Building Materials and Construction
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Module - 6
Lecture - 1
Strength of Concrete:
Fundamental Concepts

We shall start with a new module today on strength of concrete. We will look into fundamental concepts today. Let us look into what is the general outline of our lecture.

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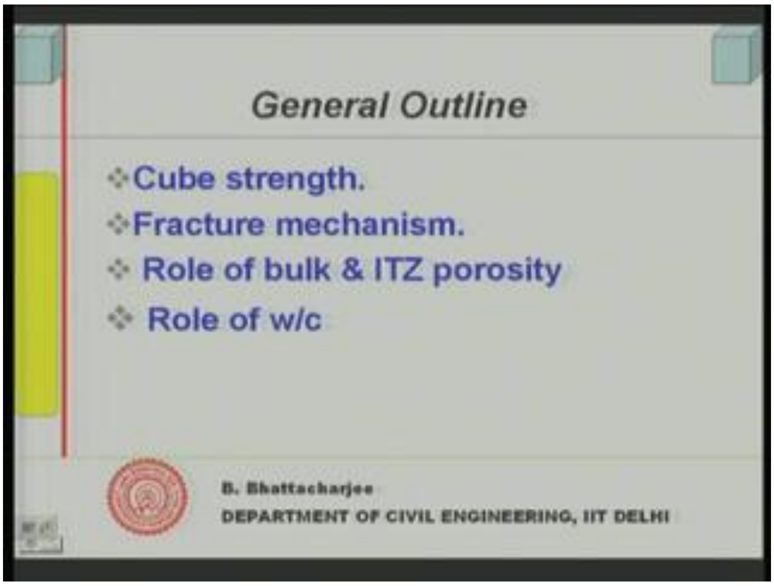

First of all, we shall be talking about cube strength; because that is the conventional way we measure the concrete strength. We will follow it by the fracture mechanisms in concrete. We will look into role of bulk and ITZ porosity, we will define them appropriately. And we shall look into, then role of water cement ratio.

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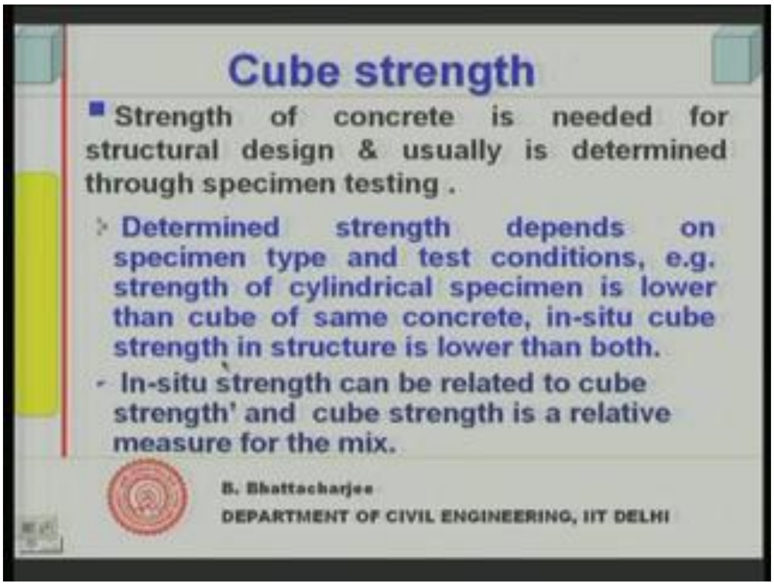

Now, let us see how we measure concrete strength first of all. Is he a structural engineer; he would need strength of concrete for structural design purposes. Usually 1 has to determine the strength through some specimen testing. For example, in steel well we are trying to determine the tensile strength, we test rod, particularly the enforcement bars used in concrete structures; we test rod themselves for finding out the tensile strength. But in case of concrete, so far we have understood that, it is a compressive strength which is important; being a brittle material is generally weak in tension and relatively strong in compression. And therefore, we look into its compressive strength. And that is what mostly we utilize in structural design.

So, how to determine the compressive strength? What should be the kind of samples 1 can use? That is what the first issue. So, we have to do some sort of specimen testing and through that we find out the strength of concrete. Now, you see the in United States they use cylinders 15 centimeter or 6 inch in diameter by 30 centimeter or 1 foot in height. Recently that has been used for finding a specimen, for measuring compressive strength whereas, British practice had been cubes 1 inch side length, that is, 115 centimeter 150 millimeter side length cube have been used traditionally in British practice. That is why actually you know North America they use cylinders, Japan they use cylinder, the Europe mostly they use cubes.

So, specific different types of specimens are actually used for determining the compressive strength. And this strength determined strength depends upon the specimen type. Not only that, it also depends upon the test condition. For example, things like the moisture condition of the specimen, the rate of loading that we applied to the specimen and size and shape of the specimen l by d ratio etcetera, there are several factors. We shall discuss this factors sometime later on and their effect on the strength measured, but at the moment, we shall understand that, strength of concrete determine from 1 type of specimen is different, then that would be determined through another kind of specimen.

For example, cube strength is higher than the cylinder strength, right or cylindrical specimen is lower, is lower than the cube strength of the same concrete. But most importantly, actual strength of let us say hypothetical cube or in-situ cube, supposing I assume there is a cube in this structure; that is totally different from this tube. Although: we should be in a position to correlate this strength; cube strength or cylinder strength to the structure strength.

So, we determine cube strength in India as per IS 456, we determine cube strength of concrete through cubes. In North America they determine through cylinder, but both can be used in designing same structure, because strength of the strength in the structure, strength of concrete in the structure hypothetical cube strength in the concrete structure, can be correlated to cube strength or cylinder strength.

So, we determine essentially strength of concrete through cubes in India 15 centimeter side cubes, side length equals to 15 centimeter. And this cube strength can be correlated to the strength of concrete in structure. Therefore the cube strength, what it measures; it gives me a relative measure of the strength giving capability of the concrete mix. Strength of concrete in structure is different, strength of concrete cubes as you test and do gradation of concrete like m 25, m 30. This cube strengths essentially a relative measure of the mix that is going, you know what is the potential, I am rather what would be the potential strength in the structure, that I can find out you know for a to a given mix. That I can find out by through from cube strength. Largely can be used for quality control and also for structural design purpose you know structural design purposes.

Now cube strength depends upon many factors. I mentioned the test factors; if you look at the cube, we actually produce them in a standard manner, cast them that is in a standard manner, compact it in a standard manner, cure it in a standard manner and then test it in a standard manner, only thing that remains variable is the concrete mix itself. So, and this manner the way in which way, we cast cure and produce this concrete is quite different from that the compaction in the structure or you know casting in the structure, curing condition in the structure and the load distribution in the structure is load duplication is also different.

So, that is cube is a relative measure; that must be very well understood, cube or cylinder they are relative measures. And this relative measures are useful; this information of the cube strength that you get is useful to understand what is the strength giving potential of the concrete mix in structures. So, that is what the cube strength is, but that is how we you know determine them.

