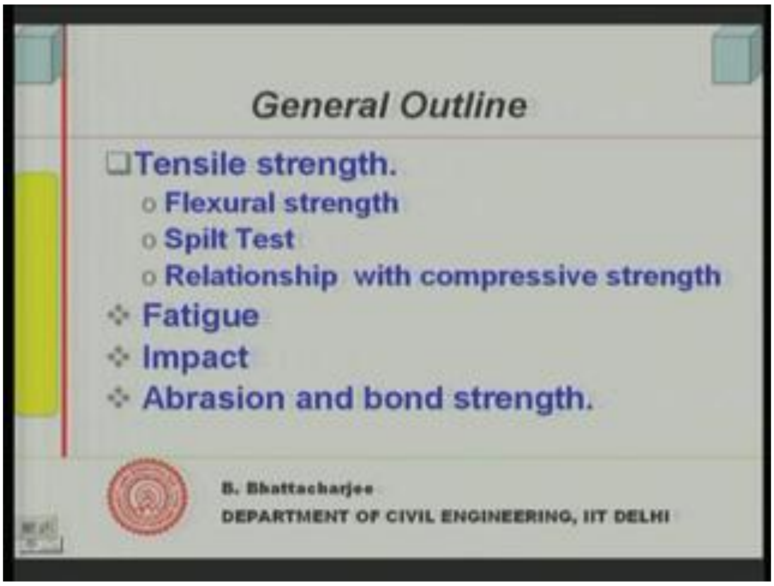
Building Materials and Construction
Prof. Dr. B. Bhattacharjee
Department of Civil Engineering
Indian Institute of Technology, Delhi

Module - 6
Lecture - 18
Mechanical Properties of Concrete: Elastic Modulus, Poisson's Ratio

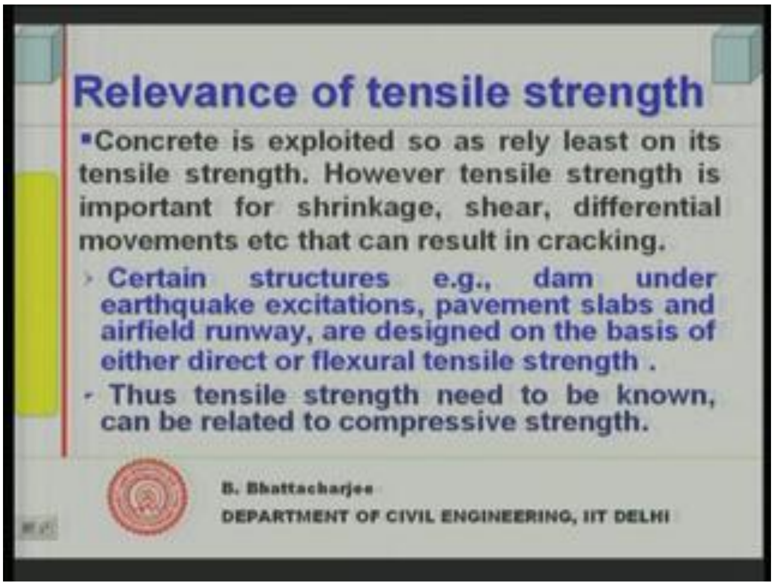
We have looked into the compressive strength and relevant you know issues related to compressive strength, in the previous lecture. Now, we should look into other mechanical properties, and today we shall look into tensile strength, fatigue strength and impact abrasion resistance of concrete right.

(Refer Slide Time: 01:46)



So, tensile strength we will look into first tensile strength of concrete and the general outline of our discussion today would be tensile strength. Now, we look to tensile strength in 2 different ways; one is called flexural strength other is split test. We will describe this and this relationship, with compressive strength that is what we look into. Then individually, we will look into fatigue strength, impact resistance of concrete and abrasion and bond strength.

(Refer Slide Time: 02:15)

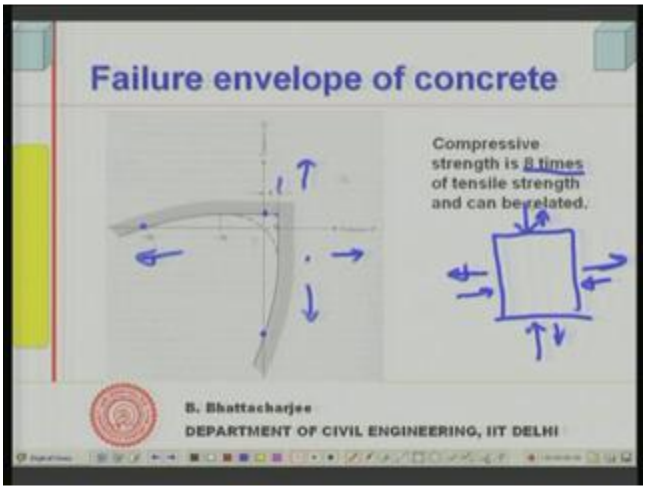


Now, let us see where why do we need at all the tensile strength of concrete, you see concrete generally we exploit its properties, in such a manner we exploit in such a manner that we rely mostly on its compressive strength. And list on its tensile strength, because we know that it is weak in tension. And therefore, we put reinforcement in reinforced concrete structures or we blister them for that purpose. So, that it can withstand certain amount of tensile loading however, in some cases we may have to still rely on the tensile strength of concrete.

The examples are for example, we have shrinkage cracks comes in you know shrinkage cracks to arrest those shrinkage cracks or shear cracks or differential movement cracks or cracks due to any other reason. So, whenever such cracks come in to resist such cracking, we have to rely on the tensile strength of concrete in many cases. Now, there are examples: where these are certain structures are designed for tensile strength of concrete for example, dam under earthquake excitations, pavement slabs, airport runways. These are designed on the basis of tensile strength direct or flexural tensile strength as the case may be.

Therefore, we got to know the tensile strength and it can be seen that tensile strength can be related to compressive strength, because as we have understood from the failure mechanism of concrete in compression; after all even in uni axial compression concrete fails in tension. So, there can be some sort of empirical relationship a correlation might exist between the 2 and they in fact they, really do exist and we relate it that way.

(Refer Slide Time: 04:12)



So, that can be understood from the failure envelope of concrete, you know if you remember we talked about bi axial testing of concrete. So, when we look into the bi axial. For example: if this axis shows the tension in a given x direction and this is tension in the y direction, in other direction bi axial situation we are looking at. This is the compression and this is also compression right.

So, this is the neutral point where there is no stress this side is a tension this side is a compression. So, if I call this plus I call this minus. This is the compression tension in the y axis and compression in the y axis goes along this direction. This gives us the failure enevelope; that means, at this point when there is only 1 compression it is a combination of load, because I am it is a bi axial loading situations and failure envelopes shows under bi axial condition how concrete fails.

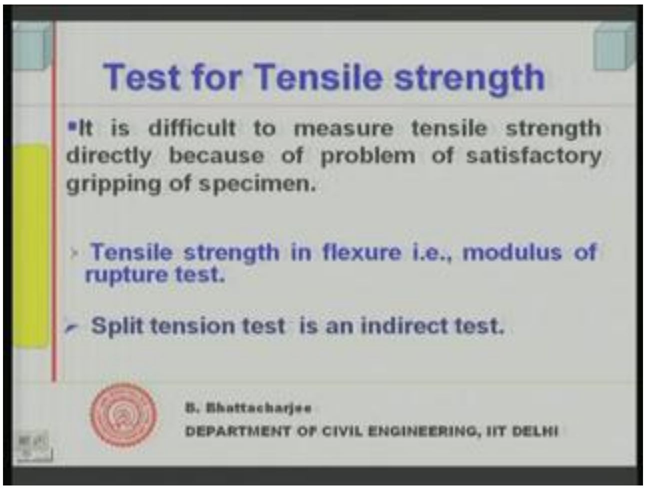
Now, this 1 would mean; this point would mean that I have compression along this x axis up to this point and then there is no tension or compression along the other direction. So, this point presents uni axial compression and you can see this value is 8k where, k is this value. Now, what does this value represents this value represents uni axial tensile strength along y direction and this is same as the uni axial tensile strength along this direction, because here the stress is along x direction 0 whereas, in y direction it is k.

So, this envelope represents a failure envelope when you have combination of tensile and compressive load on both directions; it is a bi axial situation both the direction; that means, you might have compression along this direction. In the other direction you might have tension or compression. So, that is the bi axial you know bi axial situation. For example this is your sample if you have compression. So, and may be tension along this direction or you might have compression along this direction or you might have tension. So combinations of this situation.

So, this point represents no tension compression along this direction; however, you have a pure tension along this direction along this direction. So, uni axial tension and this value is k this value is also k and this rectangular. In fact, under combination when you have bi axial tension that is also is you know this is k and k both together fails here. So, if this is k uni axial compression is eight k. Similarly, along this direction when there is no stress on the other direction, when there is no stress in x direction only y direction I have pure compression this is eight k.

So, compressive strength is 8 time of 8 times of tensile strength and therefore, there seems to be a relationship. You know it is 8 times 8 times the compressive strength as shown by this failure envelope study experimental study. So, there is some relationship between the compressive strength and tensile strength. This will be further we will look into such relationship.

