Concrete Technology
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Lecture - 24
Strength of Concrete: Aggregate Contribution

Welcome to module 6 lecture 2. We will continue with Strength of Concrete, Aggregate Contribution, also we will look at some other contribution.

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So, if general outline of this discussion should be paste aggregate bond where we will talk about paste strength then water cement ratio, surface roughness, chemical composition, etcetera related to the you know, aggregate. Then effect of aggregate properties, but we will also look in little bit on air entertainment, compaction and age, and lastly we will look just introduce the tensile strength of concrete. So, in the last lecture actually, we looked into the effect of essentially how you know strength is controlled or governed by water to cement ratio. Compressive strength of concrete of is is or cube compressive strength you know we measure in terms of cube or cylinder compression strength. And that is essentially, governed by water cement ratio is the major factor, the other factor some of the other factors will come to you know come to light today.

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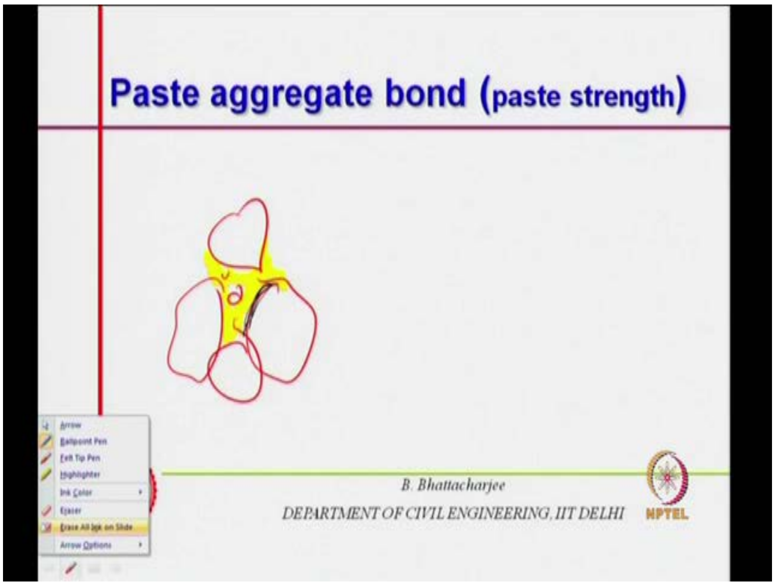

First is paste aggregate bond alright, paste to aggregate bond you know as we said that, concrete is a particulate system concrete is a particulate system like this aggregates and aggregates, etcetera etcetera all kind of aggregates you will have and they are bounded by you know paste paste system paste aggregate system. So, this bond this bond is very very important you know, yesterday we talked about we said that, aggregate aggregate paste interface, this plays a very strong role. So therefore, one has to look into how you know, what governs the paste aggregate bonds. So, let us just have a look at that and how it effects the concrete strength so you can look into that.

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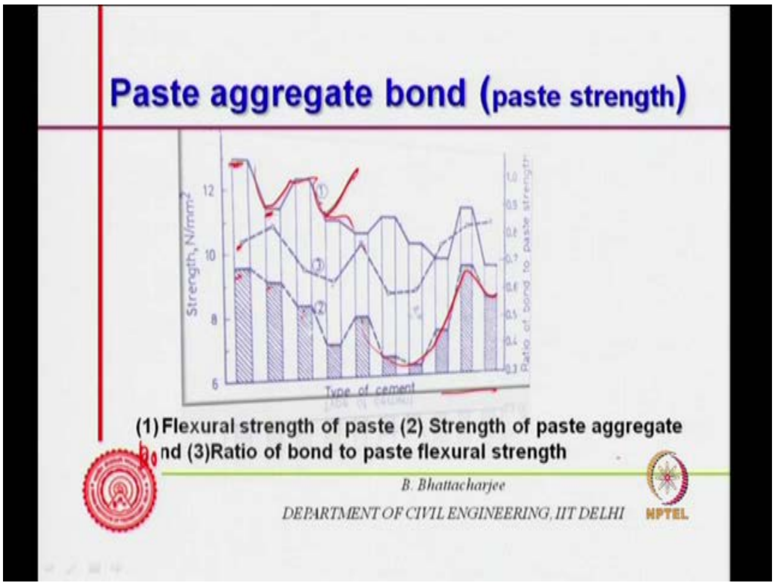

And to do that, one can look into this kind of a diagram, which shows said that figure this one this one you know this one shows diagram 1 shows, if we have different cement, the flexural strength of paste would be something like this flexural paste strength of paste would be something like this flexural strength of paste. Two shows, strength of paste aggregate bond two shows strength of paste aggregate bond so this is the paste aggregate bond you know.

So then three is the ratio of bond to paste strength ratio of bond to paste strength you know so this is this side right hand side is the ratio, these are the strength in mpa, these are the strength in mpa and this is the curve for ratio. So, for example, here this strength flexural strength of the paste and strength of paste aggregate bond and this is the ratio of bond to paste strength. So, this divided by this now, we can see these values somewhere here.

When it comes to this, this increases because this is lower this reduces but not as much as this here, it will still be low and here here basically, you know the ratio, this is quite low, this is low. So, ratio is also somewhere there but here, this increases, this also reduced so this ratio increase. So, you can see the ratio where is, it is not a constant line in other words, paste strength bond strength, paste strength do not directly govern or 100 percent govern the bond strength.

You know if had it been the case for example, if I increase the strength of the paste itself, flexural strength let us say, in this particular case or in a way, a matter of tensile strength let us say then strength of paste aggregate bond. This is strength of paste aggregate bond at this ratio you know, it will be in slowly depended on flexural strength of the paste or strength of the paste itself. Then I would have got a constant line but I am not getting a constant line it means, there are other factors which governs.

So, strength of paste aggregate bond is not only controlled by strength of the paste, not necessarily controlled by the strength of the paste where, strength of the paste is higher. Bond strength is here where in this case, strength of the paste is much lower but the bond strength strength is not that much low. So, this ratio actually increases, had it been all same it would have possibly increase and if you see here, paste strength is quite low but bond strength is quite high, it is as high as this. So, this value has increased, the ratio is increased significantly so bond strength is a function of the paste strength alright. But, you know this is I mean, it is not a constant, it is not necessary that you increase the paste strength, bond strength will increase so that is the first point.

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So, bond strength may not increase, may increase or may not increase so bond strength is lower than that of the paste that of course, you have seen. And bond strength is not necessarily proportional to paste strength not proportional to paste strength, I will call it paste cement paste strength you know, it is not proportional to paste strength. So, that is one must understand, ITZ governs the concrete strength ITZ governs the concrete strength that is what we have seen, so the bond is very, very important.

Now, what governs this paste aggregate bond, cement type is a factor but there are other factors so let us see other factors. This bond is mostly mechanical, physical and in very few cases, can be chemical but mostly, it is mechanical and at best, physical. Mechanical bond you know, you might have roughness of the surface of the aggregate and and paste might come in there, paste might simply come and sit there paste might simply come and sit there paste might simply come and sit there.

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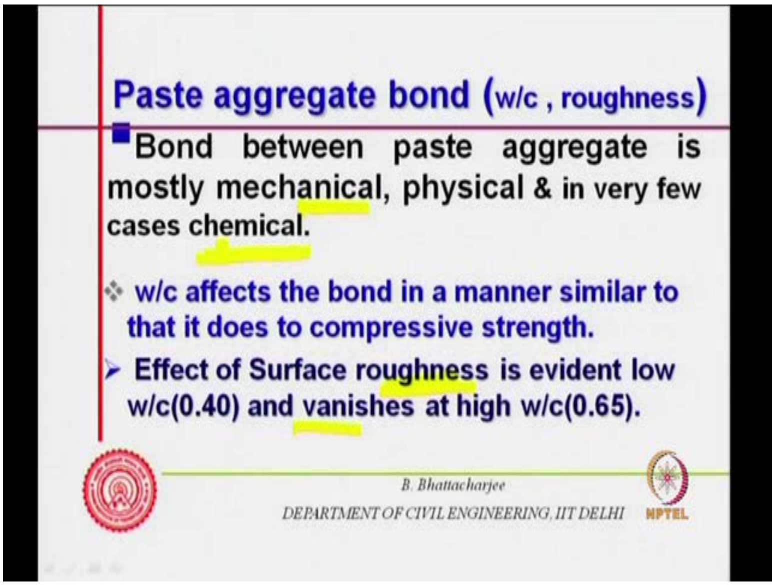

So, it is mechanical bond you know mechanically you want to pull out, this is the paste so it is it could be mechanical bond sitting on the roughness of the aggregate. Physical between the paste to paste is physical, paste to aggregate is you know not necessarily not not not many times physical bond. But, adhesive forces can exist because you know one was in plastic state, other is solid, the aggregates are generally solid, paste was in plastic state.

