Pavement Material
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Lecture 13
Classification and Gradation of Aggregates (Part - 1)

Hello, everyone welcome back.

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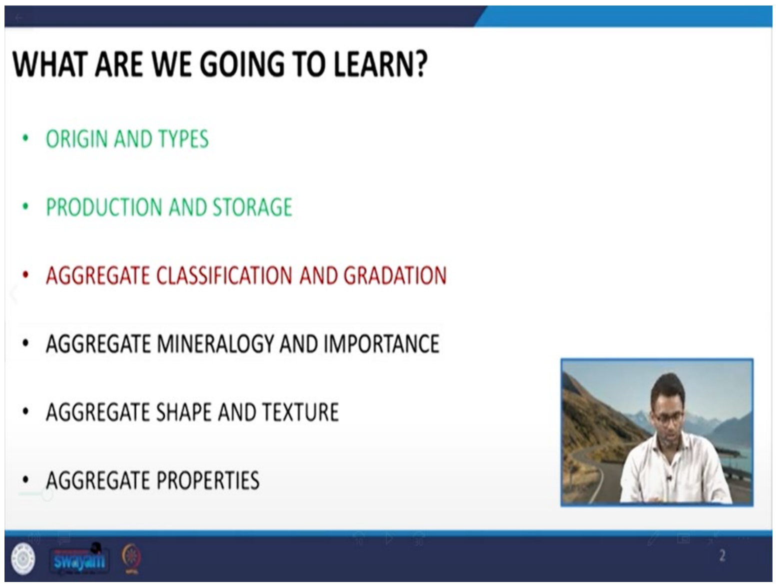

If you remember in the last class we have discussed about the production and storage of aggregates. We discussed about the quarrying operation and we discussed that through the quarrying operation the aggregates are further mechanically crushed and stockpiled into different sizes. We also discussed in brief about the storage of the aggregate in the plants which is typically in the form of stockpiles and even the stockpiles are stagged corresponding to various sizes.

We also discussed that there can be different places from where aggregates can be sampled and then further subjected to testing to represent or to evaluate the representative properties of the stockpile. And we concluded that the conveyor belt is one of the convenient places where the segregation of the aggregates will be minimal in comparison to the other locations for sampling. Today we will start discussing about aggregate classification and the gradation of aggregates and this is basically, a very important topic to discuss specifically when we try to relate this knowledge with the mixed design of asphalt mixtures and concrete mixtures.

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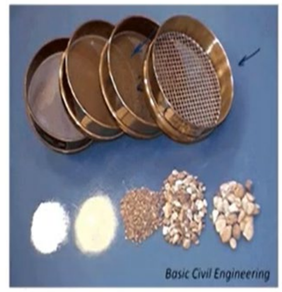
CLASSIFICATION

- **Based on Size**
  - Coarse gravel: 80 mm to 20 mm CA
  - Fine gravel: 20 mm to 4.75 mm 4.75 mm
  - Coarse sand: 4.75 mm to 2mm
  - Medium sand: 2 mm to 0.425 mm
  - Fine sand: 0.425 mm to 0.075 mm
  - Silt: 0.075 mm to 0.002 mm
  - Clay: < 0.002 mm
- Average size can be known by passing through sieves with square openings
- Aggregates are assumed to be rounded so that if the diameter is less than the size of square side, material will retain



Talking about classification mostly for most of the pavement application aggregates are classified based on their sizes. So, if we see the typical size or size distribution it can be categorized as coarse aggregates, sand and fine aggregate. Well this this is not the exact classification but an approximate classification. Another way of thinking about this classification is that we have coarse aggregates and we have fine aggregates. So, we have coarse gravels as one of the sizes and the size ranges from 80 mm to 20 mm typically. Fine gravels which are again are of large size they range from 20 mm to 4.75 mm.

So, we can say that materials which are larger than 4.75 mm are basically coarse aggregates and materials passing 4.75 mm are fine aggregates. So, in the fine aggregate the first size which we have represents the sand. So, we can have coarse sand which ranges typically from 4.75 mm to 2 mm, we can have medium sand whose range can be 2 mm to 425 microns or 0.425 mm.

We further have fine sand which ranges from 425 microns to 75 micron. And materials that passes 75 micron sieve or 0.075 mm sieve they are also called as fillers, filler particles and they are of very small size. And further again we have two more categories one is silt the size of which ranges from 75 microns to 0.002 mm. And materials which is even smaller than 2 microns they are basically categorized as clay particles.

So, this is an approximate way different specifications different guidelines have their own way of classifying the aggregates based even on sizes. This is typically an Indian classification system which is used to categorize the aggregate particles based on their size distribution. Now, when we say size of the aggregate if you remember I showed you a typical aggregate in the last presentation. And we saw that these aggregate particles they do not have any specific shape a specific standard shape such as a cubical shape or a spherical shape.

They have random shapes and therefore they also have random sizes. So, even describing an average size is also empirical when we say that there is an aggregate of size of let us say 4.75 mm or 20 mm so this is an empirical way of describing the average size of the particle. So typically, what we do the empirical average value is arrived by passing these aggregates through a set of sieves which have square openings.

So, I have some sieves here of different sizes for example you can see that this is again a sieve which is of coarser size and this is a 20 mm sieve. And you can see we have square opening here so this square opening in fact is used as the representation of the average size. Here we are assuming that the aggregates which in question they are basically rounded or spherical in nature.

So, I am assuming the aggregate as spherical in nature such that this diameter if it is less than this square opening size the side of the square opening it will get retained in this sieve. So, we will say that that particular aggregate is a material which retains on 20 mm sieve. But usually we say about the sizes based on two set of sieves is a sieve which is of larger size and the second largest size. So, let us say if we have a 20 mm sieve and the next standard sieve which we typically use is say is 13.2 mm or 12.5 mm. And I have an aggregate particle which passes this 20 mm sieve and is retained on 12.5 mm sieve.

