Admixtures and Special Concretes

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Lecture - 20

Chemical Admixtures: Understanding Concrete Rheology - Part 1

Okay, so with that we finish up our discussion on air entrainment. I will move on to the next segment on rheology modifiers which are getting increasingly important from the perspective of flowable concrete as well as from 3D printing of concrete. So of course we talk primarily in the last segment on freezing and thawing and use of air entraining agents and how to do the air void characterization to ensure that you have a proper distribution of the air void system in concrete. Now before we get into the aspect of understanding the use of viscosity modifying agents, it is very important for us to understand what is rheology of concrete and how can we actually measure this rheology because again this has implications on several different things on the use of flowable concrete, on the use of 3D printed concrete, on the use of pumping of concrete, all of these aspects are controlled by the rheology of concrete. So far we talk generally about slump or other workability test methods but that is not really capturing the entire flow behaviour of concrete. When we talk about rheology, we are trying to understand the entire flow behaviour, not just the workability.

Introduction:

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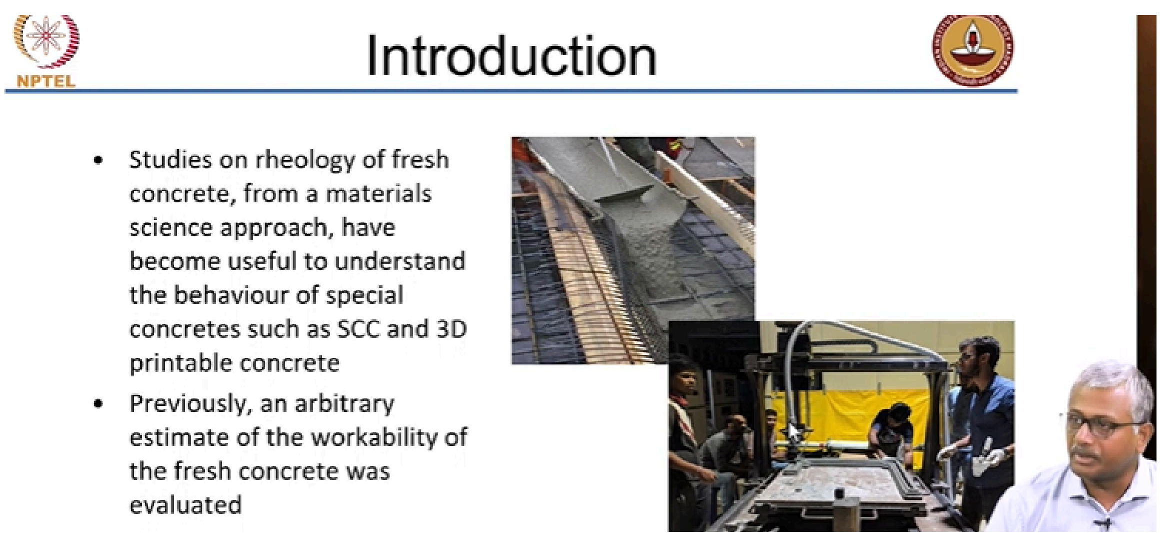

So as I said when we come to special concrete, it is not just the workability but the actual rheology that controls how these concrete actually work. When we do a slump test, we are not exactly capturing everything that workability represents. If you look at the official definition of workability, mixing, transportation, placement and compaction and finishing, all of these aspects you are trying to measure with just the slump test. It is not something that is really capturing all of those things. There are more fundamental aspects to the concrete beyond what we measure with just the slump test. Because of that we try to study the rheology of the system.

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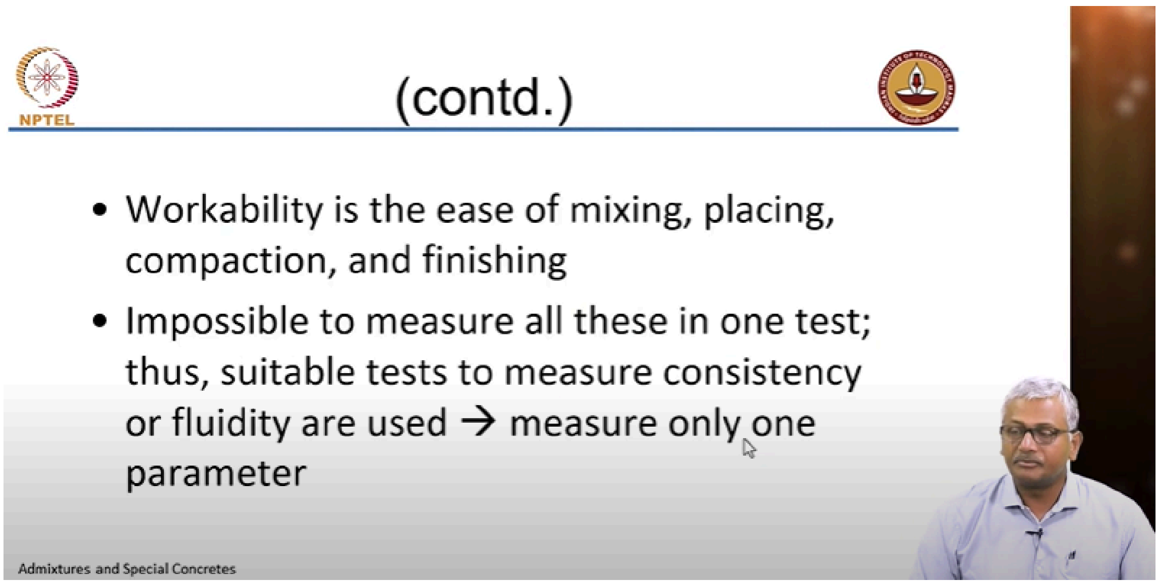

Again measuring only one parameter is not really giving you a clear estimate of what the workability is. For instance, let us say you have two concrete mixes, both with the same slump 100 mm, but one has a slightly higher fine aggregate to coarse aggregate ratio as compared to the other. When you put these two concrete which are the same slump inside the concrete pump and try to push this concrete, the one which has a slightly higher fine aggregate content will take the pumping much better rather than the one with more coarse aggregate. So we have the same slump but your concrete behaves differently under pressurised flow conditions. So what do we do? We need to measure somehow another parameter that tends to reflect what this resistance to flow is going to be.

So if you think about slump, it is sort of giving you an initial measure of the consistency or the wetness of the concrete. But is that sufficient to define how the flow characteristics will be? That is something which we need to study further with the help of rheology.