(Refer Slide Time: 07:17)



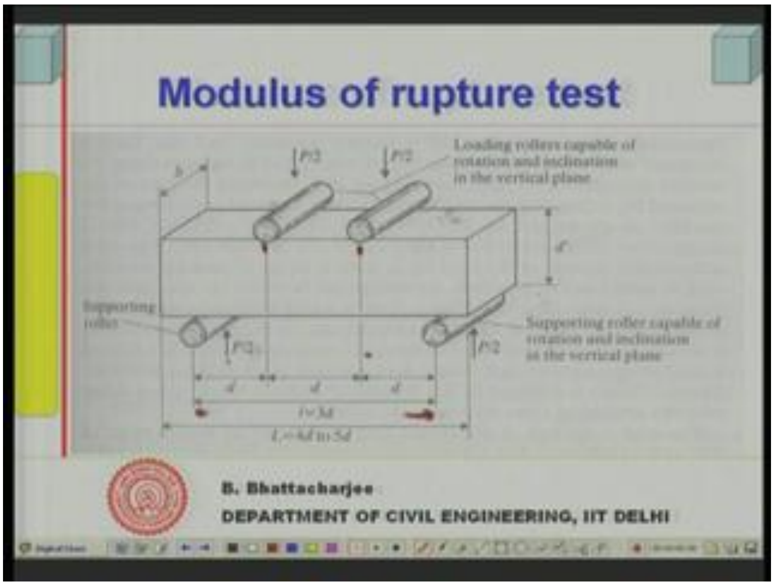
Now, how do we test for tensile strength how do we test for tensile strength? It is difficult to measure tensile strength directly, because the specimens you know initially they were tried like this initially, 1 would you know people have tried breaker test what is called breaker test. You have you have samples you have samples and like this, samples like this like mortar concrete breaker test you know and this is the sample this is the sample would look like this and you will grip this here and grip this here and try to pull. Now, what would happen in such situation.

This gripping was really proper and the failure would always take place along this direction along the grip itself. You know because of satisfactory gripping was difficult and therefore, direct tensile strength was difficult to measure. You know it is quite difficult. So, this test is not now relied upon by any code or any within, rather indirect methods are used for measurement of tensile strength of concrete. For example we after all most of the cases, we rely you know tensile strength of concrete is required possibly under flexure under bending under bending you know if you may recall under the bending situations, when a beam is loaded you know in some form it bends and the bottom is under tension.

So, when I reinforce concrete bomb beam or any beam is bending the bottom is under tension and therefore, flexural tension is an important property that we would like to know. So, one of the ways is to test a beam and this test is known as modulus of rupture test.

We will look into that test in more details in a short while. A second way to test is through what is known as split tension test and it is also an indirect. So, there are no direct test there are 2 types of test, one you call as modulus of rupture test which is nothing but strength in flexure and second one is split tension test.

(Refer Slide Time: 09:29)



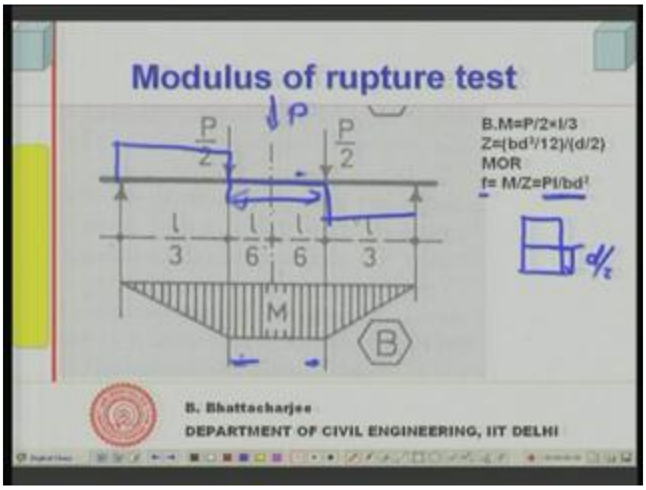
Let us see the first 1 first the modulus of rupture test. This is what the it, would look like you know this is what the modulus of specimen would look like.

For example you will have 2 point loading commonly used is 2 point loading. This is 1 point this is another point and this points are if this length is 3d. This distance is d as you can see this is d. So, you have 2 roller supports here such that, it is simply supported and you have the load coming from the top of it a single point through the single point you know you might be loading it like this using a single point P whereby, it will get divided to P by 2 and P by 2 again by roller you are ensuring that it is actually point load.

So, this is point load point load and point support and point support. So, purely simply supported system, with 2 point loading this is depth is d this is b okay. Usually 10 by 10 you know by 50 centimeter is used in IS code 10 by 10 by 50 with this being 40 here of course, it could be 4d or 5d. So, this is about 13 in case of Indian standard situation of IS I mean 16. So, 13 into 13.3 and overall is 50 meter 50 centimeter is a overall span. So, this is a simply supported these are supporting rollers supporting rollers.

This allows for rotation. So, makes it purely simply supported there is no restraint here no horizontal reactions will be available only vertical reactions, P by 2 will be available. So, you can see that P load you know P by 2 P by 2 uniform load is applied here and P by 2 P by 2 reactions would be obtained here and if you look at its bending movement diagram this will look something like this, because we are interested in finding out how much will be load carrying capacity right.

(Refer Slide Time: 11:29)



So, this is the bending movement diagram as you know, because P by 2 here P by 2 here the reactions would be P by 2 P by 2 and the bending movement diagram, would look like this because P by 2 it will be 0 here simply supported system. It will be 0 here because it is a simply supported system you know it will it will be it will be it will be 0 here, because it is a simply supported system and as you can see the bending movement maximum would be P 2 by P 2 into l by 3 because this is P 2 P by 2 and this distance is l by 3. So, maximum bending movement is P by 2 into l by 3 and same thing from here if you calculate out. So, maximum bending movement will be P by P l by 6 and how do you find out the bending stress, you find it out as f equals to M over Z and P l over b d square you know this is what will come.

Because, we know the Z for this section would be Z for this section would be b d cube by 12 for rectangular section, we are using of course, b and d in general terms, but usually they are same. So, 10 centimeter, 10 centimeter you know both are taken as same. In any case it is b d cube by 12 as you know for a rectangular section the high inertia moment of inertia is b d cube by 12 divided by d by 2, because we are interested in the maximum extreme fibre test. So, this is d by 2. So, b d cube by 12 divided by 2 would result in b d square by 6 and P l by 6.

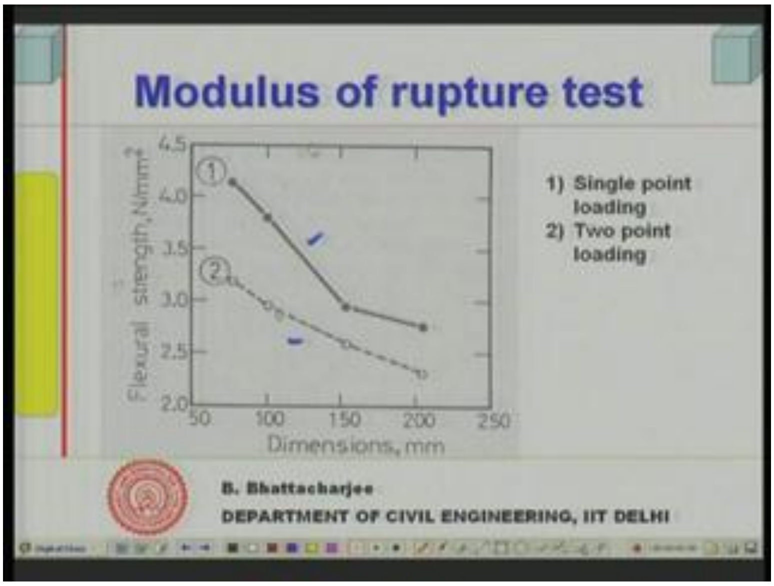
So, finally, the extreme fiber stress would be given as P l by b d square. So, if you know the P and the failure P max, if you know the P where P is the overall load applied at this point P is the overall load applied at this point. So, if you know P then the modulus of rupture will be the flexure tensile strength will be given by P l by b d square this we also call as modulus of rupture. Now, you see 2 things 1 must notice from here. First of all shear force in this zone would be 0 shear force is 0 no shear force, in this.

So, if you draw a shear force diagram you know a shear force diagram you will be possibly draw it something like this shear force diagram. So, there is no shear force her no shear force, in this zone it is pure bending pure flexure also this is spanning over a distance of d the bending maximum bending movement is spanning over a spanning over a you know distance of d. Now, we could have also used single point loading. So, if you use single point loading; obviously, shear force would not have been 0 in any part of the section not only that the maximum bending movement, would have been there only in 1 place in 1 point 1 single point.

Now, failure could take place in that point or may not take place in this point that would depend upon whether, there is an there is a weak point at just below the load or not. If the weak point is somewhere else, it will fails there. So, which means the probability it will depend upon probability of finding the weak point at the maximum load you know just below that load point-point where load has been applied. Now, this tends to give you much higher strength as we shall see.

So, that is not the best way to it that is why most of the code adopt this there is since, you can eliminate out shear from here, shear force from here you know shear force from here and also this is pure this is bending here and you have a span. So, 2 point loading is preferred over 1 point loading.

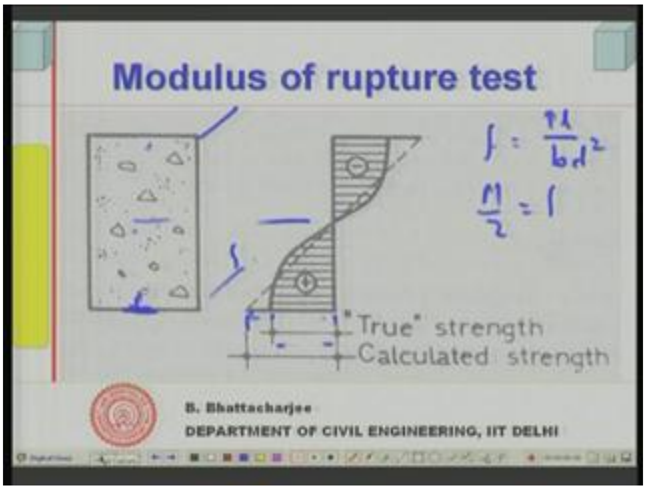
(Refer Slide Time: 15:25)



And you can see that in fact, people have tried to do the test with 2 point loading and 1 point loading and 1 point loading tends to give you always higher load 1 point loading always tends to give you higher load right.

