Admixtures And Special Concretes

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Lecture -76

Special concretes - Concrete for 3D printing - Failure modes, buildability, early-age behavior

Failure modes of 3D Printed elements:

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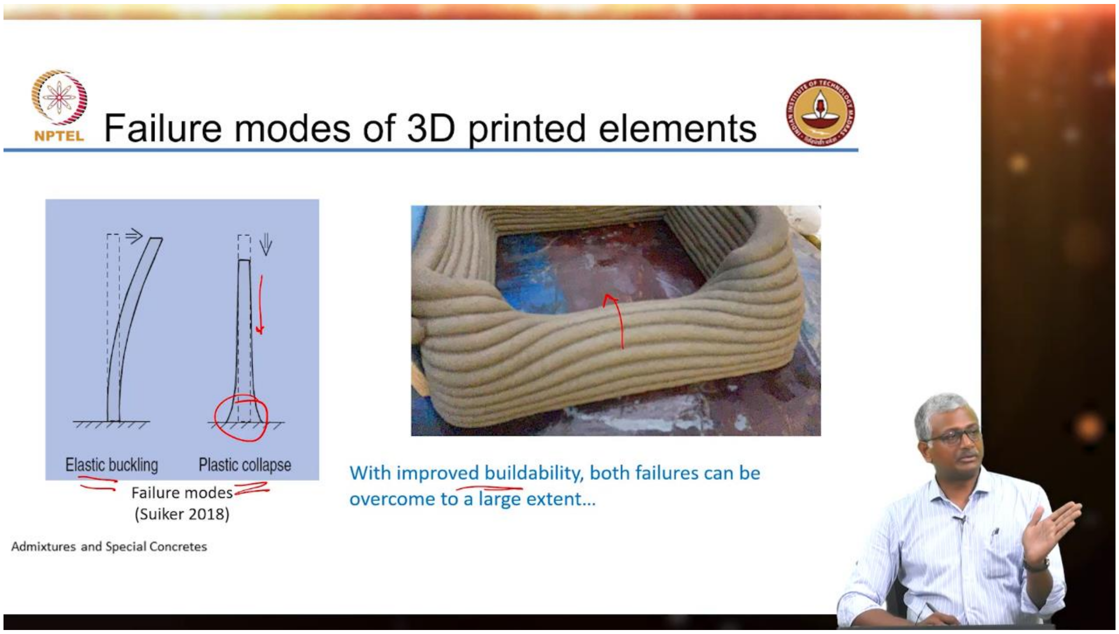

Now, if you were to look at the ways in which 3D printed elements can fail because we are continuously printing, right, if you imagine the mechanics that are in operation, you can have a scenario similar to what we otherwise known as elastic buckling. We are printing these thin perimeters one on top of each other. The stability may become questionable and then the material may collapse. Alternatively, you can also have a plastic collapse where the weight due to the layers above is simply too much for the lower layers to handle and they start bulging out. So, both these types of failure can happen.

With improved buildability, these failures can be avoided. As you can see here, (refer figure on the right) this layer is simply collapsed to the inside. You still have some stability here but this layer has started collapsing. That means at that point, the balance may have shifted so that it started collapsing.

Importance of structural build-up:

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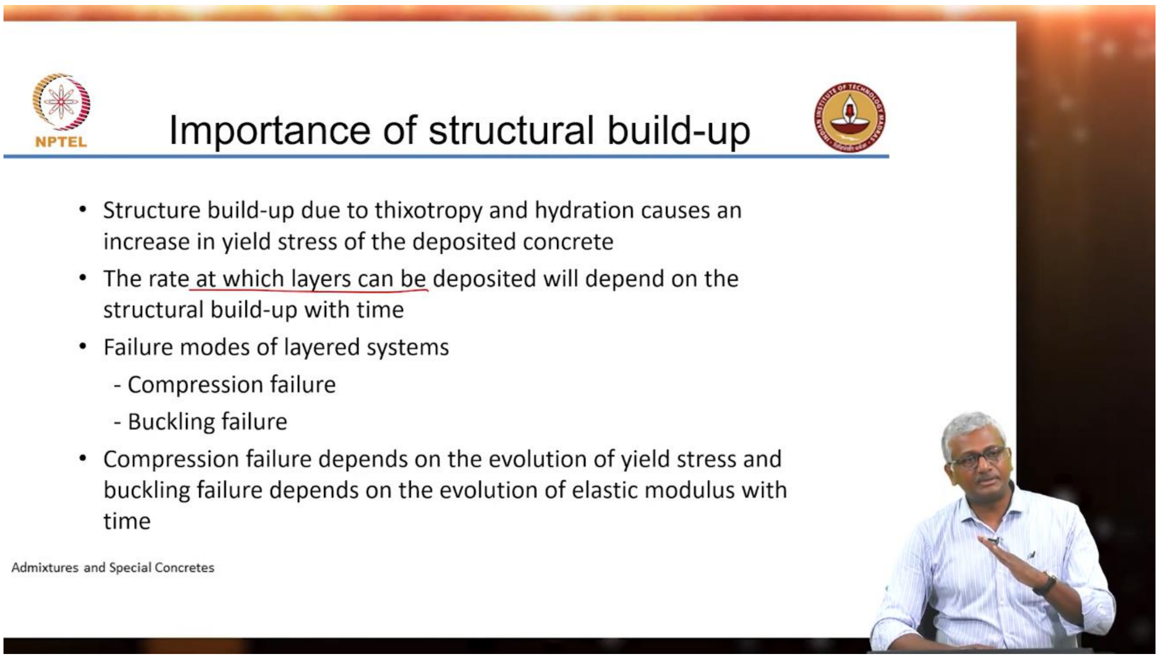

Now, that is why the internal structural build-up is important. We need the structure to build up internally and that is happening as we discussed before because of the thixotropy and because of hydration. Thixotropy ensures that without any chemical effects, you are getting some internal structure build-up. Hydration is a chemical effect where the reactions are happening and then the yield stress inside the system is increasing. As we discussed earlier, the rate at which the layers can be deposited will depend on how the structural build-up goes up with time.

Again, just to look at these failures again, compression failure depends on the evolution of yield stress, and buckling failure will depend on as it does in normal hardened concrete members and also on the evolution of elastic modulus with time because that stiffness is what prevents the buckling from happening.

Compression failure:

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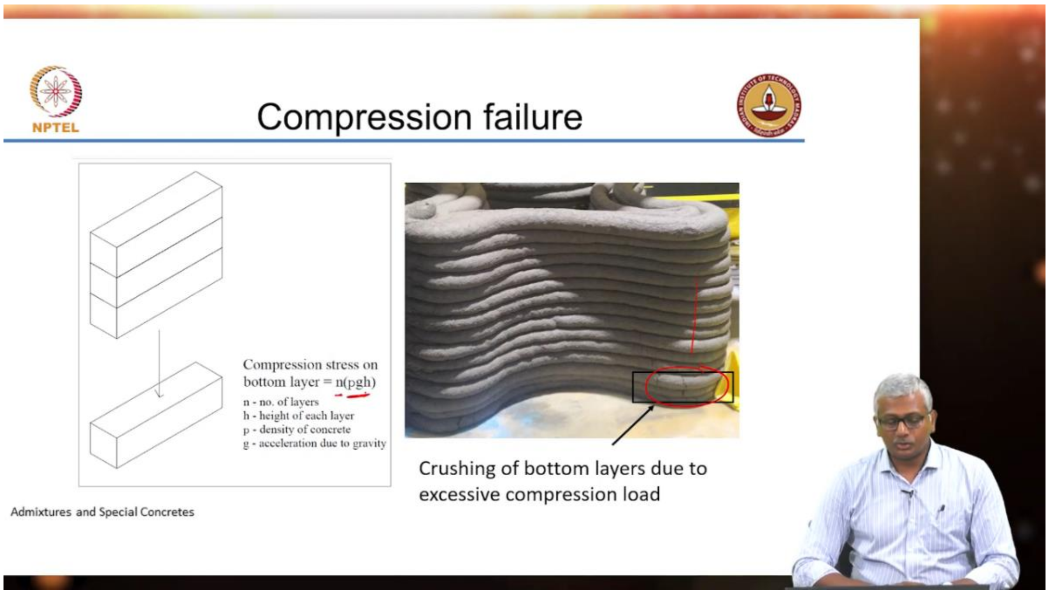

So again, another example of compression failure, you have several layers on top and the layers below are starting to bulge out and are cracking. You can calculate the stress quite easily, the number of layers into ρgh, and density into acceleration due to gravity into the height of the layer.

