Development and Applications of Special Concretes
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Lecture 21
Special Topics: Rheology

Hello and welcome back to another module in our discussion on development and applications of special concretes. In this module we will start the discussion with a special topic Rheology. That is something which we need to know as a matter of continuation from what we have been doing as far as self-compacting concrete is concerned. But as you will realize it is not only the self-compacting concrete.

But so many special concretes that we talk about need a special treatment or need the civil engineer or the concrete engineer to know at least some basic principles of the science of Rheology.

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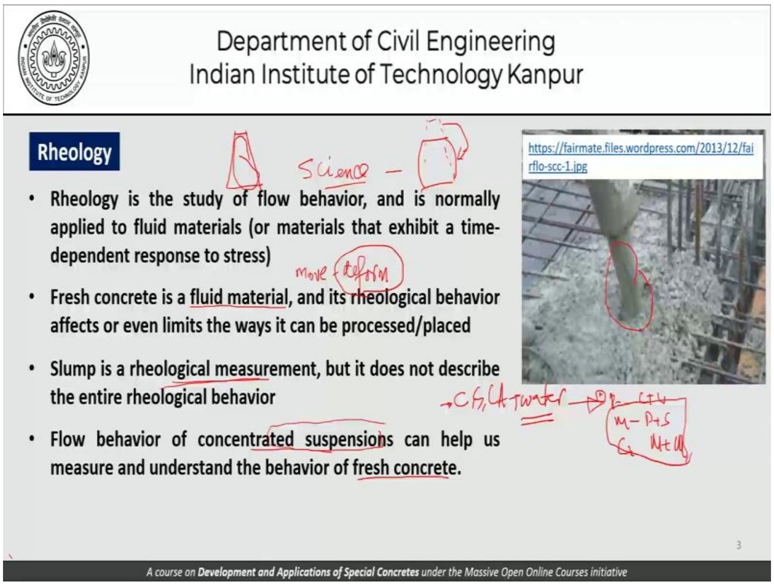

So what is Rheology? Rheology is the study of flow behaviour and is normally applied to fluid materials or materials that exhibit a time dependent response to stresses. Fresh concrete is a fluid material and its neurological behaviour affects or even limits the ways it can be processed or placed. When we say it is a fluid material of course something like roller compacted concrete would be difficult to visualize.

As a fluid other concretes whether they are self-compacting or not they do try to behave like fluids but even for the stiffer concretes we should understand that as we apply vibration to them. As we try to compact them we do expect the concretes to move and deform and this deformation is also a part of rheological studies. So that is what we need to understand a little bit about. Look at this picture here now whether this concrete is self-compacting or not it is being pumped it is flowing very much like a liquid.

And we need to understand the science of this flow in fact this lecture is targeted to go over some of the principles of the science that goes behind a lot of concrete engineering that we have been talking about. Even though, I have made a conscious effort to stick to engineering and applications for most of the discussion that we have done. This particular discussion today is focused on the science part of it what is the principles that govern the kind of behaviour that we have.

Slump is a rheological measurement but it does not describe the entire rheological behaviour. Recall how the slump is carried out we try to fill the concrete in this shape and then remove this cone. What happens is that the concrete that has been filled in this cone in this form acquires a shape which could be something like this. So there is surely some deformation from this shape to this shape and therefore to that extent it is a rheological measurement except that we do not use the kind of words which Rheologists would use.

And we do not associate words like viscosity yield stress and so on which are closely associated with rheological measurements as we will see today. Flow behaviour of concentrated suspensions can help us understand and measure the behaviour of fresh concrete. So this fresh concrete is not really a homogeneous material. It is a heterogeneous material it is actually a concentrate of particles that is what we have been talking about.

Fresh concrete is not a homogeneous material in that sense that it is not a single phase material it has water cement sand coarse aggregate some chemical admixtures thrown into it at times mineral admixtures thrown into it. So basically it is a suspension of different particles in water so instead of trying to look at concrete as a suspension of cement sand and coarse aggregate in water.

The kind of model that I have been proposing to you and I have been discussing it all the time is that we would rather split this discussion into stages and say that paste is a suspension of cement and water mortar is a suspension of paste and sand and concrete is a suspension of mortar and coarse aggregate. So this is the kind of step-wise changes that we have been talking about and therefore the idea basically is that if we want to study the properties of fresh concrete we want to impart certain properties in fresh concrete we can and we do begin with paste a study of what is going on at the paste phase.

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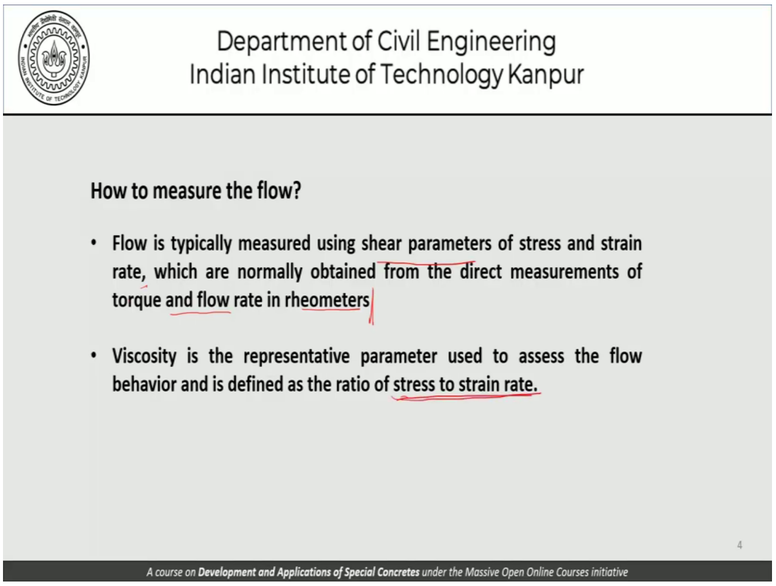

How to measure the flow the flow is typically measured using shear parameters of stress and strain rate which are normally obtained from the direct measurements of torque and flow rate in Rheometers. So, Rheometer is the device that we use commonly in this branch of science Rheology, Viscosity is the representative parameter used to assess the flow behaviour and is defined as the ratio of the stress to the strain rate.

So it is not the stress to strain but it is this ratio of stress to the strain rate that is how we are trying to define viscosity in the context of our discussion today.

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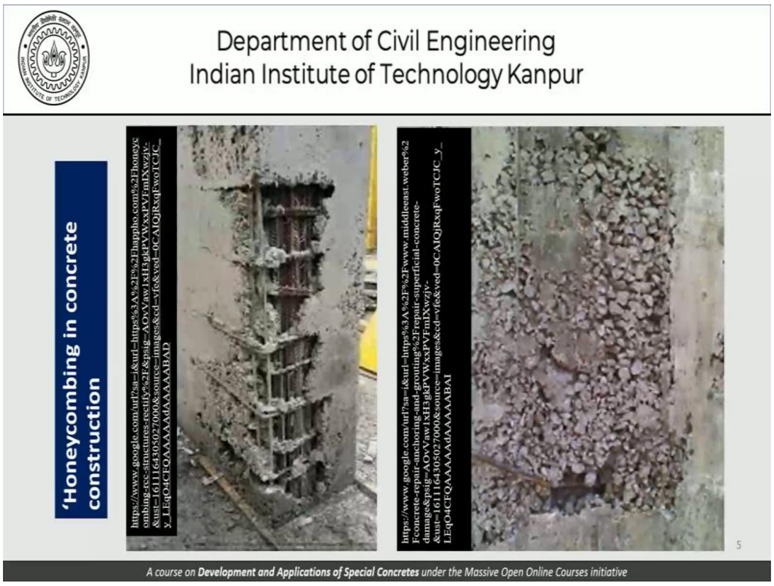

Look at these pictures once again this picture here is a clear case of concrete not having been able to flow into this part leading to honeycombing. In this case the situation is a little more complicated maybe the slurry has moved out. But this part here again concrete has not been able to move. So this idea that the concrete flows and deforms into a shape which is supposed to be defined by the formwork that is very critical.

And from an engineering point of view that is what we need but from the science point of view what causes the concrete to move into all these places here either on its own weight in which case it becomes self compacting concrete or on account of the application of vibration or during compaction of that concrete carrying out external work as far as that concrete is concerned.

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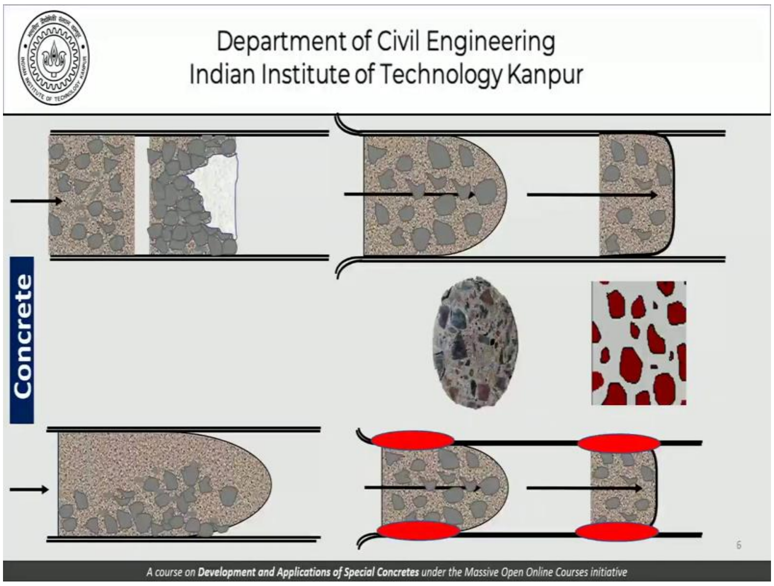

These pictures again show us and remind us that we are talking of concrete being a suspension of particles in water we can look at it in different phases. And this is our hardened concrete beyond a certain point concrete cannot be deformed, so easily it sets, gains the strength and so on. And this again is the real picture as far as concrete is concerned the rest of it is all models the kinds of things pictures that we drop to help us use scientific principles and write the kind of equations that we want to predict or better understand the behaviour here.

This picture is for segregation this is aggregate interlock this is for development of boundary layers where we may have some depositions of materials these are things which we have talked about in earlier lectures also.