So, there could be some sort of physical bonding may occur but largely it is mechanical bond. Chemical bonds are rare and this occurs essentially, in case of pozzolanic aggregate. So, we will just see that, you know we will we will come back to that come back to that sometime later on that, sometime it is chemical sometime it is chemical largely, when you have volcanic source aggregate, from volcanic source we will come to that sometime later on.

Now, what are cement ratio effects of bond in a manner, similar to that it does to the composite strength of the paste. So, water cement ratio affects the bond strength in the similar manner, like it does to the compressive strength, that we have discussed this in the last lecture that ITZ properties, it is porosity is a functions of water to cement ratio. Effect of surface roughness is evident in low water cement ratio at a very high water vanishes you know, at high water cement ratio it vanishes.

Surface roughness is an important factor, surface roughness of the aggregate is an important factor particularly, at low water to cement ratio because the bond is mechanical. So therefore, surface roughness is very, very important right, surface of aggregate, so if you see, what is surface roughness of aggregate I mean, by honeycomb aggregate. If it is a polish surface, texture is polished, you can have textures polish textures to rough texture, honeycomb texture and so on and so forth, textures of aggregate are also classified.

So, if it is absolutely polished glassy or polished texture then the bond would be poor, while if it is rough, the bond would be better. It is not nothing to do with the shape of the aggregate, shape could be circular, spherical and even, you can have surface somewhat rough or honeycomb, depending upon type of aggregate alright. So, roughness is very, very important now testing this is not very easy, effect of roughness but some test has been done. For example, bond is created between aggregates are phased in the paste and then try to find out to through a pull out kind of a test.

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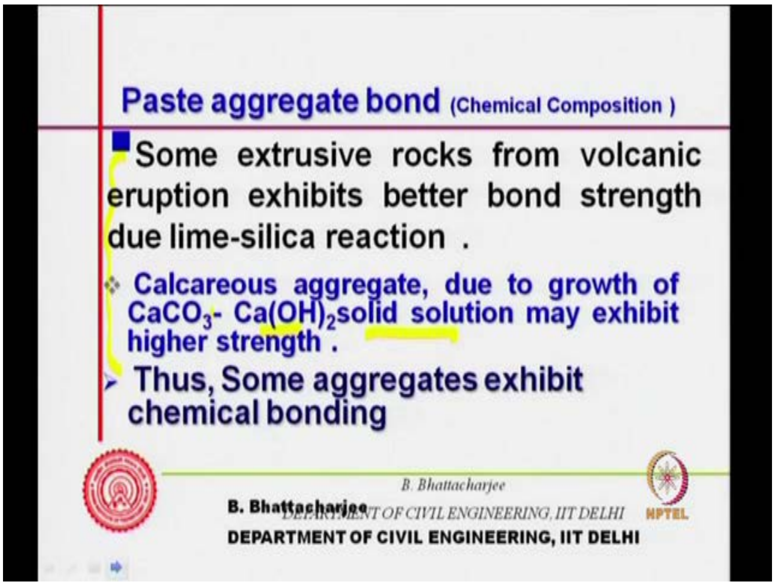

And some results are available typically, we will just show it in a kind of table so some some results are available. Volcanic as is said, the chemical bonding occurs when you have got volcanic exclusive rocks from volcanic eruption and they can have better bond of strength due to lime silica reaction. Because, cement hydrates have got lime that is what, we have seen earlier and this lime can react if the aggregate surface has got some sort of reactive silica.

So, pozzolanic sort of similar to pozzolanic reaction this can occur and some of the calcareous aggregate due to growth of calcium carbonate, calcium hydroxide solid solution may exhibit higher strength you know. So, because of solid solution of calcium carbonate, some calcareous aggregate and calcium hydroxide produce from the cement hydration, solid solution can form. So, this may exhibit higher strength but this is very rare, this is not very this two are not very, chemical bonding is not very common. So, mostly, it is mechanical as you know I mention, some aggregates exhibits chemical bonding alright.

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Now, the cement aggregate bound arises from mechanical, physical or chemical bond surface, rugosity or roughness plays a major role. Mechanical inter locking rather than chemical bonding, tackiness is a question of surface surface properties, tacky surface. So, that is, if penetrates into the pores or holes and scratches of the substrate to bond that is what I am saying suppose, you have got a surface you have got a surface like this with some hole say here surface with some hole here you know some holes here.

Honey combed honey combed honey combed aggregate surface exacerbated and the material goes inside this so it creates bond. So, adhesive that is our aggregates, they will penetrate inside to the substrate and creates the bond. So, that is what I showed earlier diagram also, that is mostly mechanical that is mostly mechanical, the roughness values although small are quite huge compared to the bond strength bond length. So, roughness values they can be small but in absolute term but large compared to bond length.

So, bonds are order of nanometer, roughness could be order of millimeters, micron surely but could be you know order of millimeter or microns surely. So therefore, they are very large and therefore, you know roughness is the major issue here so bond strength bond length is very small so bonded material, they penetrate into the roughness. When there was bond can act on surface of this similar material but this is not very major role, aggregate paste bond is mechanical.

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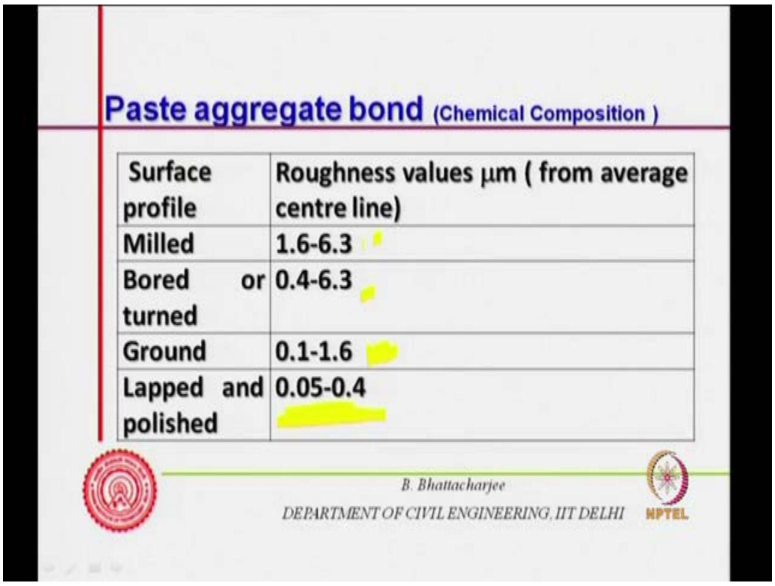

And this is what, the people you know studied related to roughness so roughness values in micron for from you know center line. So, these are in 1.6 to 6.3 bored or turned material is milled material, you will have 1.6 to 6.3 lapped or polished material. So, polished material has got the least grinded ground material is something you know grind material so milled bored. But, surface profile from average center line you know, these are the roughness values, but aggregate may have larger still larger values aggregate may have still larger values.

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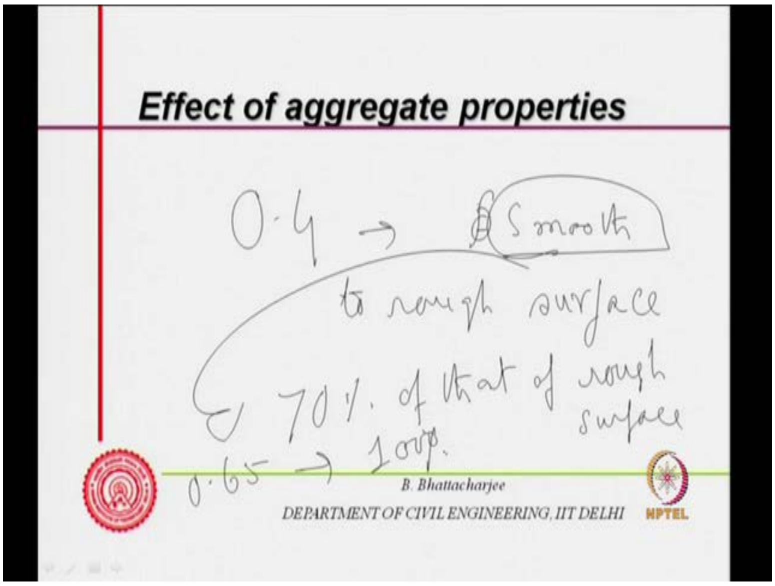

Now, this you know this how how does 0.4 water cement ratio we just mentioned earlier, 0.4 water cement ratio the reduction in strength, because of surface structure could be as low as 0.7 you know. Strength could be as we said, it could be as much as 0.7, 70 percent and it vanishes somewhere. So, if one looks at this roughness values, if one looks looks looks at 0.4 water cement ratio, a factor it can be roughness, as smooth to rough surface smooth to rough surface. If we look at it, smooth surface may have strength 70 percent of that of rough surface with 0.65 water cement ratio, same it is 100 percent. So, variation see, if you have 0.4 4 water cement ratio, strength reduction could be you know the smooth surface can result in reduction in strength to as much as by 30 percent. While for 0.65 water cement ratio, this does not have any effect so that is how the roughness effects right.

