Development and Applications of Special Concretes
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Lecture-27
High Strength Concrete

Namaskar and we start another discussion in our series on development and applications of special concretes. The focus on our discussion today is high performance, high strength concrete.

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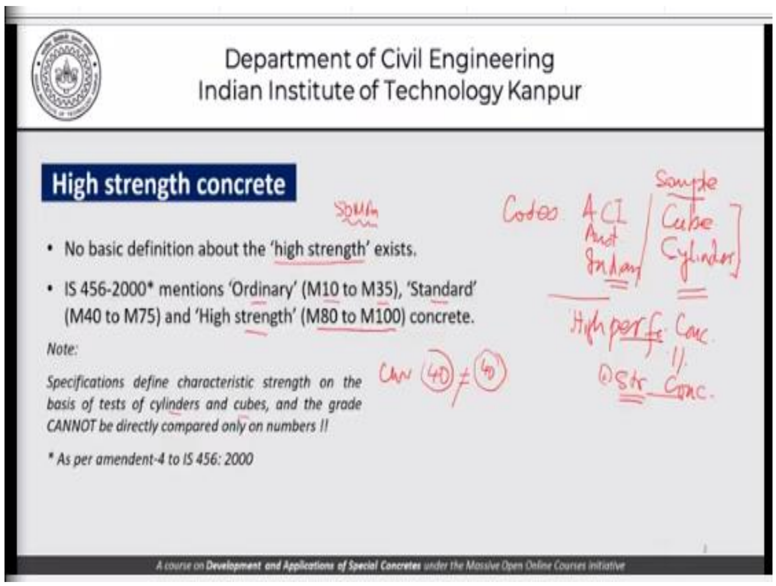

So, first of all as we start our discussion on high strength concrete, please remember or understand keep at the back of your mind that there is no definition on what is high strength concrete in terms of the strength. If there is an internationally accepted value something greater than 50 mPa or 60 mPa or whatever this number is, that is what will be called high strength concrete, no such definition exists.

And I would encourage you to read the different codes in the world, for example you could look at ACI, you could look at the Australian document, you could of course look at the Indian documents. And you will find that there is no standard definition of what is high strength concrete. Having said that it is also important to understand and keep at the back of your mind the fact that different standards use different samples or sample geometry.

For example, some of us use cubes, some of us use cylinders and it is not possible to compare directly the strength obtained from a cylinder and a cube. And therefore, an international agreement on what is high strength concrete is fairly difficult to achieve. And it is not really required at the end of the whole thing. What is important to understand is that beyond a certain point we have issues which are not important for normal strength concrete, and that is what makes this concrete special.

I have already talked to you in one of the lectures then in about the 80's about 35, 40 years ago there was a movement in the world towards high performance concrete. And in Europe and in the U.S high performance concrete was more or less synonymous with high strength concrete. And effort was being made to achieve higher and higher levels of strength as far as concrete is concerned from about 35, 40 mPa to 50 mPa to 60 or 70 mPa and so on.

As far as IS-456 to 2000 is concerned, it divides the concrete into three parts, ordinary, standard and high strength. So, as far as this document is concerned the ordinary concrete is between M10 and M35, standard concrete is between M40 and 75 and high strength concrete as far as IS-456 is concerned is concrete higher than M80, where M80 refers to a mix which has a characteristic strength of 80 mPa.

The specifications define characteristic strength on the basis of tests of cylinders and cubes and we have already talked about it. And the grades cannot be directly compared only on numbers. For example, if there is an American document which talks of a characteristic strength of 40 mPa or 45 mPa, it is not really the same thing as an Indian standard talking of. The same characteristic strength because of the simple fact that the cylinders or the cubes being tested will have their own geometric corrections that needs to be applied.

And this part has already been discussed when we were talking about the discussion here in terms of different types of samples being used in the world.

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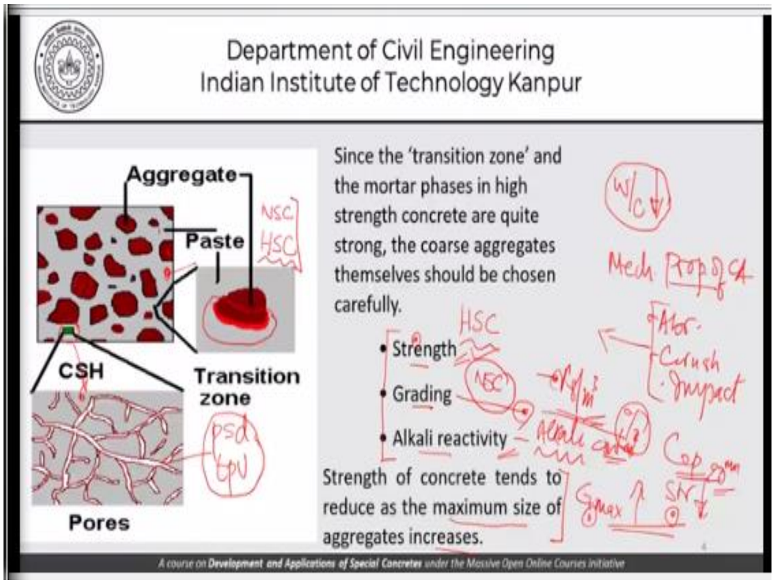

Let us recall once again what is the basic geometry? What is the basic model that we are following as far as concrete is concerned? And here we have the coarse aggregates suspended in mortar and mortar being a suspension of sand and paste. And paste being a suspension of cement particles in water. So, once it comes to higher strength concretes what really changes as far as this model is concerned, that is something which is of concern to us.

We recall that if we take a small element here that really boils down to something like this, where these parts are what is CSH or hydration products and these are what are pores. And we have pore size distributions and the total pore volume characterizing the kind of pore structure. As far as a particular cement paste is concerned which is more or less true for the concrete as well.

Having said that we also are concerned with what is going on in the transition zone. So, in the transition zone what happens with normal strength concrete and what happens with high strength concrete? And that is something which we will examine as we go along in our lecture today. Since the transition zone and the mortar phases in high strength concrete are quite strong, the coarse aggregates themselves should be chosen carefully in terms of strength, grading and alkali reactivity.

All these parameters we have to be more careful when we are choosing aggregates for high strength concrete than in the case of normal strength concrete. Because in the case of normal strength concrete this phase here is much weaker than the aggregate phase. And therefore, when we talked of the 2-phase model or the 3-phase model we could almost identify very clearly which is the weakest link.

But as we keep reducing the water cement ratio, at the end of it for high strength concrete we have to reduce the water cement ratio. And as we reduce this water cement ratio to lower and lower level the strength of this phase keeps increasing. And it does not necessarily become comparable to the strength of the aggregates but yes, it becomes closer to that level. And therefore, the aggregate strength becomes one of the important considerations when it comes to factors determining the strength of high strength concrete.

