Advanced Concrete Technology
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Lecture - 27
Fresh concrete – Part 2

So in this lecture we will resume our discussion on Fresh Concrete properties. We were talking in last lecture about how we can modify existing methods to actually try and determine some specific properties of flowable concretes like self-compacting concrete.

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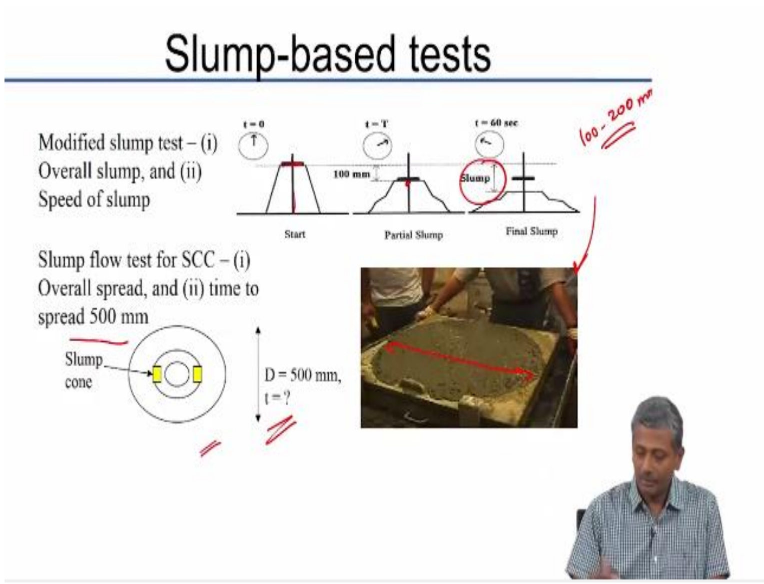

We first talked about the slump-based test, how we can actually modify the regular slump test for a flowable concrete or a very highly workable concrete and obtain some interesting data primarily in terms of how fast the slump actually occurs apart from the total slump that is also measured in the same test. So in one test you are now you are able to get 2 parameters instead of just one, . So that seems to match the requirements for rheology quite well.

And again for the self-compacting concrete you have the slump flow test where we are looking at overall spread of the slump cone.

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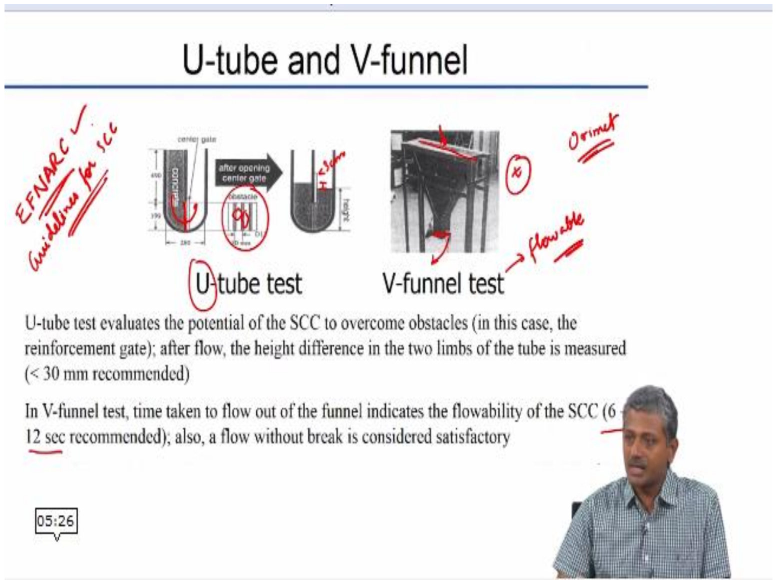

As well as the time to spread the 500 millimeters, so both these give us an idea about the rheological properties of the concrete. The other tests which are very specific to self compacting concrete involve the flow through the obstacles, primarily because self compacting concrete is not vibrated, it has to flow between reinforcement bars and try to completely encapsulate the inside of the form work which it is required to fill.

So for that, what you need to ensure is the aggregate size and the aggregate content are controlled in such a fashion that the SCC can easily flow between the reinforcing bars. So one of the tests that is prevalent for this kind of determination is the U- tube test. The tube is the shaped like a U and there is one limb of the tube where the concrete is actually first filled and there is a gate here and that gate basically has an obstacle right behind it.

So you fill up the concrete at one end while the gate is closed when you open the gate the concrete has to flow through the obstacle to the other side. Of course if you imagine that you pour water instead of concrete it will flow until it equalizes on both sides, there will be no difference in heights on both sides.

But with concrete because of its nature, because of its lack of flowablility in some instances or because the aggregate start getting blocked at the obstacles, you may not have the entire concrete rising in the second limb, . So for self compactibility, what you need to ensure is the difference in the height is less than 3 centimeters. So once you have a concrete that satisfies that requirement it is also called self compactable.

Because one of the important characteristics that it needs to satisfy the passing ability, ability to pass between reinforcement. Of course, the V-funnel test is more related to the flowability again. Now here you pour the concrete into this V shape funnel. The gate or the trap door at the bottom is first closed, . After the concrete is completely filled, you open the trap door and then allow the concrete to fall through the funnel.

So again, if you imagine if it is water it is going to fall almost immediately, it is going to come out in a single stream. If you imagine it is going to be a very cohesive or very stiff concrete, it will not fall out of this opening at all. If it is semi-stiff concrete, it may fall out, but start coming down in chunks. It will not really come down as a single pour. For self compactability you want that to come down typically as a single pour.

And generally, what there are specifications about is the time it takes for the entire concrete to get emptied from a V-funnel. You can also do this test in a different way. You can let the concrete stay inside for five minutes, right. What will that do? If there is any segregation it will happen in those 5 minutes, right. And then you allow the concrete to fall out of the trap door. So, if the concrete starts segregating, it does not have a uniform flow out of the V-funnel, right.

If it is uniform still after the five minutes, it has a consistent behaviour then it will come out as a single pour rather than coming out in chunks. So that is an important test V-funnel does. There is another test which is called Orimet. Again, this involves the flow of the self compacting concrete through an orifice which is open and you allow the concrete to flow out; measure the time taken to flow, and that is related to the flowability of the concrete.

So generally 6 to 12 seconds is recommended as far as the V-funnel test is concerned. All these guidelines for testing as well as the conditions for the acceptance of the SCC are given in a standard or in a draft guideline which is called EFNARC. EFNARC is a European organization which is consisting of the experts from the industry and academia and they had a big project on self compacting concrete in the early 2000's.

And based on that they came out with the EFNARC guidelines for SCC and these are again available on the internet. And these guidelines can be utilized for actually designing the SCC, understanding the characteristics of the SCC, testing it, understanding what changes you need to make in them, in case it is not working properly, all that is very clearly given in these guideline.

So while SCC many not be there in most of your standards, it is definitely there in the guidelines. The test methods for SCC like the U-tube, V-funnel, Slump flow all these have now found a position in the standards also. Not in Indian standards yet, but they are going to be introduced in the Indian standards also in the fresh concrete testing standards, right. In American standards, you already have standards which pertain to these tests.

So, test methods have made it to the standards. The design of the concrete is not yet standardized or there is no guideline published by the standards organization or concrete institutes in different countries for the design of these special types of concretes. So for design, the best strategy is to still use the guidelines for SCC which are given by EFNARC. I think the last version came out in 2005 beyond that there is no real change in the methodology of the design of SCC.

But what I will show you towards the end of this chapter we will talk about a specific method for mixed design, which does a little bit better than just take up guidelines from well publicized document. So what we have tried to do in this case, it was related to the PhD thesis of one of the students and he has worked on specific methodology that combines the particle packing approach along with rheology to understand how well we can describe the properties of SCC and control it through a proper mixed design.

