Development and Applications of Special Concretes
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Lecture 24
Fibre-Reinforced Concrete-III

Hello, Welcome back. Once again, we continue our discussion on development and applications of special concrete. And today we will conclude the discussion on fiber-reinforced has been the mainstay of our model number 6. We started this module, this special discussion of discussion on the rheology of concrete and started fibre reinforced concrete. Today we close the discussion on Fibre reinforced concrete.

So, let us continue the discussion on Fibre reinforced concrete. And today we focus on the properties of this concrete in the hardened state having done the properties of fresh fibre reinforced concrete in the previous discussion.

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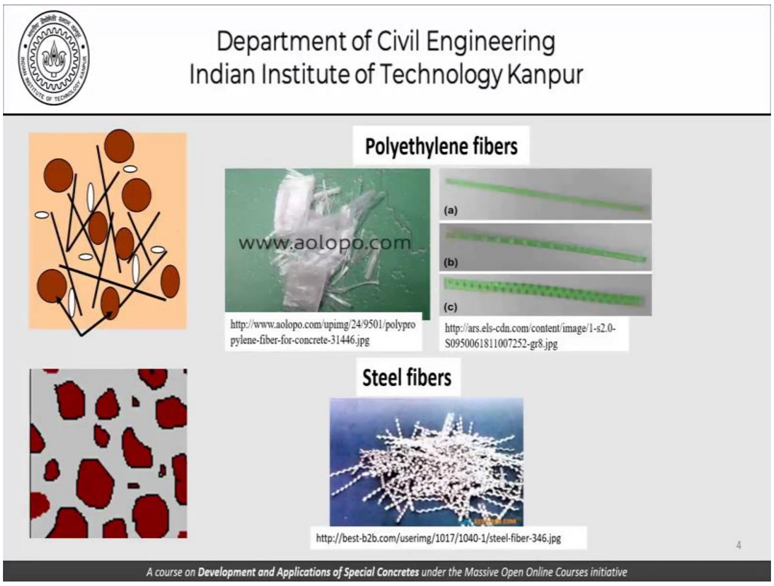

So, this slide is more of a recap. This picture here is showing the presence of fibres in Concrete Matrix with coarse aggregate. This picture is something that you are familiar with and we can imagine that in fibre reinforced concrete will have fibres of different lengths and diameters which are represented by the aspect ratio l/d, different l/d’s of different materials whether it is Steel fibres or polyethylene fibres or class or Aramid kind of fibres.

These different fibres will be mixed with concrete and what we are looking at is the properties of concrete as it hardens with these fibres.

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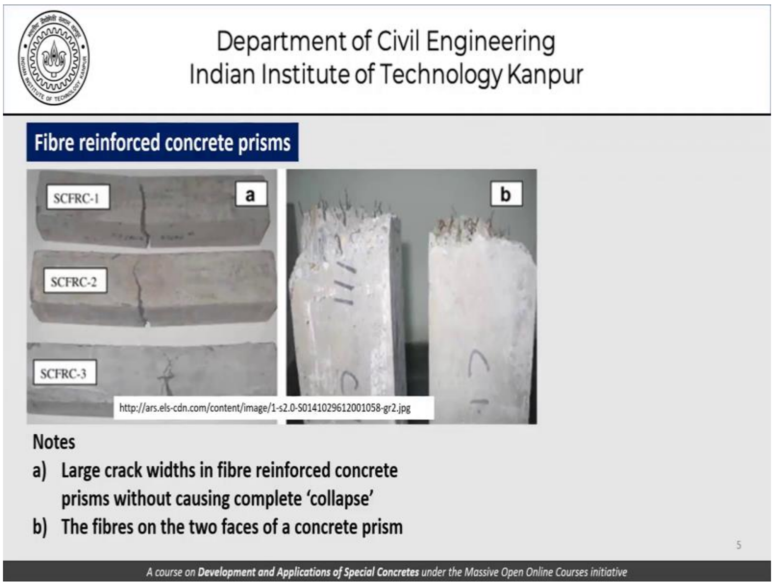

So, this picture also we have seen last time that the presence of the fibres which are seen here, which are sticking out of a surface of concrete, after it has been broken. How will they contribute? And it is their presence in the manner; it is shown that affects the properties of hardened concrete so that what we are going to study a little bit in a greater detail today.

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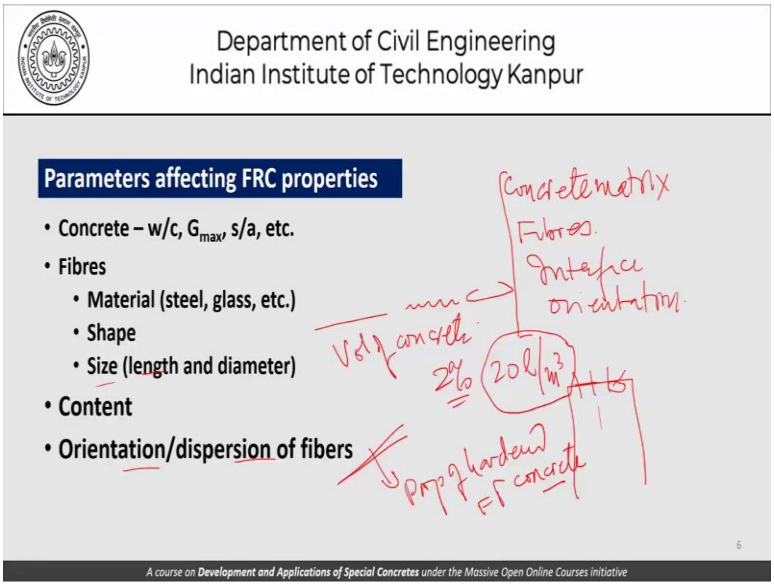

As far as the parameters that affect the properties of fibre reinforced concrete are concerned. It is on the concrete side because at the end of it, we are talking of concrete matrix on the one side and we are talking of fibres on the other. And then we are talking about the interface and orientation issues. We saw from the previous discussion that if we have a concrete prism like this and we have some fibres jutting out from here. They need not all be perpendicular like this.

Some of them may be embedded at angles; some of them may be lying on the horizontal plane along the surface which has fallen off as we tried to extract this surface and so on. These factors are actually summarised here on the concrete side, we have the water cement ratio the maximum size of aggregate, s/a. On the fibre side, we have the material which could be steel, glass aramid, polythene whatever it is.

The shape of the fibre, we talked about it last time that it need not be smooth. They can be crimped, they can be hooked and so on. Then of course, there is the length and diameter of the fibres which is together referred to as size here. And then, we have the content issue that ok how much fibre is there. Is it 1% half a percent, 2% and these numbers are given by volume of concrete.

So, when we say that, we talking of 2% fibres in the concrete weight, we are talking at 20 litres per cubic metre. This is the volume of fibre that we are talking about. So, content of fibres and finally the orientation and dispersion. All these factors put together, what we have at the end of it is the properties of hardened fibre reinforced concrete. Hardened concrete in this case it would become fibre reinforced concrete.

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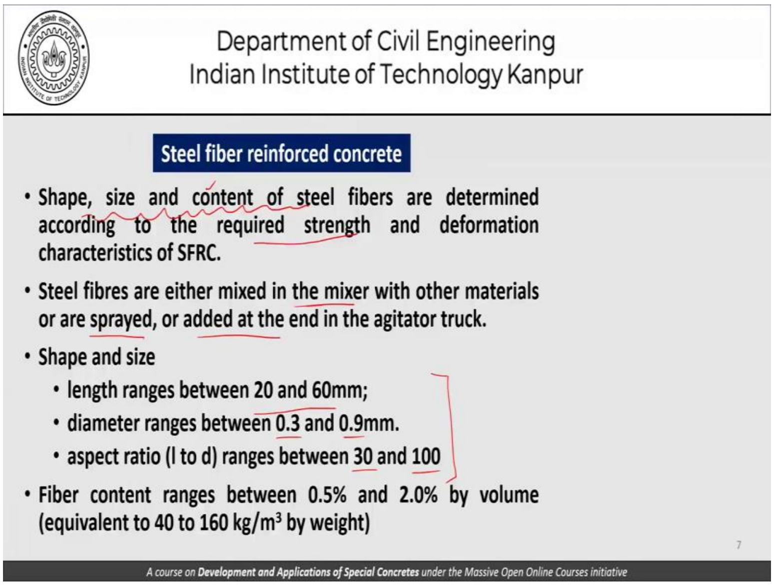

Moving forward, we have Steel fibre reinforced concrete is more of a recap, Shape, size and content of Steel fibres are determined according to required strength and deformation characteristics of Steel Fibre reinforced concrete. Of course, that is true for all other fibres as well. So, what is being said here, we talked about this slide last time. That once we have a required strength, we can change these parameters. Given these parameters, we will try to determine the parameters like strength and deformation characteristics and figure out whether it is acceptable to us or not.