We must also remember that we do not normally test the strength of aggregate in the same sense as we test the strength of concrete. I will leave it as an assignment to you to revisit and recall the 3 tests that we do for what we call mechanical properties of coarse aggregates. We do the abrasion value; we do the crushing value and we do the impact value. And these three tests essentially represent the strength of aggregates.

Which is not determined as the strength of concrete is determined by taking a core or by taking a sample and applying compressive stresses to it and causing it to fail, that is one part of the story. The second part of the discussion is the grading, because we are talking of high strength concrete the greeting of aggregates is becomes a lot more important than it is in normal strength concrete. And similarly for alkali reactivity because we are using a lot of cement, we have increased the alkali content we land up increasing the alkali content in the concrete mix.

And therefore, we have to be very careful that the aggregates that we have are truly non-reactive. Because once we have a high alkali content in cement it is not really the alkali content is cement per se. But the fact that you have a lot of cement, basically adds to more alkali content in terms of kg’s per cubic meter of concrete rather than the percentage of alkali content in the cement itself.

So, given this parameter we have to be careful about the alkali reactivity of the aggregates as well. The strength of concrete also tends to reduce as the maximum size of the aggregate increases. This is something which is known to us that if we increase the G maximum, the maximum size of aggregate, the maximum nominal size of the aggregates, the strength of concrete tends to go down.

What happens is a result of this is, that when we are talking of development of high strength concretes, we try to cap the maximum size of aggregates we use. We will see it later on, that most of the time we do not see high strength concretes being used for aggregates higher than 20 mm size. In fact, for higher strength concretes, we will find that the maximum size of aggregates has been tapped at sometimes values lower than 20 mm.

Now why this happens? Why as G max increases the strength decreases? This is something which I am leaving it to you to think about and search the literature and to reason it to yourself.

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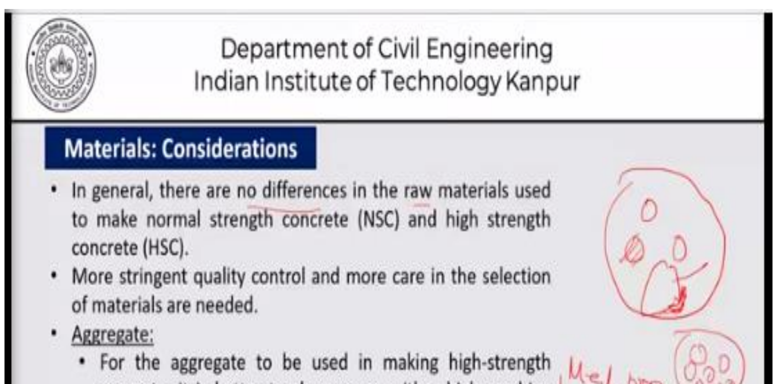

Now, coming to the materials or the considerations that operate in our minds when we choose the materials for use in high strength concrete. There is no real difference between the raw materials used in normal strength concrete and the high strength concrete. Except that more stringent quality control and greater care needs to be exercised in the selection of the materials that is needed.

We talked about the care that we need to take as far as aggregates are concerned, and the same criteria holds for the other raw materials as well. As far as aggregates are concerned, we have already talked about it for the aggregate to be used in making high strength concrete, it is better to choose one with high crushing strength if possible. So, we have already talked about it when we talked in detail last slide on the mechanical properties of coarse aggregates.

So, here we are talking about a specific property there which cause of high crushing strength. The maximum size of aggregates is usually limited to 20 mm; the limitation on the maximum size aggregate is to reduce the influence of the transition zone and to get a more homogeneous material. So, if we have in that concrete slide that we have which we are traditionally used like this.

If I have a very large particle here, then it tends to have a different distribution around the intermediate transition zone. And tends to make the concrete less homogeneous compared to a concrete which will have particles of smaller sizes. In fact, that extent the mortar will have a much more homogeneous disposition compared to concrete. In concrete, the presence of these coarse aggregates introduces an element of heterogeneity and we are willing to live with it, because, we cannot use mortar as a construction material or as a structural construction material for various reasons.

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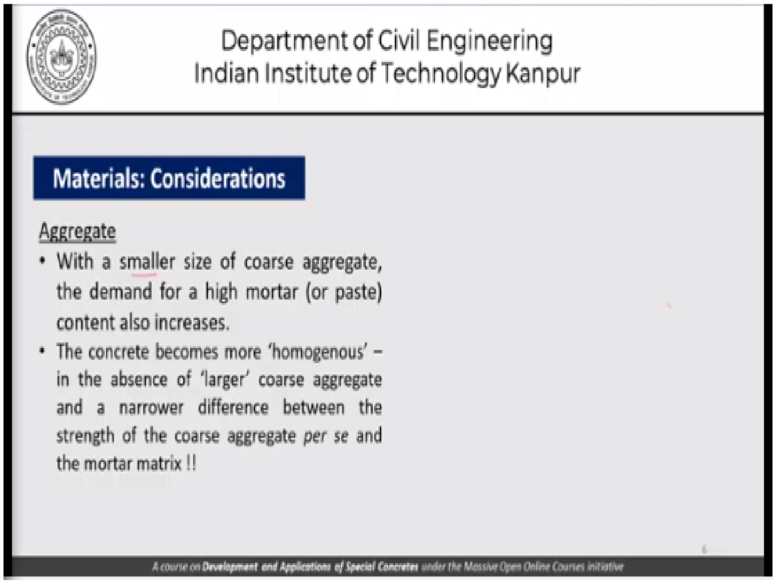

Continuing with the coarse aggregate considerations, as we make or choose a smaller size of coarse aggregate the demand for mortar or paste also increases. The surface area increases if we reduce the size of the aggregate and with the higher surface area, we need more mortar to cover it. The concrete becomes more homogeneous in the absence of larger coarse aggregates and a narrower difference between the strength of coarse aggregate per se and the mortar matrix is what characterizes high strength matrixes.

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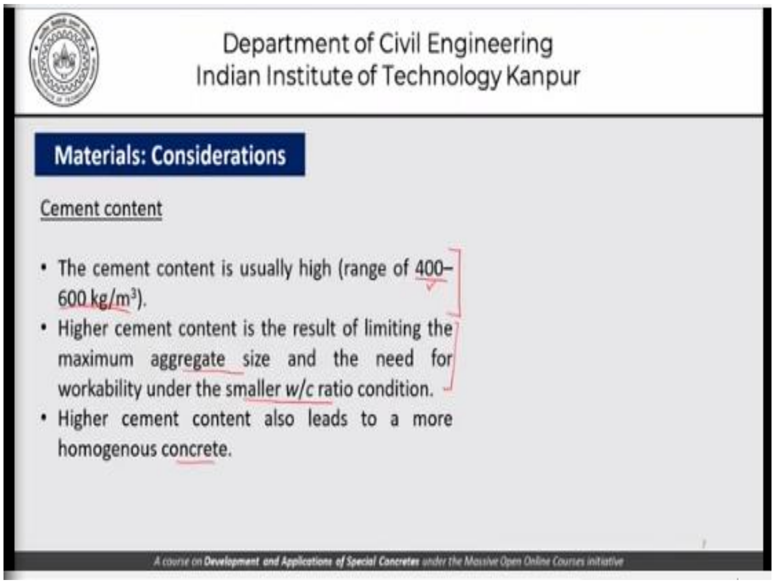

Now coming to cement, the cement content is usually very high, it is in the range of 400 to 600 kg's per cubic meter. Please remember that this numbers are much higher than that used or prescribed in specifications for normal strength concretes. The high cement content is the result of the limiting, maximum size aggregate which implies more mortar; more cement paste and the need for workability with smaller water cement ratio condition. So, all this combines to make a high cement content. Higher cement content also leads to a more homogeneous concrete.