Survey of field problems:

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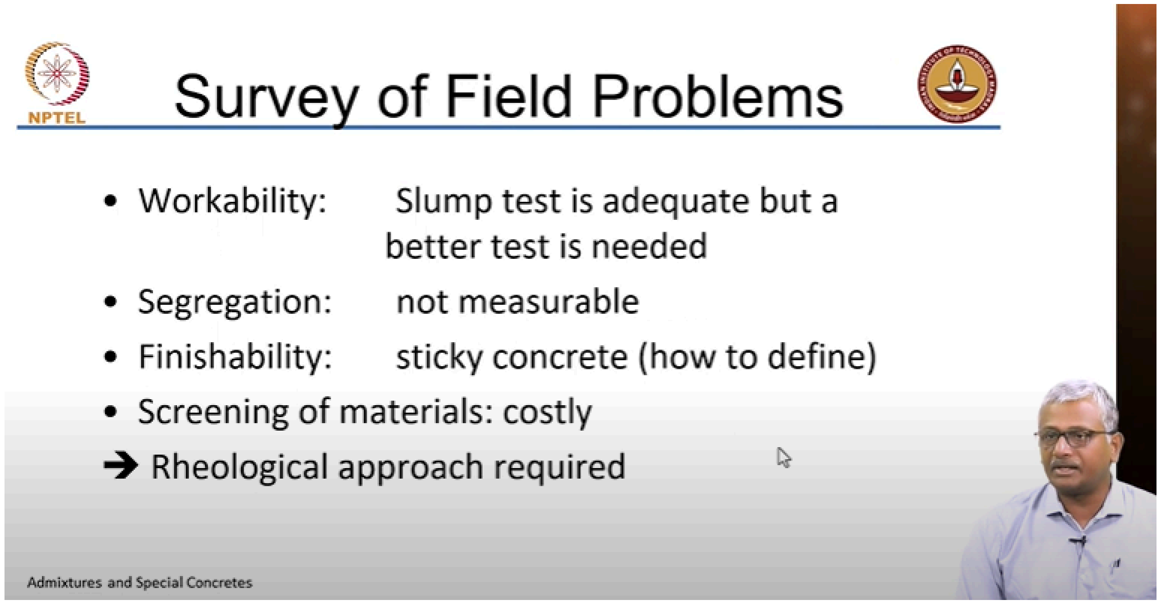

So a slump test is generally adequate but we know that definitely a better test is needed. Segregation is something that is not really measurable. We can only make some random measures for segregation. For instance, you keep concrete in a bucket, allow it to segregate with time, after some time separate out the top half and the bottom half of concrete and measure the amount of coarse aggregate in it. That is a good test for segregation. But it is not really a scientific test. It is a practical test but yes, it is not really scientific. Finishability, how do we measure finishability? Because what happens is, if you use silica fumes, we will talk about that later. Silica fume being such fine particle sizes, it tends to make the mix very cohesive or sticky. So when you try to finish this concrete with the trowel, the concrete surface will try to stick on to the trowel. It will not spread nicely, it will just stick on to the trowel because of the stickiness caused by the fine particulate nature of silica fumes.

But how do we measure this property? You can describe concrete any way you want but quantitatively can you measure it? So because of all of these things and because screening of materials for special applications becomes expensive, you need to have estimates of the rheology. Rheology is essentially the flow behaviour of materials.

Rheology:

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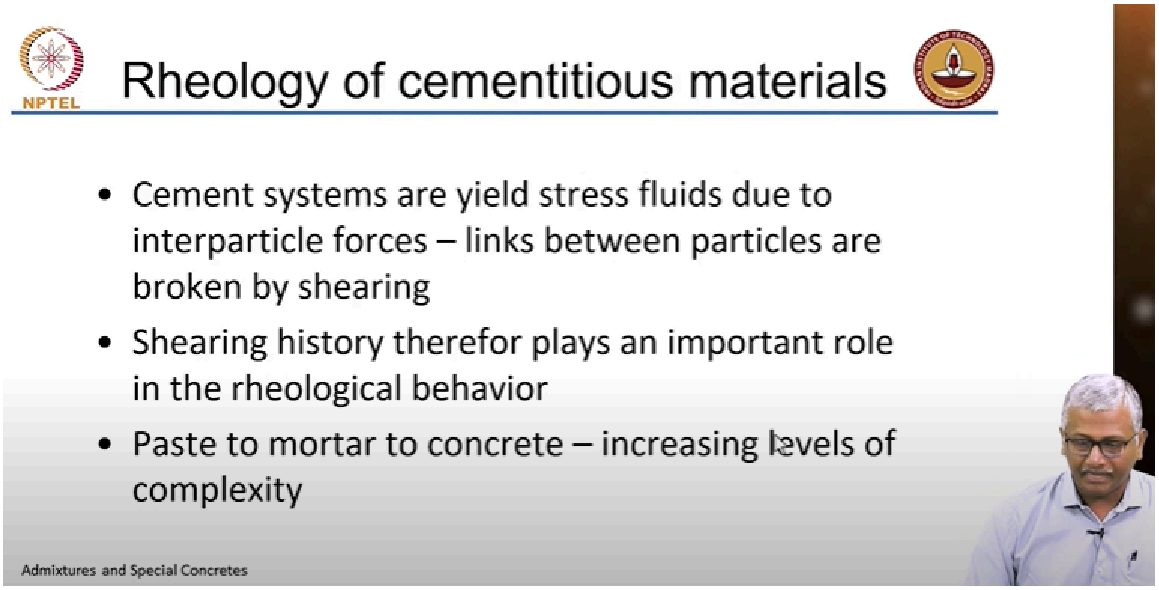

Rio means flow, rheology of course relates to study. The study of flow behaviour is rheology. Now if you remember your basic understanding of water and oil that you learnt in your science textbooks, water and oil have viscosity. But as soon as you apply any shear, water will flow. So if you have a pool of water on the table for instance, if I simply press that pool of water, it starts flowing. Concrete on the other hand, let us say you dump some concrete on the table, if I just press it, probably it may not be sufficient to cause it to flow. I may need to agitate a little bit to cause it to start flowing out. We do that in normal concrete with the help of vibration. We pour concrete into the form where if we vibrate, vibration at high frequencies tends to overcome the initial internal buildup of the concrete and causes it to start flowing. So we call such systems yield stress fluids. There are interparticle forces that cause the material to be very stable unless you apply a shear that is high enough to overcome this inter-particle force. Imagine concrete, concrete has a lot of coarse aggregate, coarse aggregate has intergranular friction. Now if you change the design so that you put in more mortar between the coarse aggregate, you are going to reduce that friction, it is going to flow better. That is what is happening in this case. But when you do not do that and when you apply vibration that vibration allows the particles to start moving past each other. That vibration does the job of overcoming the inter-particle forces to cause the breakage of these inter-particle forces and you shear the material to start to make it flow. Just to take you back to your conventional definition of rheology or conventional definition of viscosity, we remember that we have two parallel plates with the fluid in between and you are shearing the fluid by moving these plates past each other. That is a conventional definition of viscosity and you define viscosity as the gradient slope of the stress versus strain rate curve when the flow is laminar. The flow needs to be laminar. You have talked about this in your hydraulics lessons also. Flow has to be laminar. In turbulent flow, you cannot really describe viscosity. The material property of viscosity is defined in laminar flow. So that is the textbook definition of viscosity. But we will see here that the conditions do not always allow us to use this simple approach because of the sizes of the materials that are involved.