So, I can say that the average size is somewhere between $\frac{20+12.5}{2}$. So that is the an approximate average size of the particle but usually we do not talk about average sizes as single size based on single sieve it is always a two sieve in question. So, we say that we have an aggregate particle which is passing x mm and retained on y mm.

This is the way we describe arbitrarily you can say the size of the aggregate particles. And as we have discussed that aggregate particles can be of varying sizes we can have a wide range maybe from the working range let us say for a bituminous mix can be 37.5 mm or 26.5 mm down to 75 micron passing. Therefore, we also have large number of sieves with different sizes.

So, here again in this picture you can see that it shows so many different sizes of sieves with different sieve openings so we have coarser openings we have finer opening. So, here again I also have a few sieves today with me the one which I showed you initially was 20 mm then again we have further smaller sieve here so this is a 10 mm sieve. You can see the size of this square opening is a smaller in comparison to the 20 mm sieve. Then we have one more sieve here which is 2.36 mm this is again a standard size we use so this is a 2.36 mm sieve you can see when you have finer mesh you can have even finer like 75-micron sieve will be much finer.

So, it will be very difficult to understand that it has a square opening even if you see it visually. On the lower side as we are describing that we can have material 75 micron passing or 2 micron passing. So, you know making sieves with such small apertures are very difficult. So typically, we the last sieve which we have is usually 75-micron sieve or if in in European specifications it is a 63-micron sieve let us say. So, below 75-micron sieve whatever passes we typically collect it or consider it as one material. And finally, we have to collect this material in something which is called a pan which does not have any aperture here does not have this is not a sieve this is just a collector all right. So, this is called as pan now we collect everything which passes 75-micron sieve in the pan.

Now, talking about the gradation now we understand what aggregate sizes are and how do we know about the size using sieves. Now for any given mix or let us say we have a concrete mix or we have an asphalt mixture or a bituminous mixture. We will have aggregates of different sizes these are not single sized mix we have aggregates so we have coarser aggregates the voids of this coarser aggregates are filled by relatively finer aggregates again the further voids which get created are filled by further finer aggregates and this is a process of creating a stacked gradation so we have aggregates of different sizes.

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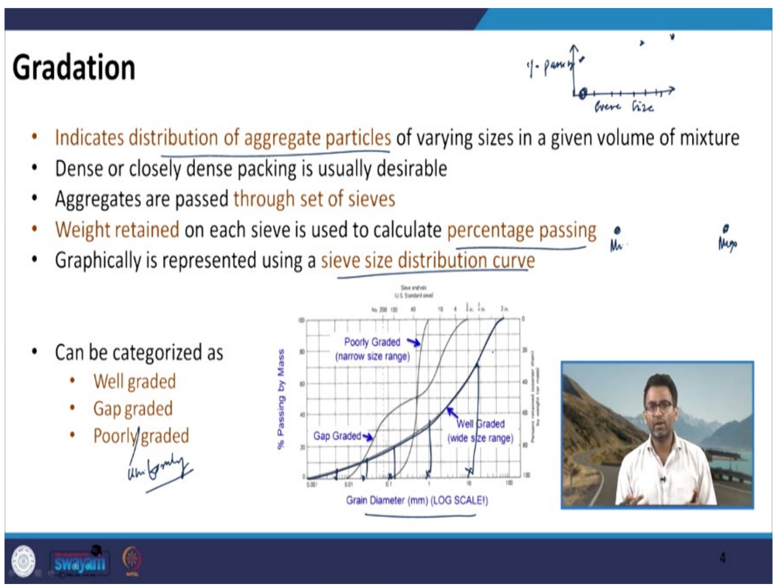

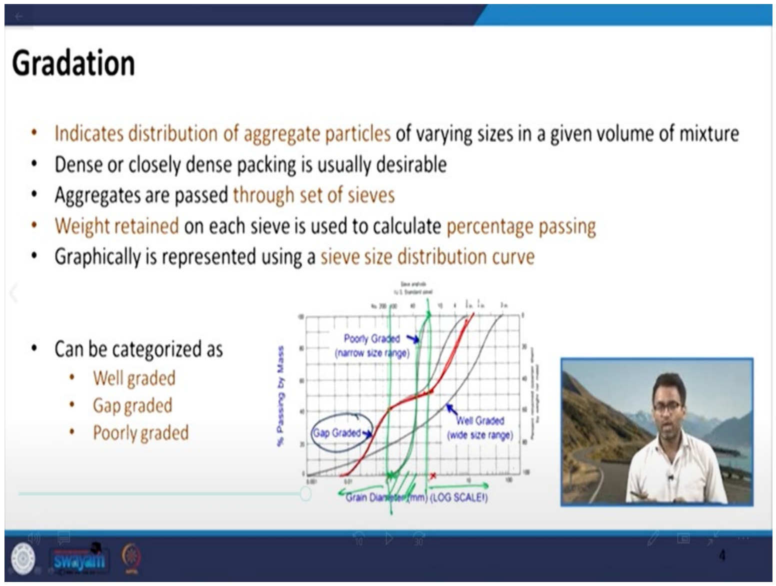

So, this gradation which will be discussing. Now, it indicates the distribution of aggregate particles of varying sizes in a given volume of the mixture all right. So, it tells us that how these sizes are distributed. Usually or generally we desire close dense packing for most of the mixtures for example in concrete mix we will desire a very dense mix.

Similarly, in an typical wearing course asphalt mixture again we desire a dense packing. But we will discuss that we do not desire extremely dense packing because of some additional considerations but overall, we need some dense packing because dense packing with will ensure proper contact between the aggregates and it will further ensure proper distribution of the load which is coming on the mixture.

Now, to define the gradation to define this packing or the distribution of the aggregates what is done that aggregates are passed through the set of sieves. So we know that there are varying sizes and in order to understand how these sizes are distributed what we do we will take a unit weight of the mixture which has different sizes we will put it on the top of the largest sieve or the sieve corresponding to the larger size in the gradation. And we will do sieving of the aggregates and after saving the aggregate through the set of sieves we will understand based on the weight that gets retained on individual sieves that how the gradation is actually distributed for any given mix.

