Concrete Technology
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Lecture - 40
Special Concrete: Fiber & Roller Compacted Concrete

Welcome to module nine, lecture five. We will continue with special concrete; and we will first discuss the remaining part of the fiber concrete followed by roller compacted concrete.

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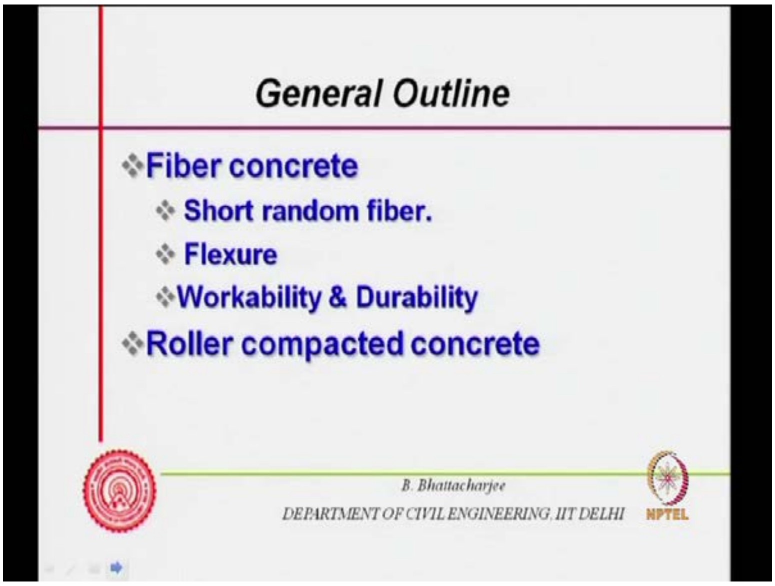

So, what was left was short random fiber. We are looking at aligned fiber to understand the basic theories, flexure, workability and durability of fiber concrete. And then we will look at roller compacted concrete. Now, if you recall from the last discussion, we are talking about the crack width in case of aligned fiber. Now, the crack width would be actually crack width, you know, if you remember, it was a continuous system, and then the cracks came in between, cracks came in between. And we talked about the strain as well, the strains, you know the matrix would have now shortened a little bit.

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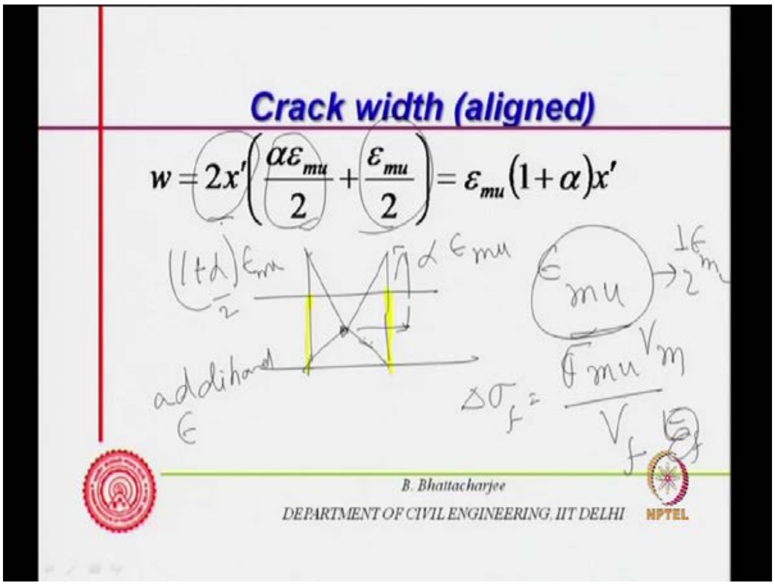

Matrix was earlier at epsilon m u strain; matrix was at epsilon m u strain. Now, part of it is only at epsilon m u, that is, this point; and rest of the place, it is less than epsilon m u. So actually, the matrix would have shortened a little bit and the stress from the matrix went into the fiber. And therefore, fiber strain actually is higher that is what we have seen in the last fiber strain increased.

And, stress in the fiber, delta sigma fiber – we said was actually sigma m u V m divided by… This is the stress that has to be taken – divided by V f. So, that is the stress divided by taken… So this is the extra stress. If you divide this by E f, you get the additional strain… Additional strain we get by dividing by E f. And then, we said that the additional strain will be alpha epsilon m u. At this point, it will be alpha epsilon m u. And, this was already there. So, the total strain will be… This is the additional strain. At this point, it is 1 plus alpha epsilon m u at this point, so that the average is half alpha epsilon m u. So, that is the strain in the… That is the additional strain in the fiber. Therefore, there is an elongation. But the matrix actually… So, the crack width will be equal to the strain in the fiber minus strain in the fiber, which is the additional strain. So, additional strain is this. Average additional strain will be this much minus the strain that has… There will be a minus… It will be plus actually; plus the shortening of the matrix.

Now, how much the matrix shortened? It was originally epsilon m u. But now, it has average strain in the matrix, has become half epsilon m u. So, the shortening of the matrix is this much. Therefore, this multiplied by the 2x distance will give you the crack width.

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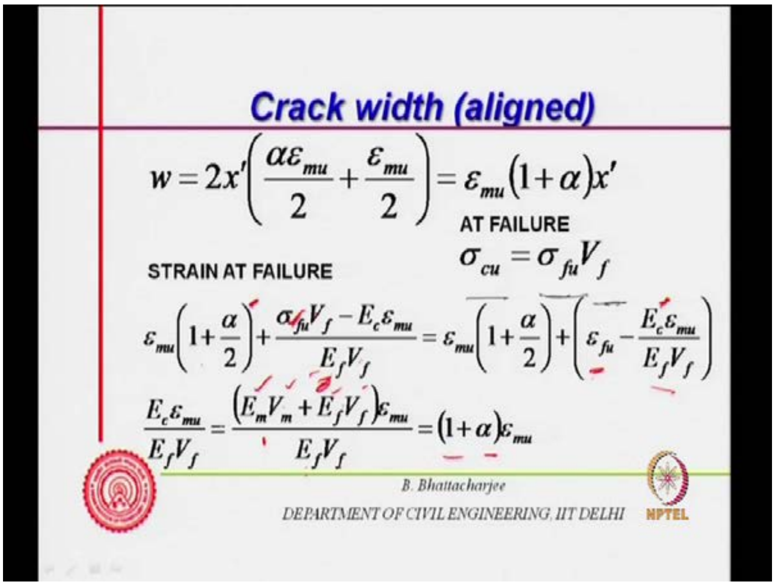

So, let us look at this again. This is the average strain increase in the fiber. This is the average shortening in the matrix. Therefore, the crack width will be sum total of this increase in the fiber strain; fiber got elongated; matrix got shortened; gap is the crack width. So, this is the average strain that has been released from the matrix. This multiplied by 2 x dash gives me the crack width – the average crack width. And, this is simply nothing but this. So, that is the average crack width.

We are just reiterating what we talked about. At failure, actually sigma c u is equal to sigma f u V f, because composite now… After that, the matrix has failed. Now, if the fiber is snapping, it will be the sigma f u V f; whatever is the type of fiber. So, that is how we got the stress-strain diagram. And obviously, stress strain at the fiber, we can find out. Now, strain at the fiber we can find out basically. We will come back to this.

But let us look at this diagram – strain at this fiber. So, if you look at this diagram, this was epsilon m u when the crack started. Then, there is a sudden increase. And, we said, at this point, I will have epsilon m u alpha by 2, because total strain in the composite would be the extension of the fiber, because the matrix is within the fiber. So, here is the fiber; matrix is simple within. So, length of the fiber – total elongation of the fiber is the elongation of the composite as well. So, strain in the composite strain is simply the total.

So, epsilon m u was there earlier – plus now average increase in the fiber is half epsilon m u by 2. So, at this point, it is half epsilon m u by 2.

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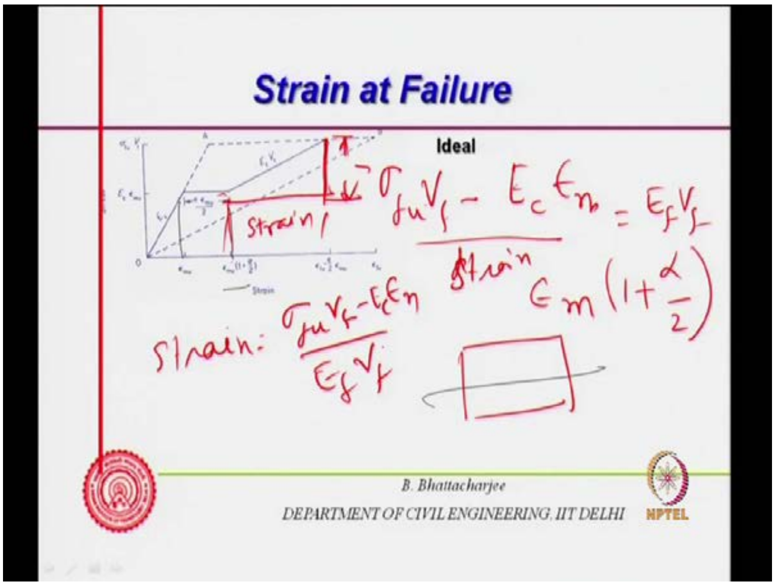

Now, we want to find out now, what is the strain at this point, strain at this point, strain at this point. Now, the stress difference here is this much; which is this we know is sigma f u V f. This stress here would be sigma f u V f. And, here it is actually E c epsilon m u, because composite modulus of elasticity multiplied by epsilon m u. So, this is the stress difference divided by… So, stress divided by strain is equal to modulus of elasticity. So, modulus of elasticity is E f V f, because it is only the V f V f here. So, this strain – additional strain – the strain that is there – strain can be written as this divided by E f V f. So, this strain here can be written as the strain here. As I am showing, will be written as sigma f u V f minus E c epsilon n divided by E f V f. And, that what is E f V f. So, this additional strain I can find out.

And, let us see what is the expression for this. The expression, so that is what we are saying. Epsilon m u 1 plus alpha by 2 – that is the matrix failure – plus sigma f u V f – that is the final stress – minus epsilon c epsilon m u E c epsilon m u – there is the stress beyond this point up to failure divided by E f V f. So that is the additional strain. This will be the sum total of strain at failure. And, this can be written as simply divide epsilon f u by E f; you get sigma f u by E f. V f will cancel out; I am left with epsilon f u minus E c epsilon m u divided by E f V f. Now, E c can be expressed as E m V m plus E f V f.

