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

Module - 6
Lecture - 2
Strength of Concrete:
Aggregate Contribution

In lecture one of module 6 we have looked into the fundamentals govern, fundamentals of concrete strength or factors those govern fundamental factors those govern the concrete strength. Namely the water cement ratio which governs the paste strength and also governs the paste aggregate interface strength which in turn controls the strength of the concrete. Today, we shall look into the contribution of aggregate and other factors we shall look into the contribution of aggregate and other factors.

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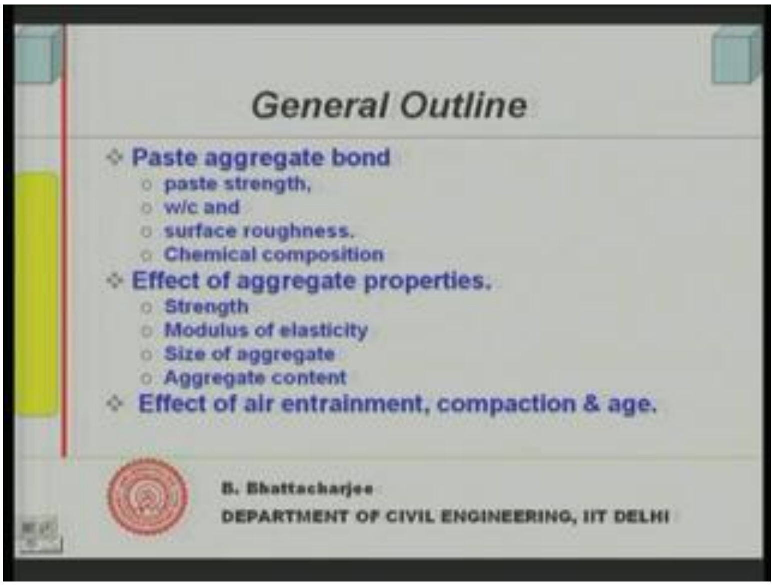

So, general outline of our discussion would be paste aggregate bond first we will look into, you know how paste strength controls the paste aggregate paste how water cement ratio surface roughness and chemical composition controls the paste aggregate bond, because this is what we have seen yesterday the most important aspect that controls the strength of concrete, the ITZ you know controls the strength of concrete. So, we are look going to look into that ITZ bond strength, between paste and aggregate then we shall look into, then we shall look into effect of aggregates properties on strength mainly strength of aggregate how it affects the strength of concrete modulus of elasticity size of aggregate and aggregate content. And lastly we shall look into effect of air entrainment compaction and age.

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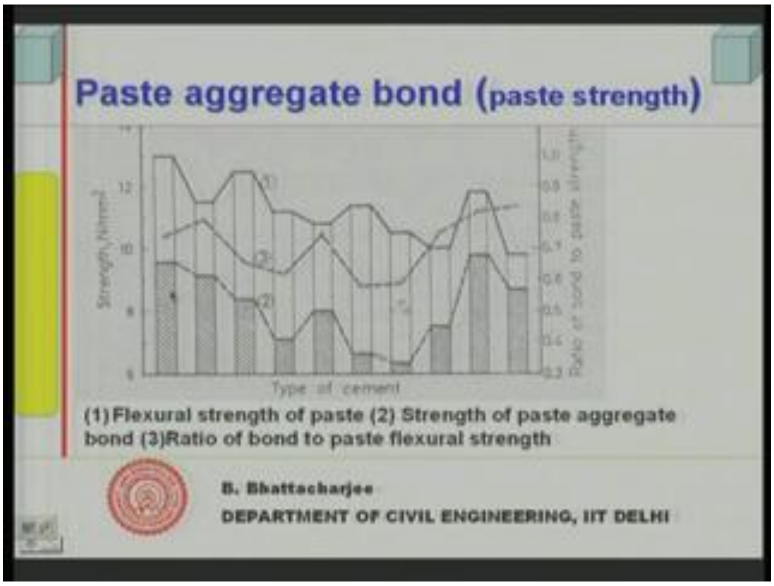

So, that would be that would how we have organized our discussion today and following it up; let us look into first the paste aggregate bond. Now, if you look at this diagram which shows, you know bond strength which shows the bond strength, flexural strength of paste bond strength of paste and aggregate and ratio of bond to paste flexural strength. So, curve 1 for example, it is this shows the flexural strength of paste curve 2 this shows the you know bond strength between the bond strength of paste aggregate bond. And if 1 calculates out the ratio the ratio works out like this and you know and you can see that, it varies from about maximum around 0.8 to somewhere to the minimum around 0.6.

So, few things become clear from this that the bond strength is lower than the paste flexural strength. You know why flexural strength this was some early work by Alexander which was done; why flexural strength I mean basically, it is a measure of the tensile strength and failure between the bond and the aggregate is due to the tension. So, therefore, we looked into the tensile strength of the paste itself, and then looked into the bond strength and obtained the ratios.

Now, 2 things becomes clear that, bond strength is lower than the paste strength and this reinforces our idea which we have said earlier that it is the ITZ which governs the strength of concrete and we have also seen that, till about 70 percent of the ultimate load, no cracks really develops into the paste it is only at the interface the strength develops you know cracks develops.

So, that that is actually reconfirmed if you look back into this; so the paste you know the paste aggregate bond, that is very important; that is what, is the second issue is confirmed is that, this bond strength is not necessarily proportional to the strength of the paste itself for example, although this place you know this has got the highest paste strength, but this is not necessarily the highest paste strength, in fact, high paste strength you see here. This is the least paste strength, but least bond strength is somewhere here. So, they are are not really necessarily related as you can see these are not necessarily related these are not necessarily related. You know, 1 is to 1 correspondence is not there although some sort of relationship do exist.

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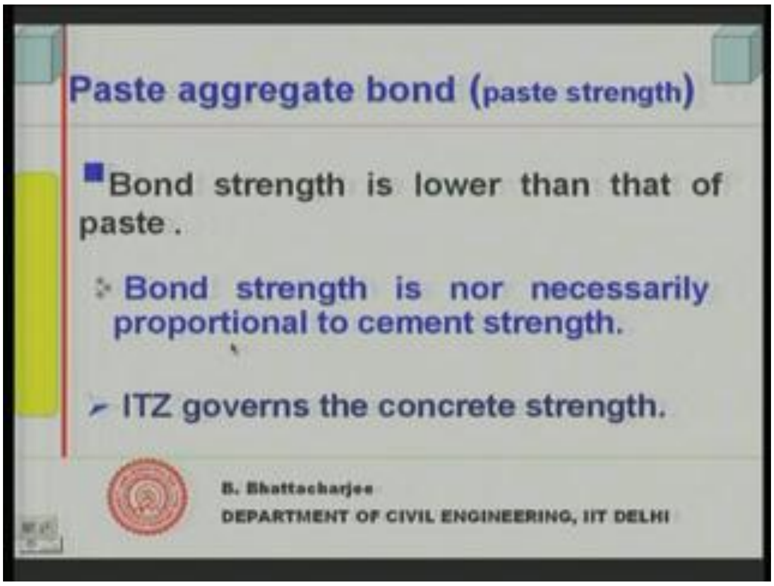

So, this is what we see bond strength is lower than that of paste. Bond strength is not necessarily proportional to cement strength and ITZ governs the concrete strength. So, ITZ governs the concrete strength that is what we see.

