Pavement Materials
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Lecture 20
Aggregate Properties (Part-4)

Hello friends, welcome back, we are presently discussing about the properties of Aggregates. And in the last lecture, we were talking about the specific gravity of Aggregates, and we discussed the, fundamentally we try to define specific gravity.

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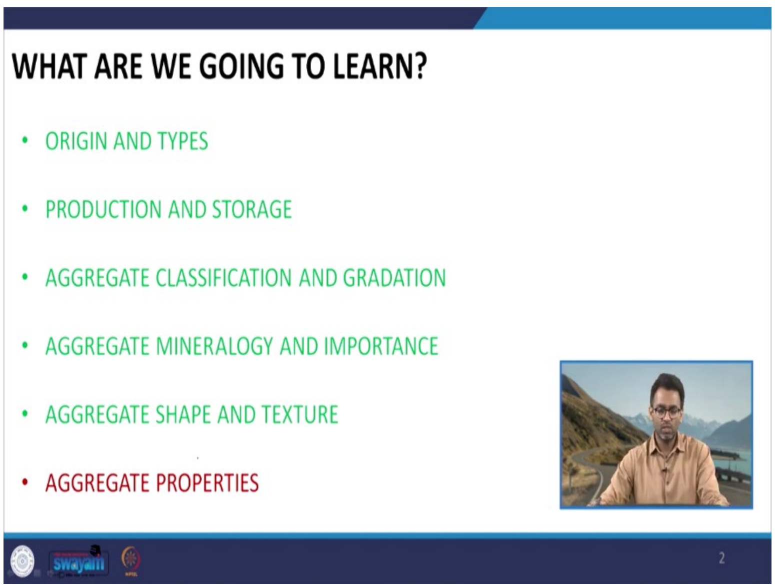

We try to understand the meaning of different types of specific gravities such as, apparent specific gravity, bulk specific gravity, and effective specific gravity. And, we also discussed the procedure of finding out the specific gravity for the core segregates and the fine Aggregates in the laboratory. I think one point which I missed in the last presentation was discussing about the determination of specific gravity for fillers, where I mean that fillers are those particles which passes 75 microns.

So, just to inform you I mean the procedure remains this same that we use a pycnometer bottle here for the determination of specific gravity of filler, but the size of the pycnometer bottle is very small in comparison to the pycnometer bottle, which I showed you for the determination of specific gravity of fine Aggregates. And also, for a filler we mostly measure the apparent specific gravity because for getting the saturated surface dry condition is very challenging especially for materials of such smaller sizes.

So, apparent specific gravity is usually measured which is taken almost equal to the bulb specific gravity of the filler particles. We will discuss few more points today and probably this will be our last lecture of module 2, which is on Mineral Aggregates. We already have understood that the accurate determination of specific gravity becomes very crucial.

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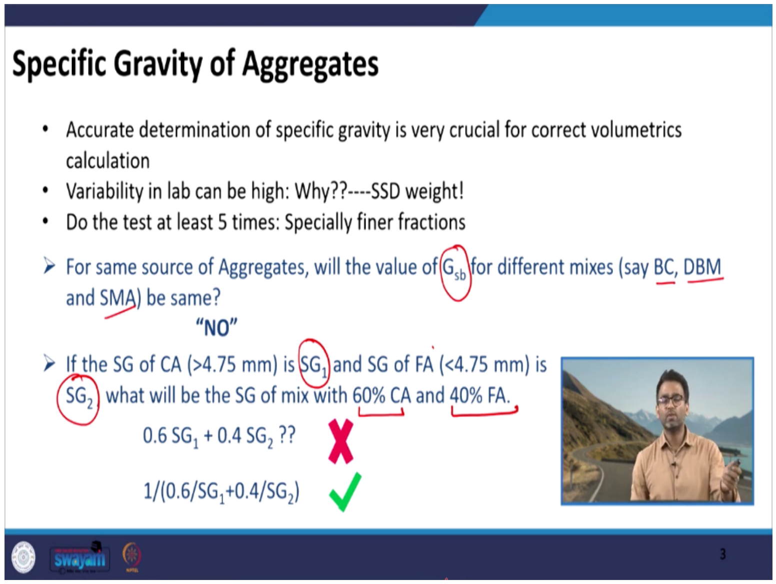

Especially, in case of bituminous mixtures we, where we rely completely on the mixed design aspects, and the specific gravity is one of the input parameter during the mix design process. As we discussed that the variability in the measurement of specific gravity can be very high, the reason being getting the saturated surface dry weight is challenging especially when the size of the particles are small.

So, it is recommended that we should do more number of repetition in the laboratory to get a proper average value of the specific gravity and should be repeated at least 3 to 5 times and this is specifically for the finer fractions, where the variability will be even higher than the coarser Aggregates.

In addition to the procedure which we have discussed for the determination of specific gravity of core segregate and fine aggregate, there are further Concepts which need to be understood when we are dealing with calculation of specific gravity, because in our case we will be interested to find out the, finding out the specific gravity not for one particular size of aggregate but for a range of aggregates size which forms the complete mixture. So, it will be a mixture of Aggregates for which we are interested to assess the average specific gravity.

To understand that, let us first try to understand few question and try to answer it. So, the first question is for the same source of aggregates, will the value of G_{sb} where, G_{sb} it indicates the bulk specific gravity of the mixture and BC is Bituminous concrete, DBM is Dense Bituminous Macadam, SMA is Stone mastic asphalt, so these are different types of mixtures. For example, BC and DBM are dense graded mixtures, Stone mastic asphalt is a gap graded mix.

So, the question is very simple, that if our aggregate query is same, we have the same source of Aggregates using which will be producing say BC say DBM or say SMA our source is same, so will the value of Gsb be same for these mixtures? So, one way of thinking about this question is based on our discussion that we say that specific gravity is an aggregate property, if the source of the aggregate is same, then we will expect that the specific gravity will always remain same.

But here we have to understand that the specific gravity is also dependent on the proportion of different sizes of aggregate, proportion of core segregate, proportion of fine Aggregate, and if you remember we have already discussed that Aggregates in the plant they are mixed from different stock piles alright. So, it may happen that to make one mix, let us say BC, the blending of stockpiles will be unique in or will be different in comparison to using the same stock pile to produce a mix such as SMA. So, the proportion of each stockpile which we are using may change from mixes to mixes.