Then we have Steel fibres are either mix in the mixer with other materials or are sprayed or added at the end in an agitator truck. Fibres can be added at the time of mixing or after the mixing or just sprayed onto the surface. There are different ways of doing it for different applications and all of them are equally acceptable provided the engineers understand the implications of doing the fibre addition in one way are the other.

As far as the shapes and sizes of fibres are concerned, we talked about it at length. The length usually varies between 20 - 60mm diameter is 2.3 - 2.9 mm, which effectively means we are talking of aspect ratios between 30 and 100. But this is not sacrosanct kind of numbers and there are smaller fibres, there are larger fibres which are used depending on what we really want to have. The fibre content ranges from 0.5% and 2% by volume which is equal to 40 to 160 kgs by weight.

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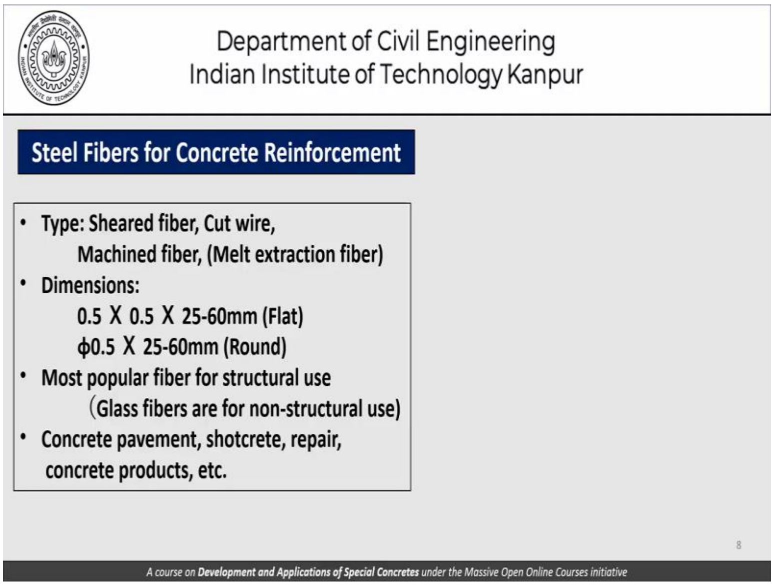

And there are different kinds of fibres which we saw in the first discussion of fibre reinforced concrete. Sheared type, cut wire, machined fibres. There are other non-structural uses of fibre reinforced concrete for example Glass fibres are sometimes used for non-structural use and of course, we have applications in terms of concrete pavement, shotcrete repair in some concrete products meet with Fibre reinforced concrete.

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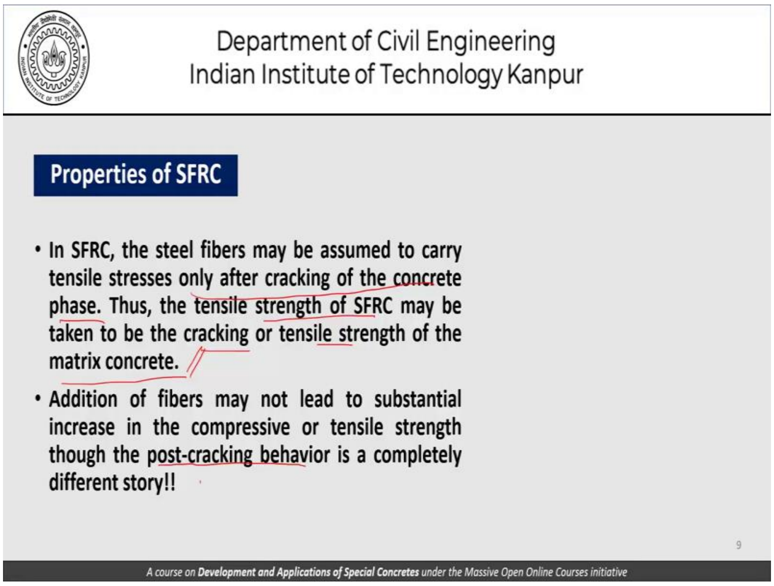

As far as the properties are concerned, let us take them up for a more detailed discussion. So in the steel fibre reinforced concrete, steel fibres may be assumed to carry tensile stresses only after the cracking of the concrete phase. As we have in the case of normal reinforced concrete, the Steel comes into play only after the flexural crack is formed. In the fibres also, tensile stresses transfer to the fibres only after the cracking of the concrete phase and thus the tensile strength of Steel fibre reinforced concrete may be taken to be the cracking the tensile strength of concrete matrix itself.

And that is what we talked about briefly last time also that unless we go towards a very high fibre content, it is unlikely that will get a major upward revision of the tensile strength or the cracking strength fibre reinforced concrete. Having said that, the post cracking behaviour is what is most substantially affected. The addition of fibres may not substantially lead to the increasing compressive or tensile strength though the Post-cracking behaviour is a completely different story.

That completely changes because only post-cracking the fibres come into play and take more and more load.

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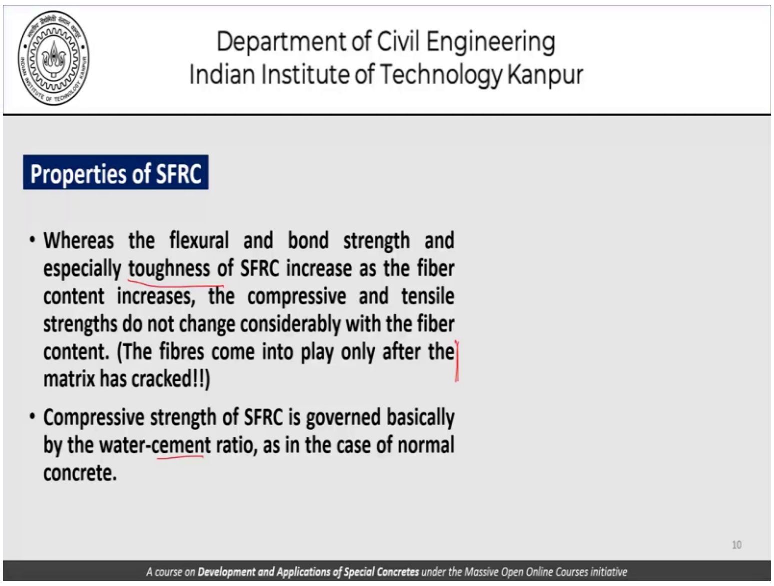

Whereas the flexural Bond stress especially the toughness of Steel fibre reinforced concrete increases the fibre content increases the compressive and tensile strength do not considerably change with the fibre content itself. As I have been pointing out all the time, the fibres come into play only after the matrix has cracked. So, the flexural bond strength and toughness definitely increases as we shall see in this presentation. Compressive strength of Steel fibre reinforced concrete is governed basically by the water cement ratio as in the case of now.