Now, what about aggregate properties itself, if you look at ordinary concrete strength versus water cement ratio, strength to water cement ratio where is, as water cement ratio increases strength decreases. But, if you come to some light weight aggregate concrete, which are weaker aggregate weaker aggregate, they actually exhibit lower strength especially, when water cement ratio is reducing. And cracks can pass through the aggregate themselves cracks can pass through the aggregate themselves cracks can pass through the aggregate themselves because weak aggregate.

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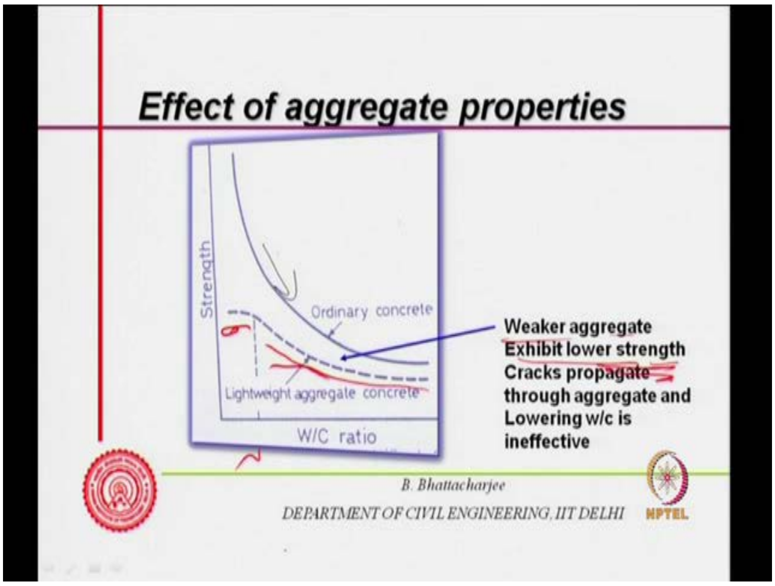

So, strength is usually governed by the weakest link, if the paste is weak and paste ITZ is weak, it will pass through ITZ, it will not cause cracking of the aggregate but it may start from ITZ in any case, if it is a largest void. But, as it initiates, it might pass through the aggregate straight way if the aggregate are weak. For example, if you just bricks low strength bricks something like 7.5 mpa or bricks or 10 mpa bricks and crush them and make aggregate out of them.

Particularly, 7.5 or so bricks and make concrete out of them you will find that, the strength of the concrete is low. Even if you have water cement ratio is relatively low, strength of the concrete is low and all the fractures planes are passing through the brick aggregate themselves brick aggregate themselves. So, strength of the aggregate is an important issue, weaker aggregate exhibit lower strength right so more so in low water cement ratio scenario.

Modulus of elasticity have exact concrete fracture properties thus, affects the strength because we said that, the you know modulus of elasticity of the four free material, that governs the critical stress, that which fractures propagates spontaneously. So, fracture properties you know and thus, affects the strength so therefore, modulus of elasticity of the aggregate is important.

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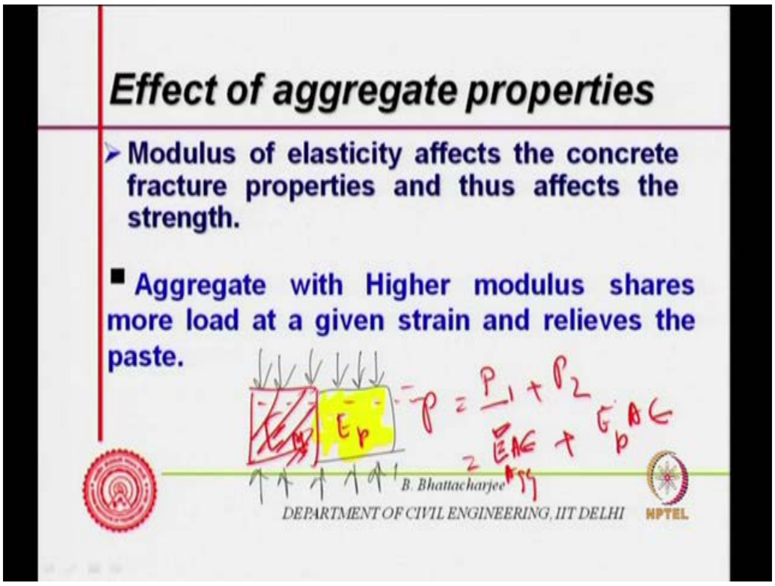

Because, modulus of elasticity will govern the pore free solids, modulus of elasticity the modulus of elasticity of the pore free concrete system is a function of the modulus of elasticity of the aggregate as well as pore free paste you know. So, if E of the concrete we just can write, it would be a function of E of the aggregate and E of the paste, no pore, pore free pore free so if you look at this, you know porosity will bring it down. So therefore, E of the aggregate has got a role, all fracture properties are controlled by modulus of elasticity of the aggregate.

And therefore, this will play a role in you know strength of the concrete, high modulus of elasticity tend to give you higher strength. Aggregate with higher modulus shares more load at at a given strain and relives the paste, so this is also an issue. For example, if you just consider, this is my aggregate and this is my paste this is my paste and I am loading, just as a simple model just as a simple model I am loading it like that. So, under same deformation so if the deformation occurs are same under same deformation, deformation occurring is same you know, deformation is same.

So, this has got low E, E is different this is let us see E is higher E A g g is higher than E p so E aggregate higher you know, it will be actually stress p by proportions, it will depend upon of course, the proportions. So, the load shared would be p 1 plus p 2 and total load p and p 1 would be related to same deformation E epsilon into you know and same area let us say, volumes are same for the time being. Then it would be simply p 1 will be equals to strain, same into E into you know A E A into epsilon. So, E aggregate into epsilon plus p 2 will be E paste into A into epsilon, both will have same deformation. So, whichever is higher, will share more the load share more load if the area is same, just for the understanding part of it. So, higher modulus shares more load at a given strain and relieves the paste, so paste will be loaded less. It can share more and it can relive the paste so that is the idea that is the idea that is idea.

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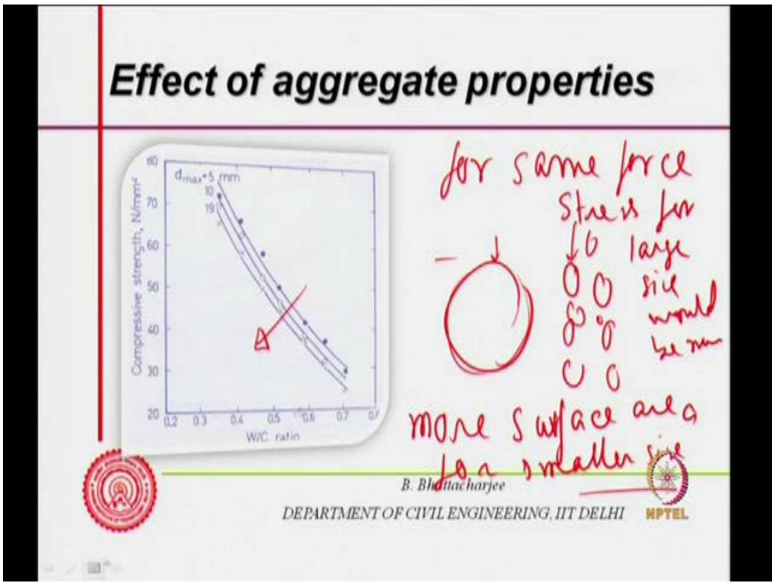

And size is important because larger the aggregate size for example, in this direction, size is increasing, larger the aggregates size right so size affect larger the size, strength to water compressive, strength to water cement ratio strength decreases. So, larger size means, stress concentration around you know same stress supposing, I have got larger size, the stress same stress has to pass through it same stress has to pass through it so this is lesser area now, we have got smaller sizes smaller sizes occupying same volume.