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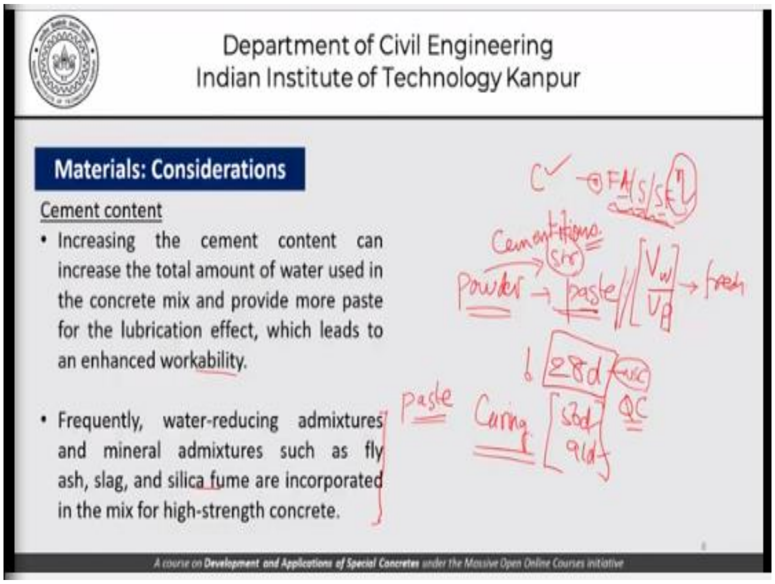

Continuing with our discussion on cement content, increasing the cement content can increase the total amount of water used in the concrete mix, and provide more paste for the lubrication effect which leads to an enhanced workability. So, there are different factors that are operating, there are different considerations that are going on when we are choosing a particular cement content.

And we analyze or try to understand the properties of concrete in that context. Frequently, water-reducing admixtures and mineral admixtures such as fly ash, slag and silica fume are incorporated in the mix for high strength concrete. Now what the addition of these mineral admixtures does is reduce the cement content and at the same time increase the paste content in the concrete. So, we have talked about this phenomenon at length when we are talking about self-compacting concrete.

That as far as the powder is concerned, that is the phase which contributes to the paste as far as the properties of fresh concrete are concerned. But this powder need not play a part as effectively or as such when we are talking about strength. Strength is more dependent upon the cementitious nature whether a powder is cementitious or not.

Cement of course yes, there is no doubt about it, when it comes to fly ash or slag or for that matter silica fume we still talk in terms of how much efficient or what is the mineral efficiency of these mineral admixtures in terms of their contribution to the strength part, but having said that the whole contribution that is the entire fly ash amount or the slag amount or the silica fume amount that does contribute to the paste content as far as the concrete is concerned.

And therefore, the properties of fresh concrete which are governed by the powder content and the paste content we have talked extensively about the volume of water to volume of powder ratio kind of discussion. If these are the kind of properties which help us get fresh concrete and then we talk in terms of higher strength concrete. Of course, what is the focus today is high strength where we say that**.** We will use these mineral admixtures to the extent that we also get the advantage of higher strength.

Having said that, using these mineral admixtures also leads to the situation where all the strength of concrete need not be developed at 28 days. So, we may have to go for a higher time, it could be 56 days or 91 days. Because if we are using mineral admixtures the strength development continues for a much longer time, and there is an argument that instead of 28 days we should do our quality control in high strength concretes at 56 day or 91 days.

So, that is what is the essence of what our discussion in this entire series of lectures has been? That for special concretes there are special considerations and something like 28 day is good enough or is good for normal strength concrete. And there is no reason to stick to this as if it was etched in stone when we are talking about something like high strength concrete where we know. That the choice of materials is such that strength development may continue for a longer time.

Having said that if the strength development has to continue for a longer time and we are relying on that, then that also increases the importance of curing. It puts more responsibility on us that we should ensure that the concrete is cured for a longer time when we are dealing with high strength concretes.

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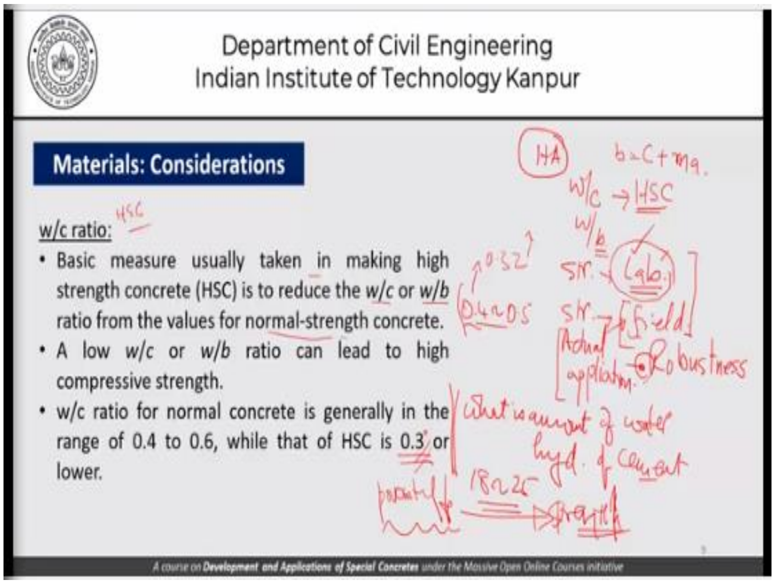

As far as the water cement ratio is concerned, in high strength concrete the basic measure usually taken in making high strength concrete is to reduce the water cement ratio or the water binder ratio from the values for normal strength concrete. So, now what is the range of water cement ratio for normal strength concretes maybe something around 0.4 to 0.5, 0.6. Whereas when it comes to high strength concrete we should reduce this value, this 0.4 should go to about say 0.32 or 0.30 and sometimes lower than this.

I am leaving it to you as an assignment to look at the published literature and try to find out what is the water cement ratio which has been used in different high strength concrete projects across the world? I must point out another thing here, that when it comes to using lower water cement ratios or lower water binder ratios where binder is defined as the cement plus whatever mineral admixtures you are using.

