Concrete Technology
Prof. B. Bhattacharjee
Department of Civil Engineering
Indian Institute of Technology, Delhi

Lecture - 36
Special Concrete: High Strength Concrete

Welcome to module nine, lecture one. Now, module nine – we look into special concrete. First one is of course high strength concrete. And in this lecture, we will cover high strength concrete.

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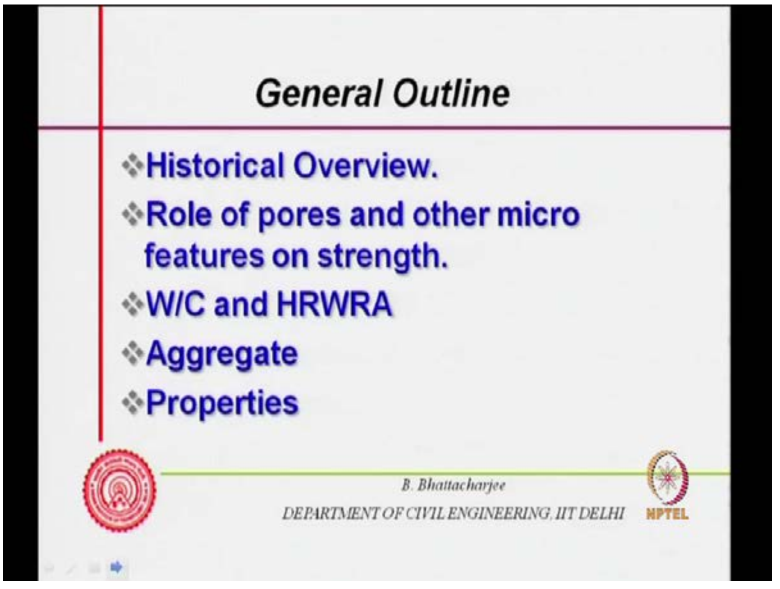

So, what will be the outline of our discussion? Historical overview; obviously, some definitions – what is high strength concrete, etcetera; and basically, the various features on strength. How do you get that high strength? What are cement ratio and high range water inducing agent; what are their roles? What is the role of aggregates? And we will discuss into properties.

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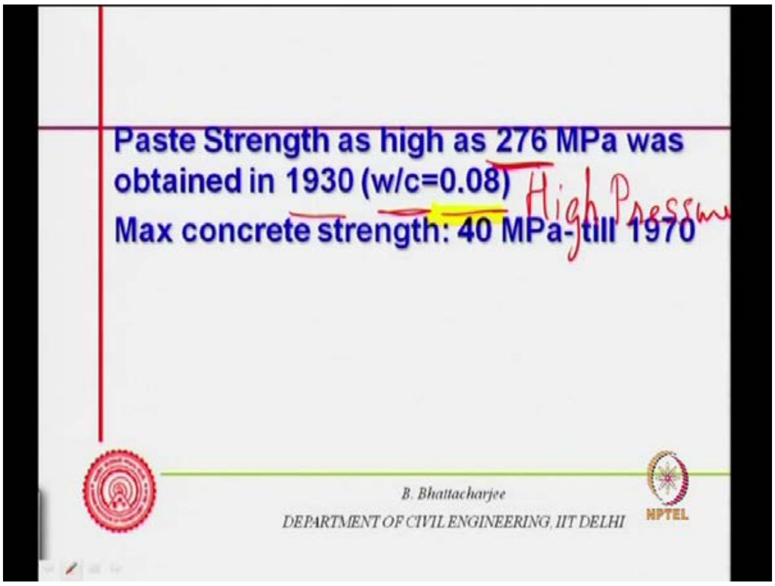

Paste strength as high as 276 MPa was obtained in 1930. D. A. Abraham in fact could obtain strength as high 276 MPa in 1930. He used a water-cement ratio of 0.08. He used a water-cement ratio of 0.08, applied pressure – high pressure; applied high pressure and could get a strength of 276 MPa. So, you see it could even right in the beginning, right in the very early age of the history of cement-based material or concrete science, one could did you find out that, their strength could be very high if you have packed it properly, if you have actually applied high pressure and if you densify it.

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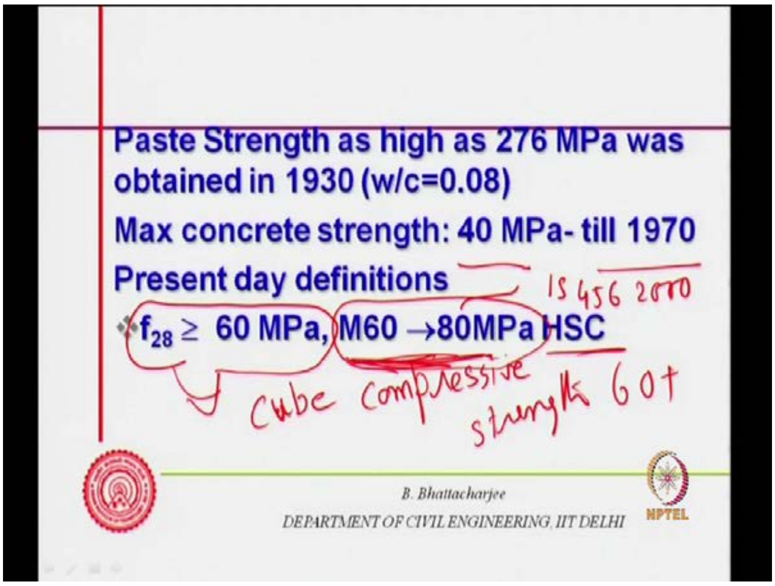

So, if you look at historically; if you look historic scenario, maximum strength was 40 MPa. Let us say till about 1970 or let us say 45 MPa; never more than 50 MPa; no case. But currently, what we define? We define 60 MPa concrete; I mean, I am talking of cube strength; I am talking of cube strength – cube compressive strength, which we have discussed so far – cube compressive strength; that is up to 60 MPa. In the reference literature, you will find cube strength up to 60 MPa, 28 days strength up to 60 MPa. That can be said as normal concrete. So, above 60 MPa, that is actually high strength concrete – HSC; that is actually high strength concrete. Now, IS 456 2000 – and, its later amendments actually has recognized M60 to 80 MPa high strength concrete; M60 to M80 as high strength concrete. Then, therefore, of course, they are talking of the grade. So, grade is 60 MPa; which means the strength is somewhere around 70 MPa, perhaps 60 plus strength to about 80 plus strength, would be high strength concrete.

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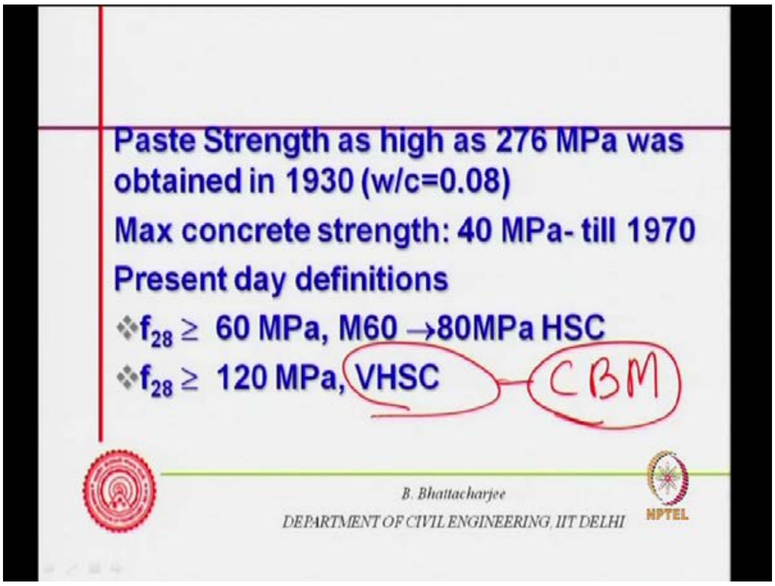

f 28 greater than 120 MPa will be called as very high strength concrete. But, many of the systems, which actually tend to become cement-based material – cement base mattresses – CBM. I call it cement-based mattresses, because some of the ingredients of the concrete may not be there. In some concrete, for example, very high strength concrete system – you may not have coarse aggregate. So, it is actually cement-based mattresses or cement-based composite; whatever you call it. That is the kind of definition we have today as far as high strength concrete is concerned. But then there are something called high performance concrete. High performance concrete, you define now a set of performance.

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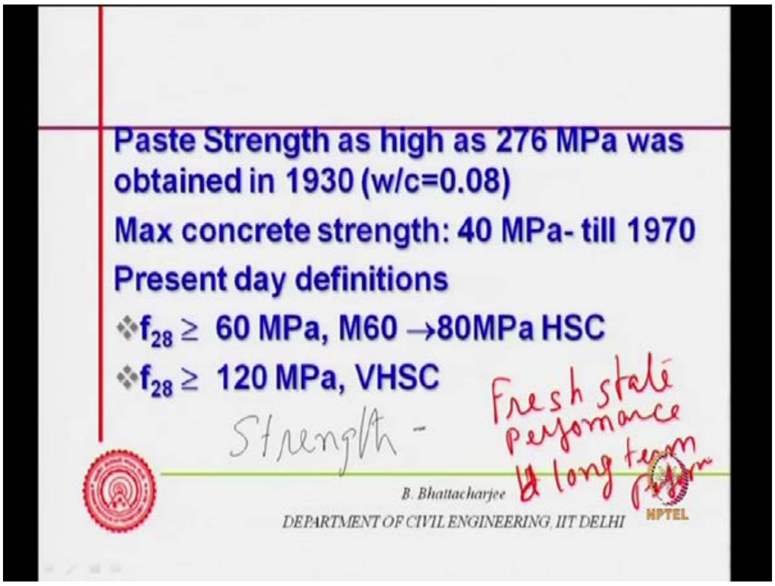

For example, strength is one performance; strength is one performance. Strength – this is one performance. But then we have come across various kind of performances: fresh state performance, hardened long term performance, hardened state performance. There are so many performances. So far, we have talked about fresh state performance like flow-ability; we also talked about little bit of vialogy, workability; whatever it is; ease of compaction and so on; whatever we define; bleeding, and then shrinkage you talked about; creep we talked about; some of them could be long term and hardening stage property, heat of hydration – generation of heat of hydration. During the hydration, hardening process; heat of hydration, early strength gain, 28 days strength or hardened state strength actually, long term durability, creep, shrinkage – all these properties. There could be several performances of concrete. And, many of them we have talked about so far.

