Admixtures And Special Concretes

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Lecture -62

Special concretes - Self-Compacting Concrete - Design principles, mix designs, concrete properties

Design of SCC combining (i) Particle packing and (ii) Rheology

(Based on PhD thesis of Dr. Prakash Nanthagopalan, 2009)

Okay, so now let us come to this example of the work that was done at IITM where SCC was designed by a combination of particle packing and rheology. So, ultimately those two things we need to address right, we talked about the fact that in any high-performance concrete if you maximize the aggregate fraction you minimize the void content right? What you have to do then is based on the void content decide on the amount of paste that you need to put in to get you the required workability and the paste itself needs to be designed with an optimal rheological characteristic to have the maximum flow possible. So, that was the strategy adopted here by Dr. Prakash who did his PhD here in 2009, of course, currently he is at IIT Bombay.

Steps in design:

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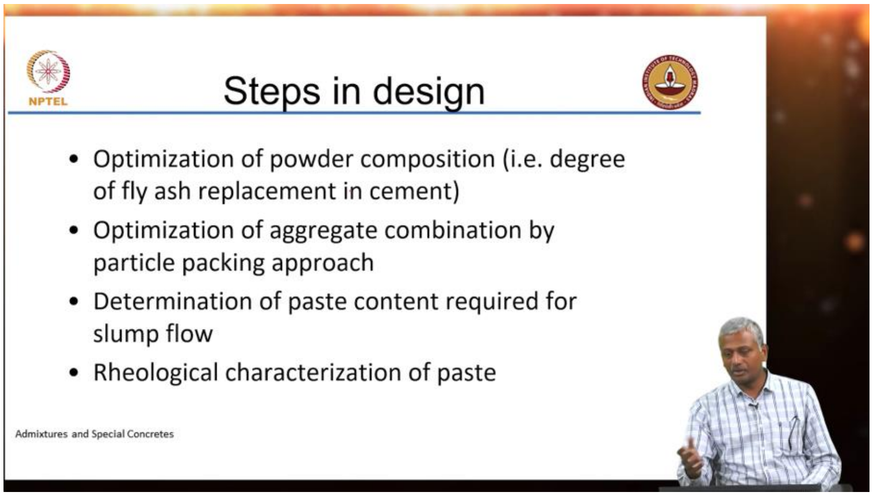

The steps in the design which were followed one was optimization of the composition of the powder.

So here fly ash was getting utilized in the SCC but we needed to find a way to rationalize the utilization of fly ash. You can always do all kinds of trial and error, you say that I will replace 10%, 20%, 30%, 40%, where do you stop is the question right? So can we find a way of rationalizing the amount of mineral admixture that was the first strategy adopted. Second you have a combination of aggregates, coarse, medium, and fine, how can we look at a way to optimize the aggregate fractions so that we have best filling possible.

Then once you have that optimization of the aggregate, how much paste is required to produce the required workability? In this case, it is SCC required, slump flow is what the paste is. And then finally how do you choose a paste that is capable of providing the best properties? All of these things were looked at as steps in the design process.

Optimization of powder composition:

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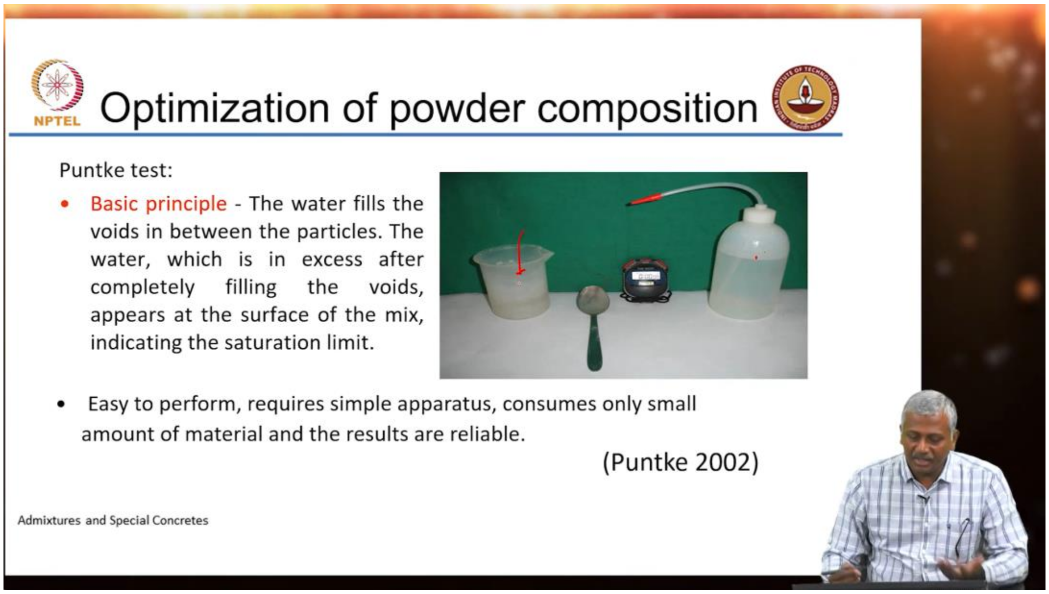

So in the optimization of powder composition a simple test called the Puntke test, it is German test was applied.

So here the name sounds complicated because it is German but the test is very simple, it is almost like a Jugaad test you can say. So, you have a container into which you fill up your combination of cement and mineral admixture. You fill up the combination of cement and mineral admixture and you know that it is not going to have perfect solid characteristics, there will be some space between the particles. What you are doing is filling up water into this mixture, using a dropper you are filling up water into this beaker which has a mixture of cement and fly ash. Then the water is filling up all the space between the particles and then whatever extra water you fill up will be excess, it will come onto the surface and provide a surface sheen.

So, it is almost like you are saturated but surface dry condition. That is what you want to determine, you want to saturate all the pores between the cement and fly ash particles but you do not want to have any excess water on the surface. So, what does that do? That determines the porosity in the combinations of cement and fly ash. So, here instead of going to a concrete and saying I will substitute 10, 20, 30, 40%, I am quickly doing this test in a matter of few minutes with cement paste. I am just adding water into the mixture of cement and fly ash and seeing at one point the water is completely filling the pores and showing up on the surface like a fine sheen on the surface.

It is very easy to perform and you do not really need any sophistication in the apparatus.