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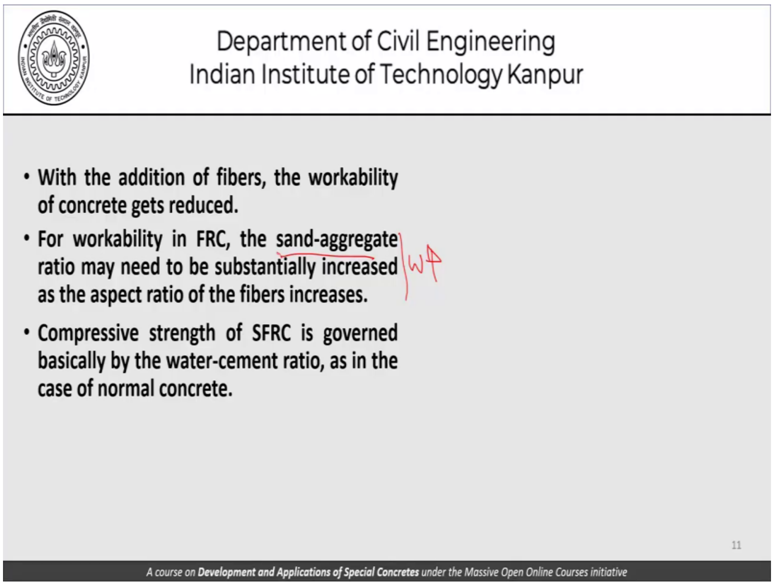

So, with the addition of fibres, the workability gets reduced. The workability in the fibre reinforced concrete, we need to increase s/a and of course, we may also need to put some more water. This is something which we have talked about previously as well for compressive strength and water cement ratio as in the case of normal concrete.

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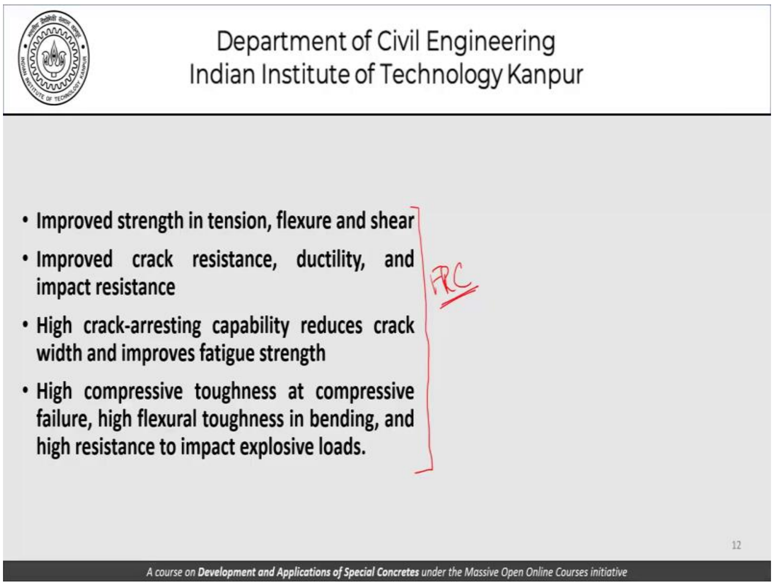

Improved strength in tension, flexure and shear, improved crack resistance ductility and impact resistance, improved crack-arresting capability, reduced crack width and improves the fatigue strength, high compressive toughness at compressor failure, high flexural toughness in bending and high resistance to impact explosive loads. Now, these are some of the characteristics of fibre reinforced concrete which make the material interesting for cement and concrete engineers to study and explore and try to use as far as construction of certain special types of structures is concerned.

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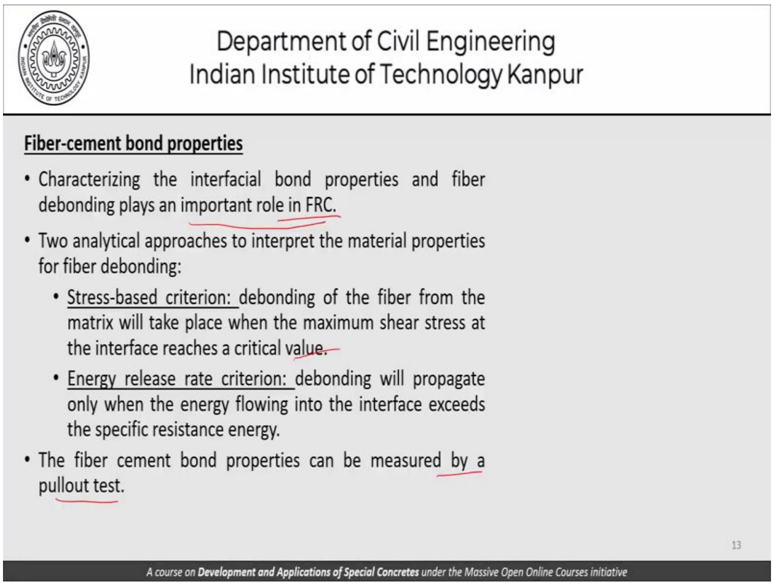

As far as the fibre cement bond properties are concerned, characterizing the interfacial bond properties and fibre debonding plays an important role in defining the characteristics of fibre reinforced concrete. So, two analytical approaches to interpret the material properties for fibre debonding have been proposed. One is the stretch-based criteria, which basically talks of the debonding of the fibre from the matrix will take place when the maximum shear stress at the interface reaches the critical value.

And energy release rate criteria which say that the debonding will propagate only when the energy flowing into the interface exceeds specific resistance energy. The Fibre cement bond properties can be measured by a pull out test. What we need to do is to carry out the pull out test for fibres individually. That is what will give us an understanding of the Fibre reinforced concrete Behaviour for a single fibre.

Of course, while we; are taking that result and taking it to the fibre reinforced concrete as a composite. We have to be careful about the reliability and scalability of those kinds of thoughts, but that is the approach that is being suggested here.

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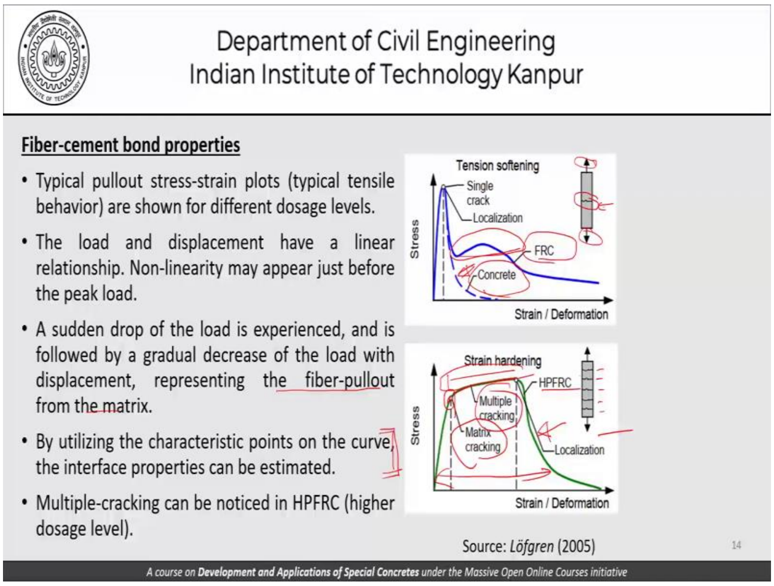

The fibre cement bond properties the typical pullout stress strain plots are given here. So, this is fibre reinforced concrete and this is concrete. And if we subject this concrete specimen or the fibre reinforced concrete specimen to the loads like this, then, the moment that is a single crack formed, strain concrete simply collapses. So, there is in no way we can have any additional load carrying capacity left in it.

But in the case of fibre reinforced concrete, there is a drop but still there is some capacity for taking additional deformation. So, the load displacement relationship will be a linear relationship to begin with, nonlinearity may appear just for the peak load, a sudden drop of the Load is experienced was followed by gradual decrease of the load with displacement representing the fibre pull out from the matrix and by utilising the characteristic points on the curve interface properties can be estimated.

So, this is the kind of approach which has been suggested in Literature to study the properties of a fibre embedded in a cement matrix. Multiple cracking can also be noticed in high performance fibre reinforced concrete at a higher dosage level and that is what we see here. That is here. Here we have just a single crack that propagates through the system or through the specimen and the concrete is not able to sustain anymore loads.