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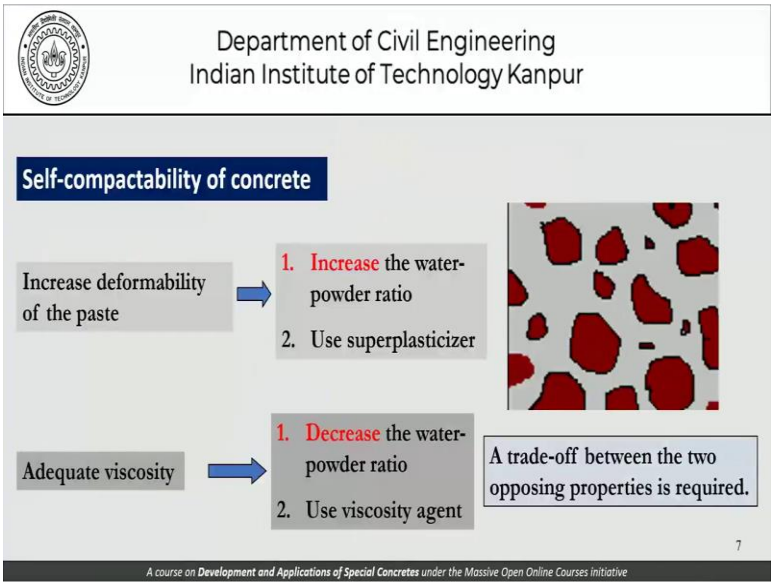

Now the self compactability part of it because that is relevant from even the rheological part. One thing that we need to do is on the one hand increase the water powder ratio that is increase the water reduce the powder that will give us increase in deformation or deformability. So we increase deformability because that is what we want from concrete but as far as viscosity is concerned we want to decrease the water powder ratio that is reduce the water and increase the powder.

So if there is a concentrate if there is a paste which has a lot of powder that is the solid component is very high then it will be viscous it will be difficult to deform. Whereas if it has less powder then it will be much easier to deform because that means this is more fluid this is less fluid if you want to use that word. This can be achieved using a plasticizer whereas this can be achieved using a viscosity agent.

So as far as a real life application is concerned we have been trying to talk about it all the time we want to trade off between these two diverging requirements.

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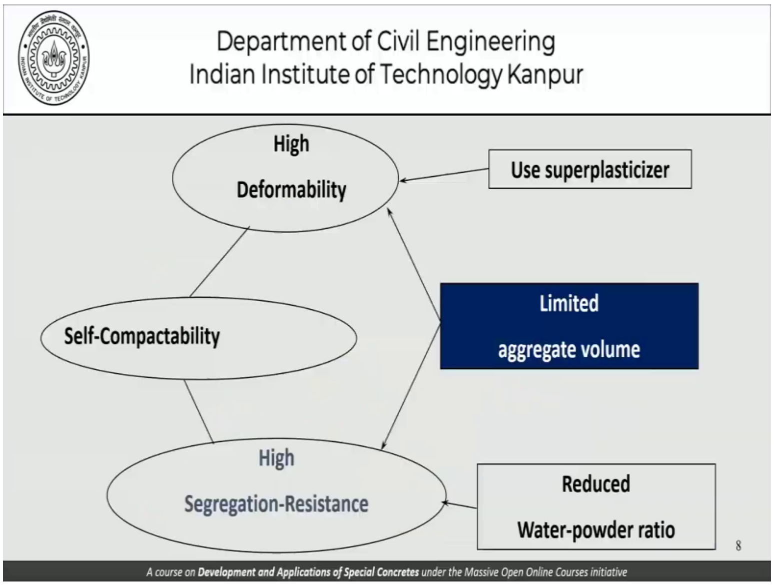

This is just another statement arising from there. When we use a plasticizer and when we use reduced water powder ratios all that happens is that we need to restrict our coarse aggregate volumes. So there is something which we have talked about as far as most of the concrete is concerned.

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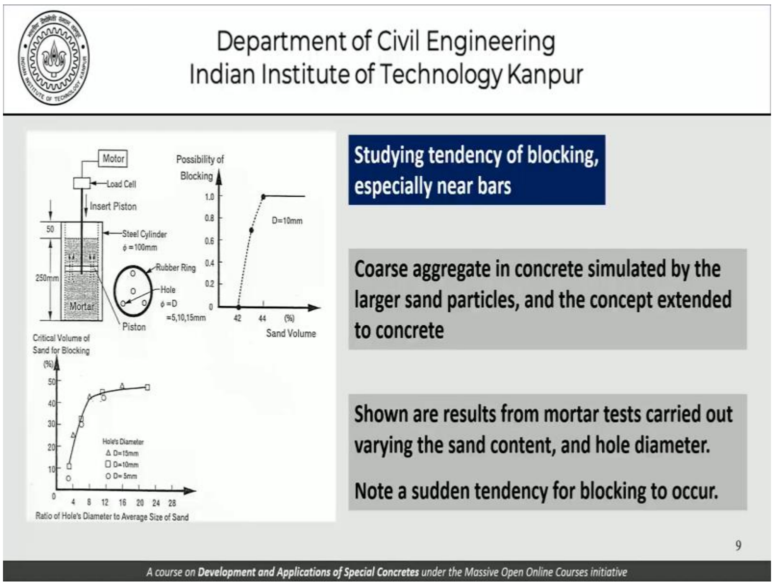

This is some experiments which were done to better understand the tendency of blocking especially near the reinforcing bars. Now these experiments need not be carried out using coarse aggregate themselves. We do not have to use at least the coarse aggregates of 20 mm. Because if we want to use 20 mm coarse aggregates there are issues relating to the size of the equipment and as you shall see the details involved therein. But if we are able to do some experiments the way they are listed here.

For example it says that coarse aggregates and concretes are simulated by larger sand particles and the concept then extended to concrete. So the larger sand particles could be any diameter so it is not necessarily now that we are sticking to a 4.75 mm kind of definition for sand. We could use some particles and say that ok this is how we are going to model it and move forward as far as our results are concerned.

Shown are the results from mortar tests carried out with varying sand content and hole diameters. Now what is the experiment the experiment is that we fill this part with water we have a cylindrical vessel fill it with mortar. And we have a piston which has certain holes 5 mm 10 mm and 15 mm diameter holes were made in different pistons there is a cylinder of 100 mm diameter. So in 100 mm diameter we are trying to drive this piston into a mortar and this piston has holes of 5, 10 or 15 mm.

This mortar has sand the particle size of which the gradation of which the volume of which can be changed. Now what will happen if this was a pure cement paste we do not have any sand then even if we push a piston with a 5 millimeter diameter hole the piston will go down and through these holes the paste will continue to ooze out. Whereas if this particle size becomes much larger then it will not ooze out it will not flow out.

So what this graph for example represents is the possibility of blocking versus the sand volume for a 10 millimeter diameter hole. So if we can see that so long as the sand volume does not exceed about 40% or 42% there is virtually no chance of blocking it at a 10 millimeter diameter hole with let us say 4.75 millimeter kind of a sand. So long as this 4.75 millimeter sand does not exceed 42% by volume of the mortar.

But if it becomes more than 44% there is almost 100% chance of blocking. So we are working in this narrow band as far as this experiment is concerned that if we use 4.75 mm aggregate which is basically the sand that we use in the mortar. We cannot use more than 44% sand if we want the mortar to freely move through an opening of 10 millimeter diameter size. Of course the results will be different if we want to increase it to 15 millimeters.

Yes, the possibility is that this 44 might become 46 or 48 or even 50. If you go to 5 millimeters maybe this 42 will come down to 35, 37 and whatever it happens. Now what does this picture tell us what are the axes? Ratio of the holes diameter to the average size of sand, the diameter of the hole to the particle size of sand and what is on the y-axis the critical volume for sand for blocking the critical volume of sand for blocking.

Now if we talk of this ratio and we take the diameter to be 10 mm the particle size is 1 mm for example then this ratio would be 10. So when we are talking of a ratio of 10 here we are talking of a 10 millimeter hole with a 1 millimeter size of particles. As the particle size increases we will move this way and if the particle size reduces we will move this way. So now what this picture tells us is that for the different holes diameters that is t is equal to 15 mm 10 mm and 5 mm.

In all these cases the critical volume of sand for blocking varies something like this. What it tells us is that if we are working at a ratio of 8 to 10 as far as this whole diameter to the particle size diameter is concerned we are always working in the range of about 40 to 45 50% or is the critical volume of sand for blocking. And this critical volume goes down if this ratio comes below this. So this is a very critical finding that we have that we should not go below a ratio of let us say 8 to 10.

But now this here is an experiment which was carried out using a piston with holes like this and varying the size of the sand in this and the percentage of sand in the mortar. Where do we take these findings as far as concrete is concerned? As far as concrete is concerned the relevance of this discussion is when we have two reinforcing bars we want the concrete to flow through it and then what is the spacing between these? What is the maximum size of aggregate that we have?

When we look at the ratio of these two and try to look at it and we look at it in the backdrop of some of these experimental results that explains to us the provisions that we have in our codes which tell us that the maximum size of aggregate and the spacing between the bars should be related. We should maintain a certain minimum spacing depending on what is the maximum size of aggregate that we are using in our concrete.

So having done all this in this slide now having discussed one set of experiments in the previous slide let us discuss another set of experiments.

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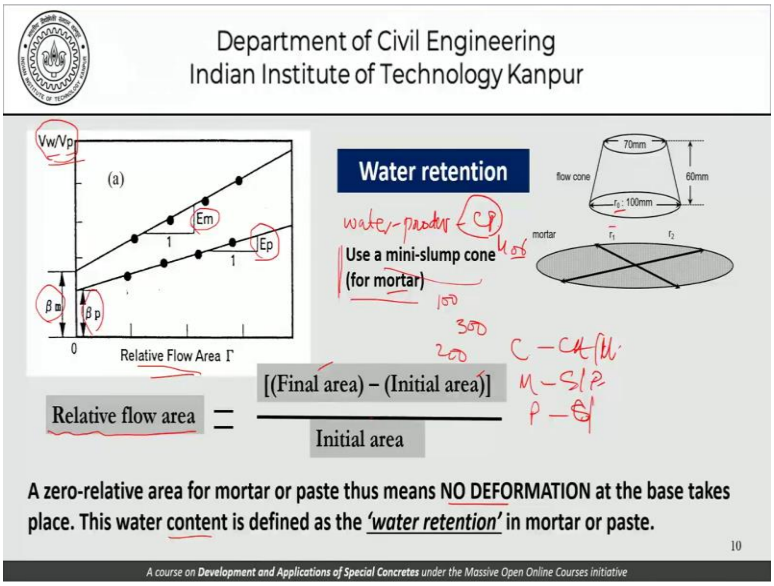

Now this is carried out using a mini slump cone. We know a slump cone for concrete has a diameter of 100 mm at the top 200 mm at the bottom and has a height of 300 mm. Now this mini slump or the mini slump cone which is used for mortar that measure 70, 100, 60 as shown here. Please note that these r values are actually the diameters that are being shown so what happens is that we try to take different pastes and mortars for different water to powder ratios.