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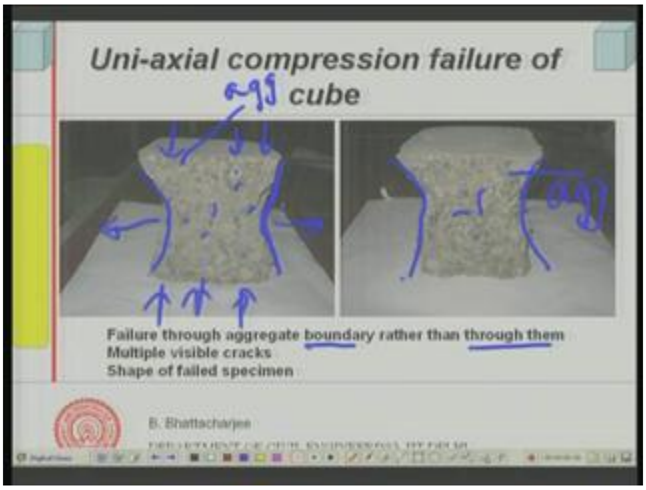

Let us see how the fail cube fails, if you look at the failure of a cube under compressive load, what we call as uni-axial compressive load, the way we test the cubes. The shape of the shape of the cube after failure would like this, but certain important features we would like to look into it.

It is the same cube seen from another side, but 3 important features which will be visible to us are number 1; the failure actually has taken place through aggregate boundaries, you see the aggregates are exposed. For example, this is the aggregate has gone out; the mortar in contact with the aggregate is now exposed. You will really see that, any aggregate has actually failed. In the other words, no cracks, no fracture passes through the aggregate most of the time it is the aggregates. So, this is 1 aggregate, this is aggregate. So, aggregates you can see them, they are exposed, and failure is mostly through the aggregate boundary, more it is through the aggregate boundary, rather than through the aggregate.

So, in either case; you can see for example, this is again an aggregate, this is again an aggregate and hardly you can see a failure through aggregate crack never passes through the aggregate. This is the case with normal strength concrete, although in high strength concrete, things could be different. What I mean is; in normal strength concrete, the strength of the concrete and strength of the aggregate is usually higher and therefore, failure really takes place through the aggregate, it takes place through the aggregate boundary. And this is important for our discussion later in this lecture.

Also you see multiple visible cracks; you know there are several cracks you can see. The failure has taken place through this plane, failure has taken place through this 1, but you will see multiple cracks there. There are large numbers of cracks you can see, cracks formation of particle crack formation would have taken place. So, there are multiple cracks would be available, although fracture has taken place through 1 particular planes. Several fractures crack and fracture planes could form. And this is important; the shape of the specimen after failure, you know typical shape of the specimen this, although today's lecture will not discuss much, but later on we will see.

And you can see that, material has gone in from here along this 2 direction, material has gone in along to this direction although: you applied a load like this. A composite load was applied, but material has moved off from this direction. So, this will be important for our discussion, later part of the discussion and discussion in the next day. So, few things we observe from this; failure takes place through aggregate boundary. This is very important in normal strength concrete and our discussion is mainly to normal strength concrete. And it is really through them, when we use strong aggregate sufficiently strong aggregate. And that is what we do in normal strength concrete. And then you will have multiple cracks and shape of course, is important as you noticed. So, this is the first thing we noticed from failure.

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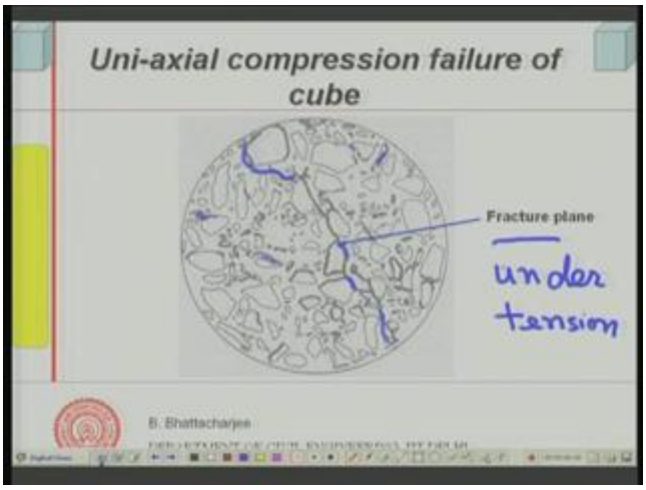

So, uni-axial failure of cube if I look it and if I extend this idea to the fracture mechanism of concrete, will see the fracture plane possibly passes like this. And I can conclude from my previous discussion that, you know fracture plane passes through mostly the aggregate boundaries, it will pass through the aggregate boundaries, and lot of cracks would have developed across the aggregate. So, it possibly they initiate, possibly we understand it in fact that, it initiates from the aggregate boundary somewhere. And then joints are through various pores those are available in the structure and when continuous fracture plane forms the failure takes place.

So, the fracture plane actually initiates at the aggregate boundary. And thus we have seen in the previous slide that, it is the aggregate boundary through which the fracture plane passes. So, aggregate mortar interface if I may call it, the fracture starts from there, it initiates from there and propagates through the mortar at certain level and usually it will interconnect all the pores their present, because you remember we discussed that the cement hydraulic cement winder will always have some amount of porosity, capillary porosity especially in normal strength concrete, where water cement ratio is relatively large, compared to let us say high strength concrete, where it is very less.

So, we have not discussing that any way. So, in normal strength concrete, water cement ratio is sufficiently large. So, the paste will have some pores capillary pores. So, fracture actually initiates from the aggregate paste or aggregate mortar boundaries and then propagates through the paste and when this join completely the fracture takes place.

Now, we had multiple cracks and you can see here also there are several cracks, you know it starts in many places which initiate, because there are many other aggregates, where the fracture might have started, but might get blocked also, because pores were not available the weak planes were not available and so on. So, that is how the fracture in concrete takes place under uni-axial compression, uni-axial tension actually, this should be, because under uni-axial compression also you will see, but it is continue with the same 1, it is the fracture plane under essentially under tension, because compression also we should see that, it would actually result in a form of tension. So, under tension this is what will happen. So, compression also generates tension that we shall see later on. So, that is what it is. So, fractures of concrete. Now, we can define various phases in concrete.

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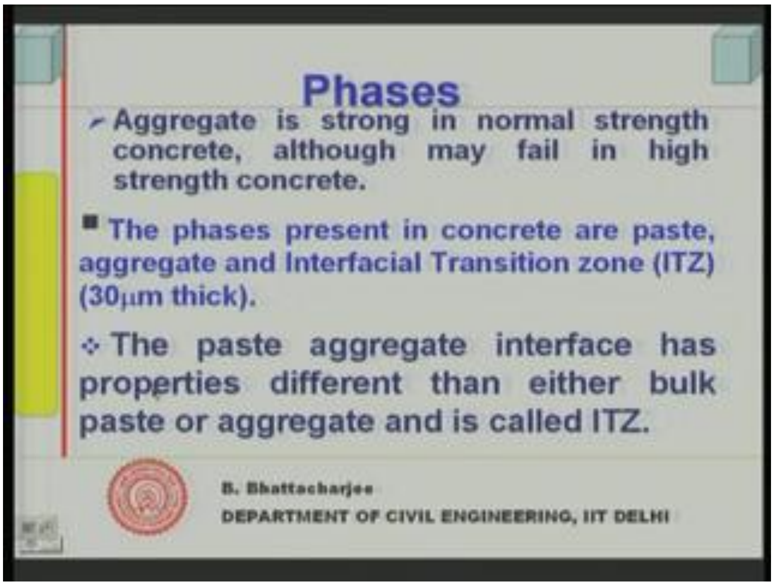

Aggregate is a strong phase. We have seen that, aggregates do not fail and therefore, aggregate is a strong normal; you know it is strong in normal strength concrete and high strength concrete can fail. Then we have got phases in concrete. Now what are these phases? The phases present in concrete, now I can say aggregate is 1 phase which is not failing really. The paste is; obviously, the other phase, you see this aggregate not failing also means that, its cracks does not pass through the sand, it only passes through the sand boundaries at best and sand coarse aggregate bond, which are there because mortar aggregate interface is where the failure takes place. So, the sands will also get separated from the coarse aggregates. So, it is all from the boundary.