So, surface area is more, more surface area more surface area for smaller size thus, as the size of the aggregate increases, strength can reduce, strength can reduce as the size of the aggregate increases. So, more surface area for smaller size for same stress, for same force same force stress, for larger size will be more larger size will be more. So therefore, because you know thus it would be more So therefore, size has got a size has got a role, larger the size strength will be lower strength will be lower right.

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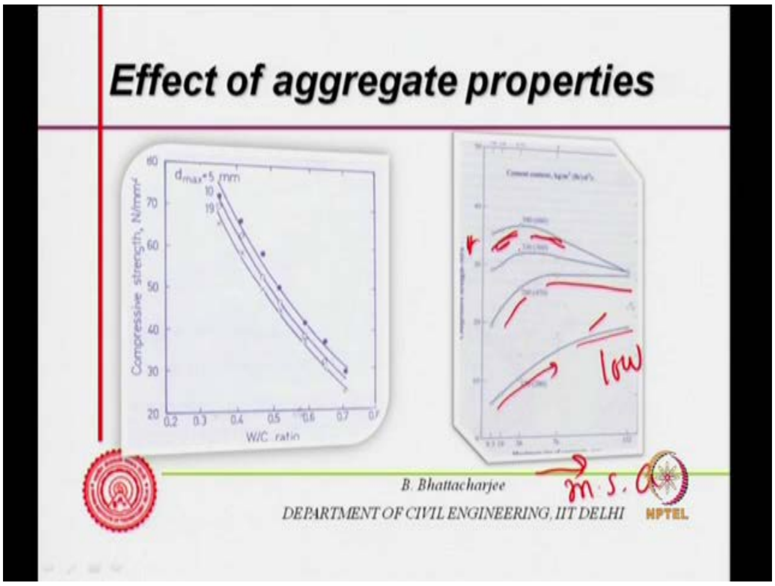

So, this curve is lower and it has been actually observed that, m s a governs the strength, how does it governs the strength, m s a governs the strength, you see it has got two kind of an effect. Larger the aggregate size, stress around the maximum size of the aggregate, larger the m s a, stress around the maximum size aggregate is going to be higher. But, it has got a role in packing to it has got a role in packing to you know, larger the size less paste should be required to fill it less paste will be required to fill it in less paste will be required to fill it in.

Now, strength could be lower their strength could be lower there so what has been observed is that, if you go on increasing m s a along this direction m s a along this direction for low cement content low cement content, strength increase as you increase the m s a. And then it does not increase further, here the strength increase becomes constant and at high cement content, strength increases and start decreasing. So, as you go on increase the you know m s a, the as you go on increasing the m s a, your aggregate itself is also strong.

Over all there is an increase but at higher water cement content, actually this effect of stress concentration around the larger size aggregate starts dominating. Here, the aggregate is paste, is not very strong, low cement content paste is not less, you have I mean, sorry paste is less and the may be your you know lean concrete situation, paste is less. So, it is aggregate, which dominates the strength, more the aggregate larger the aggregate, may be you know it is larger size of aggregate, you can accommodate strength increases, but as you increase it beyond a point, the stress concentration around aggregate starts dominating. So, m s a increasing strength increases in the beginning but here, the for you know this is for this is for high cement content situation, the strength increases this excessive strength, strength increases then it start decreasing. So, what we find is that, when you have got mass concrete where, paste is relatively low, overall strength itself is also low. So there, you can actually accommodate larger aggregate without compromising onto the strength.

While you have got you know relatively higher strength concrete, structural grade of concrete, if you increase the m s a, strength starts reducing. Because, overall strength is higher overall strength is higher, your paste content itself is higher, cement is more cement you know cement is and the stress concentration around the aggregate starts affecting lowering down the strength because strength is governed by the weakest link. So, this is the reason, why you find that m s a for structural rate of concrete is mostly 20 sometime 40.

For mass concrete, it is 75 mm or 150 mm and for high strength concrete, it might be 10 mm, simply you have 12.5, very high strength system may not have at all the course aggregate itself. Because, uniformity is required, stress concentration around the aggregate is not desirable, non uniform, one material to you know transition from one material to another material. So, it should be uniform material as uniform as possible, not uniformity always results in stress concentration because modulus elasticity of the paste and aggregate will be different. So therefore, there will be stress concentration around the aggregate system and that is reduced just lowered down right.

So, size of the m s a is important, basically presence of aggregate particle introduces stress concentration at interface, volume of region of stress around aggregate increases with aggregate size right. And in practice, lean concrete m s a is higher lean concrete m s a is higher lean concrete m s a is higher, because of lower requirement of paste and water thus, water cement ratio can be reduced with higher m s a you know. You can have low water cement ratio but but higher m s a paste should be less paste should be less. For higher strength, stress concentration discontinues, discontinue to assign lowering of bond area dominates and therefore, your m s a is limited to certain value, something like 20 or 44 structural as I mention.

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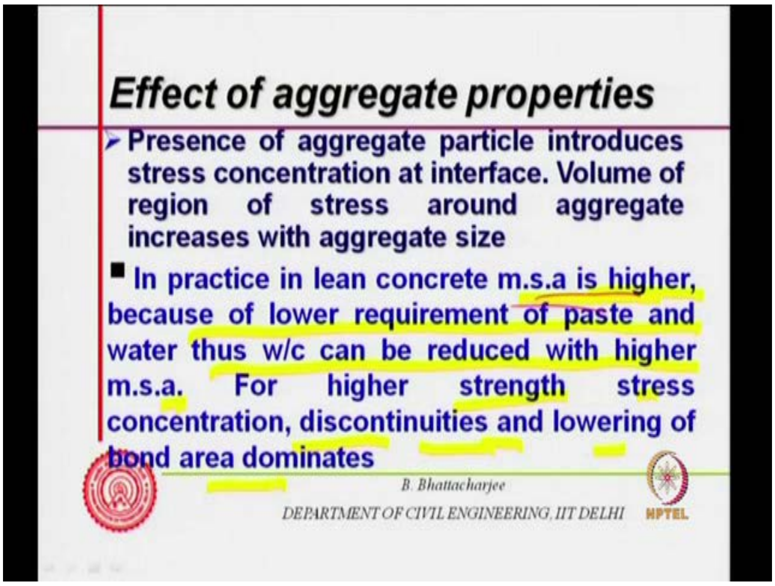

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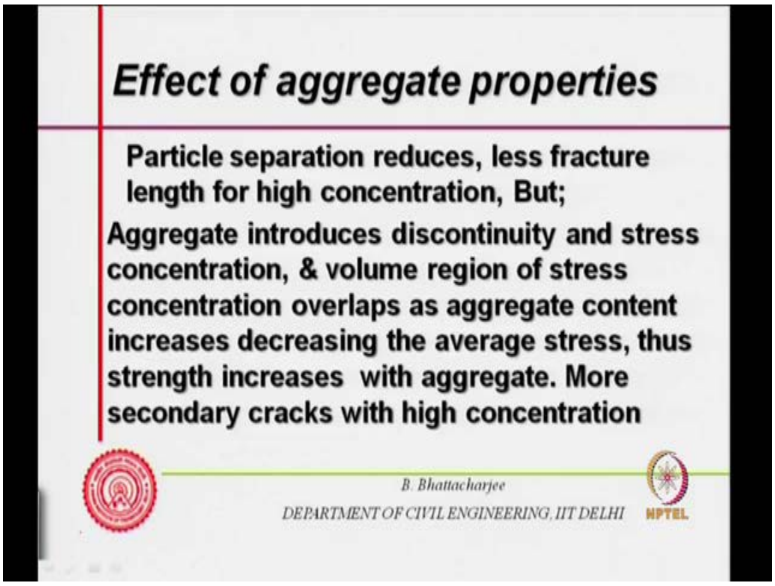

Concentration, quantity, how much is the aggregate quantity, particles separate reduces if I have more aggregate, this is less aggregate, is paste is more. Another case, I have got more aggregate so the particle separation reduces particle separation reduces, less fracture length for high concentration. So, if you have high concentration, the distance between two aggregates are small, high concentration and therefore, fracture length is lower, that is what the idea is.

But, the other side of it is, aggregate introduces discontinuity and stress concentration and volume region of stress concentration overlaps as aggregate content increases, decrease in the average stress. The strength increases with aggregate, more secondary cracks with high concentration that is also observed. So, because regions of stress concentration would tend to overlap and therefore, actual area tends to becomes larger and you know this reduces this causes more aggregate tends to reduce down the effect somewhat and strength increases well. Normal strength concrete normal strength concert actually in high very high per strength concrete, paste content is in fact, more to counteract the shrinkage effect. The shrinkage effects will also come in, as your paste is more or cement is more, there can be shrinkage effects. So, that might results in cracking of the whole thing, so your aggregate system more aggregate system, the shrinkage effects also will be relatively less.