Here in a situation like this, if you are talking of multiple cracks being formed in the System or in the specimen, then, we can always have a high-performance fibre reinforced composite where we have multiple cracking happening beyond this point and matrix cracking happening only here at which stresses are transferred to the fibres within the matrix. After this point, the load finally closed down and we can see substantial increase in the deformation capacity or the strains.

From here onwards we have post cracking behaviour and that is what is important as far as fibre reinforced concrete are concerned.

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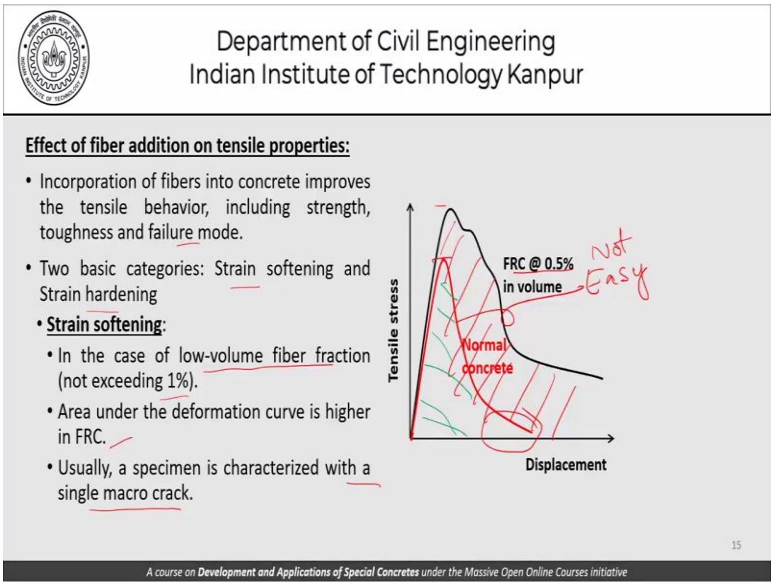

Effect of fibre addition on the tensile properties, this is something which has been discussed just like the simplified manner. Incorporation of fibres into concrete improves the tensile behaviour including strength toughness and failure mode. And we have two basic categories that to talk about. Strain softening and strain hardening. So in the case of low volume fibre edition say about 1% the area under the deformation curve is higher in the case of fibre reinforced concrete and a specimen is characterized by a single macro crack.

What we are seeing here is normal concrete, the way we discussed peak load, sudden decrease and almost going to see. I must also point out it is not easy to obtain this part of the stress-strain curve. It is only with specialised equipment where we are trying to do displacement control test, it is possible to get this kind of behaviour or get reliable data for this part of the curve.

In normal machines is sometimes not possible when it comes to fibre reinforced concrete at say 0.5% the peak load yes, it improves little bit it may or may not improve as a matter of fact sometimes. But the issue is really in terms of the increase in this area that we have compared to the area under the curve here. What we study a little bit more in detail and quantitatively when we try to study the characteristics of fibre reinforced concrete.

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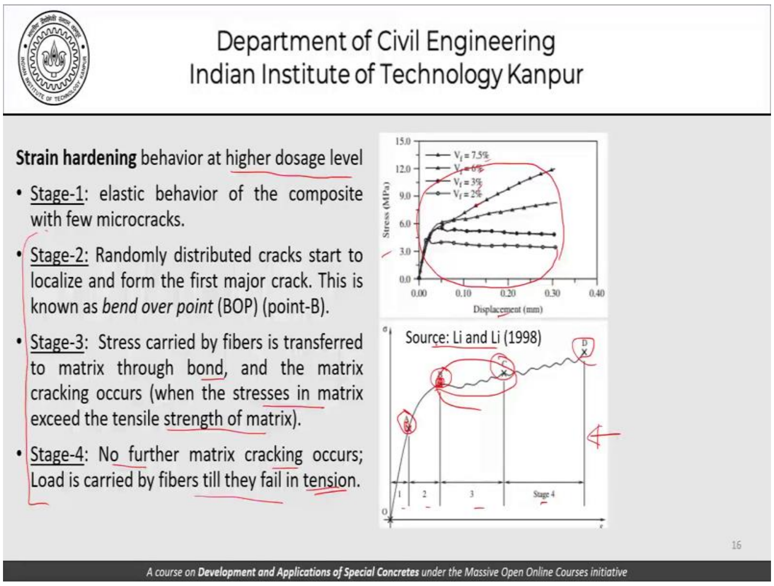

Strain hardening is a behaviour that we encounter especially at higher dosage levels. The higher dosage level of fibres if you see here, stress versus displacement kind of a graph. We see that at 2% 3% 6 or 7 and a half percent, this is what the load displacement curves look like for a particular study. Characterizing these in a schematic manner, this is the kind of picture which has been presented and we have different stages 1, 2, 3 and 4 characterized by its different points A, B, C and D. What do these points mean?

Randomly distributed cracks start to localise and form the first major crack and this is the bend over point at point P. So, this is what is happening here. Here is the point where the matrix has cracked and the elastic behaviour of the composite with few microcracks. This stress carried by fibre is transferred to the matrix through bond and the matrix cracks again, when the stresses in the matrix exceed the tensile strength of the matrix. So, this is what happening here.

And then in stage 4, we have no further matrix cracking and the load is carried by the fibres till they fail in tension or pull out or whatever happens here. So, this is the kind of stages in which a Fibre reinforced concrete fails.

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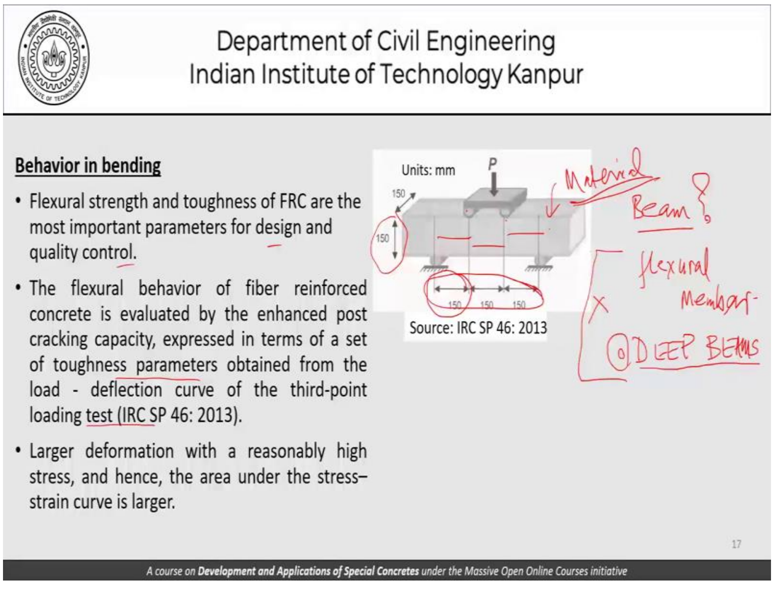

As far as the standardization of such test is concerned let us see one of the pictures from IRC the Indian Road Congress and what has been talked about is the behaviour in bending. Flexural strength and toughness in fibre reinforced concrete are most important parameters for design and quality control. The flexural behaviour of fibre reinforced concrete is evaluated by the enhanced Post cracking capacity expressed in terms of a set of toughness parameters that you just see in a minute, what these toughness parameters are, obtained from the load deflection curve of the third point load test.

So, what is shown here is IRC setup where we have 450mm here and 150 to 150 kind of size of the specimen and we have load being applied in the centre here, transferred to two places, with these distances being equal. I would also like to draw your attention to the fact that this dimension is 150 and so is this dimension? So, this does not really truly make it a beam. If you want to call it a beam, I am leaving it to you to think as to when we can call it a Beam or a truly flexural member.

Let me give you a hint as to what I am thinking about you have seen or you have a concept of deep beams. Not that it is extremely relevant here. But I think it is time that you look up this concept of deep beams and try to understand what is the difference between a deep beam and a normal beam and whether this kind of a setup here would be the best setup as far as testing deflection is concerned. The answer is yes and no. And I am not giving you the answer anyway.

Having raised doubts about this method, I must also say that given that we are testing only this material and determining the properties of this material, which is plain concrete or fibre reinforced concrete to the certain type of fibre of certain geometry and so on. It is pretty much all right to still use this test without getting into this discussion. So this discussion is not directly relevant here, but it is something which you should keep the back of your mind into some reading about.

