Admixtures And Special Concretes

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Lecture -74

Special concretes - Concrete for 3D printing - Critical parameters, yield stress

Real time applications of 3D Printing:

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And this doffing unit was put up in several Chennai hospitals. The idea was that at that time doctors had to wear the PPE kit completely covered from head to toe in the PPE kit and after they finish their rounds, they were contaminated. So, they enter through this door, they discharge their PPE kits through this chute here so that they do not get contaminated further and then they enter the other room where there is a bath so that they can come out clean and disinfect it. So, this was appreciated a lot by the Chennai hospitals. This was a corporate social responsibility project funded by Saint Gobain Research in India.

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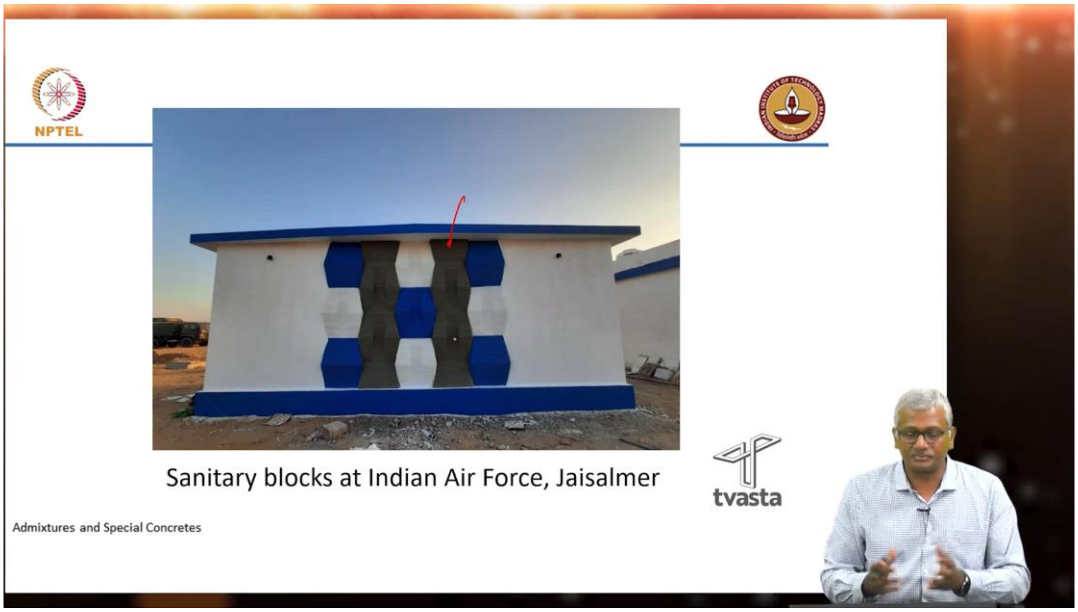

Then Tvasta also built these toilet blocks for an air show in Jaisalmer. An interesting concept of design was adopted for the walls here. The walls were, the inspiration was the step pills in Rajasthan and you can see the features that do not exactly meet with the step pills but the idea was originated from the step pills of Rajasthan.

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Another picture of the same wall.

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This was a guest house done in Gandhinagar for Air Force and again you can see the kind of texture that has been put up in the front wall which is not possible with conventional construction. So, unless we do manual 3D printing with plaster, we are not going to be able to do it. So, this is a completely machine-fabricated system. So, in this case, they ,took the printer to Gandhinagar, set it up there and they were able to deliver the entire project including two houses in a matter of 30 days. So, again that was a significant achievement.

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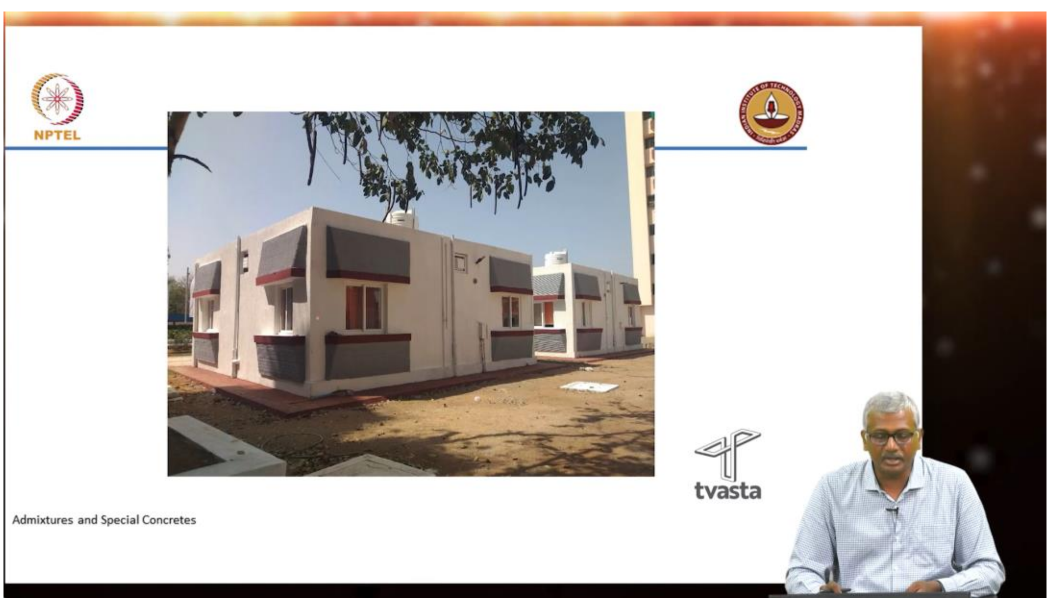

Again, another picture of the back of the two buildings.

