Advanced Concrete Technology
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Lecture - 30
Post Peak Response and Fibre Reinforced Concrete

In the last lecture we talked about different kinds of characteristics of hardened concrete and we understood that concrete has a characteristic that is quite different from that of metals. Metals like steel exhibit what is known as strain hardening behaviour in which they are able to sustain large amount of deformation with additional stress even after yielding.

On the other hand, concrete belongs to this category of material which is called strain softening where because of the development of cracks and the fact that the cracks beyond the peak continue to grow in the beginning at a stable rate and then finally at an unstable rate leading to final failure of the concrete. So, because of that you have a strain softening response that concrete exhibits.

And for the most part as I said concrete has a nonlinear response, it does not have a very large amount of linearity except at a very early load levels. But the issue is now how do we get to the bottom of understanding how the post peak characteristics should be derived. Now when you do a typical compression test on a cube you simply keep on increasing the loading until a point where the load exceeds the capacity of the concrete and the concrete simply collapses.

The issue is your loading is often done at a level which exceeds or rather the incremental load that you give to the system usually exceeds by a large amount in the total peak stress that is getting borne by this concrete. So if you have to really understand what happens beyond the peak in terms of the excess deformation that it can get from the system what you will have to do is do a controlled deformation test on the material.

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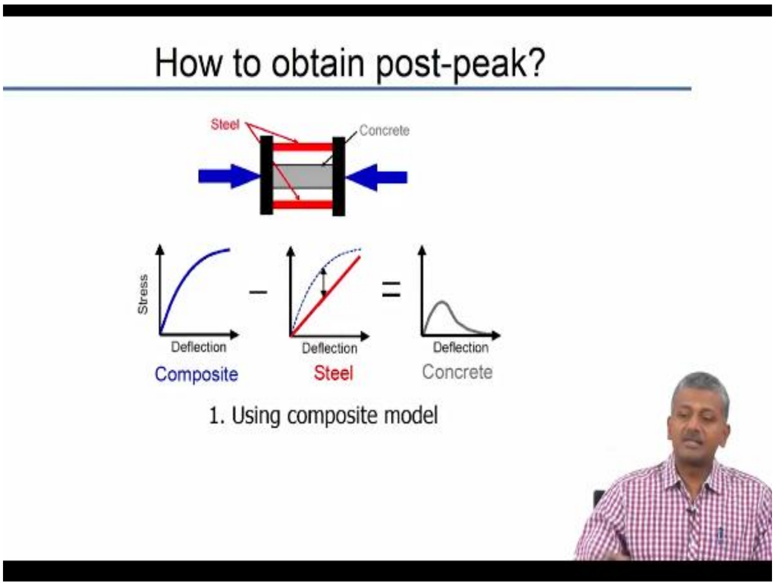

So that is one of the ways, but there is another way of obtaining the post peak behaviour and that is by using a composite model. So here, you have a cylinder of concrete lying in the centre of the loading platen and this cylinder is surrounded by an annular ring of steel.

So both are adjusted so that both of them have the same perfect levels. So now, you are compressing this entire set up together that means that the steel and the concrete will get compressed to the same extent. In other words, the deformation in the steel and the deformation in the concrete will be equal.

You know very well that for the levels of strength that concrete has the stresses that might be there in the steel are going to be very low, much lower than the yield point that means steel still happens to be in the elastic limit. So now, if you know the deflection of the steel you can obviously work out the stress. How do you work out the stress? In terms of Hooks law stress where stress is directly proportional to the strain.

So you can actually work out the deflection and from the deflection you get the stress in the steel. Now for the entire composite you get a stress deflection diagram that is plotted in the left, all you need to do is subtract the steel stress deflection diagram and you obtain the stress deflection diagram of the concrete. So this is an indirect way of obtaining the stress strain curve for concrete and you know in concrete there will be a peak stress.

And then beyond that the levels of stress are going to be decreasing because of the strain softening behaviour until a certain unstable deflection value is reached beyond which the cracks are not able to maintain the structure of the material. The cracks open up to such an extent that there is an unstable fracture which is happening in the system . So this is an indirect way because you are also compressing steel along with the concrete.

It is not that easy to setup although the concept is quite easy. It is not an easy test to set up because you have to ensure that the steel and concrete are perfectly dimensionally accurate. For example, this compatibility in terms of the deflection has to be perfectly maintained, the steel and the concrete have to deflect exactly the same amount and that may be a little difficult to setup if you do not have proper machining abilities which can get the steel and concrete to within 0.05mm tolerance to ensure that you have perfect loading maintained in the two system.

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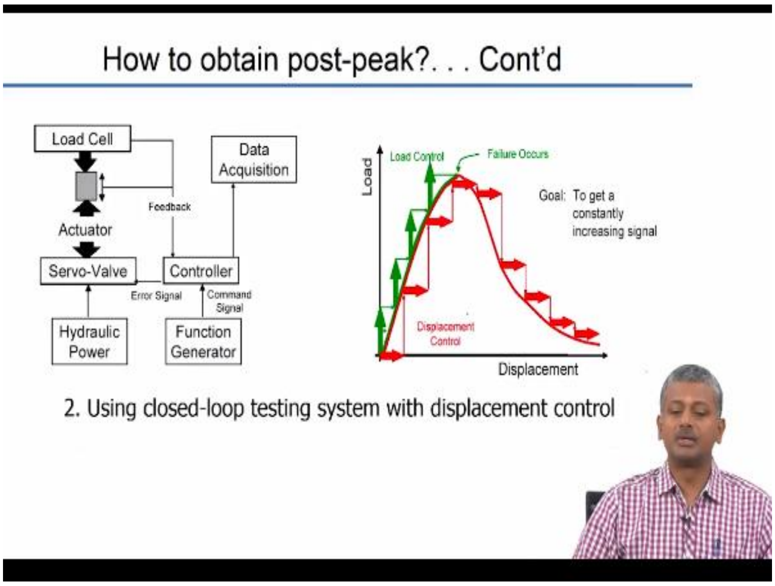

So what we generally tend to do is use what is known as a closed loop testing system with displacement control for the actual determination of the stress strain responsive concrete . So what does this mean, closed loop implies that whatever output you are getting goes as a feedback into the input system to ensure that you are able to respond to the way that the concrete is actually reforming .

And displacement control as opposed to load control means that instead of giving increments of load, you are giving increments of displacement to the material. So let us look at this diagram in the right first, here you have the load versus deflection or load versus displacement that is plotted for the concrete . The green curve is your load controlled test which you typically do for determination of compressive strength.

So what happened here you give increments of load and the system responds by having a displacement . Then you get another increment of load then there is one more displacement, of course this is done in very small steps, what is shown here is only 4 steps but actually it happens over hundreds of steps.

What happens when you reach the top is when you increase the level of load beyond that obviously there will be a sudden failure in your system and you will not be able to register the post peak response of the concrete. So in order to register the post peak response what you need to do is displacement control. Here you give an increment of displacement and you get as an output the load that has been registered for it .

So here what you need to do is ensure that you measure the displacement , and to keep that displacement constant you need to then send a feedback, so you are actually measuring the displacement and that is being sent as a feedback to the controller. Why do you need to send feedback because what happens is the system is undergoing plastic deformation

To create additional increments of deformation in the system you may not need the same level of increase of load, , because system is getting weaker as you keep on loading it more and more so it tends to deform more and more for smaller amounts of load, .

