value is to be measured, the sample has to be kept submerged in water for 24 hours at 25 degrees centigrade, and then you measure the ITS, which is your wet ITS or soaked ITS, and then you determine.

So, usually, the ITS values recommended by different specifications say that the dry ITS values may range from 200 to 350 kilopascals. So, these are some typical requirements. It depends upon specifications to specifications. The dry ITS values may be in the range of 200 to 300 kilopascals, and your wet ITS values may be around 100 to 150 kilopascals. And then, as I mentioned, the tensile strength ratio as per IRC 120 recommends a value of 0.7, which means that 70 percent of the indirect tensile strength should be retained after subjecting that sample to the soaking conditions. Then we need to work out what the ranges

are where you are able to achieve your desired results for different binder contents, where the trials have been done. We need to work out what the binder contents are and where you are able to achieve the requirements in terms of your ITS; mainly, it is done in terms of ITS and TSR. And for the payment design part, the resilient modulus can also be determined, as well as estimated using the values of ITS, and then the resilient modulus values are used in the design of flexible pavements using IRC 37:2018. These are the two main parameters: indirect tensile strength and Marshall stability, which are usually measured in the design of cold recycled mixes.

So, where do you get your minimum values for stability? Stability usually has around 5 points. We go for around 5.5 kilonewtons, as we have for most of the dense-graded mixes, where it is around 9 to 10 kilonewtons.

Here, the strength achieved is around 5.5 kilonewtons. The requirements, according to many specifications, state a value of around 5.5 kilonewtons. So, depending on the requirements of the project specification, the region-specific optimum binder content, which meets the requirements of TSR, ITS, and Marshall stability, must be chosen from three to four different trial binder contents, and that forms your optimum binder content. So, this is a brief discussion specifically on the different aspects related to the design of cold recycled mixes. So, for formed bitumen, the dry and wet ITS are plotted; this is usual, as we did in the case of hot mix asphalt design.

We can plot the dry and wet ITS values with respect to the binder content. So, select a binder content that meets the minimum requirement of ITS and TSR. Similarly, for emulsified bitumen, as I mentioned, we can have the requirements for dry stability as well as wet stability, which are determined after subjecting the samples to saturation. To determine the optimum asphalt that meets the required criteria for dry stability and retains stability. If the ITS is used, the immersion content that satisfies the minimum criteria for ITS and TSR is selected as an optimum.

So, it depends on the specification. What does it say? It says whether it refers to ITS and TSR or whether it refers to Marshall stability and retains Marshall stability. On the basis of that, you will determine the optimum binder content. This completes our discussion specifically on the design of cold recycled mixes. And finally, whenever these different recycling techniques, which we have discussed, especially one under the category of hot mix asphalt recycled mixes and the second under the category of cold asphalt recycled mixes, whichever technique has to be picked, these techniques usually offer a good amount of advantages compared to going with only the conventional methods without using reclaimed distressed pavements, but the choice of a specific method should be carefully decided. This is very important regarding the type and cause of the distress because, as we have seen in the full depth of reclamation, if the problem exists with your base courses and unbound courses, which form a significant thickness of your pavement, and if the problem

lies in those courses, going with small treatments or techniques of recycling, such as hot in-place recycling that only recycles the surface courses, may not serve your purpose.

It may not be able to address this particular concern, and the distress may recur. So, specifically in these recycling techniques, it is very important to choose the correct technique to be used for any particular type of distress; for that, we need to know the causes of the distress and which particular layer is contributing to that distress. As not all methods are equally effective for every surface course, if the problem is only with your surface courses or wearing courses, and if you are attempting a full-depth reclamation, then it is again a waste of money. So, one has to be very cautious while picking the recycling technique, depending on the type of distress and what type of stabilization or strengthening is required. So, this is all about this particular one. Thank you so much.