Puntke Test procedure:

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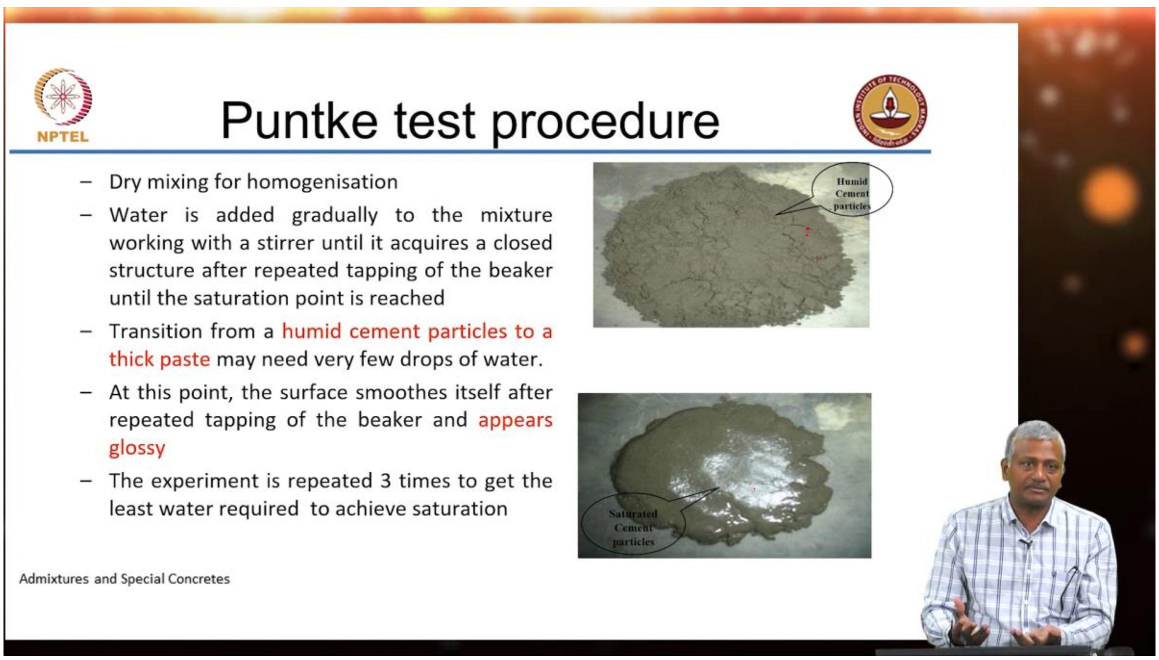

This test has to be done extremely early. I will talk about the fact that you can use other liquids also in the same test. Water may have early reactions with cement which may affect the quality of the test. So, you can test it with other liquids also that are equally capable of doing this.

So, this is a mixture of humid cement particles, cement and fly ash combination and this is a mixture at the point of time where all pores have been filled and just the surface one small sheen is showing up on the surface. There is a glossy appearance at that point of time you say that that is the water content which is equivalent to the amount of water that is required to fill up all the voids in this combination. Now the best combination again we are assuming is one which gives you least voids fraction. So, you mix cement and fly ash in different combinations.

Results of Puntke test:

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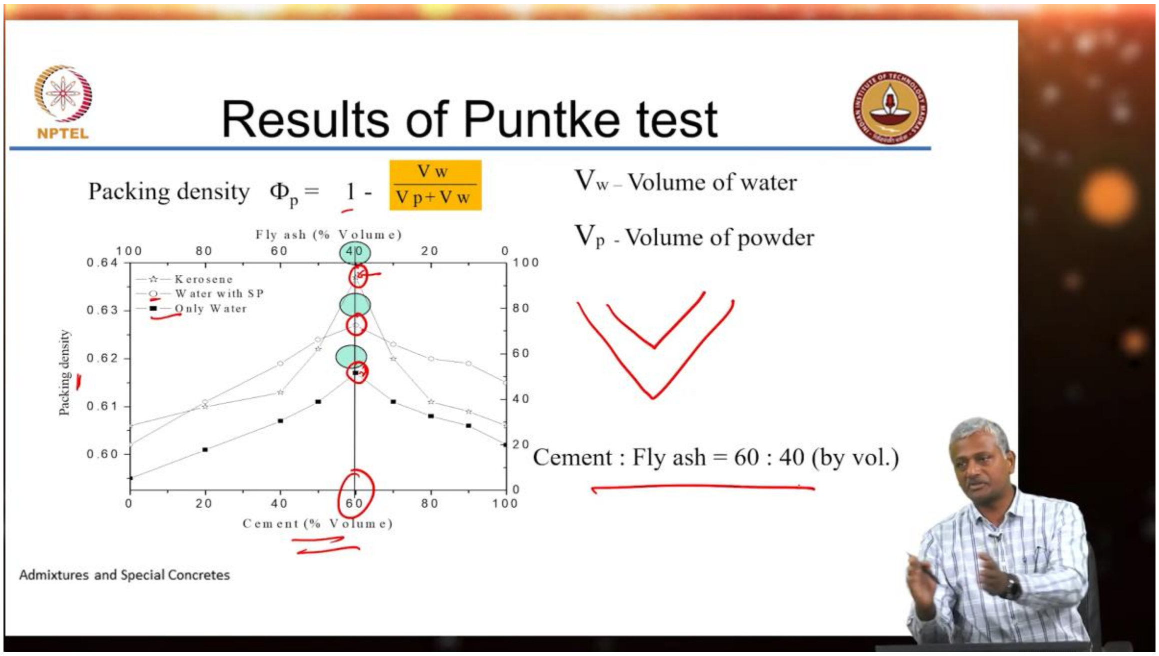

So, here cement percentage by volume is plotted against the packing density.

Packing density is nothing but 1 minus voids content. 1 minus voids content is packing density. You can also plot the same thing in terms of void content in which case you will get graph like this. So here these tests were conducted, I am sorry these circles are misplaced, this should have been on top here and here and here. So as the cement percentage increases the fly ash percentage decreases.

So, combination has to be 100 percent. So, here this first one is only water. Water with superplasticizer gets slightly better packing density, water with superplasticizer, and instead of water if you use kerosene you get slightly higher packing density but what you have to notice all of it is happening at the same volume fraction of cement. All these 3 different liquids are giving you the same volume fraction of cement at which you are obtaining the maximum packing density. So that means this test is robust, it is able to give you a very quick answer, matter of minutes you get an answer.

So, based on this the cement-to-fly ash ratio was fixed at 60 to 40 for designing the self-compacting concrete. The next step was to look at the aggregate skeleton. So, instead of using this EMA or the particle packing software, we decided that we will go with optimization of paste or rather optimization of powder, optimization of aggregate then rheology of paste and rheology of concrete. So, that is what I will show you.

Development of Ternary Packing Diagram (TPD) of Aggregates:

Test setup:

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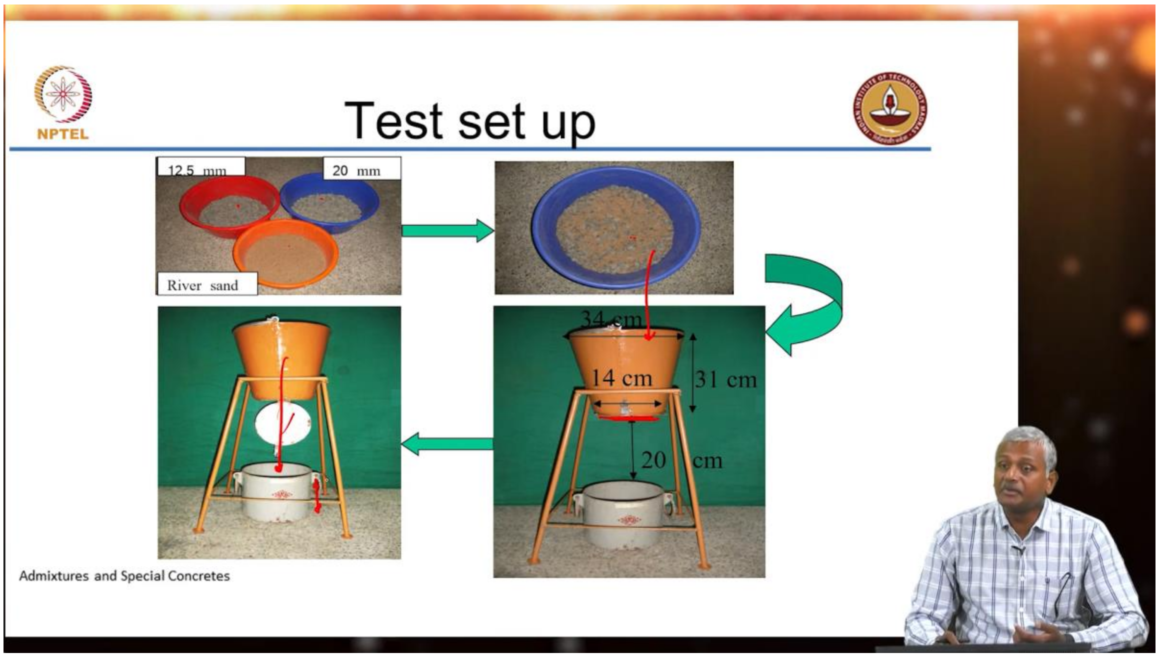