That is what we have seen. And, if I divide this by E f V f, this will cancel out. And, this I am calling as alpha. E m V m divided by E f V f – I am calling as alpha. And, this is simply 1. So, it is 1 plus alpha into epsilon m u.

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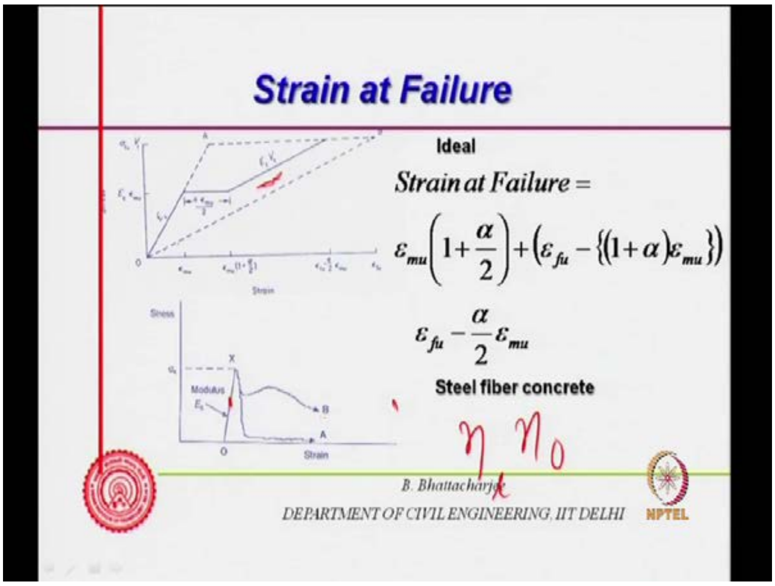

So, if I see the failure strain, then failure strain I can write as strain at failure, will be written as epsilon m u 1 plus alpha by 2, which is at the time of matrix cracking. Then, we have seen that is equal to epsilon f u minus it was E c epsilon m u divided by E f V f. And that we have derived just now as 1 plus alpha into epsilon m u. Therefore, if I do a little bit of algebra out of this, I get epsilon f u out here. Epsilon m u is there everywhere; I get this value. So this strain here is epsilon f u minus alpha by 2 into epsilon m u.

So, that is the failure strain. But this is for an ideal sort of a fiber, which will have strain enhancement. If you want to find out for real fiber, the snapping which is not very important, because most of the fibers do not snap unless they are weak fibers. But, we had usually strong fibers. So, they do not snap. But the effect of short and random fiber will always be there. So, short and random fibers – their testing behavior is actually something like this depending upon the type of fiber. If you have sufficient fiber, it might be like this; in some other cases, it will be like this depending upon quantity of fiber. So, it would be either of this kind or of this kind.

For example, steel fiber concrete – it might behave like this; it may not show strength enhancement, but it would show a lot of deformation beyond this, because after cracking, fibers can still withstand the load to a lower level. But lot of deformation it will show. So, that is how we get size pseudo ductility even in real fibers. All these formula, you want to get for real fiber, then you have to modify them as far as strength part is concerned by putting in this orientation and length efficiency factor, which we have done earlier.

So, we have just looked into the crack width for aligned fiber. Just let us look at the… and stress strain diagram for aligned fiber, and then for real fiber, because real fiber… All these modulus of elasticity for real fiber – the modulus of elasticity here will be multiplied by this and this. And, after that, also, it may not be able to take the loads; it may be less than that. So, the load it can carry would depend upon its E f and the V f content, which could be low. Depending upon that situation, real fiber behaves in this manner.

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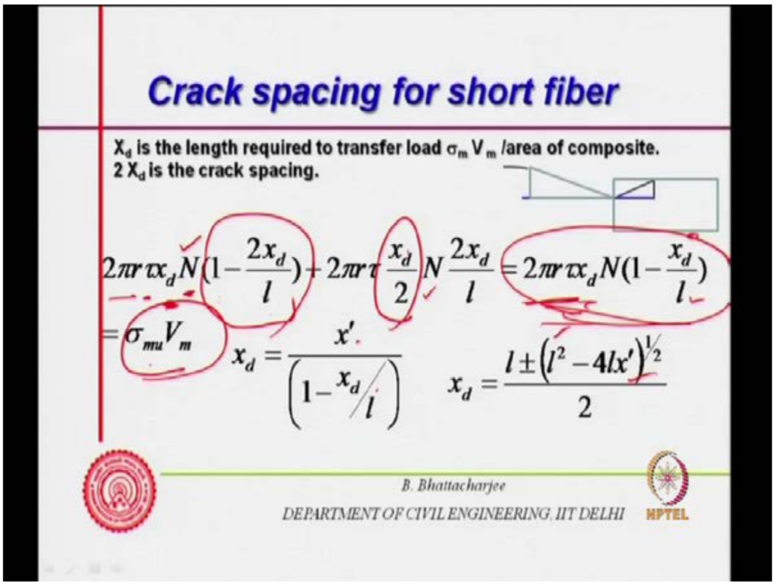

But then, they are short random fibers. Therefore, crack for short fiber we can look into. So, let us say X d is the length required to transfer load sigma m V m per unit area of composite to the fiber. So, 2 X d is the crack spacing. That is what we have seen actually. But, when you have short fiber, what will happen, one side you may have some length; another side you may have full transfer. In one side, you may have full transfer like this – full transfer; one side you may have full transfer like this, because it would not be 50-50 divided in both the direction; it will be divided… Sigma f u might attain here –

sigma f u. But this side it may not attain. So, some… One side you will have length, because it is unlikely to be unlikely to be… Even if you have sufficient length let us say l c – critical length; if you have critical length also; but then, it is very unlikely that, both sides it will be 50-50. Only one side, it will have part development strength; development length will not be full. On this side, you may have development length plus more. Therefore, the effective number of fibers one can modify.

We had effective number of fibers earlier – N equals to V f divided by pi r square. But, now, this will get modified by a factor. I can multiply by a factor such that if it is full fiber effective, then this factor is 1. But, if it is only part of the fiber effective, then I can take it something like this; I can take it something like this. So, what we are saying, 2 pi r tau x d is the length required to transfer full load; which we have discussed earlier; which we have said earlier. It is required to transfer the full load. And, this is the N fiber if it was aligned fiber. Now, the number of fibers that will be effective in transferring full load will be 1 minus 2 x d divided by l. So, l is greater than 2 x d.

So, this fraction if it is 1, then there will be no fiber effective, because it will not be… Only a small fraction will be effective, because if it is just l c, one side you will have… There will be… Not a single fiber will be actually effective to transfer full length on both the sides; no, because it will be just within the space. So, if this is bigger, then a fraction of it will be effective in transferring on both the sides.

And, the remaining fraction, that is, 2 x d by l again multiplied by… – they will be transferring partly. So, what you are doing here; you assume that there will be either transferring 0 or full length. Therefore, you take the average. So, x d by 2 you take. Here N is the number of fiber for aligned situation, that is, V f divided by pi r square. If this is the amount of fiber, which will be able to transfer the load on both the sides fully; is given by 1 minus 2 x d by l; remaining 2 x d by l will be able to transfer only half on an average. Remaining number of fiber will be able to transfer, because they will either transfer 0 or they will transfer full length.

So, we can take half length x d. And, therefore, this is the bond; this must be equal to sigma m u V m, because that is the force that can be sigma m u… This gives us the length actually; gives us an expression for length, which will give us this, because we have earlier done simply twice pi r tau x N; x dash we wrote; and, N is equal to this. But now, we are writing the same thing – x d as a new terminology using the same thing; sigma m u V m. So, this will be an equation.

And, from this equation, if I try to arrive at x d, because it will be quadratic equation in x d. x d and x d x. So, x d square. So, x d can be written as something like this. So, x d can be… It will be… It is a quadratic equation written something of this form; where, x dash stands for aligned fiber situation; x dash we have found out for aligned fiber. So, one can write x d will be a function of x d by l. How much is the x d? The x d is the half spacing between the cracks divided by l. So, that is how you can find out. So, it is a quadratic equation and x d can be obtained in this manner – 4 l x dash etcetera, etcetera. So, it is a quadratic equation and x dash can be obtained in this manner; where, l is the length of fiber; x dash is for aligned fiber; and, you can obtain in this manner.

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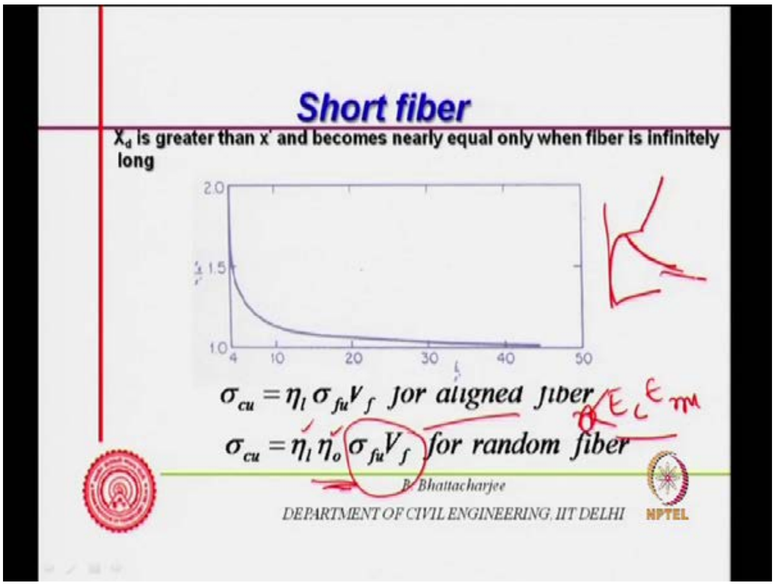

So, if you plot it against… If you plot it l by d against x d by x dash… If you plot it actually, you will get a curve like this. So, it will depend upon l by d, because this was a function of l by d. There is a relationship between diameters of the r; r is coming in here. This is a relationship between r. So, as l by r increases, this changes and you can plot it in this manner depending upon l by r. So, as l by r increases, l by l is the length by r increases. This is the x d by x dash, changes in this manner. So, this is the behavior of short fiber. And, in such case, sigma c u will be length efficiency factor sigma f u V f if they are aligned. And, if they are not aligned, then this will be for randomly oriented.

Both these efficiency factor must be taken into account – sigma f u V f. That is what you should be taking into account – the composite strength. So, the composite ultimate strength will be given by this. At failure, it will be epsilon m u.