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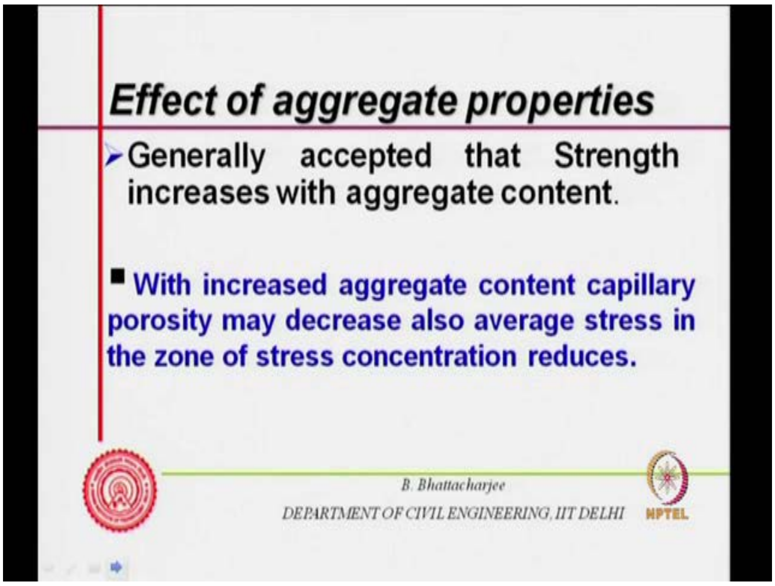

Generally excepted that, strength increases with aggregate content in normal concrete in normal concrete, generally expected the strength, increases the aggregate content. Because, aggregate themselves are strong, it is quite often more you know more stronger than the paste itself. With increased aggregate content, capillary porosity may decrease also, average stress in the zone of stress concentration reduces so that is the idea you know that is the idea. So, everything is just in a similar manner and that is why, as you increase the aggregate, strength increases in ordinary normal I mean, normal strength concrete. But, where there is x x you know high strength concrete you might have to have much higher paste content to ensure that, there is a bulk shrinkage shrinkage rather than shrinkage between the aggregate, we will come to that sometime later on.

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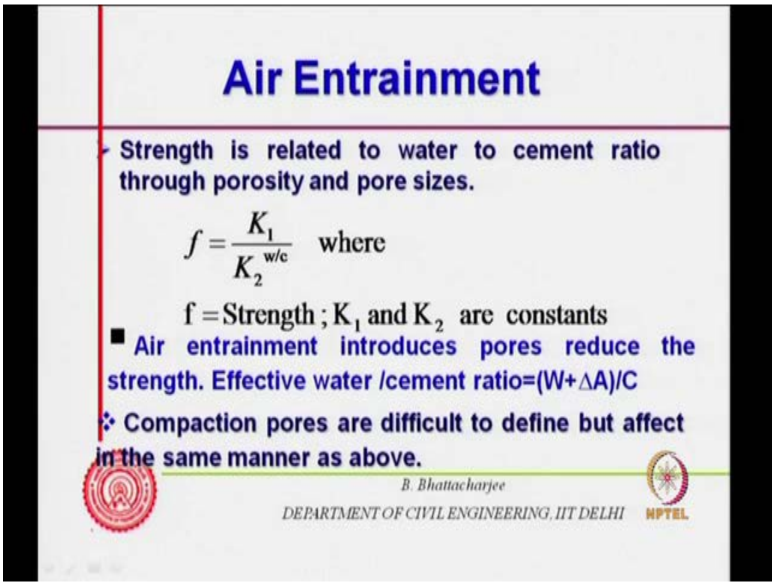

Strength is related to water content and porosity and you know cement water to cement ratio, as we have seen porosity and pore sizes. Now, this is water cement ratio governs the strength, that is what we have seen. Now, if you have air content then you introduce more porosity so effective water cement ratio in fact, would be increasing any way, I can say that way. I mean finally, the role of water cement ratio, higher water cement ratio results in more porosity, air entrainment can also can introduces pore and thus, reduces the strength.

So, you can think in terms of ineffective water to cement ratio being increased well, we can now understood understand pretty well that, actually we have been talking about that you know directly the porosity water cement ratio causes increase in porosity and pore sizes and therefore, there is a reduction in strength. Air entertainment, the pores are of course closed pores, they are closed pores are not inter connected, well distributed. But, the sizes are also quite large and they can introduce, air entertaining agent can introduce pores close pore systems and they have a tendency to reduce of the strength.

But, we might scarifies that strength if you are getting benefit in certain other properties particularly durability, which we shall see later on. So, air entertaining agent has also introduces can reduce the strength by about 5 percent, it can reduce the strength by about

5 percent. Compaction pores are very difficult to define, they can come because of the air void remaining, you have not compacted it properly. So, some air void remaining we have seen that, vibration can remove air voids but supposing we have not done 100 percent vibration. There is no honeycomb as such but the voids are remaining now, this air voids will also reduce down the strength. Therefore, proper compaction is absolutely essential in order to ensure that, your strength attain strength is proper attain strength is proper, that is what it is.

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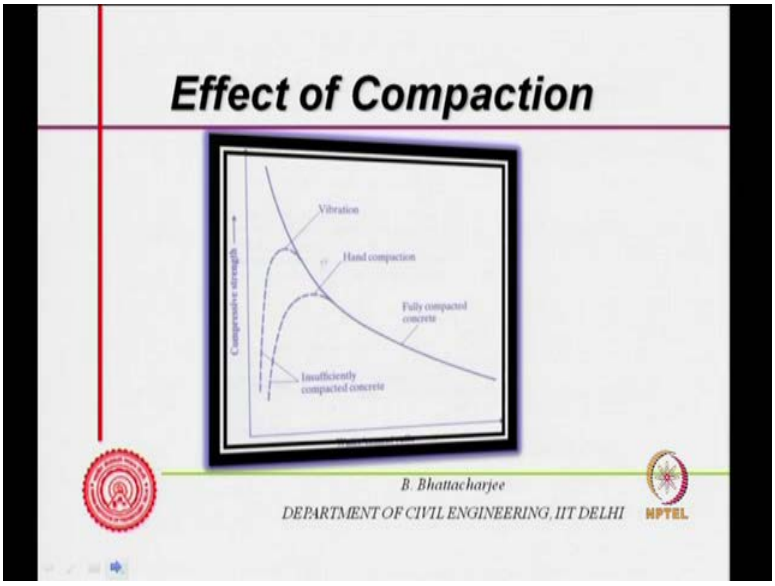

So, effect of compaction now, you can see that, this is fully compacted concrete, if you do a hen compaction, the strength might come down especially, through low water cement ratio. Because, workability you know, the consistency of the paste may not be high enough to to to compact it easily or flow properties may not be good enough for compaction. And if you have vibrated concrete of course, you can go further but still, poorly compacted concrete can show bad results and this can happen in low water low paste content.

So, this excess is actually your water to cement ratio water to cement ratio and this is your compressive strength. So, compressive strength versus water to cement ratio normally, the curve should have been like this. But, if I have a poorly hen compacted concrete, I will get like this poorly vibrated concrete I will get get like this because there will be compaction pores coming in so compaction pores coming in results in this.

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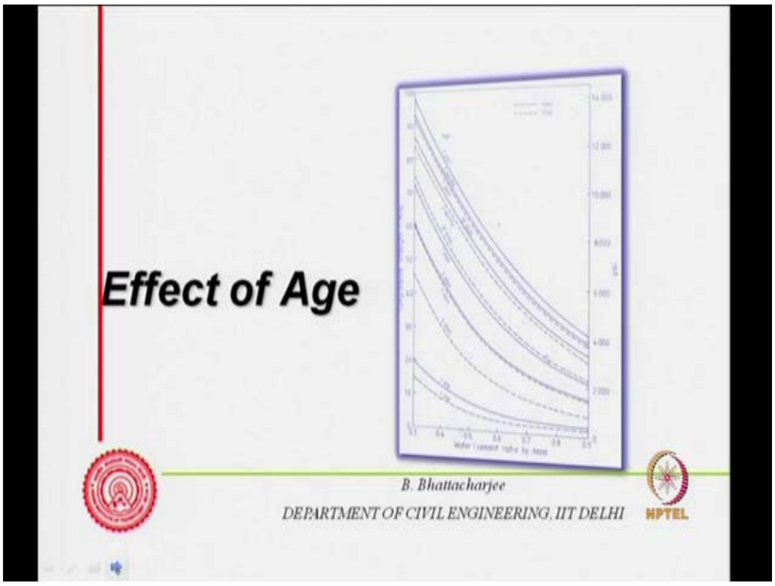

Age, strength will vary with the age for example, you have 1 day strength, 3 day strength, 20 day strength and 1 year so on and so forth. So, as the age increases strength increases, compressive strength increases, strength versus water to cement ratio this strength. So, strength verses water to cement ratio curves, they tend to go up with age and we do understand this because with age with age, hydration will progress will progress resulting in lesser lower porosity and pore sizes. So, strength so strength should increase so strength shall increase.