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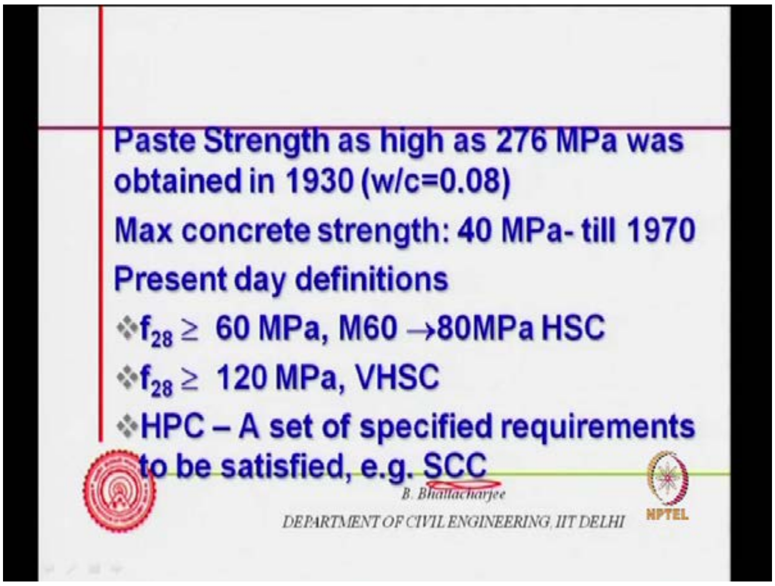

So, high performance concrete actually deals with… High performance concrete deals with a situation, where a set of performance is specified; performance requirement is specified. And, it must satisfy those requirements. For example, if I have a lower strength self-compacting concrete, this could be also termed as the high strength concrete – high performance concrete; not high strength concrete, high performance concrete. It is not high strength, but it could be high performance. So, performance is although most of the time… High performance means strength is also a performance. But, supposing I have defined certain properties that are very high level; I have specified at a given level. And, that would be performances. So, high performance concrete…

And, analogy could be looked into like limit state design or ultimate load design. Ultimate load design used to look at only at the load. It must be safe against load. And, the load is taken… That load resign is taken for the ultimate load, which it can carry as opposed to working state design, which was dealing with only the working stress situation. So, ultimate load design looks at only strength at the ultimate stage; defines one of the failure as the failure against load. But then, limit state design looks into several limits – deflection, service-ability limits – limits related to ultimate load and so on and so forth; collapse and so on and so forth. Therefore, here high performance concrete is something analogic; we are looking at many performances. And, I might define a set of performance. So, strength could be one of the performances; there could be other set of performance I define. And, that should be satisfied by the concrete. So, high strength concrete is more than high… High performance concrete is… High strength concrete could be a high performance concrete. But all high performance concrete need not be high strength; need not be although generally it is the case; there is a link. So, that is what is high strength concrete and high performance concrete; that is what is high strength concrete and high performance concrete; their definition.

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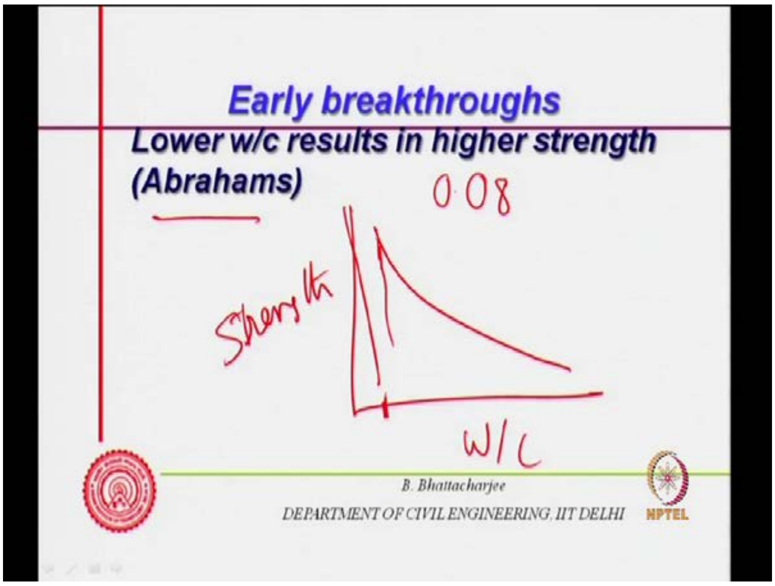

Then, I said that… What cement ratio used was 0.08 by D. A. Abraham. And, we also found that, strength is a function of water-cement ratio; in this manner, it reduces. Therefore, if I have high low water-cement ratio, strength will increase. And if you can pack it so well, you can get very high strength. Therefore, this was the understanding from D. A. Abraham's work.

This was the understanding from Abraham's work. But then, T. C. Power and their team actually found out porosity. And, they could link water-cement ratio to porosity – capillary porosity. And, this we have discussed and we have actually talked in the very first module itself. So, porosity… And, lower the porosity, better is the durability as well as strength is higher of hardened concrete. This is what we have seen in few of our discussion.

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Therefore, the whole idea to get higher strength, I must reduce porosity. But, then, I also talked about – if you recall pore size, for the same porosity, smaller pore size will give you higher strength. So, reduction of the porosity and refinement of the pore sizes are important for high strength system. So, if you want to get a high strength system, then you must reduce down the porosity and you must also refine the pore sizes.

Now, all these idea that came through over the years that result in high performance concrete, densified with small particle system; we will look that; micro defect-free mattresses, reactive powder concrete. So, these are results of… These kind of early breakthroughs will give into later understanding or later improvement by reducing down essentially pore sizes and porosity. That is what it is. So, we will look into all these high strength mattresses later on.

Now, we will concentrate into high strength concrete, etcetera. Now, which are that, if you want to get high strength concrete, then you must refine the pore and you must reduce the porosity. This is the main cracks of the manner. And, therefore, how do you do it? You use a fine pozollanic material such as silica fume, which we have discussed earlier. And, you got to use low water-cement ratio; that is what the idea. We said that, water-cement ratio must be lower. And this lower water-cement ratio means it should be able to use some sort of water reducing agent. And, obviously, the aggregate size and other things packing must be appropriate. So basically, aggregate size and packing – that should be appropriate; packing should be appropriate. This is packing.

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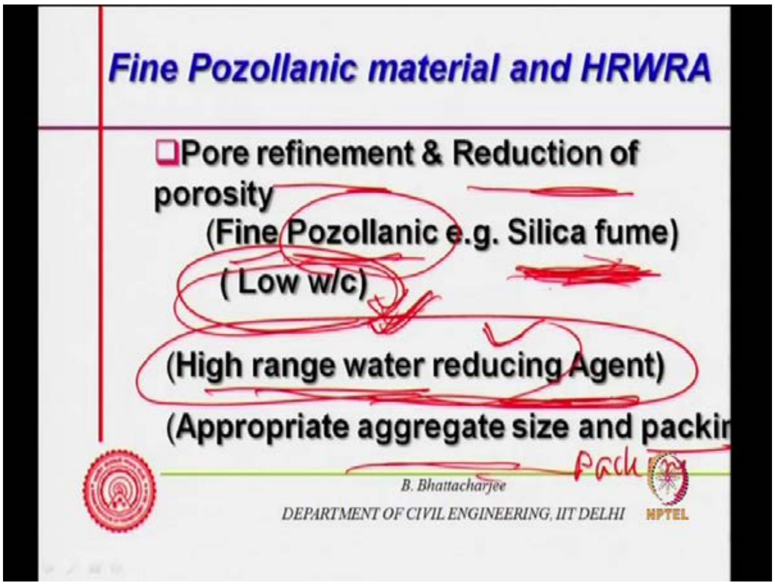

Now, just let me go a little bit historical. We have looked into all the pozollanic material in the very cementitious material in the very first module. In one of the earlier module, we have looked into these materials; and also, looked into their history; little bit of their history also we looked into. Now, remember – this is a little bit linked to other industry as well, because this is a byproduct coming out from silicon industry or ferro-silicon industry. That is what we have looked into in the beginning.

Pozollanas are used for very very long time. Historically, pozollanas were used 2000 or even more; that kind of time – historic times, just after pre-historic maybe; time – from that time, roman empire used the pozollanic material. So, they are the volcanic ashes. Then, came – I told you the lime and silica combinations were used; various kind of various ways; various part of the world including India, where we used surki and so on and so forth.

Now, this gave rise to cement. But then, material like fly ash became essentially, from the environmental concern and reduction of the cement, which is a costly material in the cement-based system. To reduce that as well as from the environmental concern, fly ash has been used. But, fly ash is not as fine as this. This was because thermal power plants came. Like 50s, 60s, thermal power plants came. So, 70s used research on pozollanic material like use of fly ash was there. Blast furnace slags were now available. Therefore, slag cement were also there. So, those research continued. But, the electronics industry, semiconductor industry started developing in 70s practically. In all those solid-state, electronics might have started from 1950s.

And, the research of transistor and all that –they have started from late 40s and 50s. But the silicon as a material – its importance started possible in 70s and 80s more. So, silicon industry or ferro-silicon industry grew. And, that gave us the product like condensed micro silica or silica fume. So, it is only 80s, when this material became available. And therefore, recall that, this material is highly pozollanic with a very fine size; reach in silica – that is what we discussed earlier. So, this material is finer than cement. And, therefore, the fine pozollanic material – that became available as a byproduct from some other industry; which actually people started looking into its utility. And, that is how the high strength concrete could come in 1980s and 90s and later on of course. Therefore, there is a historic reason – why did it come.