The next one was for aggregate how can we develop a ternary packing diagram.

So, first of all empirically you can determine the extent of voids in aggregate. You mix the aggregate in different fractions, you fill it up in a container and determine the total mass that you fill up in the container. Then you fill-up the theoretically what should be the mass based on the proportions that you adopted because you know the theoretical specific gravity of each of these phases but the fact that there should be some compaction effort in this entire system is brought about by the use of this apparatus which is a simple modification of an ASTM test, a simple test. All you do is you take up different fractions of your 3 types of aggregate that is sand 10mm and 20mm aggregate, mix it in different proportions. Let us say 50, 20, 30, 45, 35, 20 something like that, different proportions.

This is all mixed aggregate. You pour the mixed aggregate into this top bucket. You pour this mixed aggregate in the top bucket. It has a trap door at the bottom. You open the trap door, the aggregate basically falls into the cylinder. So, that is representing some level of compaction effort.

You have done the compacting factor test, same concept here. In the compacting factor test, you have 2 drops. Here you have only a single drop. So that just simulates some sort of compaction. Then you measure the void content in the aggregate fraction that you get inside this container.

So, for different proportions of your 20mm, 10mm and sand you will get different void fractions. You choose the one which gives you lowest void fraction. The problem is how many tests can you do like this? Can you automate this process?

Packing Density Calculation:

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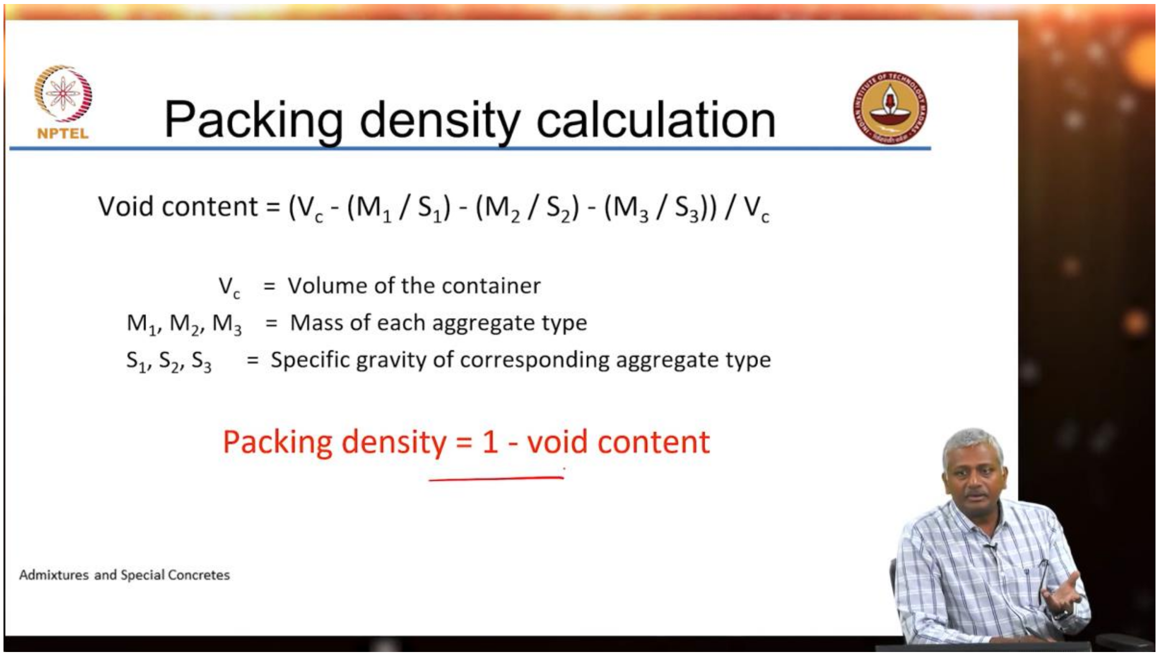

So, in this case, what we did of course as I said you need to determine the void content using this packing density once again as 1 minus void content. So, you need to minimize the void content. So, choose the aggregate combination that gives you minimum void content.

But you only have a limited range of experimental choices that you can do.

Ternary Packing Diagram (TPD)

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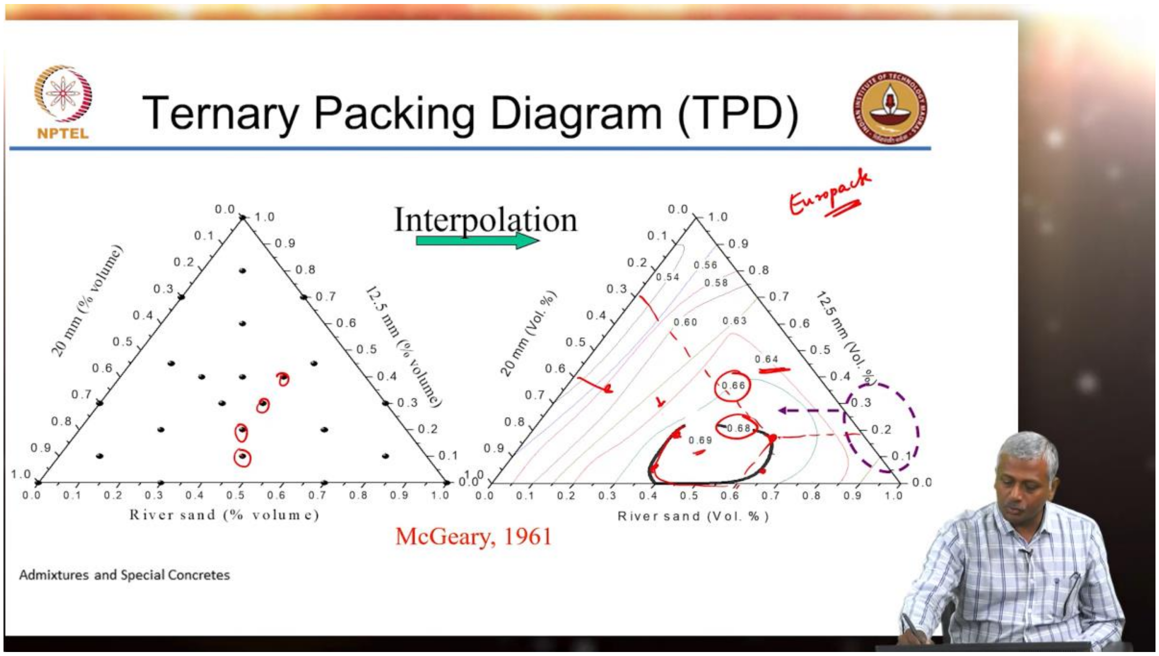

So, in this case, what was done to ensure that we had a complete understanding of this process is to look at a sort of a, I mean getting minimum experimental data and then optimizing based on a mathematical package to try and get what should be the packing density for different combinations. So here they were, essentially a ternary packing diagram was created by choosing different points which represent different combinations. And based on the mathematical package the packing densities that were obtained for all these points was converted into the packing density contours. So, these are contours for packing density that means along this line the packing density is 0.64 along this red line, along this blue line or whatever I cannot see the color 0.66 is the packing density, along this dark black line 0.68 and there is one particular point where the packing density is 0.69. So, the packing density contours can be generated by doing this kind of work and in the chapter on high-strength concrete I described this commercial package called Europack.