So because the link between particles has to be broken by shearing, the shearing history plays an important role. Therefore, shearing history is obviously very important. What is shearing history? How has the material been mixed? So in concrete what happens? The concrete in the ready mix plant gets mixed in the concrete mixer there. Then it gets transported into the truck. Now in the truck if the concrete remains stable and travels about 1 or 2 hours to the job site, after that you need to again break that stability by agitating it. So depending on how well it was mixed in the beginning, your level of agitation that is required to get it to a certain consistency will be different. Similarly if the same truck continuously agitated the concrete while you are bringing it to the site, you have continuously broken up the internal buildup of the structure. So if I apply the shear continuously, I am not allowing the structure inside to get built up. That is required when I deliver concrete. But that may not be required when I place the concrete. After I place the concrete and the concrete is stable, I do not want it to be able to flow continuously. So it should have an internal buildup that allows it to stand inside the formwork without too much deformation. And that inherent concrete property is called Thixotropy which is more exhibited by systems like clay but concrete also has the ability to exhibit Thixotropy provided it is designed correctly and that we will talk about in more detail.

So one problem that often comes in studying concrete rheology is the fact that when you move from paste to mortar to concrete, your system changes considerably. If you mix a paste, the particles of cement are typically what size? 20 microns average, it can range up to 100-150 microns maximum. So there is not really that much shear between particles when you mix paste. The fluidity is given by the water and the super plasticizer. When you move to mortar, there are sand grains which are causing additional shear. When you move to concrete, there are coarse aggregates. So the initial mass of the system is going to be significantly different or the initial resistance of the concrete is going to be significantly higher as compared to the initial resistance of a paste. To break down that resistance, the shearing that you need to do is significantly different. That is why translating rheology studies of cement paste to workability or rheology analysis of concrete is a very difficult proposition and in fact most people who work in rheology try to do this some way or the other because working with a paste system is easy. You do not have to waste too much material. It can be done with smaller systems. With concrete, everything is scaled up and it becomes expensive. So because of that people want to study paste and extrapolate to concrete but it is not very easy to do that. I will talk about this when we move on.

Rheological Models:

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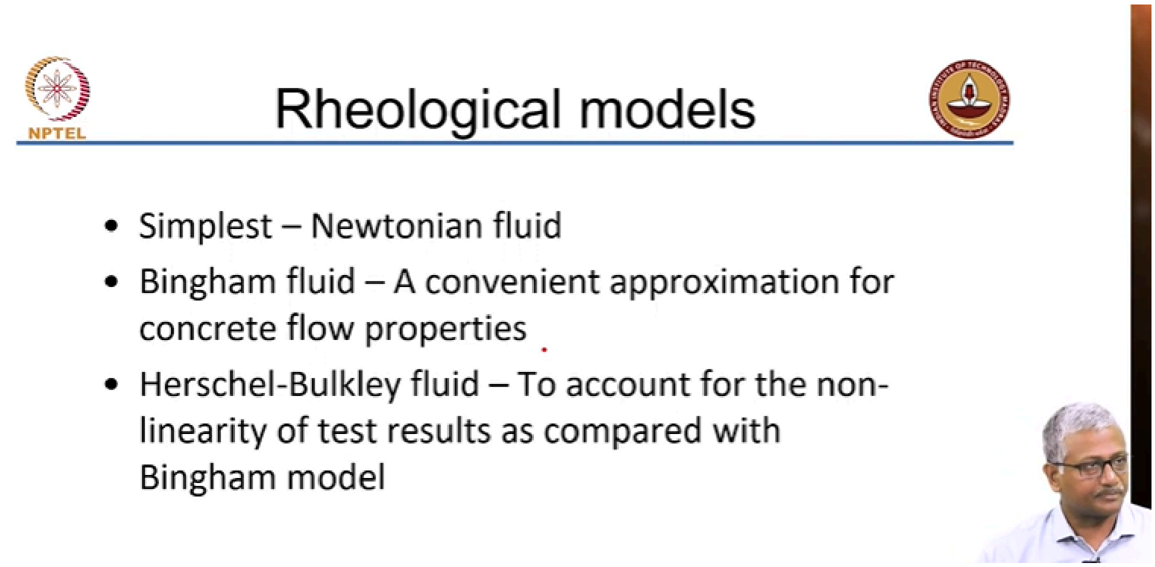

So most materials are described by their rheological behavior and this behavior can be captured with the help of simple models. The Newtonian fluid model is the simplest model which applies to water or oil. As soon as they start shearing the plates, the water will flow. Any shear that is applied will cause the water to flow.

When the fluid has an internal build up that needs to be overcome to cause the material to flow, we call those as Bingham fluids. So you have some sort of an internal cohesion that needs to be overcome to cause the flow to happen. Just similar to your behavior of granular materials versus clay. In a granular material when you draw the shear and normal stress relationship, you get a line which is straight passing through zero. But when you plot the same for a cohesive material like clay, what happens? You get a cohesion, right? That is the behavior exhibited by clays. So more or less similar to that is what you are seeing with materials that exhibit an initial yield stress. So this cohesive strength in the case of clays is similar to yield strength or yield stress in the case of fluids that exhibit this kind of behavior. That is why we say yield stress is the parameter that you need to or minimum amount of stress that needs to be overcome to cause the material to start flowing.

In some instances you may not have a nice linear relationship because of which we try to choose more complicated models like Herschel-Bulkley fluid which accounts for some of the nonlinearity. I will describe these models in a little bit more detail. But essentially you can start getting behaviors that are not linear because of the type of material that you use. Now sometimes if you think about your glue that you use, right? So what happens to the glue when you just put your dipstick into the glue it is very easy to take it out. Sometimes when you try to mix it vigorously it becomes thicker and thicker. Paints on the other hand when you, some paints exhibit this behavior that when you first try to mix them they are very thick. But when you start agitating it becomes thinner and thinner. So that means that this flow behavior is not constant with the application of shear. So that means a linear model is not applicable in such cases. So we have to describe it with higher order models which are nonlinear. So that is where our understanding of the entire system comes into play.