Now, since the proportion is changing or the amount of Aggregates we are utilizing is changing every time, and each stockpile will have its own specific gravity which we have measured in the laboratory, therefore the specific gravity of the mixture will also be different for different types of mixes. So, the answer to this question is no, that even if the source of the aggregate is same, the bulk specific gravity of the mixture will be different from for BC, for DBM and SMA, because the gradation is different and specific gravity is a function of the gradation of the Aggregates also.

The next question is more interesting, and the answer to which is most of the times given in a wrong way by many. So, the question is if the specific gravity of course aggregate, so here we are saying core segregate are materials passing or retained on larger than 4.75 MMC. Let us say, if the specific gravity of coarse aggregate is SG1 and the specific gravity of fine aggregate which are materials passing or smaller than 4.75 mm is SG2, then what will be the specific gravity of the mix which we are making using 60 percent core segregate and 40 percent fine aggregate, this is the question.

A usual answer which students always give is that, we will do the weighted average. So, the answer will be that if we know the specific gravity of the coarse aggregate, if we know the specific gravity of the fine Aggregate, and if we know the proportion of these individual Aggregates which we are using in the mix, then this specific gravity will just be 0.6 times SG1 + 0.4 times SG2, which is a very common way of you know doing the average.

But unfortunately, this answer is wrong, because specific gravity is a ratio and when we are taking the average of any ratio, so, the average should be in the form of harmonic mean. So therefore, the correct answer will be the harmonic mean of SG1 and SG corresponding to the proportion of the Aggregates. So, the answer is $\frac{1}{\frac{0.6}{SG1}+\frac{0.4}{SG2}}$. Well again, to be very, I mean to be confident about this concept, that why we say that harmonic mean is the representation of the average for the ratio, let us try to understand it using a simple example.

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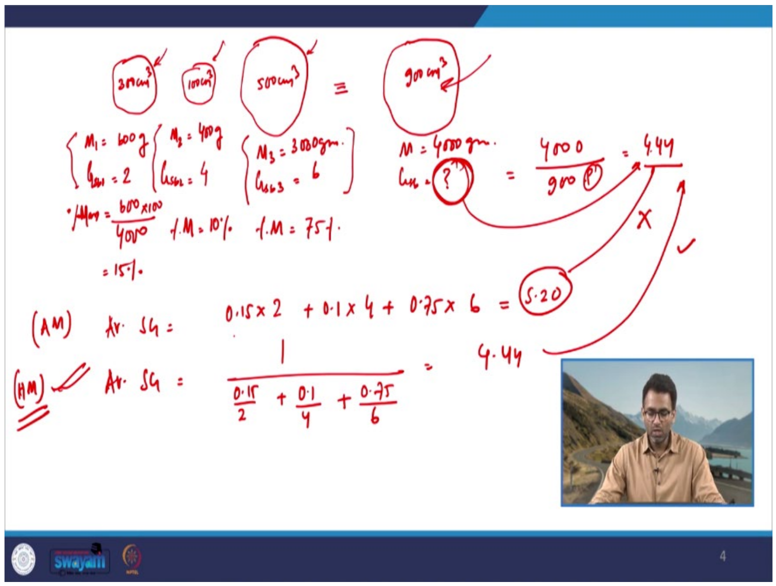

We have like three bodies, this is body 1 and the volume is 300-centimetre Cube alright. We have another body whose volume is 100-centimetre Cube alright, and we have again the another body whose volume is 500 centimeter Cube, these are let us say non compressible bodies. So, the final volume which will be created, will be the summation of all the volumes. So, the volume will be 900 centimeter Cube.

Let us say that the mass of first body is 600 grams the mass of second, so this is M1, the mass of second body is say 400 grams and the mass of third body is say 3000 grams. So, the total mass of this body will be the summation of all the masses. So, total mass is 3000 plus, so it is 4000 grams. So, if we try to calculate, now the specific gravity of individual bodies, so the specific gravity of the first body is Gsb1, the first body, it is mass by volume, so, $\frac{600}{300}$, so, the value is 2, Gsb2 becomes equal to $\frac{400}{100}$, so it is equal to 4.

The Gsb of third body is equal to $\frac{3000}{500}$, so the answer is 6 here and this is something which we are interested to find, but since we have the mass and volume, so, actual answer will be the average specific gravity becomes equal to $\frac{4000}{900 \times \rho} = \frac{4000}{900 \times 1}$, so, we are not considering that.

So, this becomes equal to 4.44, if we do the calculation which means that this value is equal to this and we now want to see, because in actual case we do not have these volumes, we only have these numbers with us this three numbers we have with us, with these three numbers I want to find this one alright, I want to find what is the Gsb.

So, now let us see that you know what form of average of the individual Gsbs will give me the final Gsb. So, before that let us see the proportion by mass for the individual sizes. So, this percent Mass of the first body is how much, 600 divided by 600, divided by the summation, so, its 3000, 4000. So, this is like 15 percent, similarly this percent mass of second body is 10 percent, the percent mass of the third body is 75 percent, because it will be $\frac{3000}{4000} \times 100$ alright, so, this is the proportion.

So, the common answer which is wrong is that the average specific gravity is equal to 0.15 × SG1 + 0.1 × 4 + 0.75 × 6. So, if you do this calculation, the answer which you get is 5.20, which does not match with our actual answer. So, if we do the harmonic mean then what we get, we get $\frac{1}{\frac{0.15}{2}+\frac{0.1}{4}+\frac{0.75}{6}}$, so, if you do this calculation, you get exactly average specific gravity. So, this indicates that average specific gravity, so this is arithmetic mean, this is harmonic mean. So, which means that the specific gravity when we are interested to find it should be the harmonic mean of the individual stock piles.

So, I hope that this concept of finding out the specific gravity is clear, and just to tell you like even if we end up doing a mistake in the Mix Design, let us say that by mistake we have taken the arithmetic mean of the specific gravities, then the difference will be very large, which means the volumetric calculations which we are doing can give us you know a very erroneous results or values of the volumetrics and this can be very critical to the final performance of the mixture.

So, we have to be very careful when we are exercising the calculation of specific gravity of Aggregates in the mixed design process. Finally, one more concept which remains to be discussed, and we will also see an example for this. So, let us say in actual practice as I said we have stock piles, we have to blend 3 stock piles.

