

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:

(Refer to slide time: 00:19)

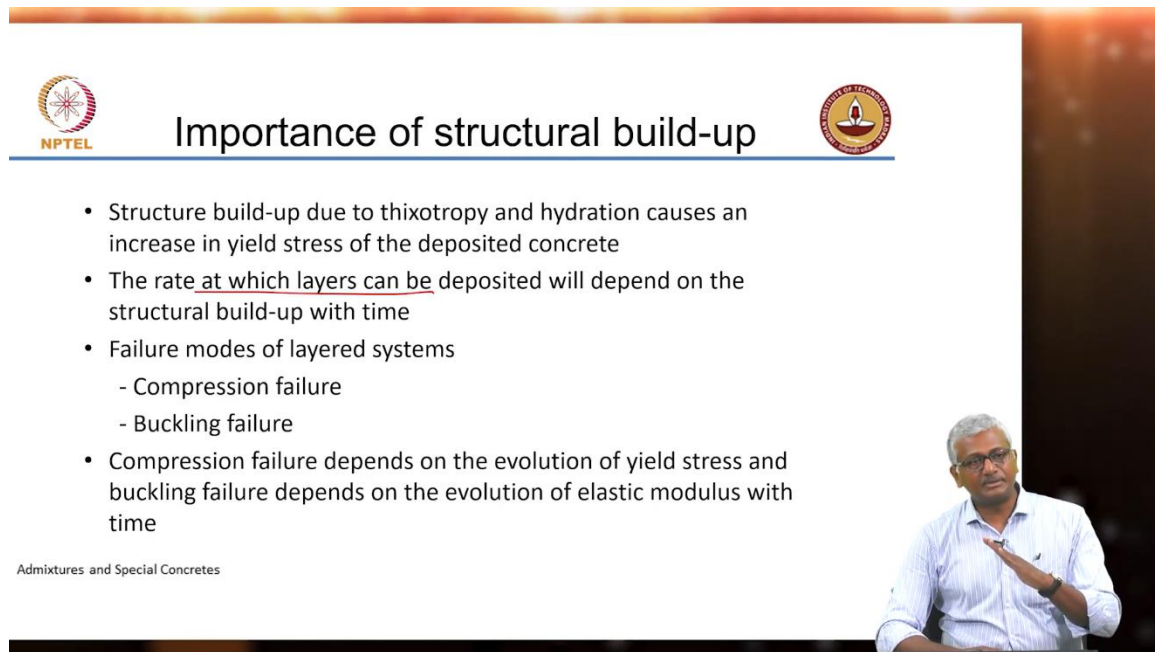
The slide features the NPTEL logo on the left and the IIT Madras logo on the right. The title "Failure modes of 3D printed elements" is centered at the top. Below the title, there are two diagrams on the left: "Elastic buckling" shows a vertical column with a dashed line representing its original straight position and a solid line showing it curved to the right; "Plastic collapse" shows a vertical column with a dashed line for its original position and a solid line showing it bulging outwards at the base. Below these diagrams is the text "Failure modes (Suiker 2018)". To the right of the diagrams is a photograph of a 3D printed concrete element, which is a rectangular frame with a wavy, ribbed texture. A red arrow points to a bulge on the side of the frame. Below the photo is the text "With improved buildability, both failures can be overcome to a large extent...". In the bottom right corner of the slide, there is a small inset image of a man in a light blue shirt, identified as Prof. Manu Santhanam, gesturing with his hand.

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 know 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:

(Refer to slide time: 01:19)



The slide features the NPTEL logo on the left and the Indian Institute of Technology Bombay logo on the right. The title 'Importance of structural build-up' is centered at the top. Below the title, there is a list of four bullet points. The second bullet point contains a red underline. In the bottom right corner, there is a photograph of a man in a white shirt, likely the speaker, gesturing with his hand.

- Structure build-up due to thixotropy and hydration causes an increase in yield stress of the deposited concrete
- The rate at which layers can be deposited will depend on the structural build-up with time
- Failure modes of layered systems
 - Compression failure
 - Buckling failure
- Compression failure depends on the evolution of yield stress and buckling failure depends on the evolution of elastic modulus with time

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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:

(Refer to slide time: 02:19)

The slide is titled "Compression failure" and features the NPTEL logo on the left and the Indian Institute of Technology (IIT) logo on the right. On the left side, there is a diagram of three stacked rectangular layers. Below it, a single layer is shown with a downward arrow indicating the direction of compression. To the right of the diagram, the text reads: "Compression stress on bottom layer = $n(\rho gh)$ ", followed by definitions: "n - no. of layers", "h - height of each layer", "ρ - density of concrete", and "g - acceleration due to gravity". On the right side, there is a photograph of a concrete specimen that has failed under compression, showing significant lateral bulging and crushing of the bottom layers. A red circle highlights the crushed area. Below the photograph, the text reads: "Crushing of bottom layers due to excessive compression load". In the bottom right corner, there is a small inset video of a man in a light blue shirt speaking. At the bottom left, the text "Admixtures and Special Concretes" is visible.