Other material is not even… Before that, material was not… perhaps known, but not to the great extent that was there. And, when it was available, it was definitely limited. Today also, it is not available everywhere. For example, in India, we have to import it; and, it is costly. However, this is the material together with this material made it possible for high strength, made it possible to produce high strength concrete, because this material is finer than cement. There are other roots tried to improve the strength of concrete, namely, polymer concrete; we will usually discuss sometime later on. Polymer cement concrete, which (( )) Again, we will discuss sometime later on. But, they were costly. They are still costly root actually. But, this gave us a viable way. After the ferro-silicon industries development took place, this gave us a material, which could be used. And, this fine pozollanic material – silica fume…

Now, water-cement ratio reduction – that is one thing. Second issue is water-cement ratio is reduction. Now, if you want to reduce water to cement or all even water to cementitious, there is a minimal required for standard consistency. We talked of it earlier that, at least you require water for standard consistency for the paste; otherwise, paste itself will be somewhere dry, somewhere solid. So, it will not be simply workable; proper dispersion of the particle would not be there. So, you could not have gone to a very low water-cement ratio, but for the construction chemical development. Now, historically, when you looked at the admixture, you could remember, historically, lignosulfonates came pretty early – 1937. This we mentioned sometime earlier – 1932. But, the melamine and naphthelene formaldehyde condensates; sulfonated melamine and naphthalene formaldehyde condensates – they came in 1970s – synthetic ones.

And then, polycarboxylate ether came later on – 80s and so on and so forth with the hyperplasticizers or very high range, ultra high range water reducing agent and so on and so forth. Now, this could actually disperse the cement or cementitious particle significantly and thereby increase. The water required for consistency could be reduced. So, low water cement ratio could be achieved only when you have high range water reducing agent; otherwise, you will have to apply high pressure to get that kind of strength like in the paste; concrete – of course, it will be fairly difficult; technologically, may not be a viable situation. Therefore, to achieve this, this played a big role. Now, this is any way required; but, these two things are the high range water reducing agent and the mineral admixtures.

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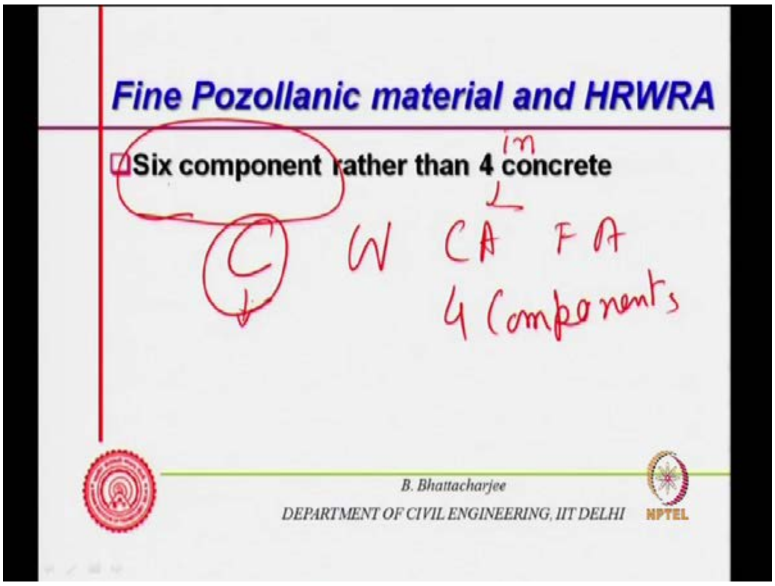

Now, that brings us to the situation that, actually, six component rather than four component concrete; six components rather than four in concrete; six component concrete rather than four; six component rather than four in concrete. So, basically, earlier, we are using cement, water, coarse aggregate, fine aggregate – four components. That is very conventional, very very old. Even modern engineered concrete of any strength should preferably be six component, because the fifth and the sixth components will be allowed to reduce cement and get better property, make it cheaper, economical, more sustainable. So, modern concrete – all should be six component.

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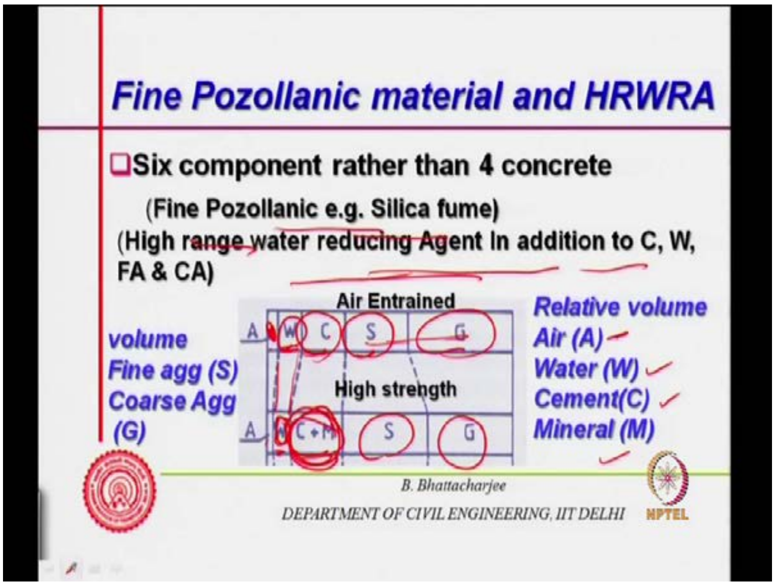

But, high strength concrete cannot be four component all; high strength concrete cannot be four component at all; it has to be a six component rather than four component in concrete – four component concrete. So, the six component is… fifth is this and sixth is this; fifth is this component, sixth is this; I mean, could be any other material or the possibility should be… possibility, any other material; but, should be fine and should have also some kind of reactive scenario, which can improve the porosity, reduce the porosity and effect in pore refinement; silica fume is able to do it. Some other material may come in future and which might be able to give it.

But, at the moment, it is silica fume, which is very very… For example, people are trying processed ground granulated blast furnace slag or maybe processed (( )) some other material, which should… But then, whole idea is that, it should be able to go into the interstitials of the cement itself and also effect in some kind of additional bond formation in future; not only just the (( )) because if it goes into the interstitials of the cement system itself, it will act like a filler; but, if it has some kind of bond, the filler would act much better.

Now, high range water reducing agent in addition to C, W, FA and CA. So, these two more component – it is a six component; concrete has to be… As I said, it is not only high strength concrete, but any concrete – modern engineered concrete should be six component; why not even n component; some more admixtures, which will come in future. And, they will improve the properties in much better manner. So, generalized system could be n component concrete.

This six is definitely… maybe seventh, eighth to improve properties in some other manner, some other properties and so on and so forth. So, you see this; if you look at it, old concrete, air entrained concrete was this one. This was the volume of air, water. And, air entrained concrete was very common in the west. In India, you may not have done air entrainment, but this will be still less; void should be less (( )) actually. This was the cement, which was relatively less; but, the large quantity of water. This is the fine aggregate; and, this is coarse aggregate.

And, if you look at the high strength concrete, this has got significantly reduced from here. It has got significantly reduced from here. And, you have cement plus supplementary cementitious material. These are the relative volume. Air volume – we are reducing the (( )) volume in the just hardened state you can think off. Water volume, which is actually reducing in the system; and, cement; and, this is mineral admixtures. And then, fine aggregate is this and coarse aggregate is this. This is the coarse aggregate. So, fine aggregate, coarse aggregate.

So, what you see, actually, this is now… Instead of this, you have got the mineral admixtures here. The water is reduced. This is reduced. This has become more; this has reduced. This fines will also increase, but this has also reduced, because this will be now… Although they might occupy similar volume, but to accommodate this more volume of the paste, you need possibly more sand in the system; reduce down the larger aggregate. That would have implications on interfacial transition zone as well as sub-shrinkage. We will discuss this sometime later on.

So, six component concrete rather than four… Six component… because to reduce this, you need a high range water reducing agent. To make it compaction possible, workability possible, workable concrete, pumping possible and so on and so forth, you need to have… To reduce this, actually you need the six components. So, you can see that, 1, 2, 3, 4, 5 plus the 6 component is the water reducing (( )) This is a must. And, as I said, there could be even more. So, that is what made it quite possible – the high strength concrete. That is what made it possible – the high strength concrete.

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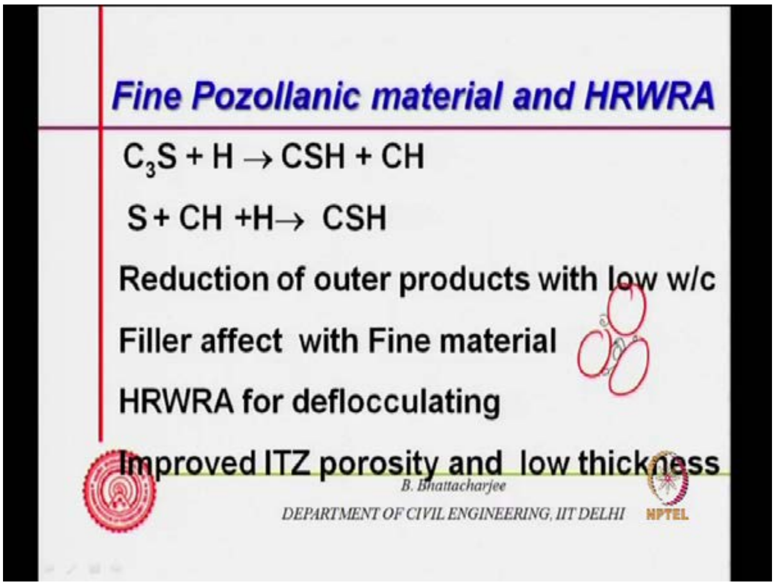

This is what the reactions we have looked into; typical C 3 S reaction would produce CH; and, this CH together with the silica fume will produce CSH gel. So, this is the secondary pozollanic reaction. This will be the case in high strength concrete too. And, this is essential. Of course, in normal concrete, you will have also if you add pozollanic material there. So, reduction in outer products with low water-cement ratio.