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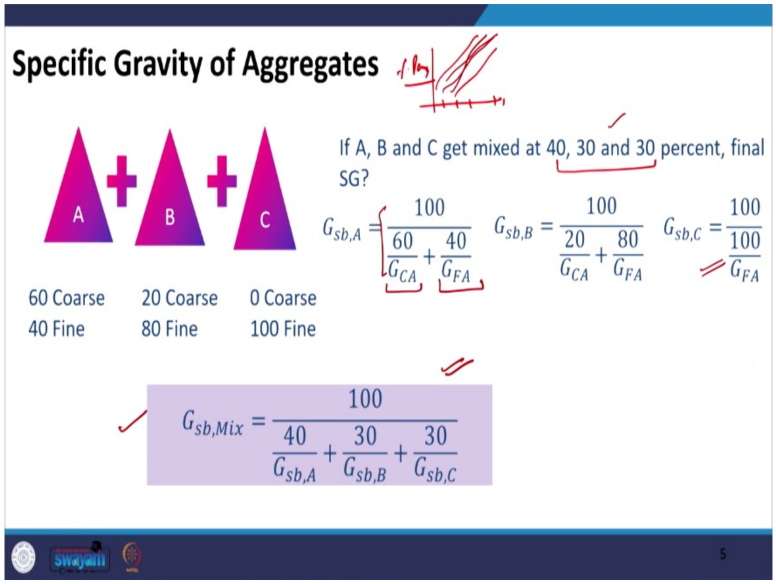

And in stockpile A, we have 60 percent materials which are larger than 4.75 mm sieve and we have 40 percent material which are finer than 4.75 MMC. Similarly, let us say we have a stockpile B with 20 percent coarse Aggregates and 80 percent fine Aggregate and we have a stockpile which is a fine aggregate stockpile.

So, we have 0 percentage of course Aggregate and 100 percent fine Aggregates and say that to meet the desired gradation what is the desired gradation just a recall for you that we have to ultimately reach within the upper bound and lower bound limits for different sieve sizes as given by the highway agency .

So, let us say that if I blend A, B, C in the proportion of 40 percent, 30 percent, and 30 percent and of course, the summation should be 100 percent. if I mix them in this proportion then we are able to meet the criteria of the highway agency of being somewhere here alright, let us say. So, now the question here is that what will be the specific gravity of this blend of A, B, and C.

So, for this you have to go for a two-step procedure, what is that procedure? First, you have to find out the specific gravity of first stockpile because you know for each stockpile, we have coarse aggregate, fine Aggregate and why we are doing this calculation for coarse aggregate separately, fine aggregate separately, because in the laboratory, I have used two different methods, for fine aggregate I have used pycnometer method and for coarse aggregate I have used a wire basket method let us say that GCA is the specific gravity of coarse Aggregate and G_{FA} is the specific gravity of fine aggregate.

So, for the first stock pile, I am finding out the specific gravity of that particular stock pile based on the percentage of course and fine Aggregate and taking the corresponding harmonic mean. Similarly, I will do it for stockpile B, taking the harmonic mean for coarse and fine aggregate fraction, and similarly for stockpile C, and here you can see we do not have any coarse Aggregates, so, we have only used the fine aggregate value.

And after finding Gsb, A, B, and C, now we have to find out the specific gravity of a mixture of A, B, and C, and the mixture is in the proportion of 40, 30, 30, again we have to take another harmonic mean corresponding to this proportion and the Gsb of the Final Mix will be equal to the, $\frac{100}{\frac{40}{GsbA}+\frac{30}{GsbB}+\frac{30}{GsbC}}$. So, I hope that again this process is clear to you, let us try to do it and you can use a simple Excel sheet to do this calculation, and let us take an example to understand the process.

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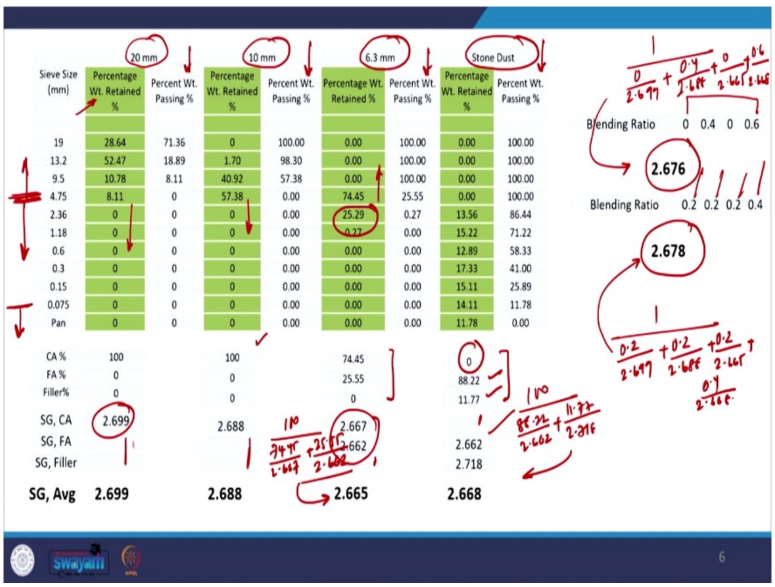

Let us say that we have four different stockpiles, we have a 20 mm stockpile here, we have a 10 mm stock pile, we have a 6.3 MM stock pile and we have a stone dust stockpile, we have four stock piles and this is the sieve size distribution of the individual stockpile which I have carried out through sieve size analysis, because we will need percentage of course Aggregate and fine aggregate, I have also to kept the percentage weight retained, based on which I can calculate what is the percentage of course Aggregate and percentage of fine Aggregate and corresponding to the 4.75 MMC.

So, one will be above this and the other will be below this. And we can also have a separate one for filler, because for filler again we are using a different pycnometer bottle for finding out the specific gravity. So, the first step will be that in individual stockpile, I have to calculate what is the proportion of coarse aggregate, what is the proportion of fine Aggregate, and what is the proportion of filler.

So, I have done this calculation, and you can see that in the first stockpile we do not have any aggregate passing for 4.75 mm sieve, so, the entire stockpile is a course aggregate stockpile. Similarly, the stockpile B which is 10 mm stockpile is also a course aggregate stockpile, we do not have any material passing 4.75.

In case of stockpile C, we have some material passing 4.75 mm sieve and the others are retained accordingly I have calculated the proportion and similarly for the filler where you can see that we do not have any coarse aggregate, we have only fine Aggregate and filler here, based on the percentage weight retained we can calculate the proportion of course aggregate, fine Aggregate and filler in individual stock piles.

And, I also have measured the specific gravity for each stock pile and for each fraction. So, that value I already have with me, I have done in the laboratory using the procedure which we have discussed, and let us say this is the value which I have got. The specific gravity of coarse aggregate, fine Aggregate, and filler for different stock piles. I hope you understand that this is left blank because we do not have any fine Aggregate and filler here. Similarly, this is left blank here, this is blank here, this is blank here, because the corresponding Aggregates are not present.