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

(Refer to slide time: 02:38)

The slide is titled "Buckling failure" and features the NPTEL logo on the left and the Indian Institute of Technology (IIT) logo on the right. The main content consists of a bulleted list and a mathematical formula. The first bullet point states: "For printing of slender elements, buckling failure may occur prior to crushing failure". The second bullet point states: "Critical height for self buckling in a column element:". Below this, the formula is given as:
$$l_{max} = \left(7.8373 \frac{EI}{\rho g A} \right)^{1/3} \quad (\text{Roussel, 2018})$$
 The third bullet point states: "Elastic modulus (E), section properties (A and I) and the density of concrete (r) are factors determining the critical buckling height". In the bottom right corner, there is a small inset video of a man in a light blue shirt speaking. At the bottom left, the text "Admixtures and Special Concretes" is visible.

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:

(Refer to slide time: 03:50)

The slide features the NPTEL logo on the left and the IIT Bombay logo on the right. The title 'Buildability depends on' is centered at the top. Below the title, there are two bulleted sections. The first section, 'Rheological Performance', lists three points: Shear yield stress, Recovery of original viscosity and yield stress before the deposition of next layer, and Printing time gaps. The second section, 'Mechanical Performance', lists three points: Early age mechanical properties, Time gap, and Compressive stress-strain behaviour with time - Transition from plastic-flow to brittle failure (elastic). At the bottom left, the text 'Admixtures and Special Concretes' is visible. In the bottom right corner, there is a small inset image of a man in a light blue shirt, likely the speaker, gesturing with his hands.

Rheological Performance

- Shear yield stress
- Recovery of original viscosity and yield stress before the deposition of next layer.
- Printing time gaps

Mechanical Performance

- Early age mechanical properties
- Time gap
- Compressive stress-strain behaviour with time - Transition from plastic-flow to brittle failure (elastic).

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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

(Refer to slide time: 05:01)

NPTEL

Compression of layers in 3D printing – considering yield stress fluid

Layer under compression

Perfect slip

No slip

Deformation

Radial velocity profile

Instantaneous

Gradual

Load

Time

Both load profile and boundary condition are critical

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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:

(Refer to slide time: 06:27)

Squeeze flow test

Velocity (mm/s) vs Time (seconds) graph showing a constant velocity of 0.5 mm/s for 38 seconds.

$True\ strain = \ln(1 - \epsilon)$
 $True\ stress = \sigma_0(1 - \epsilon)$

- Constant volume assumption

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Engmann et al. 2005

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:

(Refer to slide time: 07:08)

Behaviour in the squeeze flow test

Load vs Deformation graph showing Elastic zone, Plastic zone, and Strain hardening.

Yield stress vs Log(Time) graph showing deposition and elevation phases.

Yield stress vs log Time with microscopic structure evolution (Wangler et al. 2019)

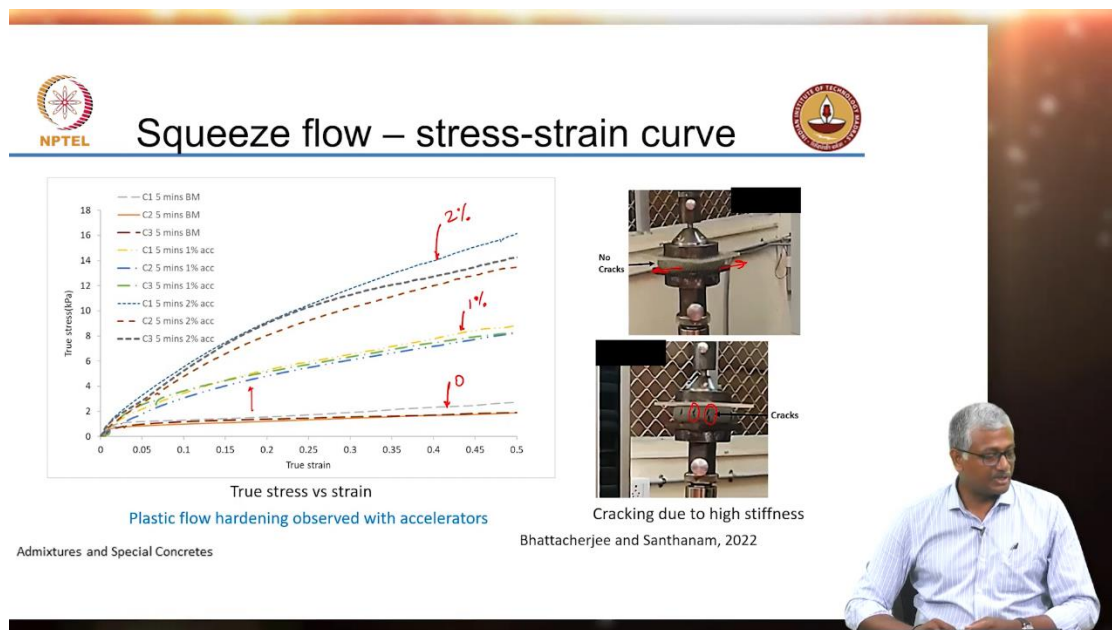
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So, when you use this sort of an approach, you get, you are likely to see this kind of relationship that in the beginning, there is sudden, there is some elasticity exhibited by the system. So, there will be an increase in load with little deformation. 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:

(Refer to slide time: 08:18)