For same level of displacement you have lesser load as you reach closer to the peak . So that means you need smaller and smaller loads to actually produce the same level of displacement of the material as it gets weaker and weaker that is expected, but what happens beyond the peak is that now to register that level of displacement in the system you actually need lesser load than what you had previously, .

So actually you need a lesser amount of load to register the same level of displacement , earlier you needed lesser increments of load, but now you actually need reduced load to actually reach the same level of displacement because the cracks have already localised and all you have to do is now open up the cracks to lead the material towards failure. So as you keep on giving the same incremental displacement your actual load registered in the machine will be lower, .

And this can only happen in the case of displacement controlled machine because if you are doing a load control beyond this point you are not going to be able to increase the load further because any increase in the load will completely collapse your material. So what is needed is to measure the actual displacement of the specimen and send that as a feedback into the controller which then directs the server valve to open up to let in a certain amount of fluid.

Because this is hydraulically operated system, the pressure is supplied by the pistol and the server valve controls the extent to which the fluid is pressed by the piston, . To give a smaller level of load increment the server valve has to open lesser and lesser, . So this is an intelligent feedback control because it tells you exactly how much extra load that you need for that same level of displacement.

So that is why it is called a closed loop testing system and open loop system means there is no feedback . You have an input then you get an output, but here the output is sent as a feedback into the system. Now of course there are lot more complications here than what I have made it out to be. So measuring the displacement of the system is very important. Now in very many machines what you may actually have is the measurement of displacement of the platten.

Now the platten which is on top and bottom of the specimen is moving at a certain rate, . Now the platten movement rate need not be exactly the same as the displacement rate of your specimen, . To be exactly accurate in the system you need to actually measure the displacement of your specimen and not of the platten, because for stiffer specimens and for stiffer machines your relationship between the platten displacement and the specimen displacement may be quite different, .

These days' displacement control machines are becoming quite common, although they are much more expensive than your typical load control machines because you need to have this feedback control and you also need to have a server valve in your system which increases the cost of your machine, but there are possibilities of using displacement control these days to obtain useful information of the concrete.

But please remember as far as plain concrete is concerned your post peak response is not something that is expected to be large. Your post peak response is not significant in the case of plain cement concrete.

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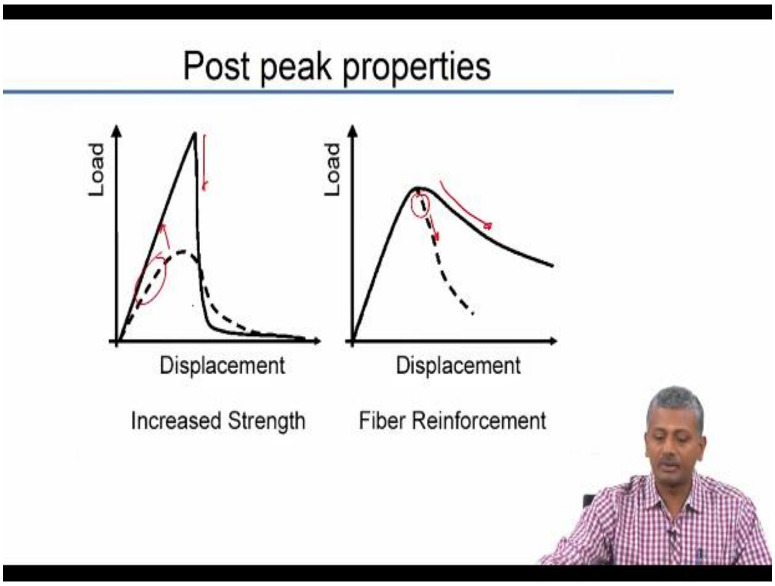

Only when you go towards systems like fibre reinforced concrete it becomes quite interesting because then you get this descending branch that is not sudden and it is well controlled. In fact, in certain types of fibre reinforced composites you may actually get a response that even causes strain hardening. So that is a strain hardening cementitious composite usually with high volume of fibres.

And these are typically of the high aspect ratio that means high length to diameter ratio of the fibres, those will give you a very good post peak response sometime even making it cementitious strain hardening and if you look at these kinds of system that are being looked at in research they are often called **engineered cementitious composites**.

One thing which we have not discussed here is how do you determine the elastic modulus of the concrete . Now there are different ways of determining the elastic modulus because the stress strain curve is mostly nonlinear. You do not get one single value of the elastic modulus.

What you do is then rely on certain values assuming that there is significant amount of linearity in the system and generally we assume that linearity exists only up to about 40 % of the ultimate load, . So if you take a slope up to about 40 % of the ultimate load then you get a value which is close to your elastic model and that is usually called as **secant modulus**. why do we call it secant modulus I will just briefly describe that.

So let us say you are considering your stress strain response of the concrete, , and what you have to do is at a very low load level you measure the strain in the material, then at a load level of about 30 to 40 % you again determine the strain in the material. You take those 2 points and plot a straight line between the points and take a slope. So even if it is non-linear you do not need to worry about that.

You just simply take those 2 points and plot a line and take the slope as the elastic modulus, that is called the secant modulus. Another way of representing modulus of elasticity could be the **tangent modulus**. Since this is a curve you can take a tangent at any point and represent that to be the tangent modulus. What you need to understand is that tangent modulus value will keep decreasing as you approach the peak load, .

Now that is interesting because now you can use the tangent modulus as an indicator of the extent of damage that you have in your system and very often the tangent modulus that you get which is the slope of the tangent drawn to the curve at any point. The tangent modulus, which I said, is a good indicator of the extent of deterioration in your system because more and more cracking implies tangent modulus will keep reducing.

So you can actually use this tangent modulus and measure the properties of your cementitious composites by non-destructive methods like ultrasonic pulse velocity and convert the velocity into the modulus in a manner similar to tangent modulus. The velocity, which will also be very high when the system is undamaged and when you convert this velocity into modulus you can again determine the decrease in modulus with increasing levels of loading, . So that is also interesting because it gives you a way to actually determine the deterioration levels in concrete with non-destructive techniques like ultrasonic pulse velocity, but for the most part for calculation purposes we use the secant modulus.

And if you look at the extent of load up to which this modulus can be measured as per ASTM it is usually 40 % and for British standards it is actually 33%, . So more or less everybody seems to agree that it is between 30 and 40%. Now when you do the same experiment in tension instead of compression, your curve will not be that much different. You may not see a large difference in the curve except that the linearity will be much more in tension. The linearity usually is much greater in tension than in compression , because the fracture is almost brittle as far as tension is concerned, but then you will still get some post peak characteristics in tension or in flexure.

So sometimes people do the same experiment in flexure. So what they do is they have this beam which is subjected to either a midpoint load or a third point load, , and then they monitor the deflection. They monitor the deflection at the midpoint because that is where you will get maximum deflection, and then this deflection serves as feedback to control the rate of loading of your beam.

So your deflection is measured at the centre and that sent in as a feedback to control the rate of loading. So you can do the same experiment in flexure also to determine the stress strain characteristics of the concrete, . In fibre reinforced concrete one of the other experiments that you may see apart from the regular ones that I have described here is the same experiment done with a notch in the centre.

You create a notch by making a slice in the centre which is up to a certain depth not up to half the depth, but less than half the depth and then when you do the flexural loading on this material what will happen is the crack width at the notch will keep on increasing. So instead of measuring the deflection you actually measure the crack width.