So we vary the water to powder ratio and try to use either the paste part the cement paste as we will call it or the mortar and try to do a mini slump test and try to measure the final area. Now the final area here is the spread of the mortar that is achieved after you take the mini slump cone off. So this r1 and r2 we take a mean of that and so on initial area is anyway known to us given the fact that the initial diameter is 100 mm.

We can find out what is being defined as the relative flow area. Now the relative flow area is being defined as final area - initial area upon the initial area. And this becomes a measure of the flow. Now this amount of flow that we have this relative area if it is plotted against the water to powder ratio what the experiments tell us is that this is the line that it follows as far as the paste is concerned and this is the line that it follows as far as mortar is concerned. And we have this βp and βm values which are nothing but what is being defined as water retentions.

Now this is zero relative flow area that is here for mortar and paste effectively means no deformation at the base takes place that is initial area the final area the same relative flow area will be zero. This water content is defined as the water retention in paste or mortar because beyond that point as we increase the water powder ratio the increase in the flow area is linear. So this is another simple experiment which tells us how we can try to better understand the characteristics of our powders.

And how the; water powder ratio with that material would change the flowability of the mortar or the paste having done that we are better equipped to predict the flow ability of the concrete. Now these two experiments are an insight into what engineers do to understand the flow behaviour of concrete. Now we have insisted that concrete can be looked upon as a suspension of coarse aggregated mortar and mortar can be looked upon as a suspension of sand and paste and paste itself can be looked upon as a suspension of cement and similar particles in water.

So going backwards from here we try to understand the properties of concrete. The importance of doing these tests is twofold. One is that the effort involved is a lot less because we can work with smaller samples we can work with the mini slump cone. For example we do not use so much of material and it also makes it easier for us to carry out the experiments. We can carry out more experiments in a given period of time and so on.

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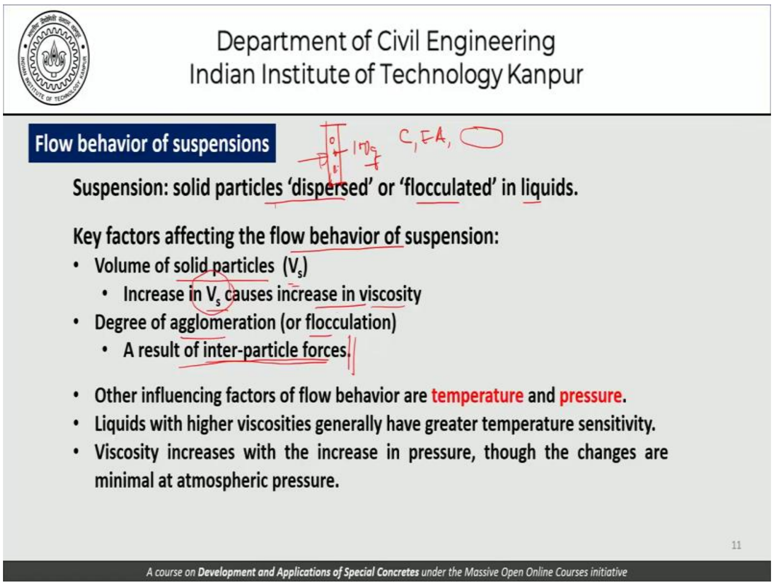

Now with this background we go back and visit our fundamentals once again. A suspension is solid particles dispersed or flocculated in liquids this is exactly what cement paste is in fact you will recall that I had suggested to you an experiment where you take about a litre of water in a measuring cylinder suspend some or mix some 100 grams of cement into it. Do not bother about the water cement ratio we are only trying to see how a suspension of cement particles in water behaves.

You can try to do that experiment now with this understanding that we have with cement fly ash and any other fine material that you want to use and try to study the characteristics of this suspension in terms of its flowability or whatever it is depending on how much of the solids you add to it. The key factors affecting the flow behaviour of suspensions is the volume of solid particles V_s added increase in the V_s causes an increase in the viscosity.

So as we increase the solid volume in this kind of a suspension we can expect an increase in viscosity and a degree of agglomeration or flocculation this is a result of inter particle forces. If you carry out these experiments you will realize that there is a certain amount of flocculation that happens as far as cement is concerned and that is what changes the behaviour of the suspension for a given amount of cement that is being put into it.

So other influencing factors of flow behaviour are temperature and pressure. Liquids with higher viscosities generally have higher temperature sensitivity.

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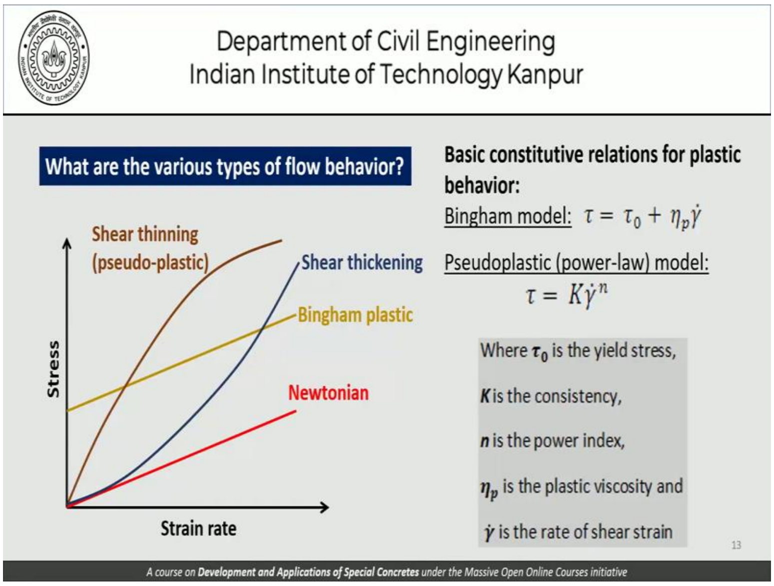

Now having seen some of the very simple engineering experiments relating to the flocculation relating to the behaviour or the study of deformation in fresh paste and fresh mortar let us try to get started with some real simple understanding of Rheology. Now as far as Rheology is concerned we are concerned with the behaviour of fluids under stress. So what we do is we study the behaviour of stress relating to strain rate.

Now as far as this behaviour is concerned we have Newtonian fluids for which the strain rate and stress is linearly related as shown here and we have Bingham plastic fluids for which the relationship is linear but with an offset. Then there are more complicated models like shear thinning or shear thickening but we would largely be concentrating our discussion on these linear models that is Newtonian fluids and Bingham plastic fluids.

As far as the basic constitutive relationships for plastic behaviour is concerned the Bingham model tells us that τ which is the shear stress this is τ here is equal to τ_0 which is given here plus η_p *γ dot. Now γ dot is the shear strain rate that we are talking about. What this line tells us is that this is the Bingham plastic model with τ_0 equal to 0, this is τ_0 not equal to 0.

So that is a finite τ_0 and this η_p is in a manner of speaking the slope of this line. If you look at what these values are τ_0 is the yield stress this is the yield stress that is this is the amount of stress that is minimum required or the required minimum stress to initiate some kind of strain rates. So the strain rates beyond this point will go linearly but this will be after this stress level of τ_0, n is a power index which we use more in the pseudo plastic kind of model where τ is given as k times γ dot to the power of n.

Eta p is the plastic viscosity which is here this is the plastic viscosity that we are talking about and γ dot is the rate of shear strain. So these are the kind of discussions that we have as far as flow behaviour is concerned. So what we have to do as concrete engineers or civil engineers or trying to understand the behaviour of concrete as a fluid. We have to try to figure out what is the behaviour of stress versus strain rate when we are talking of cement paste, when we are talking of mortar and when we are talking of concrete, and on what factors does this behaviour depend on.

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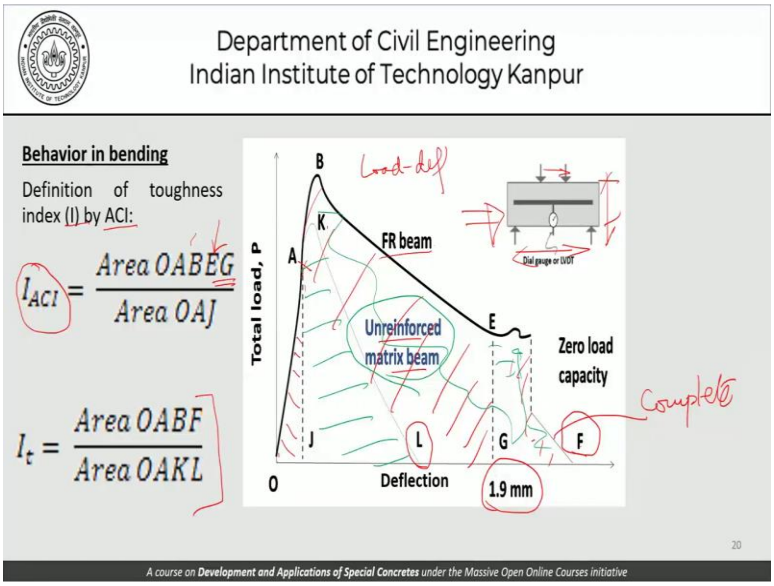

Now as far as the flow behaviour of suspensions is concerned and recalls that we have been always talking in terms of concrete being modelled as a suspension of coarse aggregate in mortar, mortar being modelled as a suspension of sand in paste and paste being a suspension of cement in water. Of course now in this context are having done all these kind of discussions with self compacting concrete and the different materials and so on.

It is not only ordinary Portland cement that we talk about here but cement like materials. So the cementitious part of it which contributes to the hydration and so on is one part and the powder part of cement that is cement plus mineral admixture plus any other material which is fines and fines you recall we have a definition of 0.125 mm and finer all these fines would contribute to the paste as far as the workability characteristics or as far as the deformation characteristics are concerned.

So there are two types of suspensions that we talk about one is flocculated suspensions and there we talk in terms of flocculation of colloidal particles that is particles less than one micron in diameter that could result in aggregation or gel formation internal forces are weak and the stress at which a breakdown of flocculated network occurs is called the yield stress. So this is the tau not that we talked about in the previous picture.