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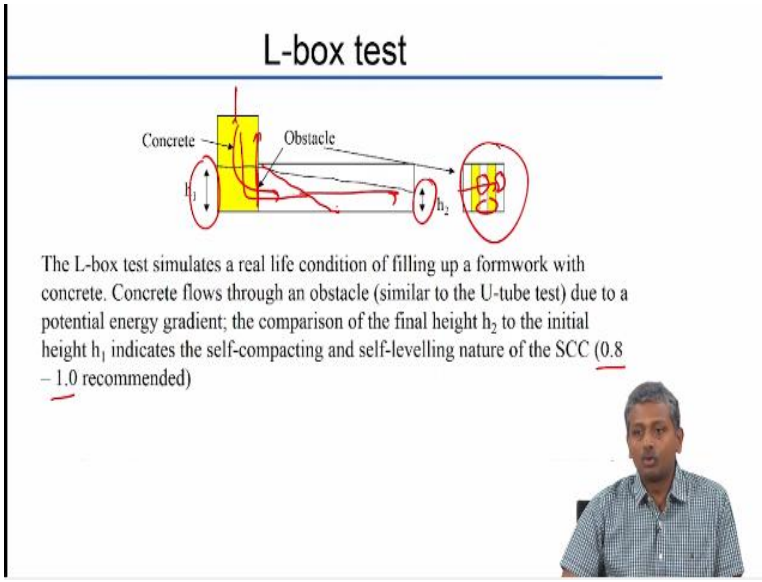

There is another test which determines the passing ability that is called the L-box test. Again this box is shaped like an 'L', right and the vertical limb of the box is where you can fill up the concrete; again there is a gate here, beyond the gate there is an obstacle which consists of reinforcement. So once you open the gate, the concrete starts flowing through the obstacle.

For the concrete that is highly flowable and has aggregate size which is well controlled and aggregate content that is less enough, it will easily flow through the obstacle and reach the other end. And once it reaches the other end, a highly self compactable concrete will have a ratio of heights at both ends which is close to 1. Generally, a ratio between 0.8 and 1 is recommended for self compactability.

For concrete that has too much coarse aggregate or that has improperly sized coarse aggregate, what will happen is it will start getting blocked at the obstacle and not be able to cross that barrier, and because of that the height differences will be very high. There are some concretes that are so cohesive that they may stop flowing.; they may not even flow at together end. So again this is a test which is probably the most stringent test amongst all SCC tests, the most stringent one is this L-box test.

So if a concrete passes the L-box test, you can consider that it will pass most of the other tests. What are not covered here is something called the J-ring test. So in elevation, if you look at the slump cone, you have a ring on the outside, and this ring is basically consisting of reinforcement bars.

So, once you lift up the slump cone, the concrete has to flow, but now instead of flowing freely, it will have to flow between the reinforcement bars. And for the J-ring test, the slump flow that you get, flow should be not less than 50mm than the regular slump flow. So if you are doing without the J-ring, if you get a certain value, you repeat the test with the J-ring, the slump flow should not be more than 50mm difference for a good self compactable concrete.

That means, in one test you are not only measuring the flowability, you are also measuring the passing ability. So the J-ring, U-tube and the L-box these are tests for passing ability. For flowability again you have slump flow, V-funnel test. Both of these are testing the flowability of the concrete.

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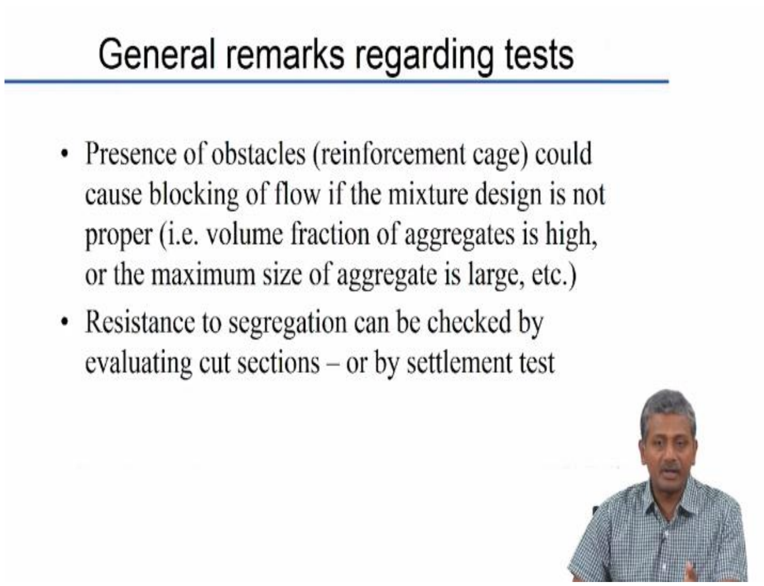

Now, in general what I was talking about earlier is that in presence of obstacles could cause blocking if you do not design your concrete properly, if you have too much coarse aggregate or if you have too large sized coarse aggregate, . And then of course you can also evaluate resistance to segregation.

The simplest way to do that, of course we already saw that in the V-funnel test also by letting the concrete sit inside the funnel for some time and then opening the trap door. The other strategy is to simply put the concrete in a bucket and allow it to settle for about 15 minutes, then pour out the top half of the bucket. What will that do? If the concrete is segregated, the top half that gets poured out will only be a paste or mortar.

So then you can evaluate the amount of coarse aggregate that we have in the top half and get an estimate of how much segregation has actually occurred. Very simple, easy to do, it is not a big deal at all. But of course you can also evaluate it after the concrete has hardened and take a core and see how the aggregates are distributed. If you have a uniform distribution of the aggregates all across the cross-section, then it is a good mix but of course but by then it is too late, because the concrete is already hard, right.

The other way to check the uniformity of concrete has been laid is to just do ultrasonic pulse velocity test. If you have a column of concrete that has been laid by the self compacting concrete, if you are worried that the segregation might have happened leading to an increase in the coarse aggregate fractions at the bottom, when you take the pulse velocity, the relative differences in the quality can easily be brought out with the help of the pulse velocity test.

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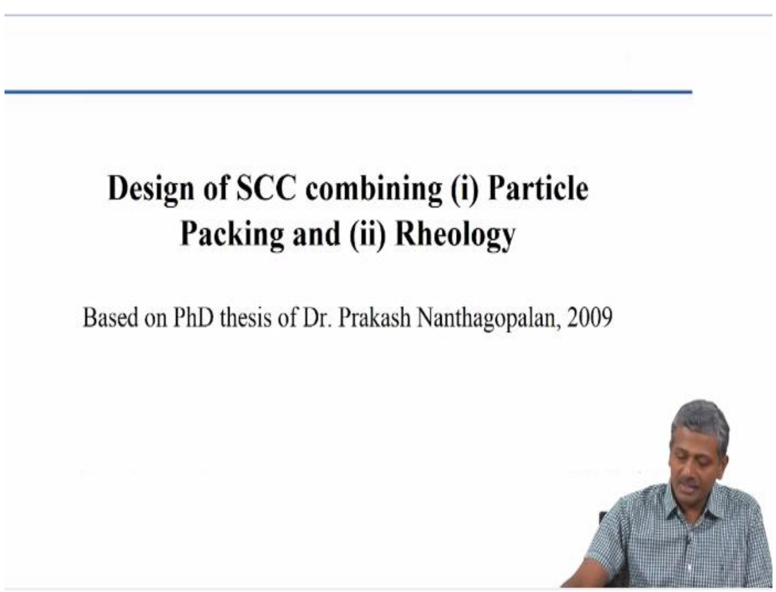

So, having looked at the characteristics of self compacting concrete and how we can evaluate those, lets now look at a strategy that was worked out based on a PhD thesis of Dr. Prakash who now he is an Assistant Professor at IIT, Bombay. So, he has devised this methodology for design of self compacting concrete combining particle packing and rheology. So let us look at how this is done. So this is a step wise process.