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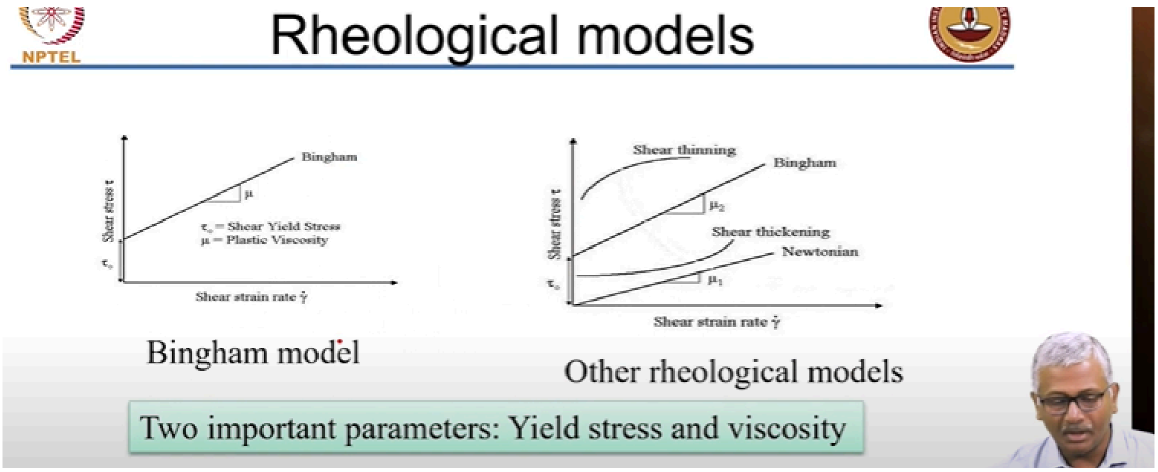

The Bingham model is the simple linear model where you have an initial shear stress that needs to be overcome for flow to happen but once the flow happens it does so with a constant viscosity okay. Shear yield stress and plastic viscosity. We call it a plastic viscosity where flow is a viscosity during the flow. That means it is a resistance to the flow that is happening to your system. Now as I said the graph is typically drawn between shear stress and the rate of change of shear strain and this is only correct in the laminar regime. The fluid remains laminar and in this regime the shear stress is proportional to the rate of change of shear strain. So the Bingham model is here, the Newtonian is here, it passes through origin. As soon as you apply shear there is a flow that is exhibited by your system okay. But when you start exhibiting other nonlinear behavior it could be a shear thinning behavior just like we talked about the pains in some cases where you have the rate of change of the shear stress keeps reducing. As you apply more and more shear, increase the rate of shear strain, the rate of change of shear stress keeps reducing. On the other hand you can get thickening in some instances where you start exhibiting more and more shear higher than predicted rate of shear when you increase the strain rate okay. So you want one of these types of behavior for your system to behave appropriately.

So let us look at the practical scenario. Let us look at a scenario where concrete is mixed at the red-mixed plant and then it is getting transported, it needs to be dumped into the formwork at the job site okay. So what kind of behavior do we expect from concrete? What kind of behavior do we want? When we are slowly agitating it in the truck is that a high shear or a low shear? Low right, it is a low shear. When we are trying to pump it, is that a high shear or low shear? We are increasing the shear rate when we try to pump it. When the system comes into the formwork and is trying to come to rest shear is low or almost zero okay. So what we have is a state of the initial state that means you need to start mixing to actually get it to a homogenous state. Then the transportation where you have a slow agitation at a low shear rate, pumping where you have a high shear rate and then deposition and stability where you want a low shear rate. So in such instances what kind of behavior would suit concrete well? Shear thinning, why? When we agitate the concrete or when we push it in the pump we need it to flow easily but when it comes to rest we want it to be stable and not flow much. So at low shear you exhibit what is a high rate of change of shear stress but at high shear I mean high speeds of shear you want a low rate of change of shear stress okay.

So shear thinning is usually the kind of approach that we want our concrete to have in order to be able to complete our concreting process in the normal fashion. I will talk about that once again with respect to what is called a static shear and a dynamic shear. If you simply approximate everything to a linear approach we can use the Bingham model which gives us two parameters, one is this initial shear stress which we call as yield stress and the slope of this line that is the plastic viscosity. So those are the two parameters most often that we try to find out in simple rheological experiments assuming that concrete will behave linearly. It does not always do that but assuming it does.

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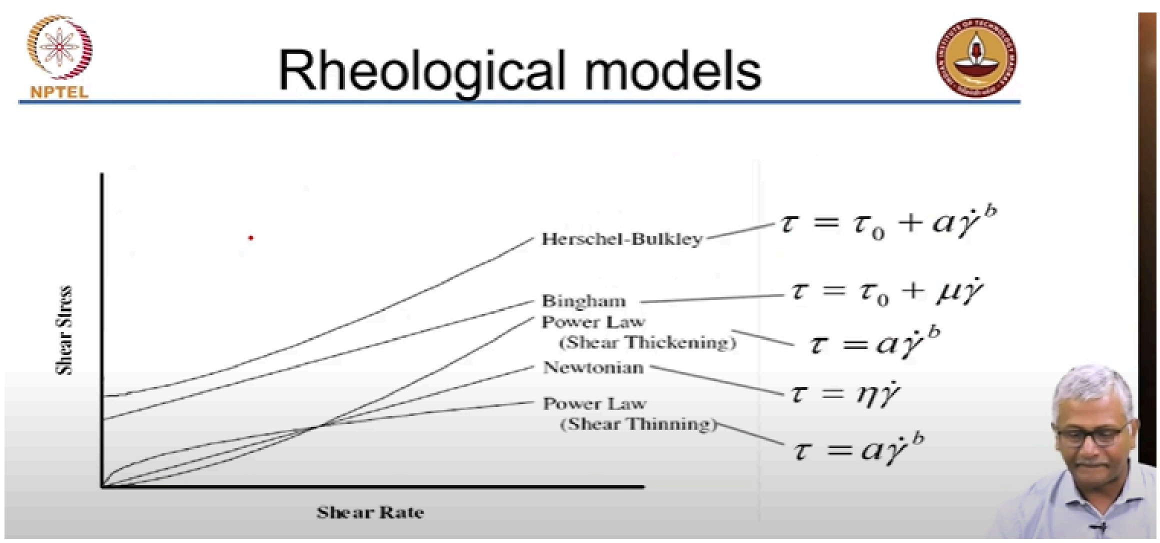

So if you were to show the other laws which are non-linear relationships those are described by the power laws shear thickening or shear thinning where the shear stress is a function of the shear rate but there are two constants a and b, same a and b in this case but there will be a difference in the nature of b in one case it will be more than 1, in one case it will be less than 1.

Now the Herschel-Bulkley as you see the second term is almost similar to a shear thinning or shear thickening but there is an initial term which is equivalent to an initial shear stress. So concrete can be most well approximated by a Herschel-Bulkley fluid. Concrete most appropriately behaves like a Herschel-Bulkley fluid. Now for purposes of simplicity many researchers who work on rheology tend to simplify it into a Bingham fluid.

It is much easier that way you only have 2 parameters here you have 3 things to measure you need to measure the tau naught, you need to measure a and you need to measure b. How do you measure, how will you do this measurement, rheology measurement? You can change the shear rate or speed of rotation of the mixer for instance, rotation per minute that is almost the same as the shear rate.

Shear stress: how do you measure, how will you measure shear stress? Let us take a simple definition of a concrete mixer: you are changing the speed of the mixer that means you are changing the shear rate. How is the shear stress being measured? Sorry, no, no in the mixer can you measure the shear stress?, because this is what the principle of rheometer is. Concrete is getting sheared at different rates and you measure the shear stress. The shear stress is measured with the help of torque. When you are trying to rotate this material you are trying to see at what torque your blade or what resistance your blade actually has in applying that rate of shear and that resistance of the torque is then converted to shear stress depending upon the kind of geometry that you use. I will talk about the geometries in just a minute. So you need to get the shear stress and shear rate and that is obtained from the torque and the rotation per minute. So the basic graph is between torque and rpm and that is converted using the kind of geometries that are used for this kind of approach to shear stress and shear rate.