Buckling Failure

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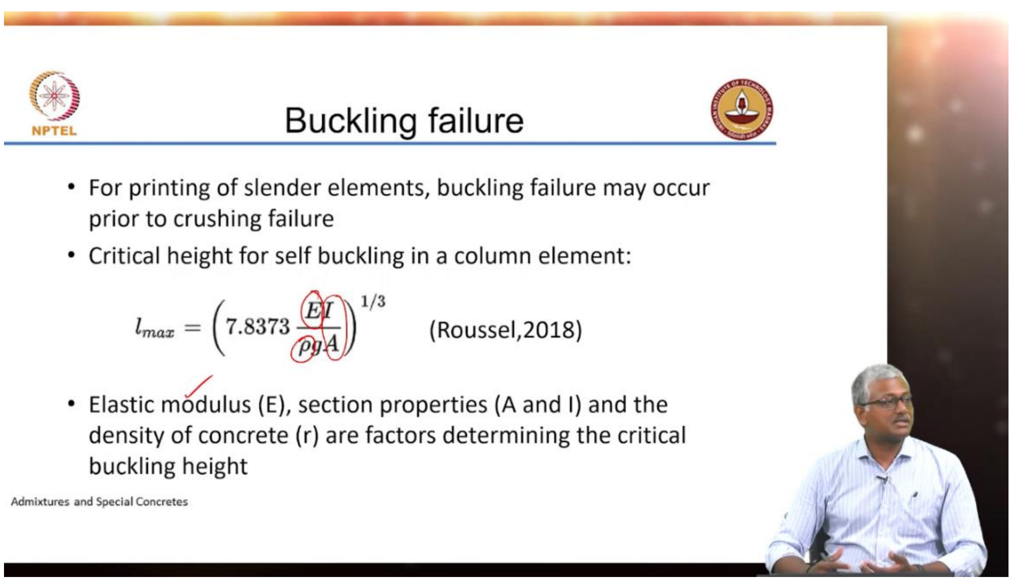

In the case of buckling, there has been some understanding of this for printing of slender elements, you can say that the maximum length or height of print that you can obtain is dependent on the modulus and of course, the sectional properties I by A and the density of the material. So, what are the ways in which we can improve or increase this length? What factors of the concrete can we work on? Increase the modulus of elasticity, right? Increase the modulus or you can decrease the density, or lower the density.

So that means when you use lightweight concrete, you may be able to build up much more as compared to normal-weight concrete. But the problem is lightweight concrete stiffness also needs to be looked at. But this stiffness here we are talking about in the initial stages when the concrete is not yet hardened. So, this is the green strength or green stiffness that we are talking about. It is not the hardened concrete behavior. But this has to be studied appropriately.

Buildability depends on:

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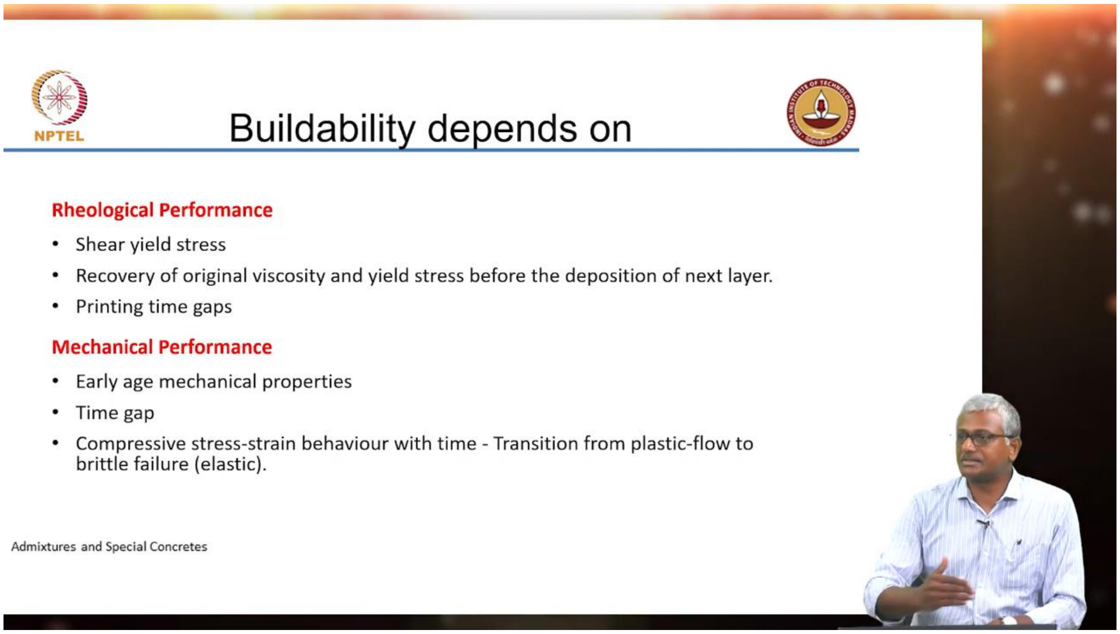

So again, as I said buildability is the critical parameter to be addressed here in order to avoid these two types of failure. It depends obviously on the rheological performance in terms of shear yield stress, and in terms of mechanical performance also. So, in terms of mechanical performance, we are talking not just about the later age but we also need to assert in the early mechanical performance, what happens as soon as the layer is printed. Now as far as the stress-strain behavior is concerned, the material is initially a liquid and slowly starts getting some stiffening.

It starts behaving like a plastic material and slowly transitions to an elastic type material. So, the structural properties of the material are also changing with time, it gets adjusted and because of that, you have to study this process over some period of time.

Compression of layers in 3D Printing- considering yield stress fluid

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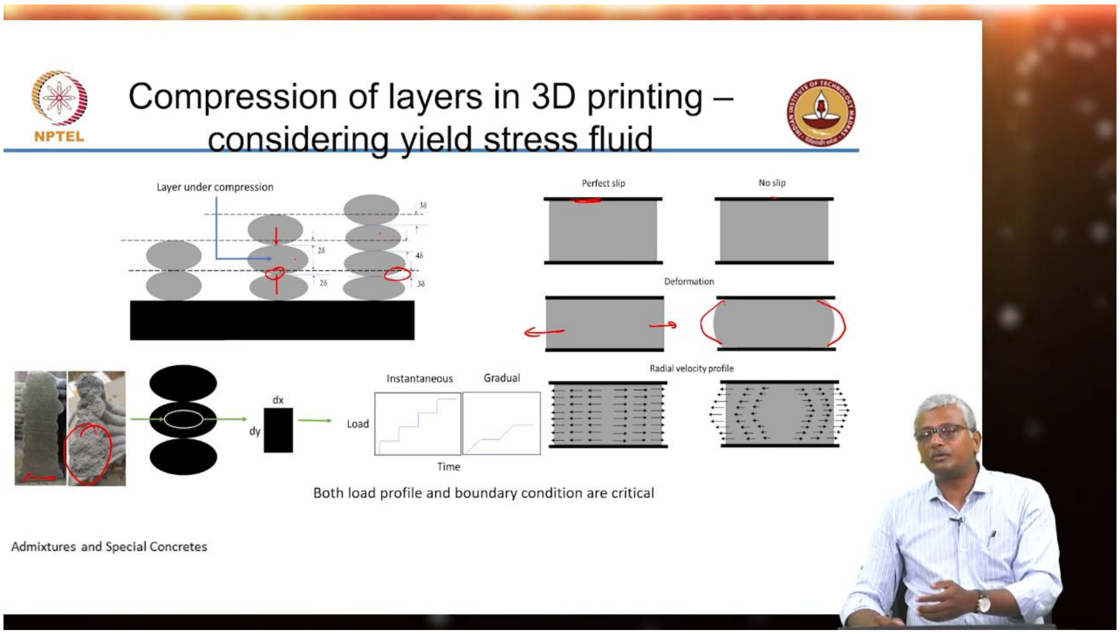

So again, just to bring that schematically you can see what really happens as the next layer is coming on top there is some compression of the bottom layer that changes the overall height of the overall element. When you bring the next layer on top the amount of deformation that happens in the bottom gets increased if the bottom is not able to simply take that up. So, you can see an example here of what has happened.

You can see that the bottom layers are bulging out as compared to the top layers. We took a cross section through a printed concrete and you can see that buildability is getting affected here. So, what we can do is study this under let us say a compression test where the fresh concrete, molded fresh concrete is taken and loaded under the plates of a compression testing machine. Assuming that you have a perfect slip at the boundary, what is likely to happen? This material will simply spread out as you are compressing it. If there is no slip, if there is perfect friction then your bulging will start from the center but the top and bottom will not be allowed to move out. So, you have to solve these end conditions and then arrive at what would happen to the system when it is getting compressed.