Now, if it is less, then… If this is less, then E c – composite E c into epsilon m u; then, you will find that the behavior is like this, behavior is like this; rather than enhancement, you get behavior like this. If this value is less than E c m c, you find the strength would actually reduce. But deformation – it can continue, because it will not splinter out, the fibers will hold it, the crack width will be initially restricted; there will be large number of cracks with small widths and number of them. So, this would be the ultimate strength. So, this will happen when fiber is snapping.

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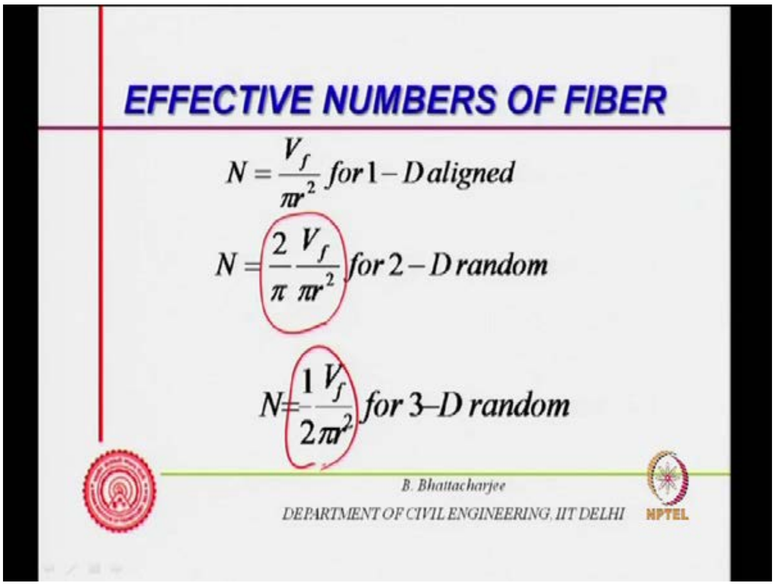

But, in reality fiber, do not snap, because short fibers – they do not really snap and they actually fail by pull out. So, we will come to that. So, number of fibers – approximately, one can take it as short fiber V by pi r square for 1-D aligned; 2 by pi V f by pi r square in 2-D random; and, number of fibers in 3-D random; one can take approximately from effective number of fibers. In 3-D random orientation, this one can take. We have written V f divided by pi r square for aligned fiber. Then, we have seen, if they are short, they will not be effective; but, we have not talked about the number of fibers; we said the effective fiber, which will be taking the load for calculating the crack width. But this is what one can assume roughly the number of fibers. It will be half number of fiber in 3-D random. Number of fibers along the direction of the load is given by this – effective number of fibers.

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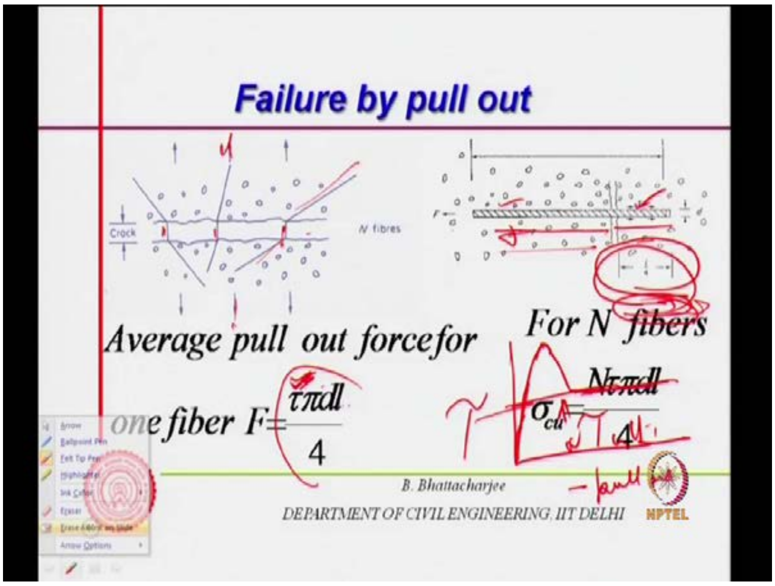

I said the short fiber usually fall by pull out, because the fibers are strong. So, before they can snap, which we have shown… Earlier we have giving the formula for snapping – nu l nu zero into sigma f u V f. But that rarely occurs; instead they pull out. And if they pull out, what happens is – supposing there is a crack, some fibers… This is the direction of the load; this is the crack direction of the load. So, this is the N number of fibers. Just now we have shown the effective number of fibers in a given direction in the direction of the load. For 1-D, we said it is V f by pi r square; for 2-D, it is pi by 2 V f by pi r square; and, for 3-D random, it is one half pi V f by pi r square.

Just now we have seen. So, these are the number of fibers. And actually, they will tend to align along… In the crack, they will tend to align along the direction of the pull. But they then gradually get pulled out. Now, this pulled out length… because on this side of the crack, I can have that 0 or l by 2; I can have 0 or l by 2. So, on an average, I can assume that, l by 4 will be the minimum length. This is larger; this is smaller; this is larger. So, out of the two, the minimum length on an average will be l by 4, because the minimum length can be either 0 or its maximum value of the minimum length above the crack – on the one side of the crack can be l by 2. So, on an average, l by 4 is the minimum length.

And, when I am talking of pulling out, l by 4 is the average length of pull out. When its pull out fail by puller out, this much length – it should pull out by this much length. So, l by 4 is the average pull out length. I can assume average pull out length is l by 4. And therefore, for one fiber, tau pi d is the perimeter – into l by 4. That is the pull out force required to pull out one fiber, tau pi d l by 4 is required. Remember when pull out is occurring, the bond… This is actually the tau is quite often, it is like this initially. Initially, there is a perfect bond. So, if I plot this tau versus pull out length, then initially, it is perfect bond and it will increase like this. As I try to pull out, they go together; there is a perfect bond.

Then, there is a bond failure. And after that, it is a friction, which will keep it on. So, the tau might be… I might take this as tau ultimate; or, tau ultimate – I might take this. So, this tau is that tau, which is actually because of friction; first, because there will be roughness and because of friction. So, actually, initially, there will be perfect bond. Once the crack has occurred actually, there is some amount of pull out. And this failure might have occurred; but, beyond that, I will have still bond available and pull out would be there. So, I take this value, which is the lower value as the value for pull out strength or bond strength for pull out. So, tau pi d into l by 4 is the force we require to pull out one fiber. And, for N fibers, I will require N tau pi d into l by 4. So, this is sigma c u. So, all the fibers you have to pull out. This will be sigma c u.

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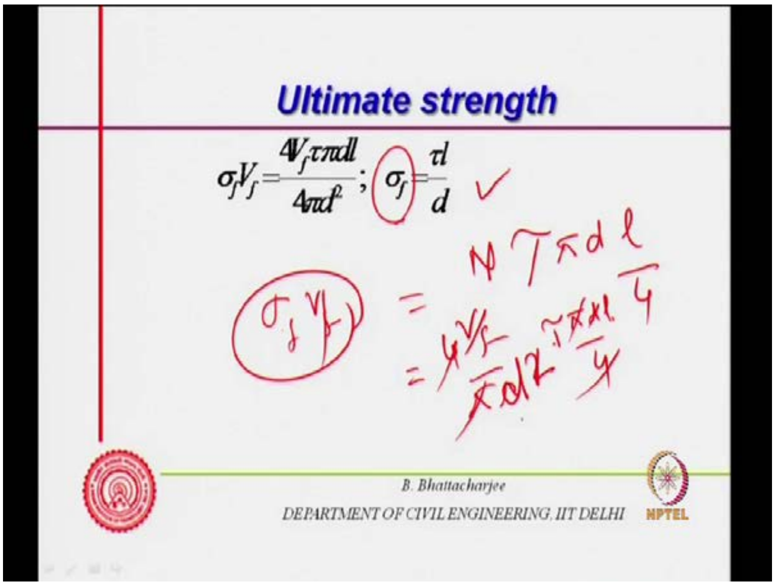

Now, N is the effective number of fibers; it will depend upon type of alignment I have. So, N is the effective number of fibers. Therefore, it will be sigma… For the fiber pull out force, we have seen sigma c u composite is like that. So, 4 V f tau pi d l over by 4 pi… I get the sigma f – the stress in the fiber. So, stress in the fiber corresponding to the pull out is basically sigma f V f and V f divided by 4 pi r square or pi d square by 4. So, sigma f V f is the stress. And, I said it is N tau pi d l by 4. It was N tau pi d l by 4, because tau pi d into l by 4 is a force for one. And this can be written as V f by pi r square or pi d square by 4. So, I write 4… This N can be written like this for aligned fiber situation – pi d l by 4. So, if it is aligned fiber situation, this pi will cancel out with this; d will cancel out with this. And, I will be left with… V f will cancel out from this side. So, I will be left with sigma f is equal to tau l divided by d. So, stress at the pull out is sigma f pi l by d.

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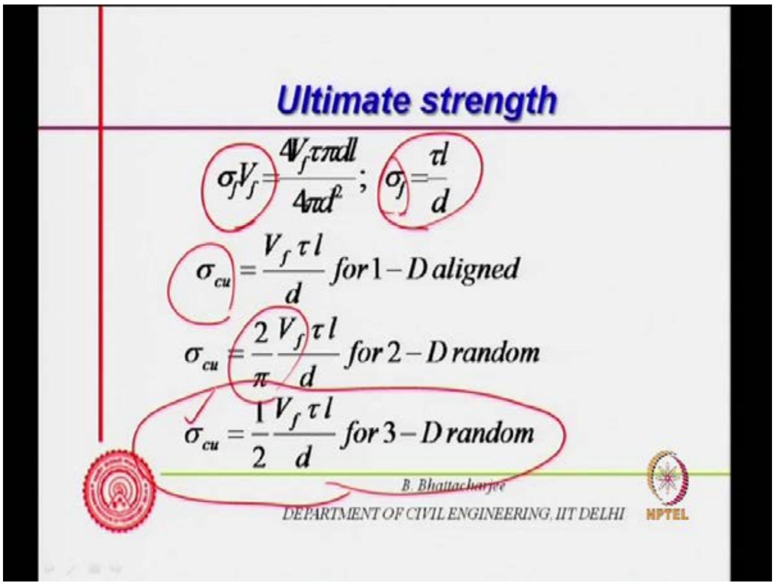

So, stress at the pull out is this. So, sigma c u… Therefore, composite strength can be written in terms of sigma f into V f; and, the stress actually – stress in the composite is V f tau l by d, because sigma f is this for 1-D aligned; for 2-D aligned, V f is for… The effective number of fibers is this. So, sigma f stress in one fiber is this and for all the fiber 2-D random. And, 3-D random, sigma c u can be written like this. So, when you have fiber snapping, the force – the tensile strength of the composite will be governed by the pull out force, because this is the tensile force in the fiber; the matrix has already failed; matrix has cracked.