Remember, we talked of inner product and outer product. This is the original cement grain boundary; the (( )) product inside this – we call it inner product. And, outside, this we be an outer product; but, if you have low water-cement ratio, outer product required will be low. And, filler affect with this fine material mineral; that means fine mineral will go inside the particle itself. These are the cement particle; let us say I have got fine minerals, which will go inside this; and, they will also be pozollanic. So, they will react.

And, you remember; we talked about their hydration process of all different kind of mineral admixtures and so on right in the first module itself. That is what we make possible the high strength concrete. High range water reducing agent for deflocculating; and, this will improve the ITZ porosity and lower the ITZ thickness also. I will come to this a little bit later more – how it actually reduces the ITZ thickness. I will just come to this in a while.

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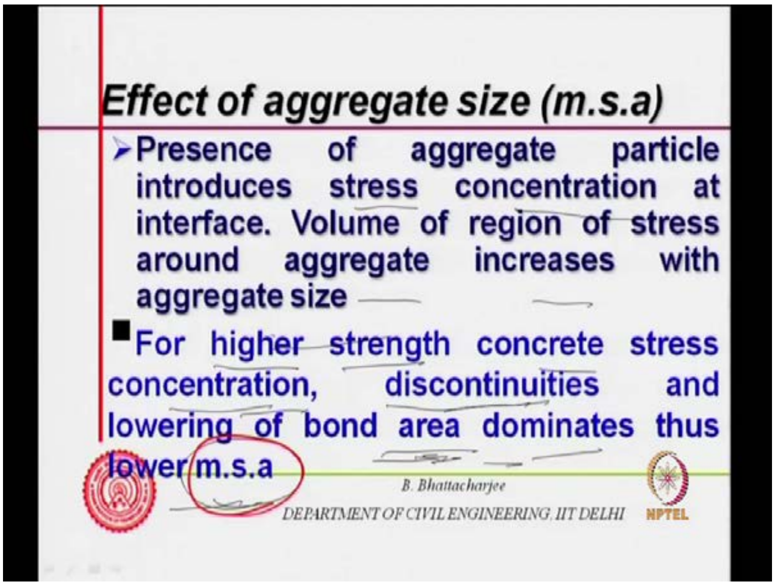

Presence of aggregate size; I will come to the ITZ reduction little bit later. Now, aggregate particle introduces stress concentration; that is what we know – at the interface. And, the volume of region of stress around aggregate increases with aggregate size. So, basically, the interface is very very important. That is what (( )) And, we have seen most of the time, the cracks starts from there. Therefore, it is important to improve the interfacial transition zone. So, aggregate particle – larger the size, actually, it increases… The more stress concretion will be there because surface area is less; large size means surface area is less. So, the same stress – if it has to pass, there will be more stress concentration. And, the volume region of stress around aggregate will increase. So, these weakest areas, (( )) volume will increase.

For higher strength concrete stress concentration – this we have seen earlier when we were talking about strength. For higher strength concrete, stress concentration around the aggregate, discontinuity is there and lowering of bond area dominates. Therefore, we use lower m.s.a, because bond area will be reduced. Same volume of aggregate let us say; one with the larger size aggregate – m.s.a being higher; that means the finer proportion will be reduced. Total surface area of the aggregate will actually… Total surface area of the aggregate will increase if you have finer material. So, if you have coarser materials, m.s.a is higher; you will have less surface area. So, the bond area actually… The stress concentration would be higher in such situation. So, all these – discontinuities at the interface, stress concentration, bond area – all these actually dominates. Thus, we use generally lower m.s.a. And this we have looked earlier also. And, we are just reiterating what we said earlier that, m.s.a should be lower in case of high strength mattresses. So, generally, you have much lower m.s.a in this sort of mattress.

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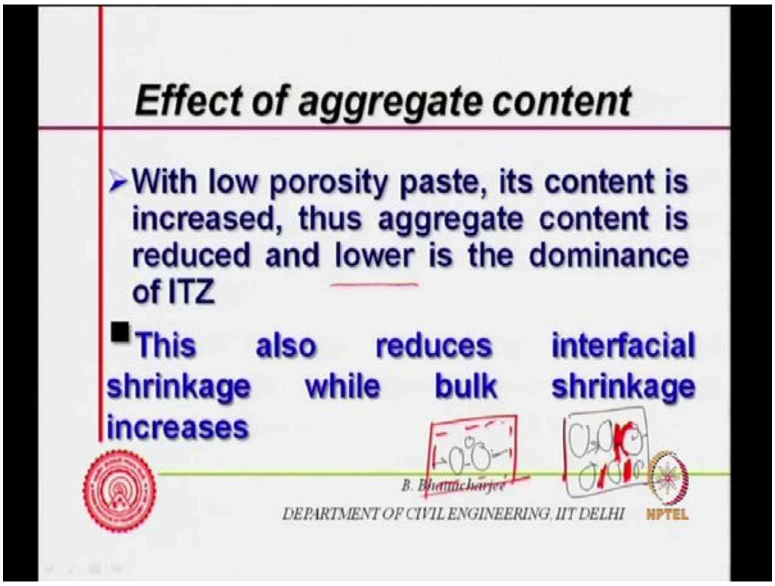

With low porosity paste, its content is increased; thus, aggregate content is reduced and lower is the dominance of ITZ. So, fine aggregate – again you might increase. But, if the volume of the material remaining same… Volume of the paste, etcetera… Volume of the paste is generally increased. So, generally, aggregate concentration or volume of the aggregate also reduces some (( )) Volume of the aggregate would required will be less also. Sometimes, this reduction in volume is required in very high strength system in order to ensure that there is bulk shrinkage. For example, shrinkage in the bulk; whole material shrinks. Rather than shrinkage like this; this is the matrix and you have got lot of aggregate; let us say lot of a aggregate, because this portion shrinks; the paste portion shrinks; aggregate do not shrink. So, you might have a cracking here actually.

And, a crack could be developing here, because one of this shrinkage of this one, shrinkage of this one, shrinkage of this, but shrinkage of this one; but, no shrinkage of this one. So, essentially, bulk shrinkage can reduce; it can actually introduce a kind of compression here on to the aggregate and improve the interfacial bond. So, this can… Reducing the aggregate quantity in higher strength system might have an advantage in terms of this as well. One thing is reduction on the interfacial transition zone, volume itself; other would be even shrinkage – bulk shrinkage; the whole thing shrink together. So, if there is an aggregate, this will also… Since everything shrinks, less aggregate. Therefore, this would actually might compress the aggregate itself. So, this one fact, which would be useful to understand very high strength concrete; why it does not use very large sized aggregate.

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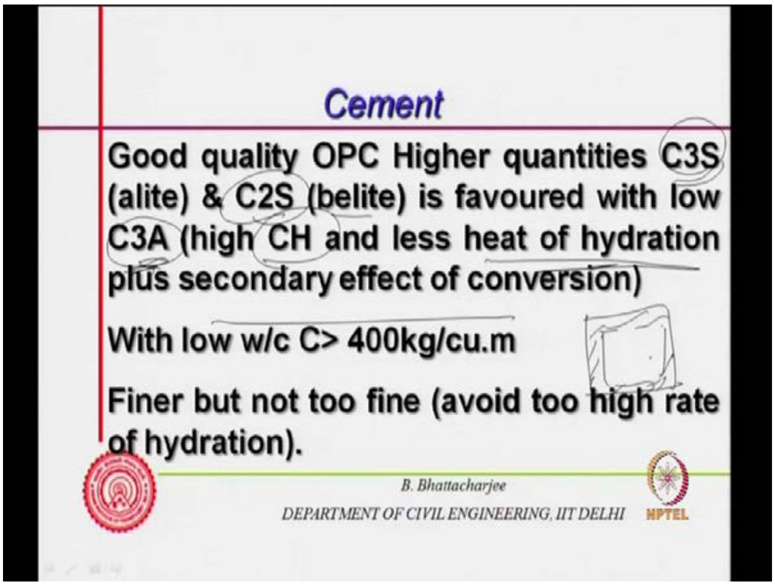

Cement – it should be good quality OPC. Preferably higher quantity of C3S and C2S with low C3A; higher quantity of C3S and C2S with low C3A, because this will ensure higher CH formation and less heat of hydration, because this is the one which is responsible for heat of hydration; it has got the highest heat of hydration. So, heat of hydration would be reduced if I have less C3A. And, this would generate lot of calcium hydroxide, which can actually react with the pozollanic material to improve the properties altogether. So, more CHs. So, this will also reduce down secondary effect of conversion.

Now, what is conversation? If you remember, we talked of high alumina cement or hydration process of cement system. We said that initially, first, it forms ettringite, which get converted into monosulphate; and, volume of ettringite – if it is higher than the monosulphate or the final product or the sulphate that forms the later situations from the ettringite; if their volume are less, then it would actually introduce new pores, because originally, it was larger volume; and, later on if it occupies lesser volume, this voids – this would generate a kind of voids. So, they become important in very high strength system; may not be important in low strength system, because there are already existing lot of pores of other kind. But, here you are trying to reduce all other kind of pores. This pores may become dominate. Therefore, secondary effect of conversion and low heat of hydration would actually… It would be better if you have low (( ))

Low water-cement ration – C – obviously, is usually greater than 400 kg per meter cube. Cement could be finer; which will be easily reactive. But, should not be too fine to improve or increase the high rate of hydration. So, some people use 53 grade of cement by Indian standard. But, it is not necessary that you use a high strength or finer cement or higher grade of cement, higher strength cement for producing high strength concrete. Even 43 grade can give good results. Heat of hydration will surely be lower in such situation. So, cement should be of good quality of this kind for high strength concrete.