Squeeze flow test:

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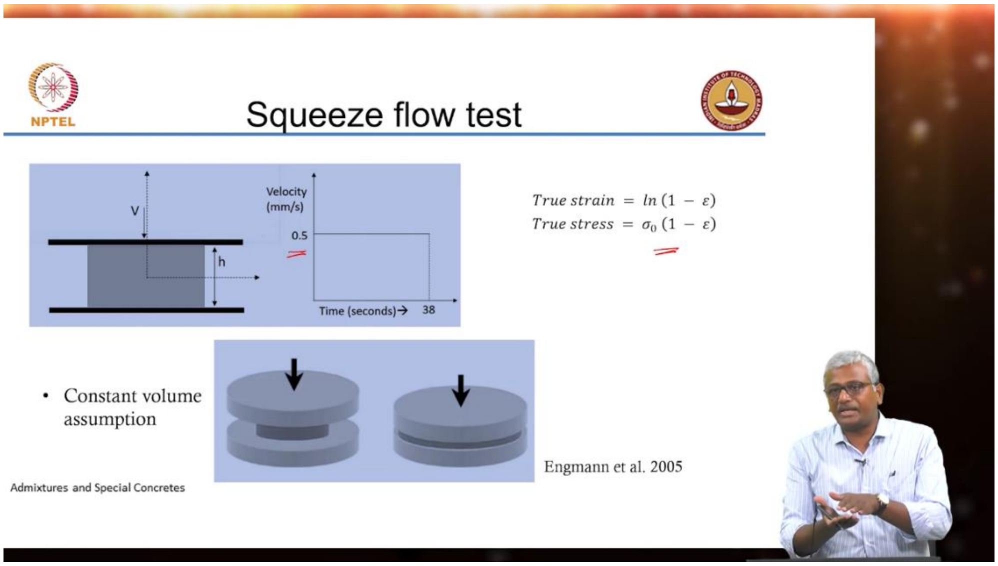

So, for that, we looked at a compressive rheology measurement called the squeeze flow test. Here again, the loading platen is moved at a constant rate. You have the initial height of the member and the velocity is kept constant with respect to time. So we assume that your system gets perfectly slipped along the boundary and assumes a different volume. So, you can then determine the true strain and true stress from this setup. Of course, true stress implies that you actually take the cross-sectional area that is changing with respect to time.

Behavior in the squeeze flow test:

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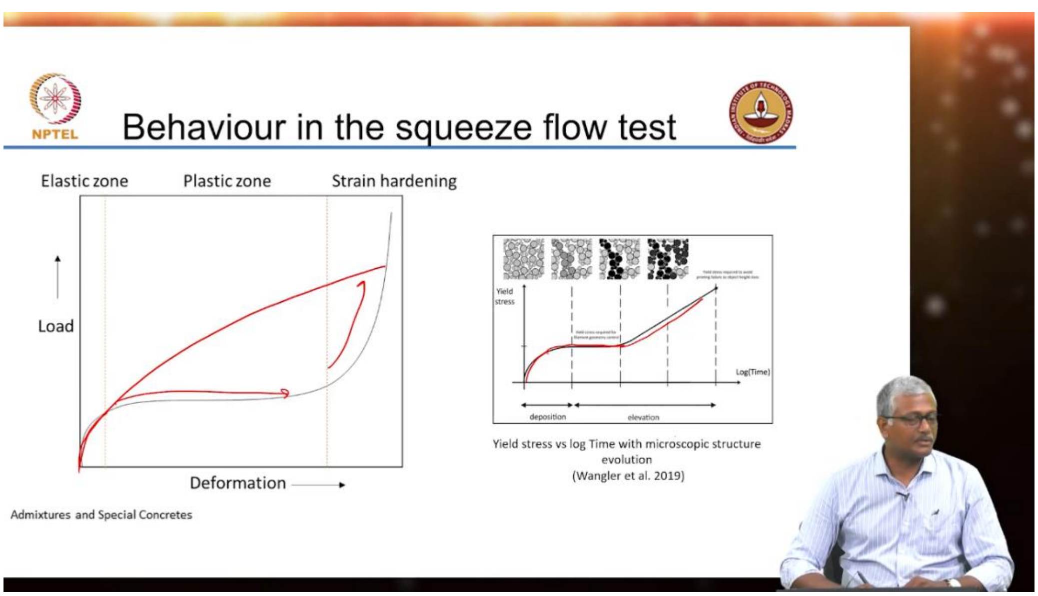

So, when you use this sort of an approach, you get, you are likely to see this kind of relationship that in the beginning, there is sudden, there is some elasticity exhibited by the system. So, there will be an increase in load with little deformation. Then there will be almost like a plastic flow and for systems that have some degree of better structural build-up, you will see some hardening. Why because the particles are coming closer together they are not getting deformed easily anymore.

That is what is schematically shown here again. You have the initial deformation and then the long deformation because of plastic flow and then you can bring your particles close together there is bridging happening between the particles that build up the yield stress with respect to time. Now for a system to perform well in 3D printing, you need something that goes like that where directly from the initial stage it starts building up stress with respect to time or the hardening type of behavior is exhibited by the material.

Squeeze flow- stress-strain curve:

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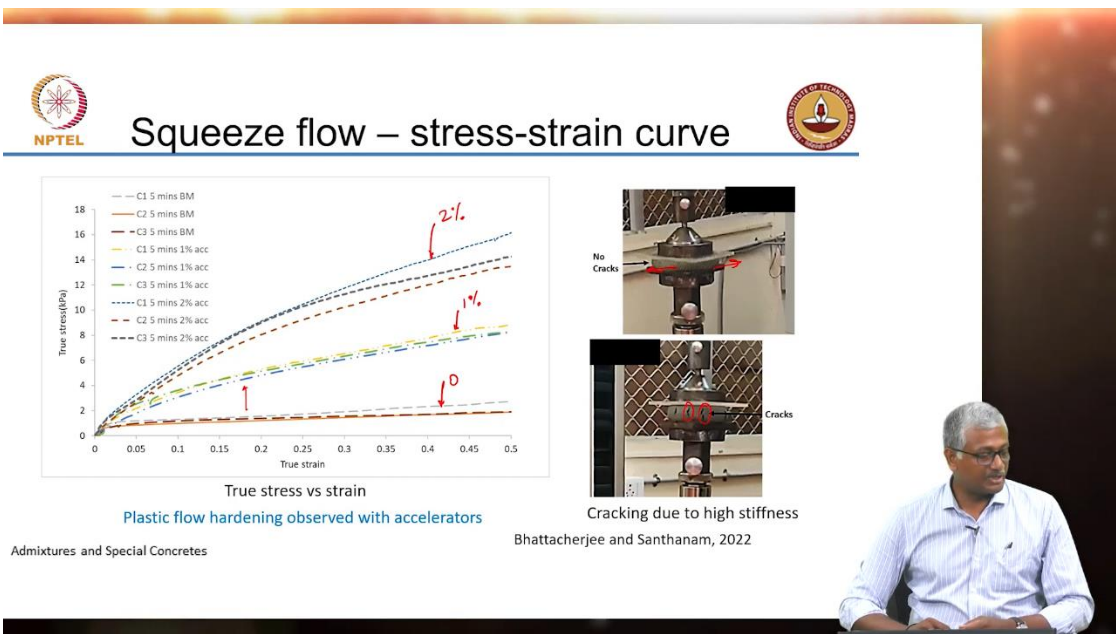

So, using this test you can see here these are mixes without an accelerator and zero accelerator, this is 1% accelerator and this is mixed with 2% accelerator. So again, this is the material that is getting deformed as the plates get closer and then if the material has too high a stiffness you start forming these cracks in the system also.

So, this kind of test will also tell you if your material that is getting extruded is too stiff when the next layer comes on top it will simply start cracking, it will not deform but it will simply crack. So, you do not want that condition also, so you want a condition where the material is able to resist deformation without cracking. So this study shows very clearly that as you increase the dosage the behavior is getting more and more towards that hardening behavior that we want to see with the accelerator and that is what exactly is coming in this approach.

Measure to improve buildability:

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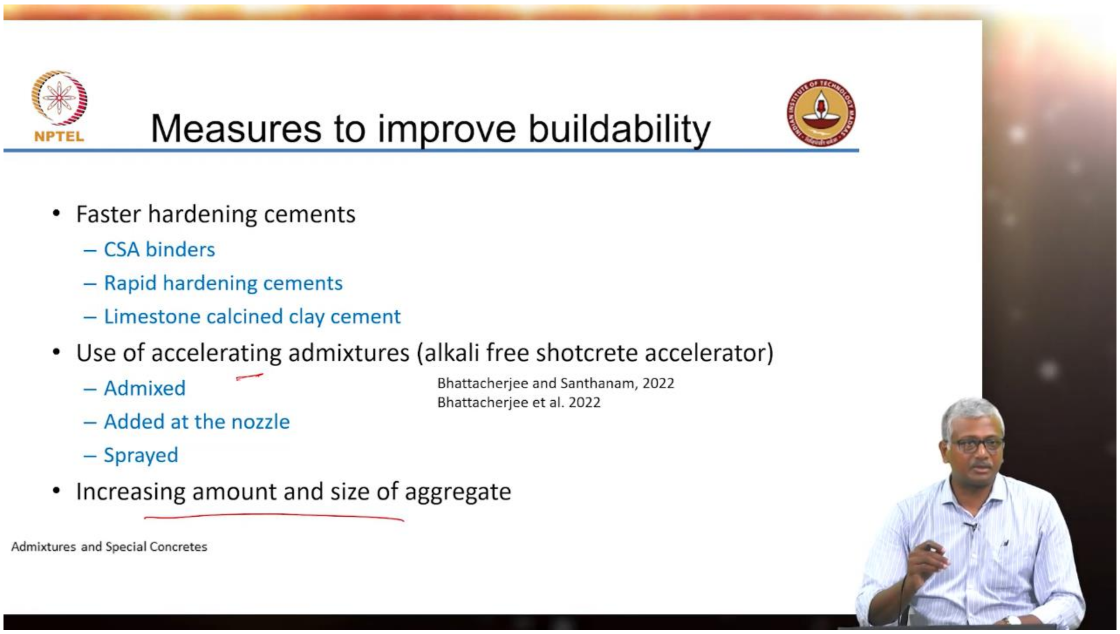

So how can we improve this buildability? One is obviously an accelerator that I showed you an example of already. You could also use rapid hardening cements something that gains strength much faster but you need to be careful about printing with rapid hardening cements because the cements may start setting inside the system and then you have lost your entire printing system.