So, single point loading gives you always higher apparent tensile strength, flexural strength whereas, 2 point loading gives you apparently low tensile strength okay. So, this is 1 kind of test that, we do and this test we call as modulus of rupture test. Now, this test you know if you remember that, we assume a specific kind of stress distribution in the calculation when, we have used the linear elastic bending theory actually.

(Refer Slide Time: 16:13)



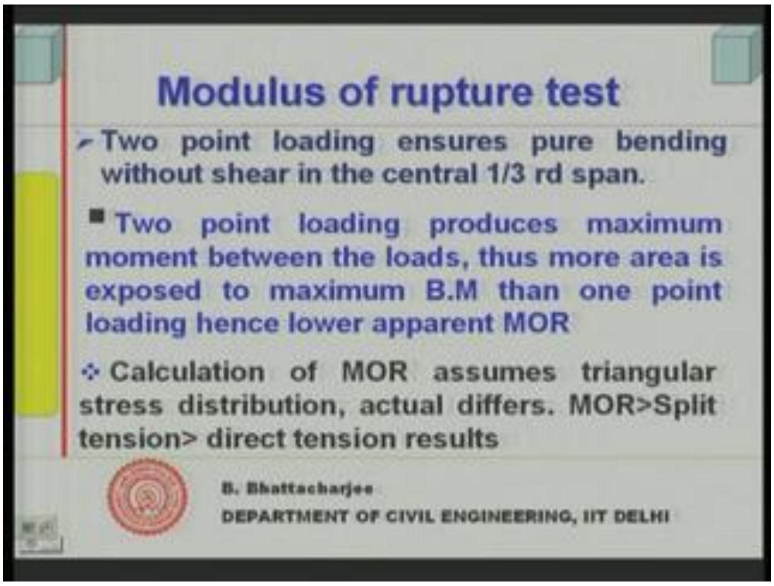
We have assume as stress distribution rectangular stress distribution simple triangular stress distribution you know triangular stress distribution. We have assumed a triangular stress distribution and calculate calculating out f equals to P l by b d square you know that, we have calculated out because we have used M by Z equals to f etcetera. If you remember that uses a triangular stress distribution, because we are assuming the linear behavior of the material, but in actual concrete the behavior is something this is your concrete beam at the failure the stress diagram is something like this, in the compression and tension zone, it is something like this and this value is actually lower than what we have calculated what we have calculated.

So, we can see that we have estimated the tensile strength as this, but actually it is this much smaller. So, we are over estimating even the flexural tensile strength, because we are using the modulus of rupture; which is calculated on the basis of triangular stress distribution triangular stress distribution in compression as well as in tension and therefore, we are going to estimate. This is 1 problem; a second problem not a problem really because we understand this. So, it is not a problem, but this is the actual you know this is the deviation from the reality.

A second aspect is that in such tests this extreme fiber is subjected to maximum stress where as all other points. This point the neutral axis let us say all other points here is subject to lesser stress than this. So, now this is the only point which is subjected to maximum stress. Now, supposing I have you know this there is some strong points here it is not the weak plane is not here. So, this fiber the crack does not propagate the crack of course, the crack would propagate I mean; we can see the other direction the crack would propagate like this.

So, the crack does not propagate or it gets stuck somewhere, by an aggregate or something of that kind then it will again tend to give you higher load. The volume of the concrete, which is subjected to the tensile stress is relatively less because this is subjected to maximum rest all are subjected to lesser and lesser stress whereas, this side is purely in compression. So, this is another reason why modulus of rupture would tend to actually over estimate. So, over estimate the strength. So, you can see that this is true strength is somewhere here and calculated strength is bigger.

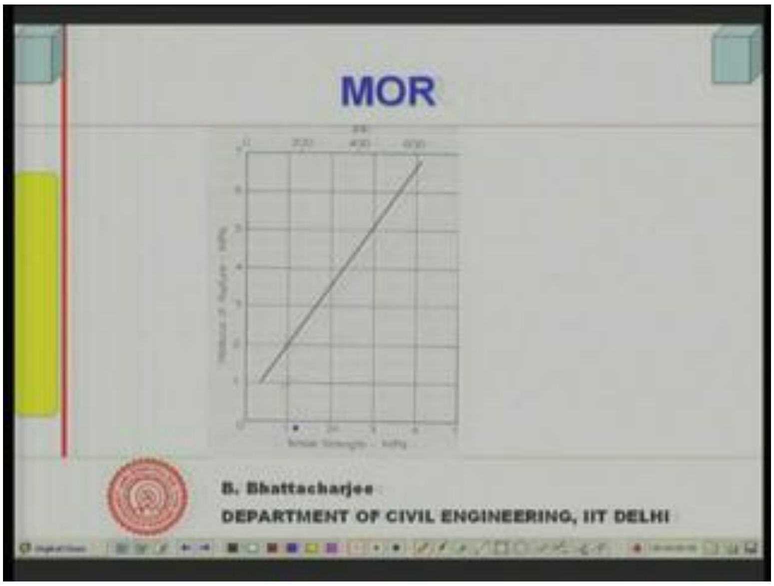
(Refer Slide Time: 18:48)



So, 2 point loading therefore, summarizing this discussion just now, I have talked about 2 point loading ensures pure bending without shear in the central 1 third span 2 point loading produces maximum moment, between the loads, thus more area is exposed to maximum bending moment than 1 point loading hence lower apparent modulus of rupture. So, when we compare between 2 point loading and 1 point loading we find 2 point loading gives us lower apparent modulus of rupture.

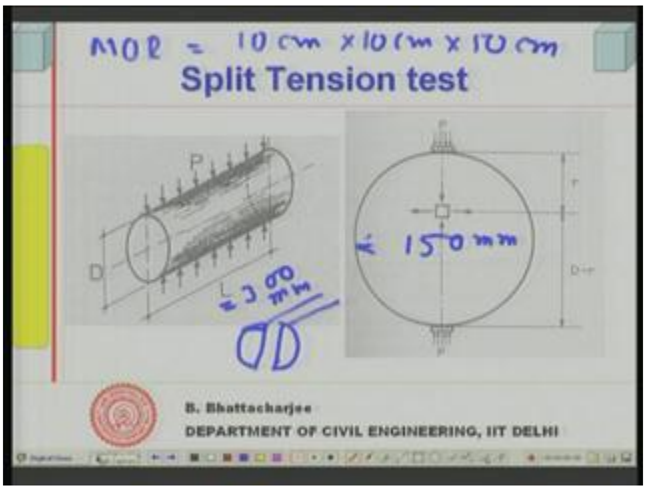
But, calculation of modulus of rupture triangular stress distribution, actual stress differs some other point; we will discuss again little bit more later on. Hence forth it has been observed that modulus of rupture is greater than the next test, I will talk about that is called split tension test or direct tension results, if they are they are available, but as I told you it is difficult to obtain direct tensile strength result. So, in any case MOR gives you higher value than split tension test well.

(Refer Slide Time: 19:56)



Tensile strength split tension related to modulus of rupture and this is what it shows. If you can see or notice this you see this is tensile strength is 1 modulus of rupture is 2. It is 2 and this is if they recall you would have got a 45 degree line, but what actually getting is vertical line. So, therefore, vertical line is you know slope of this much slope which means; that actually modulus of rupture always predicts the tensile strength.

(Refer Slide Time: 20:37)

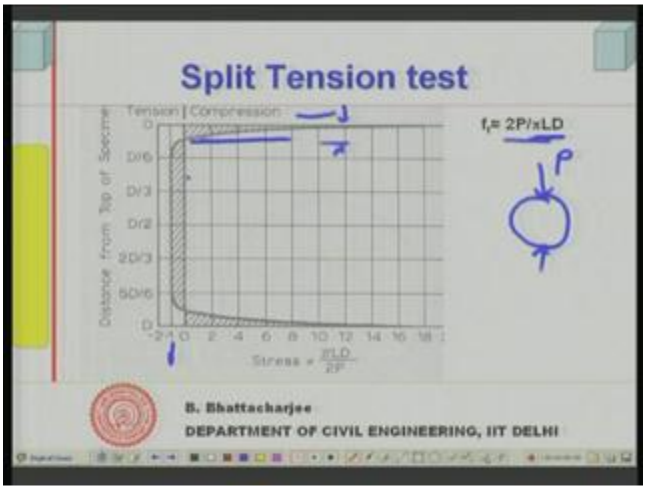


Let us see the other test which is most popular and commonly used, it is called split tension test and it would look like this. You have a cylindrical specimen or can be cube also as we shall see later. So, in this cylinder cylindrical specimen you apply load along this direction to a simple plate sort of thing and like, in case of in case of MOR test we use specimen size is 10 centimeter by 10 centimeter by 50 centimeter with 40 centimeter being the central portion you know which, where we apply the between the supports 40 centimeter.

In this case, we use this dimension is usually 15 or 150 millimeter 150 millimeter that is 15 centimeter and this length is usually 300 mm. So, 1 is to cylinder that we have been talked about that, we have been talking about that is what we use and apply load a kind of a point load this is the cross section loading cross section and you apply load here. So, 1 can look into the stress where small element there from theory of elasticity, we will come to that.