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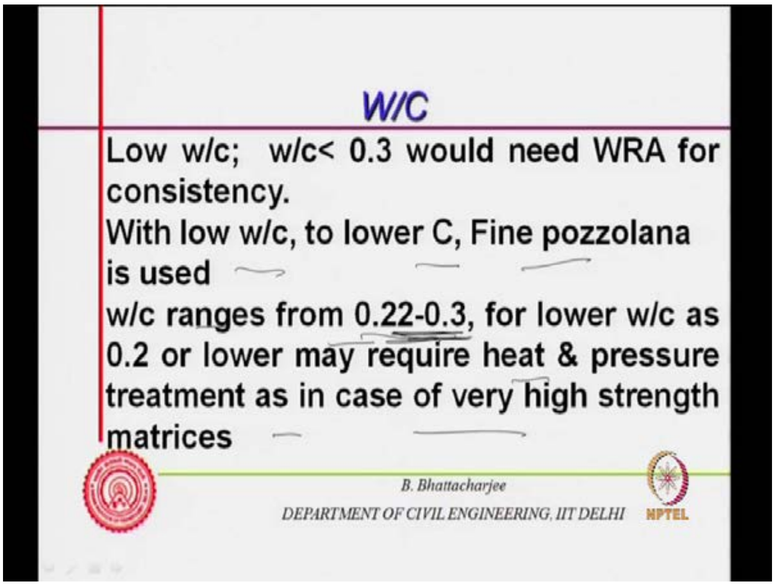

Low water-cement ratio – water-cement ratio will be less than 0.3. And, therefore would need water reducing agent for consistency. That we have seen. We have already said that, this is what we need for high strength concrete. So, what we are seeing – good quality cement preferably with low (( )) Then, water-cement ratio should be lower; and, you need obviously WRA. With low w/c, to lower C, fine pozzolana is used. So, use fine pozzolana together with this. And, its effect is something like this – water-cement ratio ranges is from 0.22 to 0.3 Usually, lower than 0.2 – there are other kind of the problems comes in; you may not get simply… you may not get high strength concrete system; in fact, strength might even start reducing. Unless you do something more – maybe heat treatment, pressure – those kind of things. So, lower (( ) lower may require heat and pressure treatment in case of very high strength mattresses. So, basically, otherwise, you may not get that improvement. So, generally, high strength concrete will restrict to usually 0.27, 0.28 and so on. So forth, water-cement ratio is this. But, very high strength system might get still work. But, below 0.2 might require heat pressure treatment for improvement in the strength – for higher strength.

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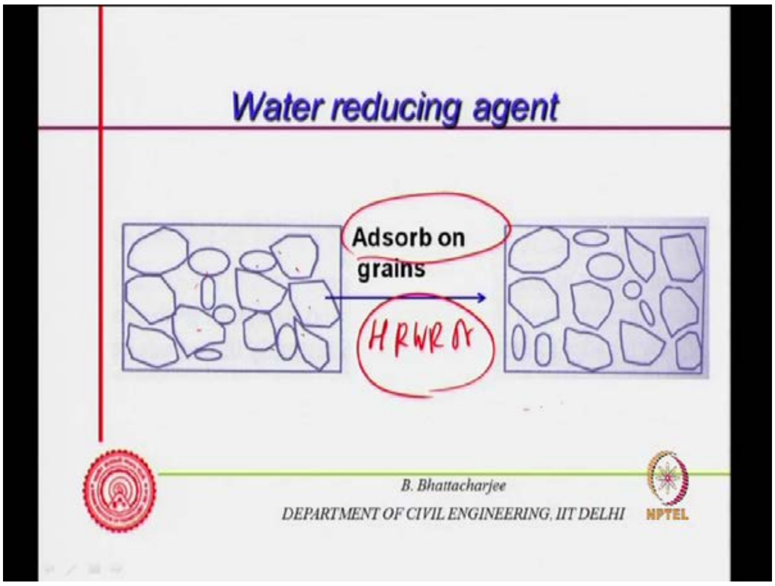

Let us see how does water reducing agent works. This is the cement before – they would be touching each other before you have add any… without any high range water reducing agent, kind of (( )) together. But you may add high range water reducing agent – they get adsorbed on to the grains and they would result in this kind of dispersion. And, this is what we have seen already. Already we have discussed this; I am just repeating, reiterating the whole thing. So, this was the scenario. With high range water reducing agent, they get better dispersed; they get separated up.

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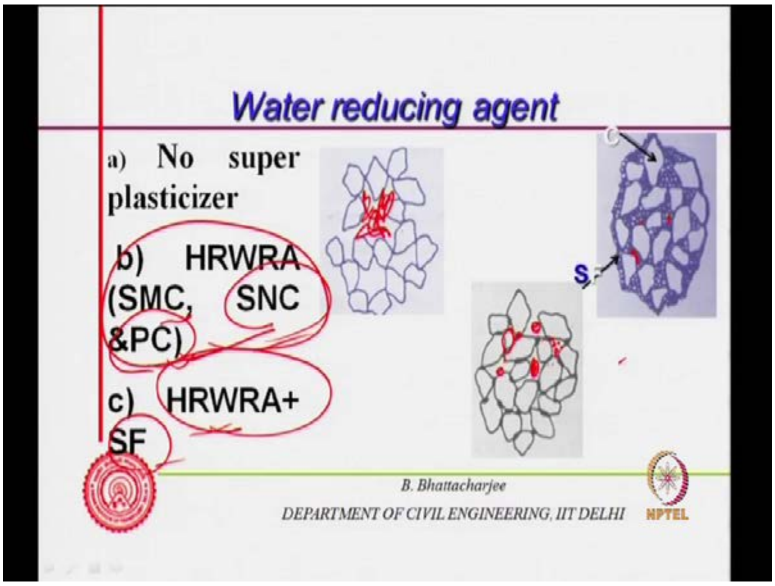

And, when you are adding water reducing agent together with the silica fume, no super plasticizer; this is the situation. With super plasticizer, this will be the situation. And, when you have silica fume or such fine material, they will just penetrate and fill in into this (( )) This (( )) and they are dispersed with high range water reducing agent, that is, sulfonated melamine condensates or sulfonated naphthalene condensates or polycarboxylic ether type of things. This is most effective. And, this with the silica fume, you will find silica fume going into the interstitials. So, when you add this, they push them apart; just there is a touch and they are not forming a kind of clog on large (( )) inside this. So, they are now more or less reduced.

And, when silica fume (( )) they go into the interstitials of the system and thereby the pore (( )) actually would further reduce. So, what is happening? You have fine material going into this interstitials; fine material going into this interstitials. So, the pore sizes, which were quite large here; they were very large here; they were very large here; very large pore sizes; where, outer product will anyway deposit, but still leave some void if the water-cement ratio is high.

When you have dispersing agent, they will obviously get reduced with a lower water-cement ratio. Surely, they would and this is the thing. But, if you put fine pozollana; the pores porosity will further reduce because of those fine material going as filler. But, they have to be dispersed and they should go well within the pore space. And, therefore, this together with this helps. And, you will have pore sizes reduction also. So, in the bulk paste, you will have reduced porosity as well as pore size reduction because of two effects: one is a filler effect; other is a secondary pozollanic reaction effect. So, they will fill in; they will get in; and, they will fill in those spaces. As the hydration occurs, they will further improve this situation. So, that is why we need this system to get high strength concrete.

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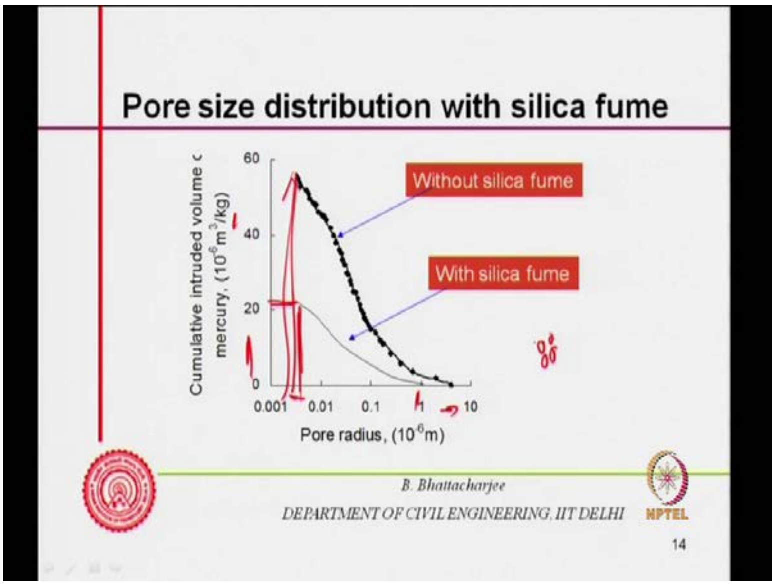

If you recall, we talked about this. This is without silica fume and this is with silica fume. So, porosity – total porosity – this axis is cumulative intruded volume of mercury. So, if you do a mercury porosymmetry, how much mercury has altogether penetrated? Originally, it penetrated more per kg or whatever it is in some volume or per unit volume or per unit mass. And, this is originally penetrated; that means porosity is more. Now, after silica fume, this is reduced. Not only this; you see the maximum size here is this; where, maximum size here is this one. Therefore, there is a reduction in the size as well as volume of the pores. Both sizes of the pore would reduce and the volume of the pore will also reduce.

Now, that is what we have seen, because it goes into interstities of the cement system and therefore reduce the porosity, act as a filler. And, further… Now, it will be the interstitials pores between the silica fumes themselves. It will be the… Simply the pore sizes will be governed by this spaces – the interstities space within this system. If I look at this interstities within this area, within this pores area – the interstities of the particles there – there they will govern the pore sizes. And, that is why they are able to reduce down the pore size so much, because pore sizes within the silica fume particle and… So, this is not between the cement particle. Therefore, this is able to reduce down the pore sizes as well. So, that is why silica fume together with high range water reducing agent are able to reduce the porosity as well as pore size distribution and therefore improve the strength of the paste if I may call it cement silica fume paste, its strength will be improved significantly.