Now, this is a function, hydration itself is a function of course, water cement ratio but as you can see, this effect should be you know this effect is quite prominent in low water cement ratio but even high water cement ratio, this is also fairly prominent. Low water cement ratio hydration possibility is actually more but then of course, there is a range beyond which, 0.4 we are taking of, 0.3 we are taking of, beyond that of course, hydration full hydration is never possible but does not matter.

This is we have discussed this sometime earlier that, full hydration is not possible beyond certain below certain water cement ratio right. But, does not matter, this it blocking or reduction of the porosity is most important aspect. So, as the age increases porosity will reduce, pore sizes will be finer, refinement of the pore size would take place. And therefore, strength increases you know and strength to water cement ratio curve tend to go higher right. So, at 1 day variation is less but if you look at the variation at 1 year from high water cement ratio to low, water cement ratio get significantly high significantly high significantly high.

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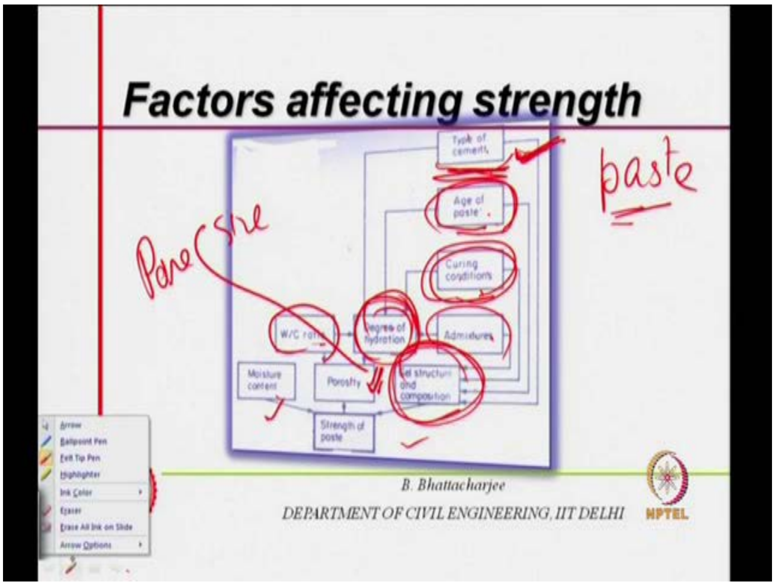

So, what are the factors those of effect strength if we look at it, first of fall type of cement has got a role. Let us say, this is a paste, effective strength of paste, we are looking at strength of paste. So, type of cement has got a role on paste strength at a given age at a given age of course, age of the paste. So, paste, age, type of cement, age, curing condition because hydration will progress only if we have right kind of curing condition and degree of hydration, this three will govern the degree of hydration.

Because, you have as low hardening cement say, one thing is rapid hardening cement now, rapid hardening cement, which we have discussed right in the beginning earlier modules, rapid hardening cement would hydrate at a faster rate. Therefore, the type of cement at any given age, how much strength development occurs or degree of hydration is also a function of that. Degree of hydration will depend upon type of cement, while pozzolanic cement or low heat cement we know that, degree of hydration will be lesser.

So, you know so this degree of hydration will depend upon age, type of cement and curing condition and if you have added that mixtures of course, they would governed. They would If you have added that mixtures, they would actually either retired or accelerate or whatever it is. So, they will also control but this degree of hydration is also function of water to cement ratio, as I mention this is a function of water to cement ratio and this degree of hydration and water cement ratio actually controls porosity right controls porosity.

Now, admixtures type of cement and all this actually controls the gel structure and composition. Now, I would like to add here the pore sizes also, pore sizes you know it is not only the porosity but the pore sizes, over all pore structure, the gel structure everything is governed by this. So, this and the measurement during the moisture condition governs the paste for example, dry specimen shows higher compressive strength but wet specimen shows lower compressive strength.

That is because when you we will talk talk about the moisture condition, sometime while doing testing that is because you know some of the surface energy, absorption of moisture would require. After that, once the moisture is absorbed, you will require less surface energy to produce a fracture surface. So, some of the moisture, you know it is surface tension property so surface now earlier it was between solid and air now, it is between solid and water.

So, the surface energy change occurs and we know the friction between the particles will also become lesser and therefore, the strength will be less so the moisture condition is also important. So, strength of the paste therefore, is governed by type of cement type of cement type of cement, age, curing condition and admixture. Of course, the strength is governed by porosity and pore sizes and which is governed by type of cement, age of the pores, curing condition, any admixtures that you are adding, degree of hydration is controlled by all of them and they control the porosity. Also on water cement ratio, degree of hydration is controlled as well as water of cement ratio governs the porosity and then gel and structure would depend upon all these factors. And finally, the moisture condition, all these actually governs the strength of paste so this is the strength of paste this is the strength of paste strength of paste.

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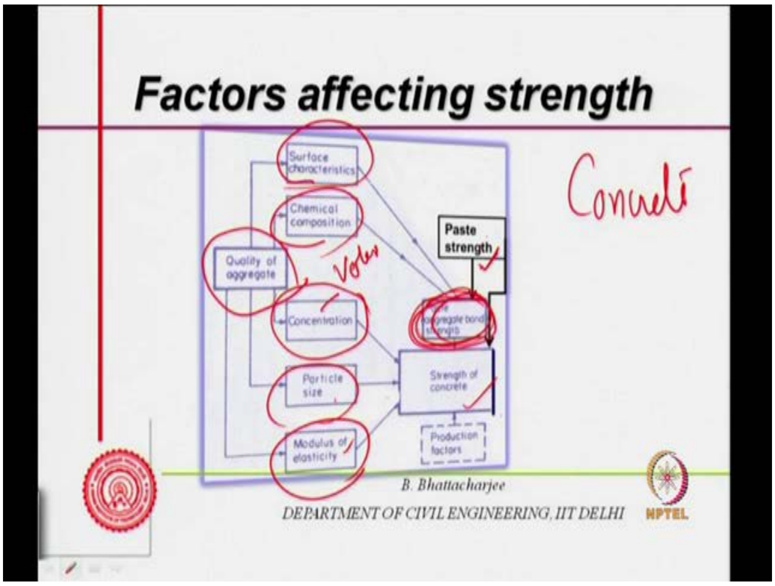

Now, strength of paste has a role in strength of concrete so now, we are talking of concrete, concrete strength of concrete. So, strength of paste you know has got a role in strength of concrete so it has got a role in strength of concrete now, just aggregate is the other one, which governs the strength. So, what are the aggregate properties, first of all basic quality of the aggregate in terms of it is you know in terms of it is particles quality of aggregate in terms of particle size, it is modulus of elasticity right.

And of course, the surface characteristics that is, roughness that we mention, chemical composition because some chemical composition can give you higher bond and it is number, volume, this is volume. Concentration here means volume, particles size, modulus of elasticity, this is all discussed. Chemical composition and surface characteristics, overall quality of the aggregate in terms of it is shapes and things like that, flakey shapes and so on they have some effect on strength.

Now, all this actually governs the paste aggregate bond together with the paste strength paste aggregate bond right. So, paste aggregate bond is controlled by the surface charactertics, chemical composition, quality etcetera but also controlled by paste strength. So, paste strength is not the only one, this all controls actually the paste aggregate bond and then this together paste strength, this together paste aggregate bond together and the the paste strength.

Also, volume concentration of aggregates that is, particle size of aggregate and modulus of elasticity of aggregate, they themselves control the strength of concrete. Because, this is the phase, aggregate is a phase, bond is the other issue, aggregate itself is a phase, if it has got low modulus of elasticity or lower strength, cracks can pass through the aggregate itself. So therefore, particle size, stress concentration, volume all this governs actually strength of concrete, together with the paste strength and paste aggregate bond.