Now, comes the first part of the calculation, where for individual stockpile I will determine the average specific gravity based on the proportion of coarse aggregate, fine Aggregate, and filler. Specific gravity average becomes equal to these values. Since we do not have anything, so, it is only 2.699, for example if you see here this will be equal to $\frac{100}{\frac{74.45}{2.667}+\frac{25.55}{2.662}}$. So, similarly this one will be $\frac{100}{\frac{88.22}{2.662}+\frac{11.77}{2.718}}$, so this is the value which you will get, I hope this calculation is clear to you.

Now, let us say this is our first blend that we are trying to blend the stockpile, where we are taking 0 percentage of stockpile A, 40 percent of stockpile B, 0 percent of stockpile C, and 60 percent of stockpile D and, you see that the summation is of course equal to 100 percent. If you do this calculation, that is $\frac{1}{\frac{0}{2.669}+\frac{0.4}{2.668}+\frac{0}{2.665}+\frac{0.6}{2.668}}$, so this is the calculation and you will get this result.

But, if we change the blending ratio let us say now, we are using a 20 percent blend, 20 percent, 20 percent, and 40 percent blend here, we have to do this calculation as $\frac{1}{\frac{0.2}{2.669}+\frac{0.2}{2.668}+\frac{0.2}{2.665}+\frac{0.4}{2.668}}$ and you will get finally this answer.

So, you can see though they are very close to each other, but they are different from each other and as I mentioned that especially in the mixed design process, it is important that we determine the accurate specific gravity at least up to three significant digits, because improper calculation can have small error in the specific gravity calculation, can have profound effect on the mix volume Matrix, which we will discuss probably when we talk about the mix design process.

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Test	IS Code	ASTM
Aggregate Impact Test	IS: 2386 (Part 4)	-
Abrasion Test – Los Angeles Abrasion	IS: 2386 (Part 4)	ASTM C 131
Micro Deval Test	IS: 2386 (Part 4)	ASTM D6928
Durability and Soundness Test	IS: 2386 (Part 5)	ASTM C88
Sand Equivalent Test	IS: 2720 (Part 37)	ASTM D 2419
Liquid Limit and Plastic Limit	IS: 2720 (Part 5)	ASTM D 4318
Methylene Blue Test	-	ASTM D 837
Specific Gravity and Water Absorption of Coarse Aggregate	IS: 2386 (Part 3)	ASTM C 127
Specific Gravity and Water Absorption of Fine Aggregate	IS: 2386 (Part 3)	ASTM C 128
Flakiness Index and Elongation Index	IS: 2386 (Part 1)	
Flat and Elongated Particles Test	-	ASTM D 4791

This slide, it shows the corresponding IS code and ASTM code for different tests which we have discussed. So, this is just for reference, you can refer to these codes to understand the process which we have discussed, during the lecture for different physical properties of the Aggregates.

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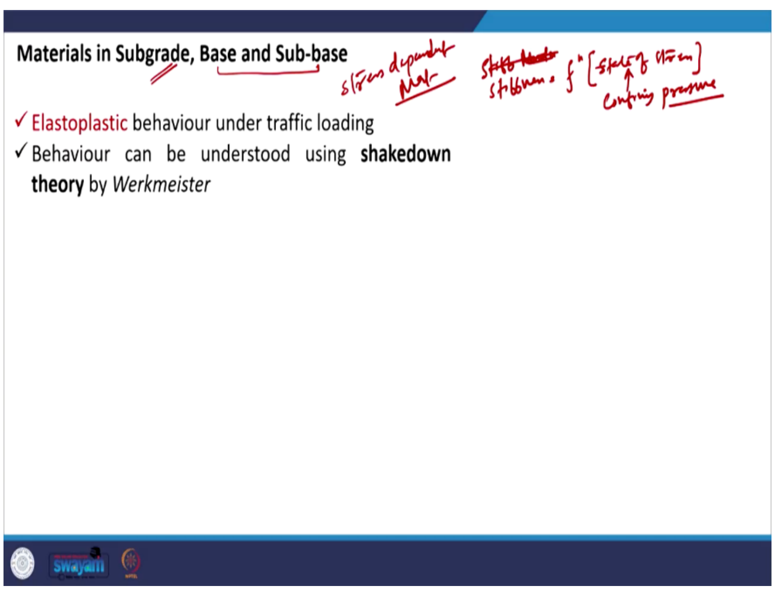

So, now let us talk in general about the properties of granular material, here we are not discussing about subgrade, of course we have soil in subgrade, but we have mostly discussed about you know larger aggregate particles, so, we will discuss about the materials which are mostly used for base and sub-base.

Before I try to explain the properties of or the behavior of the granular material, when it is subjected to in any loading condition, maybe we can have a physical experiment, a small experiment to understand that what is the impact of the confining pressure on the aggregate particle.

So, talking about stress strain or the behavior, or the response of the aggregate particles, aggregate particles are generally stress dependent materials. Which means that the stiffness of this material, the modulus if we are trying to define, a modulus is a function of there are various parameter, but it is a function of the state of stress.

When I say straight of stress, I am also indicating about the confining pressure here. The same material, if we have different confining pressure, the stiffness will be different, the modulus is not much dependent on the temperature of the surrounding as in case of a normal bituminous mixture, which has bitumen in it which is a viscoelastic material, the behavior of granular material under the traffic loading is more of elastoplastic in nature, and we will try to understand it using the Shakedown Theory given by Werkmeister, but before that let me just, you know visually try to explain you, when I say that why it is a stress dependent material.

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So, here I have you know some aggregate particles with me. So, these are coarse segregate particles, we have different sizes but mostly its these are aggregate particles which are coarser in nature, using these aggregate particles we will try to understand the effect of the stress dependency. So, what I am doing here, I am just mixing these Aggregates and I am trying to collect some Aggregates in my hand.

So, I hope you are able to see that I have collected some Aggregates in my hand now, and I have holded it from the sides, and there is some gap at the top of my hand, and some gap at the bottom of my hand, but you can see no Aggregates are falling now, because I have provided some pressure from the lateral side and just to inform you that now I am holding this aggregate particles with, you know, with little pressure, not much of pressure applied on the lateral side.