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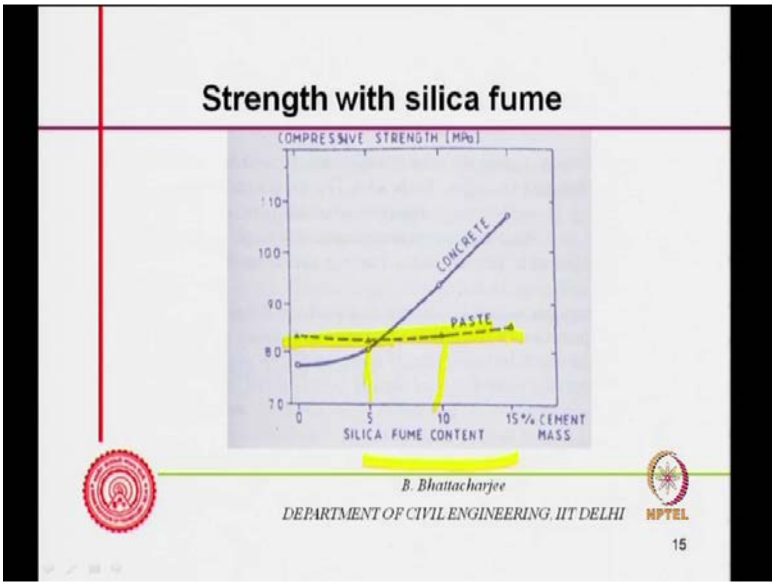

This has been observed by some people and they find the paste strength with silica fume content of course. It does not change much. Content wise, it does not change much; there is a reduction; the strength of course is 5 percent, 10 percent; beyond 15 percent, it is not able to go into the interstities anymore. But, you were adding only silica fume alone. So, pore sizes will be smaller, but the total porosity may not improve any further. So, this is one experimental result.

Supposing I add 30 percent silica fume; they will be packing… they would be actually too much quantity. So, not only they will push the cement particle out and their porosity within or the pores within the silica fume system will start dominating. That is what we talked about when we were talking of particle packing. When we were talking of packing densities and so on, there is an optimal proportion at which actually the packing density is maximum. So, here also, silica fume is acting as a filler. So, since it goes as a filler, there is an optimal quantity. Besides that, actually they will also reduce down the porosity by their secondary reaction. So, adding large quantity of silica fume does not add help. Not more than 10, 15 percent; rarely more than that; I mean it will never be more than 15 percent.

Third aspect of course is the cost of it. It is not a very cheap material. So, it might be costlier than cement as I said; where, if you are importing in India, it is about 7-8 times costlier than cement. Therefore, you can only use it in limited quantity. But, it is used at in an engineered way, so that advantages are realized in full. So, the strength of the concrete… Paste strength increases in this manner, but the concrete strength increases significantly. Now, we will come to that, why does concrete strength increases significantly? Because concrete strength is governed by interfacial transition zone; an interfacial transition zone improves. Let us see how does it do. Let us just see.

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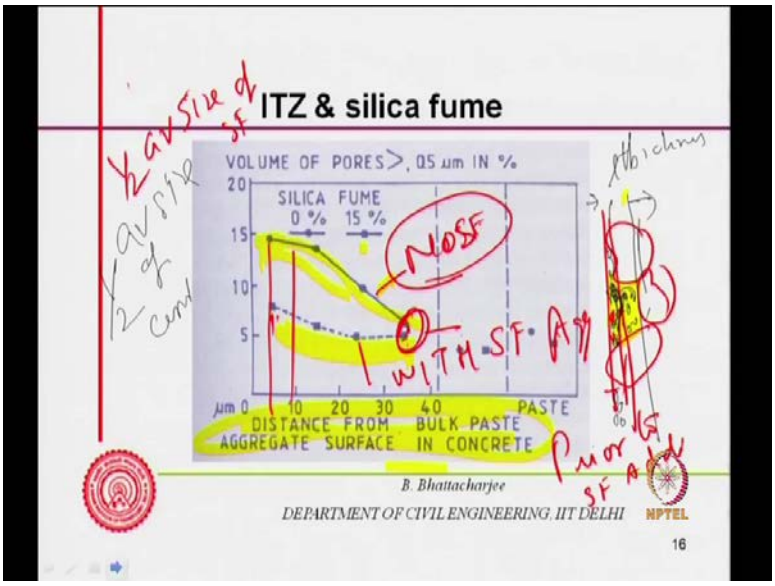

So, ITZ will be improved. It has been observed that, 0 percent silica fume and 15 percent silica fume; this is 15 percent silica fume situation; 0 percent silica fume; this is the distance from the bulk paste – bulk paste aggregate surface concrete and volume of pores with silica fume of course. Bulk paste close to aggregate – 0 percent has got high porosity; this is no silica fume, no silica fume, no silica fume, no silica fume, no SF. So, you have got close to the interface; it is in micron. So, around 5 micron, 10 micron; you have got no SF high porosity. But, if you put silica fume, this gets reduced. And, bulk paste – of course, they would be more or less similar. Bulk paste – this is with SF, with SF. So, bulk paste – their porosities are similar, no SF. But, particularly, this one – it improves. And, that is why concrete strength improves significantly.

Now, how is this possible? This was earlier our… Say this is aggregates and this was the cement particle earlier; aggregate – prior to silica fume addition or without silica fume. So, this is the interfacial transition zone, which will have porosity of this kind; which will have porosity of this kind; which will have porosity of this kind – interfacial transition zone, pore sizes and porosity. And, transition zone thickness would be largely governed by – we can say half; this is the thickness; thickness would be half average size of cement particle. We can assume that… Or slightly more; maybe sometime somewhat more.

Now, what I do, I put in actually silica fume there; I put in silica fume. So, these are the silica fume; they will come and pack in here; they will come and pack in here. So, what will happen? If they are sufficient, now, the ITZ thickness will be governed by dimension of the silica fume – half average size of SF, because it is that SF, which will pack here; it is the SF – silica fume, which will pack here; silica fume, which will pack here. It will be at the interfacial transition zone, it is the silica fume, which will pack in this manner. Still there will be some interfacial porosity – transition zone porosity; but, silica fume, which will come and pack in there, would radius significantly the ITZ porosity and size of the ITZ porosity improved.

And, secondary pozollanic reaction actually will fill in also this page. Therefore, that is why, we saw that, there was significant increase in the concrete strength, because ITZ porosity improves significantly with addition of silica fume and water reducing agent. And, this could made it possible. So, I am talking silica fume; it is not necessary the material will be silica fume; it could be any material, which is fine and has got similar up properties in terms of particle size and pozollanic properties. So, any material having similar kind of properties – not necessarily silica fume, any material. And also, similar kind of packing characteristics – it is important to understand, the silica fume particles are also spherical in nature, which you have seen earlier. So, it should be able to pack and reduce down the ITZ porosity. And if it is spherical, then dispersion is also easier; if it is not so spherical, dispersion will not be easier, packing may not be easier. So, any pozollanic material or very fine pozollanic material, which can go and improve the ITZ porosity would actually be useful in making high strength concrete.

With fly ash also, if it is a fine fly ash, you might be able to make the same high strength concrete, because as long as it is able to improve the ITZ and it is fine and it is able to get into the interstities of the cement system, then it will be the fine. But, all fly ash particles – because their silica content is relatively less. So, their pozollanicity is also relatively less compared to silica fume. So, anyway this materials we have looked into right in the beginning in the first module and we understand their behavior.

Therefore, if we get something derived out of them, judiciously, we can use and make at least some strength – maybe 60, 70 MPa concrete would be much easy to produce even with some good quality or processed fly ash and so on and so forth or processed ggbfs or processed (( )) depending upon their fineness and pozollanicity, etcetera. So, that is what I was saying that, we discussed about the interfacial transition zone a little bit later and that is what we talked about. So, that is how they are able to improve.

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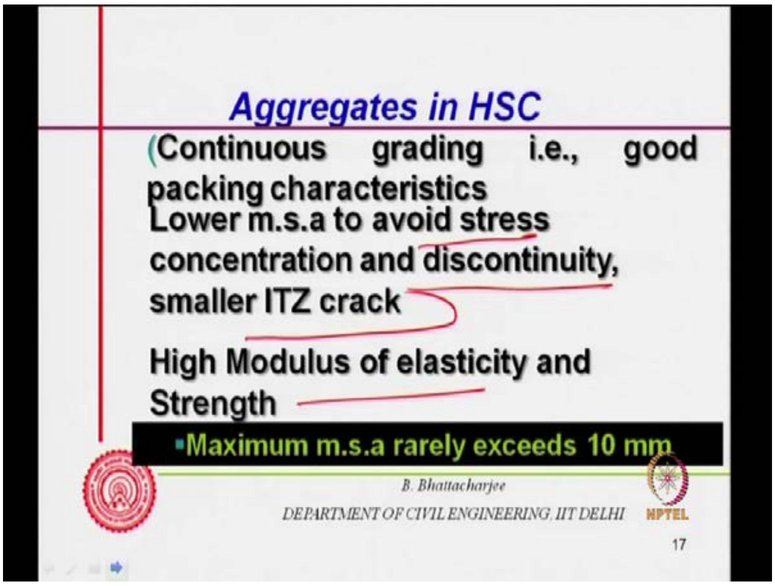

Now, what about the aggregates? I should have a continuous grading and good packing characteristics. Continuous grading means right from cement or silica fume size to the m.s.a, there should be a continuous grading. Now, this situation can well be understood; I will come back to this; I will come back to this.