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And this was an interesting bus stop designed for Godrej. It stands inside the Godrej campus in Mumbai. Four elements were printed. This is one, this is the second one, there is a third one, fourth one. As you can see it has a double curvature in this direction and in this direction.

So, there is significant bit of reinforcement that is necessary to ensure that the concrete does not fail. And this entire segment, for instance, this first segment which comes like that and comes to the base and then like that, this entire segment was cast at once. The entire casting was done at once. So, layers were placed and then the reinforcement which was required obviously to take the tension in the curved part, reinforcement was also put in between the layers and embedded, and then continuously this concreting was done. This entire segment was then put together, carried in pieces, and then put together for the bus stop.

The profile of the structure looks like G for Godrej. So, they wanted the profile to be like that. I think similar construction was done for some bus stops in Chennai also and in IIT Tirupathi they placed now a bus stop like this.

Okay, so there are several other structures that they did for India Cements that are quite popular. If you go on the Santom high road towards the Marina beach, so outside the India Cements building there is a nice monument that they have actually done. It is called the Anantasiras. So, it is four snaking arms of 3D printed concrete going up to a height of about I think 3 meters or so, 3 to 4 meters. That was done for the 75th year anniversary of India Cements. Also, if you make your way to one of the IPL games in Chennai, the new boundary wall close to the main entrance of the stadium has been entirely done in 3D printing.

That is really very interesting structure also. So, talking about what 3D printing can do is exciting obviously because there is a lot of interesting projects that we can realize with 3D printing. But one thing you have already realized is how do we actually reinforce these kinds of structures. That is going to be a major challenge. We will come back to that later.

Critical parameters for concrete 3D Printing:

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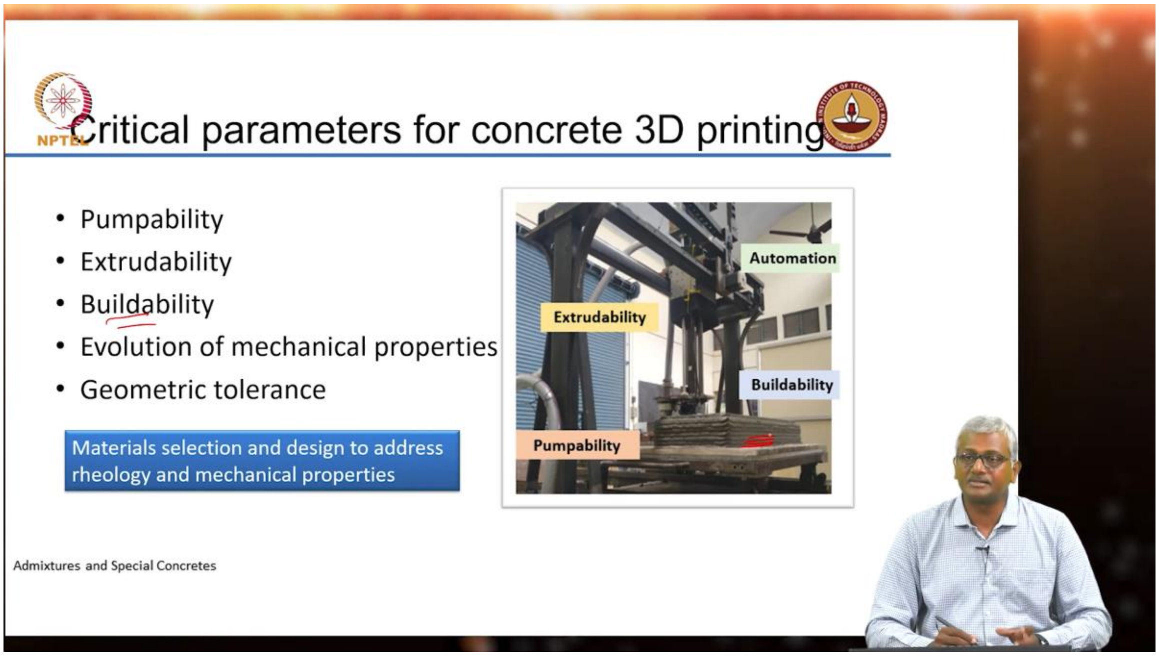

But before that let us talk about the concrete itself. So, for 3D printing, several parameters of concrete are extremely important. One is pumpability like any other concrete, 3D printing concrete also must be pumped through the delivery system to the point where the discharge is happening. When it is discharging it must maintain its shape. Right. It should extrude from the nozzle maintaining its shape. Right.