And after that, the pull out is occurring. And, this is the stress that the fiber can withstand now; that is limited by this – the pull out force. So, pull out force in one fiber is this for effective number of fibers. So, for 3-D random, it is half V f tau l by d. That is the composite strength, because the pull out will govern although sigma f u has not reached. Sigma f is governed by the pull out force, because it will pull out. And, the stress that is attained – that is the stress the composite can take it multiplied it by V f. So, that is how we find out the pull out force. So, this is this is all in axial situation. When I have a direct tension, all these have occurred.

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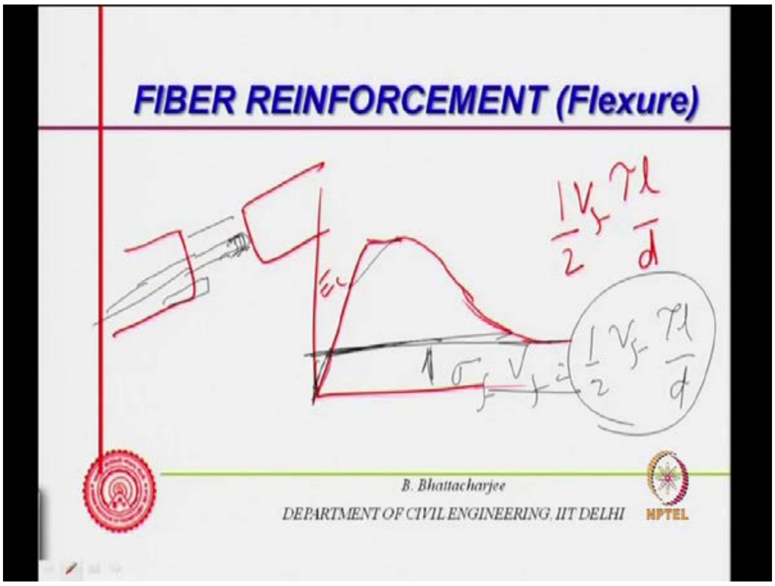

Now, let us look at the flexure. How does it behave in flexure? So, if you look at the stress-strain diagram; let us say just before that; let me look at this stress-strain diagram. Then, this could be E c; then, there may be… At the crack, it will look like this when pull out is occurring. Then, there is an increase. And, after that, it could be half V f tau l divided by d if it is 3-D random and if this value is more, because it will fail by pull out; usually, they are not. So, you might get it something like… This is of ultimate somewhere here. But then, lot of… Basically, the fiber will go on extending; matrix is inside it. Fiber will go on extending till a situation like this is arised, till that the gap has become so large such that the fiber is… This side the length is more; this side the fiber has just come out. So, this is the point of failure. So, it is actually l by 4. At least it can… On an average, l by 4 deformation it will definitely show depending upon the situation. But, all the fibers should be there. So, it will be a layer random scenario.

Many of the fibers possibly will show up here; many of the fibers… Last fiber has come out actually or it will snap, because there is only one fiber to extend the layer. So, there could be some snapping also. So, it will actually behave in this manner. And, the ultimate strength that we are taking is… Supposing I take it simply like this. So, stress-strain behavior neglecting idealizing it something like this. This will be simply sigma f V f, which will be equal to half V f tau l by d. So, I can safely assume a long deformation, long extension with this kind of strength available. So, long deformation I can assume; long elongation I can assume. So, stress-strain curve I can idealize like this.

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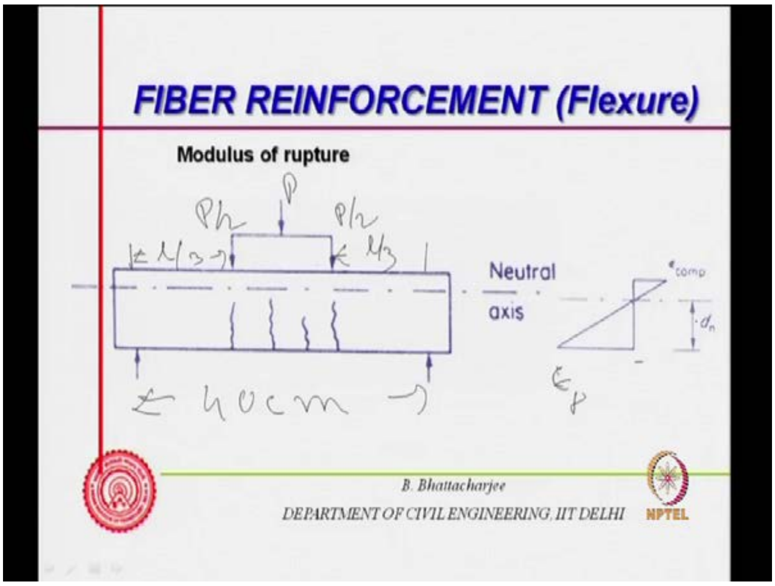

Now, in flexure, we are talking of improvement of the matrix itself. That is why we are talking of modulus of rupture. As I mentioned earlier that, we do not talk… It is not the same thing as conventional rework; that is not the case. It actually improves the material itself. And therefore, we are talking of modulus of rupture of the concrete. And, this is how we test the modulus of rupture; one-third loading – l by 3. This is l by 3; this is l by 3. You have actually 50 mm bar in Indian standard with 50 centimeter; with this as 40 centimeter; and, one-third, one–third. And, the P you apply; this is P by 2 and this is P by 2. And, you get cracks like this – modulus of rupture test that we do, because this is the epsilon compression and this is epsilon tension. So, this is the… And this is the depth of neutral axis; at failure, crack occurs. So, this is the modulus of rupture test; we know. And, we are trying to see how modulus of rupture changes with the fiber.

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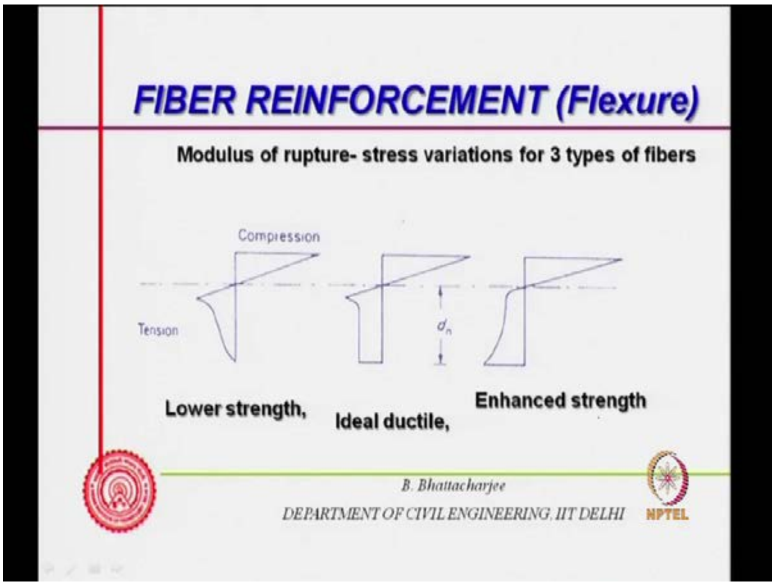

So, modulus of rupture for three types of stress variation, I can assume; I said that I can assume simply this type of stress variation; compression – stress variation will be like this; tension in this zone. So, lower strength actually. Strength is reduced significantly. In this one, what I just showed – ideal, but ductile (( )) pull out is possible. Here it is strength enhancement – enhanced strength. But in any case, the deformation available is significantly large.

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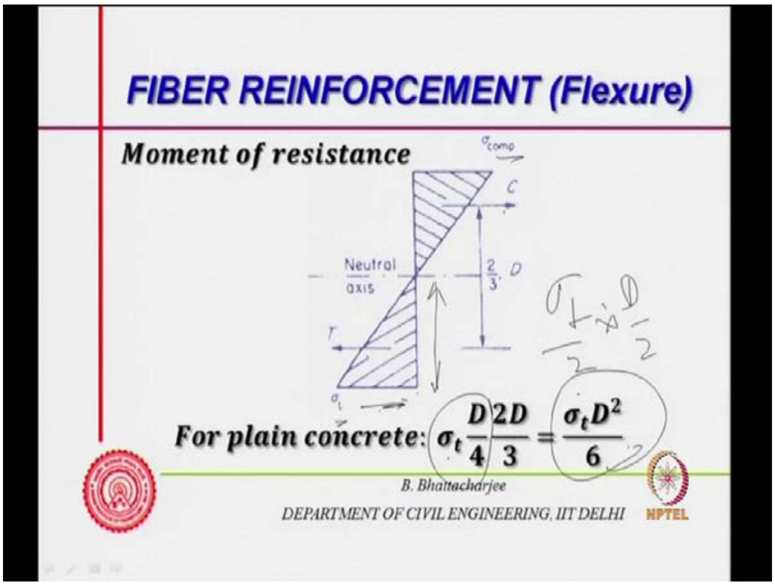

Strain available – corresponding strain available will be significantly large. So, strain available is so moment of resistance for no fiber reinforcement. Just, so what is available is a strain available, will be large. That is what we will see. So, let us look at moment of resistance for plain concrete; this is triangular distribution – strain distribution and stress distribution, both we take triangular. So, this is the sigma compressions, sigma tension, tensile strength, modulus of rupture. We assume stress is not real; stress-strain diagram variation we do not take. Actually, real will be something like this in case of concrete. But then, we do not take it; we take it triangular stress distribution for calculating moment of resistance. So, here also we can adapt the same principle and just see how the modulus of rupture change.

So, in this case, C and T… And, this distance is two-third D; C accept here – one-third D by 2; and, this is one-third D by 2. So, this is two-third D – neutral axis at the center. We assume sigma compression is equal to sigma tension of the plain concrete. And then, I can calculate this out as sigma t; sigma t because this will govern; failure will not occur here. This will govern. This will… Failure will occur here. So, half sigma t into D by 2 half sigma t; half of this sigma t. So, sigma t into D by 2. So, it is actually sigma t; half sigma t into D by 2. That is the triangular area – sigma t into D by 2. And, of course, the width you are taking as unity. This multiplied by sigma t D divided by 4 multiplied by 2D by 3 lever arm gives me sigma t D square by 6. But this you know very well. So, that is the moment of resistance for plain concrete.