And based on that you can actually workout the fracture properties of the concrete because there you are actually measuring the rate at which the cracks can open up and then propagate through the material. So you can actually determine fracture properties using a notch beam test. Of course, people can also determine fracture properties based on unnotched beam tests, but there is lot of data that needs to be understood and shared.

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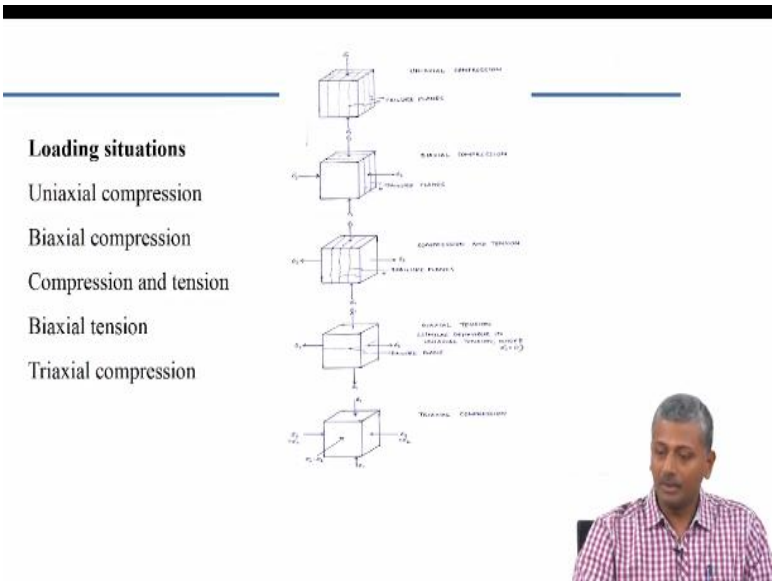

So now let us look briefly at how does concrete behave when there is a combination of loads on it. Now if you consider the case of a column and supposing I have a load that is exactly in the centre there is absolutely no chance of any tension in the column, there is only going to be a compressive load on the column.

But if I have a load in one of the quadrants what is going to happen is I may get a biaxial state of loading. So in one quadrant there will be compression and compression, that means biaxial compression in this quadrant. In other quadrants, there is compression and tension, in third one there will be tension and compression. Whereas in the last quadrant there will be biaxial tension.

As far as a column is concerned you will actually get a combination of loads. So it is important for us to understand what happens when the combination of loads acts on the concrete. So we are looking at different types of loading situations here, uniaxial compression, biaxial compression, compression tension combination, then biaxial tension and finally in a hydrostatic case you get triaxial compression, .

So let us look at these characteristics here. So the first one, the top one is uniaxial compression. So when you are compressing your concrete uniaxially what is actually happening is it gets a chance to bulge out in the other 2 dimensions. It is a cube, so we are talking about bulging out in the other dimension. With cylinder you are compressing it longitudinally, it bulges out diametrically, , circumferentially.

So what you have to do is understand how the cracks are going to propagate. So cracks in concrete will start propagating whenever the tensile capacity in the lateral direction gets exceeded. It is not when the compressive capacity in the longitudinal direction get exceeded, it is because the tensile capacity in the lateral direction gets exceeded. Concrete is bulging outwards.

So when that happens assuming that there is no friction between the platten and the concrete you get perfectly vertical cracks when you do uniaxial compression test along all phases of the cube, . Now this is a very ideal case of fracture, this probably you do not see it at all in the lab because there is sufficient friction between the platten and the cube.

What happens when you have friction? the pattern of cracking is more like some sort of an hourglass shape of fracture rather than a perfectly vertical fracture. Of course when you see the fracture in a cylinder it is inclined at the top, but towards the centre you will see mostly vertical cracks and then they will again be inclined at the bottom.

Why towards the centre you get vertical cracks? because you have a zone of pure compression exactly at the centre. So you get vertical cracks at the centre. Now when you look at biaxial compression what is happening is loading is along 2 sides of this cube indicating that along one side there will be some restraint offered to the opening of your specimen.

In other words the cracks now will form only in the third direction which is free to move, . Now because of this additional restraint that is caused by the biaxial compression you actually get a strengthening of your material. In a biaxial compression state, the actual strength that you measure will be higher than the uniaxial strength by a certain amount.

When you have a biaxial tension and compression, so this is where you have compression and then you have tension on the orthogonal face, now this is going to make the situation worse for your concrete because the cracks that are already forming because of the uniaxial compression now they are getting pulled apart much faster because of the tension that is applied on the other phase, .

In the case of a biaxial tension your situation may not be that different as opposed to uniaxial tension because already your load levels are very low in tension. So whichever direction has the maximum tension that is where the cracking will happen, almost the same level of load, not really much different . In a triaxial case that is when you need really actually estimate the true compressive strength of the concrete. Because in all the directions you have compressive loading and when you have compressive loading in all the direction, the material has to actually crush, and this crushing will indicate the true strength of the material. So for regular uniaxial strength of about 30 to 40MPa, your crushing strength maybe as high as 200 to 300MPa. The actual triaxial stress taken by the concrete maybe of that magnitude, 10-20 times greater.

But then that is not something that we contend with in real life unless we have a hydrostatic pressure. So for the most part we will be dealing with this biaxial states of compression and tension.

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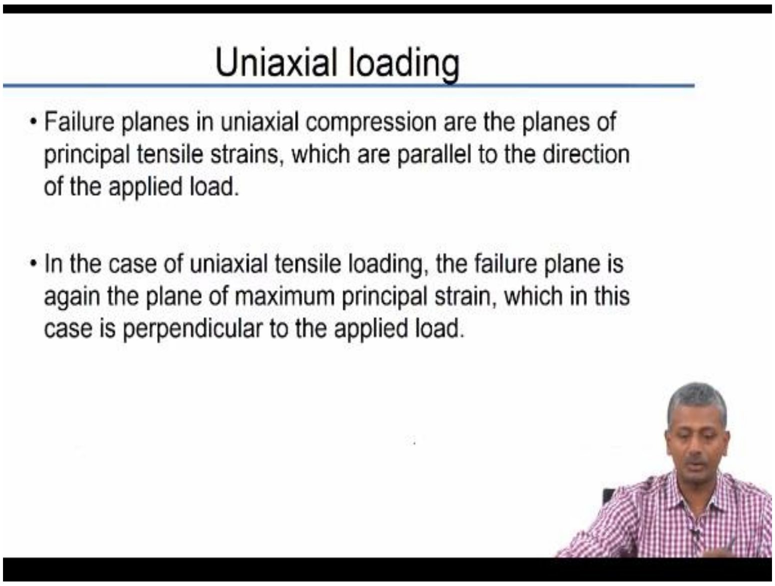

So it is useful to look at the biaxial stress interaction curves of course what I have put in the slides here is again the same discussion as what we saw from the diagrams so I am not really going to expand on it further.