So, when you apply load like this what happens is the this along this vertical diameter tensile stresses act as shown here tensile stresses very little portion, it is not tensile stresses acts here and it splits along this direction splits. Simply this will become 2 pieces something like this 1 portion and it splits into other portion. So, you will have cylinder gets splitted when you apply load like this when you apply load like this and that is why you call it split cylinder test. This also used for rocks is also called sometime Brazilian test or Brazilian split cylinder test and is been very popular for concrete now, for determination of tensile strength right.

(Refer Slide Time: 22:39)



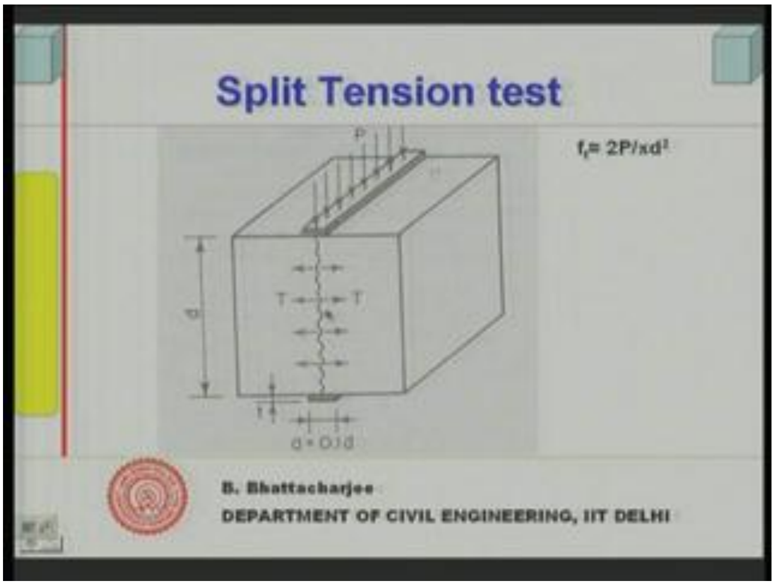
Now, let us look into the split test. This is the typical stress distribution across the across the across the diameter you know this axis shows 0 to D. So, this is the diameter of the specimen, this is the diameter of the specimen 0 to D and if you look at it this side beyond this point this point beyond this point compression we are calling it positive and tension is negative.

So, only over a small height you have compression acting, but majority of the section which is about you know you can see D by 12 or even less than D by 12 is where compression is acting on both sides, but majority of the portion, it is actually tensile stresses is acting and it is actually by an large uniform tensile stress.

So, from theory of elasticity 1 can calculate out this uniform stress and this stress uniform stress is given as 2 P over pi L D where, P is the load that is been applied on the specimen you know P is the load P is the load that has been applied on to the specimen right over a thin plate or used in a thin plate basically usually a plastic sheet or something through which the load is applied a thin plate or thin sheet through which it is applied. So, tensile stress is given as tensile stress therefore, will be given as 2 P maximum load that you can apply divided by pi L D.

So, this stress this is you can see that this is 1 pi L D minus 1 stress is you know stress multiplied by pi L D by 2 P that equals to 1 which means stress is equal to 2 P by pi L D. So, it is nearly constant at 2 P over pi L D, and you calculate out the tensile strength from this value you can calculate out the tensile strength from this value. So, this is what is called split tension test.

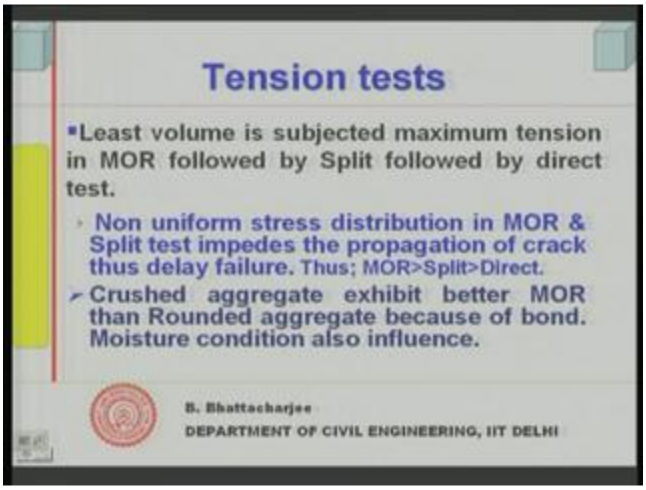
(Refer Slide Time: 24:37)



It can be done on cubes also it can be done on cubes also IS 500 and IS 500 and 16 allows it to do it on cubes or any other code allows you to do it on cubes. And this is how it is applied on a cube as well and the formula here is of course, slightly different it is twice P by pi d square, because we are calling this as d this dimension as d.

So, it is 2 p over pi d square 2 p over pi d square again this is validated from theory of elasticity that you will have a tensile stress. Physically you can understand where you are applying compressive load, it will have a tendency to go away and just, because your point load just below the load there is a high you know relatively higher tension. And since concrete fails in tension this tension causes splitting of the either the cylinder or the cube and you can find out the strength from this.

(Refer Slide Time: 25:29)



Now, again let us compare these 2 tests least volume is subjected to maximum tension in modulus of rupture test followed by split followed by direct test; how it is. In modulus of rupture test if you see the portion where tension is applied is the bottom portion and then if you assume a stress diagram you know you assume a stress diagram of this kind you assume a stress diagram of this kind. So, maximum something like this something like this maximum tensile stress is here all other portions tensile stresses are not maximum.

They are less and the volume is only not even the half you know half volume through which you are actually applying the stress tensile stress bottom half top half is in compression. So, volume of concrete which is subjected to tensile stress is in the in the central span or where you have actually, maximum bending movement. You have very little volume very little volume which is subjected to actually tensile stress and that only the bottom portion has got maximum rest all are less than that.

Now, you come to split you have split say in case of split cylinder test, you have some portion where tensile stresses are acting and this portion corresponds to about we said we have seen that this is D by about twelve on this side where it will not be acting and D by twelve on this side on which it will be compressive D by 12 on which it will be again compressive. So, you see the full section is again not subjected to direct tensile stress whereas, when you have a direct specimen direct tensile stress full section is subjected to direct tensile stress.

So, maximum tension you know volume is least volume is subjected to maximum tension in MOR followed by split followed by direct and this result, in this is the result why you have you know lower strength you know that is MOR gives you higher value than split than the direct. Also we said earlier that non uniform stress distribution in moment of I mean; in case of modulus of rupture test in non uniform stress distribution because bottom has maximum all other places it is less.

So, it is non uniform stress distribution. In case of modulus of rupture where the maximum tensile stress the bending tensile stress is at the bottom fiber other fibers above the bottom fibers, they are at lesser stress this is what happens, in case of bending you know physically we can understand this when something is bending the bottom fiber is elongated most followed by the possibly the next fiber above it and so on so forth and at the neutral axis the fiber is not at all elongated and if you go beyond, it above the fibers are actually compressed.

So, if you look at it there is a non uniform stress distribution in case of modulus of rupture test the flexure test bottom is actually, at maximum stress and the neutral axis is at no stress in between the stress varies. We are assuming it varies linearly although in actual failure condition it does not vary linearly, but in any case it is non uniform distribution. So, since it is non uniform distribution also in case of split only the central portion there is uniform distribution other portion there is less and this can impede the propagation of crack.

So, when cracks are forming the portions where stresses are less they may not allow the crack to propagate and they together with the issue that least volume is subjected to maximum tension all other points that we have mentioned. So, far and that is all confirms that modulus of rupture you know theoretically, modulus of rupture should be greater than split tension tensile strength tensile strength and then direct tensile strength you know direct tension strength.

Strength determines through direct test should be the least strength determined to split is somewhat greater than that and tensile strength determined to modulus of rupture is still greater than that right. Few more points crushed aggregate exhibit better modulus of rupture than rounded aggregate because of bond and moisture condition also has some influence. It is interesting crushed aggregate, because of the bond you know, in case of modulus of rupture the crack has to start from the bottom and then propagate upward.

As the P increases the load increases the bending stress increases the bending movement increases and the bending stresses increases. The crack has to propagate from the bottom towards the centre the neutral axis upward. Now, here if the bond aggregate provides better bond if the aggregate provides better bond you know and then the crack cannot propagate and it has been observed that the crushed aggregate shows better modulus of rupture value than the rounded aggregate. This may not be true for others.

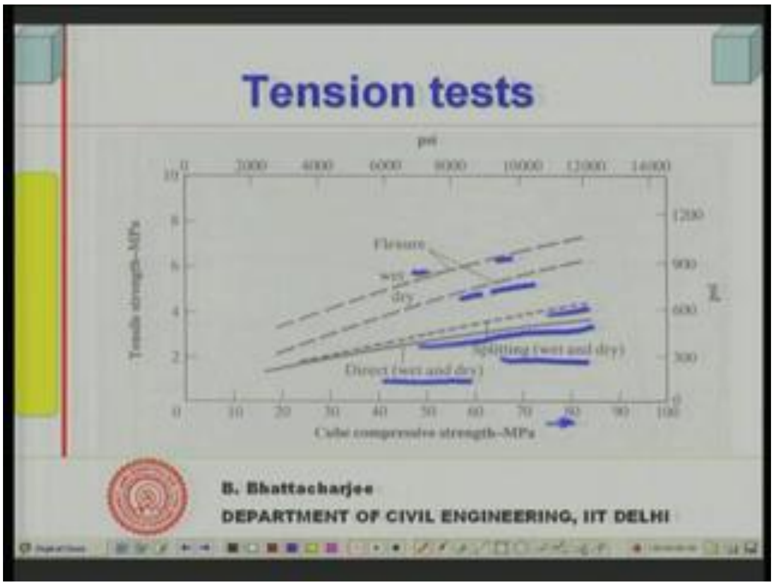
The moisture condition also has got some influence on modulus of rupture. Now, you remember when we talked about moisture influence of moisture on moisture on influence of moisture on compressive strength we said the compressive strength actually, reduces when moisture content is high. In a saturated specimen the strength would be lower than the dry specimen and it has been attributed to dilation of the cohesion force. Because moisture would get adsorbed in the gel structure, in the gel phases and this will dilate you know it will create distance between the gel or inter layer distance will increase resulting in lesser cohesion reduction in cohesion and this reduction in cohesion results in lowering of the strength.