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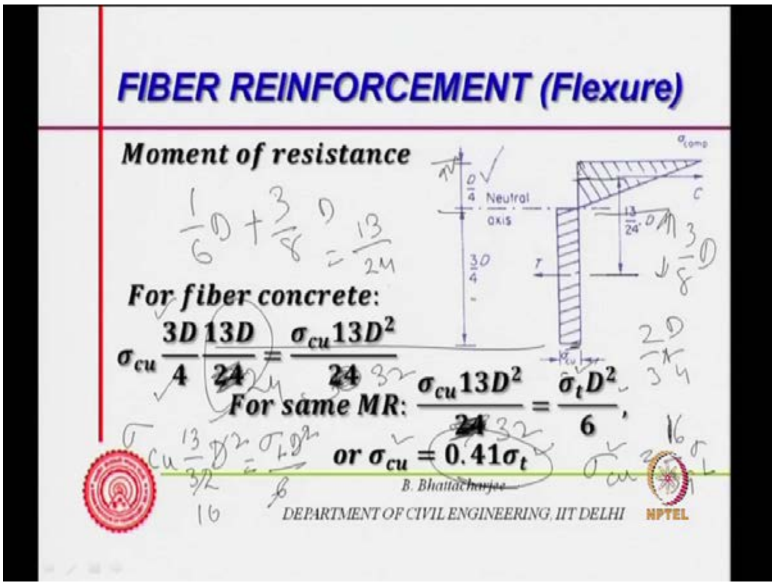

Now, let us see fiber concrete. Moment of resistance for fiber concrete – first, let us look at the diagram. Now, what we said was, the strain will be very very large. In fact, the strain diagram if I plot it, it will be very very large here; large strain diagram. Strain diagram will be large. And what I can do is strain will be very large strain, because now, it can deform quite a lot. But the stress could be very small – sigma c u. So, the neutral axis goes up significantly and I can now calculate out the moment of resistance. So, neutral axis strain would be very very large, because it can now deform quite a bit. So, correspondingly, neutral x will go up; there will be lot of rotation available, because the crack will not simply open up; the fibers will restrain the crack opening. And therefore, it actually will ensure that, there is lot of deformation prior to failure; pseudo duality and this…

The stress block in the tension zone will be something like this assuming this is the smallest one, sigma c with the least value. As I showed you, idealized one, and approximately, one can take this as D by 4, because D by 2 it was; now, I take it to be D by 4 at failure. Strain has increased; at the bottom, strain has increased so much – D by 4. Therefore, this is D by 4. So, this is three-fourth D. So, if it is three-fourth D, this is sigma c u into three-fourth D – 3 by 4 D. That is what I am doing. And, how much is this distance? This is simply… This distance is 3 by 8 D; this is 3 by 8 D. And, this distance is actually in a triangle. This is the center point of the triangle. So, this was the one-third D; this is two-third D. So, two-third D by 4. So, if I add this up, 1 by 6 D plus… This is 1 by 6 D plus 3 by 8 D. So, this will be actually 24; and, 6 is 4; 8 is 3. So, 3-3 – 9 plus 4 is 13 by 24 – 24 D. This will be 6; six 4s – 24; and, eight 3s – 24. Therefore, 9 plus… That makes it this. So, 13 by 4 D.

And, this will turn out to be sigma c u 13 by… 4 is there. So, sigma c u 13 by 24… If I calculate out, how much is this? This comes to sigma c u 8… 32. This is not 30, this is 32. This is 32 plus… Correct it. This will be 32. So, for same moment of resistance, this is 32. This is wrong; this is 32. Same moment also, this will be 32 – 13 by 32 D square. So, for same moment of resistance, sigma c u 13 by D square. So, this comes out to be 4 – 0.41. So, this was sigma t; this is 6. This will come out to be… Actually, this will come out to be… D square will cancel out.

Now, if I to have same moment of resistance; if I have to have same moment of resistance, this cancels this out. It is not 24; it should be 32. So, this should be… This is

24; this should be 32. So, this should be 32. So, it is 13 by 32 D square. So, sigma c u… Moment of resistance is given as sigma c u 13 by 32 D square. Now, if this has to be same as… Same moment of resistance if I want to get, then I want to get a relationship between sigma c u and sigma t. So, the D square will cancel out. This is 16; and, this is 39. So, I will have sigma… Sigma c u is equal to 16 by 39 sigma t; roughly 40. If you assume it, you can easily show that, it is actually 0.41 sigma t.

So, sigma… This 2D to have equal moment of resistance. What I need? This sigma c u – I need only 41 percent – 41 percent of the tensile strength of the concrete. So, even if there is no enhanced strength enhancement, then also, I will get flexural strength enhancement, because to have same moment of resistance… Now, if it is more than 41 percent of the sigma t; supposing it is sigma t, I will get actually 200 percent enhancement in strength, because it will…

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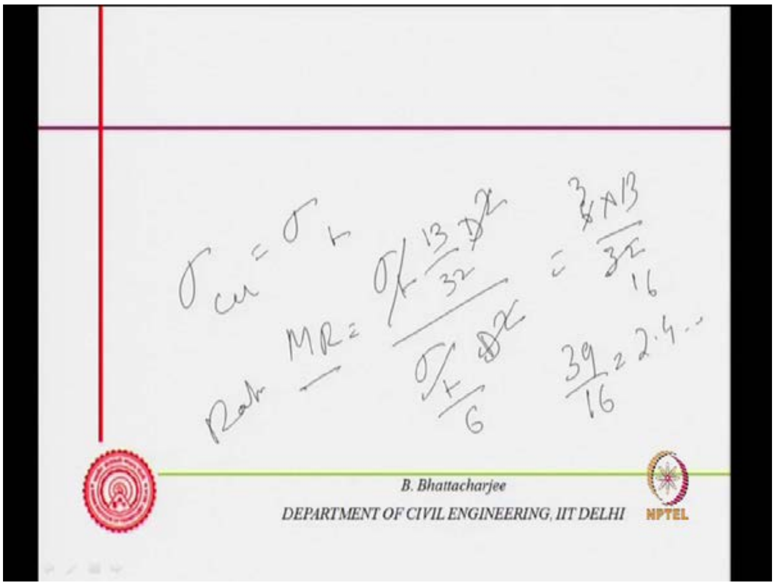

Supposing sigma c u is equal to sigma t; then, moment of resistances will be simply… moment of resistance ratio will be given as sigma t 13 by 32 D square divided by sigma t by 6 D square. So, you cancel this out, cancel this out. And, you will get actually 6 into 13 divided by 32. So, moment of resistance ratio – ratio of moment of resistance divided by 32; which means that, this is 3 – 39. This is 16. So, 39 divided by 16 will give me how much? 2…. It will be 32. So, 70… 2.4 something something. So, you can see that, if the tensile strength of the matrix and the ultimate tensile strength of the composite is same, I get flexural strength enhancement. Moment of resistance (( )) 2.4 times. So, that is a great thing. That is actually… That is where the advantage of fiber concrete is.

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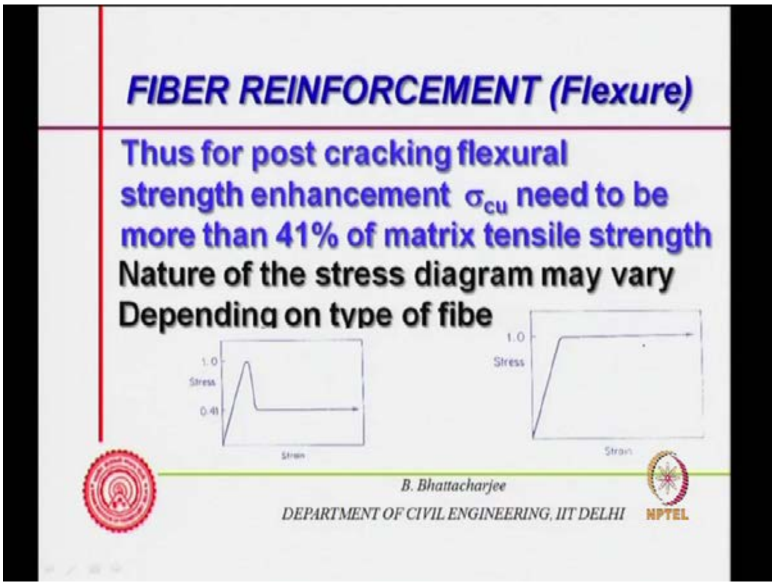

Thus for post cracking flexural strength enhancement, sigma c u need to be more than 41 percent of the matrix tensile strength. And, if it is same as sigma t, you will get more than double – 2.4 times or 4, 5 or something; whatever it is; very large; 1 by 0.41. That much time increase in the… Nearly large increase in the flexural strength. So, even if it maintains same. But actually, it does not maintain; it is lower. So, you always get a flexural strength enhancement even though you may not get direct tensile strength and (( )) enhancement. Direct tensile strength enhancement is difficult in sharp random fiber. Compressive strength really do not improve, because compressive strength is governed by tensile failure. So, it actually does not show any improvement. But flexural strength – there is a significant improvement. So, nature of the stress diagram may vary of course depending upon type of fiber as I mentioned.

For example, some fiber might show like this – 0.41 should be here. Then, it is good enough for me. Just 4 (( )) 1 has to be here. And, in some cases, if it is 1, then I will get so much of increase actually – increase in the flexural strength. Therefore, flexural strength of the concrete matrix get improved by putting in fiber although direct tensile strength may not increase, because direct tensile, you can add only 1-2 percent, very small quantity, volume metric or mass percentage; very small 1-1.5 percent you add, because beyond that, adding becomes very difficult, mixing become difficult; there are some effects, which we will come to. Therefore, that becomes difficult. So, we cannot add that much. But, even if you… And therefore, tensile strength enhancement may not be significant. Short random fiber – the orientation and the shape; orientation and the length – they start actually reduce down the strength. Further, they can pull out; thus they can reduce down the strength. But even if it is 0.41, you will get same modulus of rupture. It is something like this. You will get much better… So, that is the basic understanding of why flexural strength is enhanced in fiber reinforcement.