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:

(Refer to slide time: 09:19)

The slide features the NPTEL logo on the left and the Indian Institute of Technology Kharagpur logo on the right. The title 'Measures to improve buildability' is centered at the top. Below the title, a bulleted list of measures is presented. The first measure is 'Faster hardening cements', which includes sub-points: 'CSA binders', 'Rapid hardening cements', and 'Limestone calcined clay cement'. The second measure is 'Use of accelerating admixtures (alkali free shotcrete accelerator)', with sub-points: 'Admixed', 'Added at the nozzle', and 'Sprayed'. The third measure is 'Increasing amount and size of aggregate'. A small text box on the right side of the slide lists 'Bhattacharjee and Santhanam, 2022' and 'Bhattacharjee et al. 2022'. At the bottom left, it says 'Admixtures and Special Concretes'. A man in a light blue shirt is visible in the bottom right corner of the slide, appearing to be the speaker.

- Faster hardening cements
 - CSA binders
 - Rapid hardening cements
 - Limestone calcined clay cement
- Use of accelerating admixtures (alkali free shotcrete accelerator)
 - Admixed
 - Added at the nozzle
 - Sprayed
- Increasing amount and size of aggregate

Bhattacharjee and Santhanam, 2022
Bhattacharjee et al. 2022

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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:

(Refer to slide time: 11:58)

The slide features the NPTEL logo on the left and the Indian Institute of Technology (IIT) logo on the right. The title is "Use of limestone calcined clay cement".

- Binder with 50% OPC, 30% calcined clay (with ~ 60% kaolinite), and 15% limestone, 5% gypsum
- Undergoes faster structural build up compared to mixes with plain cement

Two stress-strain graphs are shown:

- The left graph is labeled "5 min" and plots Stress (MPa) on the y-axis (0 to 5) against Strain on the x-axis (0 to 0.3). It compares three mixes: LC2+HS (dashed red line), LC2+MS (dashed blue line), and OPC+FA+HS (dashed green line). The LC2+MS mix shows the highest stress, followed by LC2+HS, and then OPC+FA+HS.
- The right graph is labeled "30 min" and plots Stress (MPa) on the y-axis (0 to 18) against Strain on the x-axis (0 to 0.3). It compares OPC+FA+HS (dashed black line) and LC2+HS (solid red line). The LC2+HS mix shows a significantly higher stress (around 12 MPa) compared to the OPC+FA+HS mix (around 2 MPa).

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A man in a light blue shirt is visible in the bottom right corner of the slide, appearing to be speaking.

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:

(Refer to slide time: 12:04)



The slide displays three 1.1 m high concrete cylinders, each with a different aggregate-to-binder ratio. The first cylinder is labeled '1.1 m high cylinder – aggregate/binder = 1.5'. The second cylinder is labeled '1 m high cylinder – aggregate/binder = 2.33'. The third cylinder is labeled '1 m high cylinder – aggregate/binder = 3'. The slide also features the NPTEL logo and the IIT Bombay logo. A presenter is visible in the bottom right corner of the slide.

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 CO₂ emitting because you have less cement in the system.

Addressing early-age mechanical behavior:

(Refer to slide time: 13:41)




Addressing early age mechanical behaviour



- Evolution of green strength and elastic modulus can be used to predict compression and buckling failure (Voigt and Shah, 2006; Wolfs et al., 2018)
- Printable concrete cast in 63 x 126 mm (2.5 x 5 in.) cylindrical moulds
- Specimens demoulded and tested after 1 hr – temporal evolution studied
- Both transverse and longitudinal displacement captured using high resolution video recording and subsequent image analysis

Compression testing of fresh concrete (displacement tracked along the yellow lines using a video extensometer)

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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:

(Refer to slide time:14:32)

The slide, titled "Early age behaviour", features the NPTEL logo on the left and the Indian Institute of Technology Bombay logo on the right. It contains the following text:

- Cylinders tested after 1 to 4 hr of casting exhibit elasto-plastic behavior
- Stress increases up to a certain point, and there after plastic yielding occurs (onset of 'flow')
- Mix with 30% lightweight coarse aggregate showed a higher yield point as compared to control mix

The graph, titled "Stress vs. deformation for a cylinder tested 1 hr after casting", plots Stress in MPa (0 to 6) against Deformation in mm (0 to 25). Two curves are shown: a blue line for "30 % CA mix" and a red line for "Control mix". The 30% CA mix curve reaches a higher peak stress of approximately 5.5 MPa at 10 mm deformation, while the control mix reaches a peak of about 3.5 MPa at 15 mm deformation. Both curves show a yield point around 2-3 MPa.

Below the graph is a photograph of a concrete cylinder under test. To its right, text reads: "Large longitudinal and transverse displacement after yield point. No shear cracks seen during failure".

At the bottom left of the slide, it says "admixtures and Special Concretes". A speaker is visible in the bottom right corner of the slide frame.