One thing in this context about high strength concrete is to achieve high strength or a higher value of strength in the laboratory, the other thing is to achieve that strength in the field. So, you will find literature where a certain strength has been achieved as far as lab is concerned. But when it comes to field applications where we need a lot more robustness than we have in the lab, there sometimes engineering judgment prevents us from achieving or even targeting those levels of strength.

I will encourage you to kind of read literature and find out from that point of view what is the kind of strength that has been reported in literature for a strength of concrete in laboratory studies. And what is the kind of strength which has been reported in literature as far as field is concerned as far as actual applications is concerned. There are differences when it comes to field applications or actual project applications of high strength concrete.

Because of the nature of production, the curing and so on and that prevents us from achieving the kind of results that we achieve in the lab in the field conditions. So, moving forward, a lower water cement ratio or a water binder ratio can lead to higher compressive strength, there is nothing rocket science about it. It is always known to us, the water cement ratio for normal concrete is generally in the range of 0.4 to 0.6 while that in the case of high strength concrete is 0.3 or lower.

We should also remember when we are talking or when we are working at these levels what is the amount of water required for hydration of cement? Now if you read literature, you will find that this number varies from about 18 to maybe 25%. And we are coming dangerously close to this number when we are talking of a water cement ratio of 0.3 or 0.32 or whatever it is.

Which means that we are hardly adding any water for workability, all the water that is supposed to be there will be consumed in the hydration of the cement that we are using, meaning thereby that this water which has been added there cannot be allowed to escape. In fact, if it does not escape and is consumed in the hydration the porosity of the concrete will go down and this is at the root of our thought process, with that if porosity goes down obviously the strength will increase.

So, this is the kind of reason or the logical thought process completing that if we reduce the water cement ratio to about 0.3. We come to a situation where we are adding almost the amount of water which is required for complete hydration of cement. And then if we are able to maintain the curing conditions, and ensure that the water does not escape. Then we are working in a situation which reduced porosities and high resistance of concrete.

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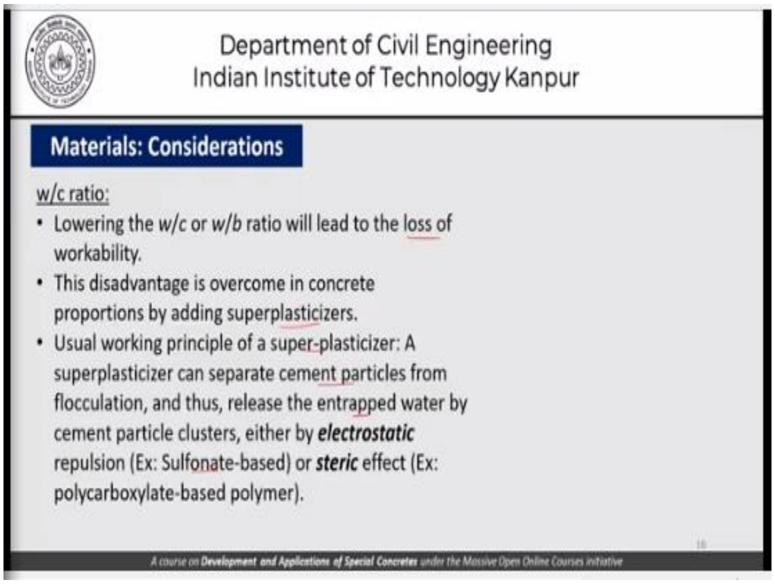

Continuing with our discussion on water cement ratio, lowering the water cement ratio, the water bind ratio also leads to a loss in the workability. This disadvantage is overcome in concrete proportions by using super plasticizers. Usually, the working principle of a super-plasticizer I have already explained to you in several times before. A super-plasticizer can separate cement particles from flocculation and thus release the entrapped water in the cement particle clusters.

Either by electrostatic separation, which is the mechanism for sulfonated-based plasticizers or the steric effect, and that is what happens in the case of polycarboxylate-based polymers or chemical admixtures. So, this is what goes on as far as water cement ratio and the strategy adopted to be able to achieve lower water cement ratios in concrete.

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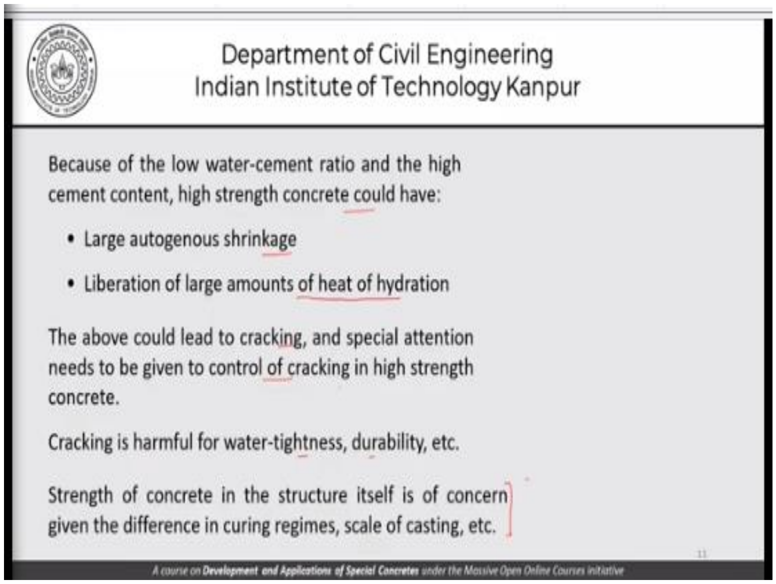

Now, because of the lower water cement ratio and the high cement content, high strength concretes could be susceptible to large autogenous shrinkages and liberations of large amounts of heat of hydration. This could lead to cracking and special attention needs to be given to control such cracks in high strength concrete, which obviously will be harmful from the point of your water tightness or durability.

So, it is very nice to be able to use high strength concrete or develop high strength concrete but along with it there are some downsides of it. Increase in autogenous shrinkage, liberation of large amounts of heat and the resulting cracking, so we have to be careful about that. The strength of concrete in their structure itself is of concern given the difference in the curing regimes, the scale of casting and so on.

In normal concretes we know that the strength of their structure or the strength of the concrete in their structure could be slightly different from the strength that we achieve as far as cubes are concerned because of the difference in curing. This difference or this point of the difference between cubes or cylinders being tested with respect to their strength of the concrete in the structure becomes very important or more important in the case of high strength concrete.

Because the kind of curing regimes are likely to be a lot more important, the scale of casting, the type of sampling or the how we take the samples, these are different things, and or of critical importance when it comes to high strength concrete because, we need to establish the relationship or the equivalence between the strength achieved in the samples and the strength in the structure.