Your calcium sulphoaluminate binders are also rapidly hardening and they are very effective in providing good 3D-printed concrete. Now in terms of limestone calcine clay cement, we talked earlier about the fact that slump loss becomes rapid, why? Because of the effect of clay. The plates of clay your superplasticizers get trapped and is not able to effectively improve the slump. But that could be an advantage when it comes to 3D printing. In normal concrete what was the disadvantage because of the presence of clay could become an advantage in 3D printing because it will help you build up the system very quickly. Your slump loss is rapid but here you are not worried about that. Initial slump is what you are worried about to really extrude.

Once the material is placed if the slump loss is rapid, it is not really a problem it is actually good for you. So the presence of limestone calcine clay cement here may actually help in obtaining a better quality 3D printed system. The other option apart from using faster hardening cements or accelerating admixtures could be increasing the amount and size of aggregate. Why is that important? How is buildability dependent upon the amount and size of aggregate? The same effect that we talked about in the case of high-density concrete, is the lattice effect. When you have a lot of aggregates it will simply prevent any collapse because of the three-dimensional network that it creates and the friction that it offers.

So, the lattice effect will be better when your aggregates are more in number and when they are larger you will be able to pack the volume much better with the aggregate. But extruding coarse aggregate is a different matter altogether it is not easy to extrude. If you are pressurizing and extruding the possibility of separation is even more when you have a coarse aggregate new system. So all the examples that you see from around the world will be primarily based on mortar very few will actually have coarse aggregate being used.

Use of limestone calcined clay cement:

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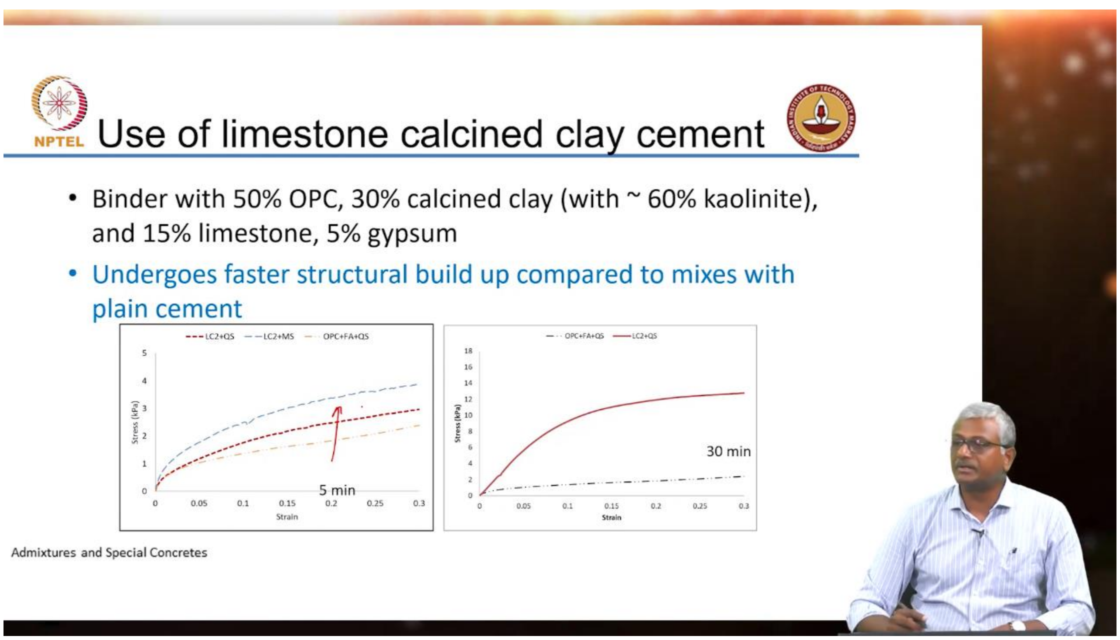

So, with limestone calcine clay cement as I clearly said you have a much better improvement in the buildability.

LC2- Increase of aggregate- binder ratio:

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With this we could produce these columns of 1.1 meter tall in a matter of 15 minutes it was cast 15 minutes is still slow but you can still speed that up. You can clearly see that the layers are quite uniform there is not much height difference between the layers closely seen but still, you can get the appearance of a very uniform material. Now this was produced by the conventional aggregate-to-binder ratio 1 to 1.5 which I showed you from the original system that is OPC plus fly ash we just modified that to bring in LC3 but when we moved to LC3 we had the potential to increase the aggregate fraction. Now what happens when you increase the aggregate fraction is you have less of paste available pushing this through the extruder with pressure means that the possibility of separation is more because you do not have that much of a cohesive material left anymore.

But when you replace OPC fly ash combination with limestone calcine clay cement you have that cohesiveness still built up in the system enough to take the aggregate-to-binder ratio to 3. Now that is the kind of ratio that we see in conventional concrete also aggregate to binder ratio. So, in other words, what it is doing is helping your material become more economical because of reducing cement and also at the same level becoming more or less CO_2 emitting because you have less cement in the system.

Addressing early-age mechanical behavior:

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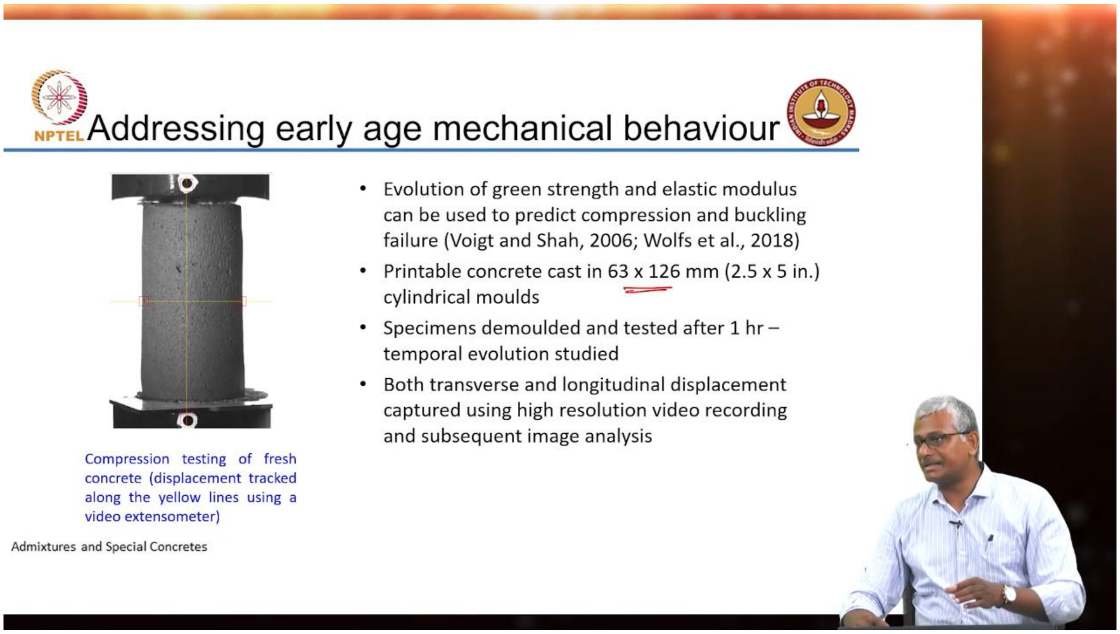

Now again the same squeeze flow test that I showed you previously here could be replaced by something that we are more familiar with like mechanical testing. Instead of the small cylinder of squeeze flow, you can actually deal with the printable concrete which is cast in molds that are larger sized, which resemble more of the hardened concrete testing that we are used to.

So in this case also we tested such specimens and video extensometers were used to test the amount of displacement happening axially and laterally while the concrete was being tested. This is fresh concrete, the concrete was immediately put into a cylindrical mold and extruded out and then the fresh concrete was tested after 1 hour of casting.