So, moist specimen in case of compressive strength compressive strength of concrete moist specimen shows lower apparent strength whereas, dry 1 shows higher, but in case of tensile strength I mean; we are talking of the flexural tensile strength it shows higher I made some passing remark in the last lecture; when we are talking about the effect of moisture content on strength of concrete compressive strength of concrete, but we see here it is other way round. And if you remember we mentioned at that time as well that the tensile strength becomes you know, in case dry that tensile strength is lower the reason is it is actually causes some shrinkages cracks.

So, initially already, because of drying there will be some shrinkages cracks. So, when you start applying load this shrinkage cracks will help you know they the possibly initiation of crack will start from may even start from such shrinkage cracks. Well shrinkage cracks also shrinkage may affect the interfacial transition zone. So, shrinkage cracks due to drying have been attributed to improvement in strength by moisture you know by saturation.

In case of compression if you moist specimen shows lower strength here a moist specimen shows modulus of rupture and moist specimen shows higher strength that because a dry specimen will have some amount of shrinkage cracks and that may lower down the strength result in modulus of rupture.

(Refer Slide Time: 33:06)

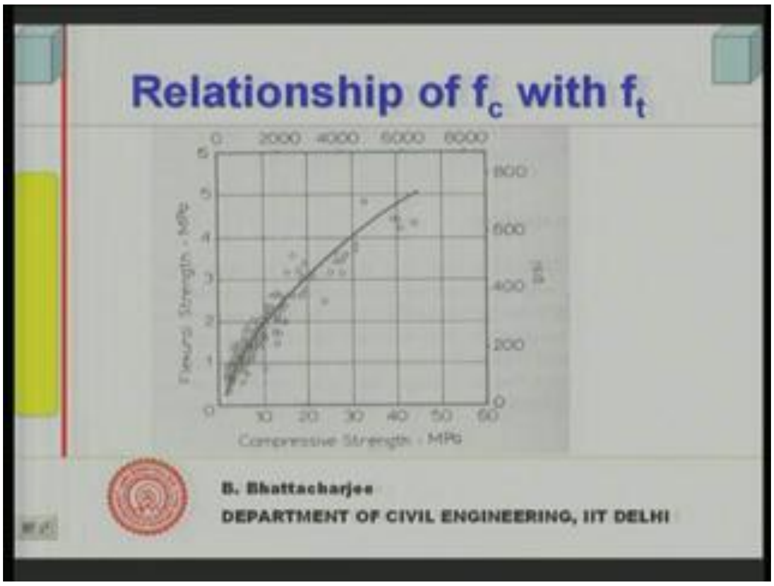


But this influence is not seen in case of other 2 that is direct tensile test and test for you know another is the split cylinder test. In split test we do not see this and this diagram shows us this behavior as we can see you see in case of splitting test splitting test both direct wet and dry is shown by this line. And which is showing least which is showing actually, least compared to all 3 splitting well wet and dry both are same.

But, you can see there is a difference and this difference of course, increases as we go towards the higher strength concrete you know in tnpa concrete shows much higher difference compared to let us say, 30 or 20 MPa while difference is less low if you go to flexure you know the modulus of rupture. This is the modulus of rupture test this is the dry specimen and this is the wet specimen you know this is the dry specimen this is the wet specimen and wet specimen shows higher strength and this is parallel these 2 are parallel and of course, these 2 are much higher than both of them.

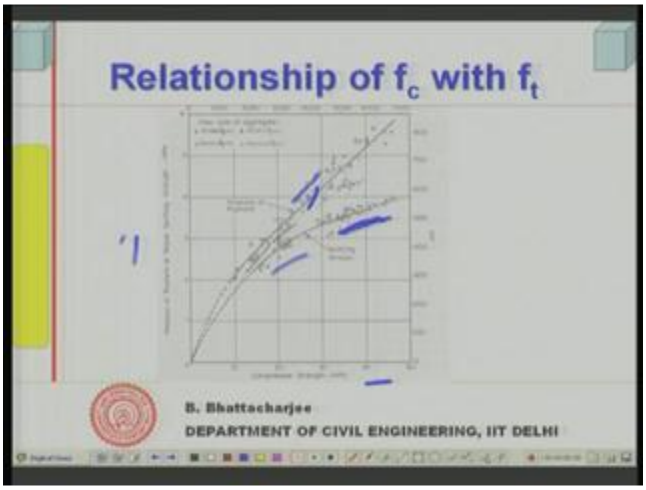
So, and this difference is also increases with either of this as the strength increases. So, these strengths are higher you know these strengths are higher and wet shows higher compared to dry and this difference is this is this is since this is more or less same irrespective to the strength and this difference had been attributed to shrinkage of concrete due to drying. So, when you dry shrinkage takes place resulting in some shrinkage cracks at various places including the interfacial transition zone and that is why the strength is lower.

(Refer Slide Time: 34:53)



So, that is what it is the influence of moisture and also aggregate do you know influence the strength of the aggregate do influence the strength of the aggregate also influence the strength of the you know concrete. Now, if you look at the relationship of f c with f t if you look relationship of a f c with f t that is compressive strength with tensile strength we said there should exist a relationship between f c and f t, because we have seen in the failure envelope of bi axial under bi axial stresses in case of concrete the compression you know compressive strength is eight times that of tensile strength. So, there must be some relationship existing between the 2. So, empirical relationship has been attempted and compressive strength versus flexural strength is something like this sort of relationship has been observed something like this sort of relationship has been observed

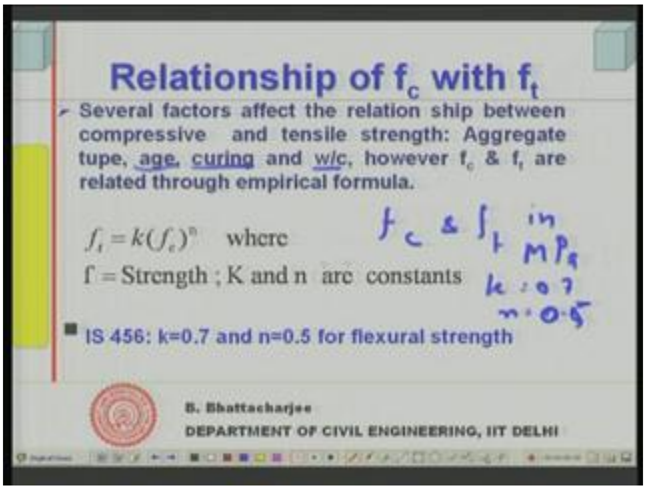
(Refer Slide Time: 35:54)



and if 1 looks into a more elaborate diagram 1 would see that in case of splitting tension test these are the results much more actually. so many,, so many test that are for various size of aggregate for various m s a right. And this is the modulus of rupture test and this is a split tension test for you know this diagram is for split tension test.

This is the modulus of rupture test for various kind of aggregate size etcetera m s a various m s a these values are given and modulus of rupture again shows lower value sorry, modulus of rupture again shows higher value split tension test shows lower value. So, relationships do exist between f c and f t, because this is compressive test f c and this is f t. So, there is relationship exist between both f c and f t in flexure as well as direct split as well as split tension test; however, for design purposes we cannot distinguish all that because we have to use 1 of them.

(Refer Slide Time: 37:12)



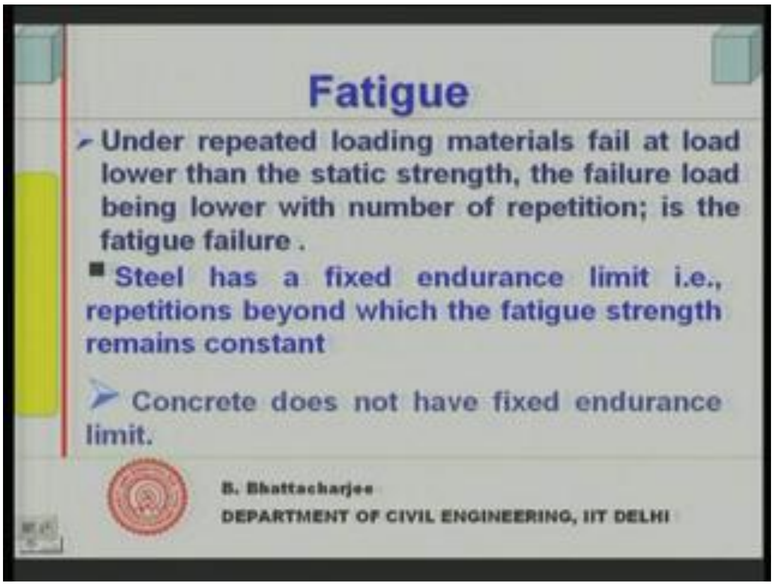
So, in case of in case of design we use specific value which has given in code. There are several sort of relationships are available. In fact, several factors affect this relationship these factors are something like aggregate type age curing condition water cement ratio.

So, various sort of even some sort of relatively more elaborate relationship has been suggested, but in the research level of course, in the code level a simple relationship or most of the codes adopt fairly simple relationship at the moment simply relates the compressive strength, with the tensile strength through formula something of this kind you know f t is proportional f t is related to k f c, by this compressive strength a power n and this is the this f stands for strength this tensile strength this is compressive strength.