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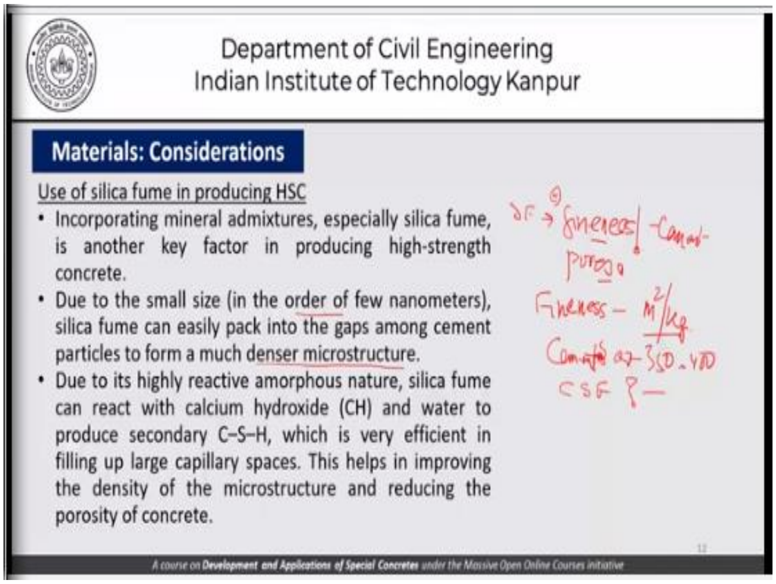

As far as use of silica fume when producing high strength concrete is concerned, incorporating mineral admixtures especially condensed silica fume is another key factor in producing high strength concrete. Due to their small size in the order of a few nanometers, silica fume can easily pack into the gaps among cement particles to form much denser microstructure. So, the silica fume is a lot more fine compared to cement.

And therefore, the silica fume particles can actually sit in the pores of the concrete or the cement paste giving rise to a much denser microstructure. So, the microstructure densification and the case of silica fume being used is not only on account of hydration and refinement of pore structure because of hydration products, but also the physical blockage of those pores using extremely fine material especially in the case of silica fumes.

Due to it is highly reactive amorphous nature silica fume can also react with the calcium hydroxide and water to produce secondary C-S-H that is the calcium silicate hydrates, which is very efficient in filling up the capillary spaces which helps in improving the density of the microstructure in reducing the porosity of concrete? And this is something which you have just discussed in the paragraphs above.

I am leaving it to you as an assignment to find out how fine exactly is the silica fume. As far as the fineness of cement is concerned, we know that it is measured in terms of a surface area, that is square meters per kilogram kind of a unit. And we have numbers which could be close to 350 or 400 or sometimes 300. So, these are the kind of numbers which we are looking for as far as cement is concerned.

My question to you is what is the range of this unit in terms of square meters per kg, if we are using condensed silica film? Try to find this out from literature and you will be better educated to understand the argument that silica fume particles could physically sit in the pore spaces of cement paste making it denser.

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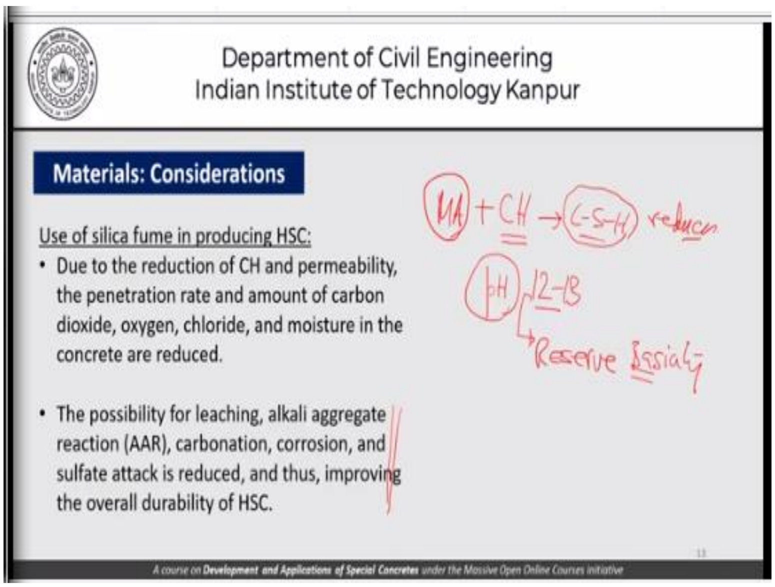

Continuing with our discussion on silica fumes, due to the reduction in calcium hydroxide and the permeability the penetration rate and the amount of carbon dioxide oxygen chlorides, and moisture in concrete are reduced. Basically, obviously as the pore structure becomes denser, it reduces the permeability and therefore the penetration rates of any material whether it is deleterious or not which could be carbon dioxide or chlorides or oxygen.

That goes down as far as high strength concrete is concerned. The possibility of leaching, alkali aggregate reaction, carbonation, corrosion and sulfate attack is reduced and thus improving the overall durability of high strength concrete. But having said that it is also important to keep in mind the fact that when we are using large amounts of mineral admixtures, these mineral admixtures react with the calcium hydroxide to give us calcium silicate hydrates.

Now what happens is that though on the one hand an increased amount of calcium silicate hydrate reduces the porosity, making the concrete denser. But at the same time this is at the cost of consumption of calcium hydroxide in the concrete. Therefore, the kind of pH values that we talk about in concrete which are normally supposed to be about 12 or 13, that could go down and what we call reserve basicity.

Reserve basicity is that amount of calcium hydroxide which continues to protect the reinforcing parts from corrosion, that amount of calcium hydroxide is simply not there when it comes to high strength concretes. And therefore, there is evidence at some points that the carbonation depths are slightly higher. So, this reduction in the amount of calcium hydroxide available in high strength concretes tends to offset the advantage that we get in terms of a densified pore structure.

So, I would like you to just keep this at the back of your mind when we are trying to use very high strength concretes as far as actual applications are concerned.

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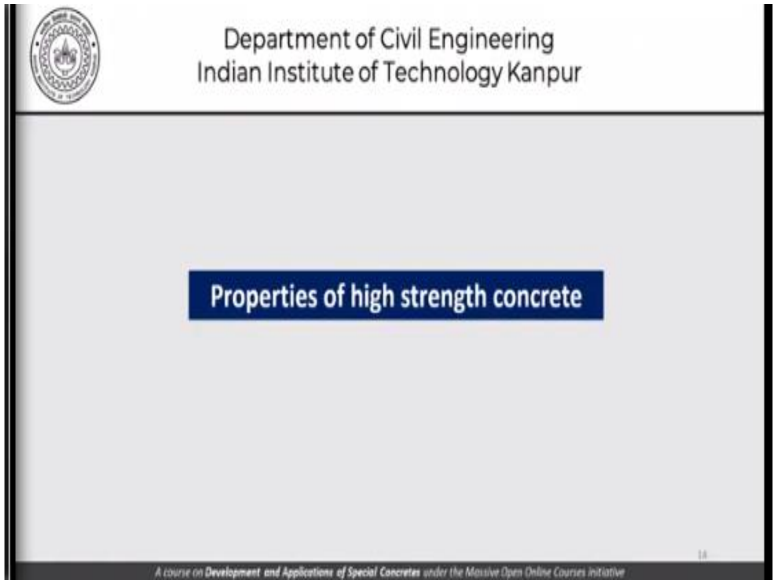

Now as far as properties of high strength are concerned.