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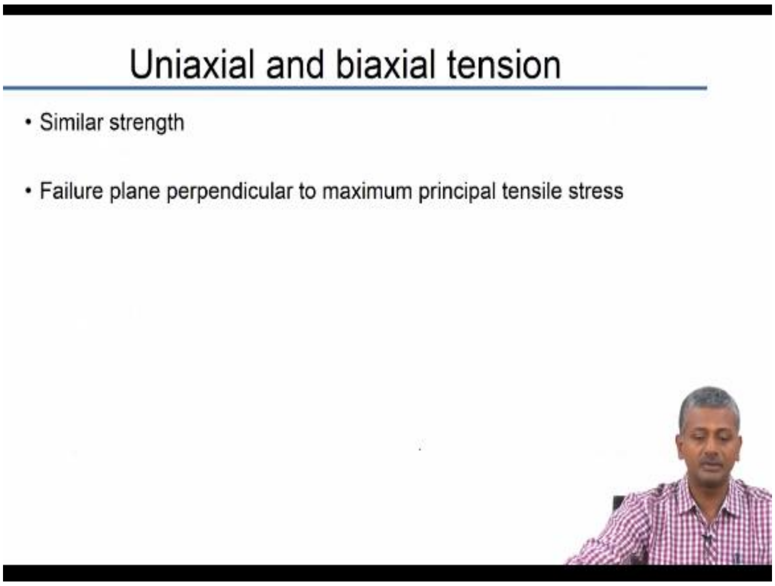

So in biaxial tension you get a strength which is quite similar to uniaxial tension because already the values are quite low and you have the cracks forming perpendicular to the plane of maximum tensile stress.

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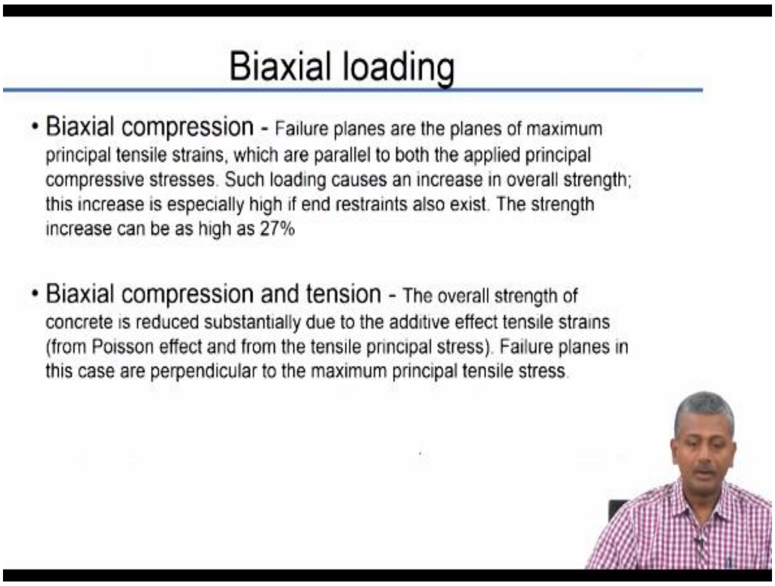

Now in the biaxial case is where you get very interesting combination of compression biaxial or biaxial compression and tension.

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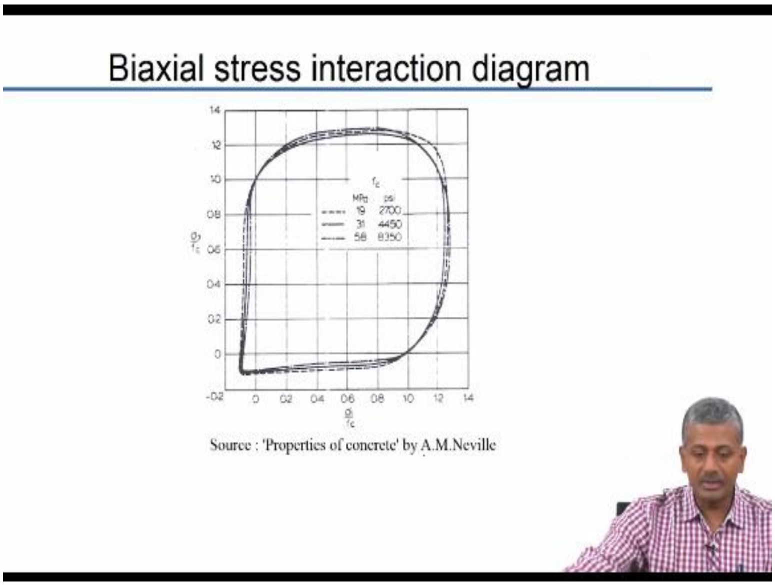

So in this case what researches do is look at the biaxial stress interaction diagram which is plotting the stress along one direction as a function of the uniaxial strength fc. The stress along the other direction as a function of the uniaxial strength fc. So the uniaxial case is obviously represented as this here when the stress σ_1/fc is equal to 1 and σ_3/fc is equal to 0,.

Similarly, that is also your uniaxial case where σ_3/fc is 1 and σ_1/fc is 0. Now what happens when you have equal $\sigma_1$and σ_3. When you have equal σ_1 and σ_3 you are somewhere in this range of 12 on x-axis and y-axis. That means when you have equal biaxial compressive stress on 2 orthogonal phases you actually have a strength increment of nearly 20%.

Your strength increment is nearly 20% when you have equal biaxial stress on both sides. So again you can see that there certain cases where you can actually get strength increment even beyond 20% levels of stress. So what this is trying to tell you is that when you have biaxial compression that means 2 phases are subjected to compression, you can get a significant enhancement of your strength up to 20 to 25%.

Now to some extent this is reflecting what you see in your cube. Even when you are loading it uniaxially, there is some level of biaxial stress brought in because of the restraint at the top. So the platten restraint creates some biaxial compression and because of which the strength of the cube comes out to be 25% more than cylinder strength, . This is not a true biaxial case because you are not applying this load in the orthogonal phases.

You are actually getting this restraint because of the friction offered by the plattens. So for a cube you have a strength which is nearly 25% more than that of a cylinder. In a cylinder we have at least a zone exactly in the centre of the cylinder which has pure compression, . So compared to the uniaxial compression case your biaxial compression will produce a stress or strength level which is 20-25% higher than the uniaxial case.

Now what happens when there is tension, now the lowest branch of this curve (parallel to x-axis) indicates what happens when there is compression plus tension. So if there is even a little bit of tension you are actually reducing your strength by almost a factor of about 10%, . So here for instance when you have tension along on phase and tension also along the other face you are actually leading to a biaxial tension case.

, here the (0,0) point and its quadrant is representing biaxial tension. So you can see here that the biaxial tension strength is not that much different from the uniaxial tension strength. So here the uniaxial tension strength is about one-tenth of the compressive strength, that is why it is at 0.1 here, . So in the case of biaxial tension your strength is not that much different from uniaxial tension case.

But when you have tension and compression which is indicated by this side (lower portion parallel to x-axis) here you get a strength of your material which is lowered between 0 and 10% as opposed to your uniaxial compressive strength. So for instance, taking a value of 60% compression and about 10% in the tension phase; what this indicates is if I have a stress level more than 60% in compression with my tension being 10% of my compressive strength I will get failure of the material . Between 0 and 10% of your compressive stress is the total tensile stress. So when I get at this point if I have applied a compression of more than 60% of the ultimate uniaxial strength, because of the tension that is there in the other phase I will get failure.

So overall this biaxial stress interaction curve seems to indicate that the zone which is inside is where your material is safe, , and outside is where it cracks or fails. So the stress interaction curve is drawn to indicate the zone of safe combination of stresses for the material.

But if I am having a tensile stress which is more than 10% of my uniaxial compression stress then I am getting failure in that case because of the lowered capacity when I have tension along one direction and especially when I am reaching the 10% value my failure can happen at much lower compression levels. So at this location my compression stress is only 20%.