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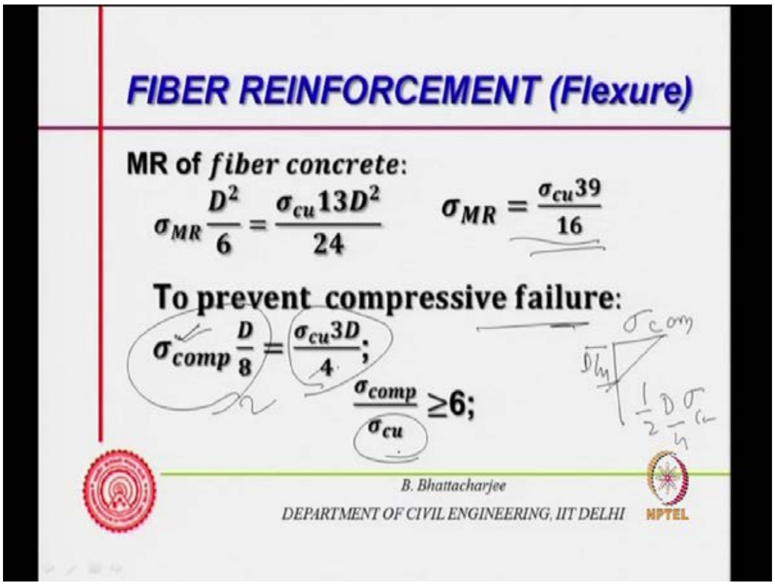

MR of fiber concrete comparison – if you see, this is what I was just telling you. Now, to prevent compressive failure, this already I have told you that it is 2. something; 39 by 16 times. So, to prevent compressive failure, the other criterion – composite should not fail in compression. So, if it is… It should not fail in compression. So, what is the compression load? This is sigma compression. This is D by 4. So, this is half D by 4 into sigma compression. That is the stress block. That must be equals to the tensile. Failure occurs by this. So, at failure, sigma compression will be this much. At failure, the compression will be this much.

So, under this condition, sigma compressive should be more than 6 times the… If you calculate this out – 4; this is 2. So, it is c. So, sigma c u… Sigma comp by sigma c u will be given as 6. So, it should be greater than 6. The compressive strength should be 6 times greater than sigma c u; otherwise, there could be failure. But, normally, this occurs, because we have earlier that, it could be 8 times easily. Therefore, this occurs… So, this is to prevent compressive failure, this ratio must be maintained. So, what we have seen so far? Facts seen so far that, tensile strength enhancement may not be significant; flexural strength enhancement is significant; crack arrestation do occur; and, we get pseudo ductility. All these properties enhancement we have seen.

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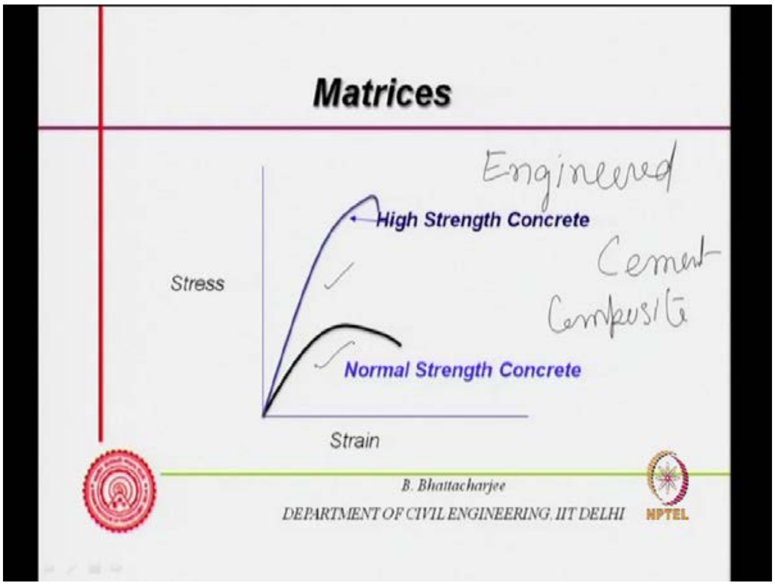

Let us see what are the type of matrices we use. High strength concrete; normal strength concrete – these are the matrices we can use. But slightly, you have to define the mix design differently. In fact, you can use micro fiber engineered cement composite. Engineered cement composite, which I am not discussing in a big way – engineered cement composite. You can actually put in micro fiber and if the length… – small fibers actually and enhance in the high strength system. People are thing of adding nano fiber, which might increase the strength at the nano levels. So, tensile strength of the matrix might increase so significantly, because nano crack it will arrest. Micro fiber can arrest micro cracks. The fiber, fiber, fiber – high strength matrices – very high strength matrices also with say polymer composite rework together with very micro fiber, people are attempting to make composites, which can be used for high strength, high endues and so on and so forth.

Normal strength concrete we know. And we can always use fiber enforcement for flexural strength improvement. And pavement, for example, where flexural strength improvement is a necessity, we can use them. Places where I need flexural strength enhancement, we can use this fiber composites – fiber enforced concrete, normal strength concrete. But mixed proportion of this one is different; you just cannot make a normal strength concrete mix and put the fiber; you will have all kinds of trouble; we will just look at that.

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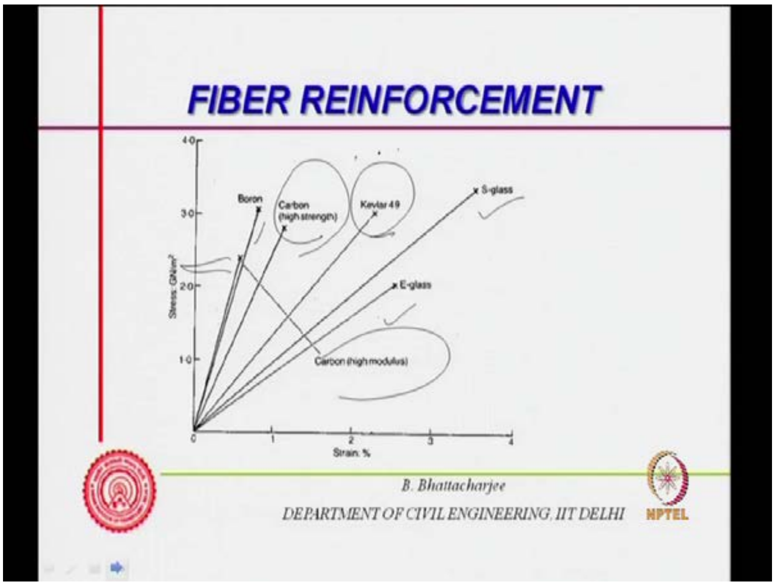

Types of fiber that you get – varieties of fiber, where you can get actually fibers of varieties of… For example, S-glass, E-glass; types of glass – alkaline resistance glass; this is Kevlar 49 is a branded product aramid actually; then, third one – high strength, boron, carbon high modulus lower strength. There can be varieties of fiber possible to be used in reinforced concrete reinforcement other than steel.

Polypropylene, polyester – these are several of them; polypropylene, polyester – they are being used today for shrinkage cracks and all, because they are… You see this is the steel – high yield steel, mild steel idealized stress-strain diagram is here; mild steel idealized stress-strain diagram; high ductility polypropylene, high density polypropylene, low density polypropylene. And, this is polyester. Then, glass high modulus polyethylene. There can be several types of fibers – they can be used depending upon their properties. But, you see the steel of course gives you high modulus; low modulus you have to… once you have understood the behavior. Therefore, you can think of how to use them, which way, how, the way they will benefit and so on and so forth. So, you have looked into the fundamentals.

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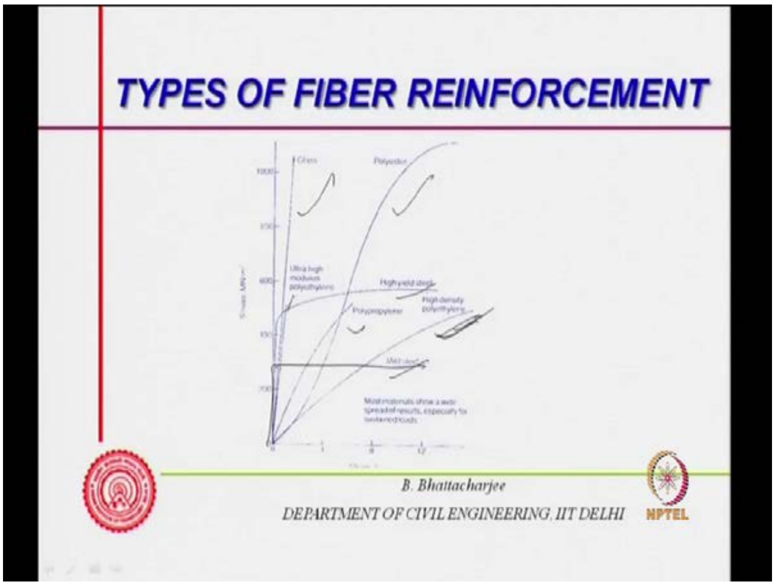

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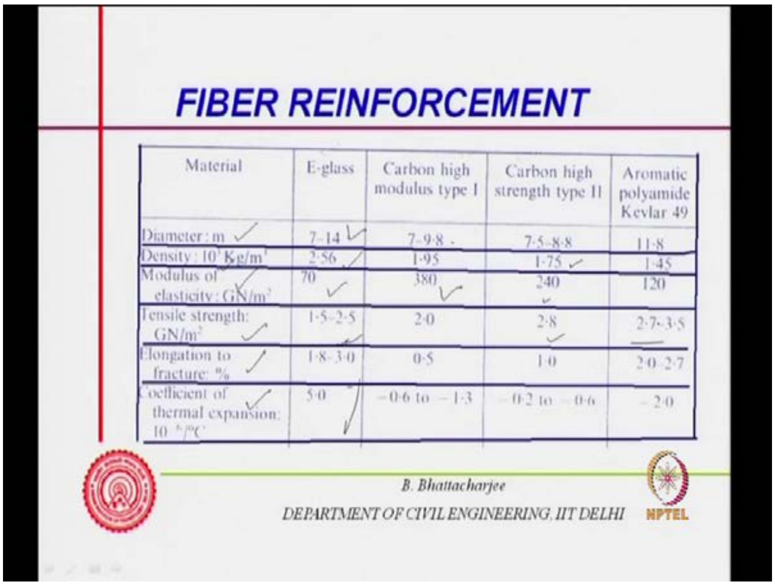

Material	E-glass	Carbon high modulus type I	Carbon high strength type II	Aromatic polyamide Kevlar 49
Diameter : m	7-14	7-9·8	7·5-8·8	11·8
Density : 10^3 Kg/m^3	2·56	1·95	1·75	1·45
Modulus of elasticity : GN/m^2	70	380	240	120
Tensile strength: GN/m^2	1·5-2·5	2·0	2·8	2·7-3·5
Elongation to fracture: %	1·8-3·0	0·5	1·0	2·0-2·7
Coefficient of thermal expansion: 10^{-6}/°C	5·0	−0·6 to −1·3	−0·2 to −0·6	−2·0

And, properties of some of them – what properties are important? Diameter – fiber diameter, density, modulus of elasticity, tensile strength, elongation, coefficient of thermal expansion. These are important properties. And, some of these properties are… Some materials are available in literature; a part of it is taken from literature actually – ((

)) book – this data. So, E-glass – density, modulus of velocity; you can see these are in GPA; tensile strength you can see. So, for example, this has got high modulus of carbon high modulus type, carbon high strength type low modulus. But the strength is tensile strength is 2.8 GPA; that is, 2800 megapascal and so on and so forth. And Kevlar 49 – this is the kind of property.