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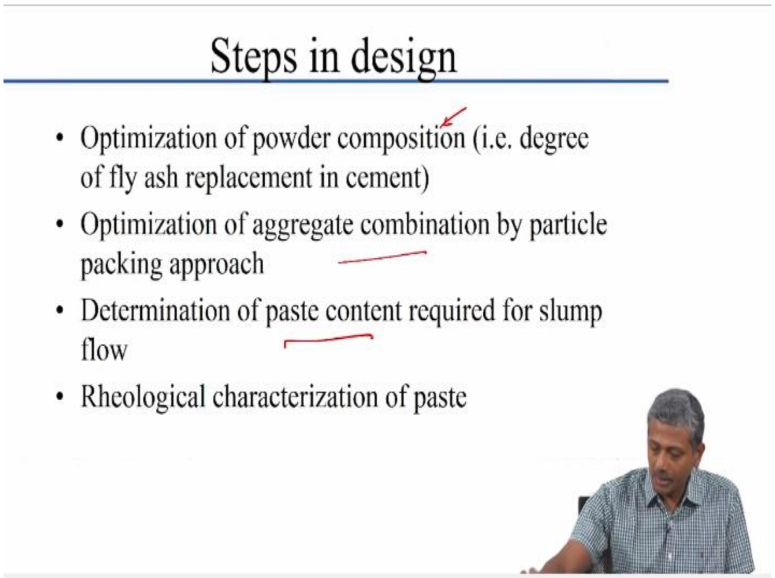

First is the optimization of the powder combination or composition. That means the degree of flashed replacement of cement. So again we have assumed here that most SSCs will have fly ash as the cementary placement material because that is what works in most cases to improve the flowability without really causing an excess increase in the binder content, . If you have to use slag or silica fume, you may get mixes that are difficult to control.

But fly ash is much easier, typically. I am not saying it is like that all the time but typically it is much easier with fly ash. The optimization of the aggregate combination is done next with a particle packing approach. Of course, if you look at the methodology of the powder composition optimization, you will see that that is also essentially based in particle packing but both these are different empirical techniques.

We are not again following the same EMMA software here, although we can do with the same to some extent with the EMMA software also. The next is optimization of aggregate combination and finally once the aggregate combination is optimized, you know exactly how much volume of paste you require to enter the voids left behind the aggregates and on top of that, what is the excess paste that is required to make the concrete flowable.

So that is what is the determination of the paste content required for the specific slump flow of applications, then of course you need to realize that the paste itself has to be designed appropriately to obtain the best rheological characteristics given the blend of the cement fly ash and the brand of the super plasticizer that we are trying to use in the project. So you optimize the paste for the best flow and that obviously involves a combination of your marsh cone and mini slump test which we discussed earlier. So let us look at this step wise process.

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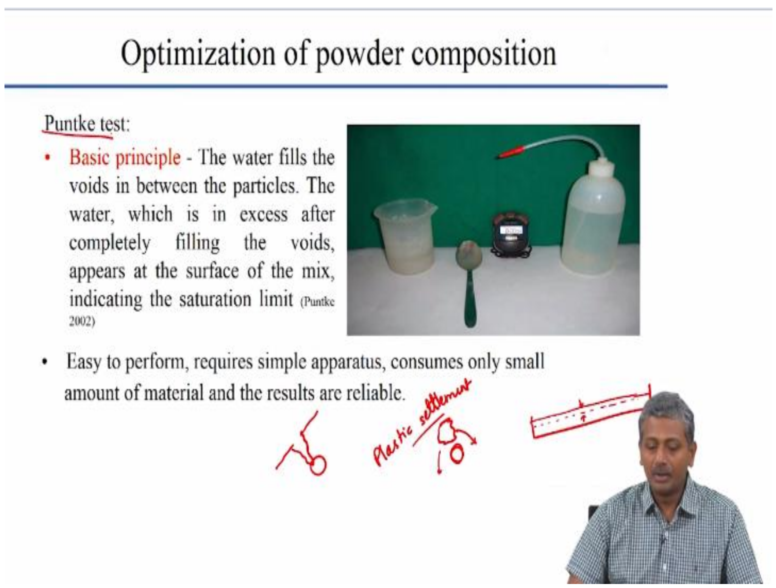

First is optimization of the powder combination. Now of course, we start off with the certain requirement of the SCC. How will you specify SCC on the site? It is not enough to just say, I want self compactable concrete. There could be some problems if you just say that, because you can produce that SCC to have a slump flow of 550 mm, you can have an SCC that have a slump flow of 750 mm.

What is the essential difference between the two? So, for example, if I choose, different types of structures, let us say I choose a column and then next I say I choose a slab. I want to design a SCC for a column and for a slab. What will be the difference in characteristics of the SCC that I desire? Of course, both have to be self compactable, they need to pass all the tests. But if I have to choose the slump flow of the SCC for the column or for the slab, where do you think I need a greater slump flow?

I need a greater slump flow for slab, why? Because your application is much easier now. All you have to do is move the shoot around and fill up the space. But why do you need to really make it flow a lot? Now what I am trying to tell you is, if you make the concrete flow too much for a slab, you may get problems. Can you tell me what problems you can expect?

You can have a problem of plastic shrinkage. Plastic shrinkage can be very large with the slab, especially if your flowability is high. How is the flowability maintained at a high level? Maybe, you have little bit extra water in it, maybe you have more super plasticizer in it. So if you have more super plasticizer what do you expect will happen to the setting time?

Setting time will also increase. So now concrete will now set much slower. So the risk of plastic shrinkage goes up as the setting time of concrete keeps on increasing. The other problem with the slab is that if you have not designed the top cover properly, for example if I have let us say this is my form work of the slab and I fill up the concrete into the slab; I have reinforcing bars just lying underneath and my top cover is let us say 15 millimeters.

Now I have designed this SCC with a maximum aggregate size of 20mm. So if you consider the reinforcing bar here, there is an aggregate piece that comes on top, what will happen with the aggregate now? It will start settling around the reinforcement. So if you have very high flowability of your SCC, you will get also what is known as plastic settlement. This plastic settlement can lead to some cracks occurring right on top of the reinforcement.

Indeed, when people started using SCC, when they produced high flow SCC and they started applying it for slab, one of the primary problems that they saw was plastic settlement cracking. You would actually see the layout of the reinforcement on the top because the concrete had started settling around the reinforcements. So they started getting cracks just on top of reinforcements.

Now, we saw these problems in some of the structures that were actually designed within the IIT campus. The engineering design building had slabs laid with SCC on top. And in these slabs, we started seeing these problems of plastic settlement cracking. So what we tried to do was, when we designed the same SCC for the slab that is right outside your library which holds the chilling water plant of the air conditioner of the library, that slab we took precautions to ensure that we will not get this type of cracking.

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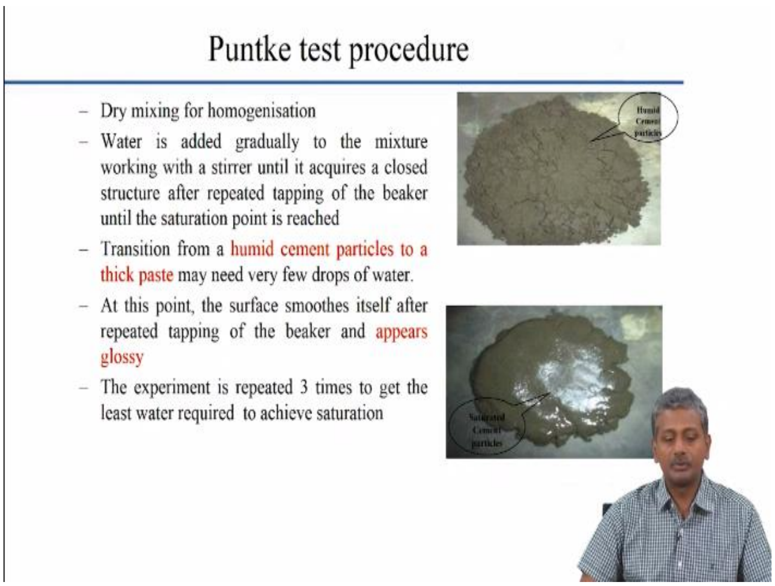

For a column, how will you pour, SCC for a column? You probably cannot pour it from the top because it will cause segregation; SCC is highly flowable. So you will start pouring, or you input the concrete from the bottom, pump it in from the bottom and just it goes up. And actually it is an ideal situation because it will completely fill up the form work without any air gaps.

If you pour from the top, one you have the risk of segregation, the other is that you can create air gaps inside. So now in a column, having a high slump flow maybe quite useful. Secondly there is no danger of plastic shrinkage or settlement because it is entirely enclosed. There is no problem there. So, the design of self compacting concrete would be specific to the type of situation that you have with the SCC, the characteristics of the SCC desired may depend on the kind of structural element.