But when I reach my ultimate tensile strength of 10% of the uniaxial compression strength I am actually very close to failure even at low compression levels that is applied. So because there I am almost approaching the case of plane tension at very low compression levels. Now interestingly what you see is for different grades of concrete 20MPa, 30MPa or 60MPa of concrete you see almost the same stress interaction diagram.

So irrespective of your ultimate compressive strength your stress interaction diagram does not change by much. So it is very useful to do this because then you can actually estimate the loading conditions for which your concrete in the structure will be in a safe condition.

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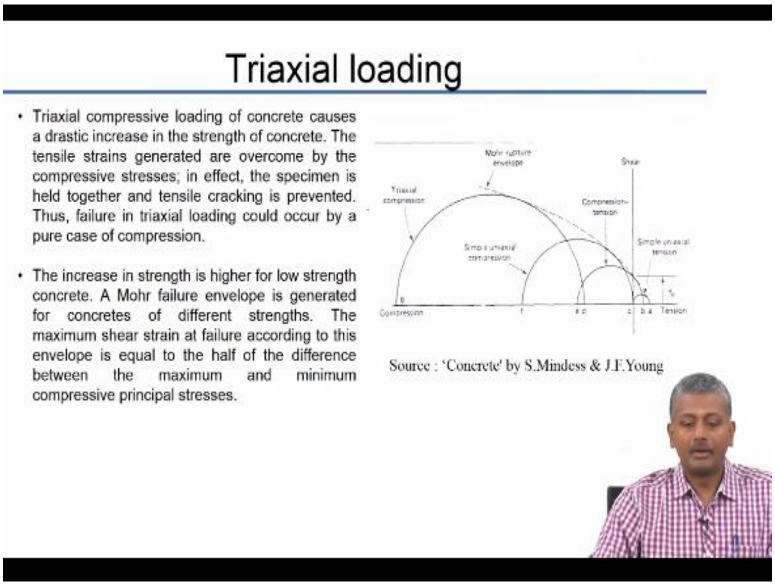

Now in the triaxial loading of course you have learnt this before when you have changes in the states of stress from pure compression to compression-tension to triaxial compression or triaxial-tension in whichever way you look at it, you see a gradual increase in the extent of stress that will cause failure.

Failure theories are based on this Mohr rupture envelope, which is a tangential curve, which is drawn connecting all the Mohr circles of these different systems that are represented here.

So the first one is the uniaxial tension system because stress along one axis is 0 and the other axis is equal to the extent of tensile strength of the material.

In this case second curve is based on a compression tension system and third cases uniaxial compression because there is 0 stress along one of the axis and then you have compressive stress along the other axis and in other case where you have triaxial compression. You have compression along all directions.

So what happens is your failure envelope starts getting more and more widespread in other words your diameter or radius of the Mohr circle keeps increasing as you are moving towards triaxial compression. In other words, the amount of stress that will cause failure is going to be increased significantly as opposed to the case of uniaxial compression, . So here you are actually going to be able to see a true compressive failure of the material because there is no scope for it to actually expand in the other direction and overcome it tensile capacity.

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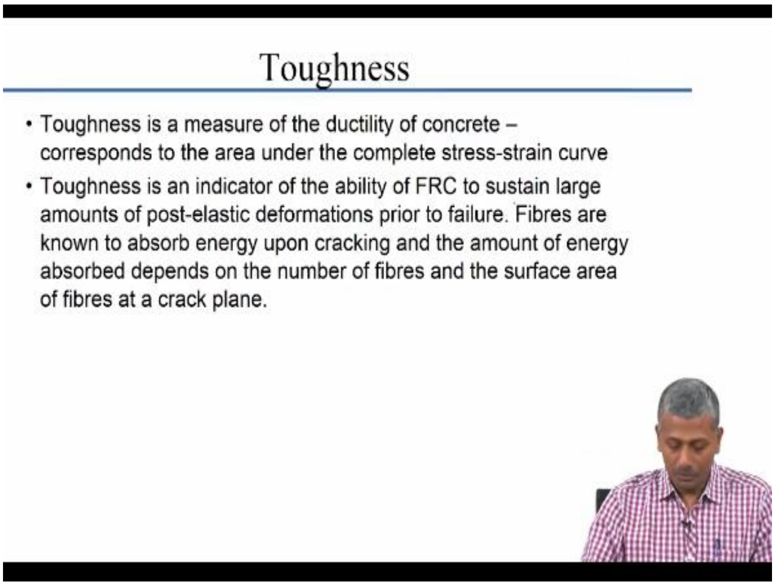

Now what we have to get at as far as fibre reinforced concrete is concerned, is not just the extent of capacity that the material has before it fails, but also the amount of energy that can be absorbed by this failure. So in a plain concrete once the crack initiates in the material it rapidly grows or propagates towards failure, but in fibre reinforced concrete case as we have discussed earlier the cracks open up gradually because the fibres are bridging the cracks.

They do not allow the cracks to open up very fast and because of this, there is a lot of energy can be absorbed during failure and this energy absorption during failure can be measured by the toughness of the concrete. Toughness is also a measure of the ductility of the concrete and we define it generally as the area under the complete stress strain curve.

With concrete we do not call it ductility, because we do not expect concrete to be ductile it is more the toughness of the concrete, and toughness especially is used as an indicator with respect to fibre reinforced concrete because it is able to sustain very large deformations before failure.

And so again fibres as I said before absorb energy upon cracking and the amount of energy absorbed obviously will depend on the amount of fibres that are actually available in the system and the aspect ratio of the fibres because that will define the surface area of the fibres that are available at the crack plane.

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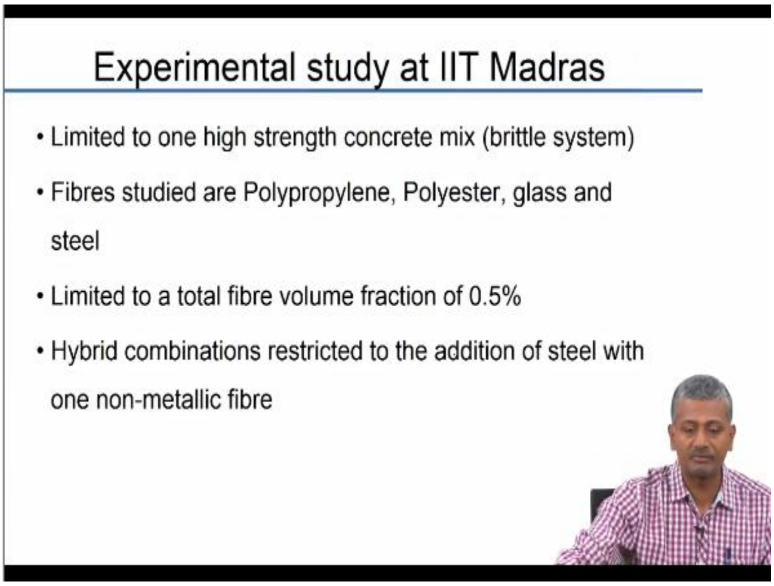

So let us look at what toughness is by an experiment study that we have done at IIT Madras. So again here we try to look at how the characteristics of a brittle system like a high strength concrete were modified because of the use of fibres. So the fibers used in this case included polypropylene, polyester, glass and steel and this was limited to a total fibre volume fraction of 0.5%.

So what was done in this case was steel fibres were primarily used as a reference mixture. Of course we had a control mixture without fibres, but we had a reference mixture with steel fibres and then we replaced steel fibre with the non-metallic fibre with smaller increments and looked at what happened to the load deflection response of the composites. So hybrid combinations were also attempted in the study with combination of steel with the non-metallic fibre.