So, the large deformation with the reasonably high stress in the area under the stress-strain curve is larger. We are not showing the stress strain curve for the load deflection curve for this particular case to be discussed it subsequently in another slide.

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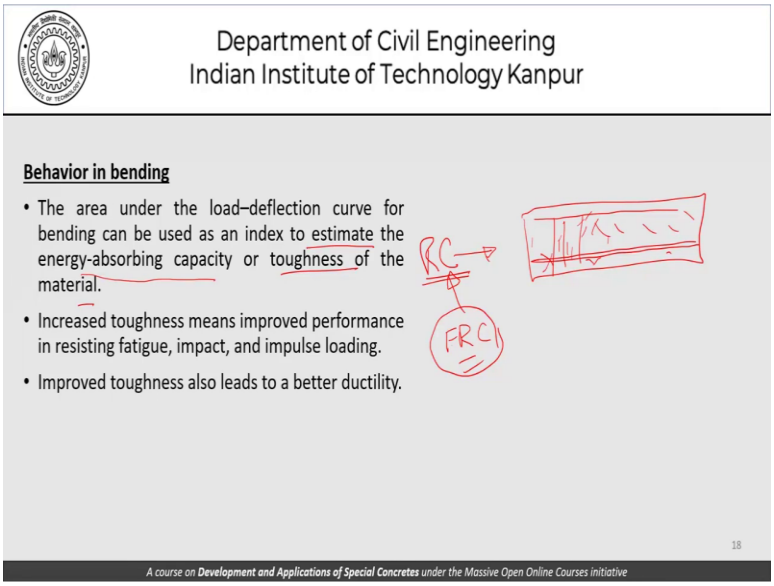

Continuing with the behaviour in pending, the area under the load deflection curve for bending can be used as an index to estimate the energy absorption capacity or the toughness of the material, increased toughness, please improved performance in resisting fatigue impact and impulse loading and in areas, like earthquake engineering design where we expect certain amount of absorption to happen in certain specific parts of a structure, for example, the beam column joints and so on.

Improved toughness also leads to a better ductility as far the performance of reinforced concrete members is concerned. Remember that I had discussed this with you that when we talk of reinforced concrete, the image that I have is that of a beam or a column with a single reinforcing bar or many reinforcing bars either here or on the top or both with shear reinforcement and so on. So, this is one type of reinforced concrete.

Then we talked of fibre reinforced concrete. So, the fibre reinforced concrete typically, the fibres do not replace this reinforcement, but change the concrete itself. So, all this concrete here has fibres and we are interested to see what is the structural behaviour of a concrete like this we could very well do test. I am going to show you one example today where we test or where tests were carried out using normal reinforcement and using fibre reinforced concrete here.

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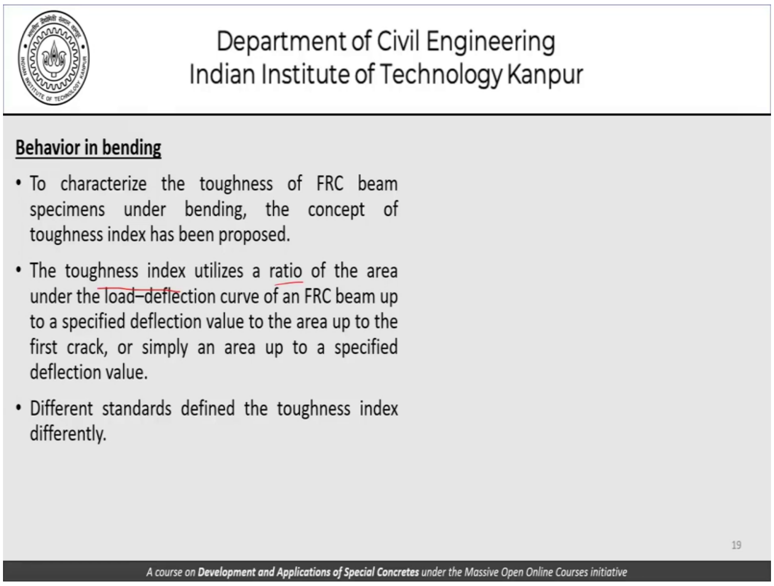

Continuing with our discussion, on the pending behaviour to characterize the toughness of fibre reinforced concrete beam specimens and bending, the concept of toughness index has been proposed and the toughness index utilizes the ratio of the area under the load deflection curve of an FRC beam up to a specified deflection level to the area of the first crack or simply an area upto the specified deflection value.

We will see those things when we come in the next slide, it will become clearer. Different standards define toughness index differently. So, so far as the concept that is the area under the load deflection curve that we are talking about is understood that it becomes a matter of standardization as to how we will calculate that area till what point will calculate the area and so on.

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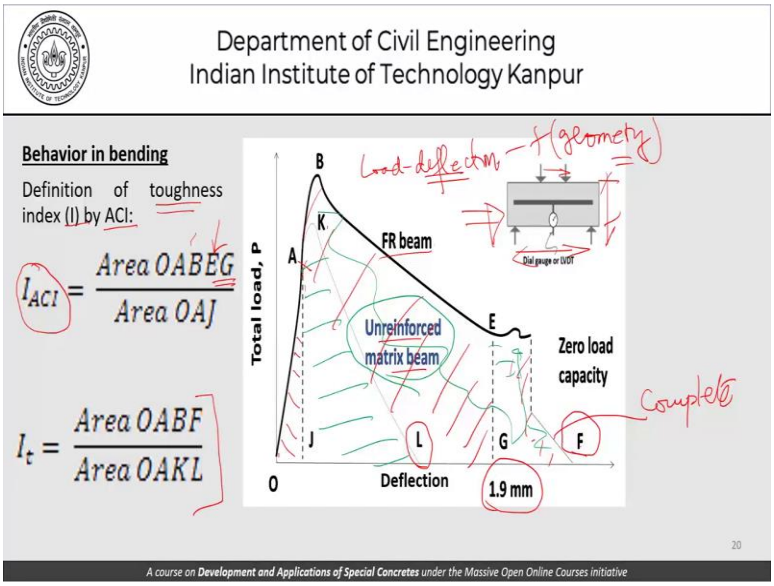

For example, as far as ACI is concerned, American concrete Institute. Let us look at this idealized fibre reinforced concrete beam, unreinforced matrix beam showing these kinds of behaviour. So, the toughness index I, as far as ACI is concerned, talks in terms of the area OABEG is divided by the area OAJ. So, we are talking of this area which is a triangular kind of an area, because this part from O to A is largely linear, so triangular kind of an area and the ratio of this entire area here upto E.

E means it is defined as a deflection of 1.9 millimetres. 1.9 millimetres and for that you have to actually see what is the geometry of the specimens that is being used? What is the size of the specimen that we are talking about? And where are we measuring the deflection? Are we measuring at the bottom, measuring at the centre and so on. So, those details are all specified in the test method as far as ACI is concerned.

So that ratio of OABEG to the ratio of OAJ is one way of defining the toughness index. Researchers however have proposed another definition which talks of the area OABF. Now OABF that means you go all the way. You take the complete area. Do not stop at 1.9 mm include all this as well. Now once you do that, what is the denominator? Not the area and this is linear part here, but the area under OAKL. So, you go all the way here to this point L here and calculate this as the base. This is the area under that curve as far as an unreinforced matrix beam is concerned.

Compare this area with the area of the entire load deflection curve of a fibre reinforced beam. So these are the two of the possible ways in which the toughness index can be defined, please remember that at the end of it, what you get from Experiment is the Load deflection curve and load deflection curve is obviously a function of its very closely related to the geometry of the specimen that you are using.

Once you are using a certain kind of geometry 1.9 mm deflection or whatever it is, it is related to that and once we get the load deflection curve as a matter of standardization as to how to go about getting what is called the Toughness Index. Basically, the idea being that if you want to find out how much is the increase in the area under the load deflection curve with respect to unreinforced matrix.