So, aggregate is 1 phase, paste is a second phase and third phase 1 defines in concrete quite often it is actually defined as a third phase, it is the aggregate and mortar, you know interfacial transitions on it is the aggregate, you know aggregate paste and aggregate mortar, interfacial transitions on particularly on aggregate paste interfacial transition zone. And this is abbreviate is the ITZ, usually can be of the order of from 30 as shown. And this is quite often treated as a second phase or third phase, 1 is the aggregates, second is the paste, third is this phase; the paste matrix paste, I mean matrix and aggregate interface or paste aggregate interface, which we call as ITZ interfacial transition zone.

Why you call it transition zone, because properties differ from aggregate to the bulk paste. So, there is a change. Aggregate has got 1 some kind of property, which is different than the bulk paste and bulk paste has got a, so different property. So, in between there is an interface, where there is a transition from aggregate to paste takes place. And the property of the transition zone is quite different from either the bulk paste or the aggregate side. And that is why it is given as if it is a third phase in concrete. And that is very important from strength and also from other properties point of you. So, this is the third phase and this 3 phases governs the properties of concrete right. So, therefore, we will look into properties of the each of these phase separately to understand the strength behavior of concrete.

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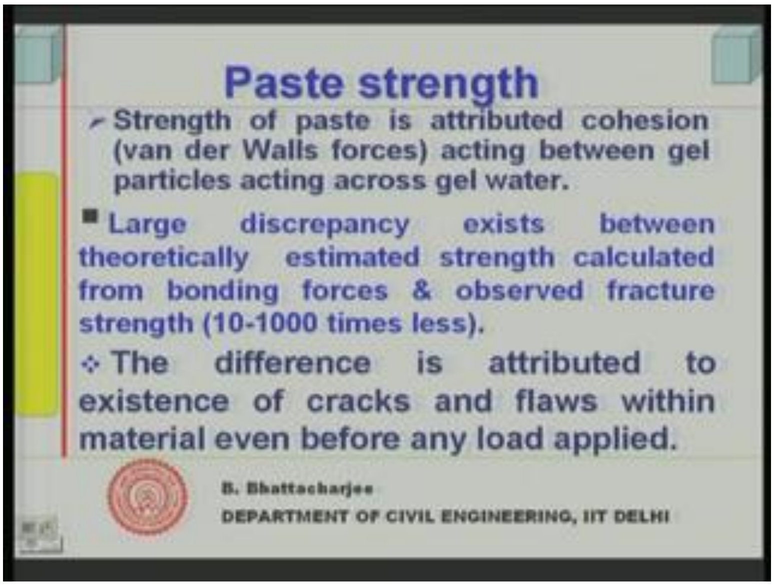

Now, what is paste strength let us look at. Strength of paste is attributed to van der Walls forces or van der Walls bonds or cohesion acting between the gel particles across gel water. There is some amount of chemical bond also between gel particles right; primary bond and this is the secondary bond. Perhaps both are effective, but this is this is quite often you know this is quite often considered as a strong force, in determining the strength of paste and strength of concrete.

Now we are trying to look at the strength of paste and then we will look into interface that is ITZ and then we can look into the overall concrete. So, paste strength is the bond is usually due to the van der Walls forces and also chemical bonds between the crystals can also be you know are also there. Now, when 1 tries to calculate out the strength of paste, from atomic concepts that is considered the number of bond per unit area and each bond strength of each bond being known, you can find out what would be the strength of the paste.

If it is the bond which is controlling the strength of the paste under tension, we are discussing mostly under tension which will translate to compression later on, since we are trying to understand the behavior of concrete varying compression, at the moment we are trying to understand the behavior in tension. It is weak in tension all these brittle material.

So, let us see supposing I want to separate the paste, then the bond would be opposing this separation and bond per unit area if it is known to me, if the bond per unit area is known to me, then I should be able to calculate out; what will be the force required to separate, because force required to separate you know separate or break a given bond that is known, the bond strength is known. Actually what happens; the crystals when you are trying to pulling them apart pull them apart, their distance between them increases and forces of attraction between them also increases. This balances the external force that you are you are applying, till a point when the suddenly there is a decrease in the force of attraction and actually the fracture takes place, you know in molecular level or in a fine level at very fine bond level.

So, therefore, bond strength 1 can determine. And if I know number of bonds per unit area, total strength I can determine from atomic theories. If I do that, if I try to do that for cement paste, what I will observe that, there is a large discrepancy between the theoretically estimated strength calculated from bonding forces and observed fracture strength, you know it can be 10 to 1000 times less. This has been observed 10 to 1000 times less.

Therefore from bond forces you cannot calculate out the strength of the concrete, I mean strength of the paste tensile strength of the paste. So, something else is happening. And this reduction in strength is attributed to actually existence of cracks and flaws within the material, even before any load has been applied. This is you know Griffith in 1925 looked into this problems of brittle material. And the theory that was developed is that, since the actual material the paste or similar other brittle material shows much lowest strength, then that is predicted theoretically. This is this must be happening, because there are some defects or flaws in the material, right from the beginning, you know they are inherit in the system even before you have applied any load. So, that is what the idea. And based on this idea, further concepts have been developed.

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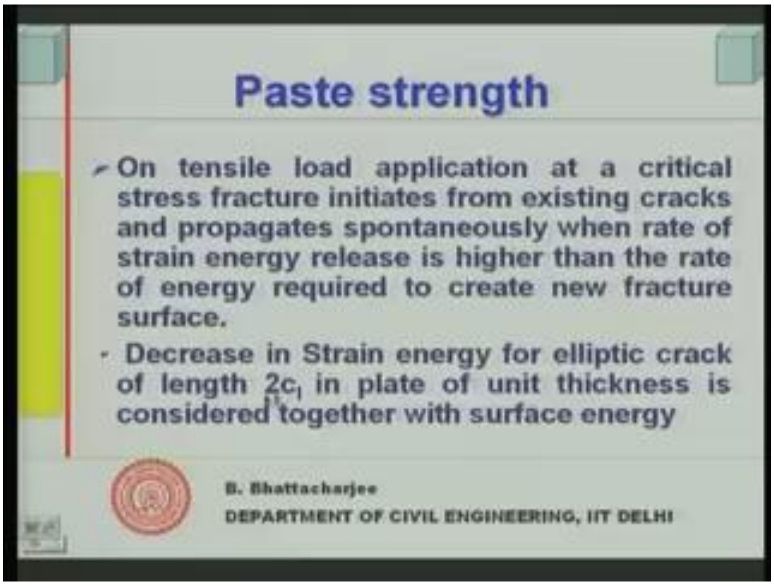

So, if you look at the paste strength, tensile strength of paste again we are continuing, say if you look into that, when you apply tensile load, this load application actually is taking can take place around defects which are present. This defect could be pores which are existing already in the cement paste, if you are looking at only paste, because we said the paste is full of capillary pores and also gel pores, but gel pores are generally small capillary pores are larger. So, consider paste bleed paste there are already pores existing in the paste.