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:

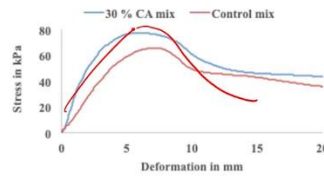
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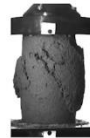
Later age behaviour



- Cylinders tested after 4 hr showed a strain softening behaviour typical of hardened concrete
- The increase of compressive strength with age was slow in the elasto-plastic region (1 - 4 hr) but much more rapid after the onset of the strain softening region



Stress vs. deformation for a cylinder tested 7 hr after casting



Failure with the occurrence of shear cracks

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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:

(Refer to slide time: 15:40)



Issues with mechanical testing



- How to establish material properties? Is it Ok to proceed with regular tests on material combinations?
- How to prepare specimens for testing?
 - As material
 - As printed element – whole or partial
- For 3D printed elements –
 - What is a representative volume element?
 - How to take into account effect of interlayer bond strength

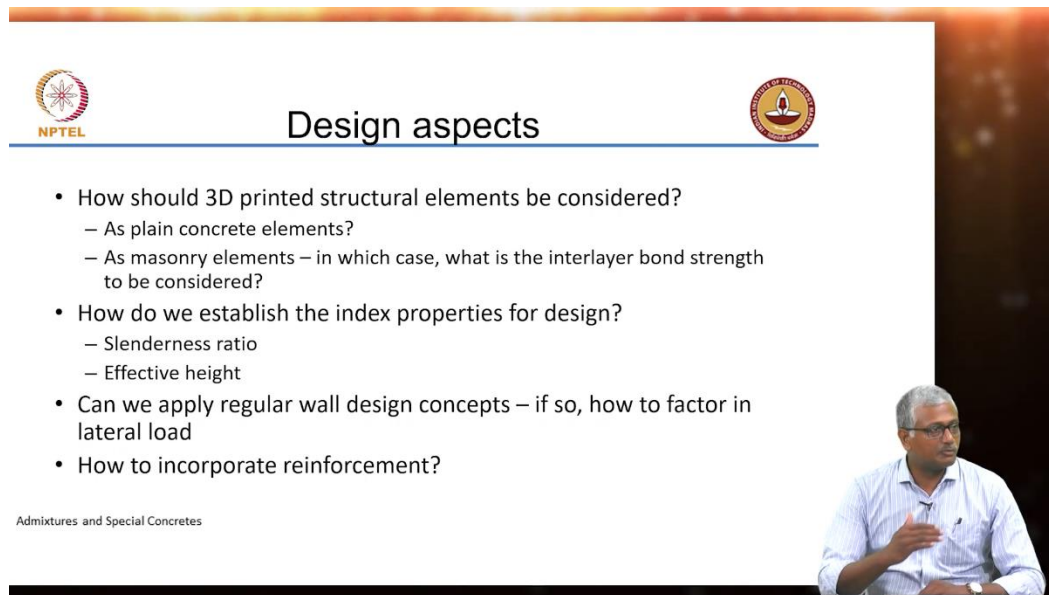
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So again, I am asking the same questions there are several issues with mechanical testing. How do we test? Is molded strength okay or do we need to bring in the layers effects? What size should we choose for 3D printed material because we are building 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:

(Refer to slide time: 16:15)



The slide features the NPTEL logo on the left and the Indian Institute of Technology (IIT) logo on the right. The title 'Design aspects' is centered at the top. Below the title, a list of five bullet points addresses design considerations for 3D printed structural elements. In the bottom right corner, a man in a light blue shirt is shown speaking, gesturing with his hands.

- How should 3D printed structural elements be considered?
 - As plain concrete elements?
 - As masonry elements – in which case, what is the interlayer bond strength to be considered?
- How do we establish the index properties for design?
 - Slenderness ratio
 - Effective height
- Can we apply regular wall design concepts – if so, how to factor in lateral load
- How to incorporate reinforcement?

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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.

(Refer to slide time: 16:57)

3D Printing opportunities:

Geometric Flexibility:

(Refer to slide time: 18:58)

The slide is titled "Geometric flexibility" and features the NPTEL logo on the top left and the Indian Institute of Technology (IIT) logo on the top right. A bullet point states: "Perhaps the biggest advantage of 3DCP!". The slide contains several images: a 3x3 grid of 3D printed concrete parts, a tall, twisted, lattice-like concrete structure, and a curved concrete bench. A caption "Various web sources" is placed below the bench image. The text "Admixtures and Special Concretes" is at the bottom left. A speaker in a light blue shirt is visible in the bottom right corner of the slide frame.

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:

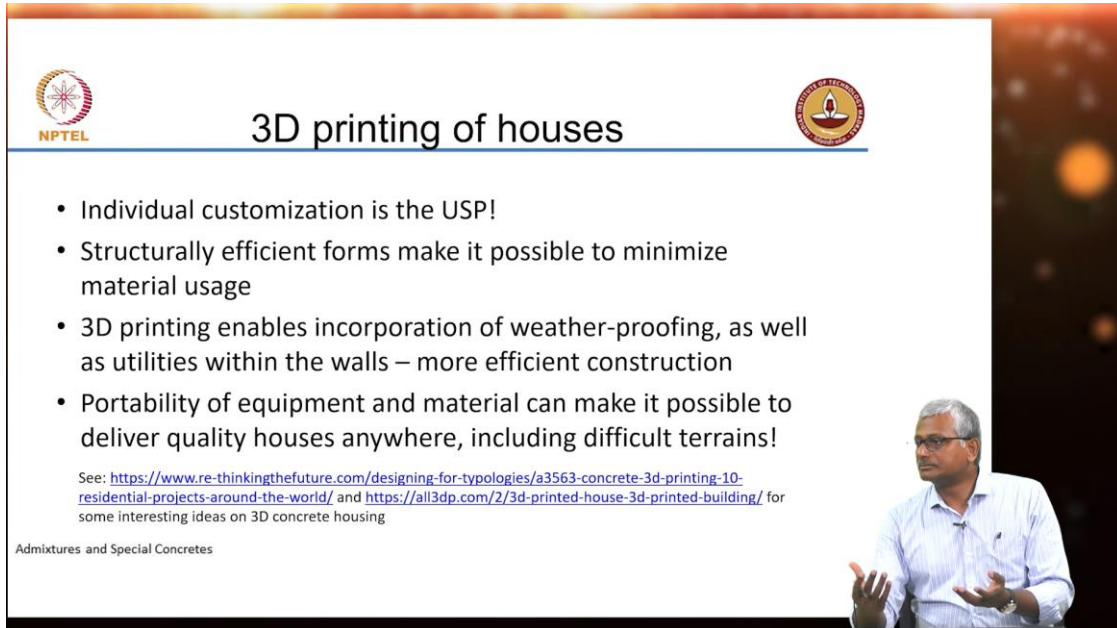
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The slide is titled "Topological optimization" and features the NPTEL logo on the top left and the IIT logo on the top right. A bullet point states: "A mathematical approach that optimizes material layout within a given design space under given boundary conditions." The slide contains a 6-step process diagram: 1. Topology Optimization of the Prestressed Girder (with equation $\min_{\rho} \int_{\Omega} \rho \sigma_{xx}^2 dx$), 2. Post-processing & 3D Design, 3. Finite Element Analysis & Dimensioning, 4. Conversion to Machine Instructions, 5. 3D Concrete Printing (Assembly + Integration of Reinforcements & Grouting + Post-tensioning), and 6. Experimental testing. An image of a printed concrete girder is shown next to the diagram. The text "Vantighem et al. 2020" is at the bottom center of the diagram. The text "Admixtures and Special Concretes" is at the bottom left. A speaker in a light blue shirt is visible in the bottom right corner of the slide frame.

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:

(Refer to slide time: 19:39)



The slide features the NPTEL logo on the top left and the IIT Bombay logo on the top right. The title '3D printing of houses' is centered at the top. Below the title, there are four bullet points. At the bottom left, there is a reference link and the text 'Admixtures and Special Concretes'. On the right side of the slide, a man in a light blue shirt is speaking and gesturing with his hands.

- Individual customization is the USP!
- Structurally efficient forms make it possible to minimize material usage
- 3D printing enables incorporation of weather-proofing, as well as utilities within the walls – more efficient construction
- Portability of equipment and material can make it possible to deliver quality houses anywhere, including difficult terrains!



See: <https://www.re-thinkingthefuture.com/designing-for-typologies/a3563-concrete-3d-printing-10-residential-projects-around-the-world/> and <https://all3dp.com/2/3d-printed-house-3d-printed-building/> for some interesting ideas on 3D concrete housing

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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:


(Refer to slide time: 20:02)



Geometric tolerance

- Linked to buildability and its long term effects
- Deviations from verticality can cause eccentricity in walls – the deviations could occur because of layer compression issues or simply because of errors in areal deposition (inconsistent width, or air gaps)
- Systems are needed to:
 - Detect layer compression
 - Detect extrusion width
 - Detect air gaps created during print
 - Detect wall buckling



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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.

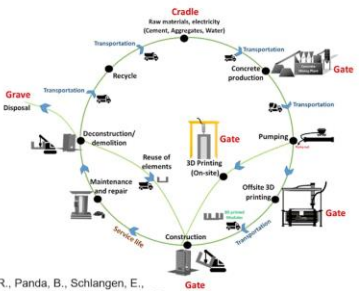
Sustainability considerations:

(Refer to slide time: 20:22)




Sustainability considerations

- Can decisions on adopting 3D printing be based on sustainability impact assessment?
- How to define system boundaries for such a process?
- How to account for the process itself – easy to work with the material numbers...



Bhattacharjee, S., Basavaraj, A.S., Rahul, A.V., Santhanam, M., Getlu, R., Panda, B., Schlangen, E., Chen, Y., Copuroglu, O., Ma, G., Wang, L., Beigh, M.A.B., Mechtcherine, V., "Sustainable materials for 3D concrete printing", Cement and Concrete Composites, Volume 122, 2021, 104156, ISSN 0958-9465, <https://doi.org/10.1016/j.cemconcomp.2021.104156>.


Admixtures and Special Concretes



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:

(Refer to slide time: 20:41)



The slide features the NPTEL logo on the left and the Indian Institute of Technology (IIT) logo on the right. The title "Architectural columns, textured walls and facades" is centered at the top. Below the title, there are two photographs: the left one shows two tall, cylindrical concrete columns with a textured, ribbed surface; the right one shows a large, rectangular concrete panel with a similar textured surface. Below the right photograph, the text "Tvasta and Godrej Construction" is displayed. In the bottom left corner, the text "Admixtures and Special Concretes" is visible. A man in a light blue shirt is seated in the bottom right corner of the slide frame.