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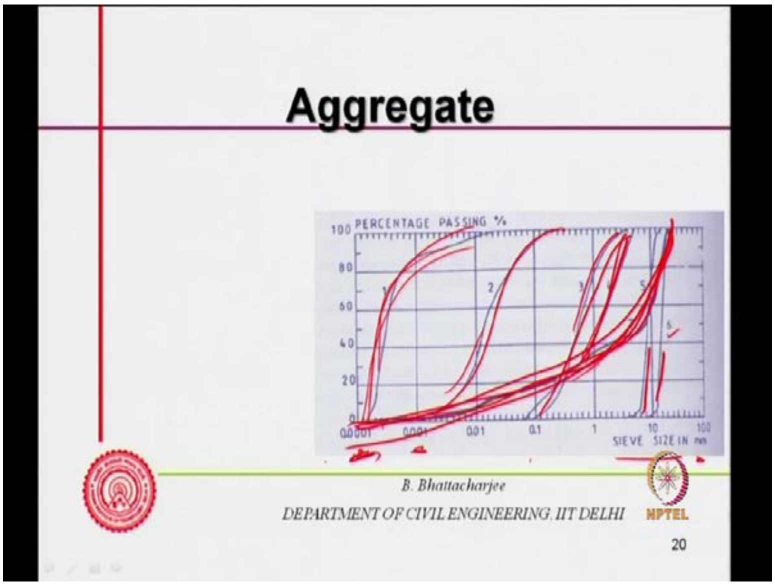

Let us see this diagram and we will go back again, go back again. This is the one; I am talking of… You see it is a continuous grading, is the best thing to have… Continuous grading is to have best things. I might mix up everything; that is, these are sieve sizes in millimeter; fine material – somewhere the fine material and the course material; but, I should have grading starting absolutely fine material of 001 mile meter; which means the micron sizes. So, this is the final grading; this is a micron size particle; this is actually, we are talking in millimeter; this is in millimeter.

So, if it is in millimeter. 0.001 millimeter is actually one micron, submicron sizes. So, this is submicron size, micron size, sand size, coarses size – basically 0.121 millimeter to about 1 millimeter. So, 1.18 – this is sand sizes or coarse fine aggregate sizes; this is also fine aggregate; this is about coarse aggregates. So, 10 mm – 10 mm size. So, this is coarse aggregates, again coarse aggregates. So, I might have all combinations and make a grading such that the packing densities best to the… Everything put together, it is the best. So, when I am looking at aggregate, I cannot look into isolation from the paste system. Therefore, I look into the packing of everything. So, everything should give me the best packing; and, best packing would also involve volume of paste and rest of the material – the coarse aggregate solid material that is there in the concrete system.

So, good aggregate packing is very very important in case of aggregate packing, continuous grading and aggregate packing. But I would say that, today, continuous grading is not an issue, because we must look at the packing densities and which we have talked about. So, we can find out the packing density of the aggregate system and determine the quantity of paste there. We have also talked about the mix design procedure using this kind of concept. Therefore, one can actually find out the packing density of different aggregate combination, find out the optimal packing density and then use the paste slightly more than that. And, it could be still more than that if it is a very high strength system. Why? To reduce down that shrinkage; allow bulk shrinkage, reduce down the shrinkage. We will look at that sometime later on.

So, lower m.s.a obviously to avoid stress concentration and discontinuity – we talked about. So, m.s.a will be lower; good packing characteristics; best packing density I will say. Hence, then it must have high modulus and high strength, because if its strength is lower, this can restrict the strength of the concrete system itself, because it is again weakest link. So, use pore aggregates, paste strength you improve; it is not going to help. Therefore, the aggregates must have high modulus and high strength. And, m.s.a – that is why never really exceeds 10 mm, 12 mm. Although people could get some 60, 70 MPa with 20 mm aggregates, but it is better to use lower. If you are not finding the strength, reduce down the m.s.a. So, generally, high strength concrete system – 10 mm. m.s.a – very high strength system, very very high strength system – there will no coarse aggregate. We will come to that sometime later on when we talk of reactive powder concrete.

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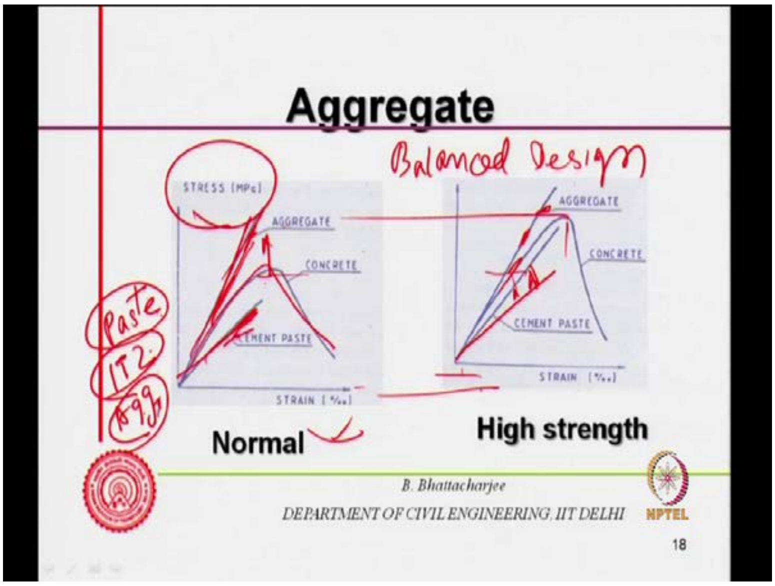

You see basically in normal strength concrete, if I look at stress-strain diagram; stress in MPa, strain here; cement paste is like this. Aggregate – both are brittle anyway; aggregate will be somewhere up there. So, the basic overall stress-strain diagram of the concrete will be somewhere in between. So, aggregates are natural system; they have their own strength. And, that is usually higher; we rarely realize this. It is like we rarely realize this actually, because it is controlled by this. But, in high strength concrete, I improve this cement paste. Therefore, this value goes up here, somewhere there (( )) If I make it here, this will be somewhere there; or, if I bring it down, this strength increases, because this would go up; this would go up; this whole curve goes up, because this pushes it up. So, we improved cement paste; we improved ITZ.

And therefore, the aggregate and the cement concrete improves. Remember, if I have this one somewhere there, then the strength would be reduced. So, I must have a good high aggregate strength. And, modulus of velocity also should be higher, because you remember, critical stress is a function of modulus of elasticity of the concrete system without force.

Now, the modulus of elasticity with the concrete system of the function of the modulus of elasticity of the aggregate and as well as the cement paste. Therefore, critical stress will be lowered if I have lower modulus of elasticity of aggregates. Therefore, one must look into this. It must have good modulus of elasticity, good strength. It is like balanced design. If you have… You must have done RC design, where we try to do a balance design; where, strength of the concrete or concrete and the steel fails together. So, it is a balanced system. Now, here actually in ITZ, was failing earlier. I have three component I will say; the matrix – I have the past matrix, the ITZ and aggregate.

So, if all of them fail together, that will be more efficient system. So, aggregate, ITZ, paste – everything should fail together. So, earlier, when paste strength was low, ITZ strength was poorer; there would have got dictated the strength. But, as soon as I increase the strength of these two: paste and ITZ strength I increase, the aggregate – everything may fail together. So, what you see is in case of high strength concrete, if you are crashing a cube, you might see the crack passing through the aggregate as well. So, it is not only the interfacial transition zone by passing the crack; I mean the aggregate themselves going through its boundaries to the bulk paste and joining up again the aggregate interface, is may not be the case here; you might find that it passes through the aggregate itself, because it is almost a balanced system, where efficiency of everything is being utilized.

And, how do you do it? By improving the ITZ through fine material, pozollanic material, which can get inside. And, water reducing agent, which will disperse the particle and allow finer material to get into them, get into the interstities of those cementitious particle. And, both at the interface of the aggregate system, at ITZ as well; and, improve this porosity and refine the pores. So, that is the principle of high strength concrete; that is the principle of high strength concrete.

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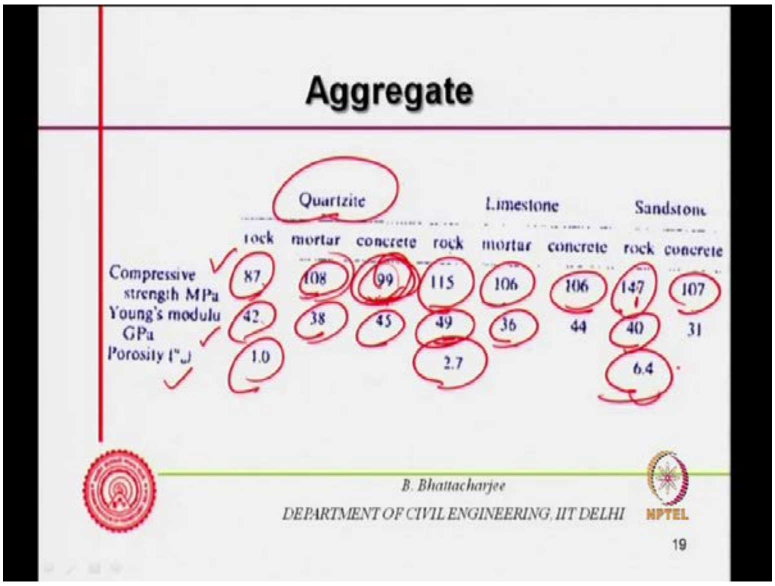

Just aggregate… The properties – if we look at it, for example, modulus of elasticity compressive strength and porosity of some of the aggregate; let us say quartzite rock – some 87 MPa would be the compressive strength; 42 is the modulus of elasticity; porosity is 1 percent. Mortar – if I prepared with this quartzite fine particle, I get modulus of elasticity is slightly reduce. If I produce concrete, then I can go to 99 MPa, because I may improve the paste; it can show you good strength. See this is better than… Mortar is here and the concrete is somewhere there because I will add coarse aggregates then; and, this might bring down the strength somewhat. Finer the particle size, strength will be higher. We talked about that also, because all the fractures have already occurred in a large sized aggregate. This we talked sometime earlier.

Larger sized aggregates – there are some filler planes already existing in the aggregate. When I crash it, the separation has already occurred in the fracture plane. Therefore, more surface energy – it has already absorbed. And, it is actually… Fracture energy – it is dissipated. And, therefore, it is most able; finest material is most able and its strength will be much higher. Therefore, coarse aggregate – when you introduce, strength could be reduced somewhat. You see rock limestone – 115, 106. This is also… Concrete is 106. And, this is sandstone – 147; concrete is 107. In between, mortar is not available. Modulus of elasticity is 40; here 39, 49 and 45 and so on and so forth. So, concrete… Rock has got 49 modulus of elasticity. So, both properties; porosity is given. This is highly porous material. Therefore, rock strength – although is high, they can bring down the strength, because cracks will pass through this. And, therefore, concrete strength (( )) 147 – all those strengths – it cannot show, exhibit that kind of strength.