That does the same thing with just a calculation, there is no experiments there, only calculations, only a software that will help you determine the best packing density. So, using this we arrive at combinations that can give you highest packing density. But now you see that the combinations could be anywhere right? 0.68 packing density, 0.69 was only one point which was, so we can discard that.

Let us say 0.68 is the maximum packing density we can get, but there are so many different combinations. At this point if you have to get the combination, how do you get that? You have to go basically towards each of the sides. So 60, 30 or 60, 55, 10 like that or sorry 55, 30, 10 or 55, 30, 15 like that, there are several combinations. What we also understand about the basic nature of self-compacting concrete is that we want to have a combination that has a higher fine aggregate content than normal concrete. So, we can then restrict the choices of our combinations to those which have a fine aggregate content of around 40 to 60%.

From all these choices, from all these points we only choose those points which will have fine aggregate content of at least close to 50% for SCC. So that is what was done in this case.

Applicability of TPD

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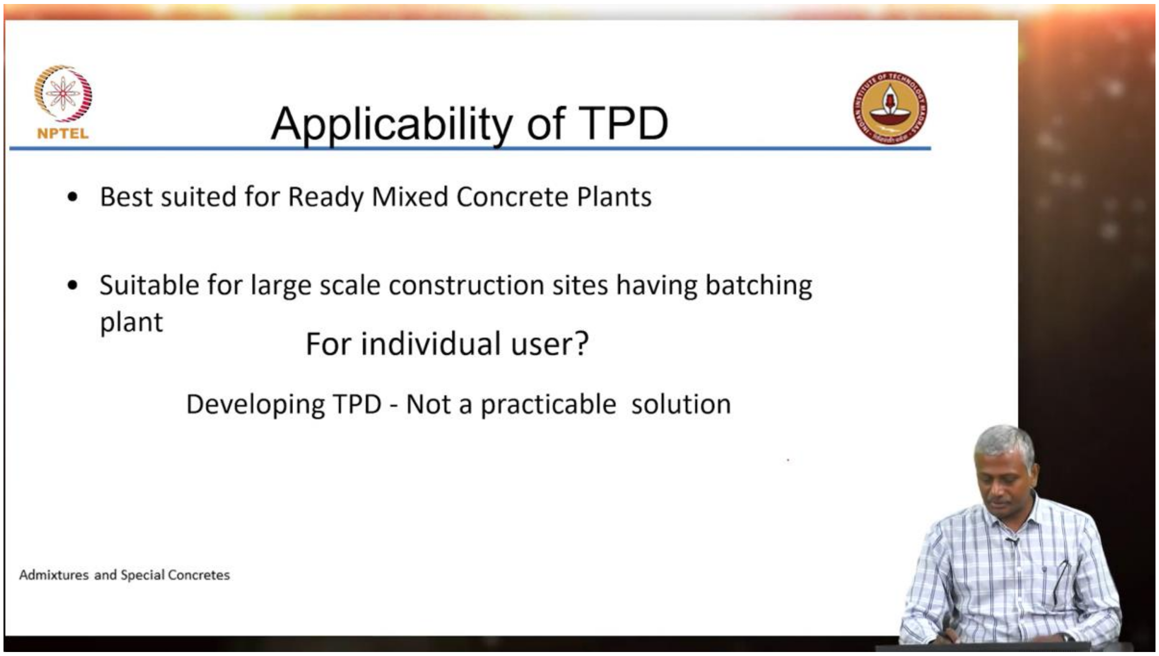

I will come to that later, but ternary packing diagram is good for RMC plants where they are getting aggregates from the same source again and again and again. So they can actually have that database generated and then keep that for a long time for different concrete mixes. Now for an individual user, let us say tomorrow you need to go to the lab and start working.

What do you do? You cannot obviously generate the ternary packing diagram, getting 24 data points to generate the contour plots will be very tough. So, if you want to go directly in, is there a solution for this? So, we wanted to again look at what aggregate characteristics are suitable for better packing.

How to determine the packing density of aggregates?

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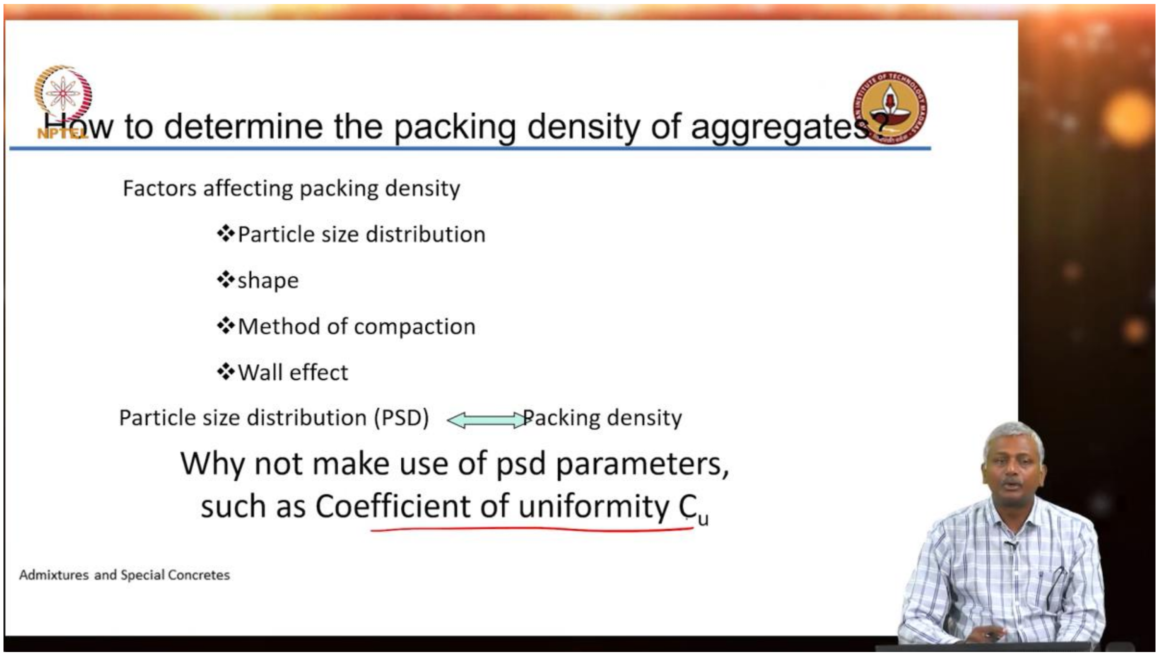

So, in this case based on the factors that affect packing density including particle size distribution, shape of the aggregate, compaction method and taking into consideration wall effects, it was seen that one of the parameters that has a primary influence on packing is the particle size distribution. So, how is particle size distribution curve represented? You have a cumulative percentage finer versus the particle size and if you remember your PSD (particle size distribution) calculations, you will describe various coefficients, coefficient of uniformity, coefficient of curvature and so on and so forth. So, here we chose to use one of these PSD parameters, coefficient of uniformity C_u.