So, the weight retained on each mix is used to calculate the percentage passing each sieve all right. So, we will discuss it in the next slide that how the calculation is done which is again one of the important thing to discuss because that will give us a working experience on how aggregates are sieved in the laboratory and how the laboratory values are further used to plot the sieve size distribution of the aggregates. So, when I say plotting which means graphically I am trying to represent the distribution of the aggregate particles and this is done using a size distribution curve. So, the sieve size distribution curve is a plot between the percentage passing and the sieve size.

So, we have different sieves as we discussed in the gradation. So, corresponding to each sieve what is the percentage passing this is what we are trying to find out corresponding to different sieves what is the percentage passing. And based on the percentage passing we will be able to understand that how in that particular mix the aggregates are distributed. Based on how the aggregates get distributed in any given mix there are various type of gradations which can be discussed all right.

It is not that all the mix will have similar form of aggregate distribution is not it so we can have multiple gradations with multiple form of aggregate distributions. So, depending on how the plot looks like between percentage passing and the sieve size we can understand that whether these gradations are well graded structures are they gap graded structures or they are poorly or uniformly graded structures let us say.

So, let me try to explain you what these different gradations mean visually first of all this sieve size distribution curve is usually plotted in a semi log graph where the y axis is arithmetic scale which is percentage passing and the x axis is the grain size but in the log scale all right. So, you see that here we have three distinct curves let us say that this is the minimum size and this is the maximum size within the gradation.

So, if we have a smooth-running curve between the minimum size and the maximum size which you see here a smooth-running curve going almost through the middle of the graph which we have drawn that is a well graded structure all right. So, this this will ensure that we have aggregates present in the mix of different sizes which means for each value of x you have some distinct value of y and this is continuous in nature which means that this is a well graded structure you have aggregates of different sizes in the structure all right. So, usually dense packing which I was discussing about are well graded structures.

We can also have gap gradation so what is a gap gradation in gap gradation some sizes go missing. You have finer aggregates usually and you have coarser aggregates but the mid-size range is missing. And therefore, you see that the gradation here it started to move smoothly but in between it is flat what does this mean that for this range of x the y is not changing much which means it is constant which means that particular range is missing here. And then again, your curve starts to move which means further you have different size of aggregate particles in the structure.

This says that there is a gap in the structure you have coarser you have finer and the mid-range goes missing so this is typically a gap graded structure. We can also have a poorly graded or a uniformly graded structure. Now this uniformly graded structure has very high voids and therefore their stability is less we will discuss more when we discuss about aggregate packing that what do I mean by stability what do I mean by voids. So, just try to understand that in well grade structure you have aggregates of different sizes though it is a close packing. In gap grid structure since few sizes are missing then you will have some more number of voids between the aggregate structure in comparison to the well graded structure.

In uniformly or poorly graded you have aggregates mostly of very small size range which means you do not have aggregates of different sizes. Therefore, you see if you see the curve here you will be able to understand here the curve starts from here and it ends here. Which means you have aggregates only in this size you do not have any you know large variation in sizes of aggregate or aggregates of different sizes. So these you can say are mostly single sized aggregates and because these are single sized aggregates the stability is less because interlocking is not achieved and also the voids are typically much higher all right so that is a poorly graded structure. So, these are three typical categories of aggregate gradations when we discuss about mixes used in in pavement structure.

In order to understand that how are we trying to draw this size distribution curve for any given gradation. So, let us understand what we do you have a mix so you take that mix you know what is the maximum size of aggregate there so based on the maximum size you place it at the top of this stack.

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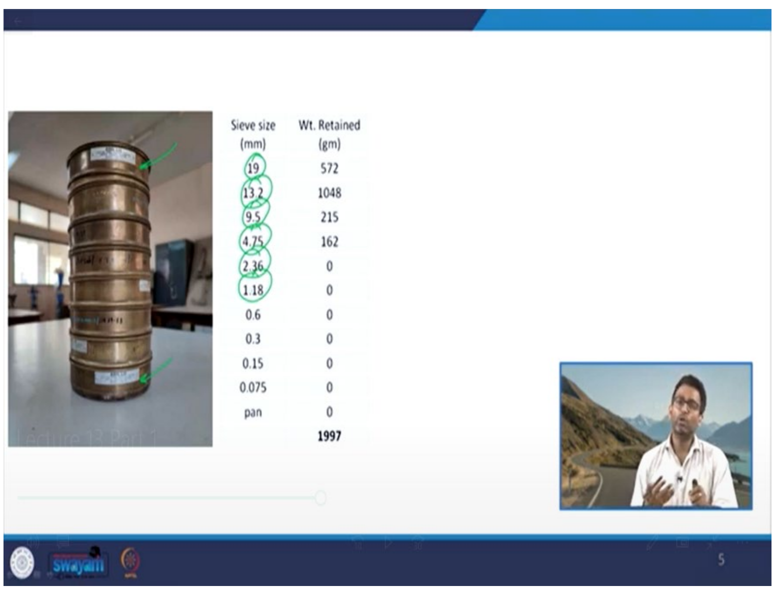