Of course you also have the requirement of strength. What do you do then? For the strength what do you do, how do you design SCC for strength? Again you assume the same water to cement ratio relationship that you typically get with the ordinary concrete. Right. That is a good starting point. You may not get the same answer. But at least for a start, when you want to design SCC, you consider the strength with the water cement ratio and for a particular strength you choose the right water cement ratio and design SCC based on that.

So now, we have a concrete that is designed for a specific application. It requires to have a certain flowability and the amount of fly ash substitution of cement needs to be determined for this case. Now the issue is you can, conduct trails. You say, I want to put 10% fly ash, 20%, 30%, 40%. Whichever is the case of the best flowability it will be the amount that I use. Doing this in concrete obviously requires a lot of effort.

So can we narrow this down, by working at the paste level? And that is where this test called Puntke test is quite useful. So here, in the Puntke test the principle is simple. When you mix 2 different powders, the mixing has to be done in such a way that the combination gives you an optimal packing that means you have the lowest void content.

So, when you mix 2 powders, how do you determine void content? You simply mix water into the powders, at the very early stages assuming the reactions are very less. This water will just fill up the voids between the powder, any excess water will come up to the surface. That is all. That is the principle of this test. Of course instead of water, you can use a different fluid also which is not reactive like kerosene for instance.

I will show you the results, which will make it clear that irrespective of the fluid you choose it seems to give you the correct sort of a picture in terms of the best combination. So here the basic principle is that water fills the voids in between the particles. So the water which remains in excess after filling the voids comes up to the surface, indicating that your mix has reached saturation level. So that is a very simple test to do. All you need is a beaker, you need a spoon, you need a stop watch and you need a water dispenser, a squeeze bottle for the water.

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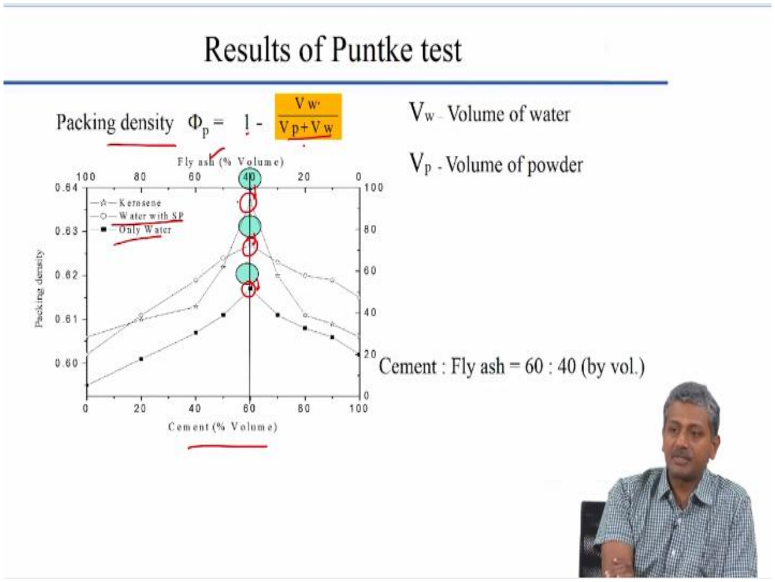

Now what you do? You are dry mixing first for homogenization of the cement and fly ash particles, then you add water into this mixture slowly until it acquires a close structure and then when you tap the beaker, water simply comes up to the surface if saturation point is reached. After it fills up entire void, it comes up to the surface. So here, the top one a photograph which shows you humid cement particles, that means there is water inside but it is not large enough to come up to the surface.

But here, in the second picture you have a saturated combination of cement and fly ash where the water has actually come up to the surface forming a sheen on the surface. So you repeat this experiment multiple number of times that only takes you a few minutes each time, to get this done right. Only thing is you need to quantify the water exactly to ensure that you are able to calculate how much water you are adding to the cement.

So based on this what you do is you plot the packing density versus the amount of one constituent by volume. So here the constituents are cement and fly ash. So you can plot the graph either in terms of cement percentage by volume or fly ash percentage by volume. What is the packing density? It is nothing but 1 minus void content and void content is volume of water divided by total volume of the system. Total volume is volume of the powder + volume of water.

$$\text{Packing density} = 1 - \left(\frac{V_w}{V_p + V_w}\right)$$

Volume of powder = volume of cement + fly ash. So for each combination you need to determine the volume based on the specific gravities of the material. So if you plot this, what you see is, when you use only water, you get a packing density of around 0.61 to 0.62. This happens at a 60% cement content. That means 40% fly ash content by volume. If you look at water + super plasticizer which is used as a fluid, it again gives you the same 60-40 combination but it gives a slightly better packing.

Obviously, you except that because there is better dispersion of the particles. Then, finally when you use kerosene, you again get the same 60-40 combination but you get a still higher packing density. So, what you can see from this is that irrespective of fluid that you use, the combination that gives you the best packing density is still the 60-40 combination by volume; by mass it may approximately be around 70-30.

What this means is, now you need to design the paste with a 60-40 combination of cement and fly ash by volume. And that already cuts down one of the variables that you have in your mixed design process for SCC, . So, simple test, easily performed, results are obtained very quickly and you have a fairly good estimate of what combination will give you the best packing.

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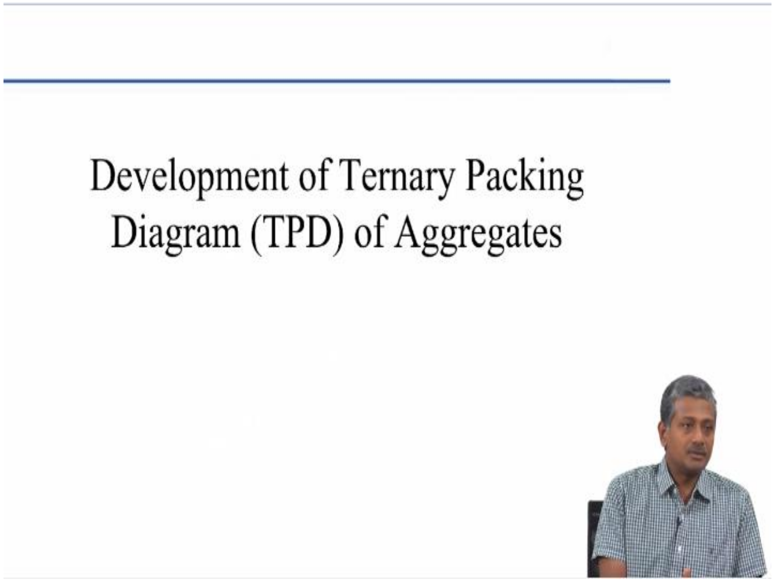
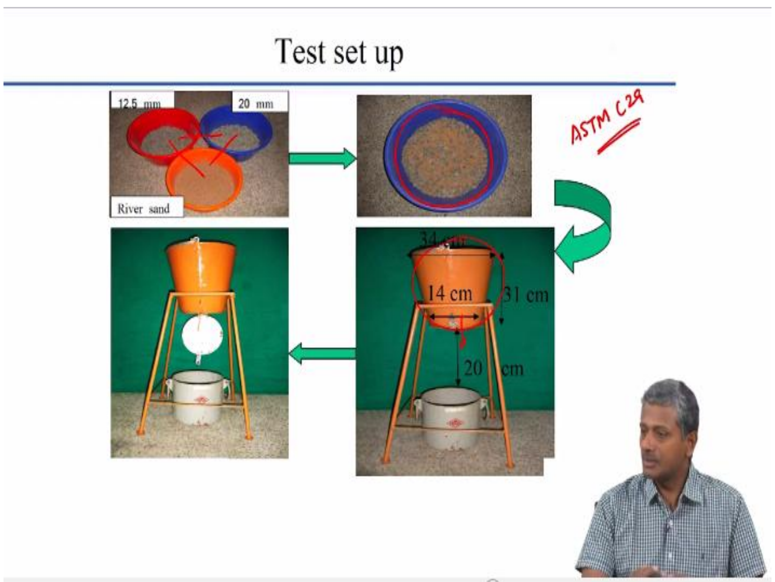


Now, we have packed the cementatious system, how do we pack the aggregate system? **(Refer Slide Time: 23:49)**



So, now if you really look at it, there are methodologies that are proposed by the standards, there is an ASTM standard, ASTM C29, which gives you indications of how best you can pack aggregates. So you need to do a regular mix design, supposing you have 3 different types of aggregates 20 mm, 12 mm and then sand; you can experiment it simply keep on mixing different combinations of these materials, put that compact that into a cylindrical bucket and measure the unit weight.