Why Coefficient of Uniformity, C_u?

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So, again what you do here, coefficient of uniformity is basically your D60 by D10.

$$Coefficient\ of\ uniformity\ C_u = D_{60}/D_{10}$$

D_{60} = 60% of the particle finer than this size

D_{10} = 10% of the particle finer than this size

It gives you a spread in the particle sizes basically. The particles finer than 60%, so 60% of particle finer than size and 10% finer than the size. So, now what we are trying to say is let us adopt a simple parameter that is expressed by your particle size distribution. So now you have done individual sieve analysis for your sand 10mm, 20mm, put it in excel, do calculations of different combinations of these materials and then calculate the coefficient of uniformity.

The assumption here is the higher the coefficient of uniformity, the more the range of particles between in the system. The more the range of particles, let us go back to our particle packing understanding, there will be a greater extent of packing.

Mapping PSD to the packing density of aggregates:

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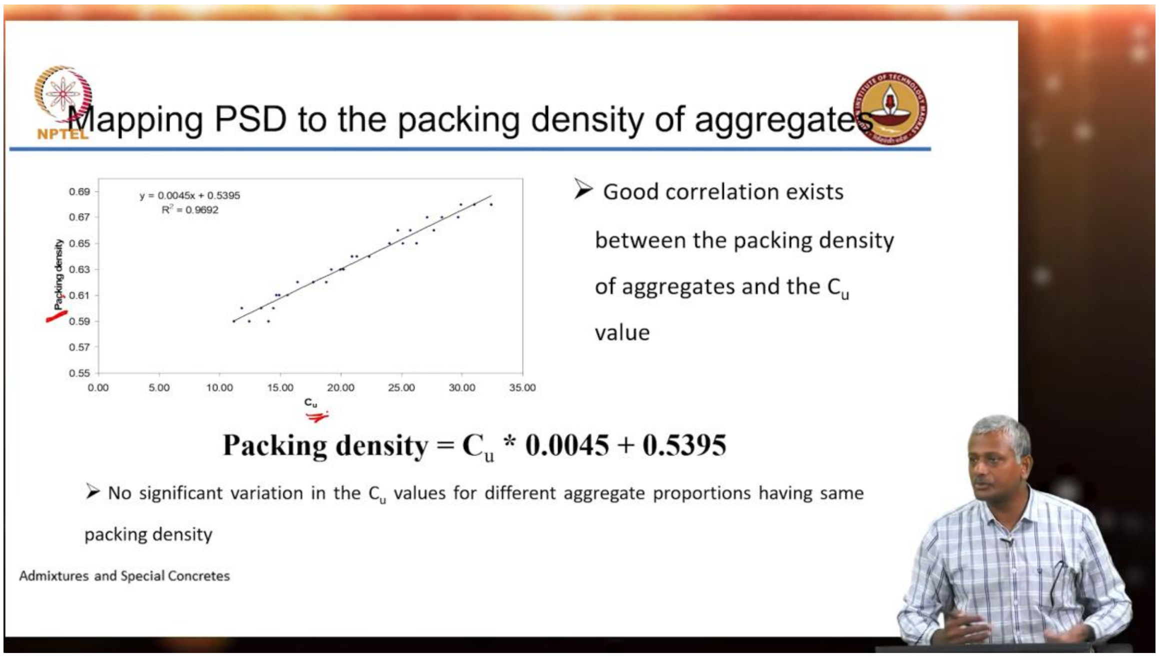

So, that is what the idea we were trying to look at, calculating packing density based on coefficient of uniformity and we got a fairly good correlation to describe for the aggregate that we have what could be the best possible. So, of course this was determined experimentally packing density, coefficient of uniformity can be determined by looking at just a calculation based on different proportions of sand 20mm and 10mm. So, this is a simpler way for a person who is starting immediately to start designing SCC.

But if you have a RMC plant where you are getting a uniform source of aggregate, you can then generate those ternary packing diagrams with multiple sets of data.

Influence of packing density of aggregates on properties of SCC

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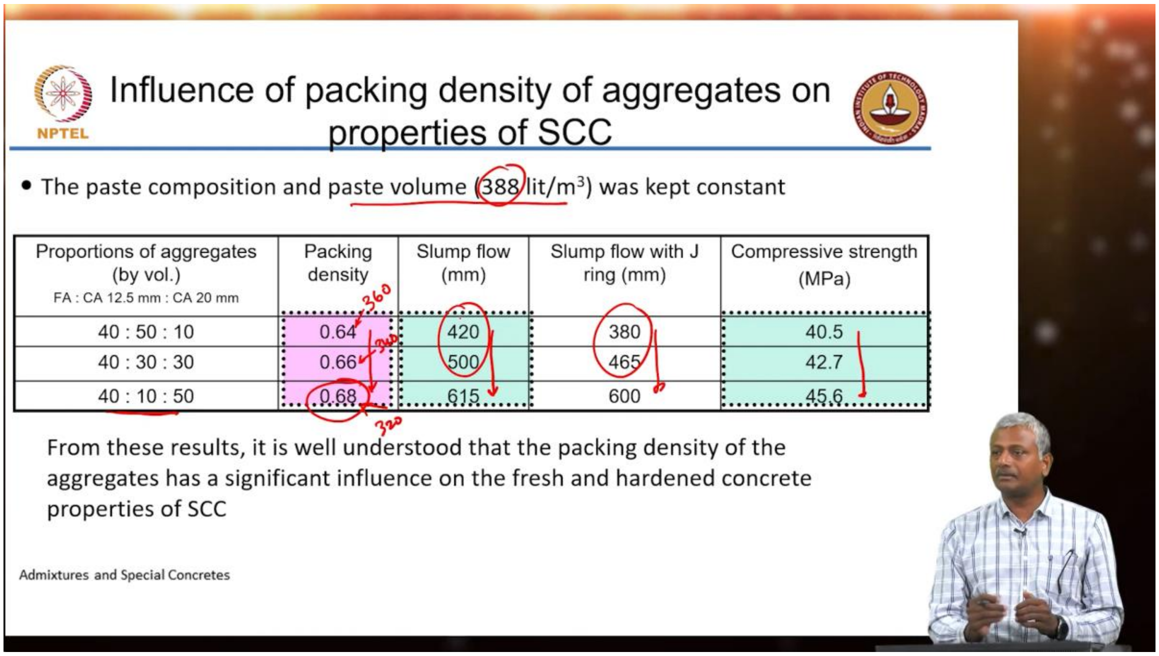

What is next? Once we know the packing density, let us say here 0.68 was achieved with 40% of fine aggregate, 10% of 12.5mm aggregate and 50% of 20mm aggregate. That was the combination that led to a good packing density of 0.68. First job was to ascertain whether our assumption is correct. Whether at higher packing density you optimize the properties or not. So look at this case here, there were 3 different combinations chosen. The packing density increases from 0.64 to 0.68.