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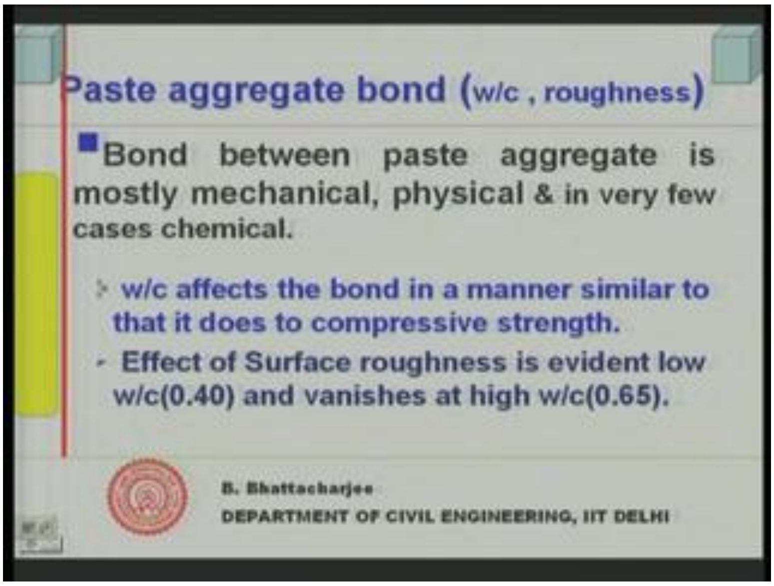

So, this is the first thing we see then continuing with the same paste aggregate bond we can see the effect of water cement ratio and surface roughness. Now, bond between paste aggregate is mostly mechanical, physical and in very few cases chemical that is what we should see. You know, if you remember we talked about that bond between the aggregate or the bond generated by cement paste itself by an large Van der waals kind of bond, with the paste and some of course, chemical bond between the crystals do exist in case of the gel themselves. Now, when it we are talking of the bond between the paste and the aggregate, it is mostly physical of this Van der waals kind of bond. And some can be mechanical simple interlocking in you know supposing the surface of the aggregate is very porous, where the paste goes in the very fine pores are there where paste can get in.

So, there will be a kind of mechanical interlocking possible. So, the bond between paste and aggregate is mechanical, physical and in very some few cases it can be chemicals also as chemical also as usual see later on. So, now how this bond be affected by water cement ratio; well. We have seen in details yesterday, the water cement ratio affects the bond in a manner similar to that it does to compressive strength, because higher the water cement ratio let me again, recapitulate the idea that we talked in the last lecture. Higher the water cement ratio there will be more bleed trap water, there will be more porosity of the you know, ITZ porosity and also shrinkages and wall effect etcetera.

So, all these are related to the water cement ratio higher the water cement ratio ITZ porosity is higher and therefore, water cement ratio affects the paste strength affects the concrete strength higher the water cement ratio, reduces both the cases same thing happens to the bond strength also. Higher the water cement ratio bond strength will be less, because there will be more bleed water trapping, there will be more poor bond due to you know, poor bond essentially because of shrinkage effects and wall effects etcetera because porosity there itself will be larger.

So, effect of surface roughness this is very important and it is evident more in low water cement ratio concrete. In fact, there is a difficulty in measuring this kind of thing because how do we measure you put an aggregate and put a paste over it and try to find out how much load it can with stand you know tensile load it can withstand. So, that is how we can find out what is the bond strength, but changing the surface roughness keeping all other properties of aggregate constant namely, it is mineralogical composition constant or sizes constant it becomes difficult.

So, you know this test is difficult, but some tests were earlier and it was observed that if you have high surface roughness it can increase the strength with aggregate with higher surface roughness, can increase the strength at low water cement ratio as much as about 38 percent increase you have observed in some cases at low water cement ratio; however, as the water cement ratio increases, this; increase in strength due to surface roughness tend to reduce down and later on about 0.65 there is no increase in strength due to surface roughness, because the water cement ratio low water cement ratio becomes. So, governing that whether you have a rough surface or a smooth surface it really makes much of a difference.

So, but at low water cement ratio this has got some effect. So, rough porous fine porous surface would have a tendency to develop better bond. Now, slightly digressing from this issue; you know rounded aggregate if they rough they are fine, but quite often gravels may have very smooth surface, like playing marbles you know supposing they are there even their shape is not rounded, but anything they would have poor ball, but usually gravels sometime may have very smooth surface it, is the surface, which is important not the shape, shape actually dictates the packing characteristics. Shape actually dictates the packing characteristics, but roughness dictates the bond strength

So, rounded you know there can be some kind of misconception that rounded aggregate would not provide bond that is not necessary, surface roughness is important, but rounded aggregate would be better packing therefore, reduce down the water requirement improves the workability. So, 1 has to see which effect is dominating quite often it may be the you can design accordingly there is no problem, even if there is little bit reduction in the bond strength because of the smoothness of the surface, you can just reduce down the water cement ratio and little bit to get the adequate strength.

So, 1 can design the mix knowing the properties or characteristics of the aggregate, but the fact remains the surface roughness improves the bond strength especially at low water cement ratio, but very high water cement ratio it has got little effect. Shape does not really directly affect the strength, but it affects the packing density. So, if you have a rounded aggregate with rough surface that might be a good 1; much better than anything else. So, that is the idea.

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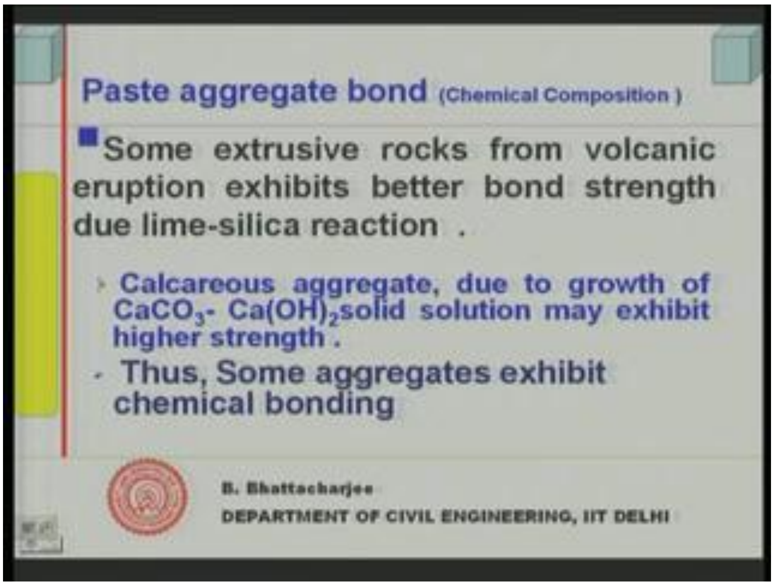

So, we can follow it up further and look into paste aggregate bond the chemical composition of the aggregate. You know most of the aggregates are supposed to be inert like, if you have quartz granite etcetera most of this aggregates are inert. So, therefore, they are inert to everything; therefore, they are inert to the cement also. So, there is hardly any chemical bond existing, but some aggregates do so a little bit of bonding characteristics chemical bonding characteristics. For example, those extrusive rocks which comes out of volcanic eruption may exhibit better bond strength due to lime silica reaction you know we have mentioned about pozzolanic.

So, extrusive rocks are those which come out of the lava, which forms from the lava you know, extrusion on the volcanic eruption and forms from lava. They might contain large quantity of silica and which are reactive silica as high as 40 to 70 percent silica may be present, which are reactive silica in those. This reactive silica because as we have understood from pozzolonas, behavior of pozzolona when we talked about pozzolanic PPC cement etcetera. We said that the clay particle which has heated up and cooled exposed to atmosphere suddenly cooled rapidly they may have a tendency to react with lime and that is reactive silica.

So, some of those aggregates may have some reactive silica and when, they are present they may react with lime present in the aggregate and thereby give you a kind of chemical bonding, but that those are not very usual. Some other calcareous aggregate has has been reported to show some sort of chemical bonding; namely you know, like some calcium carbonate reacting with calcium hydroxide and forming solid solution calcium carbonate reacting with calcium hydroxide and forming, solid solution and they might have shown they have shown some higher strength, but by an large aggregate really, do not show they are supposed to be inert and do not show chemical bonding, some aggregates exhibit chemical bonding not all. Well, but mainly it is the physical and mechanical bonding which are important.