So, tensile strength is related to some constant multiplied by compressive strength to the power some n and if you look at it the IS code values IS code, gives you this value equals to this case to point seven and n is taken as 0.5 when f c and f t both are in MPa when both are in MPa. In IS code of course, all this you know this when both of these are in Mpa f c and f t in MPa then k is 0.7 and n is equals to 0.5.

So, this is the value 0.5 this is the value suggested by the code for design purpose other codes also suggest similar values and similar sort of relationship although there can be more elaborate relationship based on water cement ratio curing condition age and aggregate type, because we have seen that aggregate type may affect this it does affect this relationship depending upon what relationship you are talking about right. So, this is the design relationship irrespective of how we measure about purposes for calculation purposes this is what is used. So, this is the idea regarding tensile strength of concrete.

(Refer Slide Time: 39:31)



Let us look into now what is called fatigue what is fatigue well, in case of concrete we will define it in 2 different ways later on, but in general first define when you have repeated loading material fails at load lower than the static strength. The failure load being lower with number of reputations you know for example, supposing, I have a load I repeat go you know I start from a load and increase the load and bring it down.

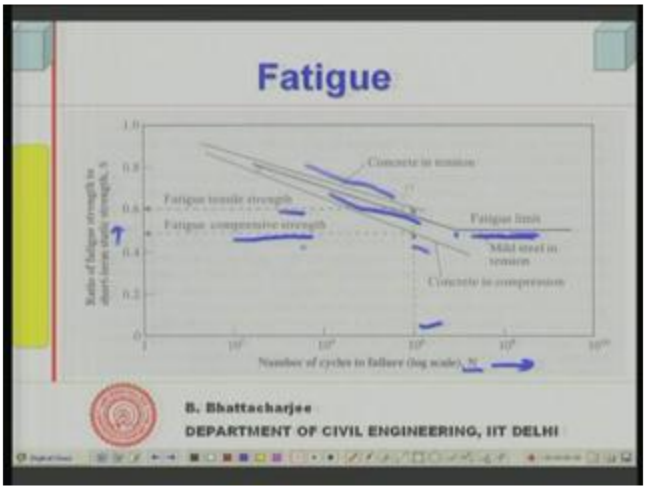
So, I go cyclically increase the apply the load somewhere I go up and go down. So, 0 to some load and something like this. So, I repeat this loads cyclically go up and go down in any manner you know I go up and go down. Now, it after certain repetitions the specimen or material will fail, but if I apply let us say: static load then in 1 cycle it fails static load 1 cycle it fail and that is what is static strength static strength that is what you call it static all static ultimate strength.

Now, if I apply repeated loading then after certain number of repeated loading the material will fail and at that time the load need not be the ultimate load it can be lower. So, this load required to fail the material depends upon the number of cycles, I have applied more the number of cycles it will fail it lesser and lesser load this is a relationship. This is a relationship called s and n relationship strength versus number of cycle’s relationship. So, more the number of cycles it will fail at much lesser load you know this value at lower of lesser of as well.

This sort of situation is referred to as fatigue failure, when you have repetitive loading it does not it need not when if you not go to the ultimate static failure load you are operating at let us say, somewhat lower load and you repeat go to that load come back 0 it or go even negative whatever, it is you repeat cyclically you go increase the load come back increase the load and come back you will find that the material fails even though you have never each other static ultimate failure load.

This is the phenomenon of fatigue, but in concrete of course, this is something else also happen we shall see first in few minutes time. So, that is called fatigue failure. Now, steel has a fixed endurance limit. An endurance limit is that many number of cycles beyond which, if you go on increasing the number of cycle the fatigue load would not or fatigue strength would not reduce that is called endurance limit repetition beyond which the fatigue strength remains constant. We shall see through a diagram the same thing, but concrete does not have a fixed endurance limit right it does not have a fixed endurance limit.

(Refer Slide Time: 42:34)



So, let us see this through a figure may this will make things or more clear something like this you know the year on this side is the number of cycles this is called an s n curve right. This n is the number of cycle usually, plotted in log scale and this is the strength, but we are talking in terms of ratio of fatigue strength to short term static strength.

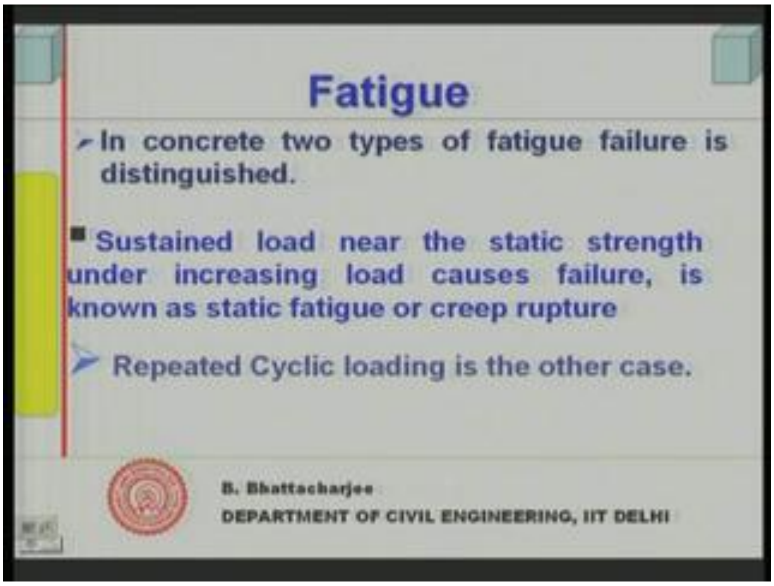
Static strength is when you have just applied the load once and it has failed that I called as static strength and this is 1 is you know this is like 1 cycle this will be 1, but when you have you know cycle increasing when you have lesser values. So, fatigue this is the ratio of fatigue strength to static strength and you can see in case of steel, in case of mild steel this decreases you know as I increase the number of repetition number of cycles, but a point comes beyond, which it does not decrease further this point is nothing, but the endurance limit and we have a fixed endurance limit clear cut defined well defined.

Endurance limit in case of mild steel, which is about which will give you fatigue strength of about 0.5 of the static strength. So, its 50 percent of the static strength right. So, if you are if you expect fatigue load in case of structure, we can you can actually deduce down your static strength by some value, in which you should be operating of course depending upon the situation.

Now, we look to concrete in tension it is something like this and there is no there is no sign of any where, actually there is a endurance limit and in compression also it reduces down and fatigue compressive strength will be somewhat this. So, what you do we define it with respect to 1 million cycles 10 to the power 6 cycles what we say fatigue compressive strength of concrete is defined with respect to 1 million cycle that is the strength which it can withstand after 1 million cycle you know.

If you have n is equals to 10 to the power 6 the corresponding strength s what you call as a fatigue compressive strength fatigue, tensile strength is similarly defined as the same 1 million cycle. So, when I have 1 million cycle the strength that can it can actually withstand that is what a fatigue tensile strength is alright. So, this is what we have in case of concrete when we apply cyclic or repetitive loading now in concrete.

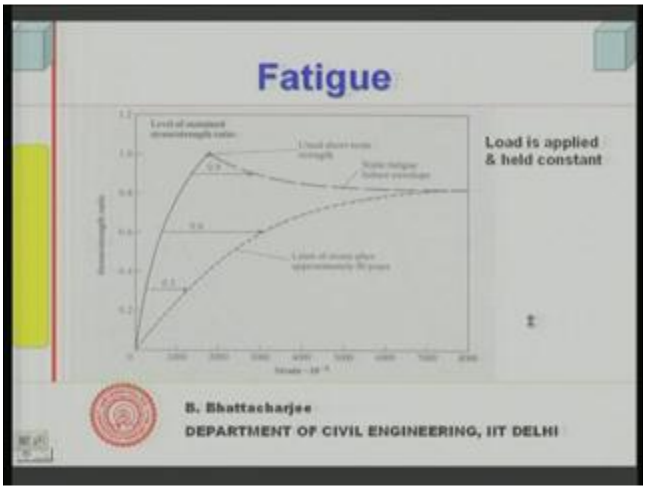
(Refer Slide Time: 45:03)



I said that there can be 2 types of fatigue behavior you know 1 is sustained load, it is not need be repetitive loading, but you have sustained load near the static strength under increasing load and this causes failure you know very slow rate of loading you have just load applied load near the near the near the static strength and its failure.

So, this is called static fatigue or creep rupture this is this is a special thing to concrete we call it creep rupture or static fatigue. Now, you see fatigue is nothing, but you are applying repetitive load. So, when you apply this repetitive load at a very slow rate very slow rate you know such that, frequency of application cycles per second is very small very small you know then such very slow rate of loading that situation shows you static that situation shows you what is called static fatigue or creep rupture. The other case I just mentioned was repeated cyclic loading or simple fatigue as you understand.

(Refer Slide Time: 46:12)



This is static fatigue this diagram shows you static fatigue. For example normal rate of loading as we have we know that 100 and 40 kg per centimeter square per minute that is what about 3 minutes, we go to failure and this is about ultimate short term strength, but if I go at a faster rate very faster rate I will get still higher strength, but if I slow down this rate, I have reached the ultimate short term strength you know in 2 minutes then my strength reduces.

I still reduce it down ion 3 days I fail the specimen and I reach here and if I do the same thing in 50 days I will reach there. So, increasing the test duration right that is decreasing the rate of loading results in this kind of a this kind of a failure, you know failure at the strain increases you know failure at the stress strain curve actually, this side is a strain and this side is a strength or you know rather strength to strength to strength stress to strength ratio. So, failure actually increases and your failure load therefore, also reduces.

So, you can see that this is you know in 50 days if I try to fail it, I fail it the failure strain is much higher now much higher and I have an envelope. This is called static fatigue static fatigue failure or creep rupture envelope.