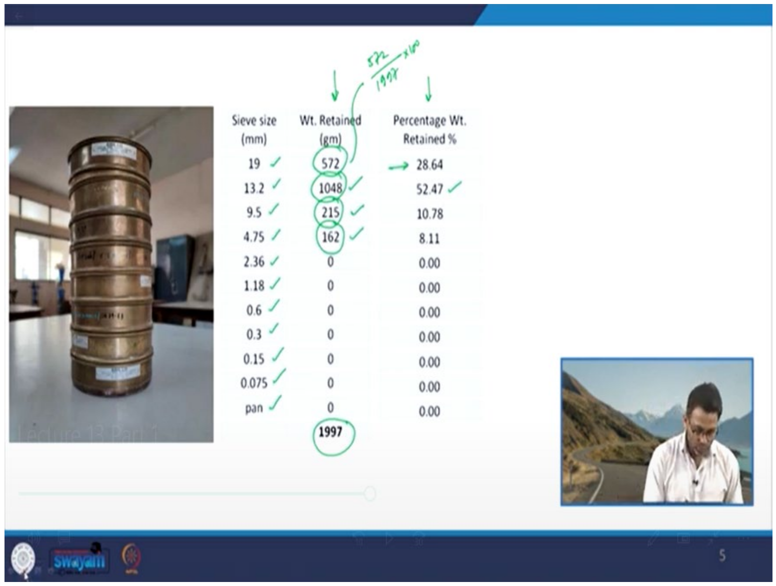

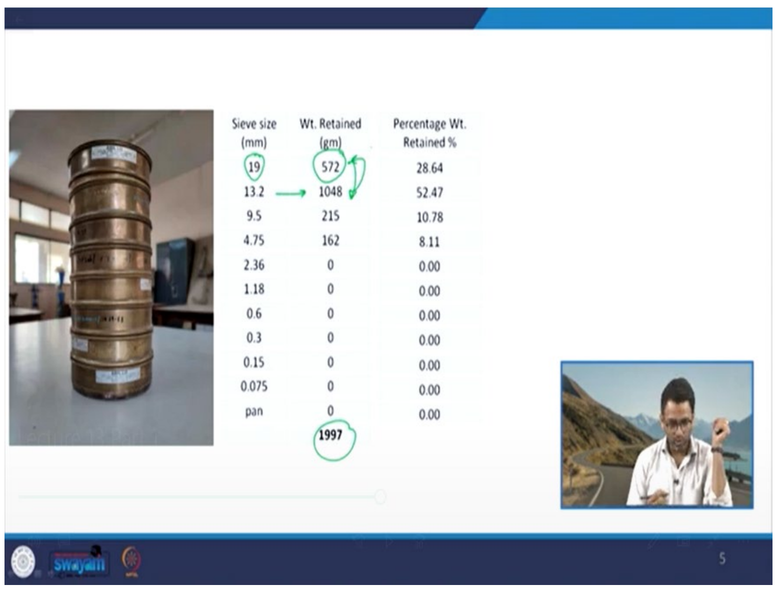

So, from the top as you move down the sizes of the sieves are reducing and at the bottom you have a pan to collect all the aggregates that passes through the minimum sized sieve let us say it is a 75 micron sieve all right. So, let us say that we have used some standard sieves which are given by given by our highway agencies so these numbers they can be different in different highway agencies. So, this numbers which I have shown you are these sieves which I have which I have written here they are typically used in Indian system you can say for bituminous mixtures for concrete mixture so these are some standard sieves we use in India.

So, let us say we have a 19 mm sieve 13.2, 9.5, 4.75, 2.36, 1.18, 600 microns 300 microns 150 microns 75 micron and pan. So, I have placed all the sieves in this order and I have taken the entire mixture and I have kept it at the top of 19 mm sieve and I have started sieving. Sieving can be done manually through shaking or it can be done automatically through automatic sieve shaker also.

So, after sieving the material sieving means shaking the material through a sieve shaker or using hand for considerable let us say 10 to 15 minutes till we are assured that all the materials have now settled as per their sizes in different sieves we will stop. And then we will take the weight of the material which gets retains on each sieve. So, this is what we expect right once we put the material in each sieve some material will get retained.

Let us say you have taken one or two kgs of material and then after taking the after doing the sieving each of this sieve will have some material retained so I am just measuring it using a weighing pan. So, let us say in this example we have taken 1997 of aggregates and I have in 19 mm sieve 572 gram got retained in 13.2 mm sieve 1048 grams got retained. In 9.5, 215 grams got retained in 4.75, 162 grams got retained. And there were no aggregate particles in the sieves below 4.75 mm means this is a course aggregate or course stockpile which we are trying to save here all right. We do not have fine particles in the stockpile which we have taken for gradation all right.

So, then what we will do based on the second column we will do a calculation and we will find out what is the percentage of this weight retained in each sieve. So, since we are calculating percentage it is very easy for example here you will do $\frac{572}{1997} \times 100$ so this will give you 28.64 percentage is not it. Similarly, this is $\frac{1048}{1997} \times 100$ it will give you 52.47, $\frac{215}{1997} \times 100$, $\frac{162}{1997} \times 100$ and so on. So now the third column I am using to calculate the percentage weight retained corresponding to each sieve based on the weight retained.

Now, I am trying to see what is the cumulative weight retained in individual civil try to understand it in this way because this is somewhere where many students get confused so you see 13.2 mm has 1048 grams retained. Let us say if we did not have any 19 mm sieve then of course this 572 will also get retained in 1048.

So ideally, the cumulative weight which is retained in 13.2 out of this entire 1997 is 1048+572 which means 1048+572 grams of aggregates are coarser than 13.2 mm sieve. I hope you are you are able to understand when I say this statement and this is what we are going to do in the next column.