It should have sufficient internal stress to maintain its shape. It should be flowable also to come out in a single continuous manner. It should not come out in lumps then you will not get your 3D printing structure. So that is called extrudability, how easily one can extrude out of the nozzle.

Then buildability, once you cast layer upon layer because you are casting everything in the fresh state. You are not waiting for a layer to get hardened and putting the next layer.

Then you will get a cold joint. You want to avoid that. So, you are placing the concrete while it is still fresh.

It is not set and to ensure that you get a proper bond between layers and still ensure that the layers below do not start deforming when you put the layers above. You need to make the concrete buildable. It should have sufficient internal stress development to keep from deforming. So, if you choose self-compacting concrete and try to put layer upon layer it will just keep flowing. It is not going to build up.

Evolution of mechanical properties obviously is important. We need to ensure that within a certain significant amount of time, it is able to get the required strength for us to take the element, put it aside for curing, and so on. Otherwise, it will remain in the print bed. We do not want that to happen. Geometric tolerance as I showed you the geometric intolerance that happened during the construction of the house which led to the masonry walls coming in between and so on.

So that is an extremely important characteristic of 3D printing. Now if you do an onsite print, you may not have that level of a problem with geometric tolerance because you are not bringing in pieces and assembling them. You are continuously printing onsite. But even their geometric tolerance can be a problem. Let us say some layers in between start squishing out and your entire placement starts shifting a little bit.

The center lines of the layers do not perfectly match. In that case, you will still get some geometric intolerance that may lead to failure. So, it is important to do a good material design and this design should address rheological characteristics and mechanical properties. So, your rheology which we learned earlier which was crucial with concrete such as SCC again is important with respect to 3D printing.

Importance of yield stress:

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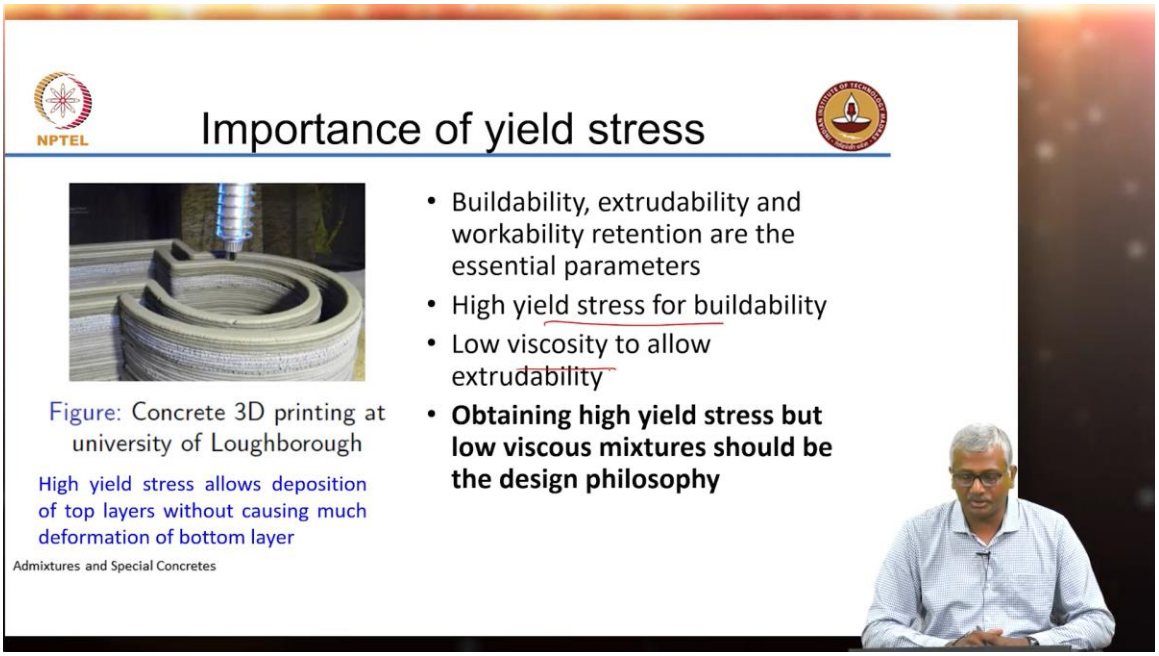

So here we have a slightly different concept. You remember in self-compacting concrete we wanted concrete of almost 0 yield stress. Concrete should simply start flowing as soon as you pour it into the formwork. Here we want the opposite. You want the concrete not to flow at all when you deposit it. At the same time, the concrete should be able to push out, and get pushed out of the nozzle.

If it is too stiff pushing it out will be extremely tough. So that is what exactly we mean here that the rheological characteristics are slightly different as compared to when you deal with SCC. So generally, we want while extrusion viscosity to be low and perhaps even yield stress to some extent should be not very high. But once you deposit it the yield stress development inside should be quite rapid and it should build up its own internal structure as soon as possible. Generally, we want high-yield stress for buildability and low viscosity to allow extrudability. It should be able to push out easily from the nozzle. So, it is a little bit on the opposite side as compared to your self-compacting concrete.