When it comes to dispersed suspensions as against flocculated suspensions they usually show Newtonian behaviour at low solids concentration and at high solids concentration they show considerable yield stress and exhibit plastic behaviour due to crowding of particles. Now what has to be seen is when we talk in terms of cement paste is it a low solid concentration suspension or a high solid concentration suspension.

Obviously you would recall that I had told you about an experiment that if I take a litre of water that is about say 1000 ml of water. And we put some cement in this say 100 grams or 10 grams this would kind of qualify as a low solid concentration and that is what we try to vary in fact when we talk in terms of the volume of water to volume of powder ratio. So if we get into this domain or in this discussion we will be able to move forward but let us try to stick to this experiment.

And I told you to look at this suspension of about 10 or 50 or 100 grams of cement watch it settle down. Now that will tell you that this suspension of cement in water is a low solid concentration suspension and the behaviour of this kind of a suspension would be largely Newtonian that is tau not will be pretty close to zero. But if we keep on adding more and more cement to this measuring cylinder the paste would become more and more thick.

And as the paste becomes thicker it is intuitively clear that the deformation behaviour will change considerably and we would have the onset of getting some kind of a tau not values when it comes to a shear stress versus the shear strain rate studies which are typically done using Rheometers as we shall see later on. So this is plastic behaviour due to crowding of particles so that is something which we need to keep at the back of our mind from a scientific perspective from the point of view of Rheology. There are no inter particle forces in this case.

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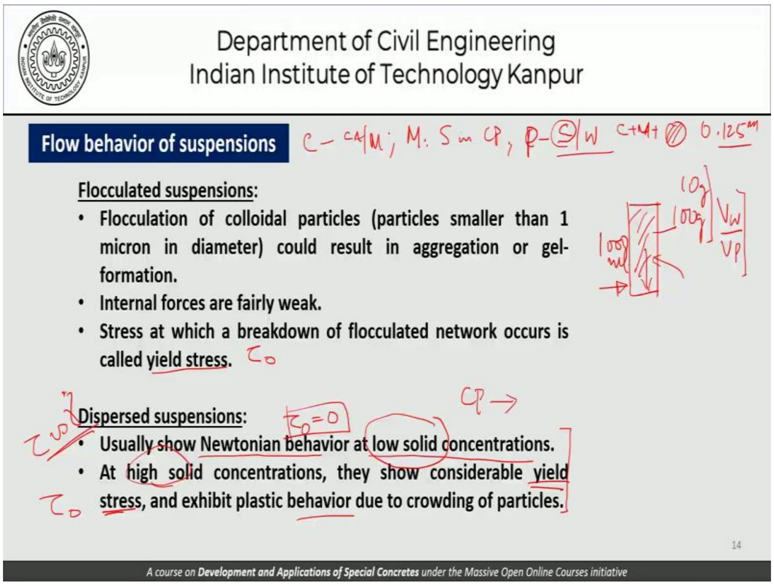

Now coming to the behaviour of cement paste in general cement paste behave as non-Newtonian dispersed systems and factors affecting the behaviour could be physical, chemical or other things. Physical factors would be something like the water cement ratio the cement grain shape and size where the water cement ratio really governs the volume of water to the volume of powder. In this case we are used to calling it water cement ratio.

But as far as Rheology is concerned we had better start talking in terms of volume of water to volume of powder kind of thing because here we are talking in terms of volume ratios whereas here we talk in terms of mass ratio. So there is a density term involved so we should be careful when converting one from the other. Chemical factors would include things like the chemical composition of cement and its structural modification due to hydration.

Now this part when it comes to hydration is an issue which is time dependence that is if we want to study the stress versus strain rate equations as a function of time then we will have structural modifications due to hydration. So we may have a certain slope in the beginning some other slope in the subsequent time domains. Mixing and measurement conditions of course it will depend on some of these conditions as well.

So as far as cement paste is concerned its non-Newtonian dispersed systems and can be studied in the framework of Rheology if we keep these things in mind.

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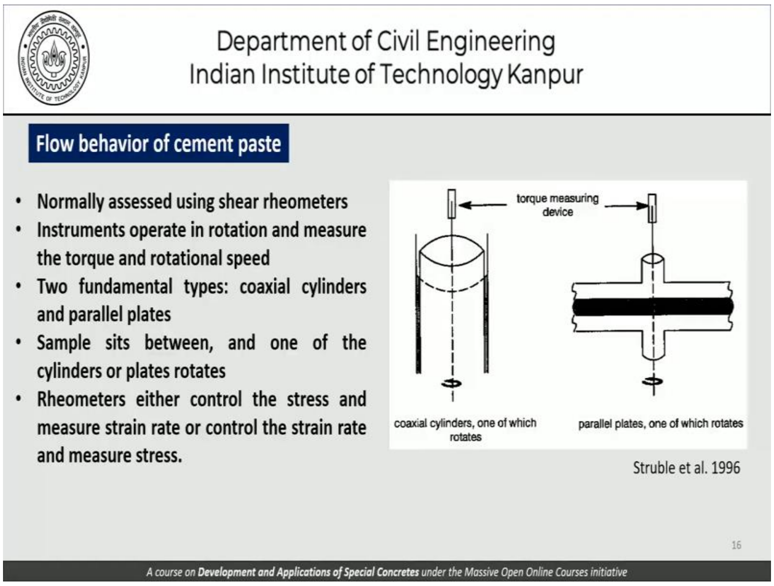

Now coming to the kind of measurements that are actually carried out we use shear Rheometers. Now what these shear Rheometers are typically is what is described here the instruments operate in rotation and measure the torque and rotational speed. And there are two fundamental types the coaxial cylinder types and the parallel plate type the sample sits in between these two plates and one of the cylinders of the plates rotates.

As is shown here there is a cylinder here this is a coaxial cylinder type and this is a parallel plate type of a Rheometer and the inner cylinder here and the outer cylinder here this space here is where the paste in our case or the sample in a more generic sense will be placed. Similarly here we will have a stationary plate and we will have a moving plate and in between the plates we put in the sample that is the cement paste that we have.

The sample sits in between the cylinders or the plates the Rheometers are run either on the basis of controlling the stress and measuring the strain or controlling the strain and measuring the stress. So it is very much similar to having the UTM's where we have displacement control and load control. So in this case also we can either control the stress and measure the strain rate or control the strain rate and measure the stress.

It is important to understand or kind of think about what should be the size of these Rheometers what should be the opening or the spacing between these two plates. In this context please remember that these instruments and this whole thought process and theory was not developed with cement paste in mind. It was developed for other fluids or suspensions with very fine particles.

What we want to do is to study the Rheology for cement paste where we still have fine particles in the water that is fine. But when it comes to mortar we have particles up to about 4.75 mm that is what sand is and sand is a part of the mortar. When it comes to concrete then we are talking of particles could be even 20 to 25 mm. Now this kind of apparatus can be used the theory can be extended to include these kinds of suspensions.

But the spacing here has to be appropriately adjusted as we shall see in one of the subsequent slides. Though I will leave it to you to do some homework as to where these kind of measurements are used. So where is Rheology used most effectively as far as engineering is concerned. What come to my mind is, places like mechanic or chemical engineering where we are trying to study the movement of fluids such as petrol or bitumen through narrow slits or through narrow or small pipes between closely spaced plates.

Reducing the friction between moving parts that is where this theory has been developed from perhaps. As far as we are concerned we could use these experiments directly only when we are trying to work with let us say grouts and trying to study how grouts can be injected into cracks. So those cracks at times are extremely thin or extremely narrow passages through which we want to push a grout without segregation.

So there, yes we can probably use some of these thought processes some of these experiments to determine the properties of grout that we need but in a more generic sense as far as we are concerned we are interested to study the flow behaviour or the deformation behaviour of concrete. And in order to get to concrete we are trying to use the root of studying cement paste first the mortar next and then trying to understand the behaviour of concrete.

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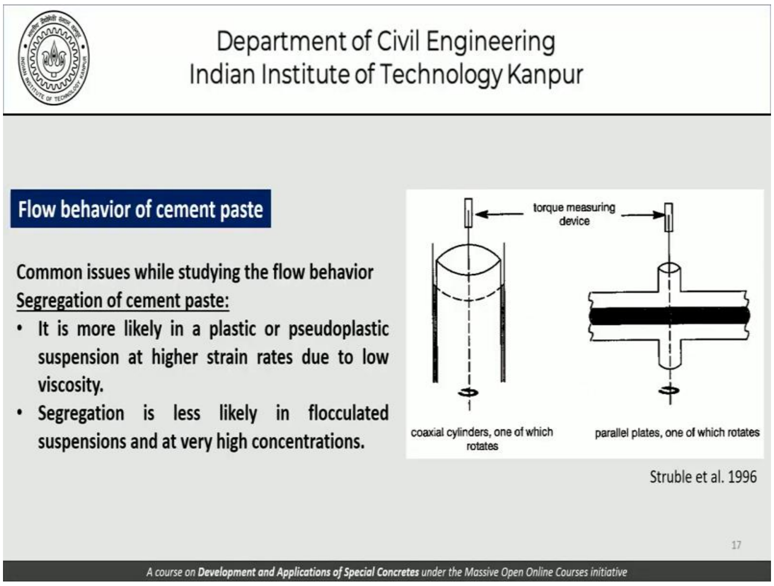

As far as the cement paste is concerned some of the common issues that are important while studying the flow behaviour would include segregation of cement paste which is more likely in plastic or pseudoplastic suspensions at high strain rates due to low viscosity. Segregation of course is less likely in flocculated suspensions at very high concentrations. So it is more of a thought experiment in fact this whole lecture that we are going through today is more a matter of thought.

We just have to close your eyes and think okay if this is what the cement paste is like this is what we are trying to do with it how will the cement paste behave? So if we have a very narrow slit here where we have filled cement paste we rotate the cylinder or we have filled the cement paste in this narrow gap between two plates and rotate this plate how will the cement paste behave? So the segregation is less likely to occur when the suspensions are having high solid concentrations.

If it was low solid concentrations with lower viscosities segregation is easier to occur. Some of these things which are intuitively obvious is what we try to establish numerically because that helps us understand a wider range of possibilities that exist as far as cement based are concerned. It is easy to understand the behaviour with very low concentrations of cement particles and very high concentrations of cement particles but we want to concentrate or we want to study the behaviour in a practical range of water to powder ratios.