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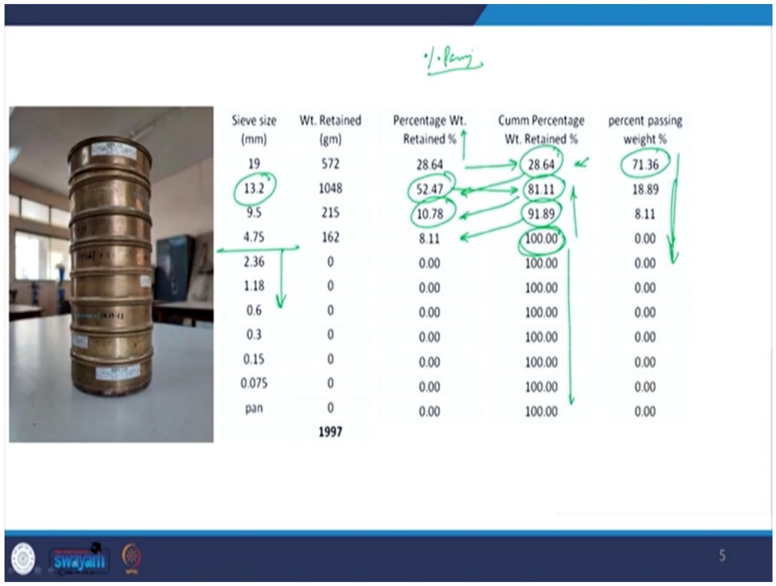

Sieve size (mm)	Wt. Retained (gm)	Percentage Wt. Retained %	Cumm Percentage Wt. Retained %	percent passing weight %
19	572	28.64	28.64	71.36
13.2	1048	52.47	81.11	18.89
9.5	215	10.78	91.89	8.11
4.75	162	8.11	100.00	0.00
2.36	0	0.00	100.00	0.00
1.18	0	0.00	100.00	0.00
0.6	0	0.00	100.00	0.00
0.3	0	0.00	100.00	0.00
0.15	0	0.00	100.00	0.00
0.075	0	0.00	100.00	0.00
pan	0	0.00	100.00	0.00
	1997			

That here I am trying to find out the cumulative percentage weight retained. So, since above this we do not have anything so the cumulative retained is 28.64. In 13.2 this is also retained plus we have some additional materials specific to 13.2 so it is 81.11. So, this is 52.47 + 28.64. Similarly, this is 81.11 + 10.78 and this is 91.89 + 8.11 which is 100 and then as you go down its always 100. Because 100 percent of the material is retained on 4.75 you do not have any material which is smaller than 4.75 mm sieve. So, we are almost done our final aim is calculating percentage passing.

So, now since we have cumulative percentage weight retained we can calculate percent passing each sieve just by deducting it with 100. So, we will just subtract 100 with this so that we get this and so on. Of course, there are other types of formula which you can apply but ultimately the percent passing weight is something which we are interested in and every time you should get the same value irrespective of any method you use to do the calculation. So, I hope that through this slide it is clear that how the percentage passing weight can be calculated.

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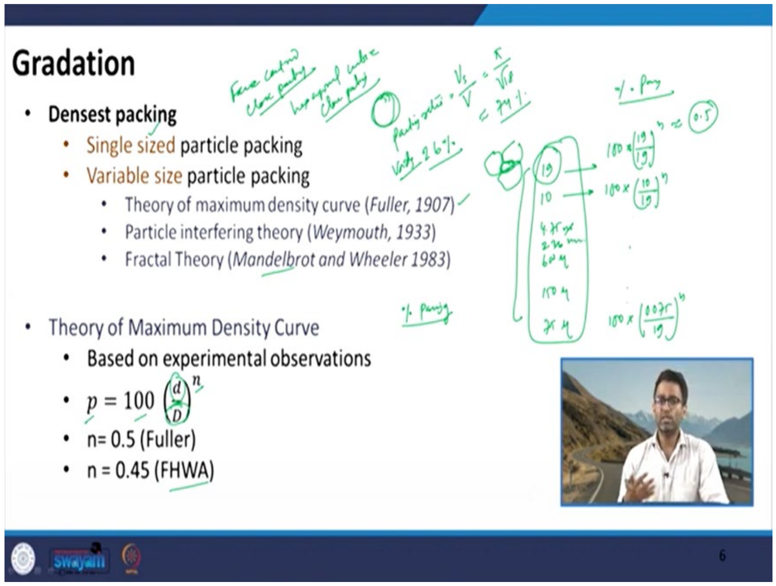

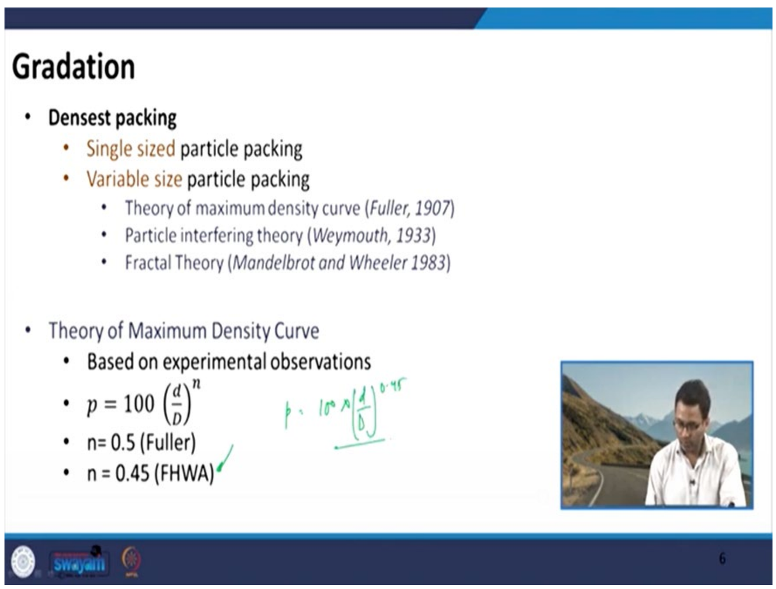

Now, we talk about the densest packing here. As I said for most of the purposes we are interested in well graded structure or a dense packed structure because it will give a better interlocking between the aggregates and therefore you will have more resistance to deformation. But in general, to understand densest packing because here the question is you know that which sizes of aggregates you are going to use. So, based on these sizes how do you generate this densest packing how will you find out that this five number of sizes of aggregates which I am going to use how they should be mixed in different proportion so that I get the densest packing out of these sizes.

So, this is a very interesting question and but again a complicated question to answer specifically for irregular objects like aggregates. Even for the regular objects like sphere or cube the question is not very simple because there can be different arrangements of packing. For example, let us talk about single sized packing if you assume that we have regular shapes like sphere so many theories have been proposed for sphere packing.