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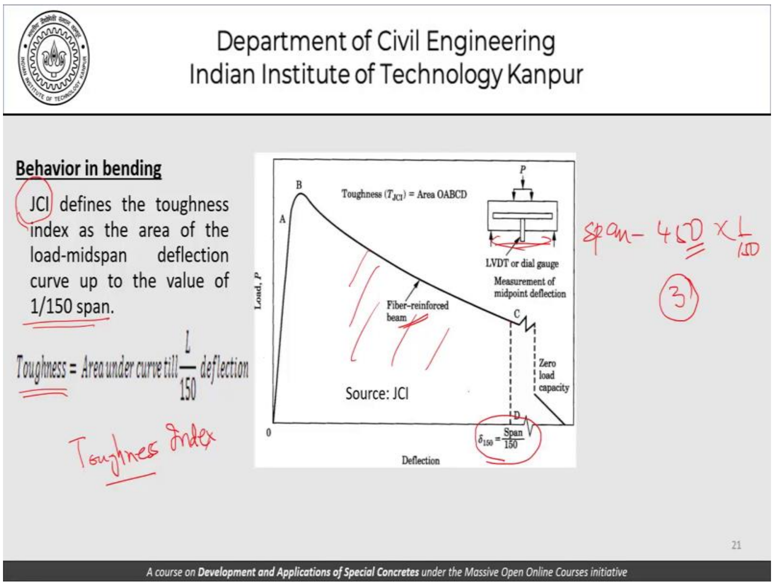

Continuing our discussion on similar lines the Japan Concrete Institute defines toughness index as an area or load mid-span deflection curve upto a value of 1 by 50 of the span. Now if you are talking of 1/50 of this span. And you are talking of this span to be 450 mm. If you are talking 450 mm span that was the span that I showed you in the IRC specimen. So, if it is 150th of that multiplied by 1/ 150 we are talking of a deflection of 3 millimetres.

So, what we know is that here, we have the area under this curve, for Fibre reinforced beam up to a delta 150 that is spanned by 150. So, this area is what we consider as the total toughness. Remember that as far as ACI is concerned they were not talking about the toughness, they are talking of the toughness index. And this area under the curve was kind of normalised with respect to the area under the curve for unreinforced specimen or an unreinforced material.

Here in JCI we are talking of the toughness itself and we talk of the area under the curve till a deflection of L/150.

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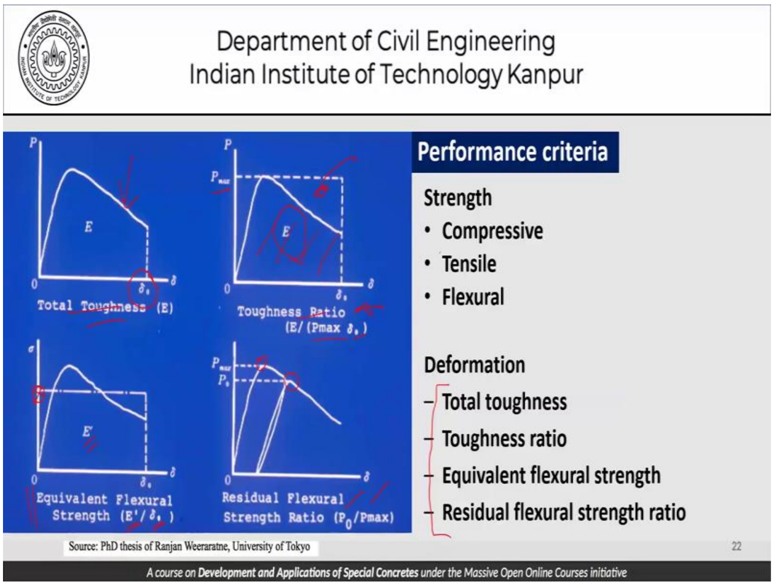

These are some of the better known diagrams that we have as far as the JCI is concerned and we can see that. We can talk in terms of compressive tensile and flexural strength, and as for the load deflection curves are concerned, for this load deflection curve that we have, we have the total toughness, the toughness ratio, the equivalent flexural strength and the Residual flexural strength ratio, which can be determined.

And they are all defined here in these diagrams and the deformation characteristics are being measured using these parameters. So, in this case, we have the total toughness at a certain level of deformation the JCI says L/150, ACI says 1.9 mm and so on. So we can talk in terms of total toughness as defined here. We can talk in terms of a toughness ratio which can be this area here which is $E/(P_{max}*\delta_0)$ which is this whole value.

That is one way of looking at it. That we do not use a comparison with the unreinforced material but we rather create this area here ($P_{max}*\delta_0$) and compare how much is E. Coming to equivalent flexural strength, we try to determine that area E' which is here and divided by δ_0. So we have this divided by δ_0 will give us some value here which will be called or which can be called the equivalent flexural strength.

We have the residual flexural strength ratio, which is P_0/P_{max} which is this cyclic loading situation where we take it upto P_{max} go back to the next time cycle at P_0 and so on. And we can find out what is P_0/P_{max}. Then, we try to define a parameter called the residual flexural strength. So there are different ways at which Researchers have tried to use or characterize fibre reinforced concrete kind of composites and they are all available in literature and have been used as far as design is concerned.

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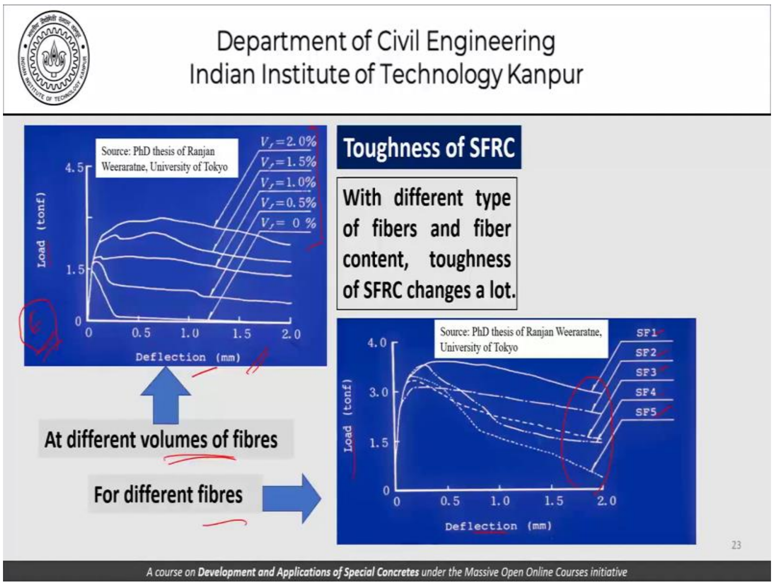

As far as toughness is concerned, once again, then there are different studies that we have. Here is a situation where toughness of the load deflection curve have been plotted for different fibre volumes. 0.0, 0.5, 1.0, 1.5 and 2.0 and we can see that how we can interpret the kind of discussion that we had just now in the previous slide in terms of the area E and compare it with toughness ratio and so on and so forth.

This is the load deflection curves observed for different volumes of fibres. We can have a similar study with different fibres and we can find that. This is SF1 SF2 SF3 SF4 and SF5 and depending on the fibres that we use, the load versus deflection curves could be very, very different.