Early age behaviour:

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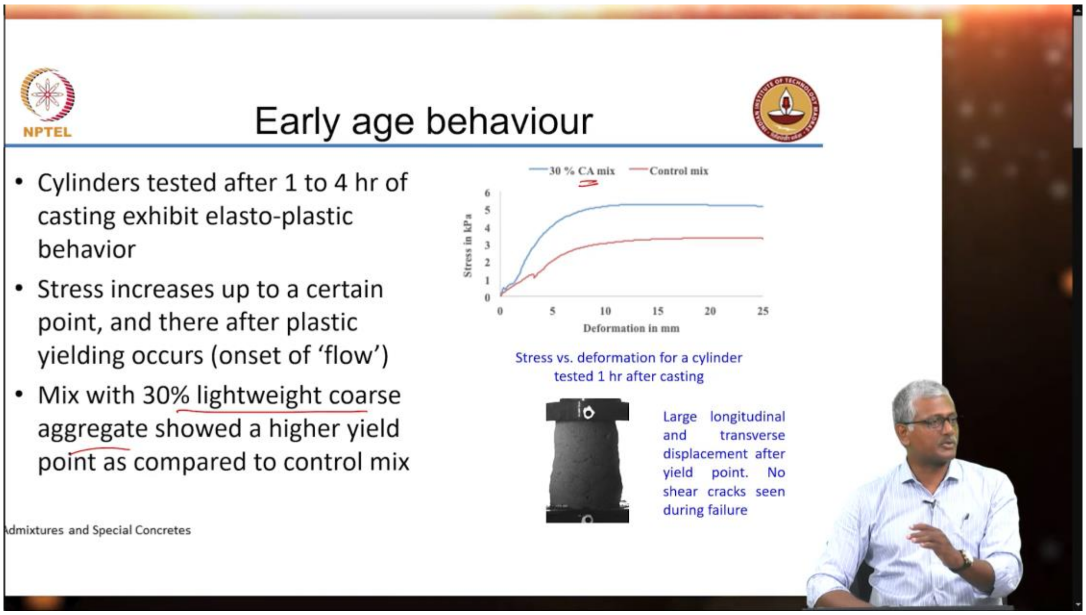

So, you can see here that when you incorporate 30 percent of lightweight coarse aggregate in the system you show a much better behavior. Why is that happening? Again, your stiffness-to-density ratio is improving significantly. Stiffness to density because density is lowered and stiffness is not changed that much because your system is still the same.

Stiffness to density ratio is improving so you get a much better performance in the system. So, this is up to 1 hour after casting.

Late age behavior:

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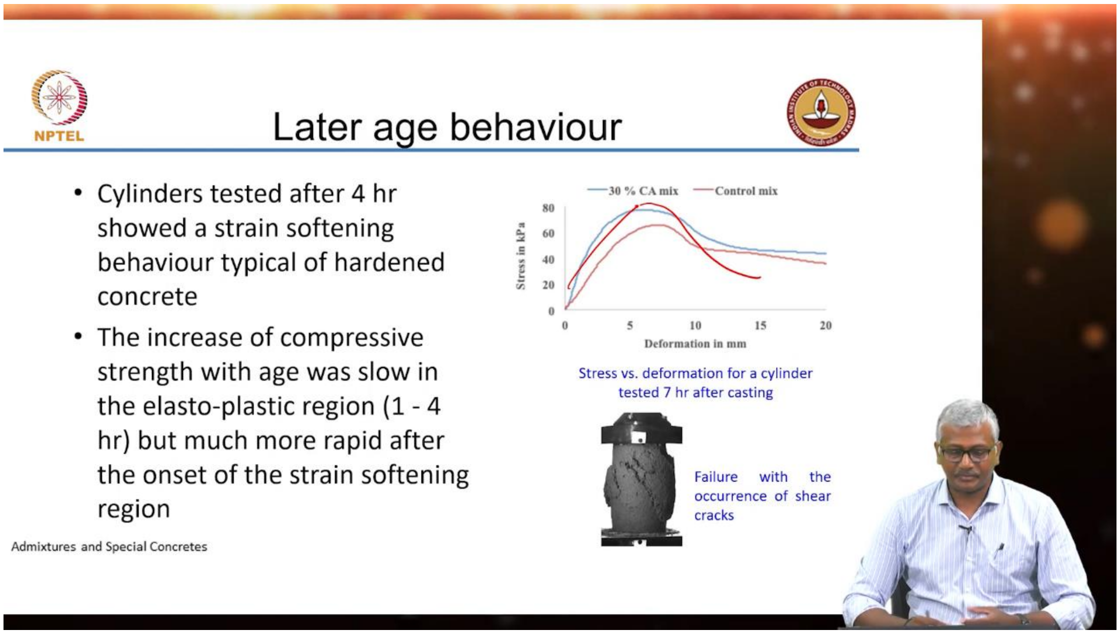

What happens in longer time periods? Your system starts behaving like regular hardened concrete. You have the rise to a peak and then you have a post-peak behavior like a regular hardened concrete would. So you want a good buildable system to move quickly to this stage rather than exhibiting the plastic flow it has to exhibit this normal hardened concrete behavior much faster.

So again, these are ways in which you can characterize 3D-printed concretes.

Issues with mechanical testing:

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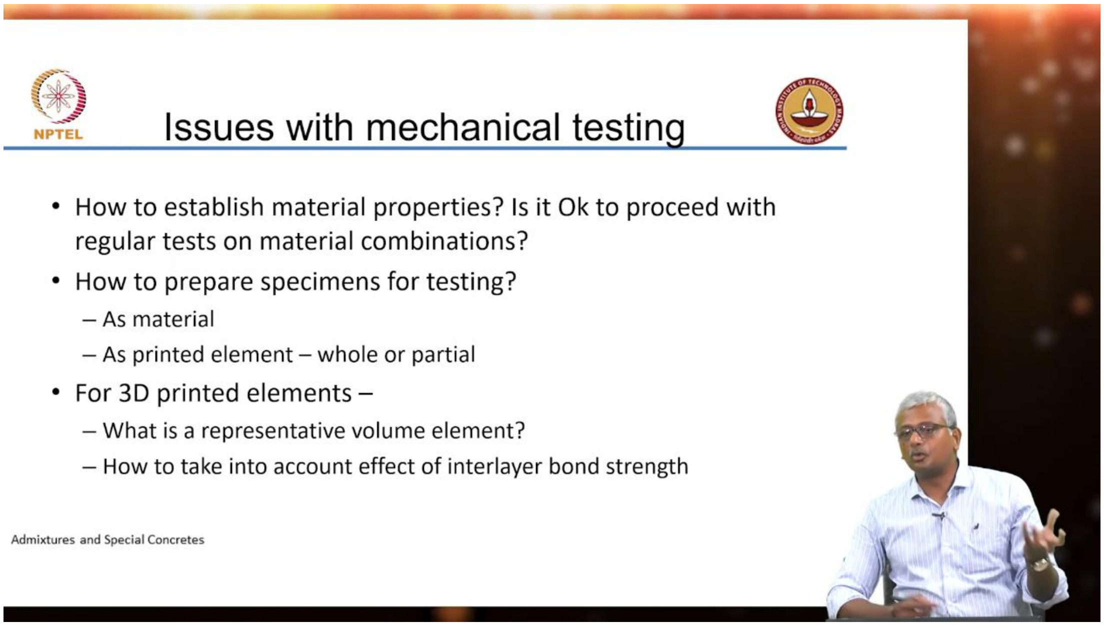

So again, I am asking the same questions there are several issues with mechanical testing. How do we test? Is molded strength okay or do we need to bring in the layers effects? What size should we choose for 3D printed material because we are building full-scale walls and columns? In normal concrete, it is all consistent everything is the same material. We can extract a core and determine that to be the strength of the entire system with no problem. We can make a cube and test the strength for quality control purposes. Here what do we do? That question still needs to be looked at carefully.

Design Aspects:

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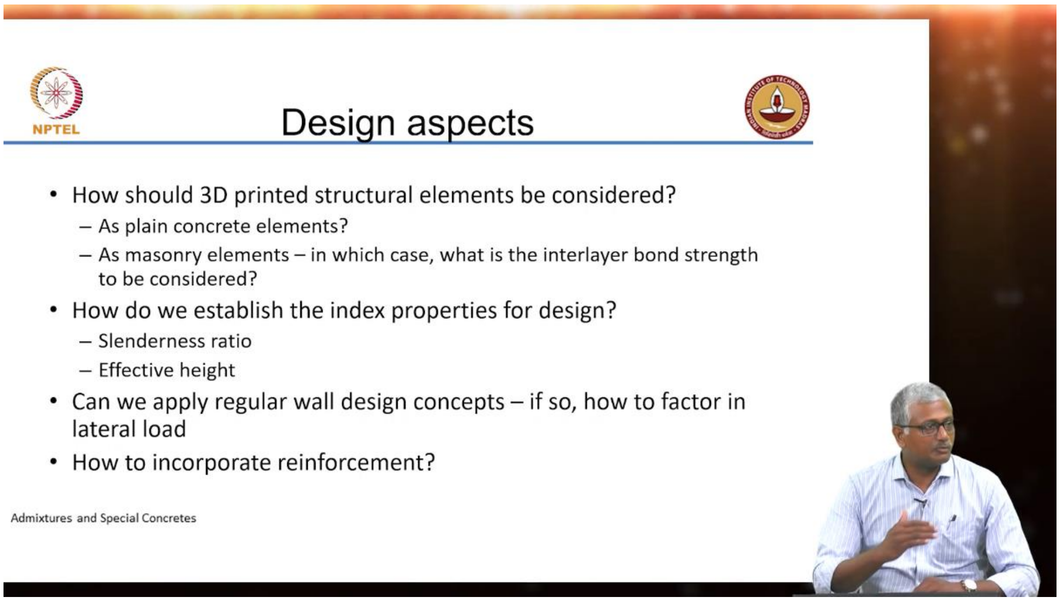

Then how do we design 3D-printed elements? Are they like concrete elements? If I print a column, is it the same as a regular reinforced concrete column? If I print a wall, does it resemble a masonry wall or a concrete wall? How do we do the design? These are some things that we need to grapple with that is why it is still at an experimental stage. So if you have to really execute a project where certification is required you would have to test full-scale elements and get them certified. Only then you can proceed with full-scale construction process.