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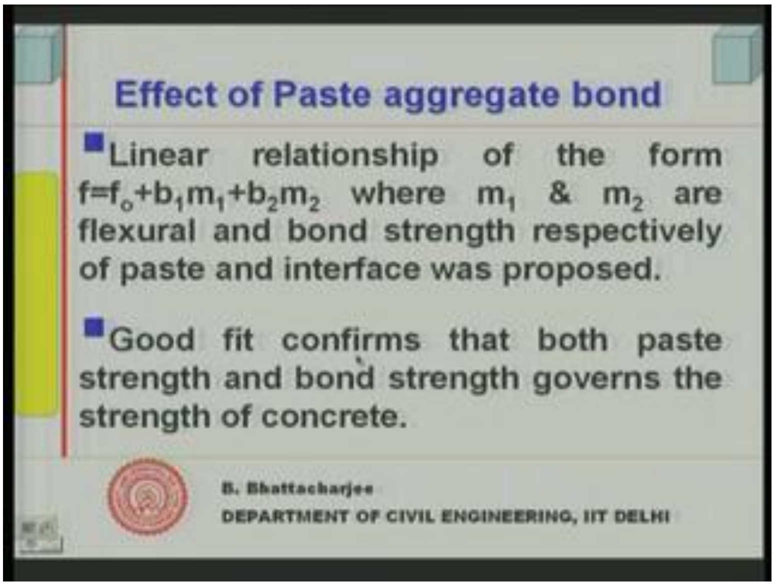

Some earlier work people have tried to actually develop linear relationship in of this form linear relationship of this form f0 b1m b2m 2 etcetera. Some constants here the f stands for strength and this is the actually one is the paste strength other is the bond strength. So, linear relationship with bond strength and paste strength that, try to relate the concrete strength pretty simplistic relationship actually. So, one of them is the flexural strength other is the bond strength and you know, this was proposed and goodness good fit was observed, very good fit was observed. That we shall see later on in the next slide, very good fits were observed and this good fit confirms that both paste strength and bond strength governs the strength of concrete.

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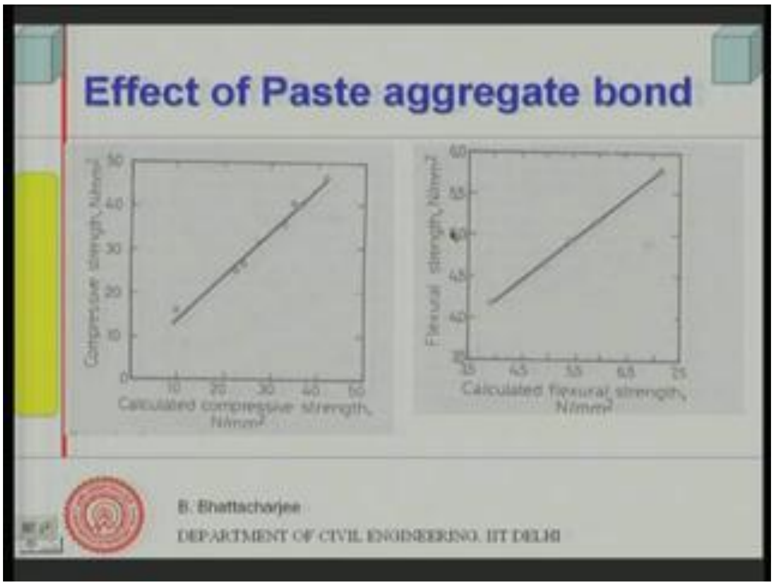

So, this is what it is good paste strength and bond strength governs the concrete and these are the fit these are the relationship, compressive strength versus compressive strength of actually estimated compressive strength. This is actually estimated measured compressive strength estimated compressive strength. From those formula and they found that, both measured and experimental they fit really very well almost in a straight line 45 degree close to 45 degree. So, there is a good correlation between the estimated strength from the model that has been proposed and actually measured strength.

Similarly, when they looked into a flexural strength of concrete specimen measured and estimated through this relationship. Similar linear relationship simple regression analysis simple curve fitting you know linear fit was obtained. So, empirical relationship and they found that this was, it shows good relationship you know it is mainly from the work of generally, a work of Alexander 1 Alexander who did this work and from this it was observed.

Now, 1 would like to conclude from this that it is the paste strength and it is the you know, bond strength between paste aggregate bond is the governing factor for the strength of concrete, is the governing factor for the strength of concrete. So, this again we reiterate or reconfirm the fact, that it is the aggregate mortar aggregate paste interface that is the bond between the aggregate and paste and the paste strength themselves which are the governing factor for strength of concrete. So, this is this is what we look.

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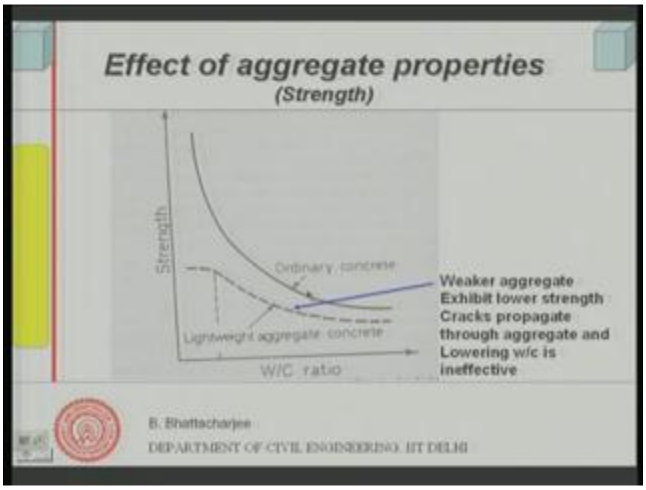

Now, let us see how that the aggregate themselves affect. You see few things have become clear from our discussion so far that, perhaps cement strength do not. So, strongly affect the strength of concrete and also it is important to understand that you can't ignore the effect of aggregates in you know in strength of concrete it will be further clear when you look further into the effect of aggregate properties. So, strength of concrete is a function of strength of paste and paste aggregate bond, but many of these are influenced by the aggregate you know aggregate themselves various properties of aggregate. For example strength of aggregate is an important factor.

Now, if you look at this ordinary concrete water cement ratio versus strength it will come like this, but if you put light weight aggregate then the strength will be something like this. In fact, in experimentation done with let us say small big pieces bundle clay big pieces if you break them down into crust or crush them down into aggregate sizes see them they are relatively weak take poor quality break and do an experiment, try to put them in the aggregate and find out the strength, you will find there is a significant reduction in the strength compared to a strong aggregate.

In normal strength concrete what we do? We actually normal strength concrete we use aggregate which are sufficiently strong quite strong, but if you use a weak aggregate then the strength will come down strength will come down. Now, this diagram shows that actually when, we have light weight aggregate concrete which are relatively less strong they are weak because they are porous in nature. So, as long as water cement ratio is high strength reduction it follows similar sought of curve, but at very high lower, you know lower water cement ratio it simply doesn't show any improvement in strength because this itself is porous.

So, the reduction in porosity due to reduction in water cement ratio is ineffective here and therefore, the strength does not reduce at all. So, strength of aggregate is very important because strength of aggregate is again governed by the pores in them, pores inside the aggregate normally this is very, very small, in case of strong aggregate; in light weight aggregates or something like brick brick bags you know brick broken brick pieces clay brick pieces of lower strength if you make I mean concrete out of them they will show you much lower strength. So, aggregate strength has a role to clay and the strength of concrete.

The weaker aggregate exhibits lower strength cracks propagates through the aggregate and thus lowering water cement ratio is ineffective in this 1. In this case, that is the idea because there are lot of pores in them itself and the crack will pass through this. In high strength concrete this is this is an as I mentioned earlier; in high strength concrete the crack passes through the aggregate themselves. Because in high strength concrete what you do, you improve the paste you increase the strength of the paste improve it you also improve the paste, aggregate interface that is the ITZ by inclusion of very fine pozzolona and water reducing agent etcetera and using very low water cement ratio.