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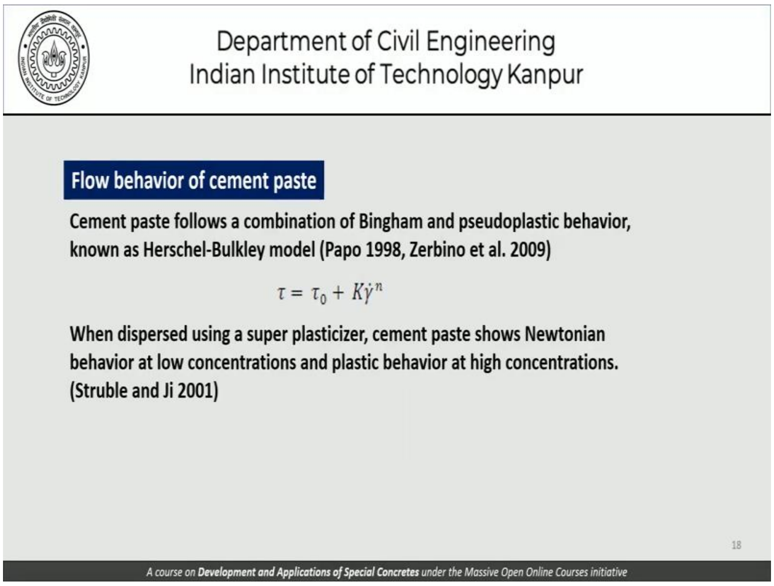

So as far as the flow behaviour of cement paste is concerned studies have shown that it is a combination of the Bingham and the pseudoplastic behaviour known as the Herschel-Bulkley model and the equation that we try to use is τ_0 + k* γ dot^n. Remember that from the previous equations when we were trying to use this power law there was no tau not term.

Whereas for the tau not term when we talked of the Bingham model we said that there is a τ_0 but this part was linear. So it is more a combination of the linear and the non-linear models with the tau not here this is what possibly represents the behaviour of cement pastes when dispersed using a super plasticizer cement paste shows Newtonian behaviour at low concentrations and plastic behaviour at high concentrations

Part of it is something which we have discussed earlier and what we discussed earlier is that if we have cement particles in water they often flock together. And I have explained this discussion of flocculation of cement particles in water when we were doing the initial mix design. What we had said at that time was that this flocculation results in entrapment of water between the flocks and this water is not available for workability.

And therefore if we use a super plasticizer or a chemical admixture to release this water how do we release this water we try to induce repulsion between these particles and these particles are separated from each other. So this water here becomes available for workability becoming a part of the other water which is sitting outside here. So with the plasticizer the amount of water available for workability is much more.

Now in the present context what is being said is that if this water becomes available here even though the solid concentration still remains the same because we are not changing the cement content per se. But the cement paste would become Newtonian would tend to show a slightly higher tendency for segregation. It would become a more Newtonian fluid show lower level of yield stress than in the case that this flocculation was happening.

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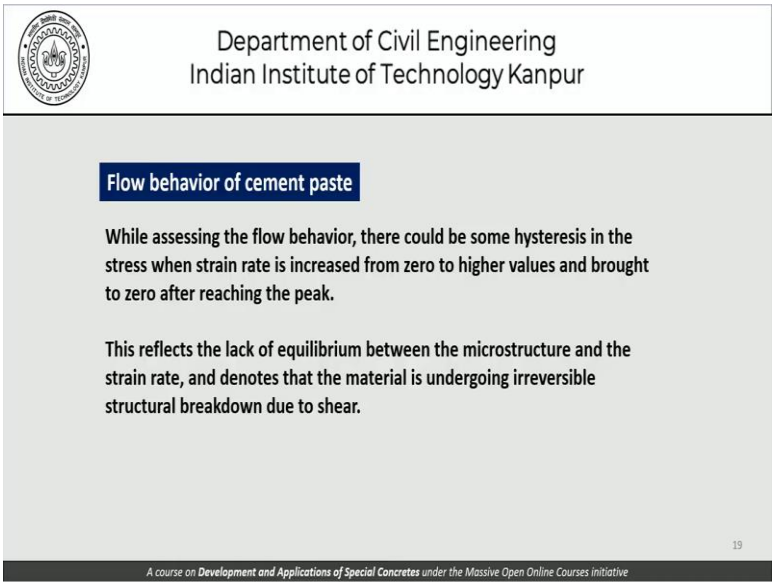

While assessing the flow behaviour there could be some hysteresis in the stress when the strain rate is increased from zero to higher values and brought back to zero after reaching the peak. This reflects the lack of equilibrium between the microstructure and the strain rate and the nodes that the material is undergoing irreversible structural breakdown due to shear. In the case of cement pastes when we do these experiments these are the kind of places where we need to keep in mind the hydration which will cause different behaviours.

As we repeat the experiment at different points in time either by loading and reloading or just carrying out the experiment at different points in time.

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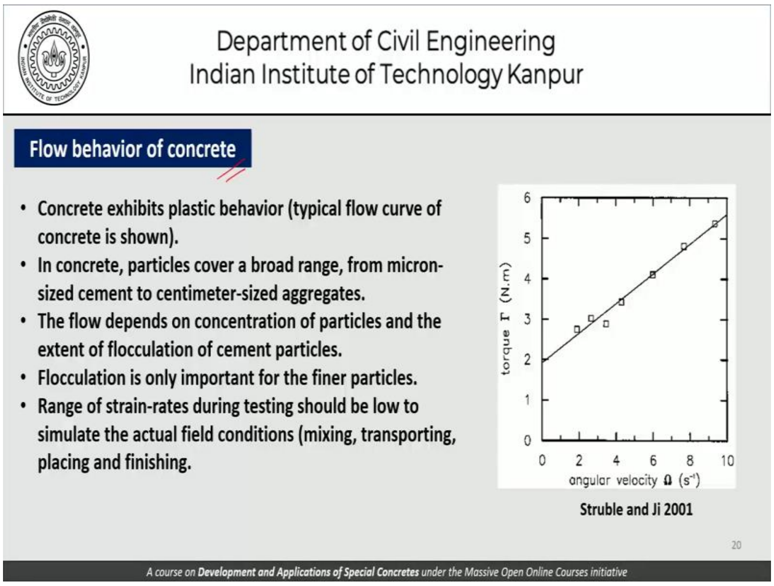

As far as concrete is concerned now we are moving from cement paste to concrete this graph here shows the torque and the angular velocity which are basically the same parameters as the good old stress and the shear strain rate. So, concrete exhibits plastic behaviour typical flow curve is shown here, so here again we have the same idea that there is a tau not and this behaviour is more or less linear.

So concrete shows plastic behaviour typical flow curve is shown. In concrete particles cover a broad range we know that from micron size cement particles to centimetre sized aggregates and the flow characteristics depend on the concentration of particles and the extent of flocculation of cement particles. Now this extent of flocculation of cement particles effectively alters only the properties of paste.

But this change in the paste properties also has a cascading effect on the properties or that are observed for the mortar and that of concrete. So flocculation is important only for the final particles we already know that the range of strain rates during testing should be low. So as to simulate the actual field conditions in terms of processes such as mixing, transportation, placing and finishing.

So what this picture also tells us is that for engineering operations such as mixing, transportation, placing and finishing they can be looked upon as processes where we try to deform the concrete through the application of certain strain rates whether it is high or low what kind of measurements to be carried out we do not even pause to think we carry out our mixing operation in the mixer without spending so much of a thought on what is the strain rate that we are using.

But when it comes to the real science of mixing, the RPM at which the mixer operates is an important characteristic in determining the kind of properties of the concrete that we get. Similarly when we are transporting the concrete in an agitator truck there is a rotation going on there we keep agitating the concrete so that it does not set at what rate that agitation is going on.

So these are the kind of things that we must keep in mind that when it comes to Rheology the Rheologist would look at mixing, transportation, placing, vibration all these things in the framework of application of a certain strain rate and trying to measure the deformability through the τ versus γ dot kind of a behaviour.

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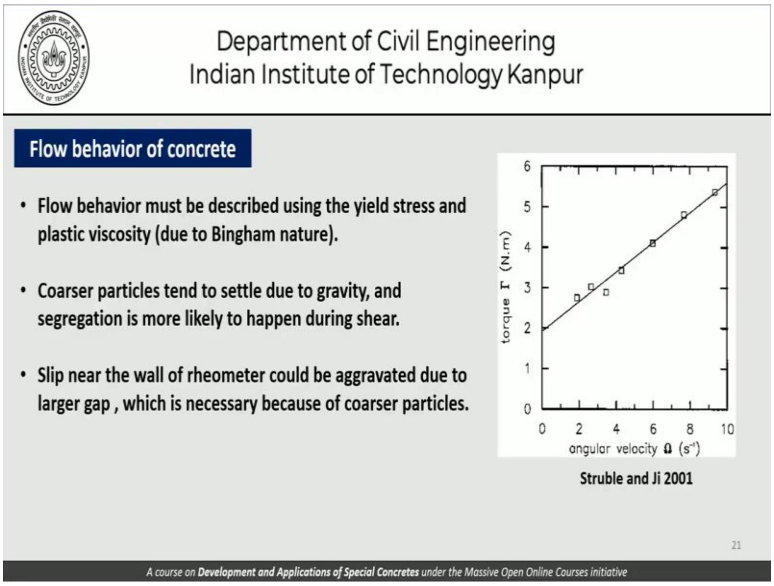

Continuing with our discussion on the behaviour of concrete the flow behaviour must be described using the yield stress and plastic viscosity model. Coarser particles tend to settle due to gravity and segregation is more likely to happen during shear. Slip near the walls of a rheometer could be aggravated due to larger gap which is necessary because of coarser particles. So here we are alluding to we are not directly talking about it but we are alluding to the gap and the importance of figuring out what the gap is.

We are alluding to and discussing how much should be the gap and what are the problems that arise if the gap becomes more one of the things being said is the slip near the walls of the rheometer could be aggravated due to the larger gap but we cannot live without a larger gap because we have coarser particles in concrete. So when it comes to concrete and rheological studies using an appropriate rheometer these are the kind of problems which a scientist or a researcher faces.