So, this is the envelope if you increase it, still further more days it does not increase beyond that it will be the failure strain you know failure strain might increase, but the load does not increase. So, this is the envelope. So, as you go on increasing the duration test duration it fails at lower load somewhat lower load somewhere around 0.75 of the actually you know 0.75 of the of the normal short term static strength and if you increase the rate of loading then it fails at much higher load.

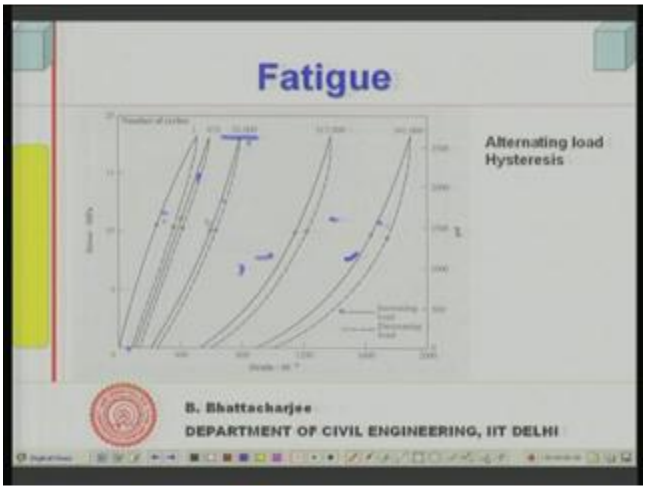
This is what we call at it in other words you know is you are applying the load once in 50 days, in this case you know once in 3 days once in 2 minutes once in 3 minutes etcetera. So, this is static fatigue behavior static fatigue behavior of concrete and there are similar curve of the similar kind, which you can see that when we have again supposing I subject the concrete specimen to 0.3 of the static strength and just keep it for long period of time what I will find out after thirty years the strain will be increased like this.

So, this is the limiting strength after 30 years beyond that there is no increase in strength similarly, if I load it to 0.6 of the static strength, I get something like this you know the strain after 30 years and so on so forth and it matches static fatigue failure and envelope matches strain. So, the strain that that strain that concrete specimen attains depends upon the load and this envelope seems to match again.

So, this also gives static fatigue static fatigue failure envelope you know with respect to usual short term strength. So, static fatigue failure is actually very slow rate of loading you find that very slow rate of loading. You apply load once in very long time and you find that it fails at much lower load. This is something due to creep phenomena which is which is occurring. In fact, creep is very closely related to fatigue in case of concrete. I mentioned to you creep sometime, in 1 of the previous lectures that creep is a time dependent deformation you keep the load deformation will increase.

So, that is what is the phenomena is creep and this is related to the static fatigue is related to creep phenomena and even in general creep of concrete even cyclic creep can be cyclic fatigue can be related to secondary creep phenomena of concrete. So, this is right this is static fatigue.

(Refer Slide Time: 50:22)



Now, let us see cyclic fatigue you see, if you apply load to the concrete specimen if you apply repetitive load to the concrete specimen, then what will happen you apply go to that place that is maximum not the maximum load, but some some loads some MPa may be some percentage of static strength ultimate strength and release the load it does not come back to its original position.

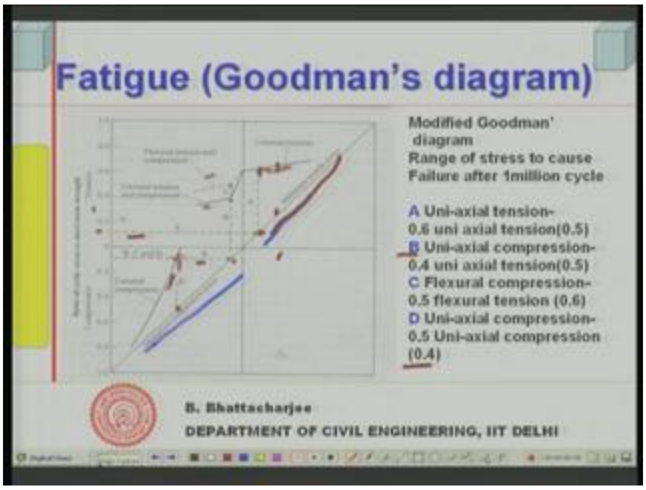
That is, because lot of cracking micro cracking takes place in concrete we shall see that later on again when we look into the stress strain diagram of concrete micro cracking occur and which will not close down. So, therefore, there is certain amount of energy lost in creating those new surfaces certain amount of strain energy has been absorbed there. So, it does not come back. Now, there is a hysteresis as we call it and then again; if I go on repeating after 675 cycle I will find that hysteresis is relatively hysteresis is you know is reduced hysteresis has reduced.

So, alternating load will have hysteresis 675 and will have hysteresis and if I go on increasing further, I find this area between the hysteresis loss the energy lost in the hysteresis is less, because this was larger area this is smaller area and this is still smaller area and you know smaller areas actually after twenty four thousand cycles you find the hysteresis is very minimum, but you go on increasing this number of cycles you know and strain also increases of course, permanent strain there will be some permanent strains here.

So, strain increases and here the strain starts increasing at a very faster rate and hysteresis also starts increasing before failure. So, this dark line shows increasing load this 1 shows the return load.

So, there is hysteresis losses and hysteresis losses reduces with number of cycles, but near the failure when large number of cycles have been applied the hysteresis loss will be still will become higher and strains will increase at a very faster rate strains will increase at a very faster rate. So, that is the behavior of fatigue behavior you know fatigue behavior of concrete.

(Refer Slide Time: 52:35)



Now, some 1 can what kind of load it can withstand is under fatigue is given by what is known modified Goodman's diagram modified Goodman's diagram you know. So, that is that shows the range of stress to cause failure after 1 million cycles that is what is called that is what fatigue is, because we are define fatigue strength of concrete with respect to 1 million cycle, because we do not have a specific clearance limit. So, we have defined it with respect to 1 million cycles the load or the you know load which under repetitive loading it can with stand.

So, 1 million cycle that is what we call as fatigue strength of concretes. So, this modified Goodman's diagram gives you various cases. For example this line it starts from it starts from this 45 degree line, which is the base line 45 degree line 45 degree line is the base line this is base line actually and this line represents this point beyond this point; it represents the minimum tensile stress this represents the maximum compressive stress right line and this line represent uni axial tension this line represent uni axial tension and compression and this line represent flexural tension and compression.

This is uni axial compression. Now, let us see how this diagram is read. For example you will have as your cyclic loading would be always based upon static loading.

So, you will have some initial stress over that the cyclic loading will be applied you know where this fatigue loading is important like bridges where, there is a static load. And over it, there are some amount of cyclic load comes or similar many other structures where, repetitive load can come off shore structures or many other structures you know where in off structures waves can come and hit repetitively, but you have repeatedly, but you have a static stress already repeated load or the cyclic load gets superimposed over it.

So, Goodman's diagram deals with such situation say case A you consider the A is this line you have some amount of static stress, which is tensile because this side is the tension and this side is the compression. So, already nearly about point 1 tensile stress is existing then from that if you apply further uni axial tension you can go up to this. This line represents the limits of uni axial tension. So, it touches here this is the minimum tensile stress line.

So, point 1 you know point 1 you just draw a line. So, this is the minimum stress line from here it can, if you are trying to find out how much is the tensile cyclic tensile load of a static strength it will have in terms of tension load this would be given by this. For example if this was 0.2 of the ultimate tensile load. If you have applied, then this much you could have gone under fatigue superimposed cyclic fatigue load would be this much the range this range is 0.5, in this particular case supposing you had 0.2 here and you could have gone here.

So, this would have been again 0.4 or may be slightly less than 0.4 or something of that kind. So, you could have gone up to 0.4 over 0.2 you can apply still cyclically 0.4 tensions 0.4 of the static strength and that is the fatigue load. So, this part of the through this you know this is the minimum tensile stress. So, minimum tensile stress here is point 1 and under uni axial tension we can go to this line this line is the maximum limit that gives you the maximum limit; that means, you can have when you have a initial stress of point 10 percent of the ultimate tensile strength.

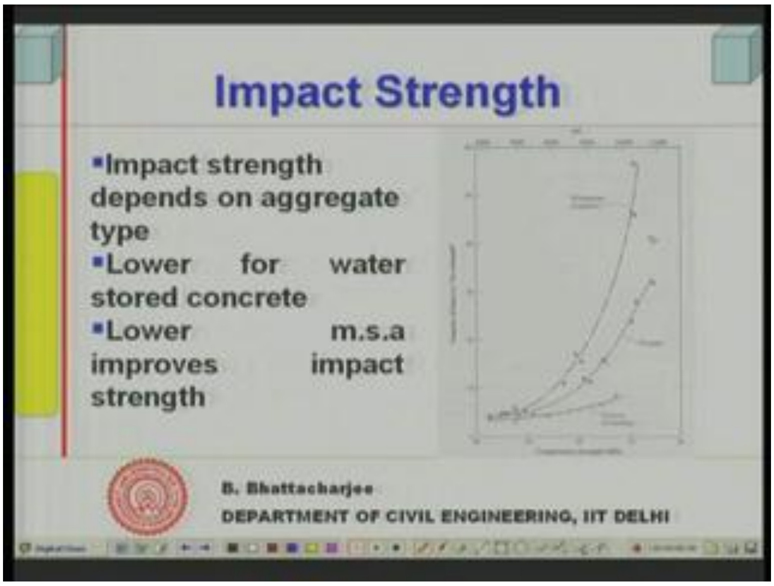
Then you can go to about 0.6 of the ultimate tensile strength repeatedly for 10 to the power 6 number of cycles, then it will fail only after 10 to the power number of 6 cycles it will fail. So, you can see that how I use this how 1 uses this diagram similarly, you go to B line B. Now, this is for maximum compressive stress that has been applied. Now, this is the maximum compressive stress that has been applied right from this; if I want to go to the uni axial tension and compression the compressive stress that has been applied.