So, you improve the paste and paste aggregate interface now the weakest link is not necessarily the paste aggregate interface and paste almost they will be similar to the strength of the concrete. So, crack can pass through the aggregate themselves as well cracks can pass through the aggregates themselves.

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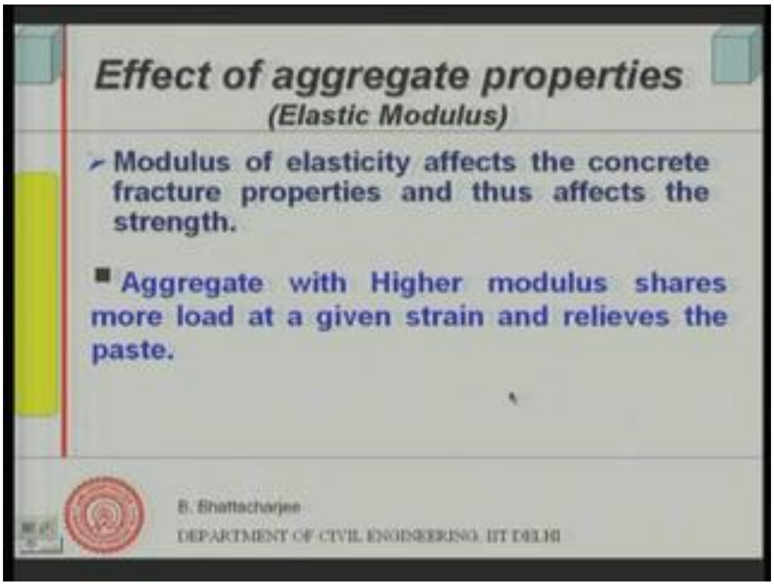

So, that is what it is and you can look into other factor modulus of elastic modulus of elasticity affects the concrete fracture properties and then affects the strength because if you remember, we talked about Griffiths critical stress where E was coming into picture. If you look into fracture toughness the E is again fracture toughness is a function of modulus of elasticity. So, higher the fracture toughness of course, it will have more resistance to us fracture. So, therefore, fracturing of concrete is a function of modulus of elasticity.

So, if you have high modulus of elasticity concrete would you know would show exhibit higher strength that is well understood. A second aspect is aggregate with higher modulus shares more load at at a given strain strain and relieves the paste. You know aggregate with higher modulus shares more load at a given strain and relieves the paste. The whole idea is supposing I have when I have loaded a concrete specimen; since they are bonded with the aggregates and paste are bonded there is a bond existing between the say, 2 they will be undergoing same deformation at their interface in other words they will be under some strain.

Now, under same strain the load would be the strain multiplied by the modulus of elasticity. So, higher load carried by each individual component will be strain. Now, strain are same in both of them whichever has got higher modulus the load carried by that will be more, because p1 or let us say, p aggregate will be epsilon the strain multiplied by the modulus of elasticity of aggregate. The paste will have epsilon same epsilon multiplied by the modulus of elasticity of the aggregate the paste will have epsilon same epsilon multiplied by the modulus of elasticity of the paste. So, that is the load carried. So, which will carry more load the aggregate will carry more load. So, therefore, it will relieve the paste of some load.

So, that is the other idea why modulus of elasticity tends to give you higher modulus of elasticity tends to give you higher strength. What about size of the aggregate it has been observed that for high m s a strength is lower.

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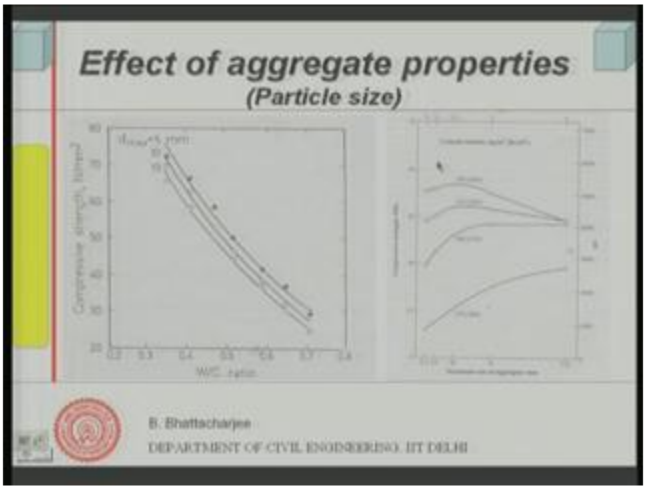

For example: this diagram will show you if you have 5 millimeter you know water cement ratio versus compressive strength as you can see; water, cement ratio versus compressive. So, when you have 5 millimeter maximum size of the aggregate its strength is higher, 10 millimeter it is somewhat lower for the same water cement ratio you take any water cement ratio and it is 19mm it will be lower strength.

So, higher the aggregate size or maximum size of aggregate diameter d max you know lower is the strength. Lower is the strength that is the observation let me just digress a little bit from this. In normal strength concrete we use around 20mm msa quite often and sometime even forty mm msa. In mass concrete of course, you go to 150 millimeter msa very lower strength mass concrete you know dam concrete and when, it comes to high strength concrete we do not use more than, 10 or 12 millimeter, 12.5 millimeter aggregate mostly 10 mm. And you look at further high strength system for example;

reactive power concrete does a not use coarse aggregate at all the 70 kilo 0.6 micron is used.

So, higher and higher is the strength of the concrete you use smaller and smaller maximum size of the aggregate. Now, we have of course, understood what maximum size of the aggregate do to water content required or workability, but as far as strength is concerned it reduces down the strength. Now, another diagram is here will explain this diagram a little bit later on this shows that m s a along this direction right. So, hundred and fifty 2 mm etcetera 75 mm and so on so far.

So, when you have 1 kg of cement this shows this is for 170 kg of cement per kg of cement per meter cube kg of cement content and this is in pound per yard cube within bracket. Now, you have low cement content as you increase the msa it increases, but it does not increase further beyond this point because it is almost becoming a straight line. You go to this when you have about, 250 kg of cement, 280 kg of cement per meter cube. And it actually does not show any increase further and if you go still further 330 it will show, maximum at this msa the strength is maximum, then it even decreases a little bit and further increase in the cement content you will see that. In fact, beyond a point it starts decreasing.

So, what we see is the there is an in this case there is an optimal msa beyond which strength will not be increase strength before that strength is lower. So, you go on increasing the msa strength increases up to certain point, and then it starts decreasing and this point msa, this msa is higher, optimal msa is higher for lower cement content concrete or lean concrete. For richer concrete this value reduces and reaches and if I further extend this to higher cement content, I will find that this value becomes smaller and smaller. And that is why, when you have a very high strength system this you know msa becomes simply do not use even coarse aggregate at all much smaller than this. So, let us see what the explanation for this one.