So, this the fracture in paste, will propagate spontaneously at some critical stress level. What is that critical stress level? The critical stress level is such that, the rate of strain energy rate of strain energy, because when you apply stress you are giving some energy to the material in the form of strain energy and you know it is half stress into strain in case of elastic material within the elastic limit etcetera. So, strain energy can be calculated for the material.

So, the rate of strain energy that I am giving to the material, if that rate is more than the rate at which it you know energy is required to create new surfaces. When you are when fractures are actually progressing in the material, that is, paste you are creating new surfaces, every surface is associated with surface energy some energy. So, to create new surface you need energy. When the rate of this energy required is less than or equals to the energy given to strain energy, the crack would propagate spontaneously.

That is the theory that postulated by Griffith. And based on this 1 can get some idea, you see when tensile load is applied, a critical stress fracture you know at some critical stress or fracture initiates from existing cracks. So, cracks will propagate, because already there are some holes the cracks or you can say pores, which are there and the you know cracks will propagate from there from this 1s, it will propagate from there spontaneously, when rate of strain increase or release in is higher than the rate of energy required to create new fracture surfaces.

So, you want to create some surfaces, you need some energy. If this rate of energy that you require to create this new surface is less than the energy being supplied through stress or strain energy, then the crack fracture will propagate spontaneously. That is the whole idea. Now, based on this, you know based on this idea Griffith actually developed a expression for critical stress and we will look into that how that was done. So, he assumed an elliptic crack elliptic crack of length twice C l, as we are expressing here in a plate of unit thickness. And then consider to this 1 together with the surface energy. Let us see next slide will show us that better.

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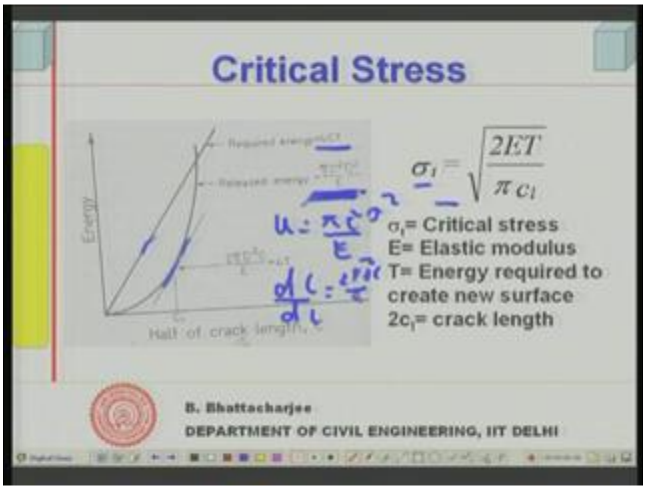

So, the stress you know critical stress calculation is like this; what he has done is strain energy released for an elliptic crack, he found out from theory of elasticity, the solutions were already available.

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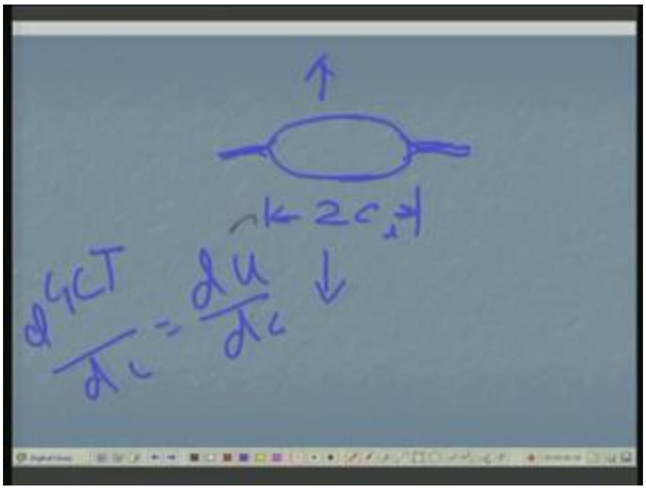

So, if you have an elliptic crack, let us say if you have an elliptic crack right, which has got crack length of 2 C l for a for a plate of unit thickness, when you are applying tensile load, when you are applying load tensile load right, the crack will propagate spontaneously. So, the reduction the due to a hole, the energy that is you know the strain energy reduction in a unit thickness plate of unit thickness, due to this hole or energy associated with such elliptic hole.

Was actually known from theory of elasticity and this is this value pi C square sigma square divided by E right, where sigma is the stress that is applied, E is the modulus of elasticity. Now, to create a surface, new surface of you know to create a new surface, what you need is you are creating new surfaces. So, to create new surface, the energy of the surface energy is T if the surface energy per unit area is T for 2 C length and unit thickness, you need since there are 2 such you know this side and this side all combined 4 C T energy and the strain energy was known to is already given. So, 4 C T is the surface energy required and this is the strain energy.

Now, rate of strain energy supplied must be equals to the rate of energy required to create new surface. So, simply what you have to do is; you have to actually differentiate this with respect to C and equate to d u d c, where u is given by this express, where u is equals to pi C square sigma square E. So, if you obtain this d u, equate this and then obtain an expression for you know, if you equate this you get an expression, you can get an expression for critical stress.

From this you know sigma express sigma in terms of all others, you will find that rate. So, you can see this is the curve showing the release, the strain energy released this is the strain energy curve, this is the required energy and rate is constant here because it will be 4 C T, if you differentiate you will get simply 4 T and if you differentiate this, this of course, the slope of this one from this slope is equals to this, because that is the rate d u d c d u d c will be 2 sigma square C, because you know 2 sigma because if you differentiate this is, d u d c would be given as two pi sigma square C divided by E, from this it follows and when you equate them you get sigma T an expression like this.

So, 2 E T under root pi C l is the critical stress, so this is the critical stress at which the fracture will progress spontaneously, you know this is the critical stress, I mean stress level at which fracture will progress spontaneously right. What we see from this? What we see 1 thing we see; this is an important thing half the original crack length. In other words, the dimension of the pore or size of the pore or crack initial crack which is available this is very important and larger the pore, the critical stress would be lower. So, that is all behavior in tension for such material. So, this is the behavior in tension for such material tension for such material.