Measurement of yield stress:

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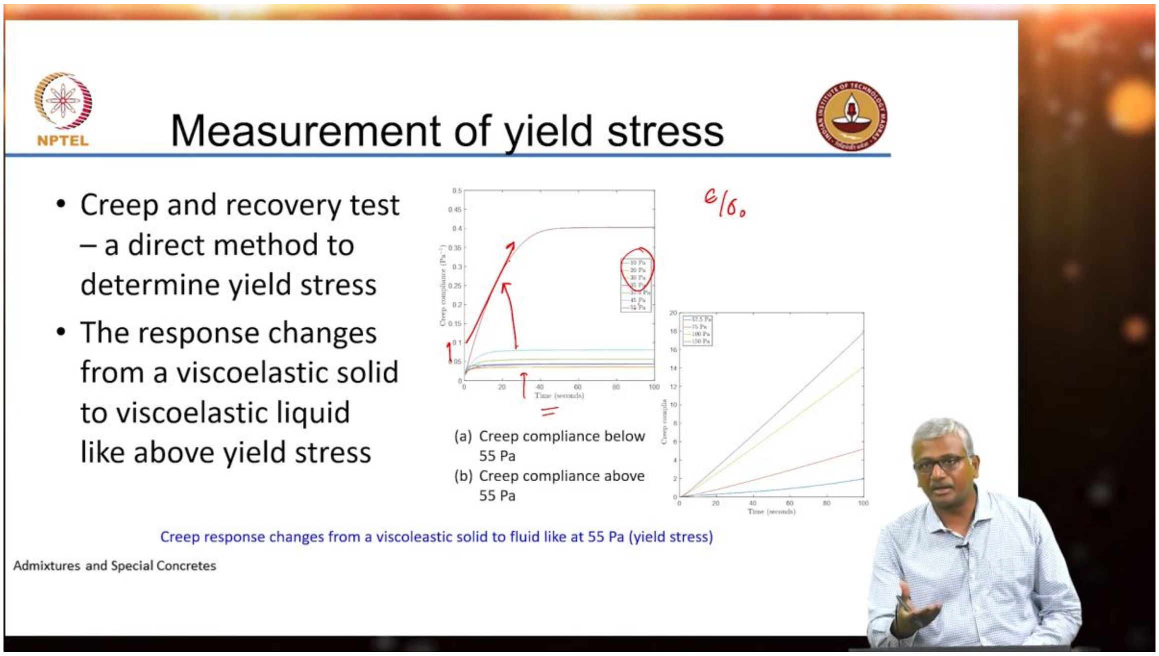

Now yield stress measurement we have discussed this previously also to some extent. So, you can do it using a rheometer, using the creep and recovery test. So, you are applying some sort of a shear constantly over a certain time and what happens is after you remove that shear the material is able to recover somewhat.

If you are beyond yield stress, if you cause the sustained shear on the sample, it will not recover that shape it will continue flowing. So, in this case in this example for instance what has happened is your creep compliance, what is creep compliance? It is the strain divided by the constant stress because in creep you know that you have a constant stress and the strain keeps changing with time. So, creep compliance is represented typically as strain over the original stress. So, this is plotted against time. So, with different levels of stress that are applied to your system, you are seeing the behavior of your system.

So at this point when you change from 45 Pascal to 55 Pascal stress your behavior of the system is changing completely. What is happening? Up to 45 Pascal stress your material was constantly flowing without really increasing the creep strain too much. But beyond 45 your creep strain underwent a massive increase which means some extent of yielding has happened in your system. Your system has started yielding. So, your yield stress basically can be taken from a creep and recovery experiment. Here in this case, 55 Pascal could be considered as a creep stress.

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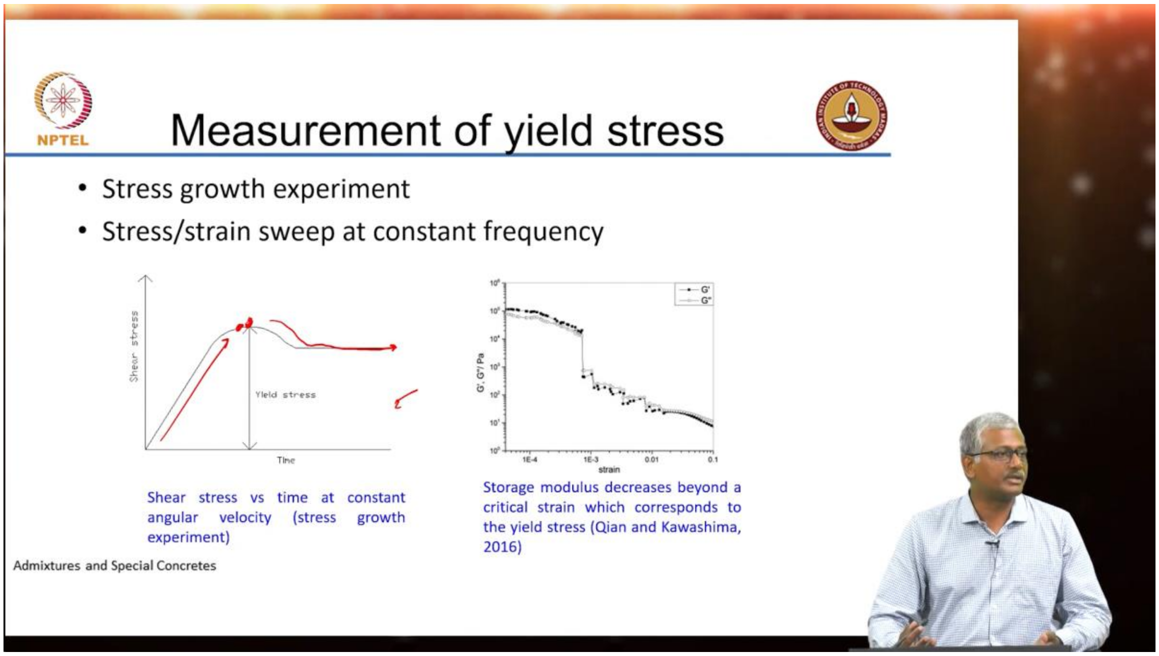