The maximum unit weight gives the maximum density. That means, the combination that gave you the maximum unit weight is the optimal combination with respect to density. The problem there is, when you mix this and then try to compact this into a cylinder and do 25 times rodding and all that, by the regular techniques, that involves some subjectivity. So can we make this test a lot more objective was the issue that we were contending with.

So, here, again you have 3 different types of aggregate, 20mm, 12mm and river sand. All you do is first make mixtures of these in different proportions. Let us say we start with 50% of sand, 25% coarse aggregate of 20mm and 25% coarse aggregate of 12mm. You know very well that when you are designing for the self compactable mixtures, the flowability is very high. So to avoid the dangers of segregation you will proportionate in such a way that you already have a fine enough aggregate content.

So you will never choose fine aggregate content for SCC that is less than 45% of the total aggregate content. If you look at any design for SCC, the fine aggregate will be closer to 50% of the total aggregate content. So, you design your mixtures of the aggregate combinations, with 50% fine aggregate and different percentage combinations of 12mm and 20mm coarse aggregate. And you do the same with 60% fine aggregate and then different proportions of coarse aggregate. Maybe you can also try 40.

So you have a number of different combinations which are possible. And each of these combinations, you first prepare a dry mix intimately mixing these aggregates together. So what we devised was this, bucket method of testing, so here, we have a top bucket, similar to your compaction factor. If you remember compaction factor test, the freshly made concrete is filled up into the top bucket, the door is opened and falls in the second bucket. Again you open the door, and it falls into a cylinder and the amount of concrete filled in the cylinder as opposed to the amount of concrete that would be filled if you vibrate that gives you the compaction factor.

Here, what you simply do is, you allow the mixture of aggregates to drop from this bucket into this cylindrical container and measure the density of the aggregates in the container or unit weight into the aggregates of the container. So instead of just making the same mixture and putting it inside and rodding it, to compact it, all you have done is just compaction energy has been given by dropping it from a height. So that, you just measure the unit weight, and based on that you can calculate the void content of the system.

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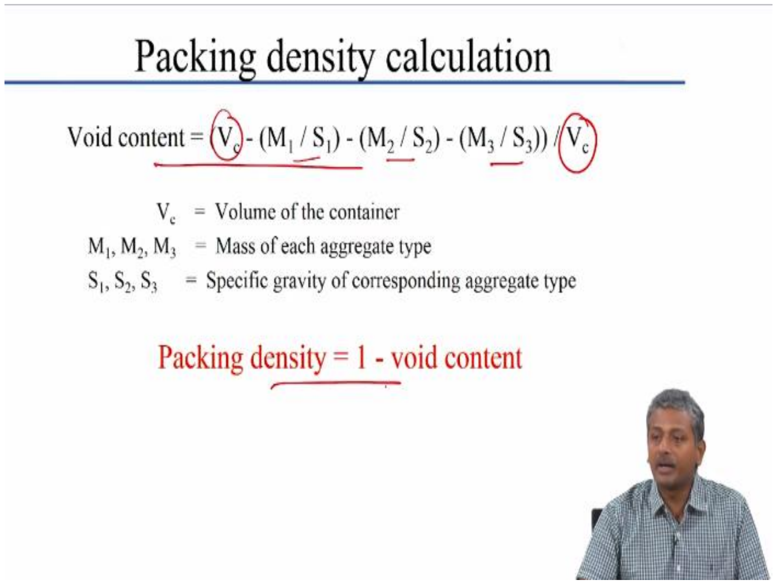

Void content of the system is shown in below equation.

$$\text{Void content} = (V_c - \left(\frac{M_1}{S_1}\right) - \left(\frac{M_2}{S_2}\right) - (\frac{M_3}{S_3}))/Vc$$

Vc = Volume of container

M_1, M_2, M_3 = Mass of each aggregate type

S_1, S_2, S_3 = Specific gravity of corresponding aggregate type

That is the voids content that you get in the system. Of course, packing density is nothing but

1 - void content.

Simple enough test once again, but interestingly gives you a very good result.

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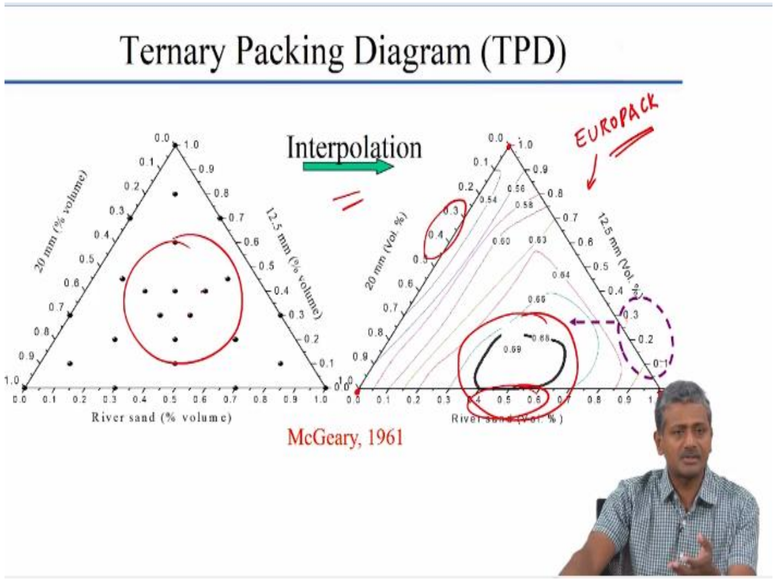

So, what you get is, of course, to make this test work, because you have a ternary combination, so you have to work with multiple number of combinations. So what Prakash did was, he picked up very specific combinations and then he did an interpolation using a mathematical software which was created in MATLAB, where these data points were actually fixed based on the determination which is required by the software.

Only some of these data points were actually measured and checked. So based on the interpolation, the contours representing the packing density were worked out and the zone where the maximum packing density was obtained was easily identified by this software. Now, actually if you look at it, this software which I talked about it in the last class EUROPACK, which I said was commercially available for a price and the EUROPACK essentially does the same thing.

It just takes the particle size distributions of the individual aggregates and that does a mathematical interpolation to combine the aggregates and get the suitable packing density that you get, when you mix different types of aggregate. So here, what was seen was the best packing densities were obtained with volume fractions of about 50 to 60 percent of river sand; and smaller amounts of 12.5mm aggregate and slightly greater amounts of 20mm aggregate.

So, you read the ternary diagram the same way as you read the ternary diagram in the case of your cementitious systems. So based on this you arrived at, the packing density you have required to give you the best aggregate combination. So, if you are running a ready mix concrete plant for instance, all you need to do is based on the supply of the aggregates that you get, keep these diagrams ready, so whenever you need to design an SCC, you can optimize the aggregate combination. This does not need to be only for SCC it could be done for any other regular concrete case also.

When you are doing conventional vibrated concrete, you will not be choosing very high amounts of sand. Your sand contents in regular concrete will be how much? 30-40% not more, yeah. If you are making pumpable concrete, you want to increase the fine aggregate content. If you are making regular conventionally vibrated concrete on grid which is not getting pumped, then 30-35% is good enough.

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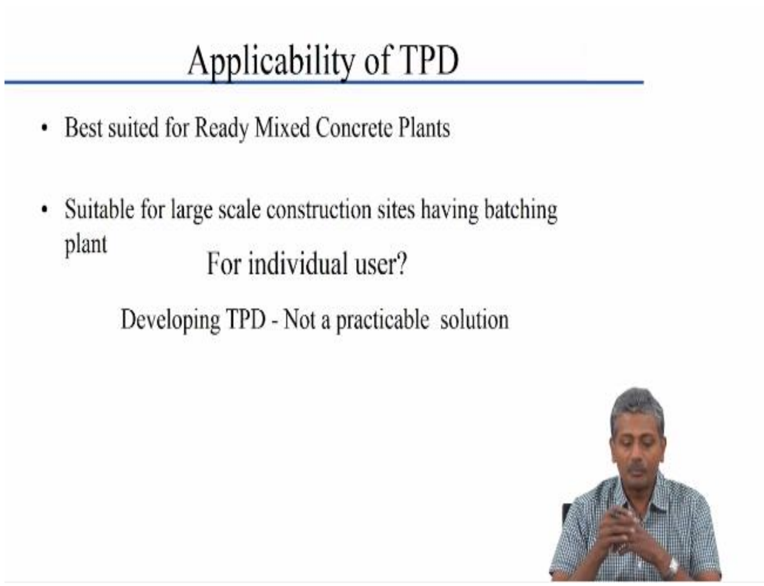

So this ideally suited for RMC plants. But if somebody wants to do this design on their own, if they want to start off doing SCC design, it may not be suitable because how will they have access to so many different materials and then try to understand how well these things combine together and so on. So not a practical solution for individual users, so something much more easier and simpler needs to be done for individual users. And what is it that can be done?