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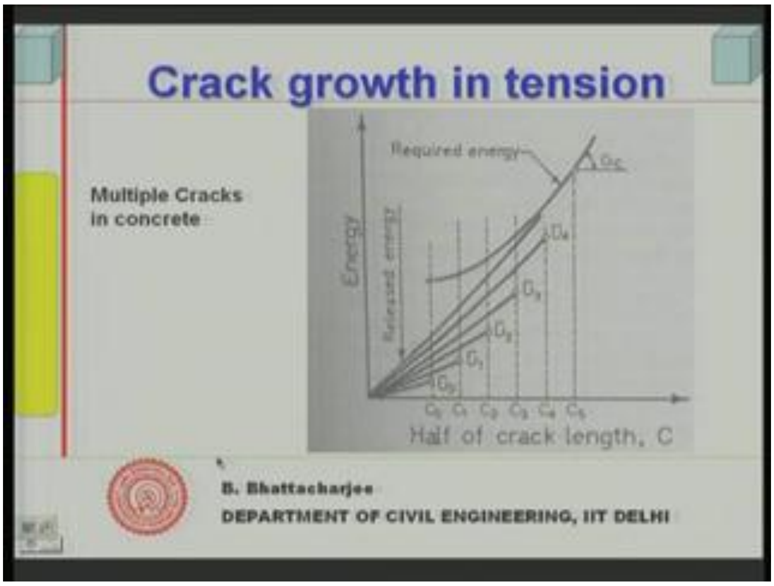

And if we continue with this, we can follow it up. Actually in concrete what happens there are multiple cracks, in concrete there are multiple cracks, not 1 there are several of them. So, you know this the required energy in this case, because there are large number of cracks and you are creating many surfaces. So, this does not remain linear any more like; previously single elliptic crack, there are multiple such cracks and therefore, the energy required will be non-linear like this as shown here. And each crack some crack will start and stop here, some crack possibly starts here and may be see 1 another crack stops here and you know 1 stops here and another 1 stops here and so on.

So, there are several such cracks and particular crack, where you know its slope is equal, then that time it will follow. In case of concrete, there is slightly or space there is slightly more complex situation, because there are large numbers of such initial flaws existing and each one of them might actually get extended at a given critical load and then again stops, some of them will stop. The 1 which results in fracture would continue.

But 1 idea we get from here is that, the sizes of the initial flaw or crack is important, possibly total number of flaws or pores or volume of the pores or porosity is also important, because if you have large number of pores, the chances of initiating from the you know crack initiation would be much higher. So, there are so many of them and they can interconnect and so on.

So, what we see from this is; what we see from all this discussion now is that, it is the pores and size of the pores in paste which are very important for strength. You know they cause the failure, the failure initiates from there. So, this is important.

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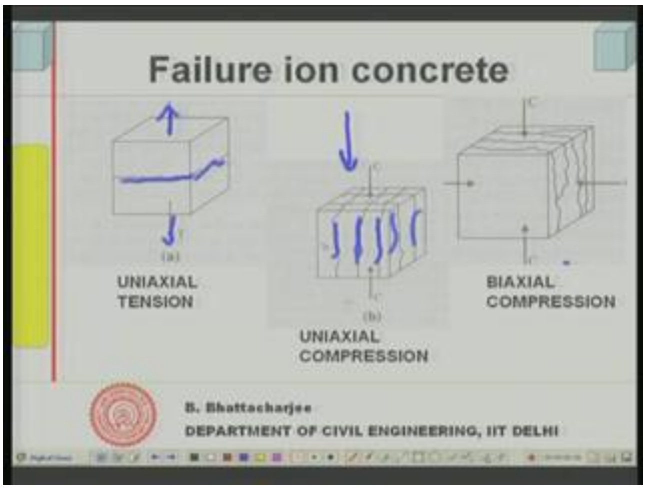

Now if you look at now extend this idea to concrete, we will come to it transition a little bit later, because we have to understand the behavior and compression. So, if we look at the failure in concrete, then behavior and compression would be quite alright. So, far we have looked into behavior under tension of paste, we will look into behavior and compression of the paste or then extend this to concrete also.

Now, to look into the behavior of concrete under compression, let us look into failure of concrete under tension as well as in compression. We have seen that diagram, but just recapture the same thing, recall the same thing and also look into little bit more. Supposing I have concrete cubes, I want I fail it under uni-axial tension, then the failure crack would appear like this; crack would simply appear like this, I have applied tension along this direction tensile force, this will look like this.

And if I apply a pure uni-axial compression, there is no horizontal force, there is no force from this side, a pure compression, then actual cracks develops like this, cracks develops like this along this direction. And if I apply compression from all directions then of course, cracks would form in this manner. But at the moment I will keep this away, but still this is important to understand, because bi axial or tri axial compression would cause give different kind of failure than uni-axial compression. That is uni-axial compression; I am applying compression only in 1 particular direction.

Now, cracks would form along the direction of the load application. I am applying load along this direction, cracks are also parallel to them in all sides. This happens in case of paste as well. And if you go to the next slide we will see that.

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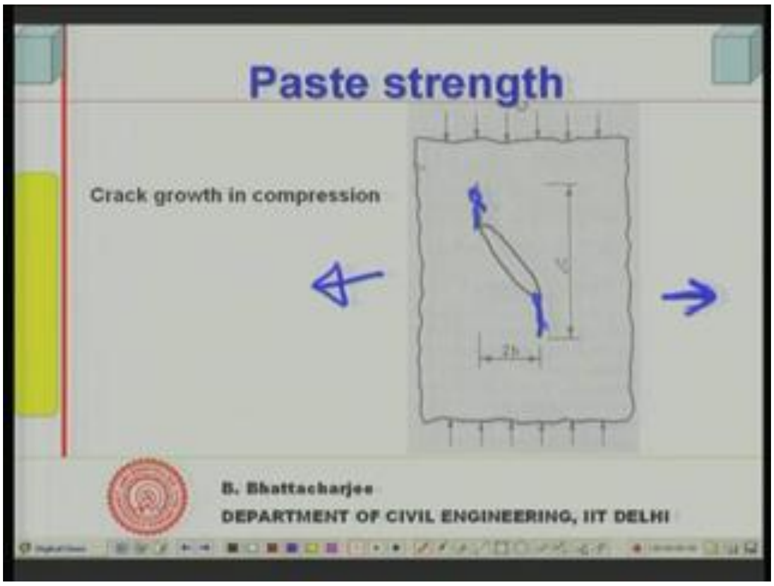

When I am trying to look at the compression, since this material is weak in tension, so compression causes actually failure due to tension along the transverse direction, failure due to tension along this direction, you know under compression due to Poisseeuille's effects, the paste or the material paste material we are right now we are trying to only discuss about paste. The paste material would have a tendency to expand in the lateral direction. So; that means, there will be tension acting along the lateral direction and this results in growth of crack original crack; which was 2 C here and to be possibly, with here growth of crack along this direction.

So, failure of such brittle material like cement, paste and even concrete particularly paste at the moment, is under compression is also due to tension along the transverse direction. We can logically understand this; you know such material you try to compress from all sides. That is why I am showing bi axial. You try to compress from all sides, let us say tri axial what will happen; only the pores will get pores will get filled up. Once it collapses; pores will get filled up, but after that you cannot do much about it. In fact, you have container in which through which u are applying the forces, all this might system might fail, because the particles u cannot break, under compression you cannot crush those particles by simple mechanical means.