So, if I am applying little pressure here you cannot see any aggregate falling freely, but if I apply a vertical load on the top of this material, which I am holding presently with small amount of pressure literally, let us see what happens. If I am applying a load from the top you can see that the aggregate particles start falling down, when the load is applied, depending on the confining pressure when I am applying the load the material has started to fall apart.

I will again hold similar amount of material in my hand, as I have done previously. And now I am applying you know too much pressure from this side, so, the amount of pressure which I am applying now is much higher than what I did in the previous case, still I have some Gap at the bottom, and some Gap at the top, now let us see what happens if I you know, if I am putting a vertical load on the top through some means.

So, if I am trying to load it from the top, now since you know I am holding it very tightly, the Aggregates are not falling apart, because of this lateral pressure which I have applied the aggregate particles are in a better interlocked position in comparison to what the position, in which the aggregate particles were in the previous case. So, I hope now it is clear through this simple experiment which we have conducted that how the lateral pressure is affecting the load carrying capacity or the stiffness characteristics of the aggregate particles.

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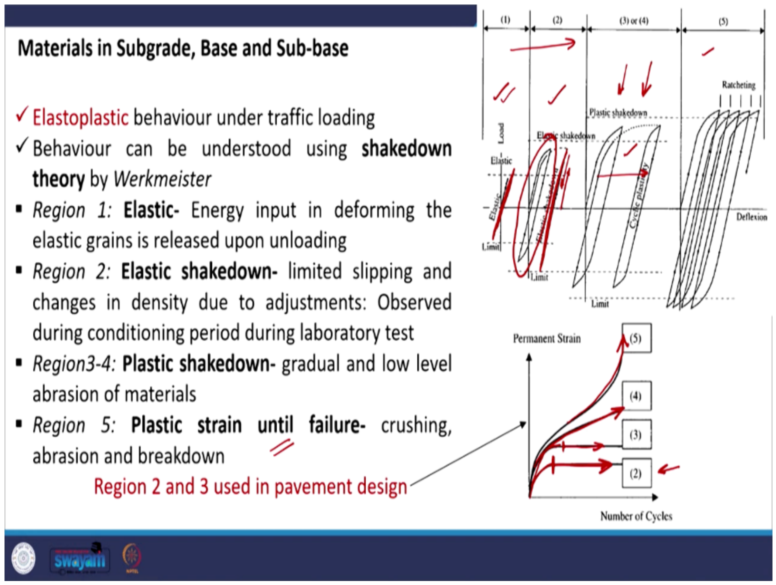

We can also understand this behavior using the Shakedown Theory as I mentioned by Werkmeisters, and this is shown in this particular figure, that what happens when the aggregate particles are subjected to different magnitude of load, alright. So, you can see that here different regions have been marked, which shows the different behavior of the aggregate particles, when they are subjected to different levels of loading, increasing levels of loading. So, from here to here the stress in the material is increasing.

So, the region 1 which corresponds to the elastic region, is basically a typical behavior when the stress which is applied is very small in nature. So, when the stress applied is very small, then the material behaves more elastically, whatever energy we are giving to deform the material is completely released and, so, you see the path travelled during loading and unloading, the path is same, this is the elastic region but here the magnitude of stress is very small.

When we increase the magnitude of load or magnitude of stress, the material will start behaving in the elastic Shakedown region. So, what is elastic Shakedown region? Here when the magnitude of load is initially applied, there is some sleeping in between the material, some additional densification, so, the material will try to adjust itself within the mass and therefore there is a deformation, from the initial State, because the material is now reorienting itself to new positions.

So, when it is reorienting itself to new position which means that from the first state there is some change in the dimensional characteristic of the material, so, some permanent strain has been induced alright, but though the magnitude of load remains let us say is higher than in in case of the elastic region, after few repetition of this higher magnitude of load, when the aggregate particles have adjusted sufficiently, and reoriented itself sufficiently, no more reorientation will take place.

So, if the magnitude of load Remains the Same, then after few Cycles the materials start behaving elastically again, which means the path of loading and unloading will be same, this path will be same, and you see that in the initial loading cycle, the path was different, the path was different considering that there is some permanent changes which has occurred in the material.

If the magnitude of load is further increased, the material can go in the plastic Shakedown region. So, before I talk about the plastic Shakedown region, if we see this elastic Shakedown behavior in the laboratory, this will happen when we are doing a repeated load test during the first few Cycles, these are also called as the conditioning cycle. So, we give the conditioning cycle, so, that the material properly adjusts itself and, so, that readings of the further Cycles will tell us about the elastic behavior of the material.

So, now if we increase the load further the material will start behaving in the plastic Shakedown region. So, what happens in the plastic Shakedown region that the material in addition to the initial adjustment, the material also you know, is subjected to abrasive action and there is some loss in the material.

So, this is a low level of abrasion and low level of loss in material because of which again permanent strain can occur and as you can see as we are moving forward we have some permanent strain which is accumulating in the material, but after more number of Cycles it may happen that the material again will start behaving elastically, that the path of loading and unloading will be same, but this region is called as the plastic Shakedown region.

If we further increase the magnitude of the load then complete failure of the specimen will take place and there will be a lot of crushing within the material, abrasion and breakdown within the material, and this is basically called as the plastic strain region, which is the fifth region. If you see the strain versus number of Cycles corresponding to different stress levels, so, this is the stress level corresponding to region 2. So, you can see that initially the strain will increase and after that it will become constant, the permanent strain will become constant. So, there is some permanent strain, and then it will become constant because complete reorientation has taken place.

In the region 3, it may happen that after a subsequent number of Cycles, when the little abrasion has taken place again, the material will start behaving elastically or else it may also happen that there will be a continuous strain in the material, this strain is increasing continuously the material does not behave elastically. So, this is region 4 and in the region 5, you can see that there is a complete breakdown in the material, so, the strain will never stabilize.

If you talk about the pavement design, so, the granular material are usually characterized under the region 2 and region 3. So, which means that we are assuming here that after subsequent number of Cycles, the permanent strain will become constant, so, after certain repetitions of loading, we can have an indication about the elastic behavior of the material, which can be Quantified using some form of modulus which will be corresponding to the recoverable strain. Because we are characterizing our material usually in the region 2 and 3, in the pavement design we have to input one of the stiffness parameter, and that stiffness parameter is termed as the resilient modulus of the materials.