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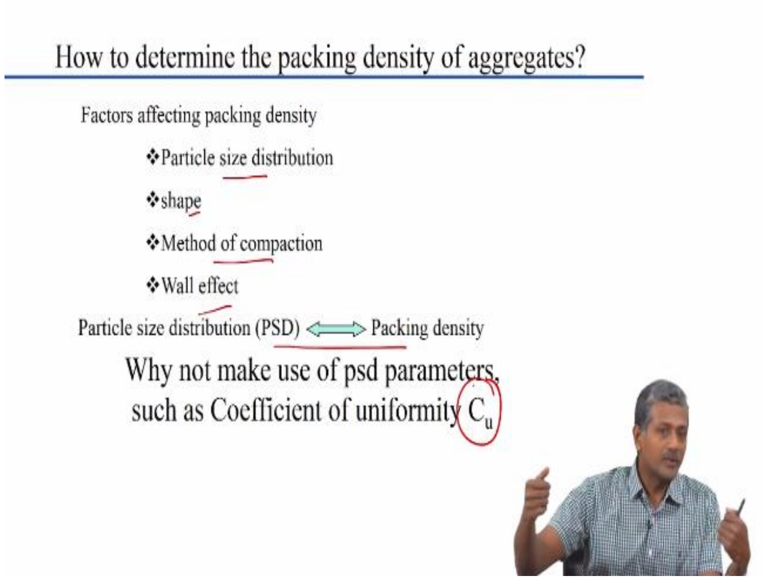

So here what was done was an analysis of what factors can affect the packing density. One is the particle size distribution obviously; the shape of the particle is also important because if you have spherical particles as opposed to angle aggregate different packing densities. The method of compaction is another important ingredient that can affect the packing density, and the wall effect obviously depending upon the size of your particles and the shape of the container or size of the container.

So the particle size distribution was considered to be the primary factor affecting packing density. And what we try to do was model the particle size distribution using a single parameter. You know very well from your PSD studies that there are different parameters designed to describe the shape of your particle size distribution, you have the uniformly coefficient, you have the curvature coefficient yes. So it defines characteristics of your diagram.

So what we thought was let us try and choose a parameter like uniformly coefficient because that gives you, since it is the ratio of D_{60} to D_{10} it gives you a range of spread of your particle sizes. So the greater the range of spread it is likely that you will get better packing, because more number more size of particles are included so greater the range is spread you get the better packing.

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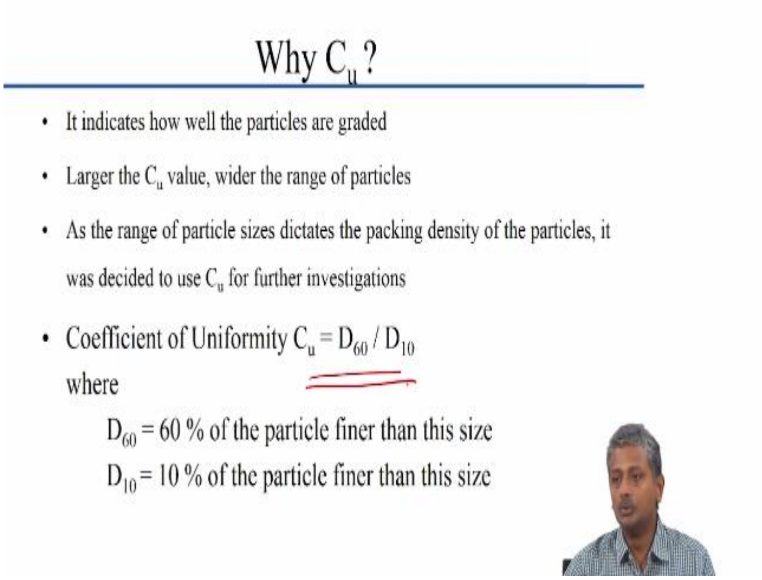

So here what we saw was when we started using Cu to describe the particle size distribution and saw its affect in packing density we saw that the packing density was very nicely correlated with the coefficient of uniformity.

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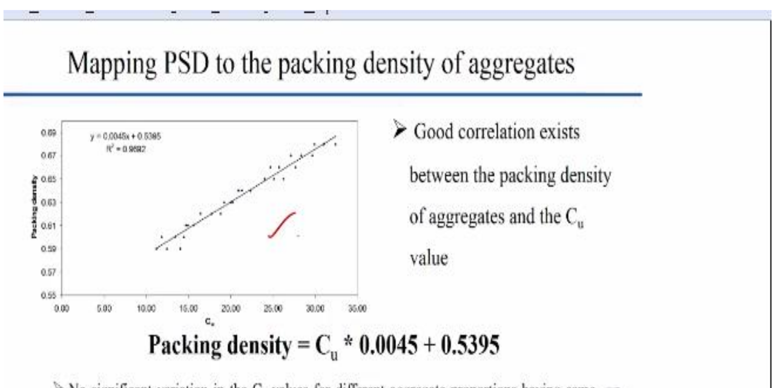

Now what you need to simply do is get the individual particle size distributions, make several trial calculations just based on combined particle distributions and obtain the Cu values for each. And based on this relationship shown below you can actually get the packing density as a fraction of as a function of the Cu.

Packing density = C_u*0.0045+0.5395

So once you get the packing density the void content is nothing but, '1 - packing density'. So there is correlation, we looked at number of different types of aggregates seem to work quite well for the design of SCC.

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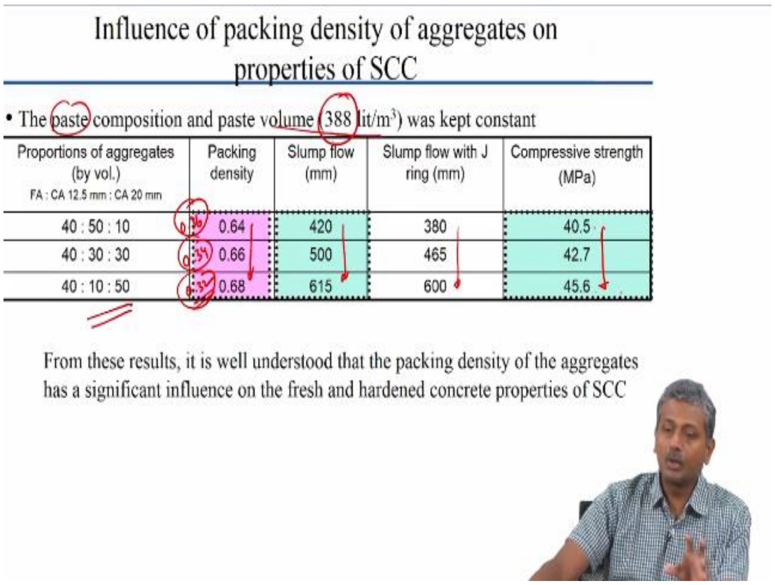

Using this system of combining the aggregate propositions we wanted to see whether it really works well and concrete or not. So to do the concrete design what we did was we kept the paste composition and paste volume as constant. The paste volume was 388 lit/m^3 and that means the aggregate volume was 612 lit/m^3.

So the proportions of the aggregates that were giving different packing densities from 0.64 to 0.68 were chosen and then we tried to look at the effect on slump flow, you can very clearly see here that the slump flow increases as I increase the packing density, the paste volume is now constant. It is not really a surprise as slump flow is increasing, why? Because here, look at the void content for first mix is 0.36, 2nd in 0.34 and third is 0.32.