You can only makes their pores equals to 0 compact and compact them to a very large extent, if you apply very tri axial stress. That means, from top, from side and from all the sides from all 3 sides, when you are applying compressive forces, you cannot really crush those individual material to atom size or anything of that kind, only pores you can reduce. But what happens if you are applying uni-axial compression. When you are applying compression uni-axial when you are applying, the material can expand along the transverse direction.

So, when the materials can expand along the transverse direction, actually tensile forces are applied you know acting along this direction. So, compression actually results in, it initiates a kind of tensile stresses along the transverse direction and therefore, you see cracks parallel to the direction of the loading, perhaps parallel to the direction of the loading. And that is what is being shown here cracks; parallel to the direction of the loading. And again here, the initial flaw in the material influences the crack growth of course, it will not be based on such simple equation, but it will be more complex, but we can understand that, this will depend upon dimension and the volumes of such pores or flaws available in the material.

So, from this what we understand that, failure of cement paste under uni-axial compression is also a function of the volume of pores; higher the pores possibly is failure at lower load and also a function of the pore sizes larger; the pore sizes it will fail at lower load. So, this is the fundamental thing that we have understood that, it is the porosity and a pore size which governs the strength of cement paste.

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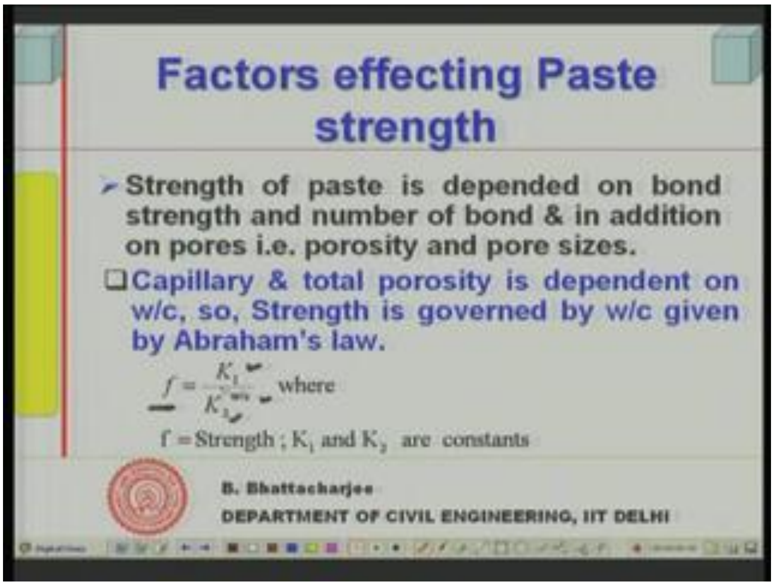

You see strength of it depends upon bond alright and number of bond, but in addition it depends upon the pores porosity and pore sizes. You know it depends upon bond alright, but more importantly possibly on porosity and pore sizes. That is what we are trying to say; the reduction from theoretical strength by 10 to 1000 times that we have discussed earlier is possibly due to the porosity and pore sizes. So, more the porosity lower will be the strength; higher the larger the pore sizes lower will be the strength. This is important aspect.

Now, we know we have seen when we were discussing hydration of cement paste. We mentioned that, there are porosity, capillary porosity and then total porosity. We got an expression for capillary porosity and total porosity. And from those expression if you remember, we have we have seen that, this is a function of water cement ratio; higher is the water cement ratio higher will be capillary porosity and overall porosity as well.

So, therefore, higher is the water cement ratio, higher is capillary porosity and total porosity. Secondly, the pore sizes are also function of the water cement ratio. High water cement ratio would lead to larger sizes of pores, because the portion of those water filled pores which will be filled by the hydration product, you know in due course is will be larger, you know it will remain actually larger portion of the unfilled pores will be there.

So, therefore, this is likely to lead to large sizes of the pore. So, higher water cement ratio leads to large size pores, also it leads to large amount of porosity. So, that is why strength is governed by water cement ratio and that is what has been given by Abraham's law. You know he found that, strength is a function of water cement ratio; pretty early in 1920s he found that, strength through empirical experiment he found strength of cement paste or even concrete is a function of water cement. In fact, it is inversely related to the water cement ratio. And that is how his expression looks like this. Strength you know strength of paste is; this is a constant, this is another constant and this is water cement ratio. In other words, inversely related to the water cement ratio and why it is inversely related to the water cement ratio, because water cement ratio results in large size crack pores and also results in large volume of pores.

So, from fundamental principle that, you can explain why strength of concrete is inversely related to water cement ratio. This is important; strength of the paste is related to water cement ratio. So, strength of concrete we shall see later on. So, at the moment we have looked into paste and we have found out the fundamental parameter which governs the strength of paste of course, the bond between the particles, but more so you know actual strength measured is more so dependent on the capillary porosity and which in turn is dependent on water cement ratio.

So, that is why water cement ratio is a very most important parameter for determining paste strength. And in turn we will see that, it is also important to you know determine the strength of concrete.

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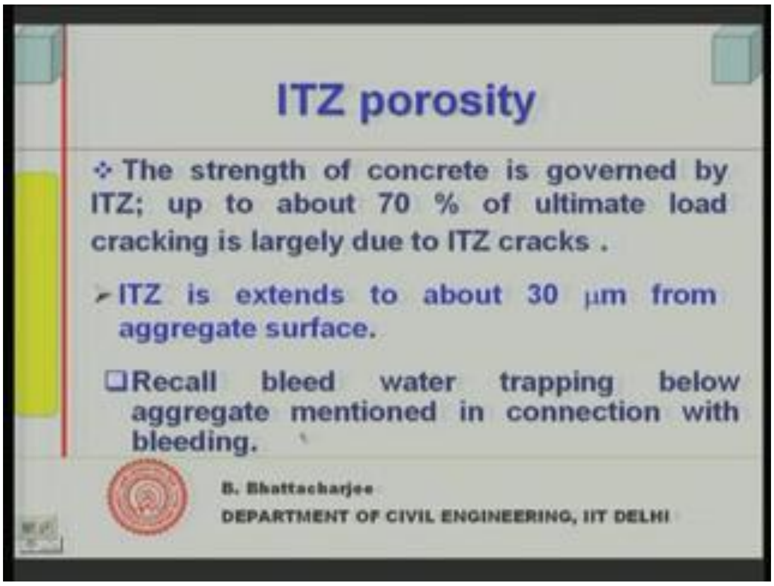

Now, let us see about interfacial transition zone. We said this is like almost like another kind of a phase, it has been observed in case of concrete, strength of concrete is is governed by ITZ more than the strength of the paste, because the ITZ I mentioned that the fracture or crack initiates from the interfacial transition zone, boundary between the paste and the aggregate. It has been observed upto about 70 percent of the ultimate load, cracking is largely due to ITZ cracking. Very first or second diagram I showed the photograph on the diagram I showed. It showed that, large cracks are there at the aggregate boundaries and that is what it is, upto 70 percent of the load the cracks that forms in normal strength, they are all at aggregate boundaries not at 1 place, but at many place.