So, one of the initial theories was a conjecture given by Kepler and he said that if you have face centered close packing or if you have a hexagonal cubic close packing. So, if you talk about these two types of packing using spherical particles of same size then the packing ratio is the volume of solids divided by the total volume. So, the packing ratio is always constant and is given by $\frac{\pi}{\sqrt{18}}$.

And again, his conjecture was proved by different researchers in different times and you know there are more such theories which have come based on even more complicated form of packing of spheres. So, if you see that $\frac{\pi}{\sqrt{18}}$ I think is approximately 74 percent which means that in the densest packing state of single side spherical particles the voids will be around 26 percent. Here we are not dealing with first of all a regular shape like sphere and here we are again not dealing with single sized particle. We are dealing with irregular shaped particles that two of variable sizes all right.

So, for variable sized particle packing again various theories were given one of the most common theory which is in use is the theory of maximum density curve and this was proposed by Fuller in 1907 when he was doing experiments for concrete mixtures. And this theory has evolved experimentally so is empirical in nature but in general has been used and is still being used to define the packing of the aggregates in asphalt mixtures.

Further there were also more theories for example particle interfering theory this particle interfering theory basically discusses that if a space is created between the aggregate particles then this space can be filled by what is the next particle which can fill this space. So, it depends on the gap created and again the next size to be used.

This was developed by Weymouth in 1933 but is not very commonly used when we talk about pavement engineering. But in pavement engineering a fractal theory has been researched a lot and various research papers can be found based on the fractal theory which was initially proposed long back around I think around 1970 which was later published in 1983. However, among all these theories the theory of maximum density curve is the most popular which is used for defining the packing of the aggregates or for understanding the densest packing. If you know that which sizes of aggregates we are going to use to develop degradation.

So, as I said that this was initially developed based on experimental observation it is also called as Fuller gradation and the formula defining fillers gradation is that p $=100 \times \left(\frac{d}{D}\right)^n$. So, what is p here p is the percentage passing all right. So, this is what we are interested in because in the y axis if you remember we have percentage passing so percentage passing corresponding to different sieve sizes defines the gradation. Let us say if we have 7 number of sieves 19 mm let us say we have 10 mm we have 4.75 mm we have 600 microns we have 150 microns we have 75 microns all right. And let us say we have somewhere in between 2.36 mm.

If I know that I have to create a gradation using these sieves which aggregates having average particle size corresponding to these sieves the question is that how do I decide the densest packing. So, here the Fuller equation helps us to calculate that what should be the percent passing corresponding to 19 mm what should be the percentage passing corresponding to 10 mm and corresponding to all the other sieves in question so that you get the densest gradation. So, for this first you have to know what is the maximum size of particle in your gradation. So, here let us say it is 19 mm what is that maximum size corresponding to which 100 percent of the material will be passing so that is the maximum size.

So, if you have the maximum size that is D and we are interested to find out the percentage passing corresponding to any other size of small d you can use this formula. So, if you if I want to find for 19 mm it will be $100 \times \left(\frac{19}{19}\right)^n$ we will discuss about n now. If it is 10 mm it will be $100 \times \left(\frac{10}{19}\right)^n$ if it is 75 micron it is $100 \times \left(\frac{0.075}{19}\right)^n$ and so on all right. So, this is the way of finding out the percentage passing.

Now, for the densest packing Fuller said that n should be approximately equal to 0.5 so this was the initial consideration to develop the maximum density line. So, if you put n equal to 0.5 you will get a gradation and as per Fuller that gradation represents the maximum or the closest packing or the closest gradation which can be achieved using these sieves all right. Later it was found that the value of n equal to 0.5 is fine but it is difficult to control the production control the performance. So, after subsequent studies later on federal highway association they said that it is better to use n equal to 0.45.

And there is a specific reason that if you use n equal to 0.45 you can control the gradation in a simpler or easy manner which is typically done. So, these days even for in the super paved mix design or in any form of mix design when the gradation is decided. It is decided based on the maximum density line and this maximum density line is can be created using the FHWA value of n which is 0.45. So, here p becomes equal p $=100 \times \left(\frac{d}{D}\right)^{0.45}$ all right.

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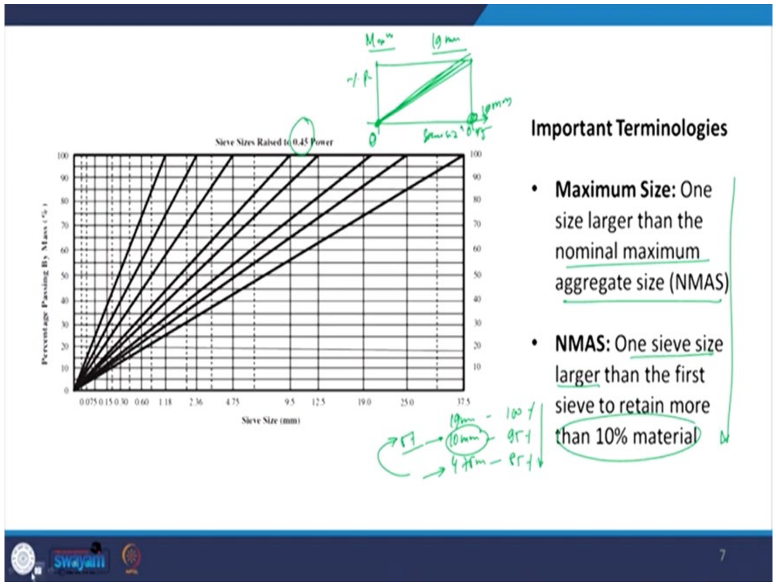

So, this is an example of the FHWA curves based on different maximum sizes of the aggregate. Now, many a times students get confused about drawing this chart because this is not only a graph between percentage passing and sieve size. It is a graph between percentage passing and normalized sieve size. And this normalization is done based on the value of n=0.45.