In other words, in $1m^3$, you have 320 liters of voids for 1st case, 340 liters of voids in 2nd, and 360 liters of voids in 3rd. When you add 388 liters of paste you are filling up the 320 liters of voids and you have 68 liters extra paste, so obviously it will have better flowing ability you have more paste available now in the system. So this paste now enables your concrete to flow better, and that is why your slump flow increases.

Slump flow with J-ring is also a much better performance when you go for the higher packing density, the compressive strength also increases, although the increase is not substantial but still there is an increase at least between 0.64 and 0.68 you are increasing strength by more than 10%. So you can still call it to be quite significant. So what we could clearly demonstrate with this was that the strength as well as the flowability was increasing as a function of packing density. You can look at it another way.

If you want to keep the workability constant, if you want to keep the flowability constant you need lesser amount of paste for the system that has higher packing density. So, that again leads you to having better savings of your concrete design.

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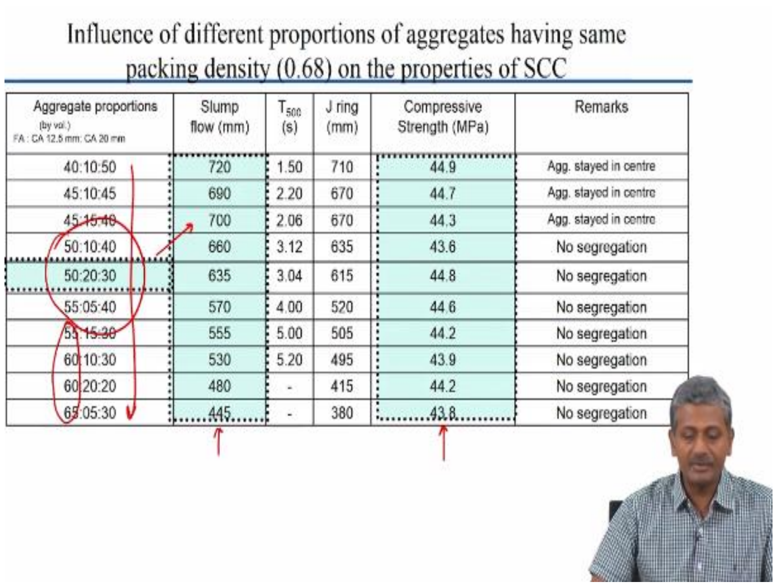

So again we did another test here to see whether the mixture proportions of the aggregates that are giving the same packing density, how was that affecting the properties of the concrete? So all these mixture proportions were giving the same packing density. Now interestingly if you look at compressive strength all these mixture proportions that give same packing density, gave almost identical compressive strength.

You can see that the difference is almost less than 1MPa between the concrete. So that strongly tells you that packing density is very well related to the compressive strength. In terms of flow there was a lot of variation. Now why did this variation happen? primarily because of the affect of the fine aggregate content in this, because you can get the same packing density with different combinations of the aggregates but the ones which have the potential to flow most will be the ones which have the greater fine aggregate content.

So again here we saw that the ones which had the ideal proportions they are actually able to get you much better flowability. Now of course here when you go on excess of 50% what is happening here is too much fine aggregate in the system is also increasing the water demand of your system and you are not getting the required flowability characteristics.

So here you have a situation where even though the same packing density is there you do not really get the same flowability but the strength is quite similar. And in some cases of course there was even segregation when the aggregates actually remain at the center and did not flow out with the concrete, so that indicates that the performance is not really very good that is because you have too much of the 20 mm coarse aggregate.

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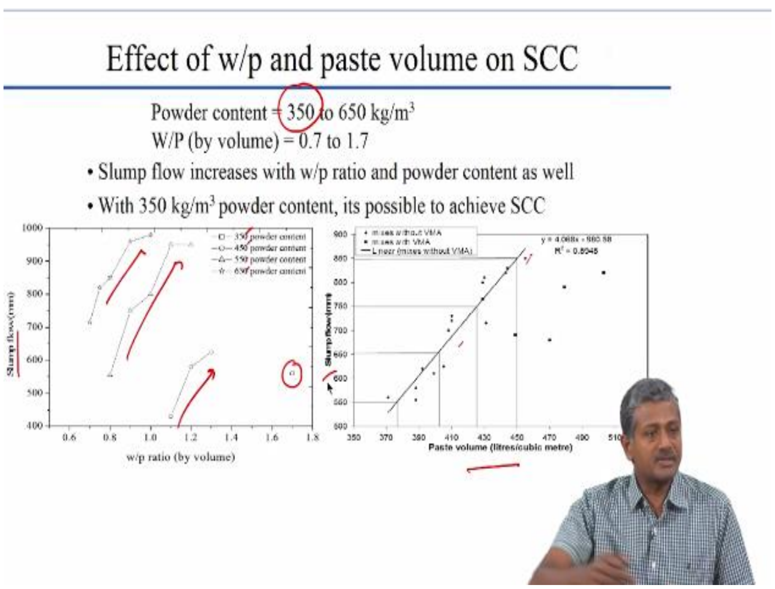

So what about the affect of the water powder ratio and paste volume? Now we know very well that water to powder ratio or water to binder ratio as you increase it you expect the flowability to go up, right. So here what is plotted is the slump flow versus the water to powder ratio by volume and for different poweder content 350, 450, 550 and 650 these graphs are now created, you see that for 350 powder content you have to go for a very high water powder ratio to obtain self-compatibility.

And there again you have a situation where it could start segregating because the amount of powder is too less, the aggregates do not really have some highly viscous particles supporting them, so aggregates can start settling. But for flowability you still need a high water content in this case. But this means that you can still provide, you can still make SCC with such a low water content because of the design of the aggregate by particle packing approach.

Now in terms of the other powder ratios as you increase the water-powder ratio the slump flow increases and that is an obviously expected result, you do not expect that to be any different. Now the interesting part here is we were talking about fact that excess paste is there in system which makes the concrete flow. So what is the amount of excess paste that is required to achieve self-compatibility over and above the void volume.

So what is plotted here is the slump flow versus the paste volume in liters per cubic meter. So here you get a fairly linear relationship that describes the slump flow is a function of paste volume. What is this telling you? As you increase the amount of paste keeping the aggregates constant you are expecting a greater and greater increase in the slump flow.

So how much extra paste do you want in the system to make the system flowable over and above what is already there, in terms of voids.

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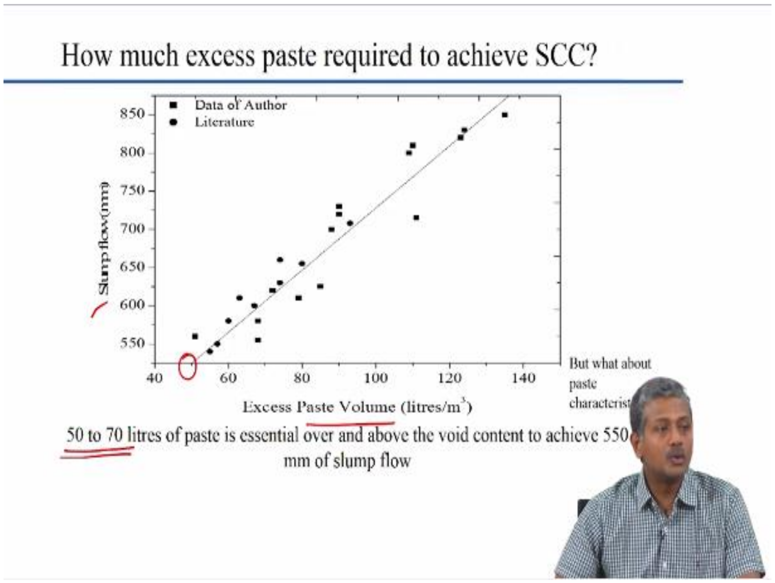

So for that what you need to do is look at data that was not only published from this research but also compare it from data from literature looking at the mix designs and trying to figure out what is the total paste content and what slump flow did that lead to. So here slump flow is plotted against the excess paste volume. What do you mean by excess paste volume? It is the volume of paste over and above the void content left behind by the aggregate.