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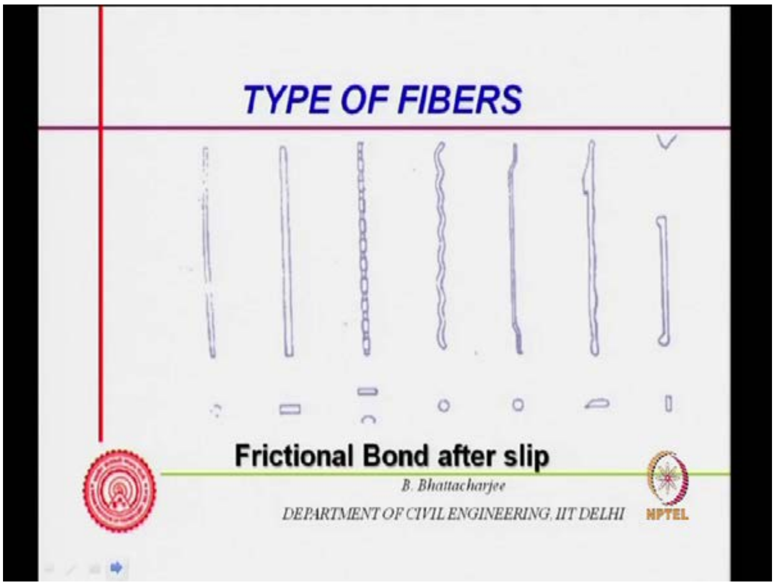

Shape of the fiber can vary. For example, you can have hooked, crimped and varieties kind of cross-section, rectangular – all kind of hooked fibers; all kind of… because bond strength is important, because I said that, frictional bond after slip – that occurs; which I showed a diagram earlier. So, bond strength is very very important. Therefore, you can make all kind of fibers and use them.

Now, in the plastic state, normal fiber concrete – we have to test by only V-B test. But that also… V-B test – we test with V-B test, because its slump is… It will not have very low slump. So, what is seen is that, V-B time tend to increase with fiber content depending upon l by d; higher l by d, V-B time is least depending upon l by d. This is the highest l by d. And, this is the next and so on and so forth.

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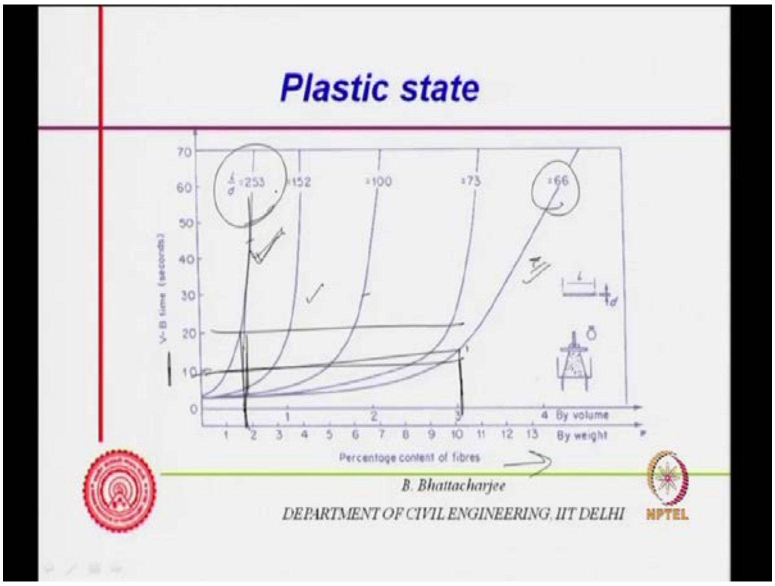

Now, what happens is, V-B time increases significantly for high l by d with small quantity of fiber increase; while this l by d can withstand a quite lot of fiber content to have a V-B time small enough as one second. Supposing I say that 1 second is the time or 10 second is the time; good enough for the V-B time; or, 20 seconds is the time. You find that, this is tended much lower fiber content for higher l by d. So, l by d governs the V-B time. It is important to understand. Higher l by d means lower V-B time.

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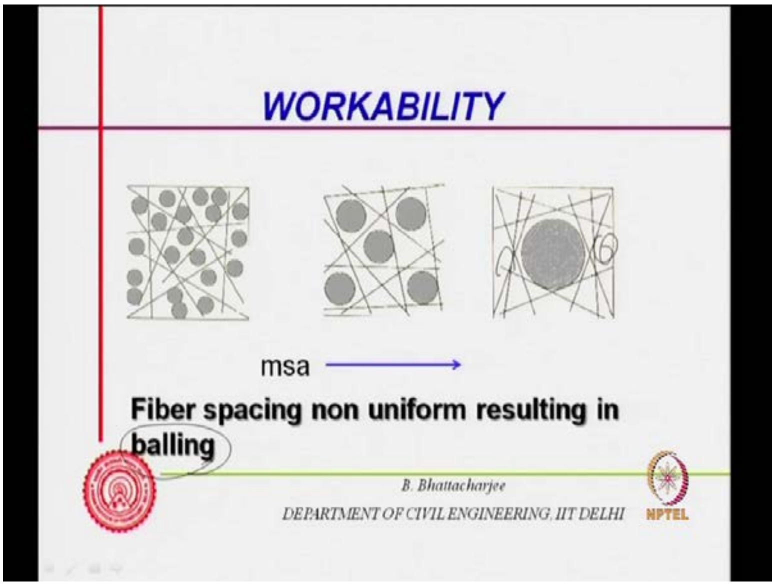

Also, the spacing of the fiber aggregate, because of the size of the aggregate. So, smaller sized aggregates spacing of the fiber is better. So, msa – higher msa – spacing of the fiber is poor. And you will have fiber spacing is non uniform in this case. Also fiber will try to bundle out and results in kind of balling or formation of bird's nest. So, workability is a function of all these.

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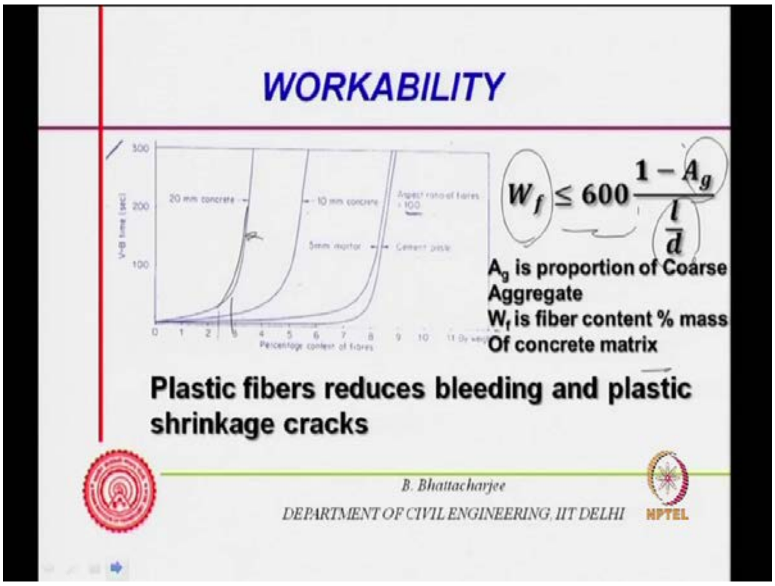

So, you have m.s.a., higher m.s.a.; again same sort of curve you see; less percentage of fiber it can tolerate for good workability. Empirical formula for steel is given as that; that the fiber content by mass or weight as a proportion of the matrix should be less than 600 1 minus A g divided by l by d. So, you have l by d higher; the fiber content you can withstand is lower. And, A g is the fraction of coarse aggregate in the system. So, higher the more the coarse aggregate in the system, less the fiber it will tolerate. So, it should have more mortar, more paste. So, it requires more mortar and more paste. Plastic fiber reduces bleeding and plastic shrinkage cracks that we have seen.

Durability – durability depends upon type of fiber. Steel can corrode, but low diameter to cover depth… because… But, this is low; corrosion is low as diameter to cover depth is small. You have very small diameter; cover depth steel is large, very large. And therefore, it is small. So, plastic fibers are also inert; they do not corrode. Steel fiber can corrode, but fiber concrete does not show that much of corrosion. Unless it is cracked and got exposed, it would not show that much of corrosion. Actually, micro cracks would not show that.

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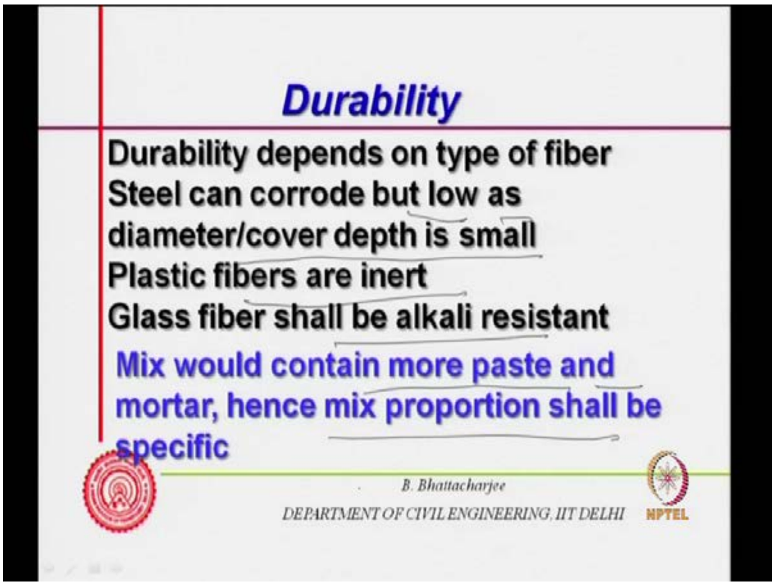

But then, you have a cover; put a cover, which .is not fiber; it will… Glass fiber shall be alkaline resistance; otherwise, cement materials can attack them. It should contain more paste; about 70 percent mortar is a good thing in this one; 30 percent aggregate. So, you see you require more paste and mortar. And hence, mix proportion should be specific. Many a times, people tend to do a mix proportion for concrete to get strength; and then, put fiber; this will not work. You have to have specific mix proportioning for this purpose. And, thus we have understood in nutshell the fiber concrete.