Now, from this I want to go to uni axial tension; that means, I am reversing I am reversing the stresses right I am reversing the stresses. So, I can reverse the stress to about 0.5, I can reverse the compression you know reverse this stress to 0.4 or 0.5 whatever, is 0.4 also and this repetition can takes place for 10 to the power 6 cycles before failure.

Similarly, look at C flexural compression C starts from here C are this line right. So, flexural compression is flexural tension compression is this curve. So, C is here from here, I can go up to this and I can recycle this cycle this for 10 to the power 6. So, this is point 1 here from 1 flexural compression I can go to this value and I can recycle this for ten to the power 6 number of cycles before failure.

So, if I want to find out how much I can apply the stress this I can find out from Goodman's diagram look at D uni axial compression and uni axial compression. So, its starting point is here uni axial compression, in this curve uni axial compression and I can go to maximum compression this much; that means, I can cycle over this portion, I can start from point 1 this is nearly about point 1 and go to about point five or. So, 0.5 or therefore range is 0.4 you see the range is 0.4. So, I can cycle over this. So, using Goodman's diagram I can actually I can Goodman's diagram I can find out what is the fatigue strength of concrete. So, modified Goodman's diagram is used in this 1.

(Refer Slide Time: 58:25)

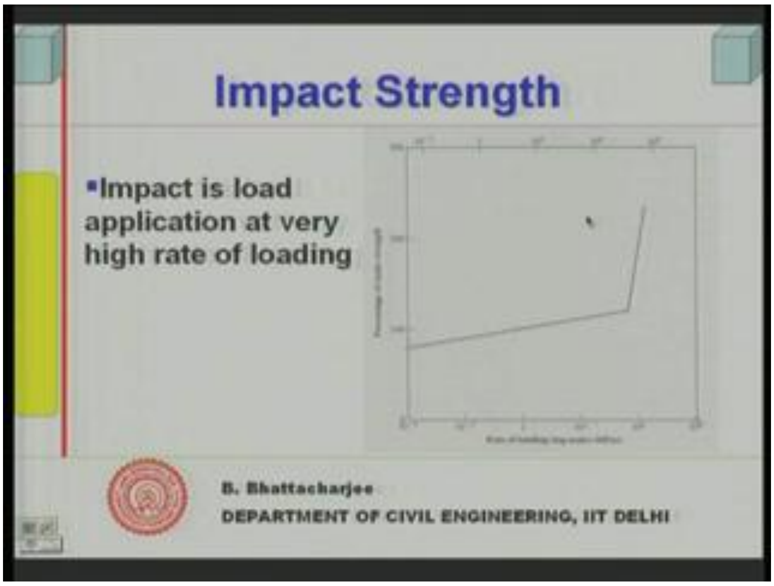


Next one is impact strength well. This is another issue important 1 impact strength of concrete, it has been observed that lower the water cement ratio you know impact strength depends upon aggregate type a strong aggregate would; obviously, show higher impact. For example some sort of you know angular aggregate this is granite this is gravel.

So, it depends upon aggregate type. A stronger aggregate can absorb a lot of energy and it can be impact strength can be related to compressive strength you know number of now, how is this measured number of its rebound is applied and number of rebound number of rebound beyond; which there will be no rebound that is called you know is a measure of the impact strength. And this increases as my you know, this increases with the compressive strength number of rebound required to come to number of required to come to come to you know no rebound situation.

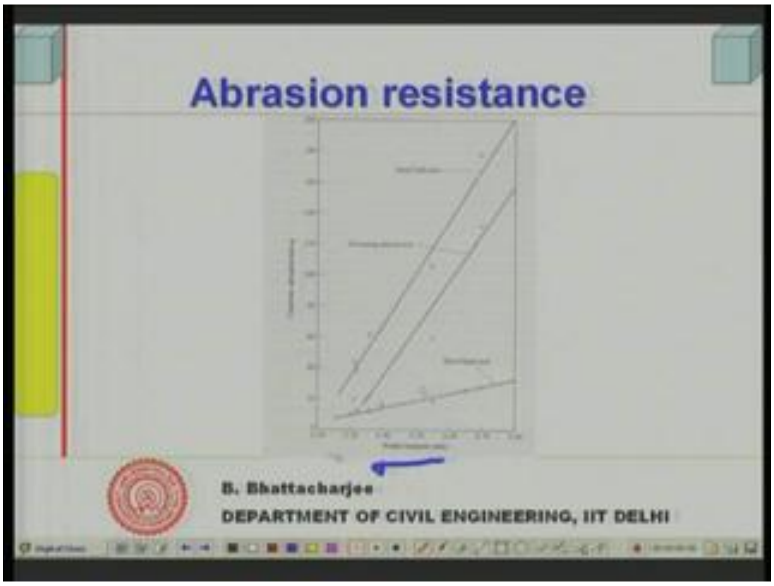
That is an impact strength lower MSA improves impact strength lower water stored lower water stored concrete. This value is lowered when you have water stored in water, but, if it is dry it is somewhat higher. Then next we can look into the last aspect of this impact is nothing,

(Refer Slide Time: 59:39)



But actually means of very fast rate of loading. So, when you have very fast rate of loading the impact strength is generally higher than, the compressive strength that 1 can understand. So, rate of loading when it is very high that corresponds to impact strength and actually strength can be 200 percent higher right; last is the abrasion resistance and this also can be related to the compressive strength of concrete.

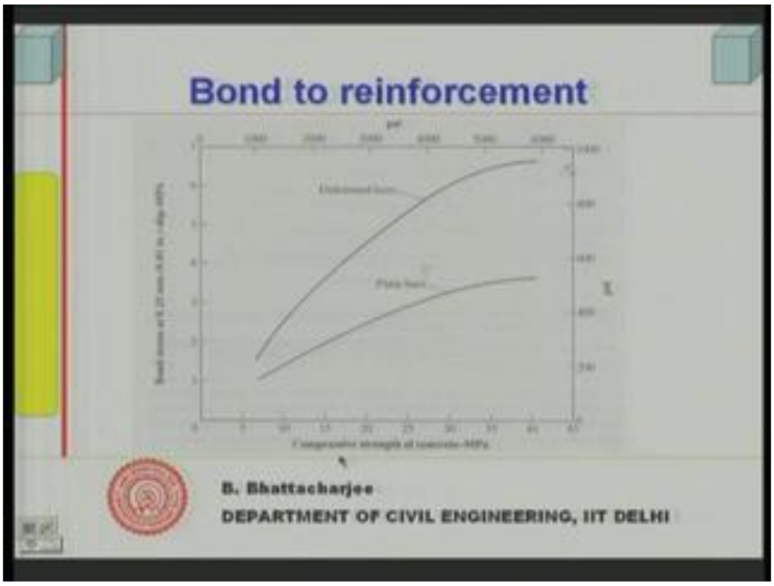
(Refer Slide Time: 01:00:00)



You see as the water cement ratio decreases as the water cement ratio decreases, as the water cement ratio decreases as the water cement ratio decreases the powder that is formed under grinding that is a measure of abrasion.

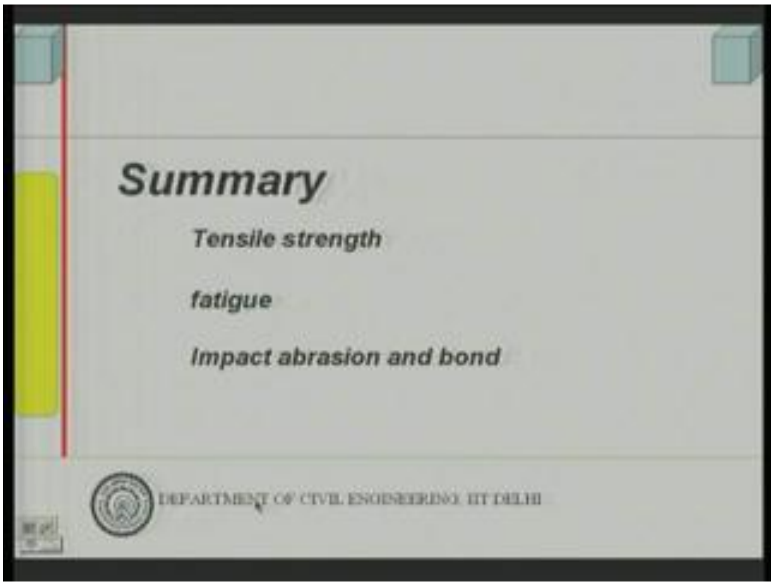
There are 3 different tests and all test you know like 1 test is you have disc, in which you grind and the powder that is formed under grinding; that is called that is the measure of impact resistance higher powder forms means; lower the impact resistance. So, as you increase the water cement ratio impact resistance reduces, impact resistance reduces right.

(Refer Slide Time: 01:00:38)



Last is the bond strength and bond strength of concrete again, can be related to compressive strength like this, bond strength of concrete can be related to compressive strength like this. You know, in this manner you can relate it to the compressive strength like higher the compressive strength, bond strength increases.

(Refer Slide Time: 01:01:00)



This for plane bars this for deformed bars. So, summarizing the whole, we have looked into the tensile strength, fatigue strength, impact resistance, and bond strength of concrete. This impact and resistance and bond strength there is not much you know the factors affecting are not understood. However, they can all be related to tensile strength of I mean, compression strength of concrete. So, almost all other strength properties of concrete can be related to compression compressive strength and that is what, I think with that we can summarize.