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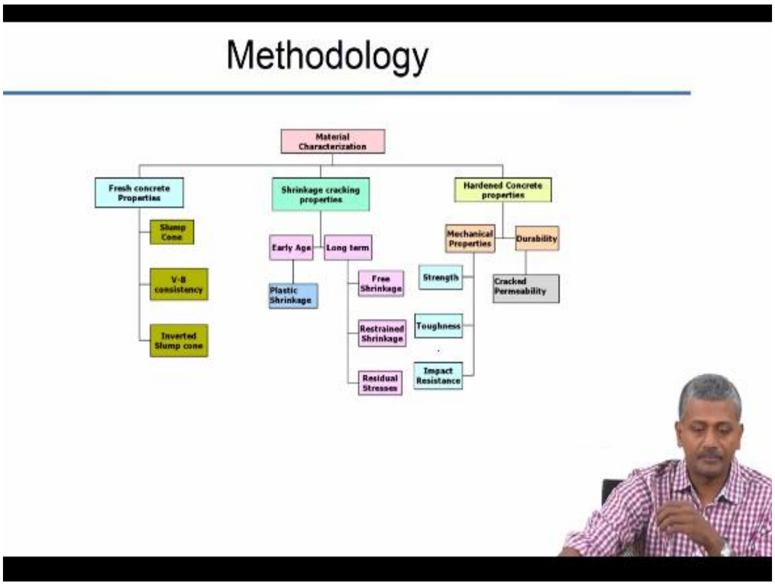

So of course this was the larger research study which included not just the hardened concrete properties in terms of the strength and toughness, but also the durability and then shrinkage related properties which we will discuss when we actually come to the chapter on shrinkage and also we discussed the fresh concrete properties in this study.

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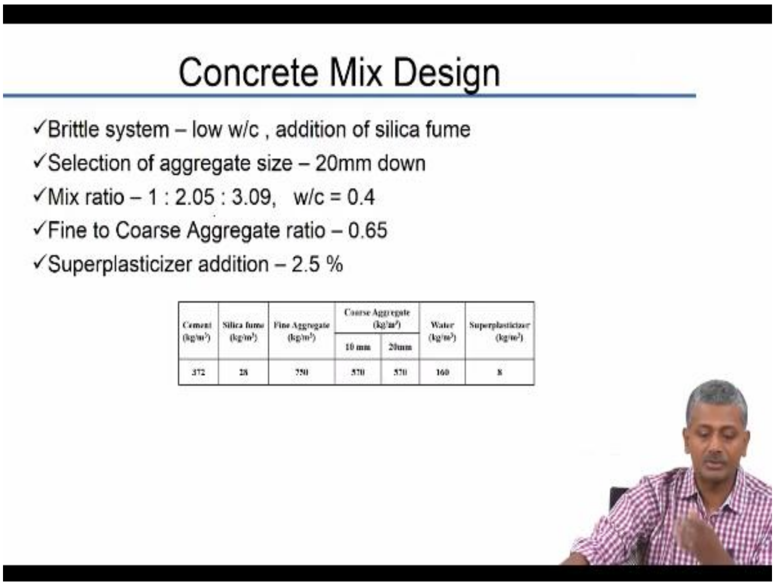

So the concrete mix design was like this. You had 400 binder content including about 7% replacement of the cement with silica fume. Then water to cement ratio was 0.4. Superplasticizer had to be added to about 2.5% to obtain sufficient workability in the system for proper compaction.

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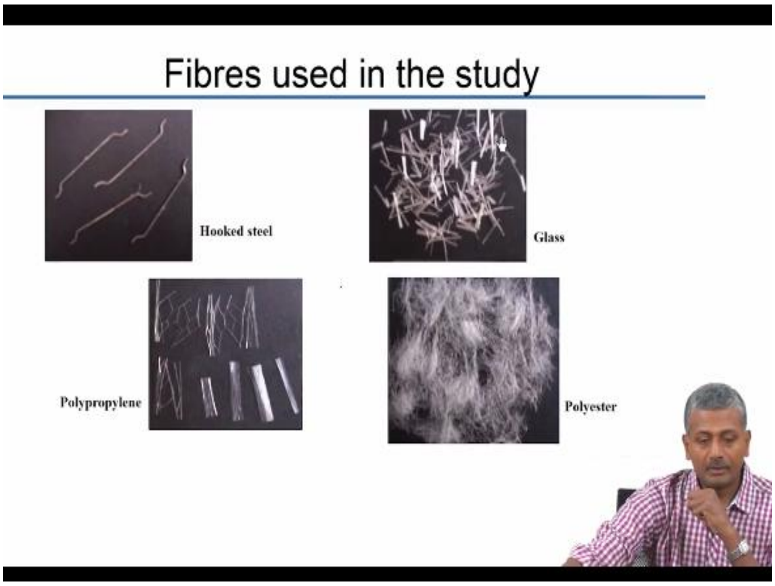

Now in terms of the fibres you have hooked steel fibers, you can see at the ends of the fiber there is hook provided. So what happens is when this fibre is inside the concrete system and there is a crack which opens up this fiber does not get pulled out easily. The hook part restraints the fibre from getting pulled out easily. So you can imagine that you have to increase the deformation more and more for that hook part to first straighten out and only then this fibre will get pulled out of the system. So hook fibres are much better than straight fibres as far as performance of steel fibres is concerned. Then we selected glass fibres, polypropylene fibres and polyester fibres. You can see polyester is basically monofilament fibres, but very thin, very high aspect ratio, diameter is extremely small. Glass fibres again are extremely thin and the length to diameter ratio of glass fibres are also very large.

Polypropylene is an interesting fibre because this is the fibrillated fibre not monofilament, but this is actually a fibrillated filament of polypropylene. You can see that it is almost like a network structure that the fibres are forming which allows them to have a better grip with the concrete and does not get them pulled out quite easily. So how does a failure of the fibre happen across the crack?

The fibre can actually rupture because the crack keeps on opening and the stress transferred to the fibre is so high that the fibre tensile strength is not able to maintain that crack from opening up further. So that ruptures the fibre. That is the failure which we do not want. We do not want that because that will be brittle failure, . You can expect that with the system like glass which has very low deformation capability, you may actually get that type of a failure.

But with steel or with polypropylene, the system does not fail very fast because the fibres themselves will have a large capacity for deformation. So fibres can deform a lot and then if you really want to maximize the use of fibre you wanted to have a failure with which it gets pulled out of the system rather than gets fractured.

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You want the fibre to completely pull out of the system and that should lead to your failure, so that means that you will absorb a lot more energy before failure actually happens and that system will exhibit greater toughness.