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So, I am not touching upon the details here because we are getting out of time but I will quickly talk about another major challenge which is reinforcement. How do you reinforce 3D-printed concrete? It is easy to reinforce along the direction of print because all you do is print and then keep one layer of reinforcement and then continue to print on top of that. But that is not the main concern no when you are printing a wall you need the reinforcement to be in the vertical direction to prevent lateral effects to take care of lateral effects. So, in such instances, you have very little choice but to complete the 3D printing and then manually add the reinforcement. Alternatively, you can have nozzles designed like this where the central reinforcement is there in place and then you print on both sides of it.

This nozzle is delivering concrete on both sides of the reinforcement. Here you have a system in which the concrete is getting printed there is also this metal wire that is spooled along and that is right in the center. So, if you take a printed element the wire will be right in the center of this printed element. So that is how they are doing this 3D printing in this picture. So this is another case of a mesh being in the center and the nozzle going around the mesh so that the concrete is completely enveloping that mesh.

Alternatively, you can come up with external reinforcing systems so like prestressing for instance without really doing internal reinforcement of the concrete. So you have to work out strategies. Alternatively, you can create a formwork on the outside and then fill it up with normal concrete with reinforcement inside. In which case your 3D printed material becomes a lost formwork. It is just formwork that is in place. It is not taking care of the loading it is simply formwork and that may not be a bad idea if you really want very high structural stability to be exhibited by your system.

3D Printing opportunities:

Geometric Flexibility:

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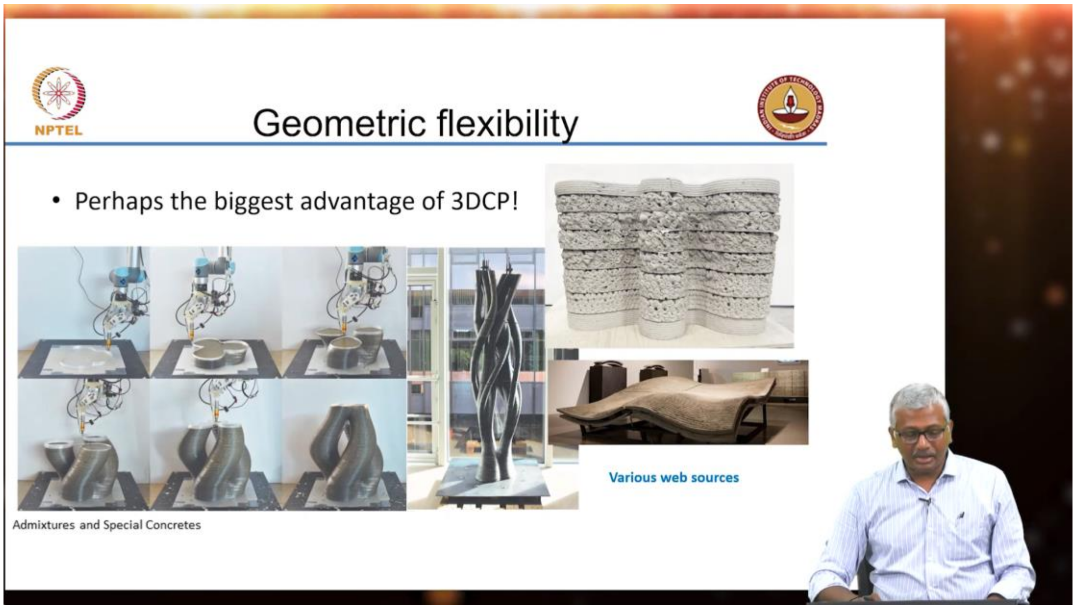

I will just skip through these slides to show you some opportunities, of course, biggest advantage is flexibility in shape which you cannot get with normal construction. With 3D printing a lot of different systems are possible.

Topological optimization:

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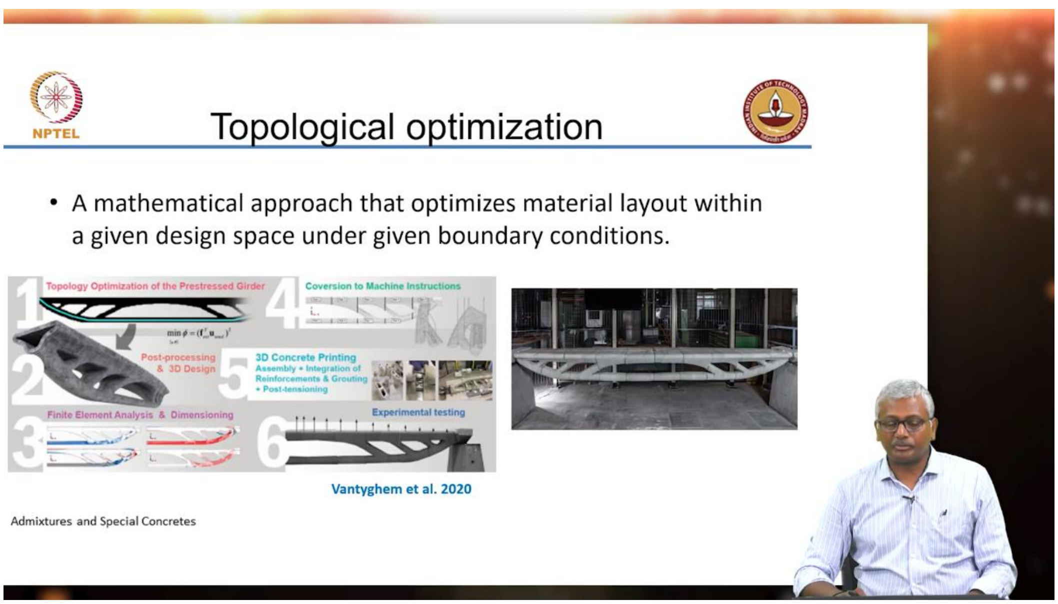

You can also reduce the disadvantage of reinforcing by topologically optimizing the shape so that you print in such a way that reinforcement is minimized. There is a lot of work going on in topological optimization also. This pedestrian bridge was 3D printed in segments in Ghent University and it is one of the first examples of topologically optimizing a bridge.

3D Printing of Houses:

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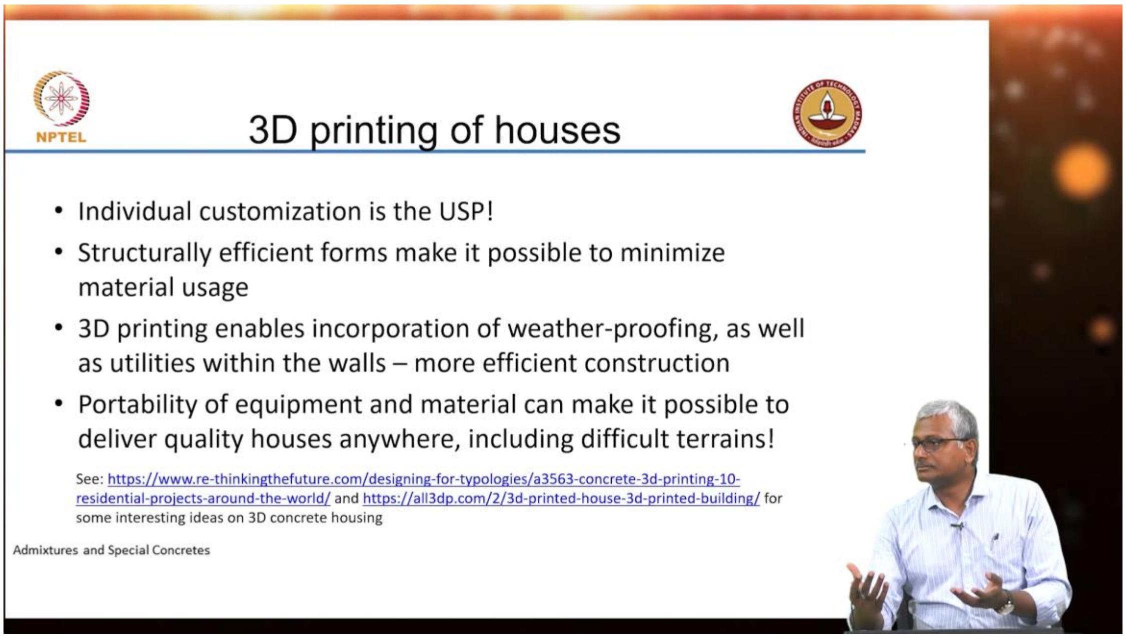

Houses present the best opportunity, not multi-storied buildings but individual houses. Why because let us say you have to develop a large cluster of housing for a rural community and each one wants its design. How do you do that with a normal construction? It is not possible. If you have to customize the design you can only do it with 3D printing.