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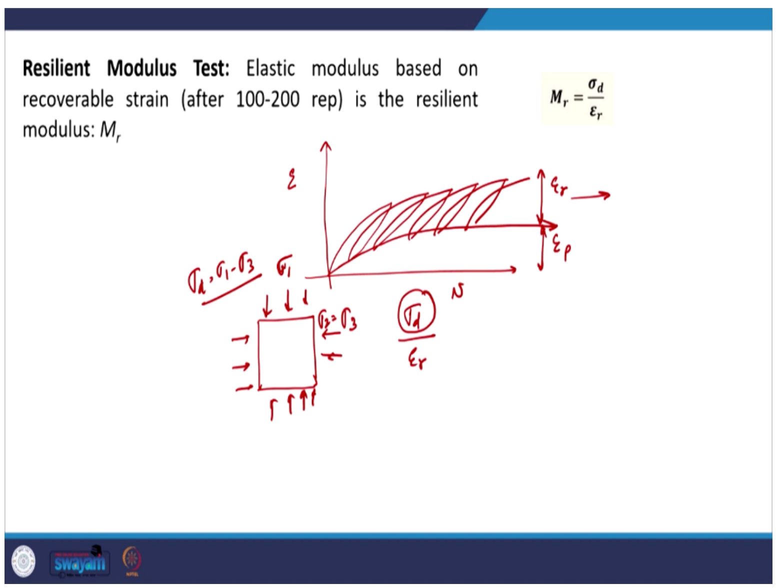

So, resilient modulus is the elastic modulus under repetitive loading, after certain cycles of repetitive loading, what we expect that the material will have no additional permanent strain, whatever permanent strain would have taken place in the initial cycle will remain constant. So, now based on the recoverable strain the amount of recovery which has taken place, we will Define the resilient modulus.

To explain it to you graphically, let us say that we are seeing strain versus number of Cycles. So, in the initial Cycles there will be some permanent strain, in these few Cycles there will be some permanent strain, so, the material will behave something like this. You can see that the accumulation of strain it will stabilize after few Cycles, this is the permanent strain and this is the recoverable strain, and this will remain constant.

So, here the resilient modulus is defined as the deviatoric stress divided by the recoverable strain. And what is deviatoric stress here, we typically do a repeated triangle test where we are loading the specimen laterally as well as actually, on both the lateral Direction, I mean Y and Z direction to or you can say X and X direction, we are applying sigma 3.

it should be σ_2 and σ_3, but let us say a $\sigma_2 = \sigma_3$, and then we have some axial stress σ_1. So, deviatoric stress σ_3 is defined as $(\sigma_1 - \sigma_3)$, this is the deviatoric stress and the resilient modulus is defined as the ratio of deviatoric stress to the recoverable strain. So, I hope that the definition of resilient modulus and the behavior of the granular material is clear to you.

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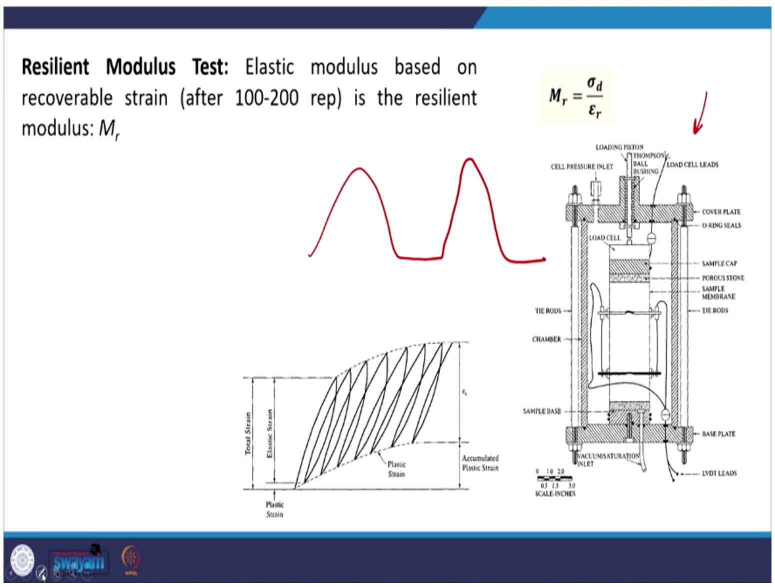

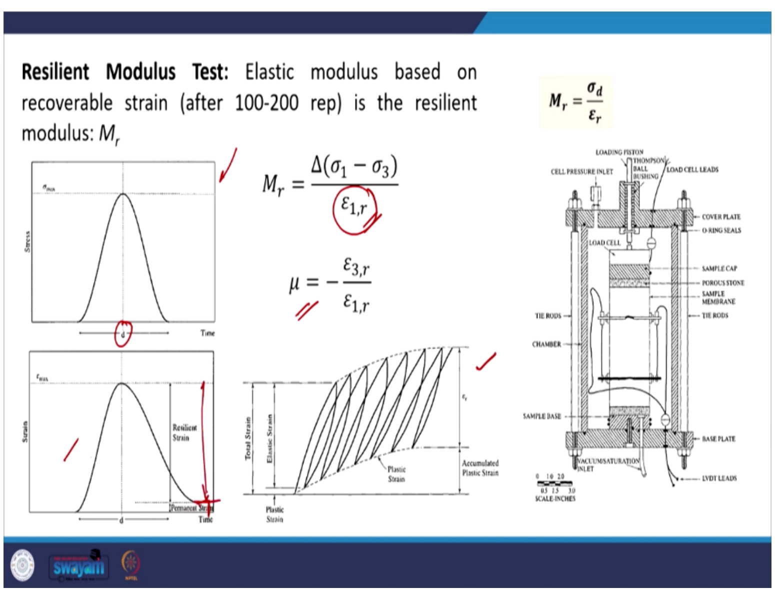

We are not going to discuss in detail about the repeated triaxial test here but as I explained the process is similar that we are applying a repetitive load here, this repetitive load usually will be in the form of loading and then a rest cycle, loading and then a rest cycle. So, it can be in this form, a loading we have a rest cycle, and then we have a loading and rest cycle, and then we see the response of the material when it is subjected to this form of loading. This figure I have already explained, that after few Cycles the accumulated strain will become constant and then corresponding to the recoverable strain, we will Define the resilient modulus.

Resilient modulus as I said is a $\frac{(\sigma 1 - \sigma 3)}{\epsilon_{1r}}$ because we are looking at the principal stress Direction, so, 1 is the principal stress Direction. And μ is defined as $\frac{-\text{ the lateral strain}}{\text{the longitudinal strain}} = \frac{-\epsilon_{3r}}{\epsilon_{1r}}$, When I said that it is the principle stress, I am talking about the major principle stress here.