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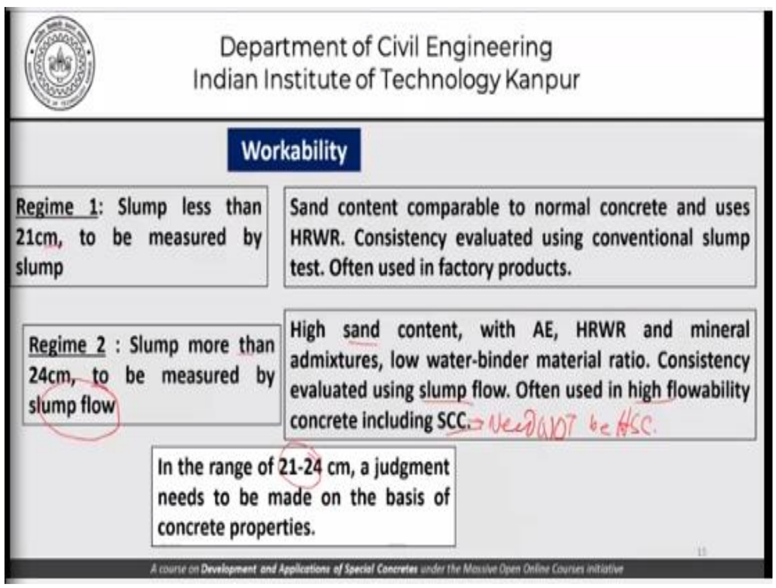

There is one regime where we are talking of slump which is less than 21 centimeters and the workability can still be measured through slump. In that range or in that regime the sand content is comparable to normal concrete and we can use high range water reducers. So, the consistency evaluated using conventional slump test is still possible and this is often used in factory products. There is another regime where the slump is more than 24 centimeters and then we really need to measure slump flow.

Now in this regime the sand content is higher, the concrete is characterized by high cement content, use of air entraining or high range water reduces and mineral admixtures and a low water binder material ratio. The consistency is evaluated using slump flow here, and this kind of concrete is often used in high flow ability concrete mixes like self-compacting concrete. We have already talked about the self-compacting concrete in a previous module.

And I had insisted that self-compacting concrete need not be high strength concrete, self-compacting concrete could be very normal strength concrete. But when it comes to high strength concrete, yes in this regime that high strength concrete could also be self-compacting in nature. So, the compatibility and strength are too not necessarily the same.

They are essentially different properties and that is something which you must keep in mind. In the range between 21 to 24 centimeters, see here we have talked about less than 21-centimeter slump, here we are talking of more than 24 centimeters slump. So, in the intermediate range that is 21-to-24-centimeter kind of slump a judgment needs to be made. And the right kind of tests whether we use conventional slump test or whether we use the slump flow test, that needs to be determined or a call needs to be taken by engineers on what is the kind of test to be used.

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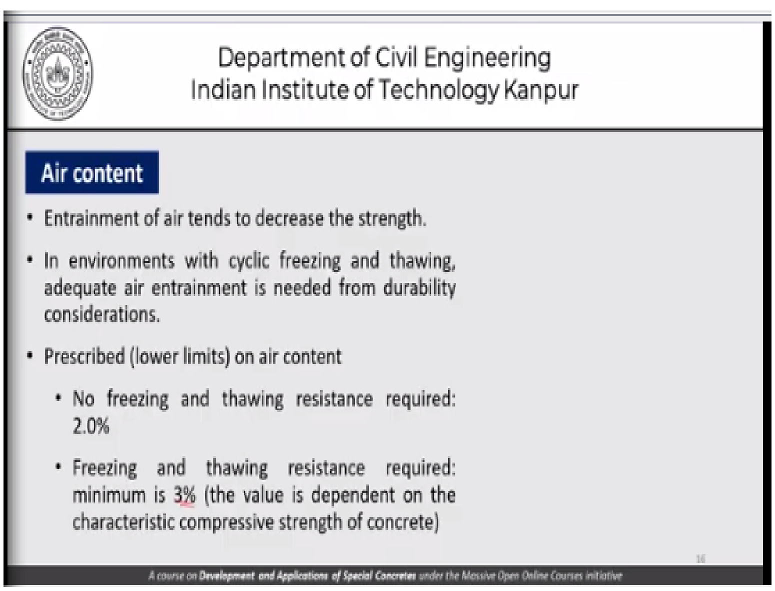

As far as air content and high strength concrete is concerned, we should remember that entrainment of air tends to decrease the strength as far as concrete is concerned. In environments with cyclic freezing and thawing adequate air entrainment is needed from durability considerations and that does not change, whether we are using high strength concrete or normal strength concrete.

And prescribed lower limits on air content could be 2% when no freezing and thawing is expected or required. And freezing and thawing resistance is required in that case we may like to have a minimum of 3% air and the value could depend on the characteristic compressive strength of concrete. So, it depends on really what kind of strength we are talking about within the high strength concrete domain when we are talking in terms of air content.

Keeping in mind the fact that, increasing the air content will have the deleterious effect of reduction in the strength (()) (31:50).

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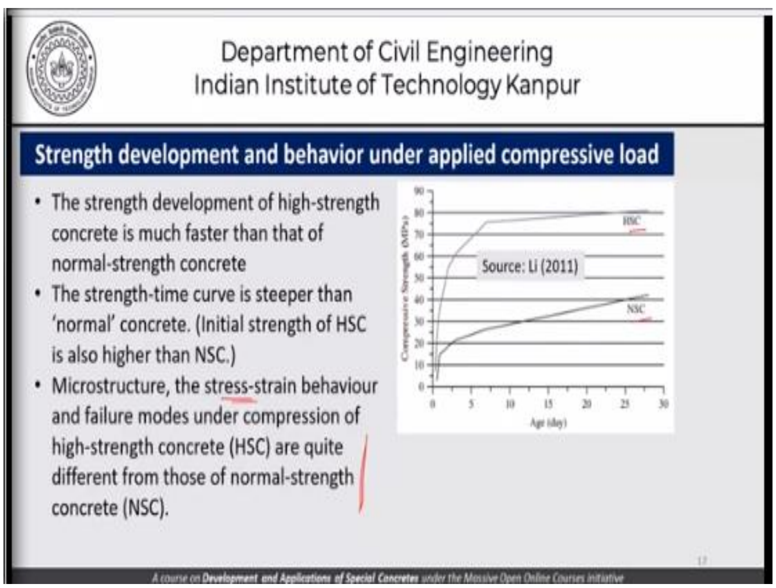

Now, let us talk about strength development and behavior under applied compressive load as far as high strength concrete and normal concrete is concerned. So, this picture here taken from a source in 2011 shows the strength development in high strength concrete is much faster than that of normal strength concrete. So, this is the normal strength concrete and this is the high strength concrete.