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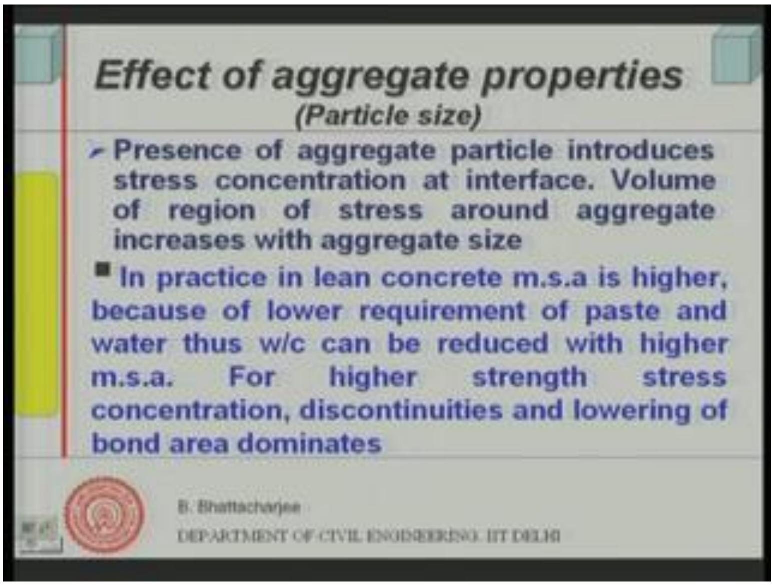

First of all presence of coarse aggregate particles introduces stress concentration because its non uniformity in the structure its non uniformity in the structure, of the you know matrix and you have some inclusion inside this. You said paste acts as a matrix and the coarse aggregate particles or aggregate particles themselves are sought of dispersed during that. So, they act as inclusion. So, for the stress flow that would introduce a kind of discontinuity and stress concentration at the boundary of the aggregate. Now, larger the aggregate size volume region of stress concentration around an aggregate particle will become larger and through a lesser surface area it has to same stresses to pass through a lesser surface area, because for the same volume larger aggregate size means lesser surface area.

So, lesser surface area when it passed as concentration effect is higher. So, when you have larger size of aggregate, when aggregate sizes are larger the stress concentration effect tends to reduce. It is non uniformity it is a discontinuity because you are adding another material which is stronger compared to the paste and in normal strength concrete will tend to give you, you know this discontinuity tends to give you lower strength. In fact, you're also your more aggregate and larger aggregate would also mean that, larger size of possibly the interfacial discontinuity or interfacial pores etcetera.

So, it has been observed that this shows lower strength as you increase msa, as you increase msa finer very fine as I said very high strength system you do not use. You do not use coarse aggregate at all we use finer aggregate al1 and we try to make it as uniform as possible.

So, now, coming to the second graph as you have seen lean concrete msa is higher this is because lower requirement of paste and water. See in lean concrete paste requirement will be lower for the same workability you can make a workable concrete with much less water. So, even if you use less cement it will you can have, relatively low water cement ratio. So, for given fixed cement content, low cement content and fixed workability I can go on reducing the water and I will still get the same workability. You know whatever the workability. So, I can go on reducing the. So, if I increase this msa if I increase the msa I can reduce the water and maintain the same workability. So, I go on increasing the msa maintaining the same workability my water requirement would be reduced every time and in the process water cement ratio itself will reduce giving strength increasing you know higher strength higher and higher strength. So, that is what it is lower water requirement of paste and water thus lower water cement ratio you know, can give higher msa, but for higher strength when you have higher strength because now you have low cement.

So, low water cement ratio now supposing in high strength you have somewhat higher cement you go to lower water cement ratio higher cement you go to low water cement ratio strength would tend to increase, but when strength increases to maintain the strength the stress concentration effect has to be reduced. So, where in richer mixes actually stress concentration effect starts dominating beyond a point; msa as you go on increasing the msa and thereby other effects as I said that could be larger size of the ITZ porosity all these actually, tends to reduce down the reduce down the strength. And you can’t reduce the water content much there because paste content required will be relatively high.

So, all this factors actually brings down the strength beyond a point and that is how towards the effect of msa on strength effect of m a effect of msa on strength this is the effect of msa on strength.

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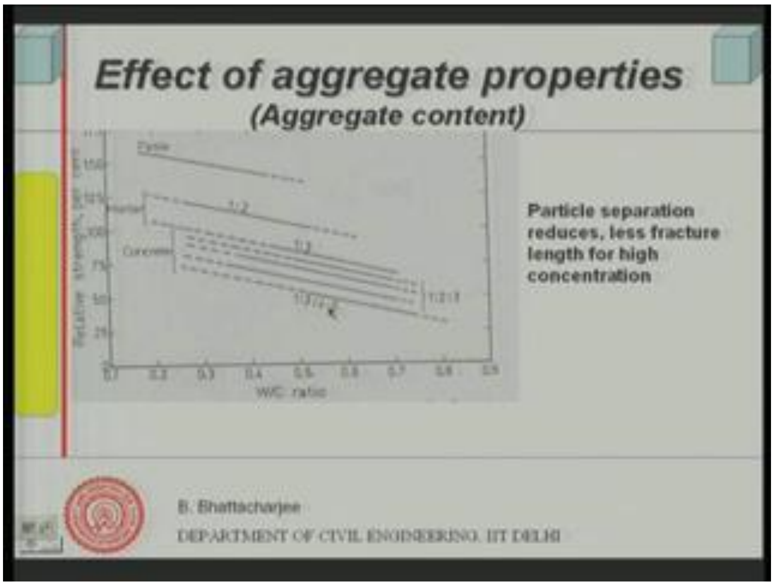

If I see aggregate content that is, aggregate to cement ratio interesting results were obtained some people found that if you have high aggregate content the strength reduces. On the other hand, some other people found we will just first look into the first case and what was the explanation given, then we will look into the second case and the explanation given and thirdly what is by an large extent.

First case, it was observed that it is for the same mortar cement ratio relative strength of concrete if 1 looks at, you know 1 calls this some strength as 1 and 1 is to 3 this strength as some 1 relative strength this is been talked about, paste is supposed to have higher strength for the same mortar cement ratio and as I go on increasing the aggregate to cement ratio mortar for example, 1 is to 2, 1 is to 3 mortar the strength seems to increase. And I have a concrete 1 is to 3 is to 4.5 this is supposed to have higher strength.

So, when I increase the aggregate content either fine or coarse the strength increases and paste has got the highest strength, well. This is not necessarily the general experience, but this is finding out of particular experimental results and the explanation given was that, particle separation reduces between the aggregate. You know, when you increase the aggregate content when, if you have less particle separation between the aggregates, then what will happen the because fracture initiates from ITZ from the aggregate interface. So, since the fracture initiates from the aggregate interface it has to travel through, smaller path lesser path if the particle separations are less.

So, it has to travel through lesser path if the particle separations are less and in such situation, what will happen the strength will be reduced strength will be reduced. So, if you add aggregate to it particle separations are less, and therefore strength reduces. This is what, one of the explanations given to this case experiment that was obtained,

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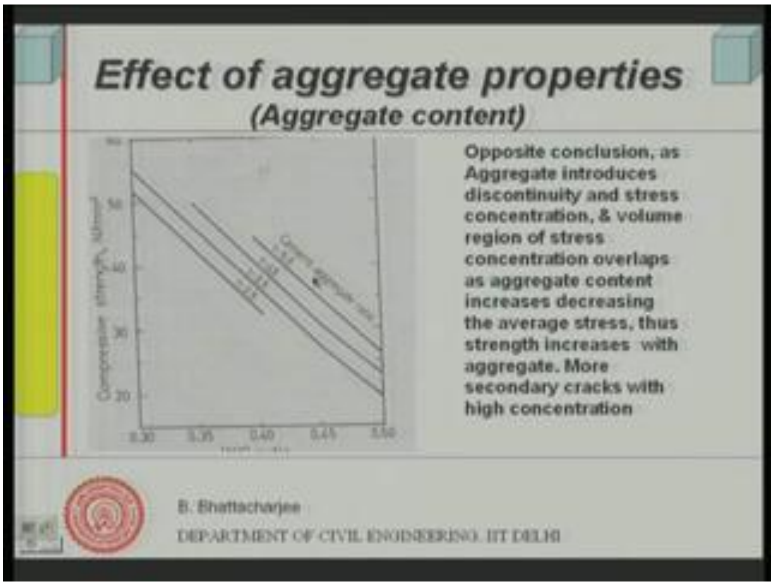

But the opposite conclusion was drawn from by many other people. In fact, this experience exactly opposite is more where it has observed that higher aggregate to cement aggregate to ratio you know 1 is to 5.5 1 is to 4.51 is to 2.5.