So, in the next slide I will show you how to create a maximum density line which appears to be typically a straight line as you are seeing in this graph. Talking about the FHWA curve it is very simple to draw a maximum density line gradation what you need to do first you need to know what is the maximum size so let us say 19 mm is the maximum size.

What you need to do just plot a graph between percent passing and sieve size to the power 0.45 all right and what you need to do you just need to connect the origin which is (0,0) with the percentage passing the maximum sized particle which is 100 percent. So, you just need to draw a straight line and this is this point is 19 mm here. So, this line represents the maximum and that is why it is easier to draw the FHWA curve and easier to control the gradation which we want to achieve relative to this maximum density line.

So, before we move forward in understanding gradations more there are two terminologies which are very important to define here one is the maximum size. So, here the definition which I have presented is the one which is used in the super paved mix design which says that the maximum size is the size which is one size larger than the nominal maximum aggregate size.

Which means that in order to define the maximum size first we have to define the nominal maximum aggregate size. Because maximum size is one size larger its not the size corresponding to which 100 percent of the material will necessarily pass it is just one size larger than the nominal maximum aggregate size.

And what is nominal maximum aggregate size, it is one sieve again one sieve larger than the first sieve to retain more than 10 percent of the material so try to understand this. Let us say you have so many sieves so we are expecting that the maximum size will have or the sieve the top sieve will have hundred percent material passing the next size will retain some material the next size will further retain some material.

So first you identify the sieve which retains more than 10 percent material. Let us say we have a 19 mm sieve a 100 percent material is retained or 100 percent material is passing we have 10 mm sieve in which let us say 95 percent material is passing which means 5 percent material is retained here.

Then we have let us say a 4.75 mm sieve through which 85 percent material is passing something like this. So, if you see these three numbers in 10 mm only 5 percent material is retained all right. In 4.75, 85 percent of the material is passing so we have 15 percent material retained so which means that this sieve is retaining more than 10 percent material.

So, nominal maximum aggregate will be one size larger than this size. So, in our sieve the one size larger sieve is 10 mm so 10 mm will be nominal maximum aggregate size. Some of the specifications also defines nominal maximum aggregate size as the sieve in which at least 10 percent of the material is retained all right. So again, as I said that this definition which we are looking here is based on the super pave mixed design criteria.

So, I hope through this you understand what is the meaning of the maximum size and nominal maximum aggregate size. So, now let us see that how can you conveniently draw a maximum density line because many a times when students they attempt to draw the maximum density line based on FHWA equation or you can say Fuller equation taking n = 0.45 they still do not obtain a straight line. And that is where the question comes that how FHWA curve says that it is just a straight line it is not a straight line. So, what you have to do you have the sieve sizes with you for each sieve size you first calculate the percentage passing.

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This percentage passing can be calculated based on the formula p =$100 \times \left(\frac{d}{D}\right)^{0.45}$ all right this formula you can use. And then you create another column which will be the sieve to the power 0.45 so this will be $19^{0.45}$,$12.5^{0.45}$ and so on. And then you plot the graph between sieve to the power of 0.45 and percentage passing. And when you actually do the x axis is this the actual x axis but since this is a normalized scale the different points represent different sieve sizes so which means 3.763 is representing 19 mm. So, the last point is basically 19 mm this actually is 3.76 but it represents nineteen mm. So, this again 12.5, 10 and so on.

So, this you can create separately this scale to see that which sieve is you know lying at which place in the graph and you will get a completely straight line in this this way. And then for any given gradation we can compare the gradation with this maximum density line to see how dense is our gradation.

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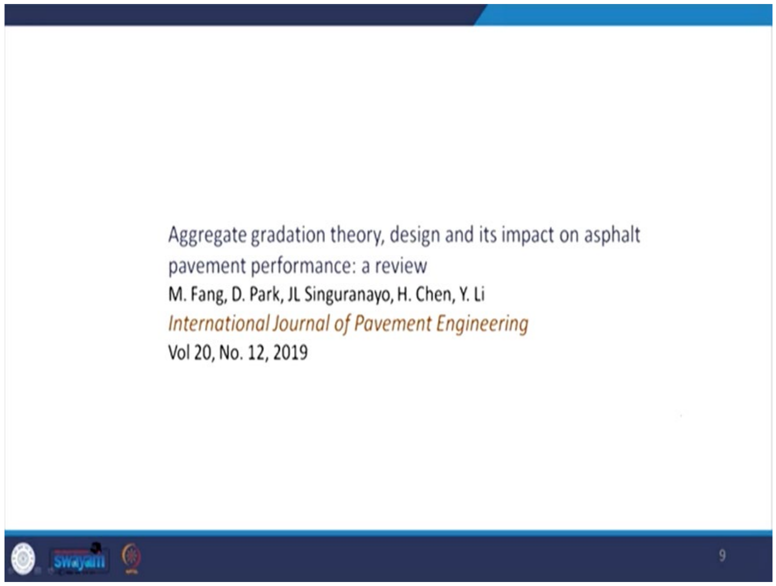

So, one of the good papers which you can refer is the aggregate gradation theory design and its importance of on asphalt pavement performance which is a review paper. I found this paper very interesting to understand the concepts related to gradation of aggregates. This maximum density line is the theoretical maximum density line but when we are actually deciding the gradation for any given mixture a concrete mixture or asphalt mixture we have to deviate from the maximum density line.

Now, the question is why try to imagine that you have a volume where you have to place the aggregates. So, if you are using the maximum density line you are creating a gradation which has the least number of voids. So, by if you see by volume the volume of voids will be very less it cannot be 0 of course but it will be very less depending on the corresponding to the maximum density line.

But imagine that you have an asphalt mixture and if you imagine the volume you will see that in the asphalt mixture you have aggregates you have bitumen and you have also have some voids. And later we will discuss that why do we desire some voids in the asphalt mixture not in todays lecture or class but in in some other lecture when we discuss about the mixed design of asphalt mixtures.