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

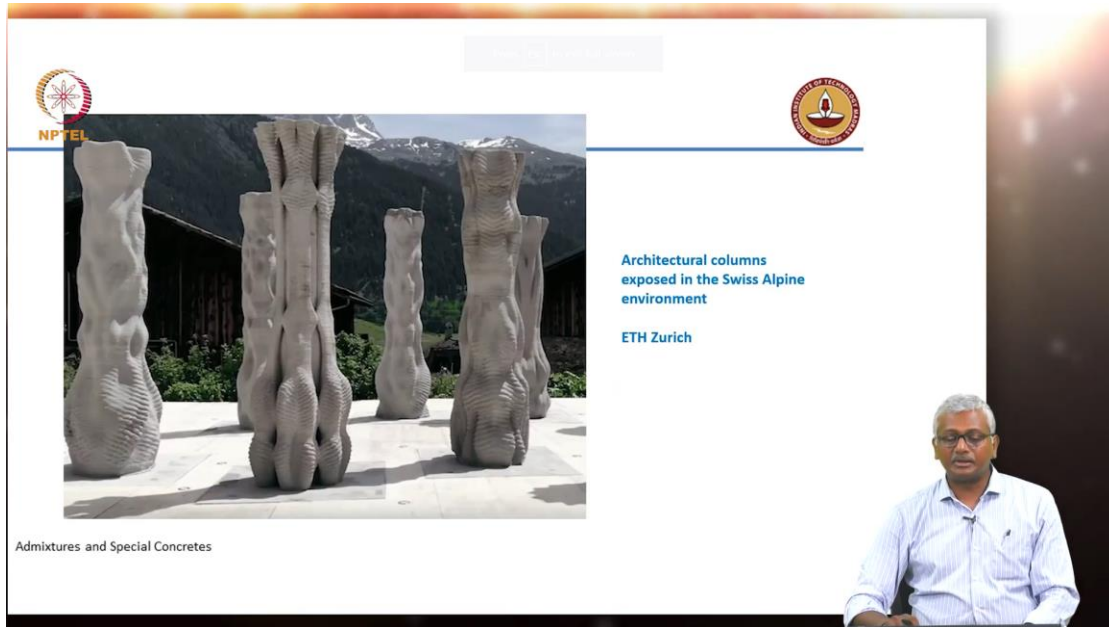
(Refer to slide time: 20:47)



The slide features the NPTEL logo on the left and the IIT logo on the right. It displays three photographs of 3D printed concrete architectural elements: the first shows three tall, cylindrical columns with a textured surface; the second shows a rectangular panel with a textured surface and a circular opening; the third shows a large, rectangular panel with a textured surface. Below the second photograph, the text "Loughborough University, UK" is displayed. In the bottom left corner, the text "Admixtures and Special Concretes" is visible. A man in a light blue shirt is seated in the bottom right corner of the slide frame.

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

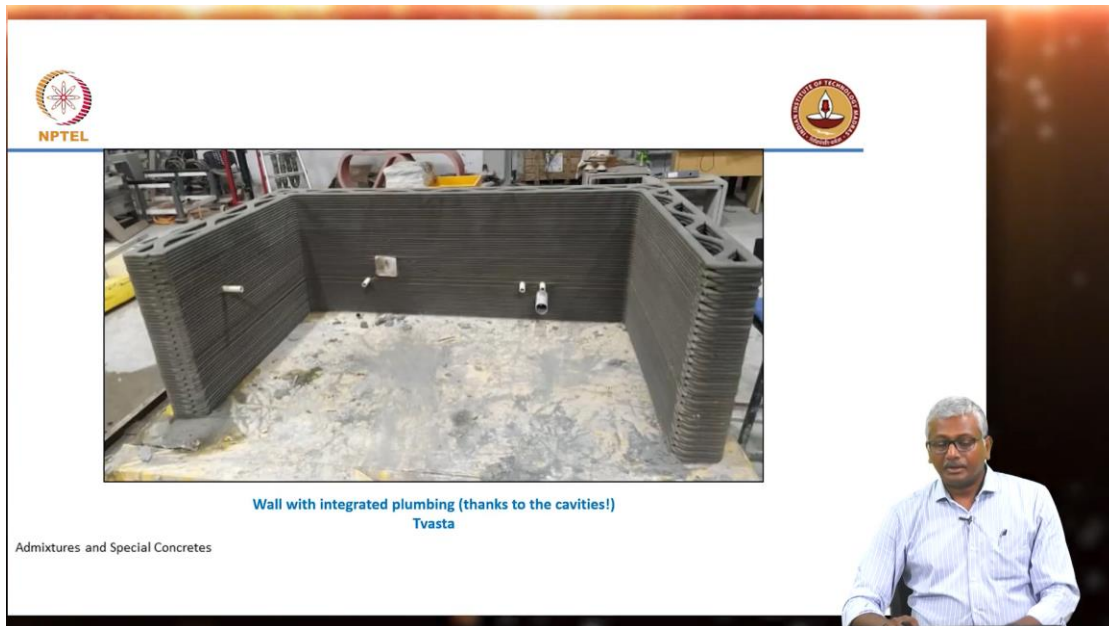
(Refer to slide time: 20:52)



The slide features a photograph of several tall, textured, grey concrete columns standing in an outdoor setting with mountains in the background. The columns have a complex, organic, and somewhat twisted appearance. The slide includes the NPTEL logo in the top left and the Indian Institute of Technology Bombay logo in the top right. Text on the slide reads: "Architectural columns exposed in the Swiss Alpine environment" and "ETH Zurich". A small text at the bottom left of the image area says "Admixtures and Special Concretes". A man in a light blue shirt is visible in the bottom right corner of the slide frame.