Well again, this picture explains the response to the loading condition for 1 cycle. So, let us say if this is the 1 cycle with a duration of D, then this is how the strain response can be, you can see that the strain response shifts here, and we have some permanent strain in the material, and then we have the resilient strain or the recoverable, strain corresponding to this strain, I will calculate the resilient modulus. I will show you in the next slide about the calculation of resilient modulus.

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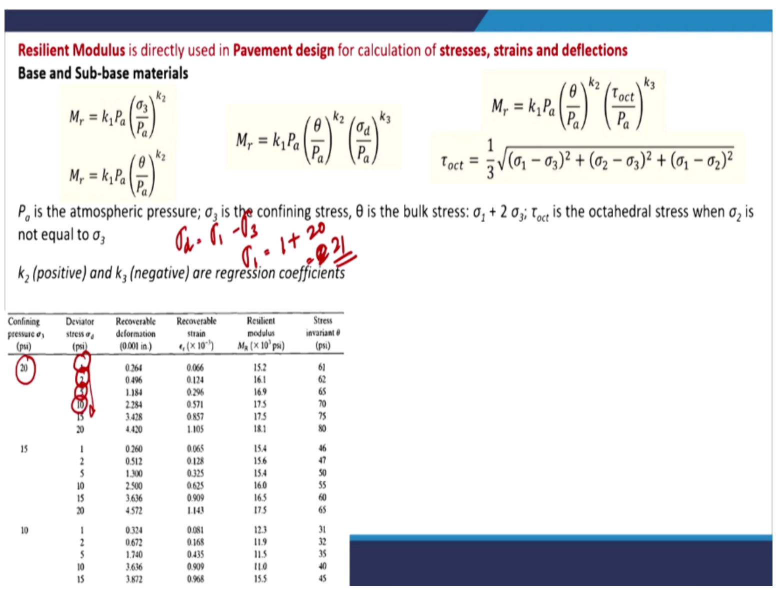

Confining pressure σ_3 (psi)	Deviator stress σ_d (psi)	Recoverable deformation (0.001 in.)	Recoverable strain ϵ_r ($\times 10^{-3}$)	Resilient modulus M_R ($\times 10^3$ psi)	Stress invariant θ (psi)
20	[illegible]	0.264	0.066	15.2	61
	2	0.496	0.124	16.1	62
	5	1.184	0.296	16.9	65
	10	2.284	0.571	17.5	70
	15	3.428	0.857	17.5	75
	20	4.420	1.105	18.1	80
15	1	0.260	0.065	15.4	46
	2	0.512	0.128	15.6	47
	5	1.300	0.325	15.4	50
	10	2.500	0.625	16.0	55
	15	3.636	0.909	16.5	60
	20	4.572	1.143	17.5	65
10	1	0.324	0.081	12.3	31
	2	0.672	0.168	11.9	32
	5	1.740	0.435	11.5	35
	10	3.636	0.909	11.0	40
	15	3.872	0.968	15.5	45

For calculation of resilient modulus, there are various models which have been proposed in the literature. These models can be in different forms, and these are some forms which I have taken from the literature, where you can see that the resilient modulus is a function of σ_3 which is the lateral stress.

In another model it is the function of stress invariant Theta, which is the summation of all these stresses, this is basically $\sigma_1 + 2\sigma_3$, because $\sigma_2 = \sigma_3$. So, this is also called as the K-θ model and one of the very famous models which researchers have used over a period to assess the resilient modulus or resilient behavior of a granular materials.

Well, some researchers have also included models which include both stress invariant and the deviatoric stress in some form, so, this is again one of the models. Now, just to tell you this k1, k2 whatever values you are seeing, these are just model parameters depending on the type of Aggregates we are testing. There are also models which includes both stress invariant as well as octahedral stress, so, the octahedral stress is given by this equation. Now, this equation is when $\sigma_2 \neq \sigma_3$, when $\sigma_2 = \sigma_3$, we will just you know re do the calculation and calculate Tau octahedral, again this is one of the models which have been proposed in the literature.

Here, Pa which is shown in most of the equation, it is the atmospheric pressure, σ_3 is the confining stress in the repeated triaxial test. So, just to again explain you if, this is the sample, this is sigma 3, the confining stress which we are giving. Theta is the bulk stress, which is sigma $\sigma_1 + 2\sigma_3$, this is the octahedral stress when s $\sigma_2 \neq \sigma_3$, but when $\sigma_2 = \sigma_3$, we will just change the form of this equation.

Now, let us see that how people have developed these models, and how the k-θ model has been developed. So, let us say that we have done a test in the laboratory and usually for granular material what we do, corresponding to each confining pressure we vary the debuted stress alright. So, we fix the confining pressure, and we are varying σ_1. So, since we are varying σ_1 σ_D will keep on changing alright. So, since σ_D for example here is sigma $(\sigma 1 - \sigma 3)$, so, $\sigma 1 = 1 + \sigma 3$, which is 20, so, 21 alright. So, σ_1 is 21 here, 22 here, 25 here, 30 here, and so on.

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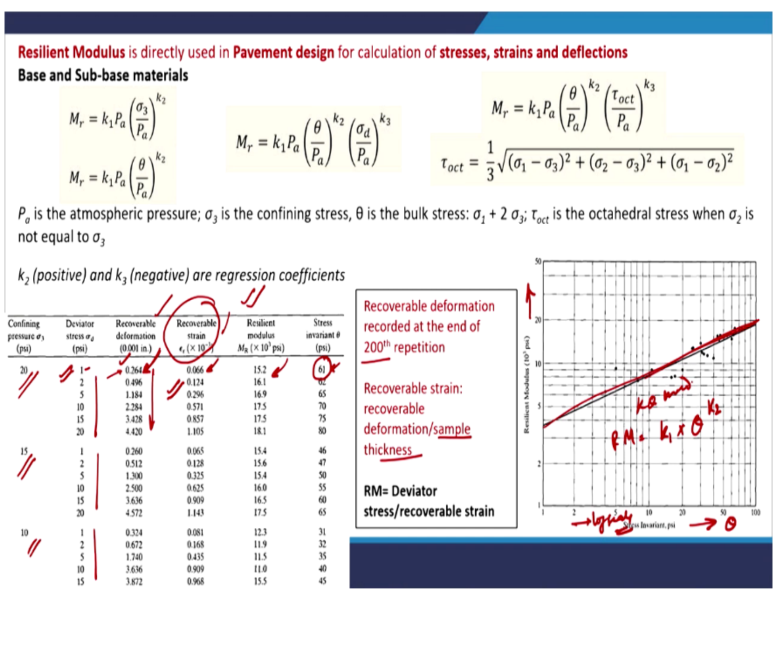

Confining pressure σ_3 (psi)	Deviator stress σ_d (psi)	Recoverable deformation (0.001 in.)	Recoverable strain ϵ_r ($\times 10^{-3}$)	Resilient modulus M_R ($\times 10^3$ psi)	Stress invariant θ (psi)
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And this is what the Strain gauges have given the result, that when we apply a diabetic stress of one PSI, the recoverable deformation which using the strain gauge we can calculate is 0.264. So, this is in unit of 0.001 inches, this is what the instrument or the equipment give us for the corresponding material, alright.