Bingham Model Concept:

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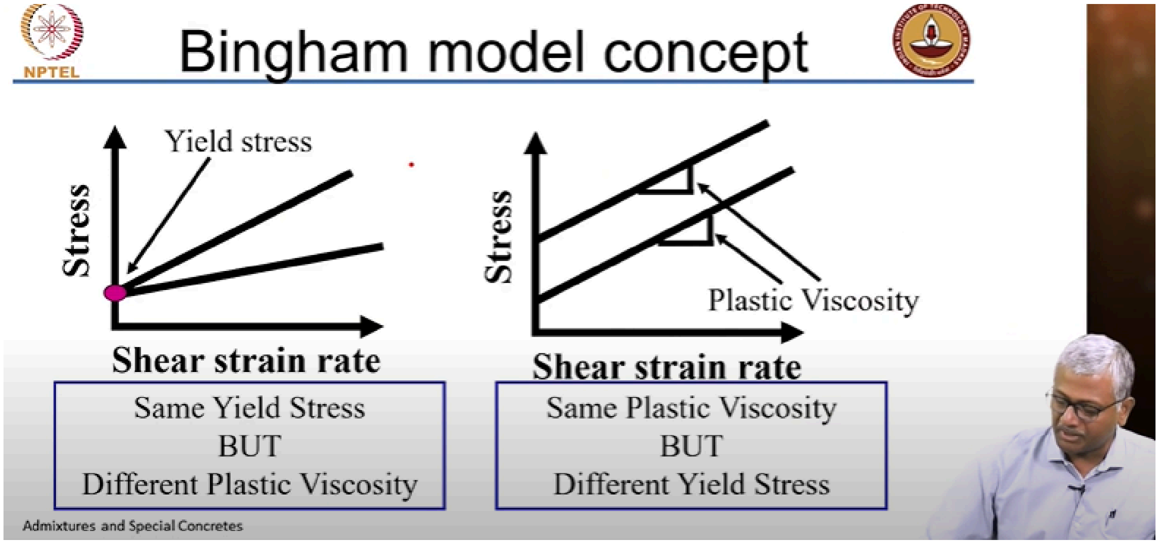

So I will show you different types of rheology models but just to give you a physical understanding of the concept better. So when you have a graph which looks like this where you have the same shear yield stress but different slope of this graph you are talking about the same yield stress but different plastic viscosity. Now can you think about how this would capture the kind of example I gave you earlier. Same slump but because of different fine to coarse aggregate ratios your concrete is getting pushed differently. So that is the same case. You have the same stress shear stress but different plastic viscosity. On the other hand what you have simply done is used a super plasticizer in your system. You increase the slump but the concrete probably is still exhibiting the same level of flowability. So that is the same plastic viscosity but different yield stress. So you have overcome that initial resistance of the concrete to flow.

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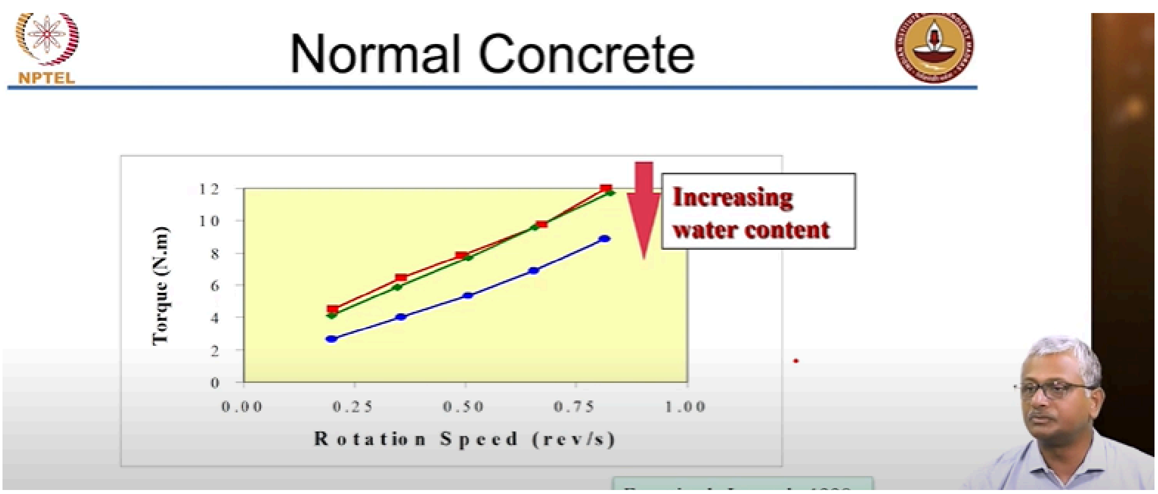

So what happens in normal concrete when you increase the water content you are generally trying to reach a state where you reduce your initial shear that means yield stress is getting reduced but because you are increasing water your viscosity will also reduce, so the slope will also keep reducing. So slope 2 will be less than slope 1 generally. So this is the basic diagram that is drawn between torque and rotation speed. Now in self-compacting concrete, so in normal concrete when you increase the water content your shear stress S2 is not that much different from S1 but in self-compacting concrete when you increase the water content your shear stress and the viscosity both start reducing in self-compacting concrete. When you increase water both your shear stress and viscosity start going down.

Self-compacting concrete:

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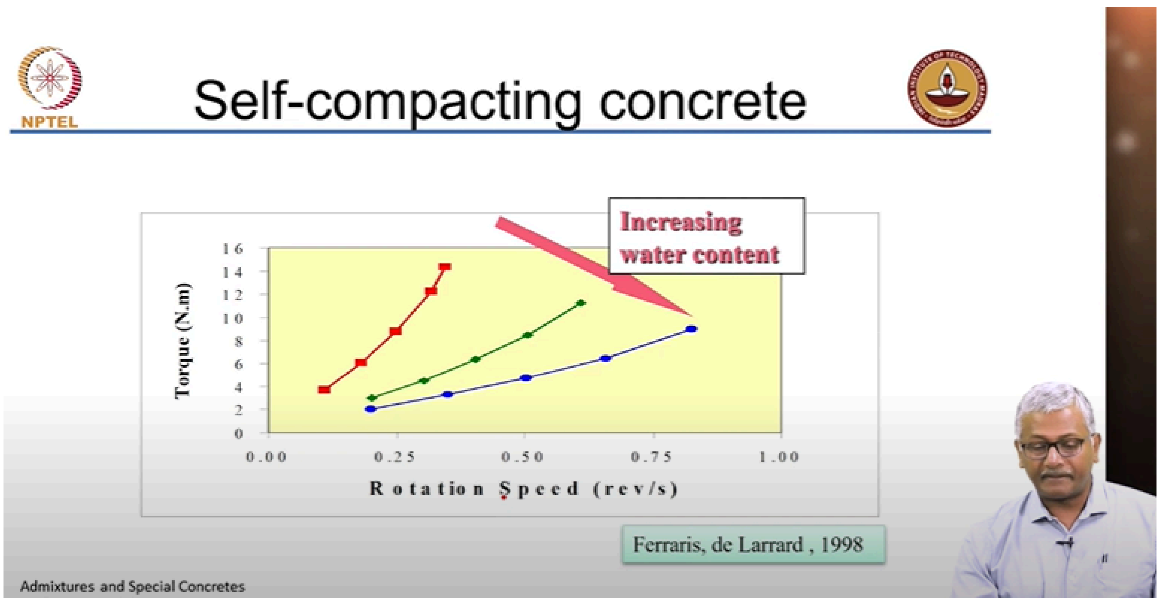