So, this is what, we have discussed and this gives diagram gives you the complete idea and then of course, you have production factor. Production factor is important, which governs the strength of concrete, if you have not done compaction properly, strength of concrete may not be appropriate. So, that is the idea, these are the ones you know all controls the properties of concrete. So, we looked into paste strength and then into, how you know paste strength, what governs the paste strength.

And past strength itself governs the paste aggregate bond and also the strength of the concrete because in the concrete paste is the phase. Bond is also a phase, you know ITZ so this is what it is but aggregate is also a phase therefore, aggregate properties also governs the strength of concrete, that is all governs the strength of concrete.

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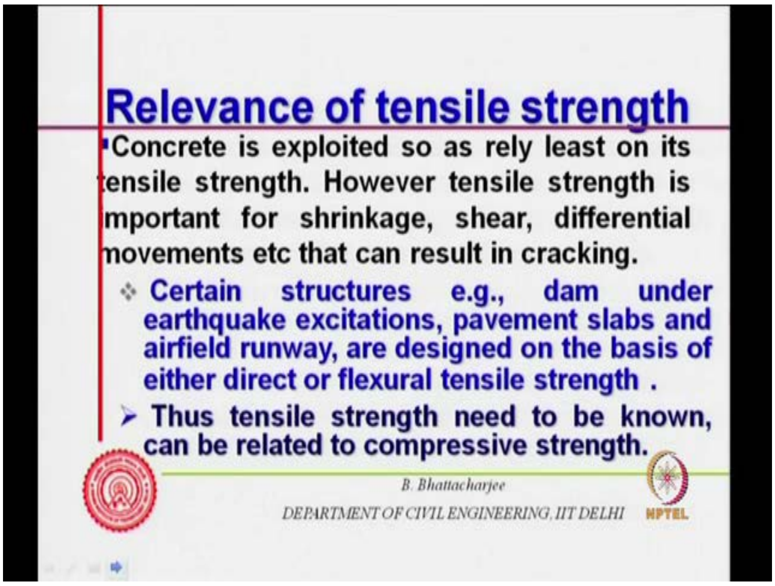

Now, we can look into the tensile strength of concrete so main properties of concrete is a main main mechanical properties, with which you are concerned is a compressive strength but then sometime we are also interested in tensile strength of concrete. Let us see, when we are interested in tensile strength of concrete, you know we rely mostly on it is compressive strength, very little to rely on its tensile strength. However, tensile strength is important for shrinkage, shear, differential movement, etcetera because they can result in cracking.

So, unless you have right kind of tensile strength, it can results in cracking because if you have restrained shrinkage, is something is trying to short and you are not allowing it, which can happen in structures. So, you have restrained shrinkage, there will be tensile forces coming in and it can results in you know… You may not apply directly the tensile force may not apply, may not accept the direct tensile load to be you know resistant by the concrete but tensile strength coming because of the shrinkage.

Shear is always complementary as you know flexural shear, there will be tension and compression I mean, shear can be reserved into two component of tension and compression. Then any differential movement, some place is gone down you know moved relative to the other, that results in internal stresses and all this can results in cracking, because of the low tensile strength. So, cracking because of the cracking occurs, because separation of the particles, separation of the material and that is because the low tensile strength alright lower tensile strength.

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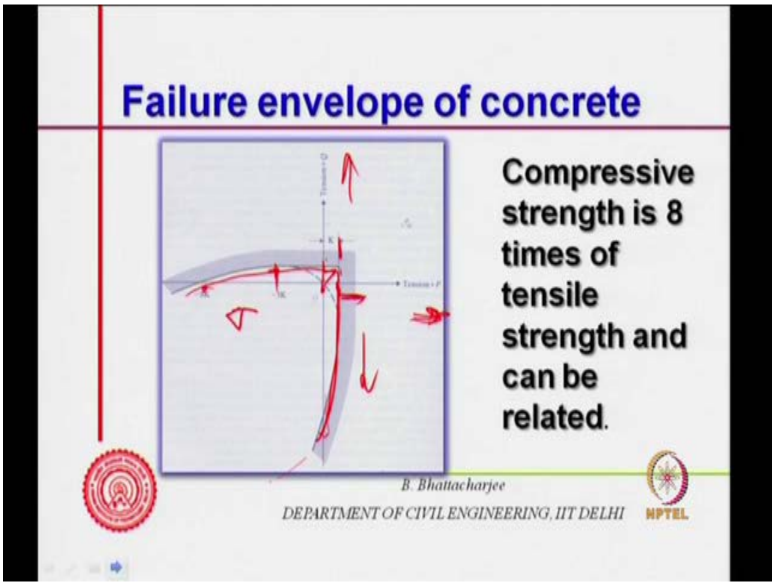

Certain structures for example, dam under earthquake excitation, pavement slabs and airfield runway design on the basis of either direct or flexural strength or tensile strength.

Water retaining structure, you do not want them to crack because you do not want water to penetrate. So therefore, there are also tensile strength because important, pavement slabs tensile strength are important and earthquakes dams earthquake excitation, this is the some places where, we rely on the direct tensile strength or flexural strength of concrete. So, tensile strength need to be known but fortunately it can be related to the compressive strength, it is need to be known but fortunately relate it to the compressive strength.

Let us see the failure envelope of concrete under biaxial situation that means, you have applied this one direction and this another direction, biaxial situation. So, this this side is tension this is compression. this is tension this is compression so p is applied here, p minus is compression so thus, the failure envelop of concrete. This is the failure envelop concrete that means, this is the boundary, if you have tension alone in one direction, more than this it will fail.

Even if this is 0, there is no force on the other direction, tensile force it can withstand this much k as a tensile strength, either direction individually, uniaxial and of course, biaxial situation it can you know biaxial compression it can withstand lot more. So, it can withstand if I look at compression along only this direction, there is no along this direction, it can extend around 8 k. Similarly, k here 8 k there k here and 8 k there so but but combinations if you look at it, this is the situation.

For example, in this case, it is 3 k right is a compression less than a k, in tension slightly less than k, in tension in one direction tension in one direction and compression in the other direction is 3 k. So, it can withstand that much whereas, it can withstand here k and k, tension in both the direction, that is sort of thing. So, this is the failure envelope so what we see is, compressive strength is around 8 times of tensile strength. And therefore, there can be relationship exist can exist between the tensile uniaxial tensile strength and uniaxial compressive strength you know so one can look into this.

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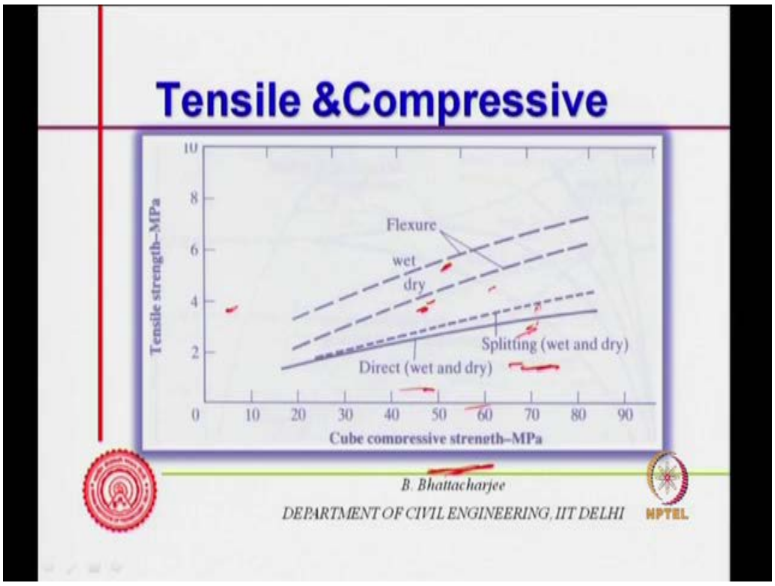

Now, we measure tensile strength in two different ways actually, we will discuss this on the next lecture. We we actually measure them in two different ways, it is of course, difficult to measure direct tensile strength, although there are people now there are some some attempt to do it. But, most commonly we measure by specific method called split split tension method, split cylinder method and this is splitting so which gives you some indication of the direct tensile strength.

And another way is to measure the tensile strength under bending load where, because bending induces tension you know in a simply supported system at the bottom fiber with a load at the top, the bottom fiber is under tension. So, the concrete we can test in that manner and that is flexural tensile strength, that is usual is higher and that can be related to compressive strength you know. Dry and wet condition we can see that, dry and wet condition, moisture condition also (()) strength as we have seen.

So, when we do we do you know when we look at the lecture in method of you know test methods then we will come back to split tension test and flexural test. But, we find that the strength in you know varies, compressive strength varies I mean, tensile strength varies with the compressive strength, both split as well as a flexure. Wet and dry condition, we will discuss this sometime later on because dry condition you can see the strength is low, wet condition strength is higher for a specific reason of shrinkage actually, we will come to that sometime.