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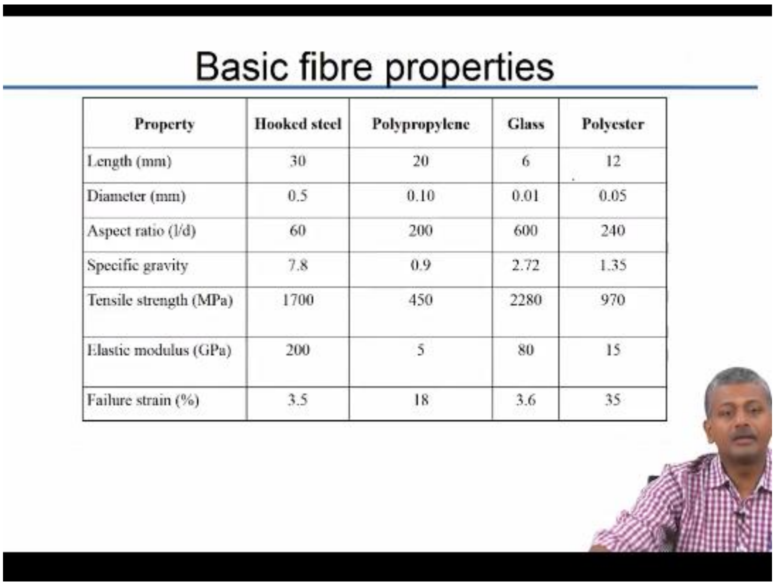

Property	Hooked steel	Polypropylene	Glass	Polyester
Length (mm)	30	20	6	12
Diameter (mm)	0.5	0.10	0.01	0.05
Aspect ratio (l/d)	60	200	600	240
Specific gravity	7.8	0.9	2.72	1.35
Tensile strength (MPa)	1700	450	2280	970
Elastic modulus (GPa)	200	5	80	15
Failure strain (%)	3.5	18	3.6	35

To really cause that pull out first you are overcoming the deformation capability of a fibre and then you are utilizing the bond stress between the fibre and the concrete. If the bond is weak you have a problem, but then for the most part the fibres are designed to have a good bond with the concrete. So in the polypropylene the gripping is essentially made enabled by this fibrillated system.

But there are monofilament polypropylene fibres also. So what happens is surface characteristics of fibre are modified by processing in such a way that it has a good affinity for the concrete. So fresh concrete is wet, so if you have a hydrophilic surface it gives a much better bond with the concrete system. So fibre properties can be modified by surface treatment.

Now of course glass fibres have to be treated first to ensure that they do not interact with the alkalis in your concrete system. So these are mostly treated glass fibres , because otherwise they will create a problem setting in your concrete. So these are the properties of fibres, you can see that the length of the steel fibre is 30 mm, and diameter is 0.5 mm that leads to an aspect ratio, length to diameter ratio of 60.

Compared to this polypropylene has an aspect ratio of 200, glass is 600 and polyester is about 240. Look at the specific gravities of course steel you know is about close to 8, polypropylene is 0.9, glass is 2.7 and polyester is 1.35. Now since polypropylene and polyester have such low specific gravities, if you are replacing a certain mass or using a certain mass of the material to replace, or to input the fibre inside the system then the amount of fibres that is available polypropylene and polyester are going to be much greater than the amount of steel fibres available. For the same loading the amount of fibres that you have in the system are much greater with polyester and polypropylene as opposed to steel. And glass marginally greater because the densities are not different by more than a magnitude of 3, .

The tensile strength of steel fibre is 1700MPa, glass is even stronger, but then the polypropylene and polyester have a low strength. But look at the failure strain for polyester and polypropylene you have very large failure strains, that means your deformation capacity is very high for these fibres. Whereas glass and steel have nearly similar deformation capacities. Steel has a much better elastic modulus. So resistance to deformation is much more as opposed to glass and definitely much better than polypropylene and polyester. So fibre properties are quite widely varying and these will obviously have an impact on the load deflection response in the system.

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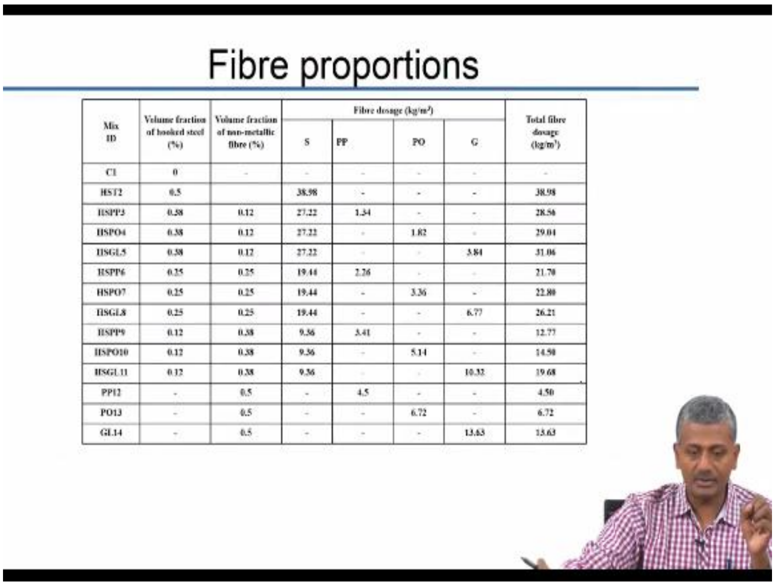

Fibre proportions

Mix ID	Volume fraction of hooked steel (%)	Volume fraction of non-metallic fibre (%)	Fibre dosage (kg/m³)				Total fibre dosage (kg/m³)
			S	PP	PO	G	
C1	0	-	-	-	-	-	-
HST2	0.5		38.98	-	-	-	38.98
HSPP3	0.38	0.12	27.22	1.34	-	-	28.56
HSPO4	0.38	0.12	27.22	-	1.82	-	29.04
HSGL5	0.38	0.12	27.22	-	-	3.84	31.06
HSPP6	0.25	0.25	19.44	2.26	-	-	21.70
HSPO7	0.25	0.25	19.44	-	3.36	-	22.80
HSGL8	0.25	0.25	19.44	-	-	6.77	26.21
HSPP9	0.12	0.38	9.36	3.41	-	-	12.77
HSPO10	0.12	0.38	9.36	-	5.14	-	14.50
HSGL11	0.12	0.38	9.36	-	-	10.32	19.68
PP12	-	0.5	-	4.5	-	-	4.50
PO13	-	0.5	-	-	6.72	-	6.72
GL14	-	0.5	-	-	-	13.63	13.63

As I said, you have a control system when there is no fibre and a reference system with 0.5% volume fraction of hook steel fibres. The other cases are actually combinations of steel and polypropylene, steel and glass, steel and polyester and then you also have a system where there is no steel fibre but only the plain polypropylene glass and polyester fibres.

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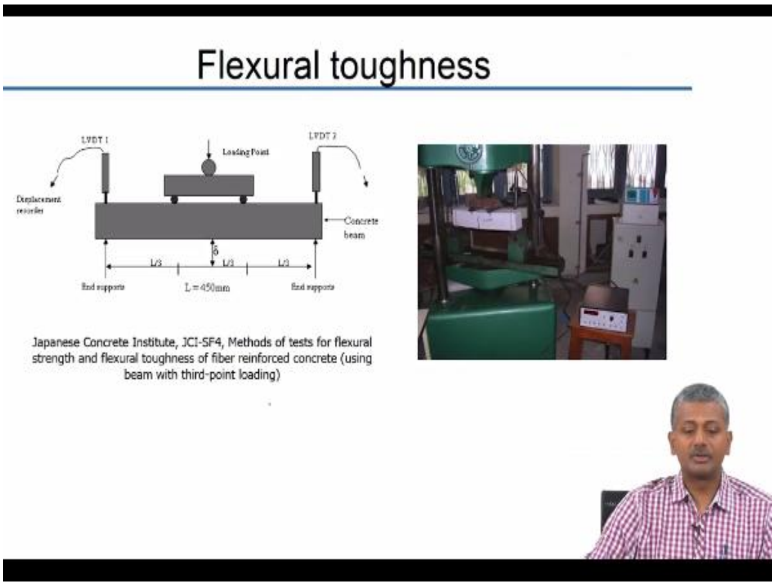

So this was the setup which was used to determine the flexural toughness of the system. So again you had a third point loading applied to this concrete beam and the deflection in the centre was measured. Unfortunately, this was not a closed loop system. So deflection could not be fed back into the system to control the rate of deflection, . So what we assumed was that the piston displacement was continuously incremented in the system.