What is a desirable system in self-compacting concrete? Your viscosity high or low? Shear stress be high or low? Should the shear stress in self-compacting concrete be high or low? Because as soon as you place it, it needs to be compact. So shear stress should be almost zero. But what about viscosity? Should it be low? It comes to rest, concrete comes to rest. If the viscosity is low what will happen? The aggregates will start settling, segregation will happen. So you have to control the viscosity in self-compacting concrete. That is why it is not a great idea to increase water content significantly when you use self-compacting concrete because water increase will lower the viscosity so much that your system will become prone to segregation. There will be resistance to flow but because of this low shear stress and so let us say there is resistance to flow what will happen is when you pour the concrete in a given location it will not spread out too much but all you need to do is move your chute along that is it and because of the low shear stress it is going to simply fill up the entire volume of the formwork you see.

Shear yield stress:

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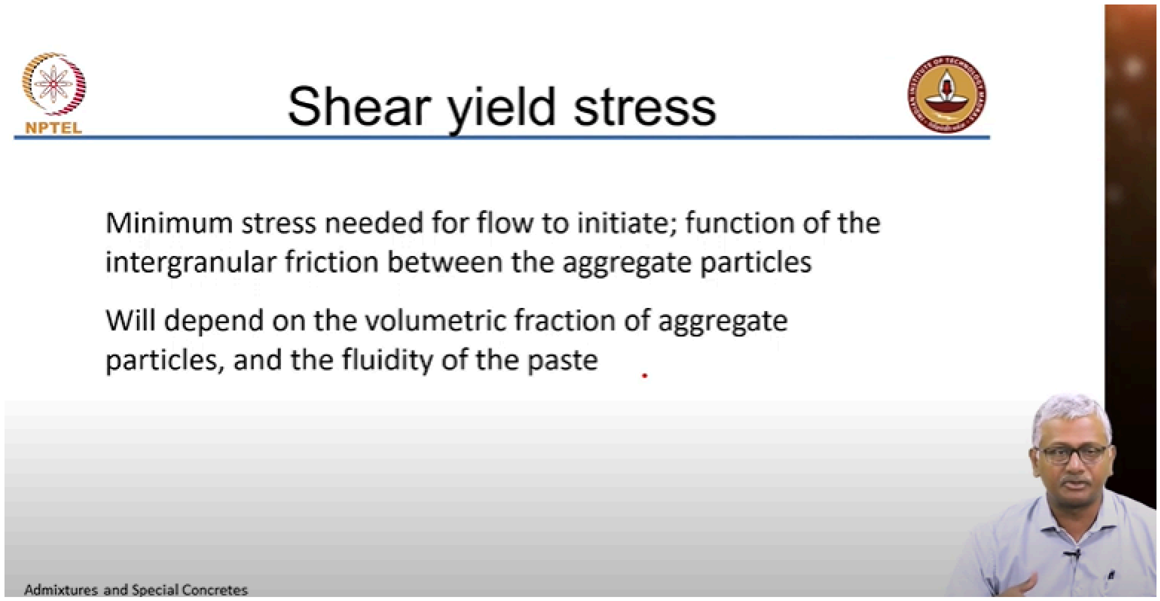

So if you look at the physical definition of shear stress it is a minimum stress required for flow to initiate, it is a function of the intergranular friction between the aggregate particles. So in a system that has got more coarse aggregate or more aggregate less paste what will happen if there is more friction, more shear stress. So that is why when you move from paste to mortar to concrete your range of shear stresses is dramatically changing. So generally it depends on the volumetric fraction of the aggregate particles and the fluidity of the paste because the more fluid paste will be able to carry the aggregates past each other. Less fluid paste means you need to overcome that resistance by vibration only.

Plastic Viscosity:

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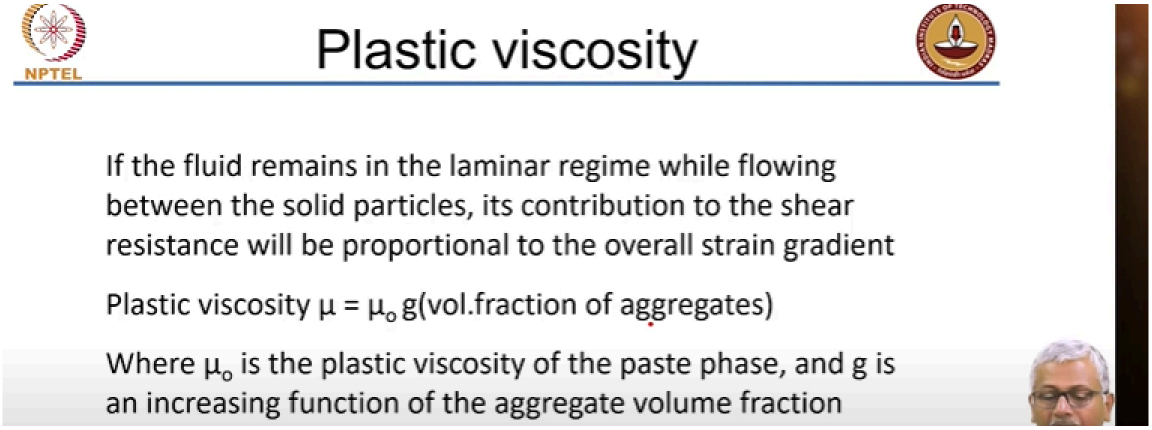

Viscosity once the flow happens what is the resistance to this flow that is defined by viscosity. So viscosity of concrete is a function of viscosity of paste and a function of the volume fraction of aggregates. Again why because if you have a lot of aggregate even if paste is less viscous it needs to carry this aggregate along with it. The paste has to carry the aggregate along. So if you have more aggregate that viscosity will become higher for the concrete. Even if the paste is less viscous it still has to carry this aggregate along. So because of that if you reduce the volume of aggregate you get a more or lesser overall concrete viscosity. So all this has to be looked at carefully when you do the mix design for different types of applications you may need different approaches for different applications.