But ideally in the asphalt mixture you have aggregates you have bitumen and you have air voids which means in addition to the aggregates you also need some space for bitumen and air voids. So, if you use the maximum density line you are creating a dense aggregate gradation undoubtedly but you are not allowing any space for additional material to come in to occupy the volume. Therefore, you have to deviate the actual curve which you are going to use from the maximum density line so that you can incorporate these additional volumes. If you think about a concrete mixture in the concrete mixture we do not desire voids we desire a void less mix very dense mix.

But, even there in addition to the aggregate you have cement you have water you can have admixtures which means that you need again sufficient volume for them to come in. For example, cement and water if it will not be present then again sufficient cementing property will not be achieved so and then hydration takes place their products comes in so the volume requirement is of other materials are much higher in case of concrete mixture. So, there also we have to deviate our gradation from the maximum density line so that we can have enough space for these materials to come in.

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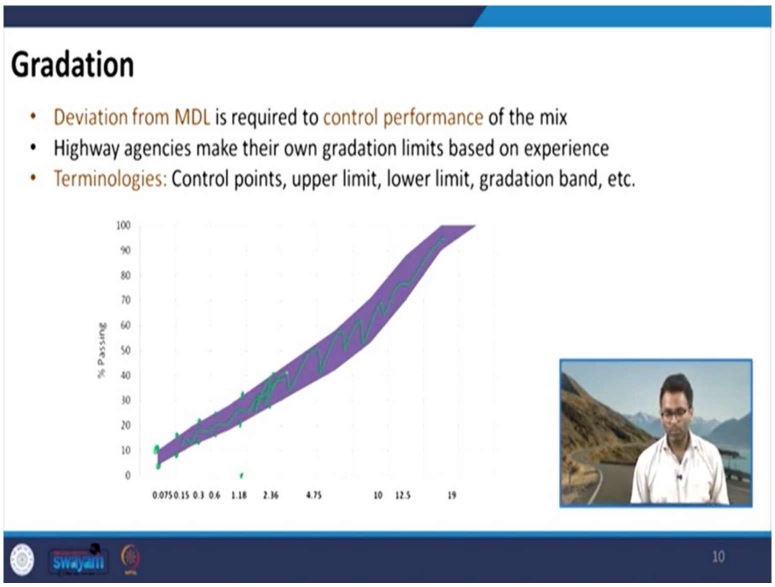

Now, the question is that how do we decide that which means what gradation should we use. So, highway agencies they make their own gradation limits based on experience. So again, this is more or less empirical in nature the way we decide the final gradation deviating it from the maximum density line. So, different highway agencies has their own control on gradation.

For example, this is a gradation given by ministry of road transport and highways in India for a conventional dense graded bituminous mixture. So, here you will see there is a band so this band represents that corresponding to each size you have a lower limit and you have upper limit.

So, you have two limits here two values two values of percent passing corresponding to each size lower limit upper limit. And these limits are decided empirically based on experience but of course this gradation will be somewhere near to the maximum density line. So, maximum density line is the reference and we deviate our final gradation. So, why there is a band so that we can have provision that when we mix different stockpiles the final gradation should lie somewhere between this curve.

Now, these points this upper point upper bound lower bound which I was just referring that you have two points these are called as control points these are also called as upper and lower limits. This can be called as a gradation band or you can you know call it by any other name but they all represent that you have range of values of percent passing corresponding to each size.

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The graph which I have shown in the last slide is shown with more clarity here where you have the lower bound lower limit and upper limit corresponding to each sizes and it is also compared corresponding to the maximum density line here. So, you see how it deviates from the maximum density line. And this picture is the picture of the orange book or the specification for road and bridge works given by the ministry of road transport and highways. And all the gradations options which we have to use in pavement construction can be found in this particular handbook.

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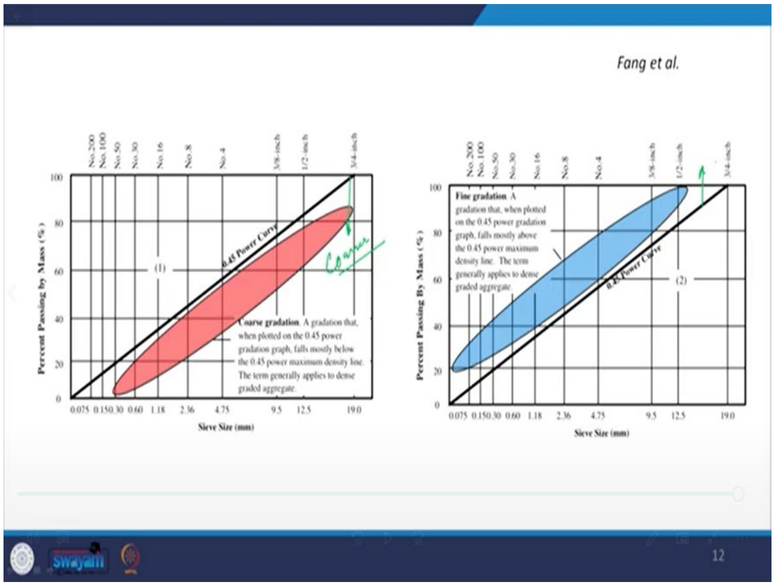

Now, depending on whether we are keeping our gradation above or below the maximum density line, our gradation can be a coarser gradation or can be a finer gradation. So, if our gradation target gradation is on the lower side of the maximum density line these gradations are typically called as coarser gradation.

And if we have gradations which is above the maximum density line then these are usually final gradations. So, these terms are generally applied to understand whether the gradations are coarse in nature or fine in nature. So, let us stop here today and we will continue our discussion from here and we will start discussing about the blending of the aggregates which is again one of the very important components to understand the mixed design process. This we will start in the next class. Thank you.