So we did not actually used this is as a feedback. We actually simply used the piston displacement and control the rate of that displacement. So it is not really truly a strain controlled or displacement controlled setup because this was from our old machine which could not be made into a proper displacement control machine. So we used this Japanese Concrete Institute test method for flexural strength and toughness of fibre reinforced concrete using third point loading.

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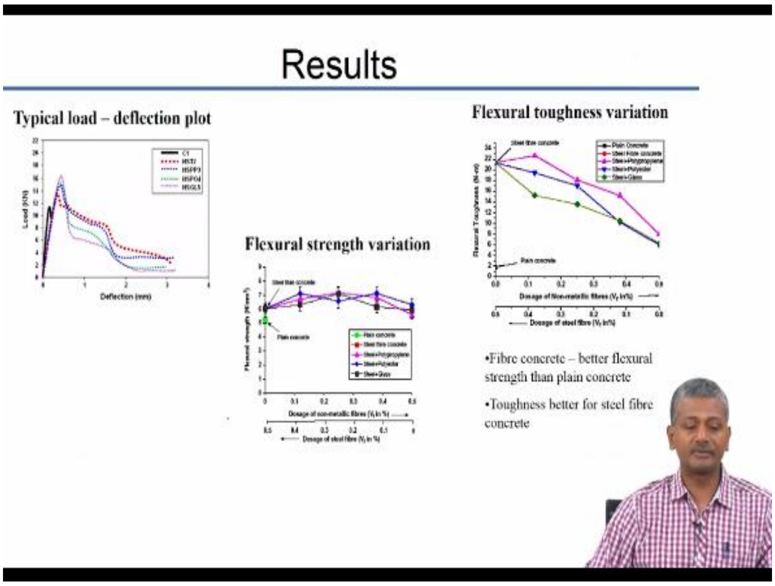

So based on this these were the results that we produced. You can see here the load deflection response of the concretes. This is the plain concrete, the black curve here and you can see that after the ultimate stress has been reached there is no significant deformation capability for this concrete. If you look at steel fibre concrete, there is a red curve here. It reaches a slightly higher flexure strength as opposed to plain concrete. But look at the extent of deformation that is possible before failure actually occurs. Now when you use polypropylene, polyester or glass, the ultimate flexural load is actually increased because again please remember these are smaller than steel fibres and they also have a high aspect ratio. So you can imagine that these are also bridging the micro cracks and that leads to an enhancement of the strength of the materials.

Steel fibres on the other hand are stiff and fairly long. So they are not really going to be able to bridge across micro cracks leading to an enhancement in the strength. They will cause an enhancement in the toughness, but strength is not there as much. So here you have enhancement in strength, but when you see glass fibres you actually see that the curve indicates there is not that much toughness in the material.

Polyester slightly better than glass but not as good as polypropylene which is matching steel to some extent, but overall toughness of polyester fibres is reduced as compared to steel. If you look at the diagram, which at the centre, is actually plotting the flexural strength as a function of the dosage of non-metallic fibres in your system. So you see that the flexural strength is enhanced by almost let us say 10 to 15% at some loading of the fibres.

But not really significant, but when you have of course this is for the system which is a hybrid combination of steel and glass or steel and polypropylene . For the plain steel fibre reinforced concrete your system is slightly higher than that of plain concrete, . But the more important part is to look at the diagram in the right side which is plotting the flexural toughness which is the area under the stress strain curve against the dosage of the non-metallic fibre.

So for plain concrete the flexural toughness is close to 0 because there is not much of an area underneath. It can’t be 0 as it has to be a positive value but then there is not much area in the post peak regime because of which the area is quite low. In terms of the steel fibre concrete when you increase the level of substitution of steel fibres with non-metallic fibres your extent of flexural toughness is reducing significantly except the case of polypropylene at fairly low dosage levels.

Especially with glass your reduction is quite drastic as opposed to steel fibre concrete. So as the fibre gets more and more brittle you actually experience a loss in your overall ductility of the concrete system which is expected, . With the steel fibre concrete you get the best performance, but with some small dosage of polypropylene you are able to marginally enhance the flexural toughness value of the concrete.

So again steel still happens to be the best fibre in terms of hardened characteristics, but a combination with non-metallic fibre can actually cause your system to have a positive contribution in the fresh characteristics like resistance to shrinkage cracking for instance and that part will actually come about when we discuss shrinkage cracking towards the next chapter, when we talk about shrinkage and creep.

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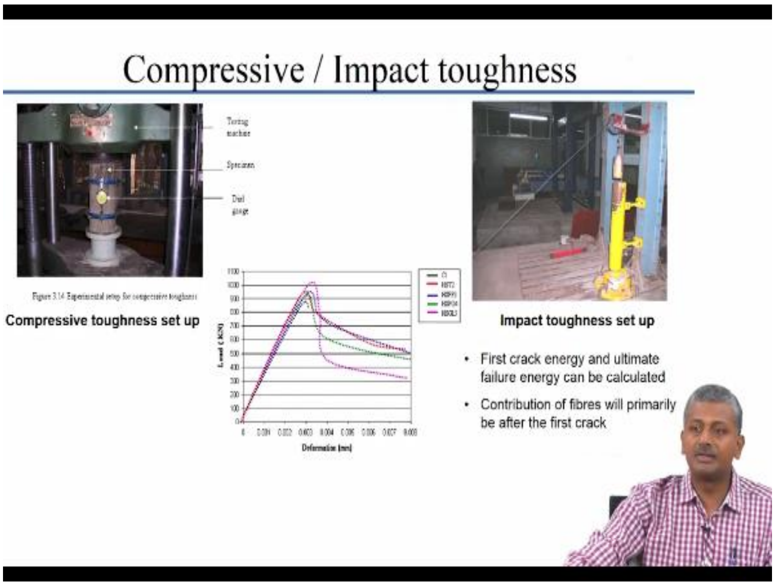

In the same test study, a compressive toughness test was also determined. You had the system under compression, and a compressometer which is typically used to determine a modulus of elasticity, was used to actually record the displacement levels. So deformation levels and the same things were plotted in this case, the trends were quite similar to what we saw previously with the flexural toughness.

The control of this experiment was a lot tougher as opposed to the control of flexural experiment. The impact toughness was also determined by using discs of concrete on which a hammer was made to drop, a load was made to drop a number of times. So what will happen is for plain concrete after the load has been dropped 3 or 4 times there is a crack that forms and this crack simply causes complete failure of the system.

In a fibre reinforced concrete the crack will form almost with the same load but then for it to actually completely collapse the material you will have to have many number of drops of the load, , so that is basically the impact toughness set up which can be used to determine the first crack energy and the ultimate failure energy of the system by multiplying the load by the amount of distance over which it is dropping that is basically the energy which is transferred to the concrete, .

So as the dosage of fibres increases obviously you have a greater amount of difference between the failure energy and the first crack energy. In a plain concrete system there is almost no difference between the failure energy in the first crack energy.