The slump flow increases from 420 to 500. The paste volume was kept constant. 388 litres per cubic metre of paste was used and the remaining 612 litres per cubic metre because there is 1000 litres in 1 cubic metre, remaining 612 was the aggregate combination. So here slump flow is increased, slump flow with J-ring also is increased as the packing density increases.

The compressive strength also increases. Now compressive strength you are all aware of definitely, it should go up with more packing density because you have less voids. But what about slump flow with J-ring, why are they increasing? See I have 388 litres of paste. Here how much voids do I have? If I take 1 cubic metre I have 360 litres void, 0.36 void content, 360 litres of void is there.

Here 340, here 320. So, what is happening? In the first case, I have only 28 litres extra paste available, in the second case I have 48 litres extra paste available, in the third case I have 68 litres extra paste available, more paste, more flowability. So, this also means that now a good step to the design process is to estimate this excess paste that I require to cause the concrete to become self-compactible. These two are not proper, these two are not enough for me. I need to get to a level which is at least 600 to achieve self-compactibility. So here I am determining the excess paste that is required to get self-compactibility.

So that is also another approach that we can take. So, one thing we confirmed here is that increase in packing density leads to an increase in flowability, leads to an increase in strength.

Influence of different proportions of aggregate having same packing density (0.68) on the properties of SCC

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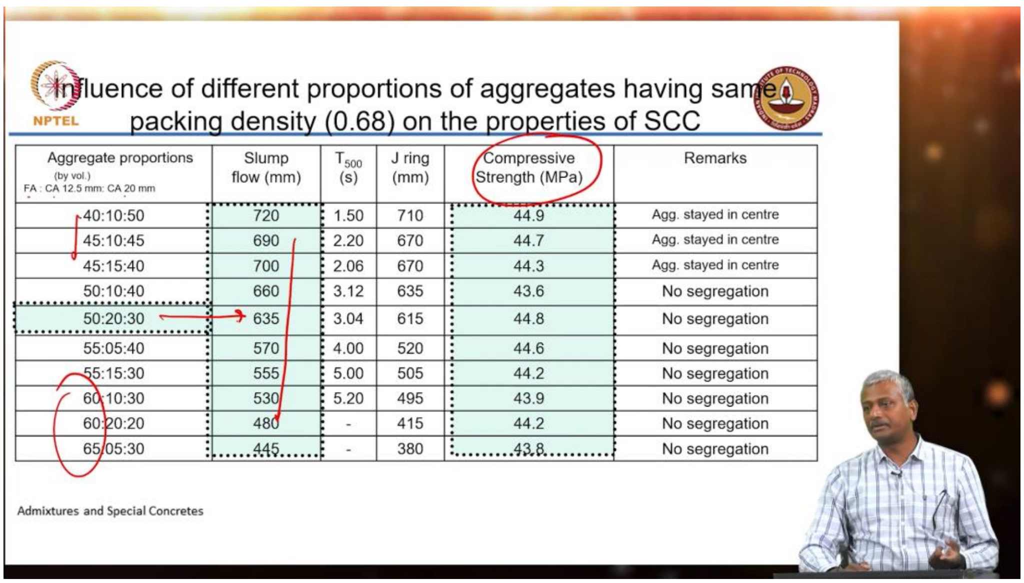

Now this exercise is what happens when you have the same packing density but you have different combinations. So, you have different combinations of fine aggregate to coarse aggregate 12.5 to coarse aggregate 20. But as I said self-compactibility you need to have a fine aggregate content at least of 40%. So we chose only those combinations where the fine aggregate was 40 or above. So first let us look at the strength. Same packing density, the assumption is should have the same strength. Are we getting that? Yes, more or less all the things are within about 1 MPa of each other.

So definitely for the same packing density irrespective of my aggregate combination, I am getting the same strength. But what is happening to the slump flow? It is undergoing a drop when I go for very high levels of fine aggregate in my combination. So, I need to optimize the aggregate combination to a level where fine aggregates are enough to lead to a good slump flow characteristic. So here for instance we decided that for further tests we will go with this 50-20-30 ratio.

50% fine aggregate, 20% 12.5 and 30% 20 mm coarse aggregate. So again up short is at the same packing density irrespective of aggregate combination you will get similar strength. But your workability will depend on the combinations. So, you have to be careful about. So again, if you remember I talked about the same thing when we discussed particle packing also.

By choosing different Q values you are increasing packing density but you still have to look at how to provide the workability and that is where your choice of superplasticizer rheology of the concrete become very important.

Effect of w/p and paste volume on SCC

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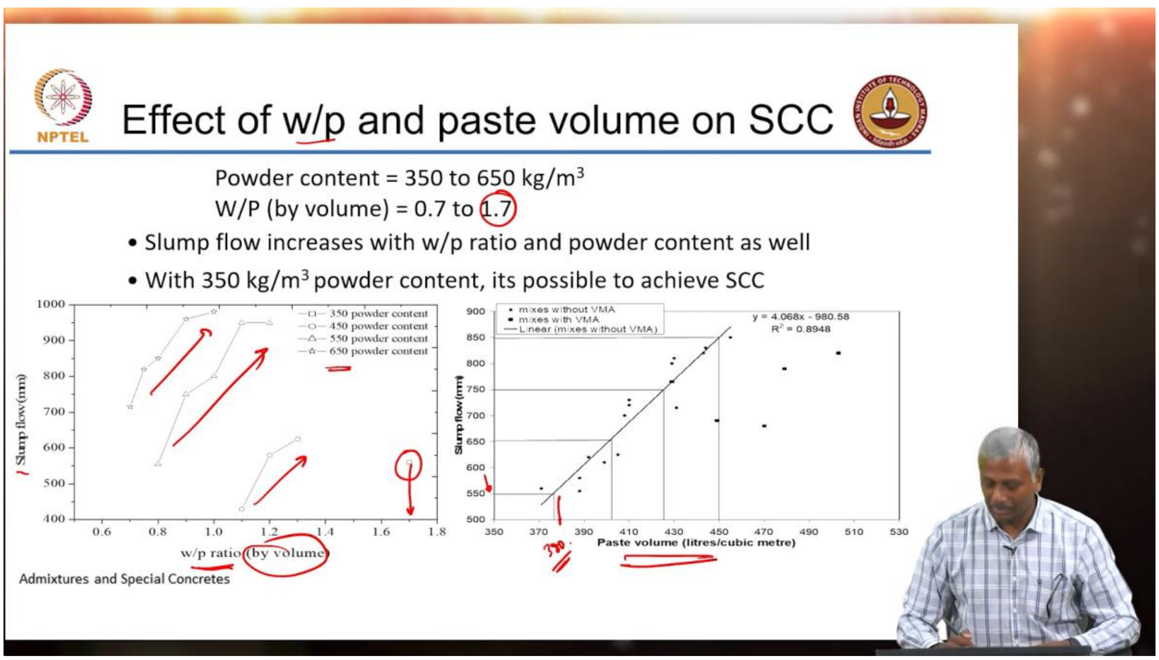

Now again here adopting that mix design we wanted to look at adopting the aggregate proportions of 50-20-30. Here this is just a simple exercise doing the effect of water-powder ratio and paste volume. So here slump flow is plotted against water to powder ratio.