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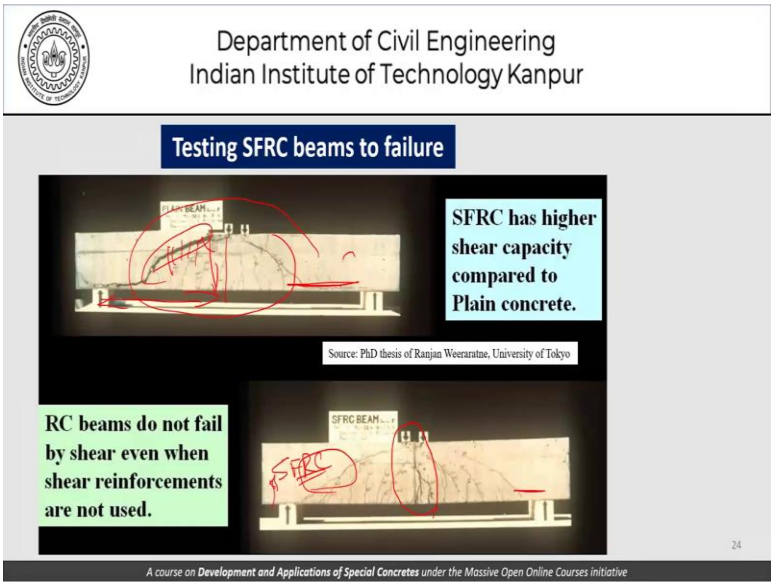

This picture here shows how steel fibre reinforced concrete beams have been tested to failure. If you look at this beam it shows a failure which is in shear, this is the propagation of the crack whereas the same beam cast with steel fibre reinforced concrete. With a certain amount of reinforcement here which is not shown, the structural behaviour changes and we see a flexural behaviour. And in this case Steel fibre reinforced concrete shows its strength in terms of resisting the growth of these large shear cracks.

RC beams do not fail by Shear even when Shear Reinforcements are not used. So there is enough shear strength in this portion here which helps us obtain or get some kind of flexural failure. It is when we are testing beams of this size, of this nature then we come to realise as to what is the importance of this ratio. Which is sometimes called the ratio a/d ratio. And I am leaving it to you to just think about what a/d ratio is and how it is relevant from the point of your flexural behaviour of beams and in terms of the deep beams that we talked about.

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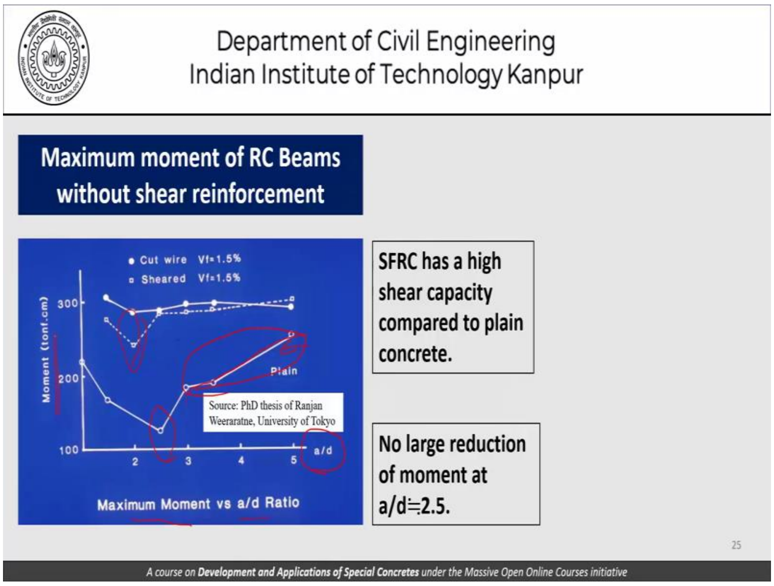

This is a pointer in that direction. We have the maximum moment versus a/d curve here, so if a/d was plotted on this axis and the moment was plotted in this axis, we find that there is some kind of a minimum that is seen here, especially for plain beams and then beyond this point the moment capacities are something here, they increase. Meaning thereby that as far as beam behaviour is concerned, as what is real beam behaviour is concerned, it requires a certain minimum a/d to be able to talk in terms of flexural behaviour or proper flexural behaviour without the shear behaviour becoming a major player in the game.

We are not opening this discussion in a bigger way than that except to note that Steel fibre reinforced concrete has high shear capacity compared to plain concrete and this is what has pushed these values somewhere here that we do not see any pronounced Shear failures. We do not see any large reduction in the moment at a/d of 2.5.

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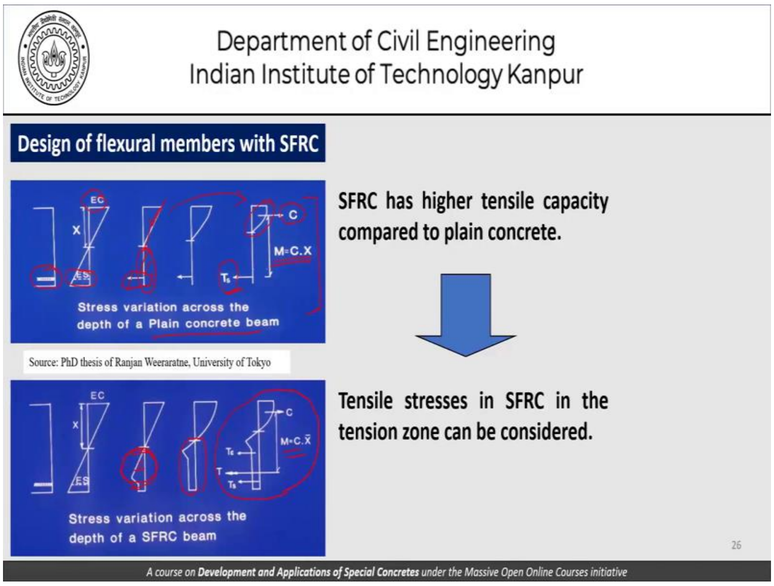

This picture here shows the idealization of the stress-strain curve and the load carrying mechanism of beams. For the stress variation across the depth of a plain concrete beam, we are familiar with this diagram this reinforcement. This is the Steel strain, there is a strain in concrete and then we neglect the stresses being carried by the concrete here and we concentrate only on the stresses in steel on the compression side, Of course, we have this available to us and finally we try to come to a position something like this.

We say that whether it is linear or is not linear, some kind of a stress block develops with a certain centroid, the kind of force that happens here, this force and this force being equal then this moment arm and we get the moment capacity. This is how we do normal plain concrete beam analysis. When it comes to fibre reinforced concrete, the major change over here is that for this particular strain distribution.

There is a certain amount of stress being carried by the fibre reinforced concrete also, which is something which we neglected in plain concrete. This becomes my strain distribution on the tensile side of the beam compression side whatever changes happen they happen and finally we create a more complicated model as far as the force equilibrium is concerned and we create or determine the moment capacity of the section.

So this kind of a thought process goes on, when we try to design flexural members with steel fibre reinforced concrete or any fibre reinforced concrete beam for that matter. So Steel fibre reinforced concrete has high tensile capacity compared to plain concrete in these tensile stresses in the Steel fibre reinforced concrete, the tension zone can be considered, in normal concrete we simply ignore them.

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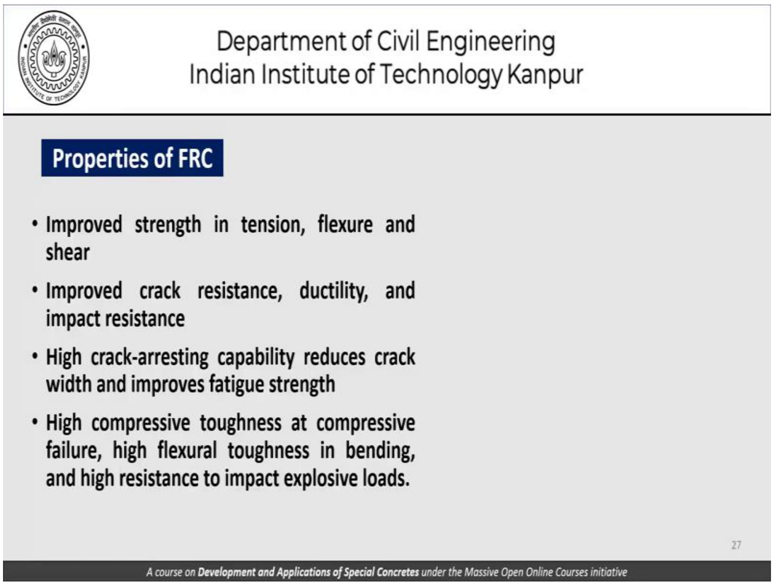

Once again to reiterate, the properties of fibre reinforced concrete are largely in terms of improved strength in tension, flexure and shear. Improved crack resistance, ductility and impact resistance. High crack-arresting capability reduces the crack width and improves fatigue strength and high compressive strength and fatigue failure and the high compressive toughness, flexural toughness and bending and high resistance to impact explosive loads are some of the characteristics of the fibre reinforced concrete.