Now, if you consider same water cement ratio any water cement ratio you will find that, the lower the higher the aggregate, higher is the strength lower the aggregate content strength is less the paste is not necessarily higher strength. Now, therefore, this experience would say. So, this was actually attributed to basically discontinuity introduction of discontinuity by; you know, this was attributed to discontinuity that is introduced by aggregate and the stress concentration and overlapping volumes of stress concentration.

You know because when you have more aggregates they come closer to each other stress concentration area gets overlapped and you have kind of average, stress of the whole less effect of stress concentration has been given as the explanation. Because when, you have more aggregate more and more aggregate effect of stress concentration would be reduced because it would tend to cause overlapping of the volume or region of region of stress concentration and kind of average stress that that will be you know stress concentration that would be reduced down that was the explanation given.

So, more ever it was another idea which is given was that more secondary cracks are possible when you have more aggregate content it means you know simultaneously lot of cracks will develop if you have less aggregate, then only few cracks would develop at the aggregate interface and that would finally, cause cracking, energy required to you know like to create new surfaces would be more, when you have multiple cracks, but most of them do not actually converts into a complete failure plane only 1 finally, a critical 1 possibly done.

So, when we have to produce multiple surfaces, multiple crack surfaces you require lot most end energy, therefore it can send lot most end energy and that is the idea given as far this is concerned that is the idea given as far this explanation is concerned.

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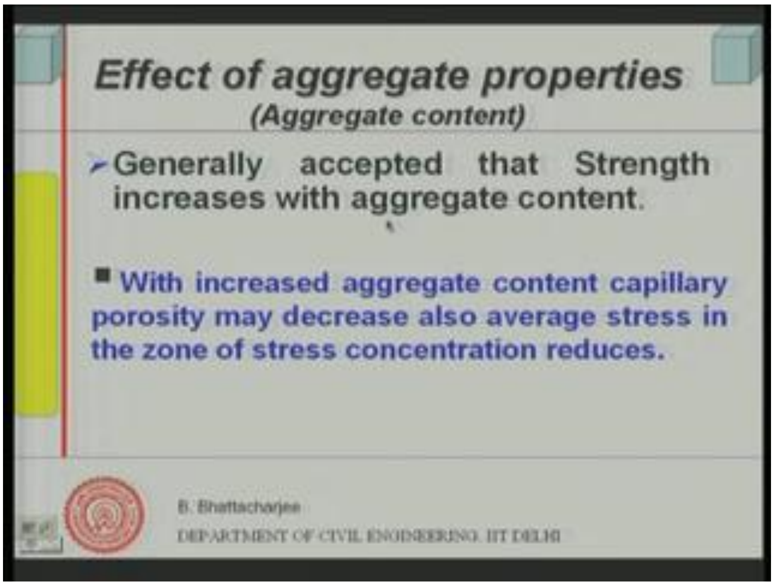

Generally, accepted is the second idea is the strength increases with aggregate content generally accepted is the strength increases with aggregate content, especially in normal strength concrete with increase in aggregate content capillary porosity is the third explanation also given is a when, increase aggregate content may reduce the capillary porosity because capillary porosity is essentially is a part of paste system and therefore, it may reduce the capillary porosity and may decrease also a average stress in the zone of stress concentration.

So, cracks lesser cracks could be formed I mean more cracks are formed and therefore, can observe a lot of energy all this put together this is been the general idea accepted in normal strength concrete in normal strength concrete because the paste strength is relatively low paste strength is relatively low aggregate strength is higher you know paste modulus is low aggregate modulus is higher. So, when you add more and more aggregate it tends to show you somewhat higher strength, but that does not mean that all aggregate would have you must have sufficient aggregate to have the kind of workability.

So, that is the case if you have higher aggregate concentration maintaining the workability proper this possibly would give you better strength in normal strength concrete. In high strength concrete or very high strength system, in fact, you can have sufficiently large paste content to take care of say in reactive power concrete to take care of the shrinkage effects etcetera. Because shrinkage affects starts dominating in these ones and since aggregate do not shrink the paste shrinks. So, if you have small quantity of paste they, might introduce shrinkage cracks at the aggregate cracks at the ITZ, but on the other hand if you have large amount of paste and some aggregates are embedded in them. As the whole paste as whole will shrink and there will be no tensile stresses at ITZ rather there will be a compressive stress, because paste will also shrink together with the I mean aggregate will also shrink together with the paste.

So, that is a kind of idea about aggregate content, but normal concrete if you increase the aggregate content tends to increase. So, long as you have sufficient amount of paste to maintain the workability of concrete and fill in all the void space and slightly more.

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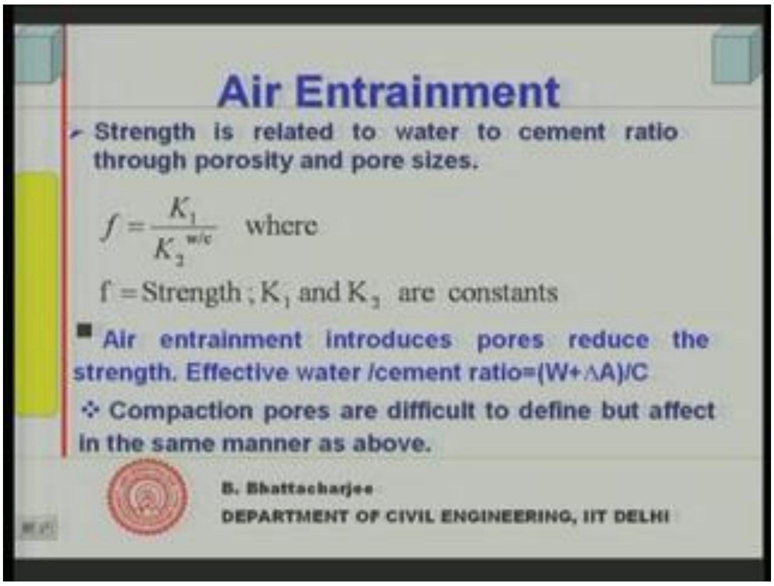

Let us look into another case air entrainment we have seen that, strength is related to water to cement ratio through porosity and pore sizes. This we have understood from our previous discussion, then strength is related to water to cement ratio because water to cement ratio increases the porosity and also increases the pore sizes in bulk paste as well. As interfacial transition zone and again repeat this because this is the most important factor water cement ratio actually causes increase in porosity and also pore sizes, both in bulk paste as well as ITZ therefore, this is what actually causes higher water cement ratio causes reduction in strength. This is the most important factor the other factors are there like we talked about aggregate type and you know, aggregate properties etcetera, but most important factor is this fundamental, this is the first thing you know this is the major controlling factor other factors are of course, next.

So, this is true for concrete we have understood this in our previous lecture and we just repeat. This is very important and same Abraham's law similar other laws are existing Farad's law gel space relationship, but this seems to be most acceptable in many design procedure some variation of this form in graphical form etcetera. So, that is why I am repeating this there are some other relationship also exist. So, this seems to be very valid even, in case of concrete like the cement paste we have mentioned and as water cement ratio increases strength reduces K1 and K2 are some constants depending upon, type of aggregate type of cement everything all other things remaining constant strength of concrete is inversely proportional to you know, in power inversely proportional to in terms of power to water cement ratio, that is the most important idea.

Now, what happens if I have air entrainment? Air entrainment also introduces pores and pores of course, in the sense that not really compaction pores, but they are macro pores again and well distributed throughout the structure or throughout the cement matrix and they are closed pore system, they are closed pore system; however, they will reduce down the strength because pores porosity close are interconnected both will reduce down the strength.

So, they will reduce down the strength even though the interfacial ITZ porosity or at the large aggregate interface the pore or flexure that would be existing in the beginning might be still larger than this pore sizes. Air entrained pore sizes you know larger than the air entrained pore sizes and therefore, crack might initiate from those places, but this will help because they crack can propagate through the air entrained pore. 1 of the ways, people try to relate this is to because we do not have a really I mean; you can from fundamental concepts the strength compressive strength of concrete relating it to fundamental properties still waiting.