Powder implying cement plus fly ash. Water to powder is water to binder same thing. Please note that this is plotted in terms of volume.

In terms of mass it will be around 0.35, 0.36 like that. What do you expect here obviously as the water-to-powder ratio increases your slump flow increases. What is also shown here is the slump flow increase for different powder contents, different binder content. Now interestingly we were also able to obtain self-compactable concrete with just 350 binder content and that is because of the adoption of the strategy of maximizing the particle packing of the aggregate. So even with 350 binder content we could get it but the water to powder ratio to be adopted was 1.7, lot of water in there. Danger of segregation is high. Danger of segregation is quite high.

Now this is what I was talking about excess paste. If you look at this slump flow versus paste volume- as the paste volume increases you are expecting a higher slump flow to happen. Now where is this 550 achieved at around 380 paste volume. So for an aggregate combination that gives you the best packing at a 320 litres void volume you need at least 60 litres of excess paste to achieve self-compactibility.

So that is a good starting point. Calculate void content, add 60 litres to it that could be the paste volume that you want. That is a good starting point for a mix design process. Instead of shooting in the dark mixing all kinds of concretes you can reduce the effort that you take towards approaching the design process.

How much excess paste required to achieve SCC?

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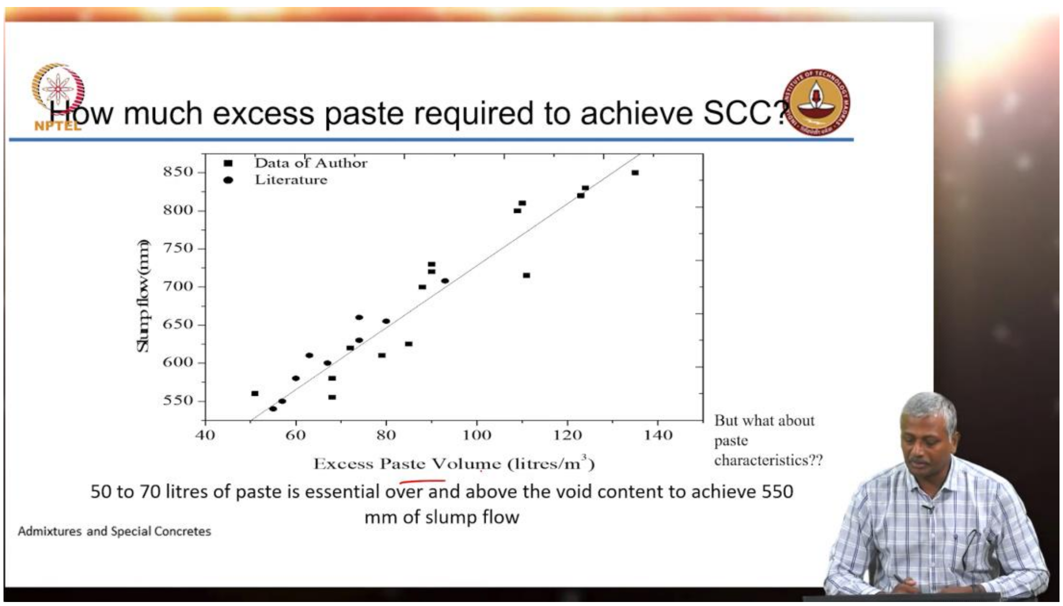

Again, this is the same thing excess paste volume is plotted by subtracting the void content from the paste volume. The same graph is repeated here and you get the excess paste volume here.

And paste characteristics, rheology you need to address separately by the test that we discussed earlier.

Rheological characterization of SP for SCC:

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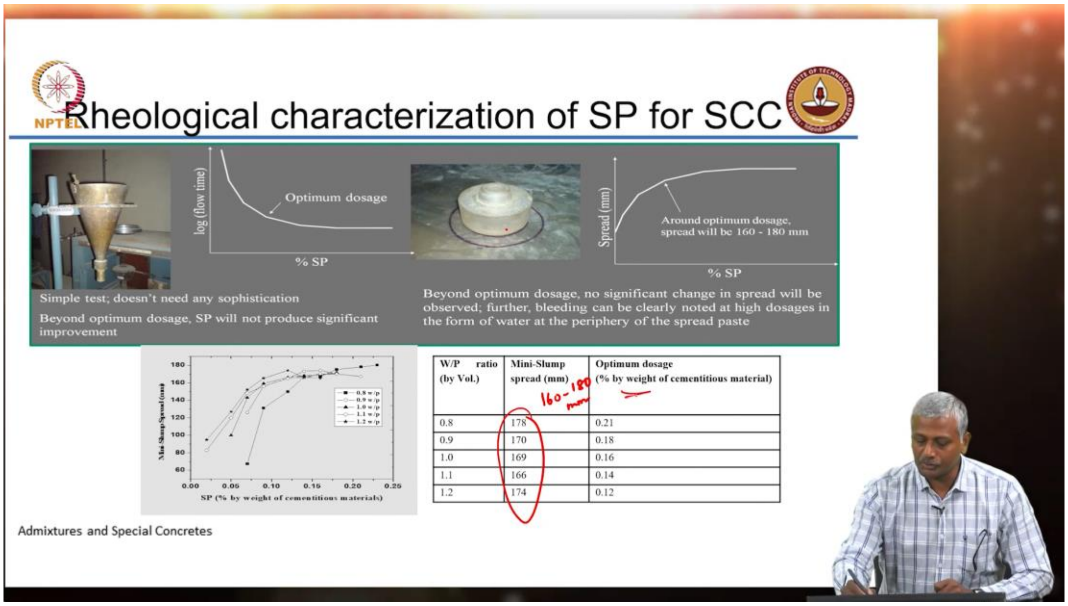

The marsh cone, mini-slump and even a rheometer. So here if you look at the water-powder ratio by volume 0.8 to 1.2 the mini slumps spread in this test. You see it is all in the range of 160 to 180 millimeters. So that is a desirable range for paste that is suitable to make self-compacting concrete. And optimal dosage here is determined by a combination of your marsh cone and mini slump test.

Rheological studies:

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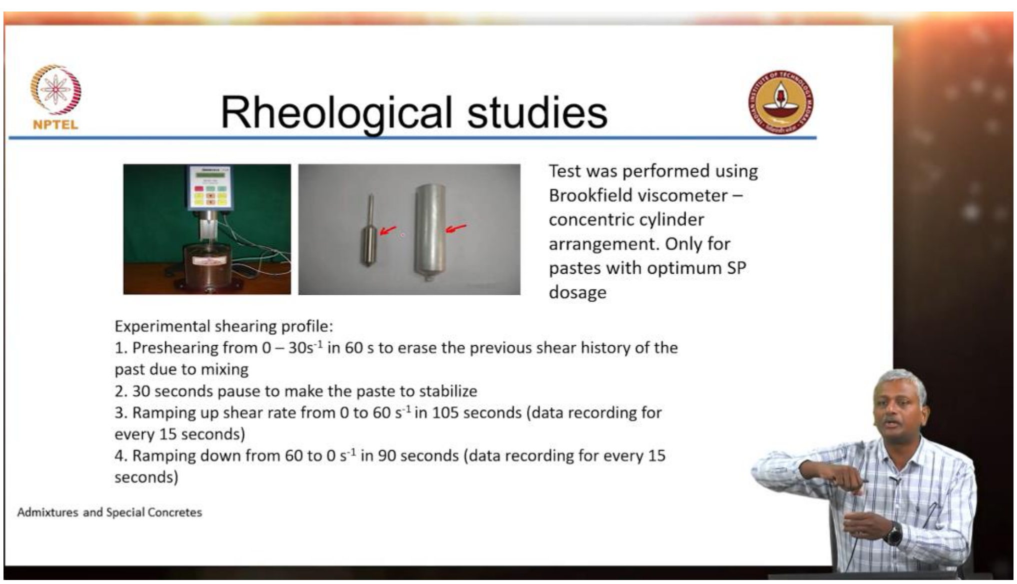

You can also do rheological studies. Of course, we have not covered the methodology of rheological studies earlier but we looked at some geometries of rheology.