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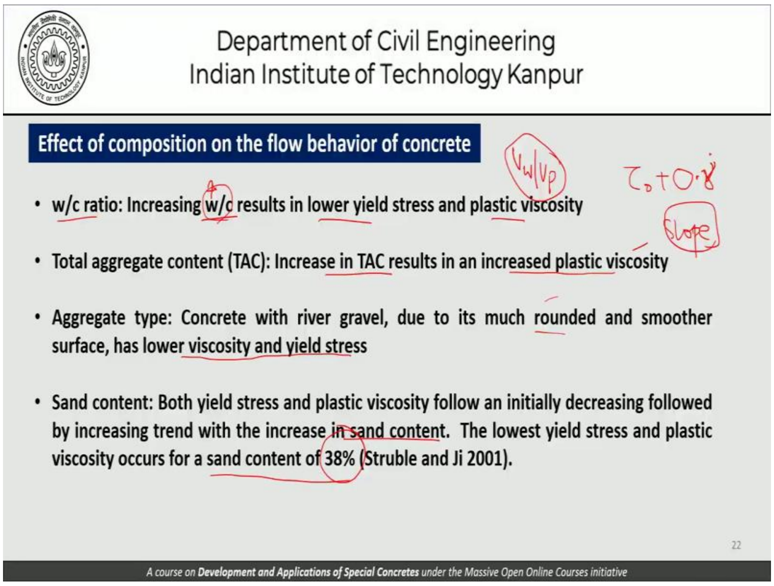

So what are the kinds of factors that affect the flow behaviour of concrete one of them is very obvious the water cement ratio. So, increasing the; water cement ratio results in a lower yield stress and plastic viscosity. Increasing the water cement ratio means increase the water. So if we increase the water which in the case of rheological studies would basically boil down to increasing the volume of water to the volume of powder ratio in concrete terms its water cement ratio.

If we increase this we are increasing the water volume in the system that results in a lower yield stress and plastic viscosity. The total aggregate content if we increase the total aggregate content we increase the plastic viscosity. So the plastic viscosity term here remember is the slope of the straight line that we talked about when we said that it is tau not plus the slope times the shear strain rate.

So this plastic viscosity is the slope of this line. Aggregate type of course also becomes important concrete with river gravel which is much more rounded and smoother has lower viscosity and yield stress values compared to concrete which has crushed stone. As far as the sand content is concerned both the yield stress and the plastic viscosity follow an initially decreasing and then an increasing trend with the increase in the sand content.

As far as the minimum is concerned it has been found to be at a sand content of about 38% but that number that is this 38% could be a function of the kind of sand we use the kind of other materials which have been used and so on. But it is a guiding principle that yes this is the ballpark number that we can expect. On either side of which the yield stress and viscosity would be different and it would tend to increase.

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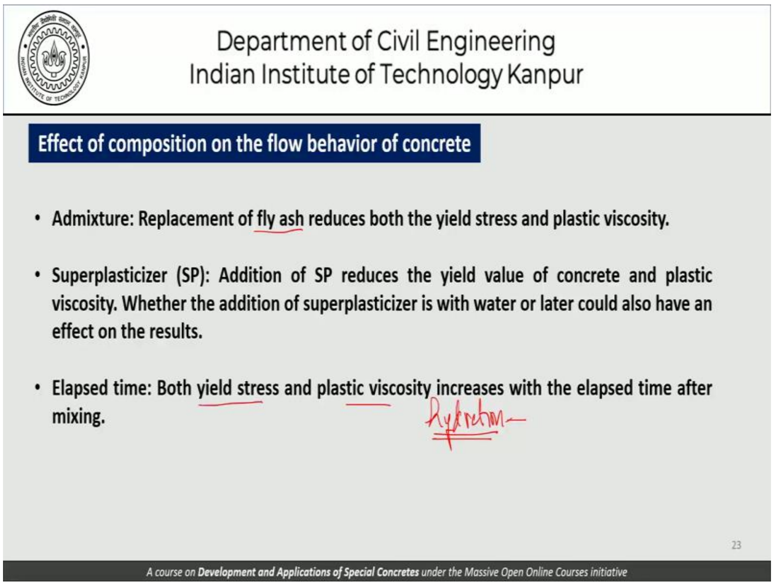

As far as the admixtures are concerned we could replace cement with fly ash if we are using fly ash we could probably reduce the yield stress and the plastic viscosity because the nature of the fly ash particles. If we use another mineral admixture then fly ash then this reduction in yield stress and plastic viscosity need not happen. When it comes to super plasticizer the addition of superplasticizer reduces the yield value of concrete and the plastic viscosity.

We discussed this a while ago when we said that the use of superplasticizer essentially releases the water present within the flocks for workability and in the context of Rheology what it means is that the yield value of concrete and the plastic viscosity goes down. However whether the addition of super plasticizers with water or later could also have an effect on the results what this sentence means is that whether the plasticizer is being added to concrete with water at the time of mixing as a single shot.

Or it is used in stages that would possibly also be an important factor when it comes to the effect on the yield value or the reduction in the yield value and plastic viscosity is concerned. Elapsed time both yield stress and plastic viscosity increase with elapsed time after mixing this is a direct reflection of the hydration that will happen. So the hydration does not necessarily mean that it will suddenly become hard the concrete is still hardening.

And that hardening process in rheological terms is reflected by an increase in the yield stress and plastic viscosity values.

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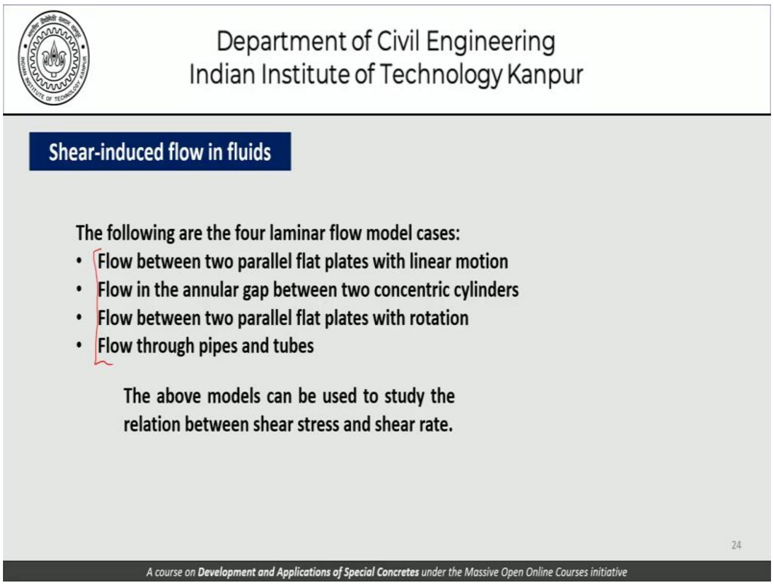

As far as shear induced flow influence is concerned there are these four models which are often used. The flow between two parallel flat plates with linear motion flow an annular gap between two concentric cylinders flow between two parallel flat plates with rotation and flow through pipes and tubes. These models have been used to study the relationship between the shear stress and shear strain rates.

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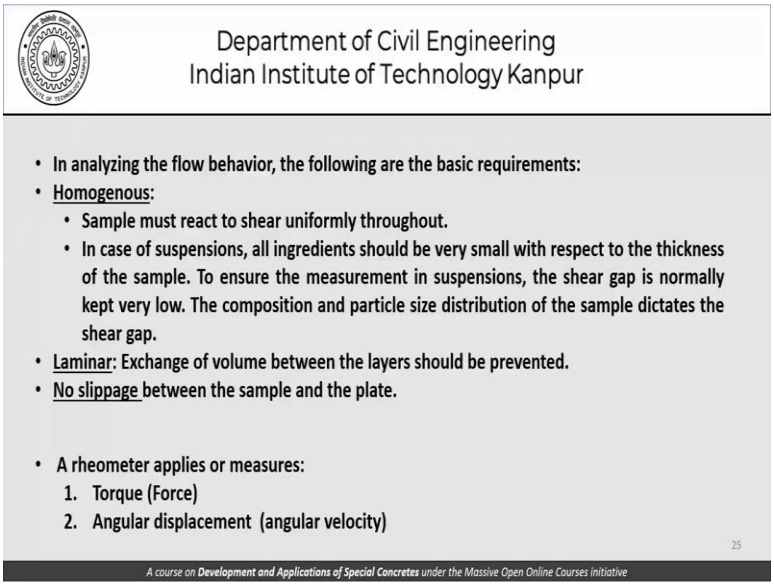

In analyzing the flow behaviour in concretes or for that matter any fluid the following are the basic requirements. One is homogeneity of the sample the sample must be such that it shears uniformly throughout. In case of suspensions all ingredients should be very small with respect to the thickness of the sample. To ensure the measurement in suspensions the shear gap is normally kept very low the composition and particles as distribution of the sample dictates the shear gap.

So this is something which we have alluded to or talked about briefly when we said what should be the gap between the coaxial cylinders or what should be the distance between these stationary and the moving plates this is obviously related to the size of the particles. And in our case if you are talking of cement the particles are extremely fine but the moment we start getting into mortar then we have to be very careful about the kind of gaps that we are talking about.

Laminar, exchange of volume between the layers should be prevented and there should be no slippage between the sample and the plate. So these are the kind of basic requirements when we talk in terms of analysis of a flow behaviour. So the rheometer or the equipment that we use applies or measures the torque which is the force and the angular displacement which could be angular velocity. So these are the two things and we could vary one independently and measure the other as a dependent variable.

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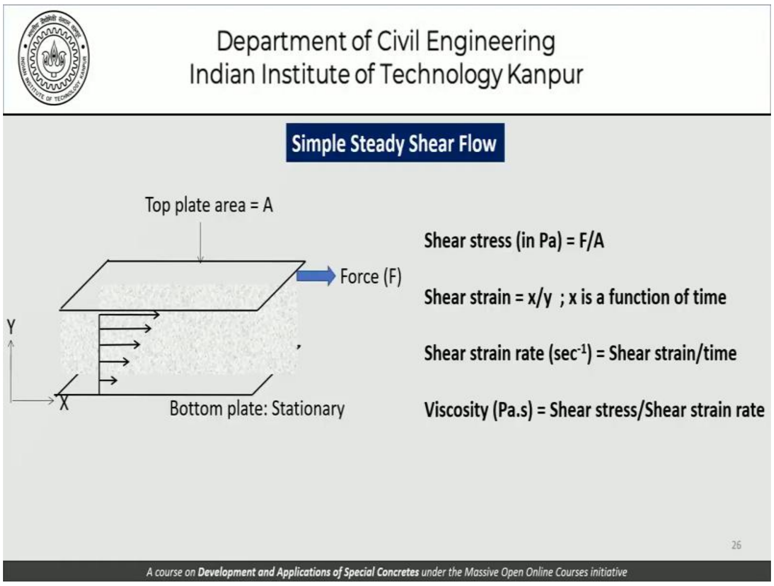

If we look at a simple steady state shear flow between two parallel plates we have a bottom plate which is stationary and a top plate with an area of A and we apply a force F here. We get this to be the velocity profile that we have. The shear stress in Pascal's would be F/A force divided by area over which it acts the shear strain is x/y with x being a function of time and the shear strain rate which is per second is the shear strain versus time.