So, recoverable strain can be calculated, and this recoverable deformation is basically at the end of 200 repetition, initially because there will be some permanent strain accumulation and then the permanent strain will be constant. So, this recoverable deformation is recorded at the end of 200 cycle.

Recoverable strain is nothing but the recoverable deformation the change in the, change in the dimension divided by the original Dimension which is the sample thickness, alright. So, this is just value divided by the thickness of the sample. And then, resilient modulus is simply calculated as the ratio of deviatoric stress divided by the recoverable strain.

And of course, you can understand what is Theta here, why it is 61, because σ_2 = σ_3 = 20, and σ_1 is 21, so, the summation gives the value as 61. Likewise, you see at different confining pressure we have varied the deviatoric stress and the response of the material is captured in the form of recoverable deformation after 200 repetition, which is finally used to calculate this strain, and this strain is used to calculate resilient modulus as the ratio of deviatoric stress by the recoverable strain.

And then we can plot this variation for this material, this is might be for a specific material. So, we can plot the variation of theta stress invariant versus the resilient modulus, and then you can see how the data points are scattered, and this can be modelled using a straight line. So, that is why this is a k-θ model where basically resilient modulus can be written as $M_r = K1 \times \theta^{K2}$, because this is in log scale. So, that is why it is written in the form of power, so, if you put it in logarithmic form, it will be a straight-line equation. This is just for explanation how these models are usually created. But that is also a simplification which we assume.

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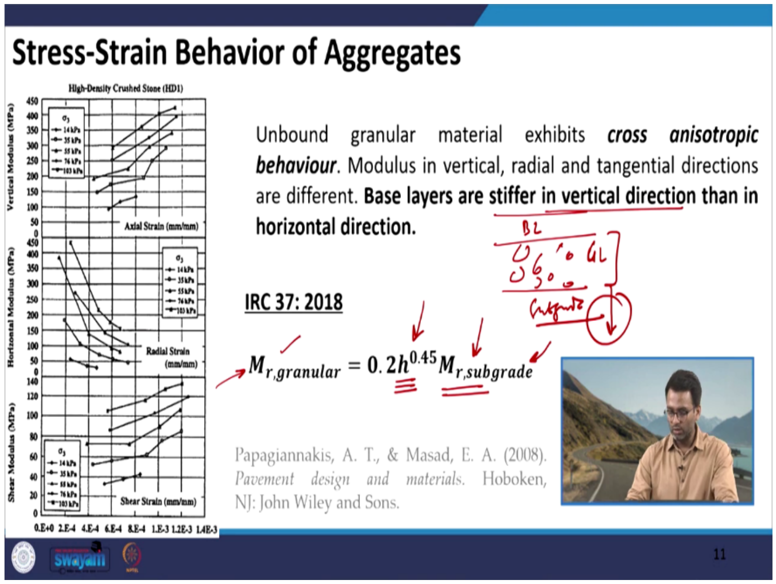

Most of these Studies have shown that granular materials are in fact more complicated in nature, and they so cross an isotropic behavior, which means that the modulus in different directions are also different. Usually, when we talk about pavement construction the base layers or the sub bass layers, they are stiffer in the vertical direction than the horizontal direction.

So, the modulus in the vertical direction will be higher than the stiffness or the modulus in the lateral Direction. But we do not use so much of complication when we are doing the payment design. So, models have been developed to simplify the assessment of resilient modulus which is used as an input in the pavement design.

For example, if you see IRC37 guidelines which is used for flexible pavement design in India, there the stiffness of the resilient modulus is a function of the thickness of the granular layer, now I think it is clear why it is it will be a thickness, because based on the thickness this strain value is changing, so of course thickness will be a parameter, and it is also a function of resilient modulus of the subgrade.

So, if this is the granular layer, this is let us say the bituminous layer, this is the granular layer, and this is the subgrade. So, this equation says that the stiffness of this layer is also a function of the stiffness of the soil. Now, many a times there is a doubt that why the subgrade should influence the stiffness of the granular layer. So, again you know we have just discussed that granular materials are stress dependent material.

So, depending on the confining pressure, the amount of pressure its applied from the bottom also will affect the stiffness of the mix in this direction, and therefore basically this correlation has been developed through data collected and studies carried out in India. And this equation again, was developed based on the similar concept of stress dependency of the granular materials and this is just an empirical equation which has been created through the data points which were collected or which were measured during this study.

You can refer to this book, which is pavement design and materials, you know, there are several chapters and one of the chapter talks about the behavior of the granular material and soil, and in fact most of the discussion which I have presented today has been taken from one of the chapter from this textbook, you can also refer to the textbook.

I think with this we have completed our module second, which is on Mineral Aggregates, and in this module, we have discussed about various aspects related to Mineral Aggregates. We have talked about a simple laboratory investigations or simple physical properties of these Aggregates, we have also discussed about the importance of these physical properties in relation to the performance.

We have talked about important Concepts such as assessment of specific gravity, understanding specific gravity, and also specific gravity of mixtures. We have talked about aggregate blending, we have discussed in detail, the importance and the process of doing aggregate blending which will be used in the mixed design process.

We have also talked about the surface characteristics, the mineralogical characteristics, which are very critical in relation to the performance, and which are usually not used in specifications. We have discussed about the estimation of surface area of the aggregate particles, and later we will use this discussion to calculate the film thickness of the bitumen over the aggregate particles in a hot mixes fault. We have talked about the mechanical behavior of Aggregates today, that it is a stress dependent material, not very simple to characterize. However, for simplicity researchers have developed correlations which we use as an input in fact in in the design of pavements.

With this, we will end here today, and in the next module, which is on bitumen, we will talk about various you know properties of bitumen, and we will try to understand bitumen as a paving material, and the importance of the properties which will be discussing in relation to the performance of the pavement. Thank you.