The other possibility is to use your stress growth experiment like what you do in your vane shear test. Again, vane shear we have the vane rotating at a constant speed. And with respect to time as soon as we start rotating it, it is trying to push the material which is resting and getting it to move. So that is why your stress builds up to a maximum level and then once you obtain a consistent flow of the material the stress reduces and then remains constant.

In this test, in the stress growth test the yield stress is taken as the peak stress. If you remember our discussion of SCC, we called two types of yield stress static yield stress and dynamic yield stress. So, what would this be correlated with? Static or dynamic? This is static yield stress. Dynamic happens when you shear it, lower the shear, shear it again, lower the shear finally the amount that it settles on at the end is called the dynamic yield stress. That is much lower than the static value.

So, there are several ways of using a rheometer to determine the yield stress but a simple way for most 3D printing applications is just to use a vane shear test. Using a vane shear you can determine the yield stress quite accurately.

Importance of structural build-up in 3D Printing:

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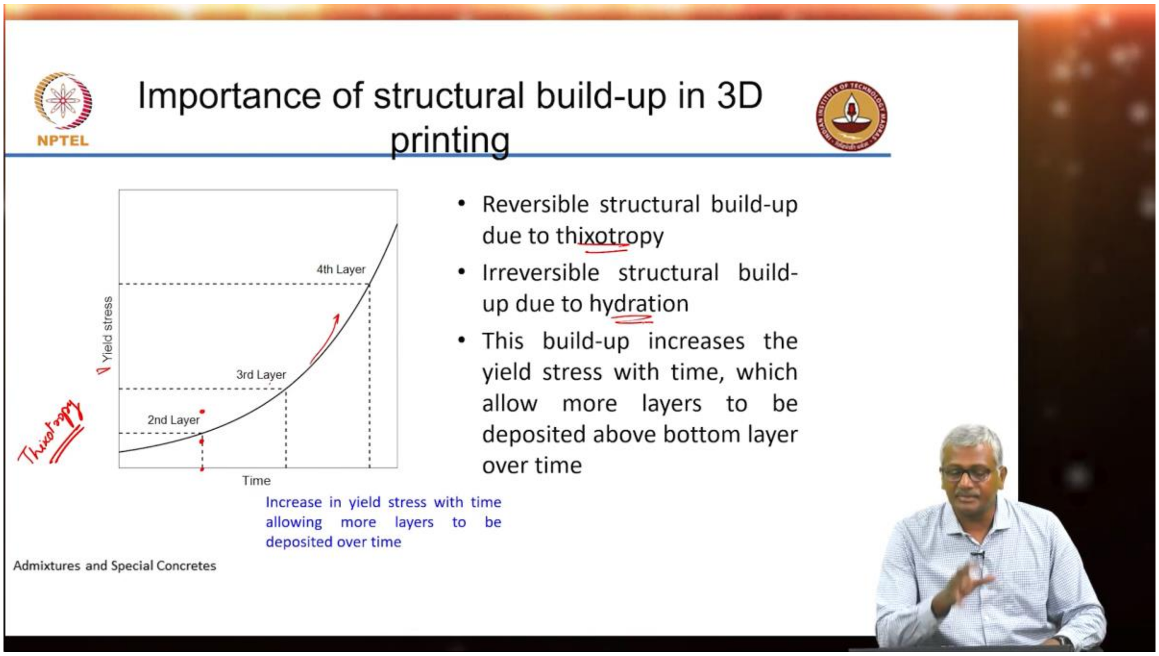

Now once you put the layer on, it starts developing an internal stress. It is not hardening it because as I told you, you need to put the next layer before the first layer is even started setting. In fact, in real construction operations, we are talking about a time gap between the first layer and the second layer of only a few minutes, 5 to 6 minutes that is it.

You place the first layer; the printer goes all around the building by the time it comes back to the same location it will be about 5 to 6 minutes because most printing happens at the speed of nearly about 50 to 150 mm per second. So, imagine 100 mm per second means in 10 seconds the printer is already moved by 1 meter. So, for it to come back depending on the size of the building and the peripheral length that you have in the building by the time it comes back to the same point it may be a matter of only a few minutes. But within those few minutes, your material should exhibit some internal stress build-up. Why? Because when the next layer comes on top there will be added weight because of that which will push down on the bottom layer and that added weight will cause the bottom layer to start spreading out.