So, this relationship is an empirical relationship and to use in a empirical relationship 1 of the ways is use equivalent water cement ratio W plus delta A where delta A is the air content and then you WA by C relationship WA by C; relationship use W plus delta A divided by C relationship for water cement ratio. In the same relationship water cement ratio in the same relationship to get the strength of concrete.

So, this is how air entrainment it reduces can reduce the strength as much as 5 percent. But if you do not mind, because it gives you other positive effect in terms of freeze thaw resistance, where freeze thaw resistance is a concern you know where in cold climate where freezing is a problem, still you can use air entrainment and sacrifice 5 percent of the strength does not matter because I can design my concrete. If I know, how it behaves I have no problem you know in 5 percent strength is there I do not mind losing that 5 percent strength, what I will do? I will do my mix design accordingly, when things are happening by design there is no problem, but if it happens by default then there is a problem.

We are I know that there will be a loss in strength and accordingly I design the concrete for the strength. And there is no problem I can it can take care of my freeze thaw resistances and also improves the workability as a kind of fringe benefit. Compaction pores will also behave exactly in the same manner because they are also pores, but you see they are much larger size pore and this is difficult to define, what the compaction pore should look like, but they can be anything honeycomb should be very weak point.

So, compaction pores if they are air remaining air remaining in the concrete system. If the air is remaining in the concrete system we have not been able to effectively drive it out during compaction they will reduce down the strength although there is now, way to take this only thing is you make proper compaction and air content of the concrete is taken care of in mix design. So, that is what it is…

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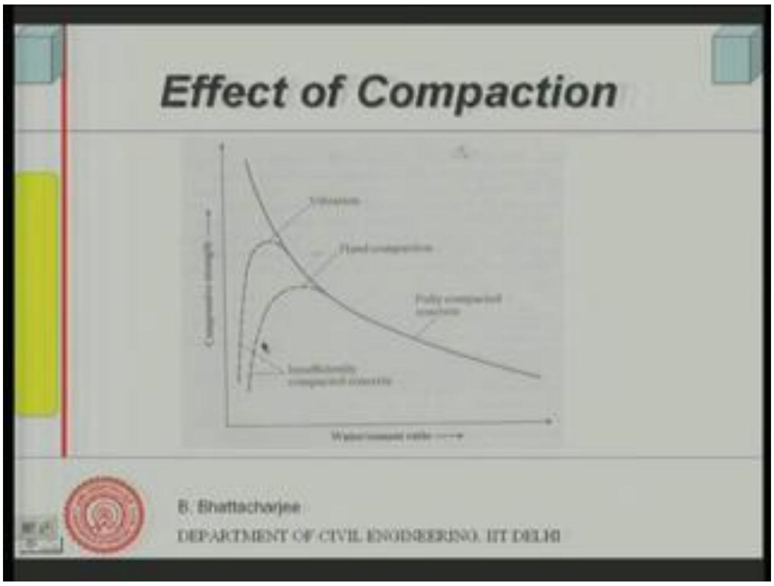

Let us see what the effect of compaction is; this is what the effect of compaction is. You know, water cement ratio versus compressive strength; supposing, I do a full compaction fully compacted concrete vibrations only no problem, but standard proper kind of vibrations. So, if I do hand compaction I will find insufficiently concrete as I go to the low water cement ratio, because the flow ability of the concrete will be less. A very high water cement ratio concrete would require very less of work. So, hand compaction also you can do.

So, very high water you know water cement ratio concrete in other words, weak concrete leaner concrete you can even do hand compaction, but when it comes to stronger concrete if you do it. You will find there is a reduction because you will introduce lot more compaction pores and even, vibration in some cases can introduce lot more compaction pores. So, proper vibration full compaction could be achieved especially in with all kind of efforts in low water cement ratio. So, by compaction is very, very important. So, 1 has to ensure that you get compaction do not get compaction pores.

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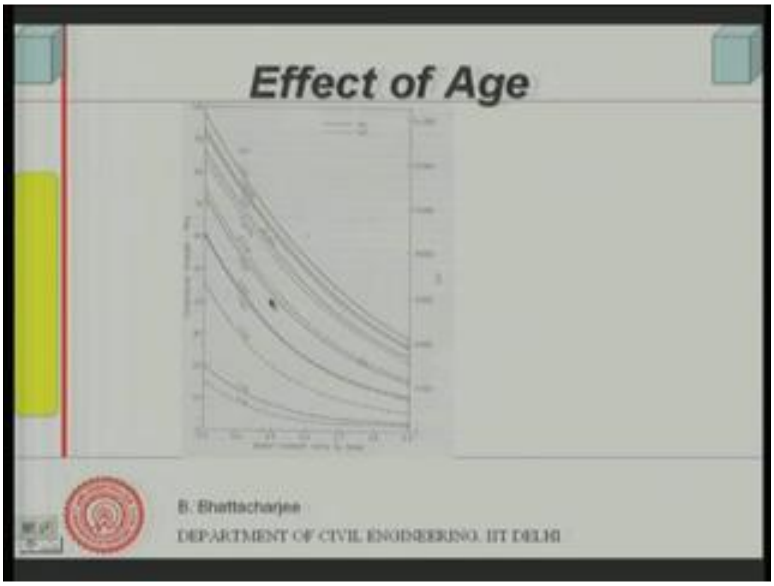

Effect of age if you look at this is water cement ratio versus again compressive strength and you can see, as it changes with the age this is you know, this is 2 different concretes, 3 days 7 days; as I increase 1 day concrete 3 days concrete. So, as I increase the concrete I mean age, the strength of concrete increases;, because these curves are this is for 1 day curve this is for 3 days curve and as age increases strength also increases. So, strength also increases. Now different age of concrete, etcetera.

Now, why does it increase because degree of hydration would be more? In other words the hydration product filling, in the void space will be more if you remember when you talked of curing we said that, the hydration product through curing only we achieved discontinuity of pore system you know segmentation of capillaries. It is possible what you mean, is you have a cement particle it requires time to actually hydrate. So, initially some portion of the cement particle will hydrate, and then it would actually fill in some of the originally water filled space through the hydration product.

So, as you continue the curing process in other words as the age increases more and more particle will hydrate and they will occupy the pore space, that was occupied by the water before and therefore, overall reduction in the porosity would be there. So, since the overall reduction in the porosity since there is a overall reduction in the porosity therefore, since there is a overall reduction in the porosity strength would increase. Not only, is it the overall reduction in the porosity the pore sizes will also reduce. Because initial size of the void space the water filled space depends upon of course, the amount of water presents with respect to cement and now, it would get filled in by the hydration product.

Now, 2 things more and more this paste gets filled in the sizes get reduced, not only the volume of pores would get reduced sizes of the pores will that reduce. Because initially it is all interconnected water space water filled space interconnected water filled space. Now, as the hydration process after sometime, there will be segmentation of the capillaries they would get block. Now, this pore space you know they will be then isolated pores; let us say, relatively lower cement ratio much lower than 0.7 say 0.5, 0.4 etcetera.

So, as the hydration progresses sometime they will get actually capillaries will get segmented. So, if they are segmented they are now, isolated pores this isolated pore has got a given size. As an further hydration progresses size of the pore will also reduce. So, it is not only the volume of the pores, which will reduce with age and hydration it also you know size also, reduces and therefore, since the size of the pore and volume of porosity, both reduces strength increases with age and the relationship of water cement ratio to strength is something of this kind.

So, we can understand age is a factor well for that is why normally we take 28 days strength of course; it will depend upon type of cement rapid hydrating cement would give you high early strength. The nature of the strength increase with age would not be same it will not be same for given you know for 2 different types of cement. For a given type of cement it remains of course, constant and for different types of cement actually it will change this is what is shown in this diagram.