Rheological Characteristics:

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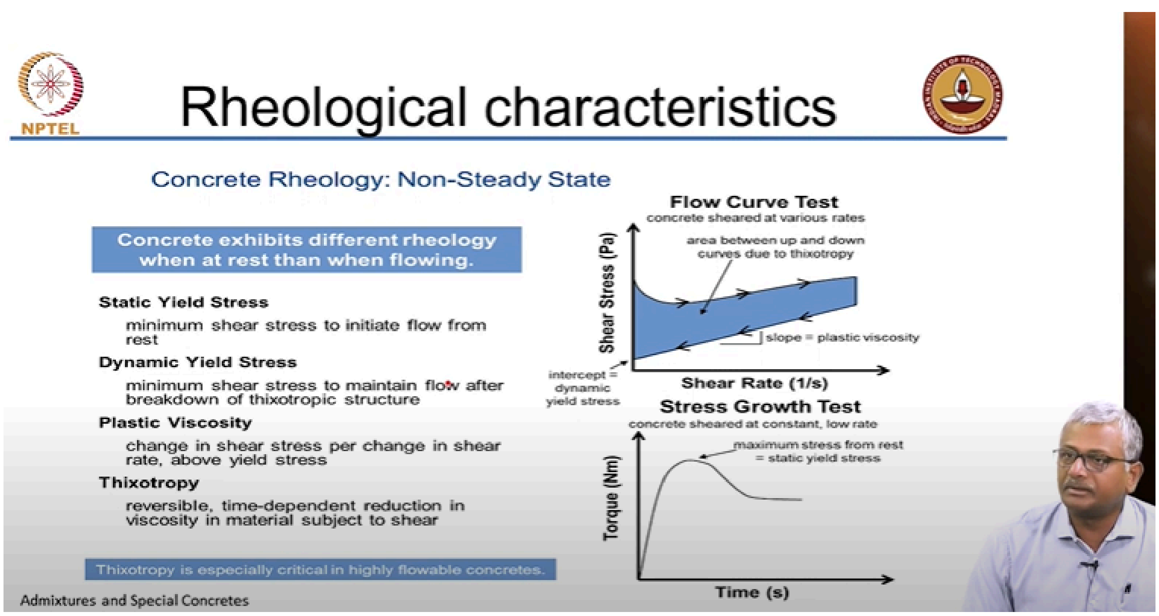

So taking a little bit different approach to understanding this behavior because we start from a period where the entire system is being mixed for the first time. So it is almost like from rest you are starting to agitate and then you allow a time for the concrete to start getting delivered to the job site. At the job site you increase the shear again and you cause it to start flowing out. So there are different types of shearing that you are doing in this entire process. So because of this you need to actually start looking at defining or looking at various segments of this rheology. So one is obviously you have to assume that concrete rheology has to be studied in the non-steady state.

Water we call it a steady state rheology. Why? Because once you apply the shear water flows. When it comes to rest it will come back along the same path. When you apply shear again it will flow again in the same path and come back. So the shear stress versus strain rate graph for water will be the same up or down because it is Newtonian it will behave the same way if it goes up or down. Concrete on the other hand does not always behave like that because it has got these particles suspended to initially get these particles to start moving past each other. The initial yield stress that you need to overcome is called the static yield stress. You have to overcome the static yield stress and that is typically determined by what is called the stress growth test where you study the torque as a function of time for a constant low shear rate. So what will happen in this case is the torque will build up, reach a maximum and then become stable. So this is a stable value of the shear stress with respect to time at a constant shear rate. The maximum that is achieved in this case is called the static yield stress.

So you can easily imagine that if you have a concrete and a container you take a stick and start moving it the resistance will gradually increase until it reaches a certain point but when you continuously move it at the same speed with time the resistance will come down and reach a stable value. So that is exactly what is happening. The concrete is getting mixed from the static state that is why you need to apply a higher stress to cause it to mix. But when the flow happens at higher shear rates the shear stress grows at a certain point if you reverse the shear rate it comes back down a different line it does not follow the same path. So we call this phenomenon as, what do we call this phenomenon as? It is a common phenomenon seen in many materials when you do not have the same path up and down "hysteresis" we call it hysteresis. It happens in magnetism also. So hysteresis is when you are not following the same path up or down but in the case of fluids we do not call it hysteresis we call it Thixotropy. What happens between the up curve and the down curve is because of the Thixotropic nature of the material.

Now in concrete it is generally observed that when you do this up curve you get a slight deviation from linearity but the down curve is mostly linear and you can take that slope of the down curve to be the plastic viscosity and the intercept of the down curve to be the dynamic yield stress.

Why is it dynamic yield stress? Because that is the yield stress that the concrete is exhibiting while it is under proper shear. It is the yield stress that concrete is likely to exhibit when you are trying to agitate it or pump it through your system that is the dynamic yield stress. So dynamic yield stress will generally be lower than the static yield stress because static yield stress is the minimum shear stress to initiate flow from rest from the position of rest. Dynamic is minimum shear stress to maintain flow after the breakdown of the Thixotropic structure. You have applied enough shear to break it down and that is the shear stress that is required to maintain flow. So you need to have shear stress applied beyond this level to have the flow happening. Plastic viscosity is the rate of change or change of shear stress per change in shear rate above the yield stress. So this slope is called the plastic viscosity and Thixotropy is the reversible time dependent reduction in viscosity in material subjected to shear. So it is a time dependent reduction in viscosity. So with time the Thixotropy also will change, the reduction in viscosity also will change. If you work with the concrete right after mixing versus working with the concrete after one hour, the buildup of the internal structure will get affected significantly at that stage. So with time the Thixotropic nature of concrete is also likely to change.

Thixotropy:

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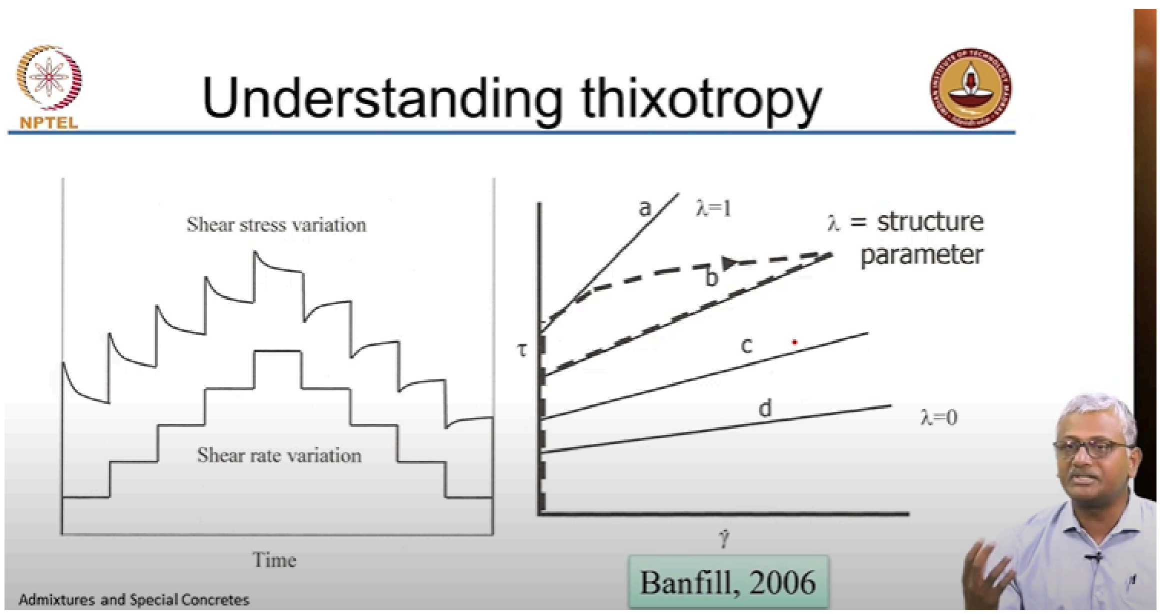