So here for instance, if you plot yield stress versus time for your concrete this is the development of the yield stress with respect to time. So, if your second layer is coming at this particular point at this time and let us say the stress because of the second layer weight is somewhere here. What will happen to your system? The stress due to the weight of the second layer is greater than the yield stress of the first layer. So, what will happen? What will happen to the first layer? It will collapse, it will start spreading out. So, you want to design your material in such a way that when you add the second layer the weight due to the addition or the stress due to the mass of the second layer is lower than the yield stress that is getting developed in your system.

Which means that you need to do a proper rheological design of your concrete to achieve that structural build-up, internal structural build-up which we had called previously as Thixotropy. When the material is at rest it builds up an internal structure which resists further deformation that is basically Thixotropy. If you start now deforming this material by applying too much stress it will deform. But here you do not want it to deform so you want to keep the stress level because of the added layers to lower than the internal stress build-up. Similarly, when you add the third layer you want the weight because of the second and third layers together to be below the yield stress which is now present in the bottom layer.

So, this is the structural build-up. Usually, structural build-up we are talking about in the first few minutes or first couple of hours of placement in which case it is mainly Thixotropy that is playing a role there. Unless you have a rapidly hardening system or rapidly setting system in which case there will be some irreversible structural build-up also because of hydration. If you are using a high-strength cement for instance it will start reacting very fast. And in such case, the yield stress development will not just be because of the thixotropic nature of the material, it will also be because of the hardening that happens because of hydration. So, all of these studies need to be done before you really define the properties of your system.

Modelling the structural build-up:

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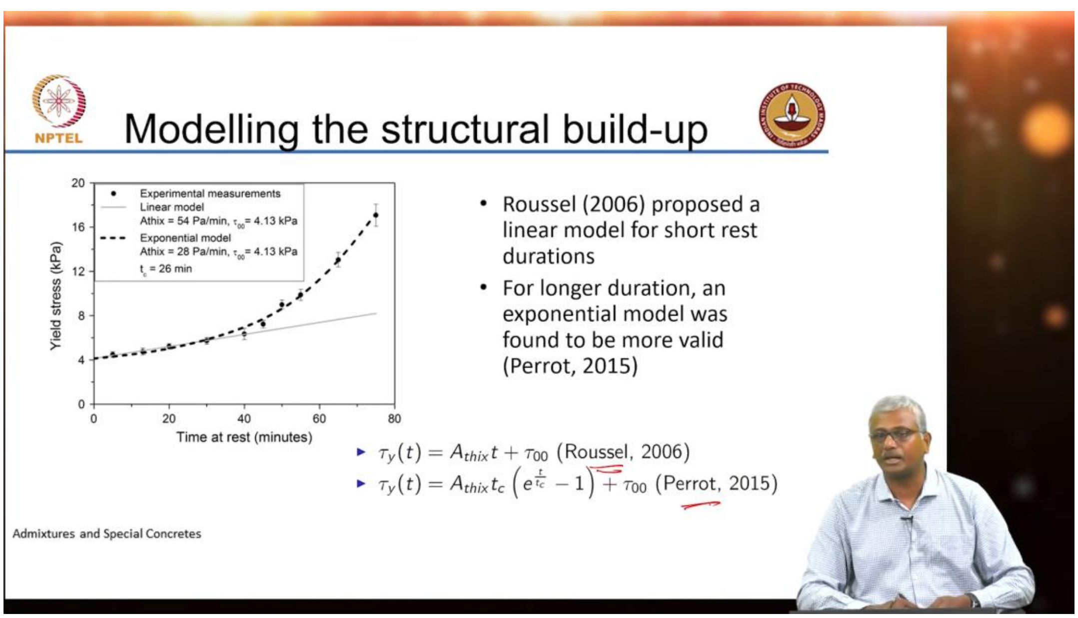

So structural build-up can be modeled. There are existing linear and non-linear models which can be used. So here, for instance, there is a model by Roussel which is a linear model and there is a model by Perrot which is a non-linear model. So, various different models seem to fit quite well with the experimental data that have been generated for concrete systems with respect to yield stress development with respect to time.