But at some place where it forms, it further propagates and then joins up the pores beyond 70 percent ultimate load of ultimate load and then fracture continues right or failure progress of failure takes place. I also mentioned that, ITZ extends to about 30 millimeter it extends to about 30 micron from the aggregate surface. In fact, it would be you can say half the cement diameter close to that or slightly more than that, because cement particles you know cement particles will go and get actually packed near the aggregate boundary. This is aggregate boundary, these are cement particles and they are packed.

So, half of this in this zone the packing cannot be as good, packing cannot be as good as the bulk paste, where there are all cements. So, this is the zone where there are weaknesses. It could be slightly more than the half the cement dimension average cement size or slightly more than that you know more than that actually. So, there the packing of the paste or cement is not very good and there are bleed water trapping. If you remember we mentioned there are bleed water trapping below the aggregate. And that also leads to formation of large fractures or crack right in the beginning. There are other reasons and we will come to that right now. So if you look into the pores in cement based materials including concrete right now.

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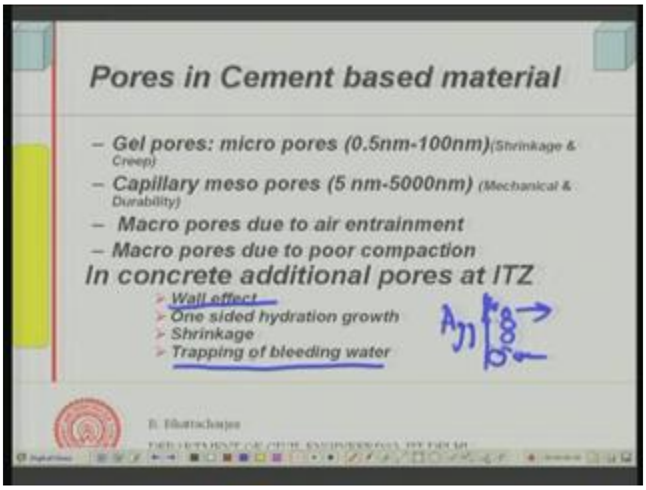

First thing we have seen is gel pores, which are very small pores which were part of gel structure. This we mentioned in connection with hydration. So, gel pores which are 0.5 nanometer to 100 nanometers and these pores are not directly responsible for strength, because they are too small to affect the strength, they are more responsible for shrinkage and creep, and sometime we will be discussing this. The next pores are capillary pores which are meso pores, larger size pores and their sizes vary from 5 nanometer to 5000 nanometer. These pores are all there in the paste and they are responsible for the strength of the paste, already we have discussed.

Macro pores due to air entrainment, if I using an air entraining agent, there will be macro pores which is due to this and this is there in concrete normally and we will discuss this sometime later on. And also macro pores due to poor compaction. So, they could be of the in the millimeter, both these types of pores macro pores can be order of millimeters may be present in concrete due to poor compaction air entrainment. Air entrainment is well distributed throughout the structure, compaction pores which could be because of honey combing or bad compaction etcetera can be of large size and they are the other kind of pores, which are present in concrete. And all they all these major 1s meso and macro dictate the strength.

But from fundamental point of view, we are trying to look into the meso pores in paste. Now, this paste are present in can be present in paste also, but in concrete additionally we will have pores in the interfacial transition zone. And effect I mentioned was wall effect that is, packing. Packing near the aggregate acts like a you know this is aggregate and particles are fine, the cement particles are fine and packing cannot be very good close to the wall. This is called wall effect, packing cannot be very good close to the wall and this is called wall effect. 1 sided hydration growth, when there is a particle here its hydration will growth would take place only from the outer side and may not be possible from inner side. So, you have 1 sided hydration growth.

Second issue is shrinkage, paste shrinks aggregate does not. Therefore, shrinkages may result in fractures or cracks here, because paste shrinks aggregate does not. So, some tensile stresses will be developed here, because aggregate will have restraining effect of shrinkage. So, you can have cracks formation here. And bleed water trapping we have mentioned earlier, in connection with bleeding that, when you have bleeding it can get trapped bleed water can be trapped at the side of the aggregate and this results in fracture formation. So, we see that, interfacial transition zone, you have additional pores coming because of wall effect, 1 sided hydration growth, the shrinkage effect and trapping of bleed water.

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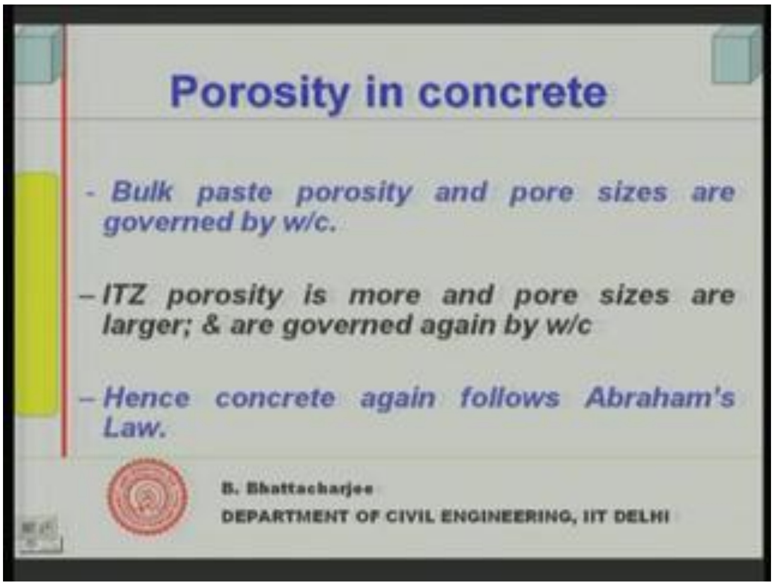

All this results in actually pore porosity of concrete or you know pore porosity at the aggregate, I mean inter you know aggregate paste interfacial transition zone. And their porosity is more porosity there is more. So, bulk porosity and pore sizes are governed by water cement ratio. And ITZ porosity is more, because there are additional effects there like wall effects, shrinkage effects, 1 sided hydration growth and bleed water trapping effect. All this makes the porosity or pores at the ITZ much more. There are fractures existing right from the beginning. And higher the water cement ratio bleed water trapping would be more, porosity, packing characteristics you know packing with wall effect all these effects would be even more and leading to more ITZ porosity.

So, bulk porosity is governed by water cement ratio, ITZ porosity will be always more than the bulk porosity and it is also governed by water cement ratio. So, water cement ratio therefore, governs all the porosity in concrete system. In paste you have seen the water cement ratio governs the porosity and pore sizes in concrete also, because the paste are there in concrete, paste is there in concrete, so those porosities would be there, but additionally I have got ITZ porosity ITZ pores and this interfacial transition pores at the aggregate boundary, they are also governed by water cement ratio.

Higher the water cement ratio more will be such pores, mores will be such features, because more will have bleed water trap, more you have shrinkage and all this effects. And therefore, water cement ratio again will find major factor, which governs the porosity and pore sizes in concrete as well. Not only in paste, but in concrete also we see porosity and pore sizes are governed y water cement ratio. So, concrete again therefore, follows same Abraham's law that we are talking about.