Let us look at another concrete. We have looked into self-compacting concrete, which is free flow. Now, look at the other concrete, which is actually high slump. So, it has got very low consistency represented by no slump condition, zero slump condition. This is called roller compacted concrete placed by asphalt paver in pavement and compacted by high density vibratory roller used in earth or rock-fill construction. So, in case of pavement, you can put it by a small paper type of thing.

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In case of a coarse mass concrete, you have to carry it by truck – non-agitating truck generally. And, segregation of course is an issue to them. But, use finally, compacted by vibratory roller. So, it has to be dry – absolutely dry zero slump. Compaction and water content governs the strengths. Therefore, it is a compaction and the amount of water content. You are treating it like soil. So, water-cement ratio is not the issue here; So, you have m.s.a., higher m.s.a.; again same sort of curve you see; less percentage of fiber it can tolerate for good workability.

Empirical formula for steel is given as that; that the fiber content by mass or weight as a proportion of the matrix should be less than 600 1 minus A g divided by l by d. So, you have l by d higher; the fiber content you can withstand is lower. And, A g is the fraction of coarse aggregate in the system. So, higher the more the coarse aggregate in the system, less the fiber it will tolerate. So, it should have more mortar, more paste. So, it requires more mortar and more paste. Plastic fiber reduces bleeding and plastic shrinkage cracks that we have seen. But, compaction and water content is a issue. Shall be dry enough to support roller and wet enough to have uniform distribution of paste. So, that is the basic idea. You have paste distribution well – sufficient paste and well distribution of paste – just wet enough to get maximum compaction. But, it should be dry enough to support the roller.

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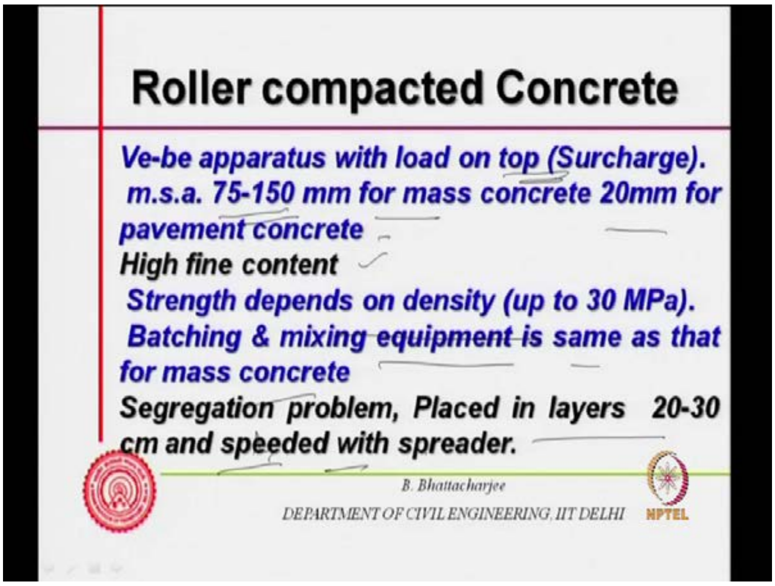

Ve be apparatus with load on top is what we use; with a surcharge we used. And, its m.s.a. can be 75 to 100 mm for testing the workability. We will come to that a little bit. I can have m.s.a. 75 to 100 mm for mass concrete, 20 mm for pavement concrete, which can be as strong as 30 MPa or 30-40 MPa you can get; 30 MPa is easily attainable in Indian scenario. It will have high fine content. Strength depends upon density; you can get around 30 MPa easily. Batching and mixing – in cylinder strength, 30 MPa is not difficult if you use ACI method of mix design. Batching and mixing equipment is same as that of normal concrete or mass concrete for mass concrete. And then, segregation problem is there if you are taking it by truck. It is placed in layers of 20 to 30 centimeter and spreaded. It is spreaded with spreaders; it is generally spreaded with spreaders.

So, cylindrical surcharge could be of this kind for pavement concrete. Typical ve-be test and put a surcharge here. So, this is the… Surcharges are here. These are the surcharges; let me use red color. These are the surcharges; additional surcharge you put. Do the ve-be test ASTMC1170 gives you the idea. So, ve-be test with surcharge. That is the idea.

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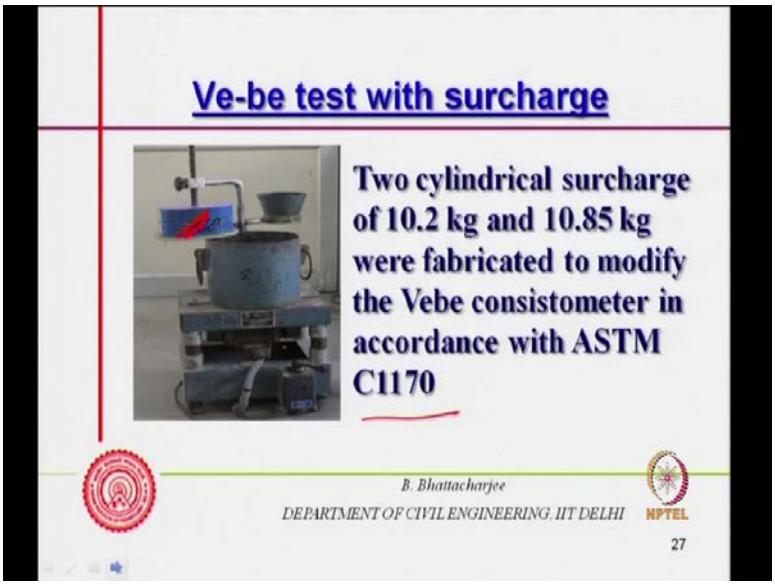

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And, RCC requires no forms; requires no conventional finishing. Therefore, big advantage; less cement actually; in this, you can design it for lower cement in fact. So, it is proctors compaction what governs the strength. And, you can use ASTM D1557 selected combined aggregate proportion; packing density is important here. you pack the aggregate pretty well so that paste content is reduced. Then, fly ash around 25 to 30 percent easily you can use and must use. And mass concrete obviously, we are going to use them because of heat of hydration. So, fly ash – you use this kind of thing; all specific cementitious material. And then, put them together and do a proctors compaction test by varying water content. So, this is the proctors test.

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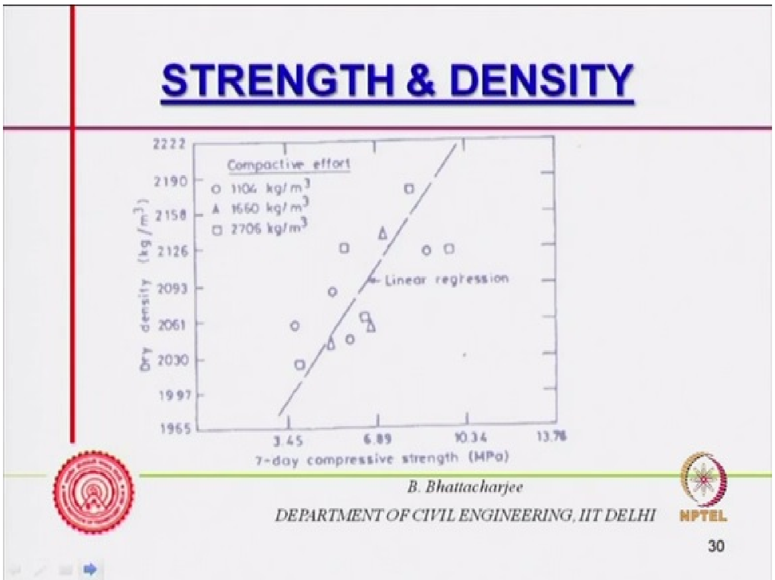

Strength and density relates. There will be proctor test actually. Proctor test you will get here. Proctor test you get here.

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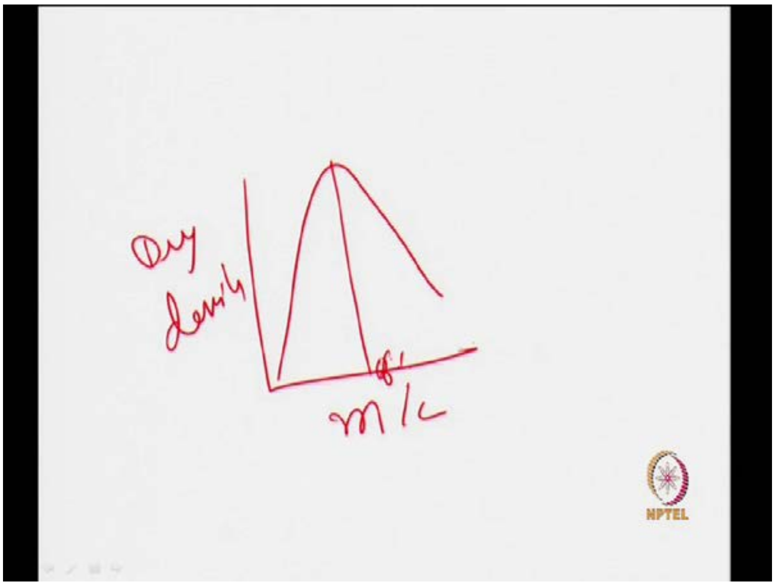

The variation you get something like this; moisture content versus density – dry density. You plot it like this – moisture content. Choose the optimum moisture content – 6 percent or 5 percent as per the methods that they have. And then, that will give you the maximum density. So, density versus strength relationship is like that; so 7 days strength, dry density. It could be better for better concrete.

Therefore, what we have looked today? We have looked into flexure or fiber strength concrete; types of fibers that we can use; and, lastly, roller compacted concrete. So, roller compacted concrete to handle, they will just summarize the roller compacted concrete as the zero slump concrete; generally can be used or generally used in pavements as well as in mass concrete dams. And it might turn out to be cheaper basically, because you are doing away with the formwork. Cement content could be less. And then, same equipment that you use, you do not require special equipment; same equipment that you use for pavement construction or for mass concrete construction; you can use the same. So, with this, we conclude our discussion on fiber concrete and roller compacted concrete and lecture five.

Thank you for hearing.