Work Done in IITM:

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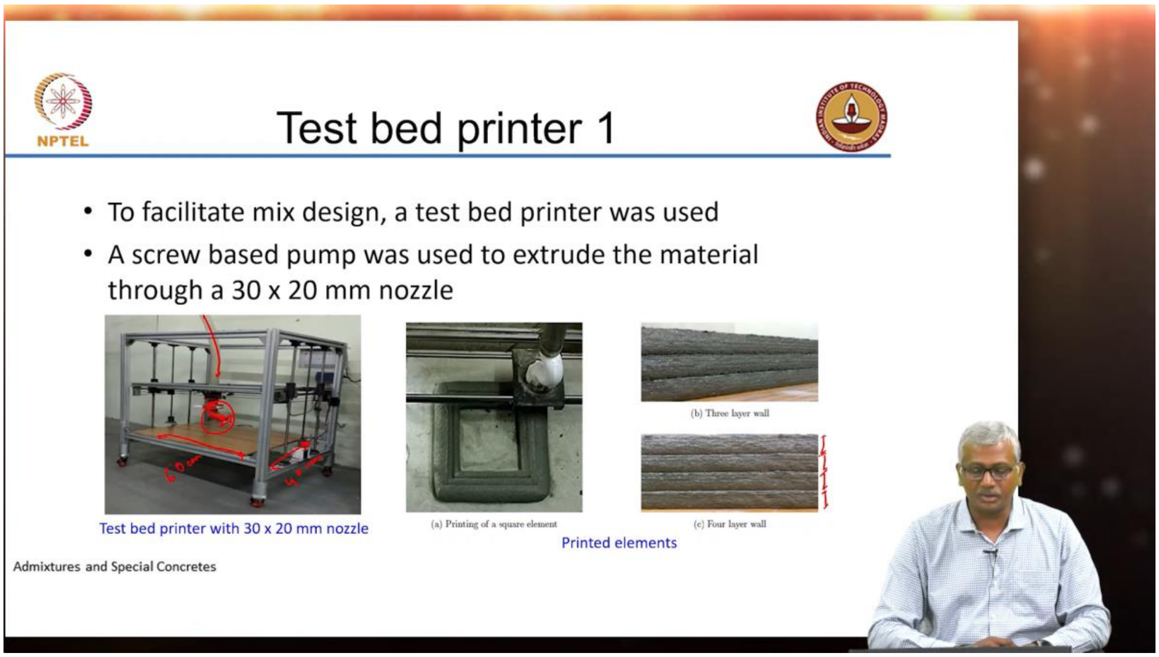

So, at the work, we did in IIT Madras, the first set of studies were done using this extremely small printer. Here the overall bed size was only about 60 cm by 40 cm.

That was just the size of this. It is almost like a tabletop-type model. And you had this pipe carrying the concrete to the nozzle in this case a rectangular nozzle is being used and this nozzle you can see is shaped in this direction. So, you are essentially moving the nozzle and the concrete is getting placed directly. The next layer comes it places the concrete in the first layer it is not pushing the concrete into the next layer.

If you had a circular nozzle that opens right at the bottom that will push the concrete in the next layer. So, in this kind of a system, the bond between layers could be a bit of a problem. But if you have a circular nozzle that pushes the concrete down into the first layer you can overcome bond effects to some extent. So, using this several different types of elements were cast you can see a 3-layer wall and you can see that the height of the layers is fairly consistent. The 4-layer wall you can see that the height is fairly consistent which means the system is buildable.

The mix design is suitable for building up with 3D printing. Extrudable because the material is coming out with a definite shape and maintaining that shape that is basically how you define extrudability.

Extrudability and Buildability Tests:

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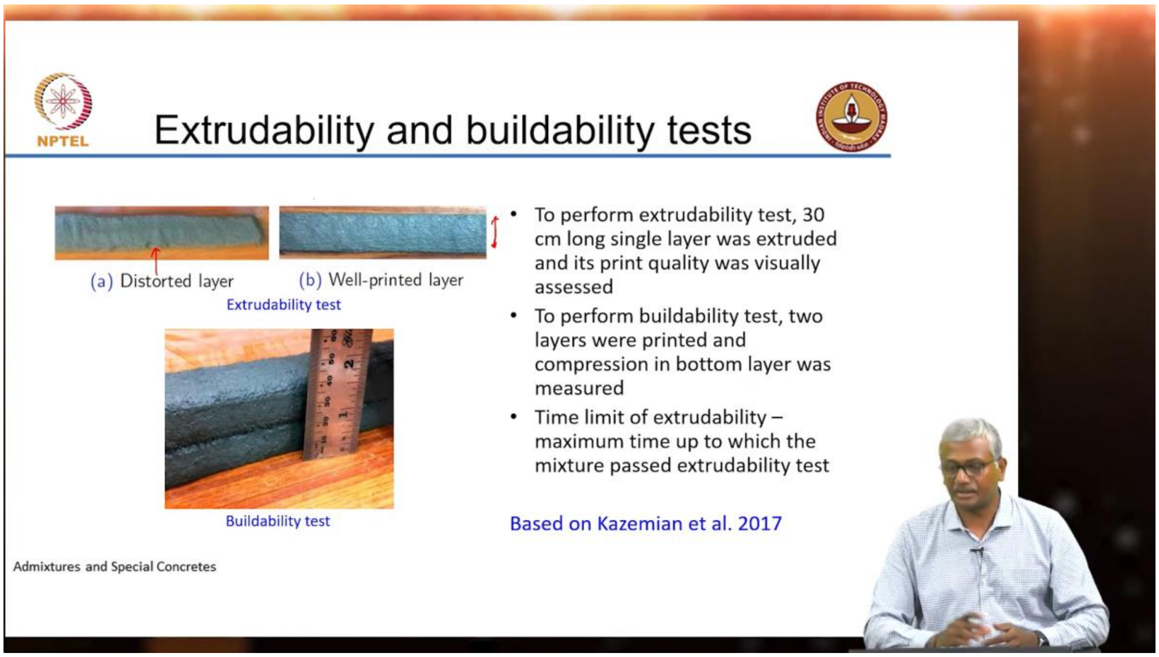

As I said for a material to be extrudable your layer dimension should be consistent throughout a length. So, in this case, we printed a length of 12 inches or 30 cm continuously and saw that there were no distortions in the extrudable concrete mix. But here you can see there are a lot of distortions so this is not an extrudable mix.