This is the concentric cylinder geometry. You have the outer cylinder and the inner cylinder. The paste is filled into the outer cylinder and the inner cylinder basically is made to rotate and then you measure the torque versus the rotation speed.

Results:

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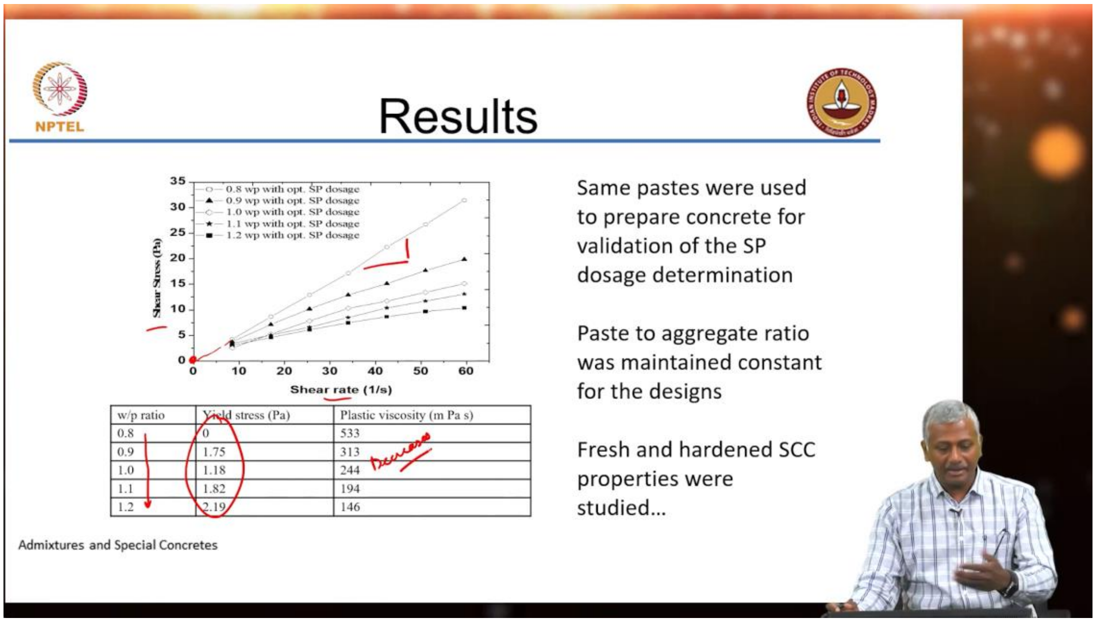

w/p ratio	Yield stress (Pa)	Plastic viscosity (m Pa s)
0.8	0	533
0.9	1.75	313
1.0	1.18	244
1.1	1.82	194
1.2	2.19	146

So, based on that you plot the shear stress versus shear rate and if you remember your Bringham parameter basically it is a linear relationship where it crosses the y axis is your yield stress and the slope of this is your plastic viscosity. Now these are all self-compactable concretes so yield stress as you can see is close to 0 within about 2 pascals very small negligible yield stress. But plastic viscosity as the water-powder ratio is increasing the plastic viscosity decreases.

More water less viscosity in your system. So, the strategy of design of SCC encompasses several characteristics understanding the powder combination, understanding the aggregate combination that gives the least voids content, using that void content to determine how much excess paste volume is required to get self-compactibility and designing the paste with appropriate rheological characteristics. So that is the overall design.

Concrete properties:

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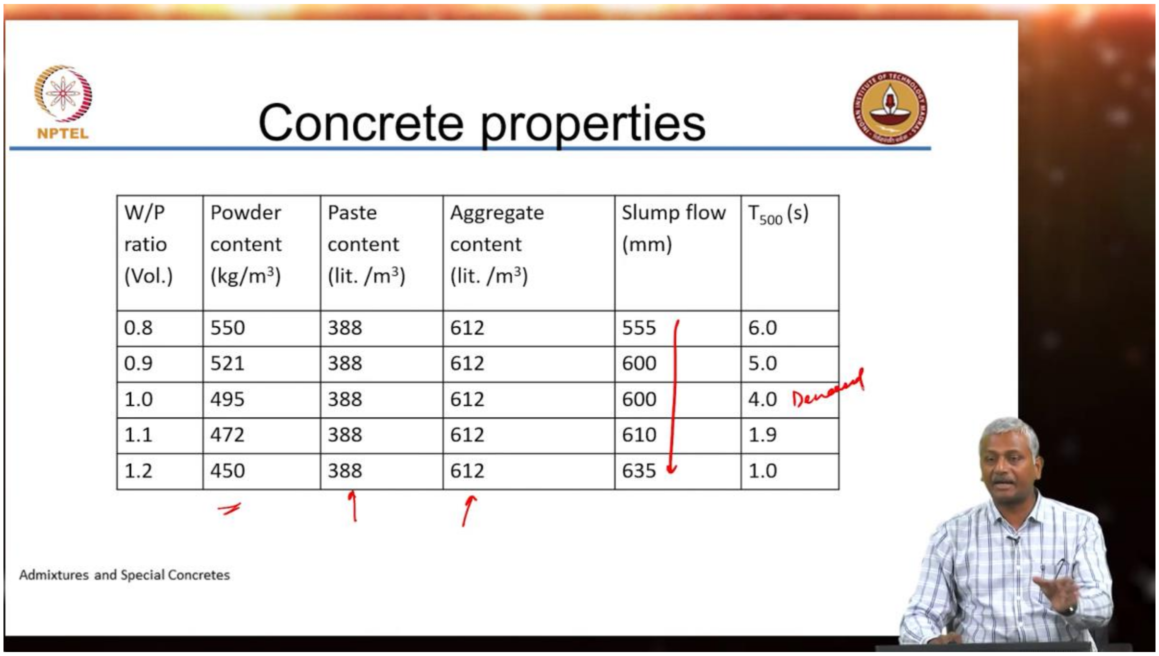

So, here this is just presenting you the concrete properties that were achieved with all of these water powder ratios and different binder contents. So paste content here and aggregate content were maintained constant for all of those water powder ratios and you can see again that as the water powder ratio increased the slump flow increased the T500 which is a measure of viscosity of the system it decreased.

As you can expect more water more slump flow less viscous mix. At the same paste an aggregate content. So with that we stop and we come to the end of this chapter.