And the viscosity is defined as the ratio of the shear stress and the shear strain rate. So that is how we analyze a simple steady shear flow.

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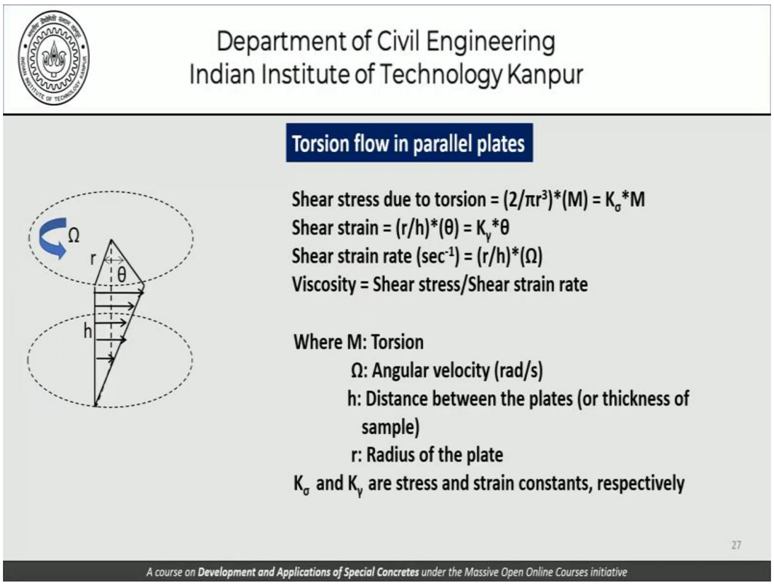

From a linear parallel plate if we talk in terms of a torsion flow in parallel plates the situation becomes a lot more complicated as we have a variation in r as well as the theta directions. So in that case the shear stress and the shear strain the shear strain rates are defined in a lot more complicated ways except that of course the principle viscosity it being the ratio of the shear stress to the shear strain rate still remains the same.

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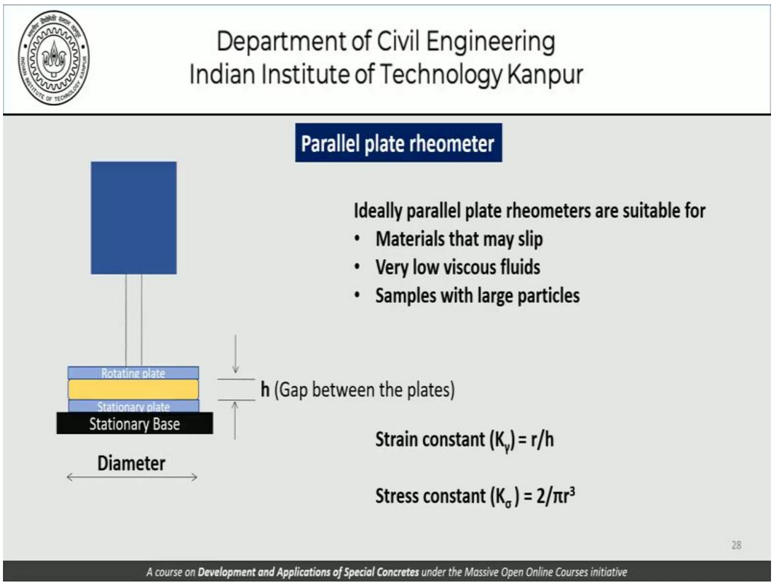

Let me move on and show you the basic structure of a parallel plate Rheometer which is ideally suitable for materials that may slip which are very low viscous fluids and samples with larger particles here the gap between the plates is edge the plates being stationary plate at the bottom and a rotating plate on the top.

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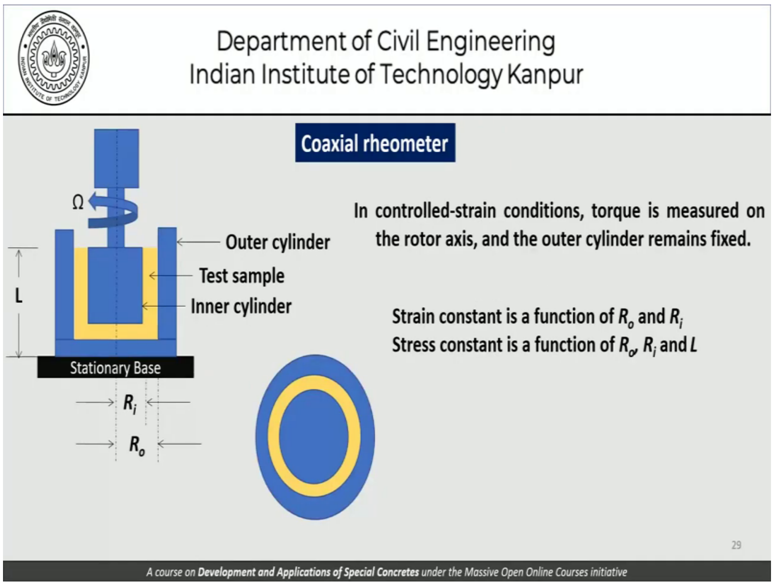

Another type of a rheometer is a coaxial Rheometer where we have an outer cylinder and an inner cylinder and in between that we put the test sample. So this assembly in plan looks something like this the outer cylinder the inner cylinder and the sample in between. So in controlled strain conditions torque is measured on the rotor axis and the outer cylinder remains fixed. So we try to rotate the inner cylinder and try to measure the torque.

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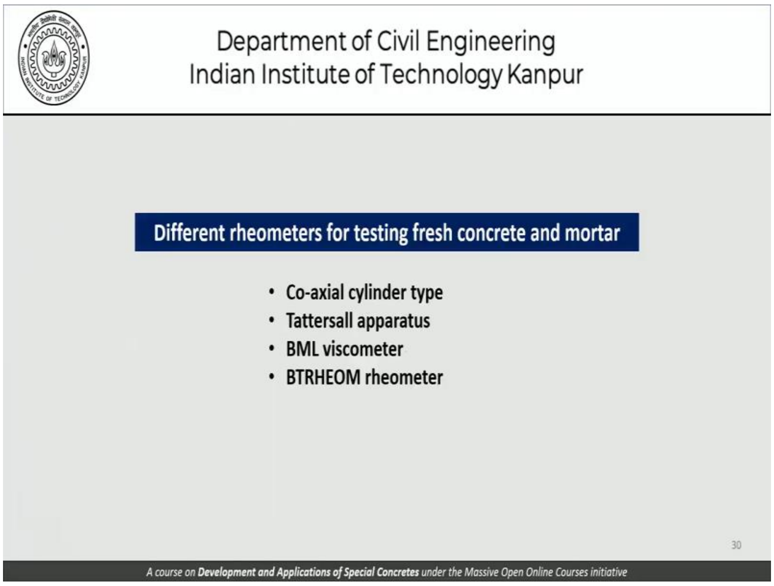

As far as commercially available Rheometers are concerned for measuring or testing fresh concrete and mortar there are coaxial cylinder type the Tattersall apparatus, the BML viscometers and the BTRHEOM Rheometers. So I do not want to get into the details of each of these the next few slides I am going to quickly just show you those viscometers or the type of apparatus that we use and leave it to you to do some reading on your own.

The whole idea of this exercise today was to introduce to you this important field of Rheology to a concrete engineer. We carry out the slump test or the slump flow test without blinking an eye but what we must remember is that there is a lot that there are scientific issues involved. There are principles of viscosity involved which can be measured it is not that they cannot be measured.

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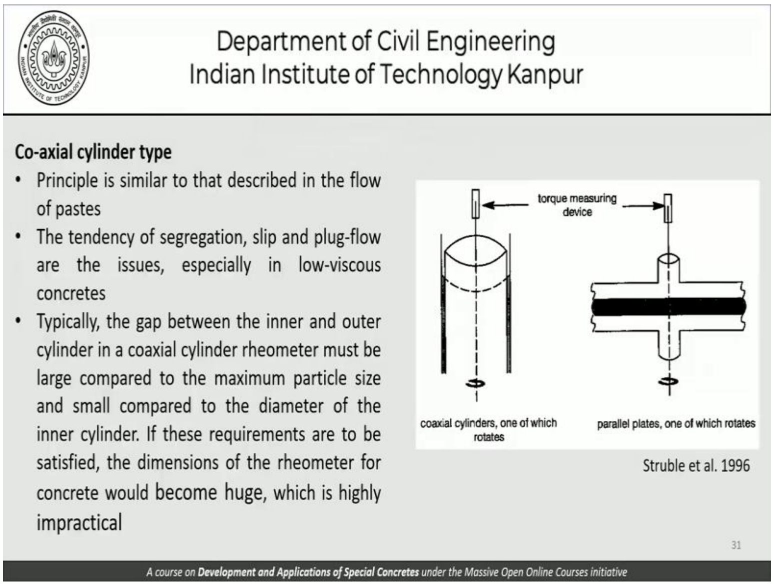

The picture and the schematic representation here is that of a coaxial cylinder type of device where the principle is similar to that has been described before. The tendency of segregation slip and plug flow are the issues especially in low viscous concretes and typically the gap between the inner and the outer cylinders in a coaxial cylinder rheometer must be large compared to the maximum particle size that we are talking about and that for concrete sometimes becomes unwieldy it becomes a very large system.

So we need to be careful as far as what is the maximum size of particles that we can use when we are testing the concrete for Rheological measurements using this device.