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

(Refer to slide time: 21:02)

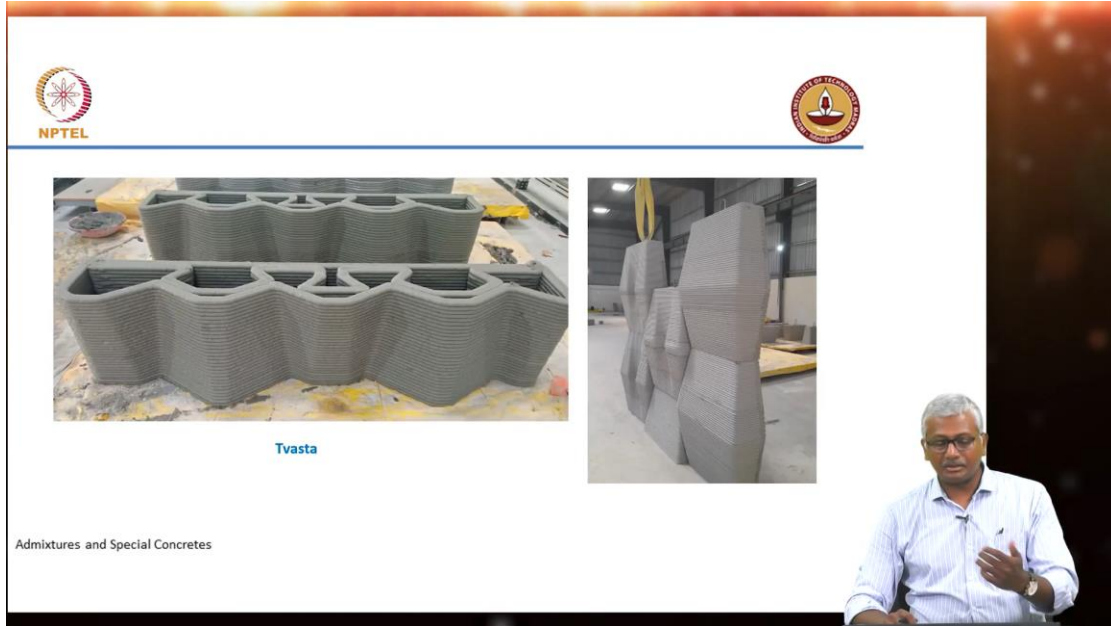


The slide shows a photograph of a large, rectangular, grey concrete wall structure in a workshop or factory setting. The wall is composed of many thin, stacked layers of concrete. The interior of the wall has several small, circular openings, some of which have pipes or conduits inserted. The slide includes the NPTEL logo in the top left and the Indian Institute of Technology Bombay logo in the top right. Text on the slide reads: "Wall with integrated plumbing (thanks to the cavities!)" and "Tvasta". A small text at the bottom left of the image area says "Admixtures and Special Concretes". A man in a light blue shirt is visible in the bottom right corner of the slide frame.

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.

(Refer to slide time: 21:22)



The slide features the NPTEL logo on the top left and the Indian Institute of Technology Bombay logo on the top right. It contains two photographs of grey concrete blocks with a wavy, textured surface. The left photo shows a row of these blocks laid out on a workbench, with the word "Tvasta" printed below them. The right photo shows a stack of the same blocks. A man in a light blue shirt is visible in the bottom right corner, gesturing as if speaking. The text "Admixtures and Special Concretes" is located at the bottom left of the slide.

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:

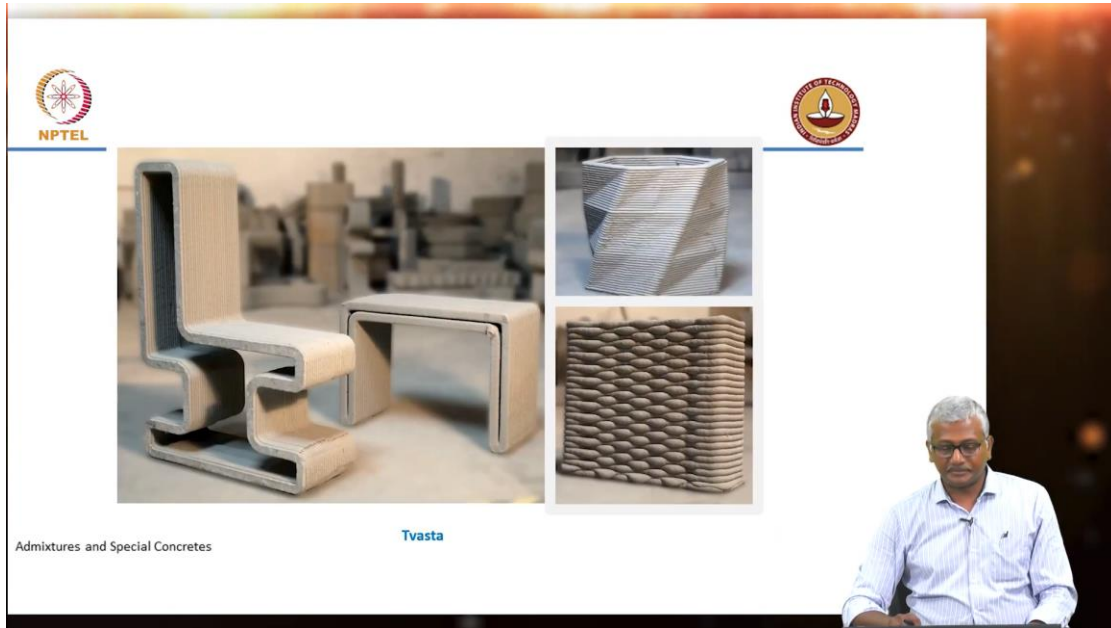
(Refer to slide time: 21:32)



The slide features the NPTEL logo on the top left and the Indian Institute of Technology Bombay logo on the top right. It is titled "Street / garden furniture" in the center. It contains three photographs of grey concrete furniture pieces, including chairs and a table, with a wavy texture. The text "Tvasta and Godrej Construction" is printed to the right of the photos. A man in a light blue shirt is visible in the bottom right corner, gesturing as if speaking. The text "Admixtures and Special Concretes" is located at the bottom left of the slide.

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

(Refer to slide time: 21:41)

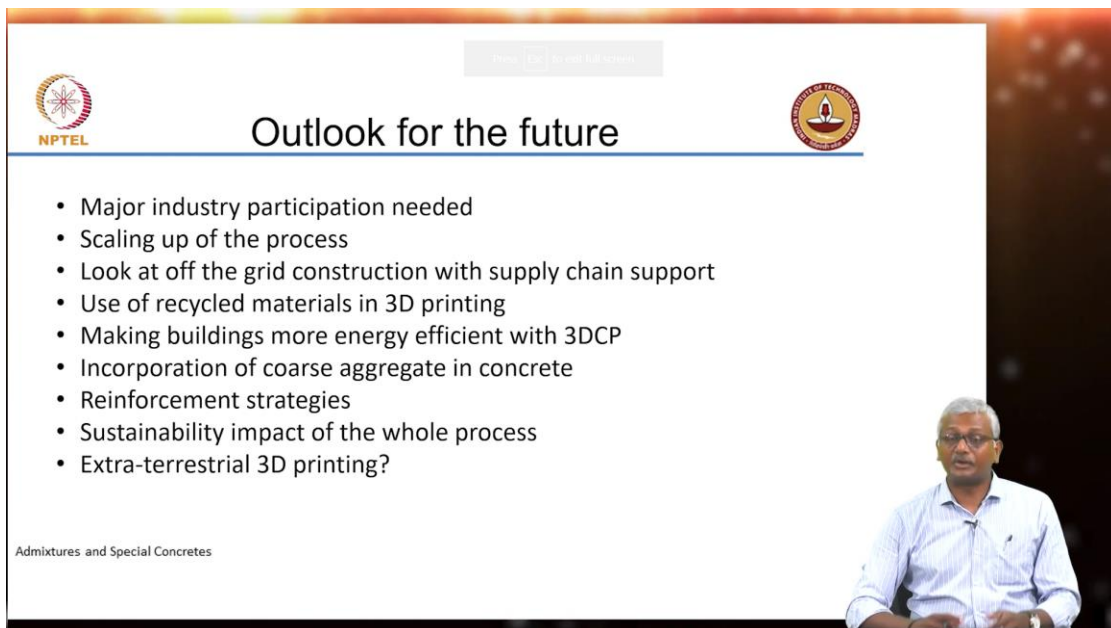


The slide features the NPTEL logo on the top left and the IIT Bombay logo on the top right. It displays three images of 3D printed concrete street furniture: a large L-shaped bench, a square trash bin with a woven texture, and a rectangular trash bin with a brick-like texture. The word "Tvasta" is centered below the images. In the bottom right corner, a man in a light blue shirt is visible. The footer text reads "Admixtures and Special Concretes".

So, lot of interesting textures can be brought about.

Outlook for the future:

(Refer to slide time: 21:44)



The slide features the NPTEL logo on the top left and the IIT Bombay logo on the top right. The title "Outlook for the future" is centered at the top. Below the title is a list of seven bullet points. In the bottom right corner, a man in a light blue shirt is visible. The footer text reads "Admixtures and Special Concretes".

- Major industry participation needed
- Scaling up of the process
- Look at off the grid construction with supply chain support
- Use of recycled materials in 3D printing
- Making buildings more energy efficient with 3DCP
- Incorporation of coarse aggregate in concrete
- Reinforcement strategies
- Sustainability impact of the whole process
- Extra-terrestrial 3D printing?

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.