While split tension the difference is very very little, so wet and dry the variation is very very little. So they, but what one can see is that, one can relate the compressive strength and tensile strength and people have done that.

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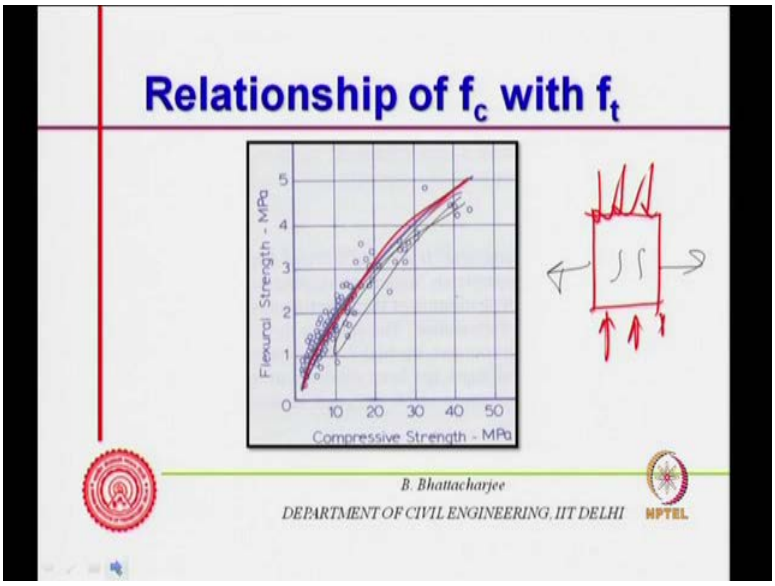

So, basically tense compressive failure is also a tensile failure that is what, we have seen in the other other other other lecture, because it is a failure occurs in the transfers direction right fails occurs in the transverse tension in transverse direction. When applying compressive you know uniaxial compression failure occurs because of this, transverse failure occurs because of this, cracks can occur because of this and therefore, they are related.

So, compressive strength versus flexure strength, one can relate it in this manner, one can get curves of this kind, one can got get curves of this kind generally lot of scatter but variation of the something of this kind. And similarly, if you measure by speed tension you know, you get it for split tension, you get it something like this, this is the flexural test we will talk about that some time later, so generally with various size of segregate so you can see typically, it will vary in this manner. Some sort of a variation is available and people have try to empirically relate the tensile strength with, this is split this is flexure, related to the compressive strength.

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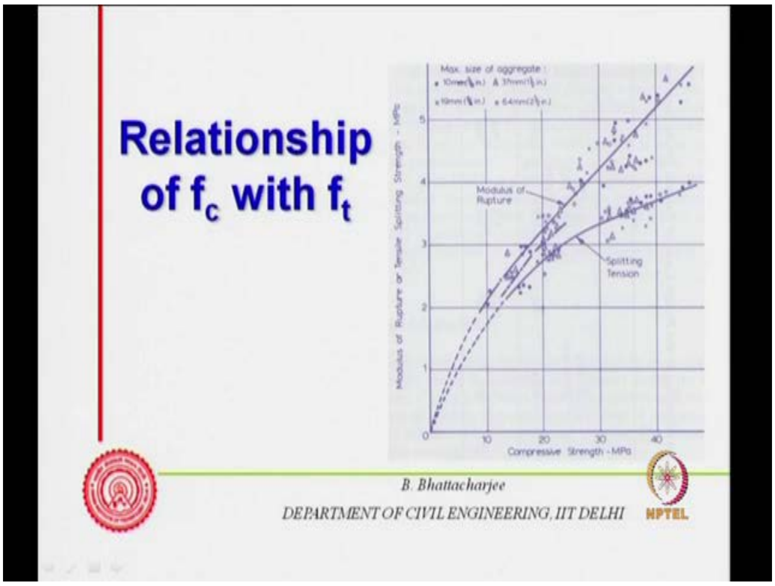

Some equations have been developed and several factors of course, will effect this relationship, as we have seen in the previous curve as we see in the previous curveyou know. The type of aggregate the scatters is because of the type of aggregate, m s a values and maximum you know m s a values and there could be other cases such as moisture condition, etcetera, etcetera many factors would affect this.

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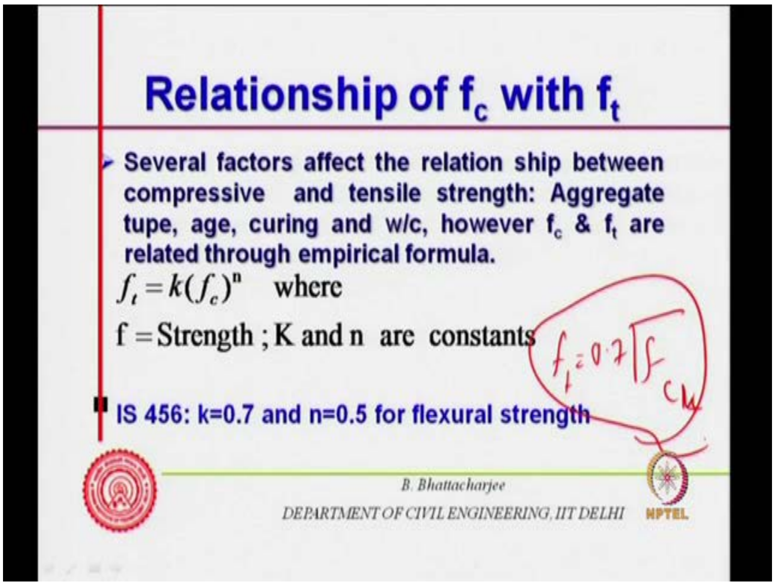

So, several factors affect the relationship between compressive and tensile strength of aggregate, you know it is aggregate type, age, curing, water cement ratio. But, through empirical formula, one can relate them one can relate them through empirical formula for example, f t is equals to k f c to the power n where, f is strength, k and n are constant. So, n would depend upon what type of strength you are relating right and k would also depend upon what type of strength is you are relating.

For example, for flexural strength, k can be different, n can be different, for split cylinder the test, k can be different, n can be different. So, IS 456 of course, it says k equals to 0.7 and n is equals to 0.5 for flexural strength. So, f p is given as 0.7 under root f c k is characteristic strength, f c k character not f c but f c k characteristics strength. So, this is largely for design purposes, little bit of conservative value it would be so design purpose this is what, gives you Indian standard code, all other codes have similar sort of formally available. So then what we have looked into so far, we have looked into the role of paste in the compressive strength.

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We looked into role of ITZ blast time but then we have right now, we have looked into a little bit more the bond strength we have looked into bond strength we have looked into bond strength. In the context of aggregate, we have looked this into context context of aggregate and what we have seen that, paste strength, aggregate properties and paste aggregate bond, all go under strength of concrete.

Paste strength itself is controlled by type of cement, type of you know admixture if you are using and water to cement ratio, degree of water to cement ratio as well as age, both this actually controls the degree of hydration as well. So, one can get an idea, what governs paste strength, so far we have looked into but paste aggregate bond is governed by the aggregate property as well.

Last last lecture we discussed about paste, strength of paste, water cement ratio and those factors but the bond between aggregate and paste is governed also by aggregate properties like surface roughness, you know texture essentially and some cases, there could be chemical bonding, that is what we have seen. And then aggregate properties, paste properties and paste aggregate bond, all of them together with the production factor governs the strength of the concrete. Then we have lastly looked into the strength of tensile strength, we have looked into the tensile strength of concrete.

And we have said that, this can be measured in two ways, which we shall see later on, test method just we will see in the next lecture. But however, both this can be related to the composite strength, because fail after all compressive failure of uniaxial compression failure of concrete is under transverse tension only. So, there has to be some sort of relationship tensile and compressive strength, it could be 8 times compressive strength could be 8 times, that we have seen from the failure failure we have seen from the failure envelope.

So therefore, you know one can can a (( )) relationship typically, empirical relationship has been established. Large number of factors governs this relationship and they are of the kind of f t is equal to f some constant into f c to the power l. Different code uses different values of n and k and also, it might differ depending upon type of the cementitious material you are using and so on and so forth. But, code gives you a conservative value and IS code of course, gives you a value of f t is equals to 0.7 under root f c k where, f c k is the characteristic strength.

So, I think with this, we conclude our this lecture and of you know lecture of 6th module. Next class, we will look into the test factors, which governs the strength of the concrete. Test factors, you know both tensile, compressive as well as tensile.

Thank you very much.