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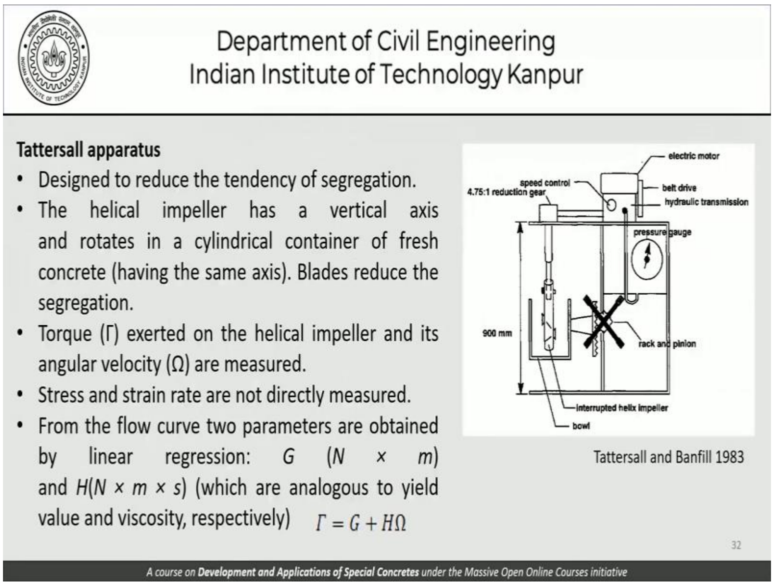

So as far as the Tattersall operators is concerned this is designed to reduce the segregation tendencies and we use a helical impeller and so on. So I do not want to get into the details of this, this is not the purpose of this course and the intention is only to give you a glimpse of the kind of measurements that people have carried out earlier to better understand the deformation of fresh concrete.

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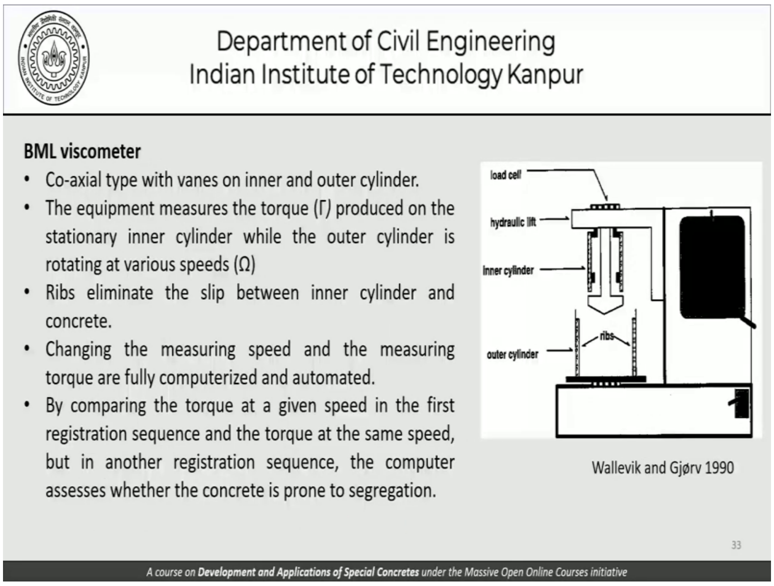

As far as the BML viscometer is concerned it is a coaxial type with veins on the inner and outer cylinder. Please see that to simplify the picture let us put it this way we have an outer cylinder here and we have an inner cylinder here and we want to put the sample in between. It is not necessary that the walls of the outer cylinder and the inner cylinder are smooth. So we can have some kind of perturbations on these two walls and that is what is reflected here as far as the ribs are concerned and the veins are concerned.

So of course the intention in this course is not about getting into the details of this equipment but only to show you the kind of equipment which has been developed and used by researchers trying to better understand the flow behaviour of the concrete in the fresh state.

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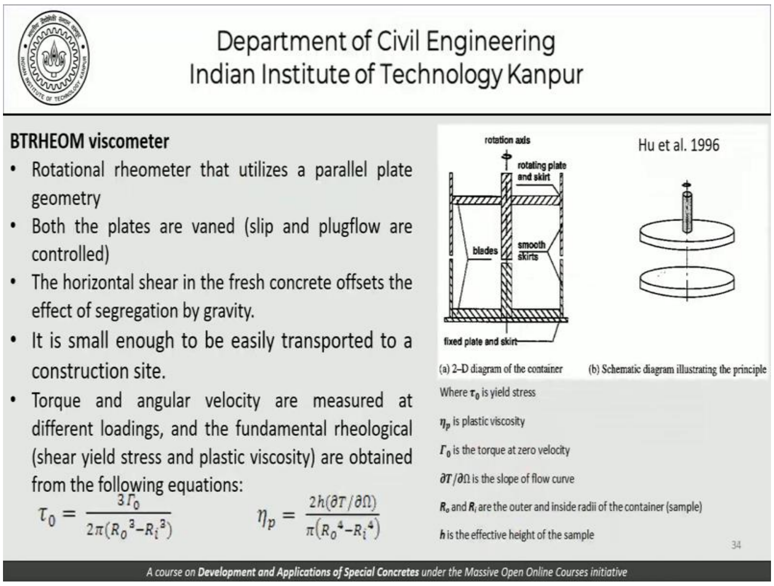

As far as this rheometer is concerned it also uses a parallel plate geometry the both the plates are veined in this case. So it is not necessary again that the two plates that we use are smooth we can have some kind of surface perturbations on this and then have one of these plates to rotate with the sample being there in between. Of course as far as this particular rheometer is concerned there have been efforts to economize there have been efforts to reduce the size of the equipment to be able to carry it to a construction site and use it for real measurements of concrete at the site.

Having said that please remember that these are equipment which are very rarely used as far as real engineering practice is concerned except that of course for research purposes beyond the lab. If, you want to test our hypothesis if we want to test the kind of data that we have got from the labs we, really need to go to the site and for that we need to carry these equipments to the concrete site to the construction site. Because it is not possible to get the concrete from there to the lab in a reasonable time frame.

So the idea of all this discussion today was to introduce to you this very important very interesting field of geometry. Where we study the deformation of paste mortar or concrete try to study the flow characteristics in an effort to understand or better understand the segregation flow ability viscosity and so on for fresh concrete.

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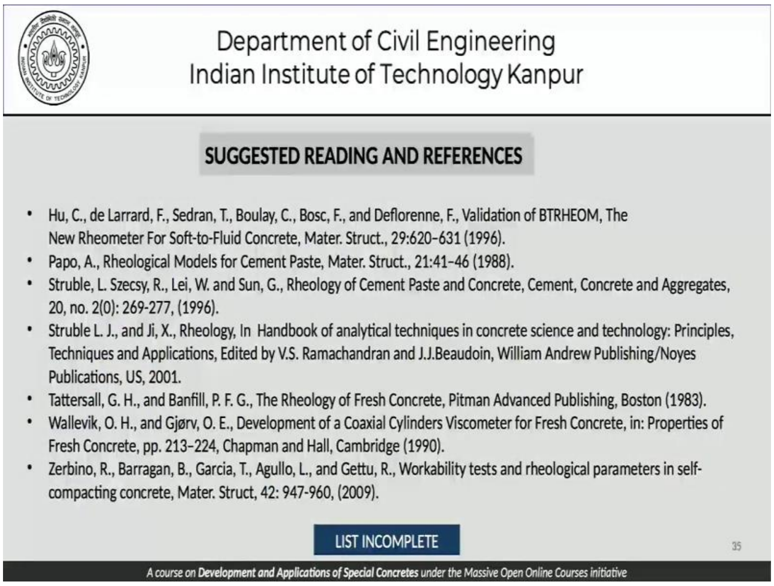

Here is a set of reading material that you may find useful to understand Rheology is little better. These are some of the problems that we alluded to when we were discussing the subject.

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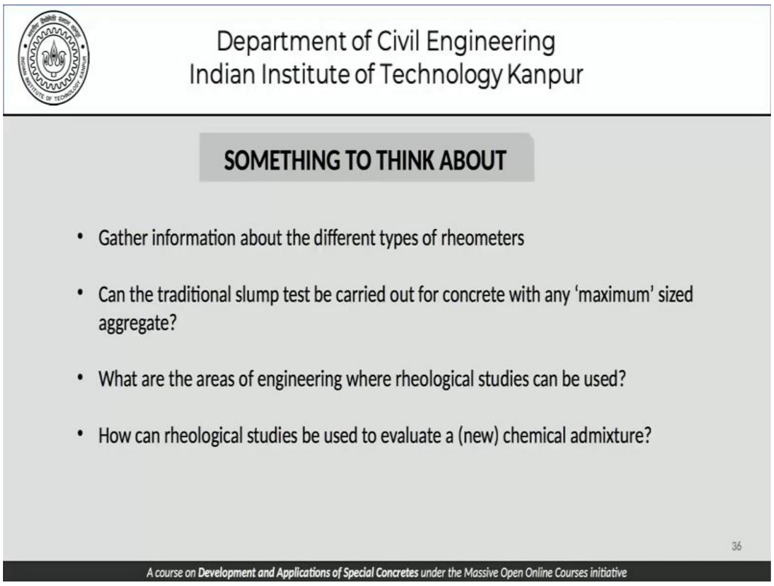

And I am sure you will find a lot of other things which are stimulating if you read the material to think about yourself.

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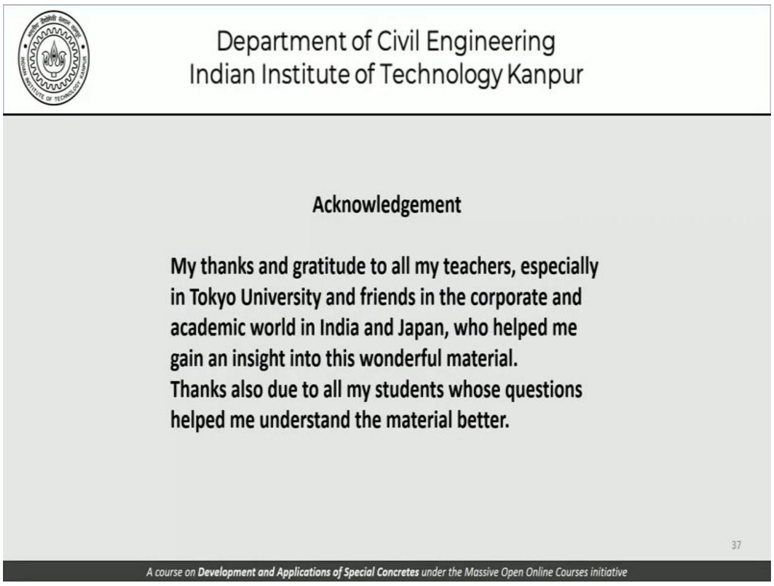

My thanks to all my teachers friends and colleagues and my students who have helped me understand concrete better. And who motivated me to myself understand a little bit of Rheology and applications of Rheology as far as fresh concrete is concerned. And with this I thank you once again for being with me on this lecture and I look forward to continuing our discussion on special concretes possibly with fiber reinforced concretes from the next lecture onwards in this module. Thank you once again.