Now to understand Thixotropy we have to adopt some regimes in our rheology studies. Most commonly what we do is we either have a shear rate variation that means we step up the shear rate so from zero to a certain value, we maintain that shear rate for some time then step it up again and maintain it to study the Thixotropy. So when you do the shear rate variation like this what happens is the shear stress it reaches a certain value as you maintain the shear rate at that level there is a small reduction and then when you again increase the shear rate the shear stress again goes up to a certain value and when you maintain it there is a reduction in the shear stress. This is the same phenomenon as what you are seeing in this case. As you are maintaining the shear rate the shear stress reduces from the maximum value to a stable value. Now of course if you give sufficient time here if you maintain it for a long time then it will each cycle it will come to the normal value. So to study Thixotropy this is what is typically done. The shear stress is determined as a function of the ramping up of the shear rate. So it is ramped up to a certain level and then you work in the opposite direction, ramping down because you have to study what happens as you go up and then start coming down in shear rate also. And then you plot it here as the function of shear stress versus shear rate. If you have a behaviour like this or like this your structuration parameter is considered to be zero because you are going up and coming down along the same curve. But when you have a curve which is like b your shear stress is going up and then coming down along a different line. So there is some internal build up that is happening that is causing this to be Thixotropic. So there is some level of structural build up that is going on in this case. So that is described by what is called a structure parameter. Now of course this is only mainly for understanding. We are not going into a much more detailed expression of understanding Thixotropy but you have to understand that these are the critical things that play a role when you are mixing the concrete in the drum, pumping it through your pipes and then the concrete comes to rest in the formwork. All of these factors are affecting all that behaviour.

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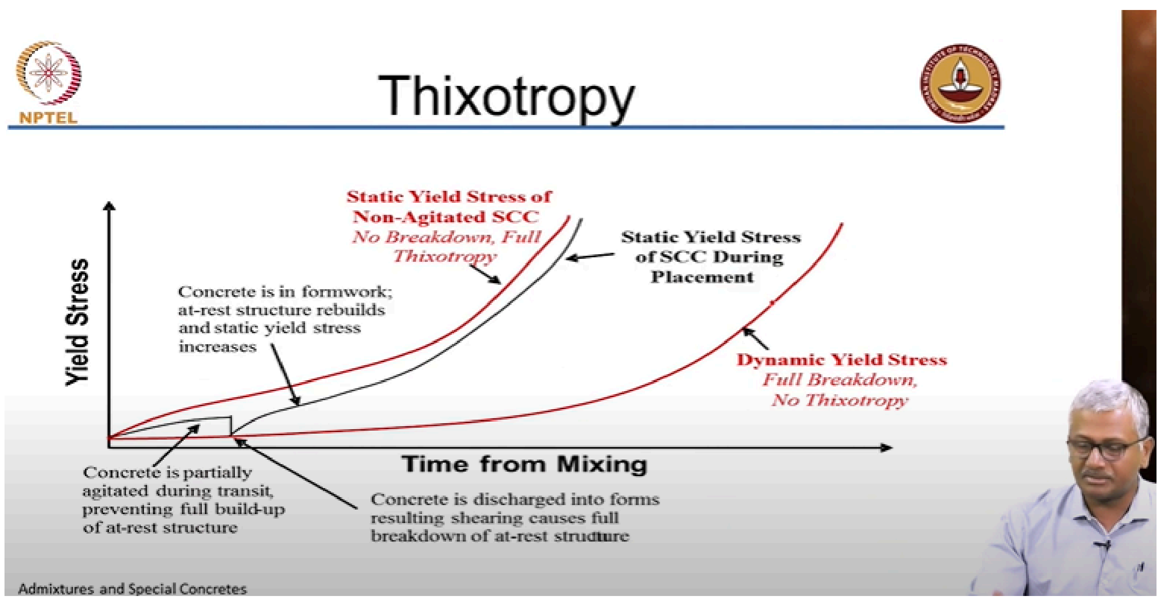

Just to capture the same thing as what I just said, let us talk about yield stress versus time from mixing. So what happens here is your concrete is ready to be dispatched from the RMC plant. It has been mixed, it has got a certain yield stress value. So now here static yield stress of non-agitated self-compacting concrete. So assuming that you take this concrete that is produced in the plant, put this in a truck and send it to the site without rotating the drum. You do not do any agitation, without rotating you send it to the site. The internal structure continuously builds up. The internal yield stress continuously builds up. So it is going to go up significantly. That means it is exhibiting full Thixotropy. You are not breaking down the shearing or breaking down the structure by shearing again. Now in this case the dynamic yield stress is when you are continuously agitating it at a high speed. But even there you expect that the yield stress will increase with respect to time because of other phenomena like hydration. It is not going to continuously have the same fresh property. With time it is going to start stiffening and that will lead to an increase even in the dynamic yield stress.

In this case there is no Thixotropy, there is no internal structural build up. There is hydration. Hydration is not the same as Thixotropy. Thixotropy is the internal build up when you come to a lower strain rate. But it does not mean that hydration has already started. So between two cases of static yield stress and dynamic yield stress development, you have the actual static yield stress during placement. So here you have concrete which is partially agitated during transit preventing full buildup of the structure. Then when it reaches the job site, you start rotating the drum faster to cause it to get discharged. It is rotated obviously in the opposite direction. The drum, RMC drum, is rotated in the opposite direction to push the material out of the chute. So in this case you are again reducing your shear stress to a level which is equivalent to a dynamic yield stress. After it gets placed into your formwork, the stress basically builds up. Concrete is in formwork at rest structure, rebuilds and the static yield stress continuously increases. So your actual behaviour is between the static yield stress of SCC that is not agitated and the dynamic yield stress when it is continuously agitated at a high rate.

So again very practical implications of understanding your basic rheological parameters as to how they control your entire system. Where is viscosity coming into the picture? We are talking only about yield stress. What about viscosity? As we discussed when you put your concrete in the formwork, if it is highly viscous it is not going to move out. So you have to shift the position of your chute. If it has got less viscosity then as soon as the pour it will start spreading completely. So that again needs to be controlled with your viscosity. So all of these have repercussions on the way that you use flowable concrete for different types of segments like a column or a beam or a slab and that is something we will discuss when we get to the chapter on self-compacting concrete. But all the basis of that lies in the understanding of rheology. We will stop with that for today and continue from here.