So, what it shows is the strength time curve is steeper than the normal concrete. That is the initial strength of high-strength concrete is higher than normal concretes. Of course, something which is not shown here is the stress strain behavior, what is shown here is the development of strength with time. In the case of stress strain behavior also the microstructure the stress strain behavior and the failure modes under compression of the high strength concretes are quite different from those in normal strength concretes.

So, this is something which I am not showing on purpose and expecting or leaving it out to you expecting that you will do the homework and see what is the difference between the microstructure and the stress strain behavior and the failure modes? We will talk about the microstructure and the failure modes a little bit in the next few slides, but I would like you to read about the stress strain behavior as far as high strength concrete is concerned. And it is comparison with the stress strain behavior in normal strength concrete.

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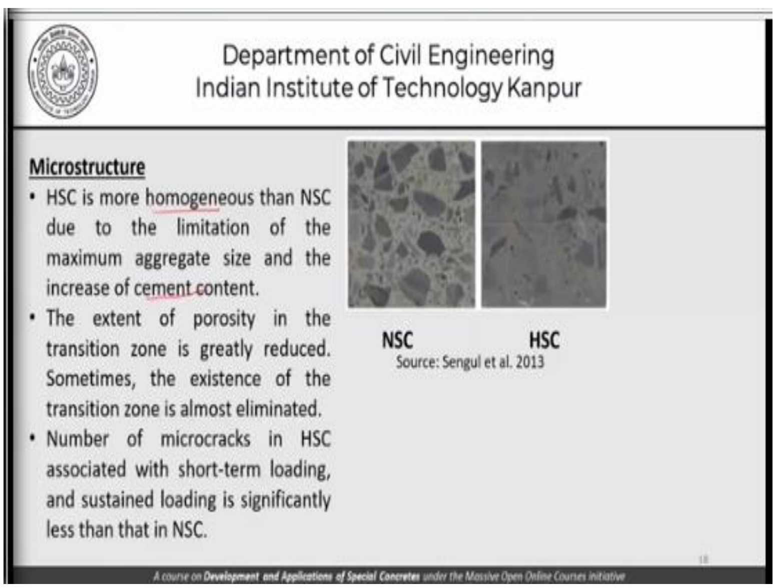

As far as the microstructure is concerned, this is from a study in 2013. High strength concrete is more homogeneous than normal strength concrete due to the limitation on the maximum size of the aggregate and the increased cement content. The extent of porosity in the transition zone is greatly reduced. And sometimes the existence of the transition zone is almost completely eliminated.

The number of micro cracks in high strength concrete associated with short-term loading and sustained loading is significantly less compared to normal strength concrete. So, this is what is the characterization that has been proposed as far as high strength concrete and it is microstructure is concerned.

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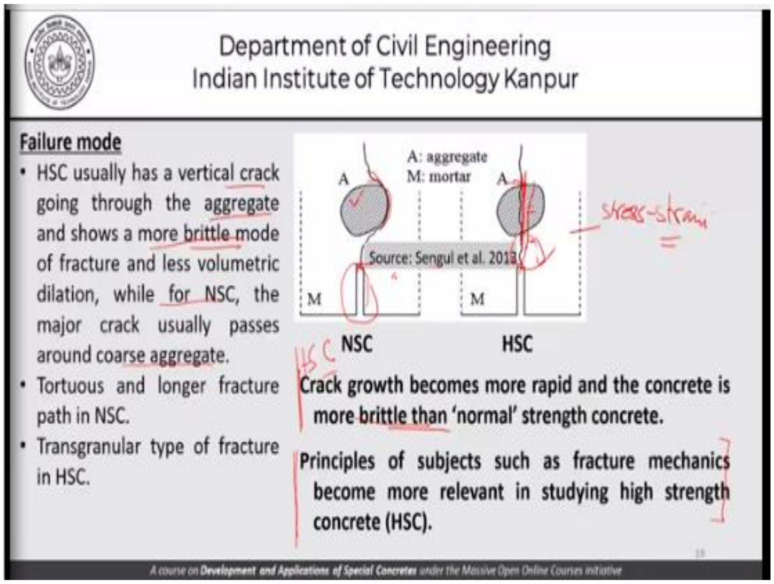

As far as the failure moods is concerned in normal strength concrete and high strength concrete from the same study that we just cited in 2013. High strength concrete has a vertical crack going through the aggregate and shows a more brittle mode of fracture and less volumetric dilation. While for normal strength concrete the major crack usually passes around the coarse aggregate, this is what is represented here in a schematic sketch that if we have.

A notch which we are using to initiate the crack propagation from here, in the normal strength concrete it will tend to circumnavigate or go around this coarse aggregate here. Whereas in high strength concrete because of the comparable strengths of the mortar phase and the coarse aggregate, this mortar being much stronger than this mortar here, the aggregate tends to break and the crack propagation occurs through the concrete.

So, that is a very important difference as far as crack propagation in high strength concrete versus normal strength concrete is concerned. In fact, there is an interesting discussion on this aspect if you kind of read some literature for example that is given in the book by P.K Mehta and others. You will find how this kind of crack propagation around the aggregates or through the aggregates the crack propagation within the mortar phases, how it actually affects the stress strain behavior of concrete?

That is something which is very interesting to read and I hope some of you will find the discussion interesting as to how the stress strain curve of concrete is non-linear. And the extent of non-linearity actually reduces because the concrete becomes more homogeneous in the case of high strength concrete and the crack propagation occurs through the aggregates. In the case of normal strength concrete, the same thing is being explained or expressed differently.

The crack path is tortuous, more tortuous I should say and a longer fracture path than in the case of high strength concrete. So, you can imagine that the path from here to here is much straighter compared to the same path in the case of normal strength concretes. Transgranular type fracture in high strength concrete is more common which finally leads us to the fact that crack growth becomes more rapid and the concrete is more brittle than normal strength concrete.

This is what is characterizing the high strength concrete. The high strength concrete the crack growth is more rapid and the concrete is more brittle than normal strength concrete. The principles of subjects such as fracture mechanics become more relevant in studying high strength concrete. So, in fact those of few who are interested in this subject of fracture mechanics would probably find that there are books which tell us that fracture mechanics principles are more applicable to high strength concrete than normal strength concretes.

That is the first thing and in fact we can use fracture mechanics principles to study and characterize high strength concretes better than using simply strength. So, there are other parameters which are coming from the fracture mechanics domains which help us characterize high strength concretes better. This of course also imposes a little bit of a limitation on the use of high strength concretes when it comes to design.

Because all our conventional design principles are based on strength, and it requires a special kind of training on the part of designers to be able to incorporate in their thought process or in the design process, the parameters that are coming out of fracture mechanics. So, as far as this course is concerned, we stop this discussion here and leave it to those of few who are more interested to do some selfish study. And see what are the principles or what are the parameters coming out of fracture mechanics which can be used to characterize high strength concrete.