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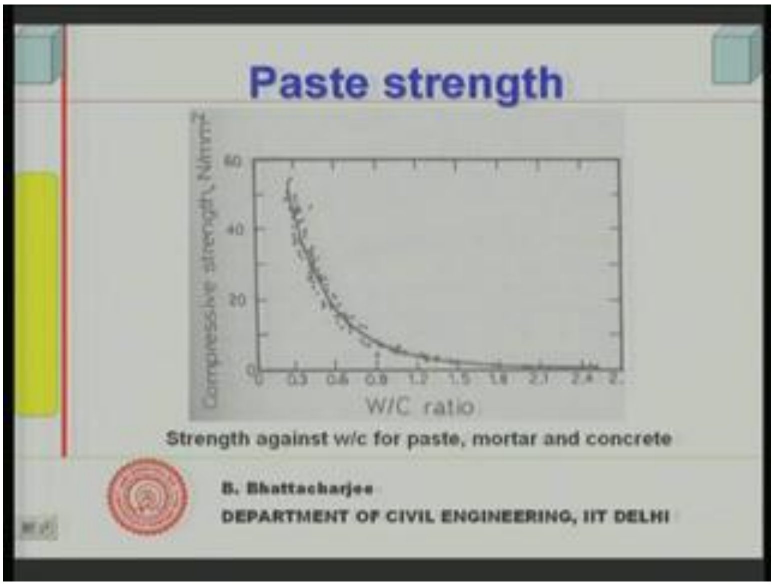

And this is what is the curve, which is you know this is the curve which shows that, how water cement ratio governs the paste, concrete and mortar strength. All although at top it is written paste strength, it is actually water cement ratio governs the strength of paste mortar and concrete. That is, because water cement ratio controls the porosity and pore sizes in pore sizes in paste as well as the interfacial transition zone and thereby actually thereby it controls the strength of concrete or paste both all cement based materials for that matter. So, let us now start summarizing.

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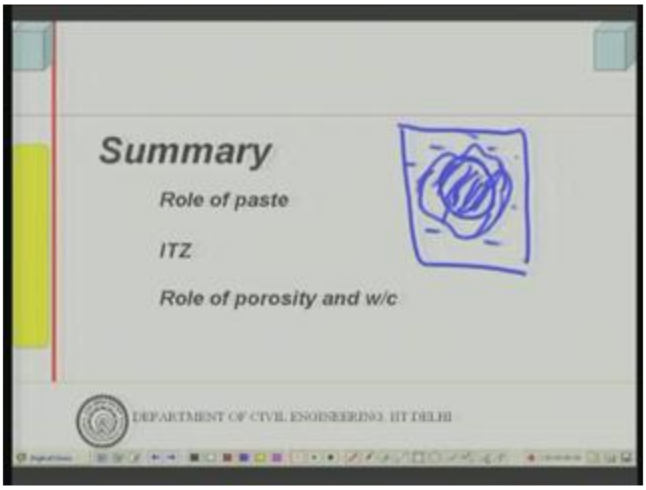

Now, first we have looked into the role of the paste. What does paste do? The paste of course, provides the bond between the aggregate system and also bond between themselves. If you recall our lecture, related to workability of concrete we said that, aggregate is dispersed in the paste matrix. Therefore, paste provides the bond with itself and also paste provides the bond with the aggregate system. And this bond comes through largely through van der waals forces which are more of not so much of chemical bond, they are secondary bonds and relatively weak compared to let us say primary chemical bonds.

So, primary chemical bonds which are usually also present in gel structure between the gel crystals, in addition to that the secondary bonds are there. And it is been the strength of the gel system or bonding capability of the cement paste has been attributed to this sort of bonds. This is number 1. When I have some unhydrated cement, let me put it this way; when we have some unhydrated cement in the concrete or cement paste system, they also act like aggregate or they act like some inert material as fillers and the only the hydrated portion provides the bond.

Now, unhydrated cement a particle does not themselves are sufficiently strong and act like inert aggregate and therefore, they do not reduce the strength or anything of that kind. But the main strength reduction of cement paste coming from the porosity of flow in the material and we know the cement paste themselves are capillary porous. Higher the water cement ratio, high is the capillary porosity.

Total porosity which is the sum total of the gel pores gel porosity and capillary porosity both are governed by water cement ratio. In addition 1 can understand that, size of the pores that would be there particularly capillary pores that would be there; that would be also function of the water cement ratio, because across a.

Let us say if this is my cement particle and you remember we discussed about hydration growth. And let us say if I have water in the surrounding, this is my water these are my wall in the surrounding, volume of this water associated with a single cement particle would be function of water cement ratio. Now, higher this water cement ratio, the volume of water will be more. And the hydration product which it will fill in, it will fill in only some portion and large sizes of large sizes on you know or large portion of the unfilled water will remain actually vacant, if the if original water cement ratio is high. Original water is high compared to you know associated original water associated with unit mass of cement is high.

So, the size of the pores also functions of water cement ratio, in case of paste and also in case of concrete. Therefore, when you look at the role of paste, the paste strength is governed mainly by the pores, total porosity and the pore sizes. And then when you come to concrete, the additional feature comes in at the interfacial transition zone. This interfacial transition zone is formed at the boundary of paste and aggregate. This has got somewhat different property than the bulk paste and; obviously, it is different from the aggregate. In normal concretes aggregate do no fail, all failures actually takes place through this interface.

This interface has got additional pores porosity because of wall effect, where the cement particles cannot pack together very well. 1 sided hydration growth on the aggregate side there will be no hydration and then there is shrinkage: paste shrinks aggregate does not shrink. So, there will be a risk you know there could be tensile stresses developed, because the restraining effect of the aggregate on shrinkage of paste. And lastly bleed water trapping could be there; therefore aggregate paste interface is usually weaker than the bulk paste. And when you apply compressive load, the failure takes place due to the transverse tensile deformation that is likely to place because of Poisseeuillee's effect.

So, when you apply compressive load uni-axial compressive load, the transverse Poisseeuillee's effect results in deformation along the transverse direction and this results in crack formation initially at the aggregate mortar or I mean ITZ which, because of their large size of the pores existing there, fracture existing there. And till 70 percent of the ultimate load ultimate failure load of the concrete, it has been observed that, the cracks that generate cracks that actually develop in concrete are all at the interface. And several cracks can start, multiple cracks can start and this multiple cracks,out of this multiple cracks some cracks would propagate through the bulk of the paste, causing failure of the material.

Now, therefore, finally, it is you know to conclude that, what it is the pores the volume of pores and the pore sizes, which are responsible for low strength of the concrete compared to the theoretical strength. And there the governing factor for strength of concrete. And this strength is then mainly controlled by water cement ratio therefore; water cement ratio is of course, fundamental parameter which controls strength of concrete. And that is how Abraham's law came by where it has been shown that, strength of concrete or paste is inversely relative to water cement ratio.

So, at this point, I would like to mention that, high strength concrete therefore, is possible to be developed or it has become possible to be developed, because we have reduced down, we have reduced you could reduce down the total porosity and overall porosity of the system, by lowering down the water cement ratio and manipulating the pore structure altogether. So, high strength concrete is possible; if you can lower down the water cement ratio and manipulate in such a manner that, sizes of the pores become smaller. So, I think with this we can conclude this discussion on fundamental of strength. And next we will follow up the factors those control the strength namely; the aggregate and you know air entrainment, compaction etcetera.

Thank you.