Extrudable mix will have a consistent shape and size when you print it. Buildability, of course, you can measure the heights of the layers when you add the next layer onto it. So, weldability can be seen by the number of layers that can be deposited without causing a failure. I will come back to that point towards the end of the lecture also.

Robustness based on yield stress:

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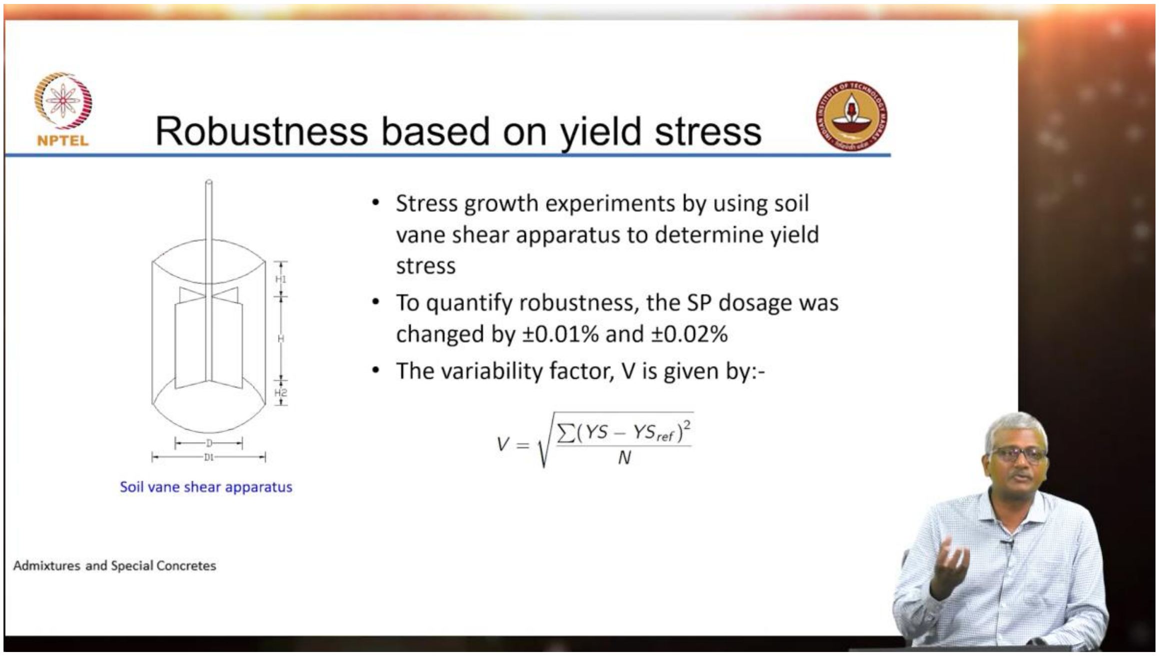

One thing you must remember, of course, I can always improve the buildability by waiting a long time before I pour the next layer.

I may as well wait for some more time the layer below will get somewhat hardened then I place the next layer I will not get a problem of changing the dimensions of the layer. But the problem there is your productivity has gone down and secondly the bond between layers also will go down if you wait too long. The general thumb rule is that before the surface moisture on the layer dries up you should place the next layer. Why? Because moisture implies that there is still some freshness in the material and that point bonding with the next layer will be better. If the layer starts drying up and there is no surface moisture left you will not get a good bond with the next layer.

So, it is very important to have a proper placement strategy. So again, the yield stress measurement by vane shear was done in the study. You can see the dimensions of the vane. Stress growth experiment just like what I showed you previously with the vane being moved at a constant rate and the stress being measured up to a maximum and then it comes down. So maximum value of stress was recorded as yield stress. Here we wanted to look at a mix design and decide whether it is robust.

Now this robustness is something that we did not touch upon in self-compacting concrete also but it is a very important feature of any concrete mix design. So, robustness means that if you take a concrete mix from lab to site it should act the same way irrespective of the small variations that may happen on the site because of the deficiencies in your batching equipment. For instance, if you put 5 kilograms extra water the mix should still be able to get the correct workability range, the correct strength development and so on. So that is called a robust mix which is able to adjust to the inconsistencies that you may see at the field. Similarly, here we wanted to ascertain that the concrete mix design that we have come up with is robust but in this case, since we are dealing with very small quantities, we looked at the variation in superplasticizer dosage as to how it affected the robustness.

I will come to this study in the next class on Thursday because we are out of time for today. We will continue from this point onwards.