Geometric Tolerance:

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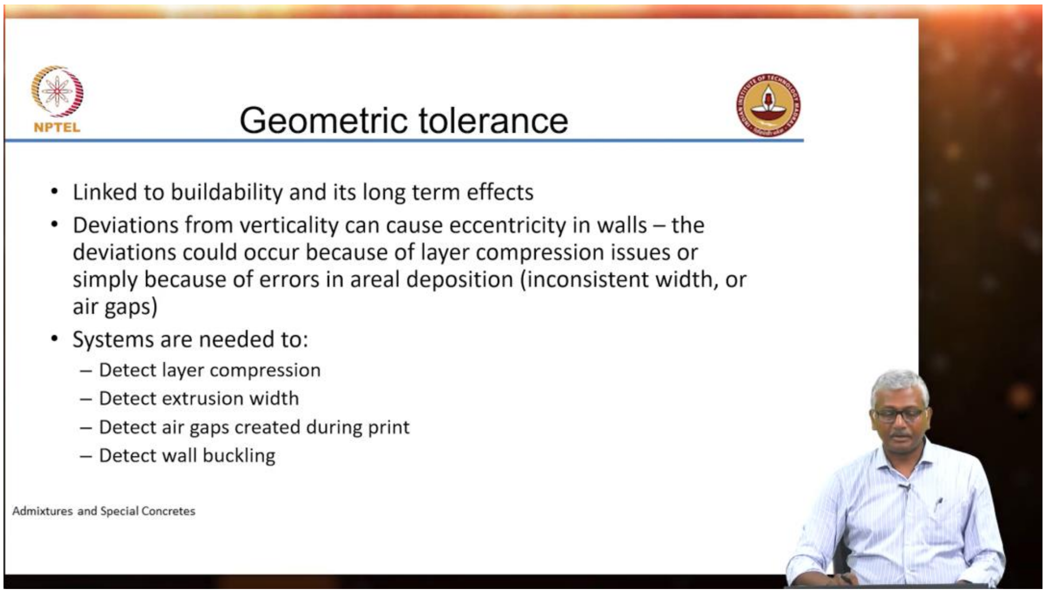

Challenge geometric tolerance, I talked about the fact that in this building we had a lot of problems with it but this can also be mechanized using lasers at the tip of the 3D printing nozzle you can determine whether you have to adjust for the height or whether the layer is bulging out and so on and so forth. So, a lot of things can be done.

Sustainability considerations:

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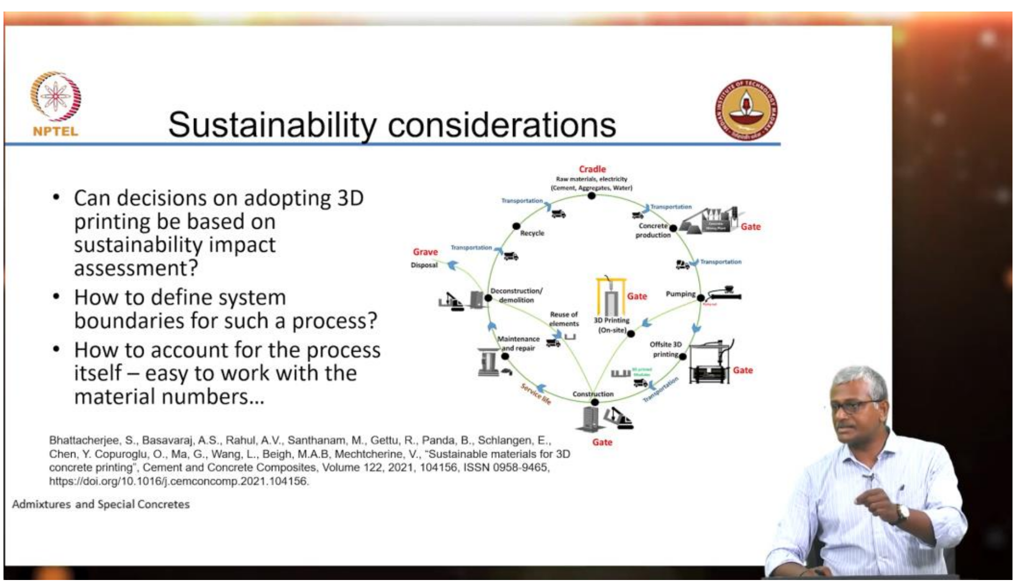

You need to also ensure that the system that you are designing ultimately is also sustainable and you cannot just stop at the material sustainability you have to address the entire process. So again, some aspects are brought about in this paper which was written by us in combination with several authors from across the world.

Architectural columns, textured walls and facades:

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Now architecturally 3D printing can give you a lot of opportunities. You can see these columns and facades.

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Examples from the UK again of specialized columns that were printed.

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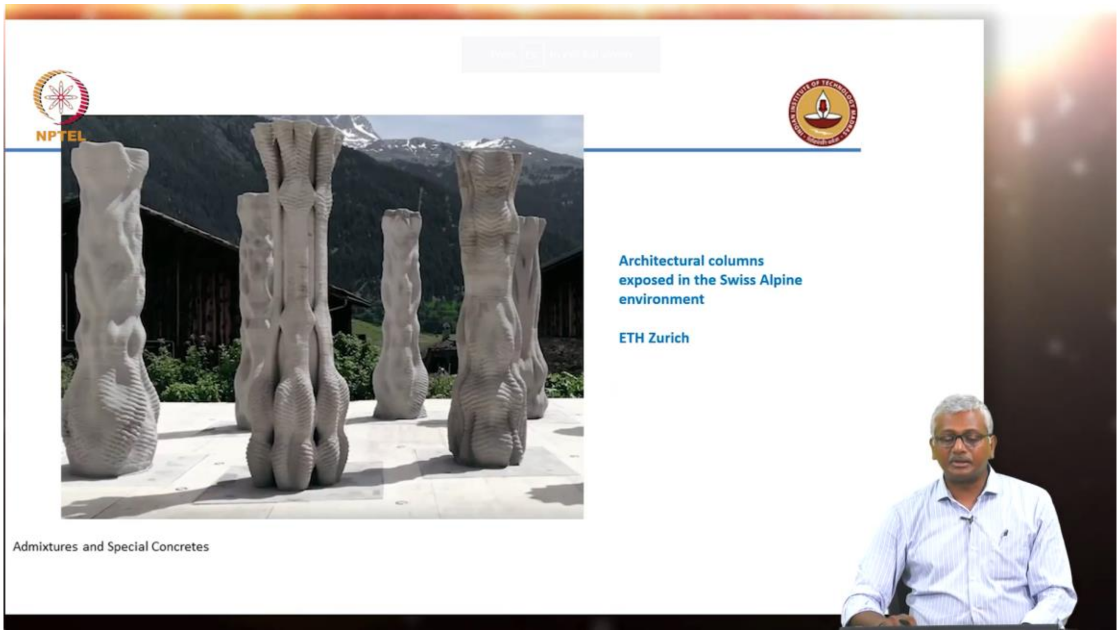

These columns were printed in Switzerland at ETH and they are subjected to external freezing and thawing environment just to look at the performance.