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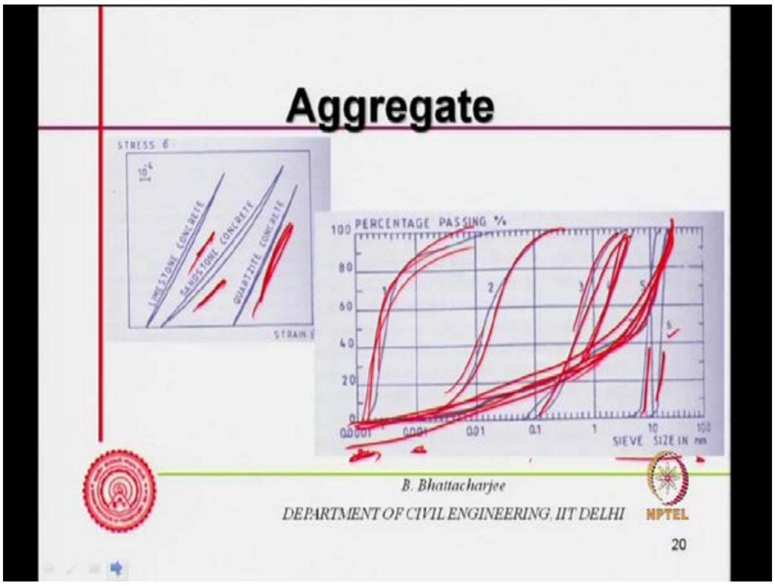

This we have already discussed – the particle packing. Therefore, quartzite concrete is somewhere here, stress-strain curve; standstone concrete is somewhere here; limestone concrete – stress-strain curve is somewhere there.

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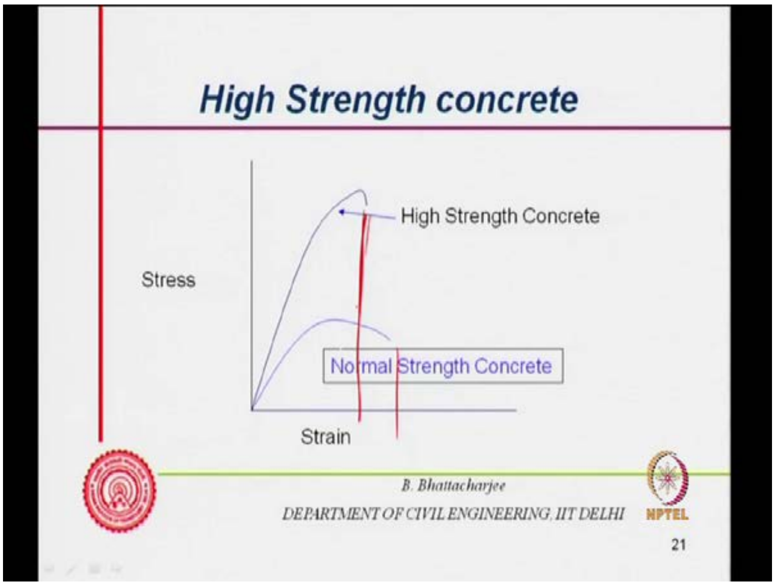

High strength concrete – therefore, would exhibit highest strength; but, it will fail at lower strain. This is not a problem; this is not a problem, but we must know it, because brittleness, the ductility of the concrete – we know that concrete is weak, it is brittle. Therefore, we reinforce it to get the ductility or at 5 hours to get pseudo-ductility in micro level. So, that kind of thing. Therefore, this is not a problem; there is no advantage neither. This is not a… But negative aspect also, because high strength mattresses – we do not rely on the ductility of concrete; we really rely on the ductility of the reinforcing material. Therefore ordinary reinforced concrete structure is not a problem; but, there are other places, where we take foot in fiber to improve… For example, engineered cement composites, microfibers might be added to improve the strength. But, we know that, if strength is higher, modulus of elasticity is higher.

If I look at its other properties, this is tensile strength; this is compressive strength 1 for normal concrete, ordinary concrete. So, relative strength I am talking of; tensile strength may be three times more, while its compressive strength may be two-five times more. So, relative strength of high strength concrete – if it is two-five times more compressive, then tensile strength could be of the similar order or slightly higher.

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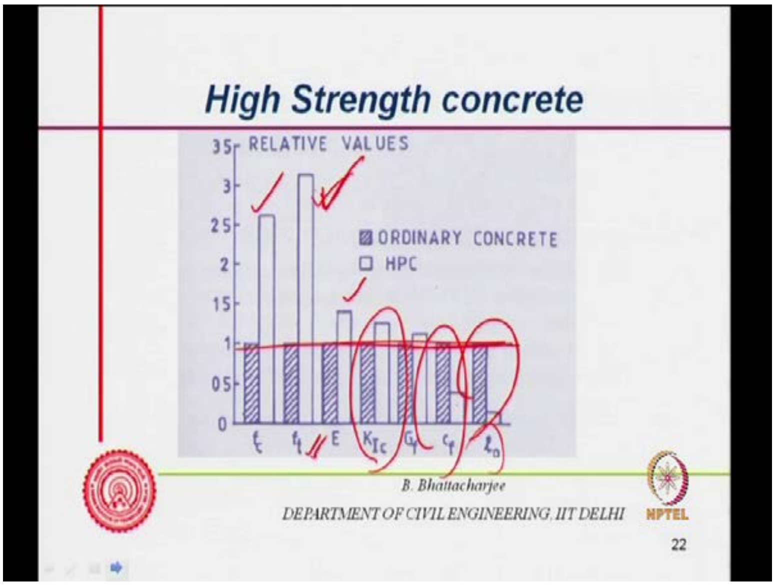

Then, this is modulus of elasticity – definitely higher. These are the fracture properties – the various kind of fracture properties; I will just define them. Some of the fracture properties, for example, energy absorbed will be lower; the length of the fracture, length around the tip would be lower. Some of those things are lower, which is actually sign of brittleness and so on and so forth.

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Some properties – strength obviously improves, tensile strength also improves; modulus of elasticity also improves not to the proportion of the compressive strength; but, it improves. So, one would to… There are people who have done some research on those from the design point of view. We are talking in terms of general ideas; modulus of elasticity will surely improve, but not as much as the compressive strength. Tensile strength improves further. But, other fracture properties also improves. So, high E, low fracture toughness, because energy absorbed is less; stress-strain curve – area under the stress-strain curve is low now. It was somewhere here; now, this area is lower compared to this. Therefore, toughness could be lower. Very good durability, because low porosity, nothing can enter. But one must see against magnesium sulfate, because magnesium sulfate can attack the CHS itself. So, it is still good against all sulfate, all kind of durability, because its strength – it does not allow anything to penetrate.

Improved mechanical properties – so, fracture energy, k I c stress intensity factor – this is lower; fracture energy is lower l 0 is the dimensions of micro cracked zone ahead of the tip advancing crack. These are lower. This is lower; this is lower. That is what we have seen. That is what we have seen earlier. This is lower; this is significantly lower. So, this is the… Around the crack, the micro cracking zone; and, fracture energy is of similar order. And, this k I c is the intensity factor – fracture intensity. So, this stress intensity factor is similar. So, these are some fracture properties. This is like this.

Fire properties suspects – some people say for it is not very good against fire unlike the conventional concrete, because of is low porosity. When hydrated water wants to get out of the system, it has no way to get out; one of the theories is put forward. Therefore, there are cracks; CHS gel – when it breaks down under fire; if you heat it to 600 degree centigrade, 4-500 degree centigrade to 600 degree centigrade, CHS gel will break down; so is calcium hydroxide. So, when they break it down – 700-800, even 750 degree centigrade, calcination of… – calcium hydroxide will break down and it will go out… it will remain as calcium oxide and water will – H 2 O will glow.

Now, water does not have a way to get out, because it is fully dense, no porosity. Therefore, cracking may occur, (( )) occurs easily. So, fire properties suspect. One has to see what properties are good and what properties are not good. But, we have seen that, strength is very good; durability is also very good. And, we have also seen the fracture properties – creep, shrinkage, etcetera has also to be seen in this light; their properties also to be seen.

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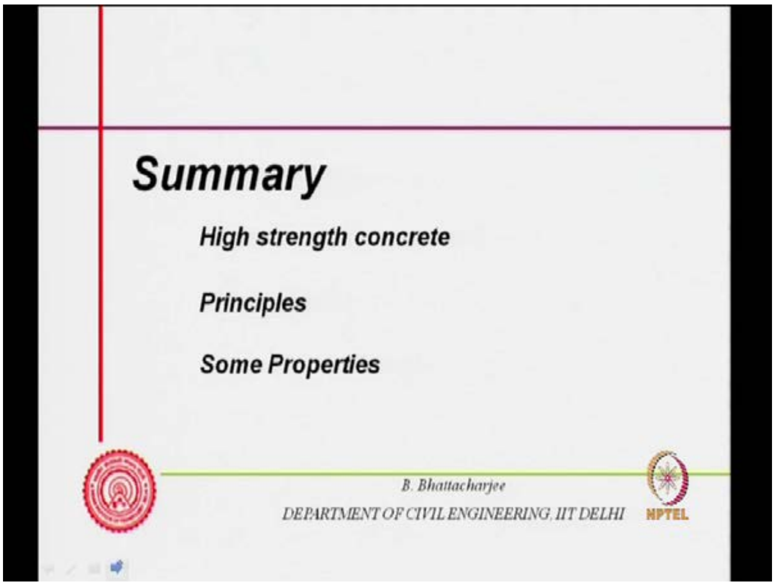

Maybe next class, next lecture, we will look into some of this. So today, in this lecture, we have looked into high strength concrete, principles and we have looked into some properties. Next class, we will look into the additional properties, whatever is left – mix design procedure; then, we will look into other high strength system.

Thank you very much.