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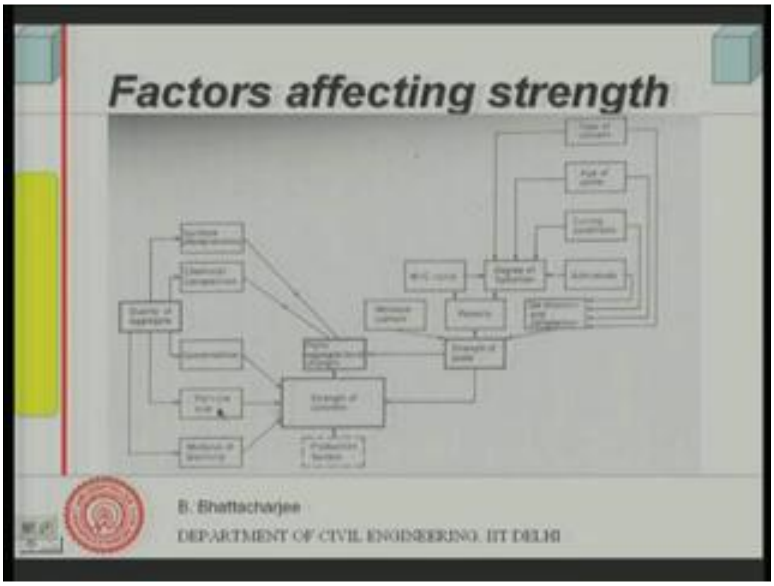

So, let us look overall factors affecting strength of concrete. Now, this diagram shows you overall factor affecting strength of concrete. You see this is the strength of concrete and production factor of course, and then dictates final strength of concrete production factor. This is the strength of concrete this is small factor let us say production factor means mixing, batching mixing how accurate they are we have discussed. This altogether production, factors means; batching mixing transportation placing and compacting and curing all these are production factors. So, they control the strength of concrete that is what we have seen. Now, let us see what are the other things we have seen that, paste aggregate bond is a 1 which strongly controls the strength of concrete and strength of the paste itself control the constant of concrete. In addition to we have changed the quality of aggregate out of which, concentration means; aggregate content how much concentration of the aggregate is there, the msa and its modulus of elasticity these are the 3 major factors from aggregates point of view they control the strength of concrete.

So, production factors paste aggregate bond and strength of paste now, this is the aggregate content you know quality of aggregate if you see it controls this concentration particle size and modulus of elasticity. You go back, this quality of aggregate again controls the chemical composition of you know of the concrete can give you better bond. As you have seen in some cases, but surface characteristics is 1 of the major thing that is surface roughness and pores surface pores, if they are surface pores they will bond better.

So, some quality of aggregate improves the paste aggregate bond that is what we have seen today, we have also seen that some properties of aggregates will be controlling the strength of concrete directly. Now, come to the strength of paste several things would govern the strength of paste. First of all let us look at this strength of paste will be governed by the porosity, of the paste itself the moisture content of course, would govern the paste when, you know paste strength is also governed by the moisture content of the paste.

We shall see the effect of moisture content of strength of concrete and you know concrete cubes sometime in connection with the test. So, we will see that moisture content actually governs the strength of paste then porosity porosity. In fact, 1 factor that would govern this is the strength of the paste governs this.

Now, strength of the paste and strength of the bond both you know strength of the paste governs this and you can see the porosity which is controlled by water cement ratio then degree of hydration age. So, degree of hydration and water cement ratio controls the porosity also gel structure, which is governed by admixtures curing conditions age of the paste and type of cement. So, type of cement age of the paste curing condition curing condition and admixtures all actually govern the curing condition age of the paste and type of cement and admixtures all govern the structure gel structure and its composition structure of the gel structure you know that, we mentioned and this in turn actually controls the strength of the paste.

Now, this also these admixtures also can control the degree of hydration because you can have something like accelerators or retarders. So, this can govern the degree of hydration together with water cement ratio controls the porosity and degree of hydration is also governed by curing condition age and type of cement. So, finally, you can see strength of concrete is governed by all these factors and, it is essential to understand all the water cement ratio is the major factor controlling the strength of paste I mean, strength of paste the other factors aggregate properties they also do contribute.

The cement al1 does not contribute to the strength of concrete main factor of course, has been recognized as water cement ratio because even this bond will be controlled by water cement ratio although, this diagram does not show this, but ITZ characteristics controlled by water cement ratio particularly, the bleed water shrinkage these are controlled by the you know water cement ratio. So, water cement ratio plays a very strong role in strength of concrete. In addition, the cement also plays a role in strength of concrete in addition cement also plays a role and aggregate also plays a very strong role.

So, you can't ignore the effect of other most important is what water cement ratio, most important is water cement ratio others do play a role, that includes both aggregate as well as cement both aggregate as well as cement. So, relating strength of concrete al1 to cement strength al1 to aggregate strength this you know for, I mean; al1 to cement strength or al1 to aggregate strength or for a given water cement ratio to either, only aggregate strength or to cement strength is not really may not be really scientific.

So, strength should be related to water cement ratio and you know this should preferably be related to all factors together and that is what Abraham's law. It relates it to the strength and the constant that I mentioned earlier, K1 and K2; actually related to the you know the constant K1 and K2; these are related to both cement all cement and aggregate both cement and aggregate system. So, that is what the strength of concrete is. So, if you summarize today's discussion, we had we discussed the role of concrete strength.

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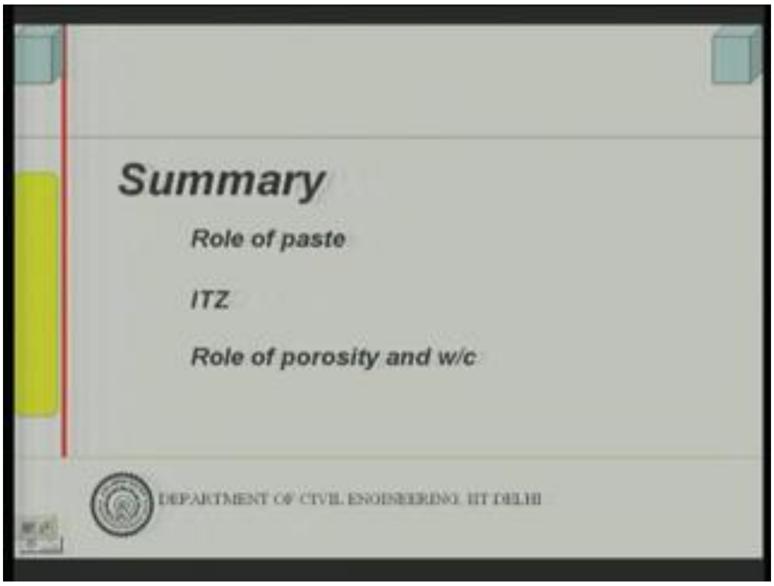

If you summarize first we looked into role of paste, role of ITZ then role of porosity and today we actually looked into from fundamentals we went today we went a little bit beyond and we looked into the role of aggregates mainly compaction etcetera, but still fundamentally it is the, you know porosity and pore sizes that finally, governs the strength of concrete and that is controlled porosity and pore sizes; that is controlled by both ITZ characteristics and bulk paste porosity both that is mainly controlled by water cement ratio.

So, we have seen that water cement ratio of course, affect the strength of concrete, but further you have seen that in addition to that bond characteristics govern somewhat by cement somewhat by cement although higher strength cement not necessarily, give you higher bond strength, but we have also seen that aggregate has got a strong role to play as far as strength of concrete is concerned.

So, in the next class, next lecture we will look into the test aspect of you know the test because test factors, control the cube strength as you measure the measured strength and in our next lecture we shall look into the aspect of the test which actually controls the strength. So, that that would give us brief idea of the cube strength which we started, in the first class; to you know, various factors which affect the cube strength both measurement as well as factors related to mix parameter.

Thank you.