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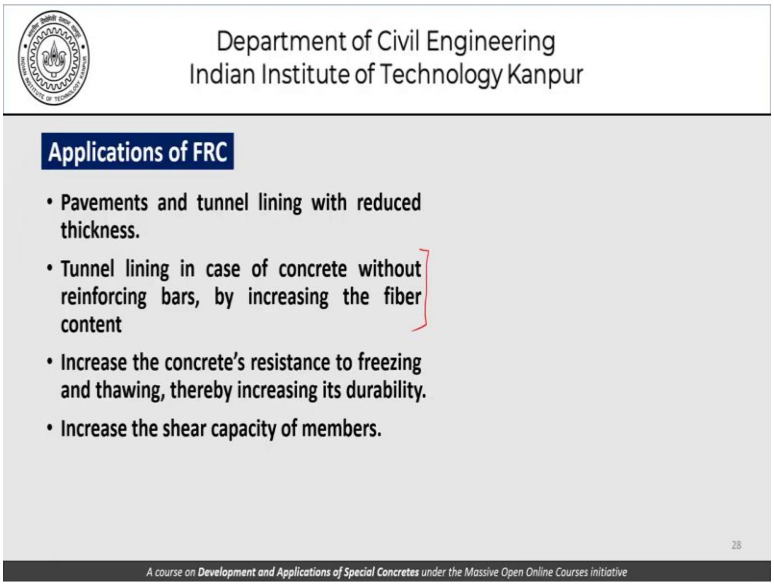

As far as the application of material is concerned, there are several of them, Pavements, tunnel linings, when we have a reduced thickness. Tunnel lining in case of concrete without reinforcing bars by increasing the fibre content we can get very interesting results here. Increase in the concrete resistance to freezing and thawing thereby increasing its durability and increasing the shear capacity of the members.

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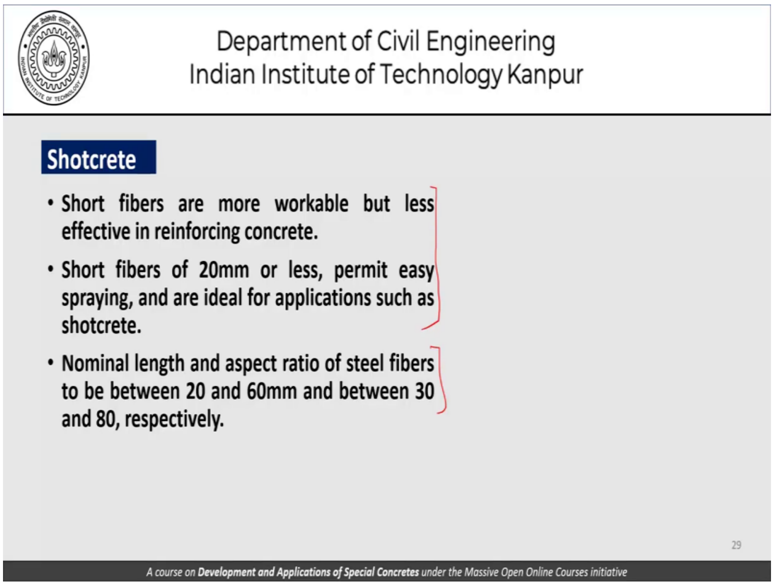

As far as the application is concerned, shortcrete is an interesting example where short fibres are more workable but less effective in reinforcing the concrete and that is what I had said when we say that the short fibres should not be used in concrete because they are less effective. It is not that they cannot be used, only the effect will be lesser. So in certain cases if you are willing to live with that, for shortcrete could be an example, the short fibres are more workable, they contribute less to the reduction in the workability that we have.

But they help us effectively increase the strength of concrete to some extent at least. Short fibres of 20 mm or less permit easy spraying and ideal for applications, the shortcrete and the nominal length and aspect ratio of steel fibres between 20 and 60 mm between 30 and 80 respectively. So this is something which we have to keep reading and understanding with a Pinch of salt and try to study the different applications on a case to case basis and then try to choose whether we want to use the fibre reinforced concrete or not.

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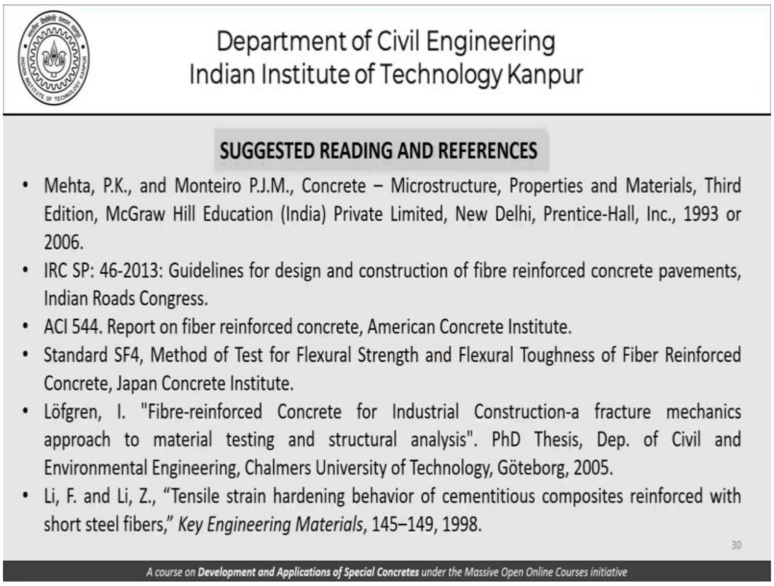

With that, we come to an end of our discussion today. On the properties of hardened fibre reinforced concrete. This is a set of suggested reading and reference material and with that we have another set of reading material, but at the end of it, like I said the other day the list is incomplete and I would be happy and expect you to actually read not only this but also a lot of other more recent material.

What we have done here is right to use some fundamental material which was developed not so recently but there have been recent developments based on this material which will probably help you understand the properties of fibre reinforced concrete better. So with this we come to an end of our discussion as far as this material is concerned.

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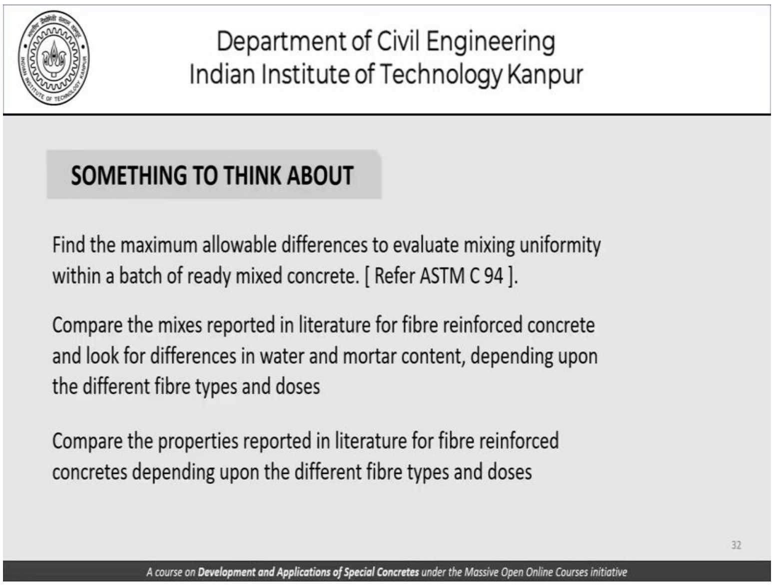

And as far as something to think about this concerned, here are some of the assignments that you could do and I am sure we do some reading on your own, there will be so many other things you will learn and you will be able to contribute to the understanding of the material. Thank you once again, I thank all my teachers, friends and colleagues who helped me understand this material especially, Ranjan Veerath whose PhD thesis I have referred to in my presentation extensively today.

And I look forward to see you once again in the next module with this lecture we come to an end of module 6 and now I will see you in module 7 while we talk about some other interesting aspects of development and applications of special concretes. Thank you.