So here you get a very good relationship and it intercepts the x-axis at around 50, that means you need at least 50 litres extra of paste to really have a slump flow which is above 500 mm. So usually most self-compacting concrete applications will see slump flow required will be above 500, 550 mm. So if you want to get that you need at least 50 to 70 liters of paste over and above the voids content to achieve that slump flow characteristics, .

So what this tells you is you can start off your concrete mixture design for SCC by doing an aggregate combination, determining the voids content and already your paste content is worked out as something that is at least 50 to 70 liters above the voids left behind by the aggregate combination.

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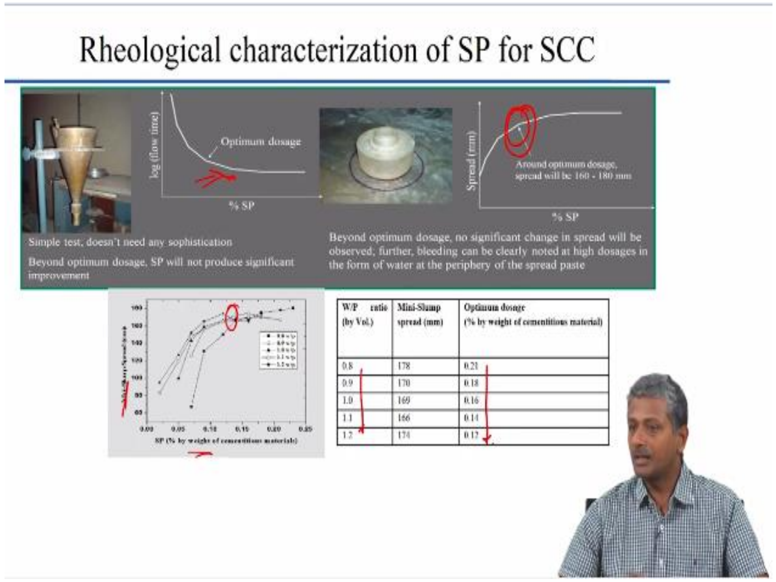

But the paste itself needs to be again optimized to give you the best performance and for that we talked about the fact that you can determine the optimum dosage of superplasticizer using marsh cone, right and then look at the spread of the cement paste using mini slump. So in this case what was done was the optimum dosage was not only picked out from the marsh cone test but we also wanted to pick it out as a point that led to about 160 to 180 millimeters spread in the paste.

Of course please remember the paste has 60-40 combination of cement fly ash of the volume, and then the water to cement ratio was based on strength, water to cement ratio is based on strength, . So the paste was prepared with different dosage of the SP and the dosage of SP that led to a spread of 160 and to 180 millimeters which was always to the right of the optimum dosage was taken as the dosage required to produce SCC.

This is again plotting the mini slump spread versus the superplasticizer content by weight and the 160 to 180 is being achieved at that level of dosage. So what we saw was the optimum dosage obviously was depended on water-powder ratio, as the water-powder ratio increased the optimum dosage required to get the mini slump spread in the correct range was reducing and that we expect anyway as the water increases you need less superplasticizer.

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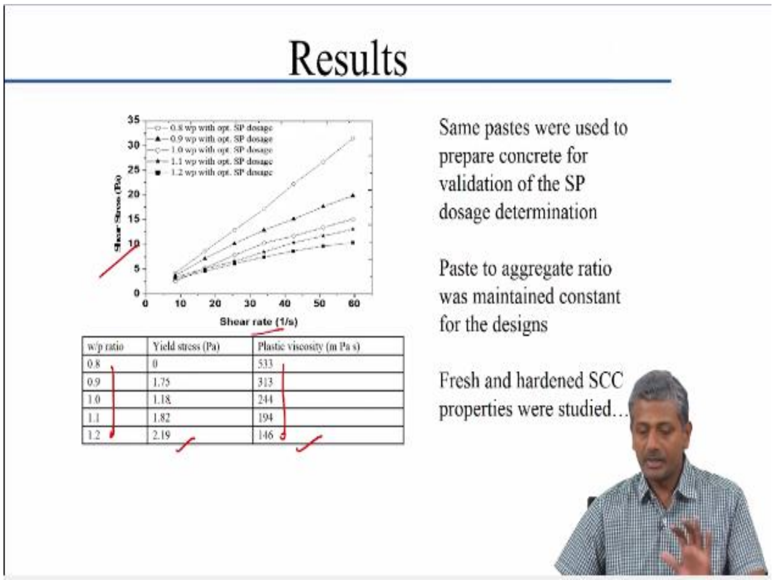

But we did not stop with that, we wanted to characterize rheological properties of this type of paste and for that we use the viscometer which is typically used for measurement of viscosity of asphalt.. So here again you have an outer cylinder just like we discussed with coaxial cylinder diameter and this is a inner cylinder which was made to rotate. The paste basically gets sheared between these 2 cylinders and registers a torque in the instrument.

The torque versus RPM was plotted and then you get the shear stress versus shear rate relationships. Now when you test fluids what you need to do is, if there has been a previous mixing history for example, you would have prepared the paste by mixing it in a asphalt mixture. So that previous mixing history has to be erased before you do these flows experiment by doing some specific shearing profile. You do a pre-shearing that means you mix it first for some time and then you give 30seconds for it to stabilize.

And then you keep on increasing the speed and then decrease the speed and when you increase or decrease the speed you start measuring the torque, . So again we will not get into the specifics of how this measurement is done. Essentially you produce this graph between shear stress and shear rate and this graph gives you obviously values of yield stress and plastic viscosity like we saw earlier.

If you are approximating this to a Bingham model you can plot the linear relationships and get an estimate of the Yield stress and Plastic viscosity. As the water-powder ratio increases what happens to your plastic viscosity? It starts decreasing, . Now interestingly, your shear stress is not really very much it is between 0 and 2Pa, so it is almost like close to 0. For self-compactable paste your yield stress should be almost 0. So what we did, was based on this optimal choice of the paste we determine the Fresh and hardened properties of SCC.

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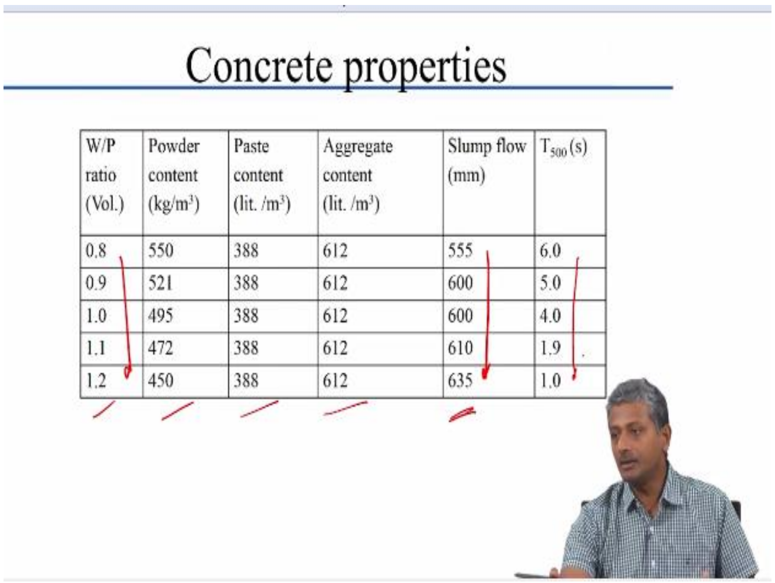

W/P ratio (Vol.)	Powder content (kg/m³)	Paste content (lit. /m³)	Aggregate content (lit. /m³)	Slump flow (mm)	T_{500} (s)
0.8	550	388	612	555	6.0
0.9	521	388	612	600	5.0
1.0	495	388	612	600	4.0
1.1	472	388	612	610	1.9
1.2	450	388	612	635	1.0

So this is just giving a snapshot. Different water-powder ratios, different powder contents, paste content was kept in the same level, the aggregate combination is kept at the same level and based on this we obtained slump flow between 550 and 650. And as you can rightly estimate the slump flow increase as you increase the water-powder ratio that is quiet expected. The T500, time taken to spread 500 millimetres reduced as you increase the water-powder ratio. Again, you expect that more water will start spreading much faster. Less water will be more viscous.