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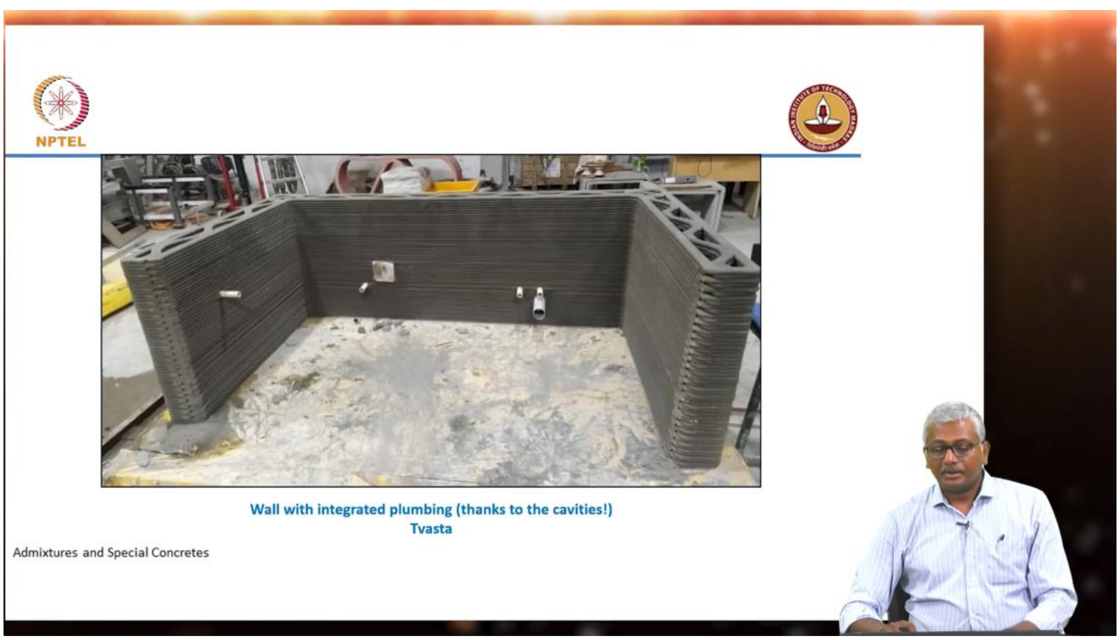

The other important thing to understand is in 3D printed concrete you have these cavities that can be made use of by making space for utilities like here plumbing electrical utilities you do not have to start damaging the concrete again you can plan for these to have the utilities in place.

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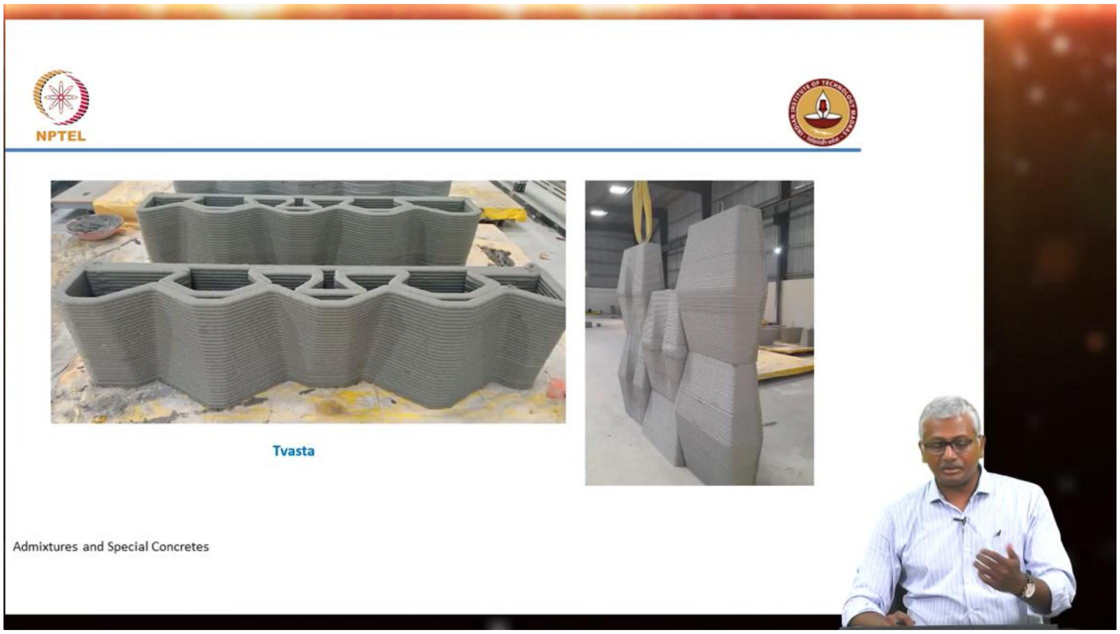

Again, textured wall and so on. This is the same wall that was used for the Jaisalmer sanitary block that was done.

Steel/ Garden Furniture:

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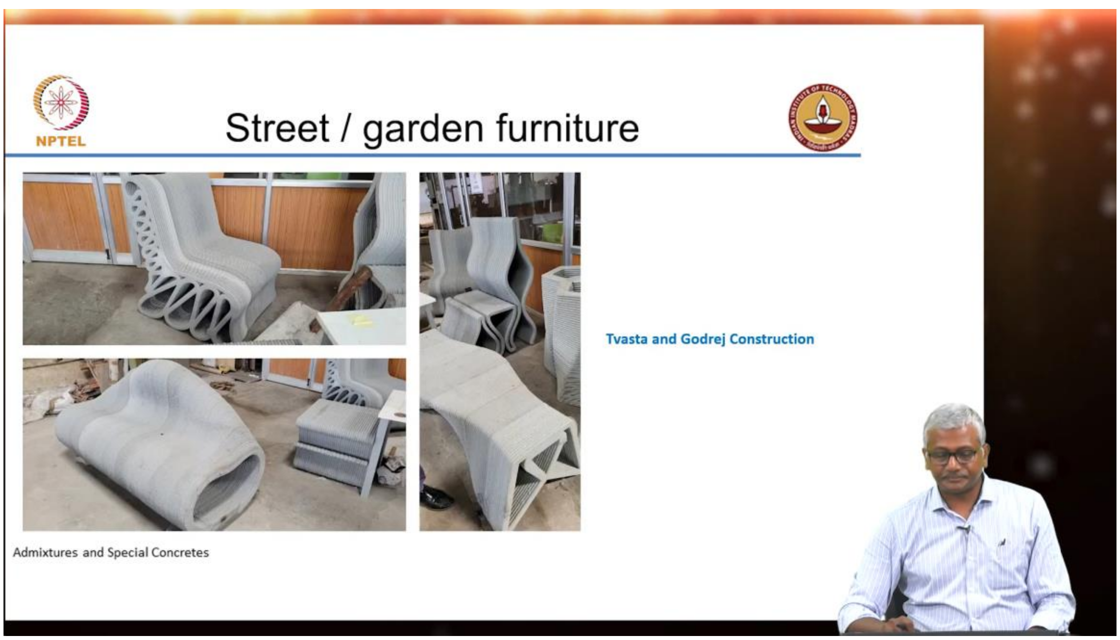

Street furniture again presents a lot of opportunity obviously because not a crucial member with respect to load carrying ability.

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So, lot of interesting textures can be brought about.

Outlook for the future:

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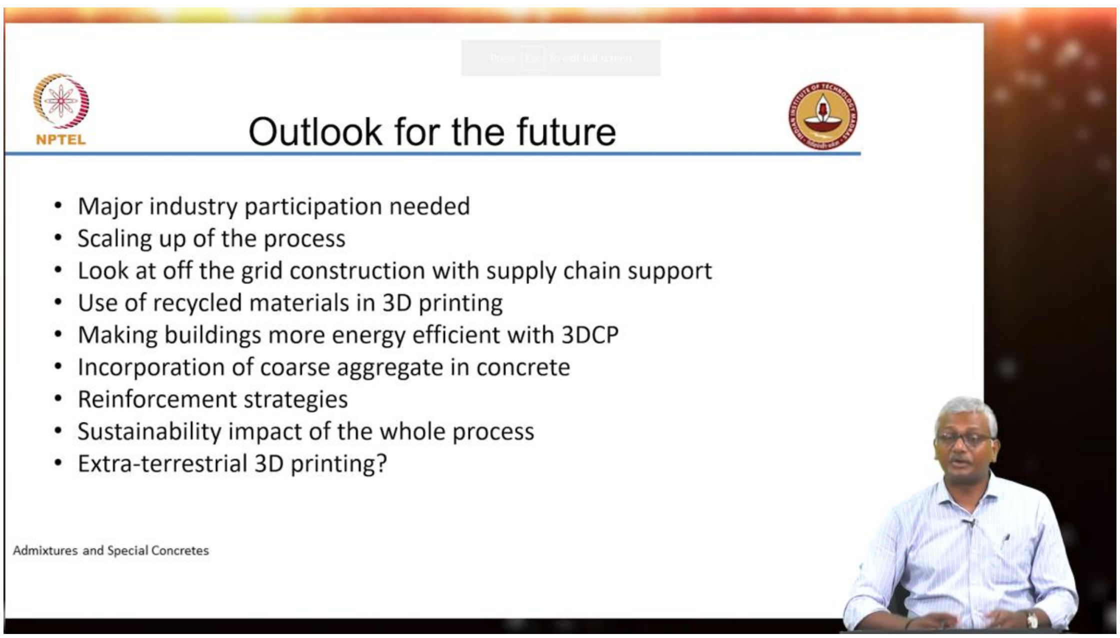

So for the future of course lot of industry participation is required to take this to the next level. Making concrete more sustainable, and economical will be a challenge but we have to look at the opportunities correctly. One opportunity that is, keeping people very interested is extraterrestrial 3D printing also. How to take this out to a location where you cannot really provide workers, you cannot provide equipment that can be 3D printed outside earth? Thank you.