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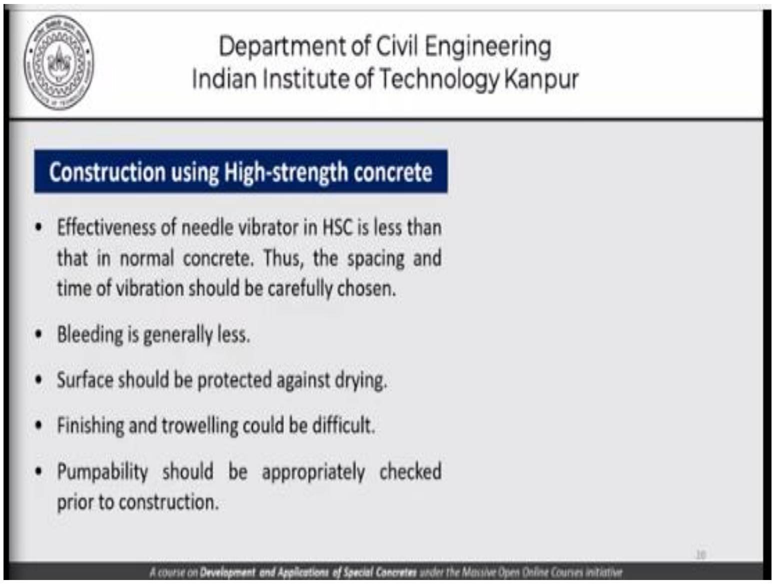

As far as construction using high strength concrete is concerned, let me try to point out a few things. Effectiveness of needle vibrator in high strength concretes is less than that in normal concretes and therefore the spacing and the time of vibration should be carefully chosen. Breathing is generally less; surface needs to be protected against drying because we are anyway using very little excess water.

And therefore, whatever water is there it should be ensured that it is used for hydration of cement and is not allowed to escape. Finishing and traveling could be difficult as far as high strength concrete is concerned. And pumpability is another issue which needs to be appropriately verified prior to going to construction using high strength concrete. So, the kind of equipment that you need or you will use or you can use is quite different in the case of high strength concretes because of the very high volume of powder and the paste involved in the mix.

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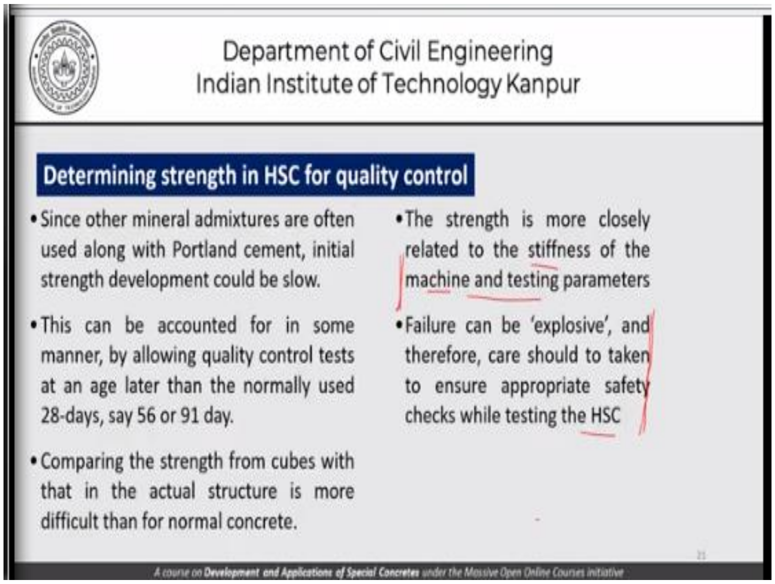

As far as determining the strength in high strength concrete for quality control purposes is concerned. Since mineral admixtures are often used in Portland cement, initial strength development could be slow. This could be accounted for in some manner by allowing a quality control test at an age later than the normally used 28 days to say 56 or 91 days as we discussed a little earlier today.

And comparing the strength from cubes with that of actual structures is more difficult than that in the case of normal concretes, this also we have discussed before. The strength is more closely related to the stiffness of the machine and testing parameters. So, as we go higher in the strength, the stiffness of the machine or what kind of a compression testing machine is used to determine the strength of concrete also starts coming into play.

Failure can be explosive and therefore care should be taken to ensure appropriate safety checks while testing the high strength concretes. So, this is something which is on record as far as literature is concerned and I would like you to read a little bit more about the nature of failure as far as high strength concrete is concerned in terms of it is brittle nature.

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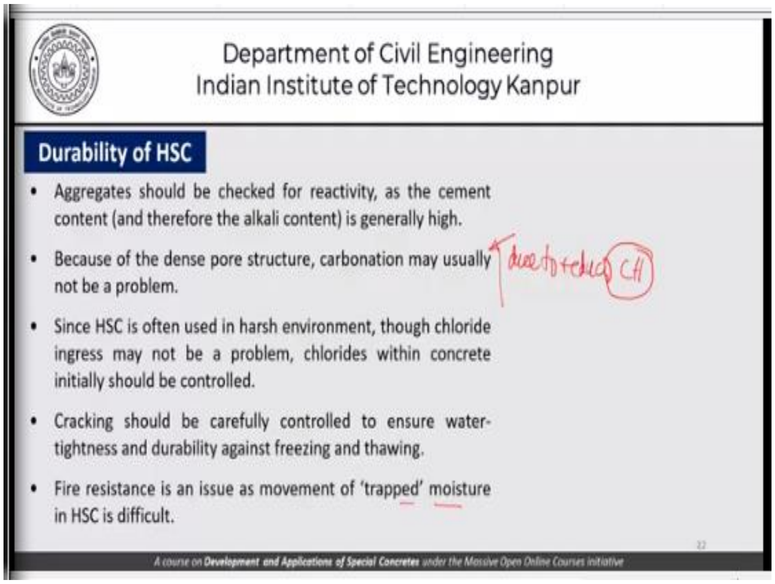

Now coming to the last aspect of durability in high strength concrete, the aggregate should be checked for reactivity as the cement content is generally very high. Because of the dense pore structure carbonation may usually not be a problem. But I have already pointed out that due to the reduced amount of calcium hydroxide available. We have to be careful of using this alone as a sales point or as a selling point in high strength concrete.

Since high strength concrete is often used in harsh environments though chloride ingresses may not be a problem, chlorides within the concrete initially should be controlled. Cracking should be controlled very carefully to ensure water tightness and durability against freezing and thawing, we have already talked about this. And we know that cracking could be an issue because of the shrinkage and other issues which are coming out of the Heisman content.

Fire resistance is also an issue as far as high strength concrete is concerned, because the movement of trapped moisture is difficult. And therefore, in the case of fire, high strength concrete may not be the best material compared to normal strength concrete. So, we have to be a little more careful when we are using high strength concrete in structures which are susceptible to or likely to be exposed to the danger of a fire.

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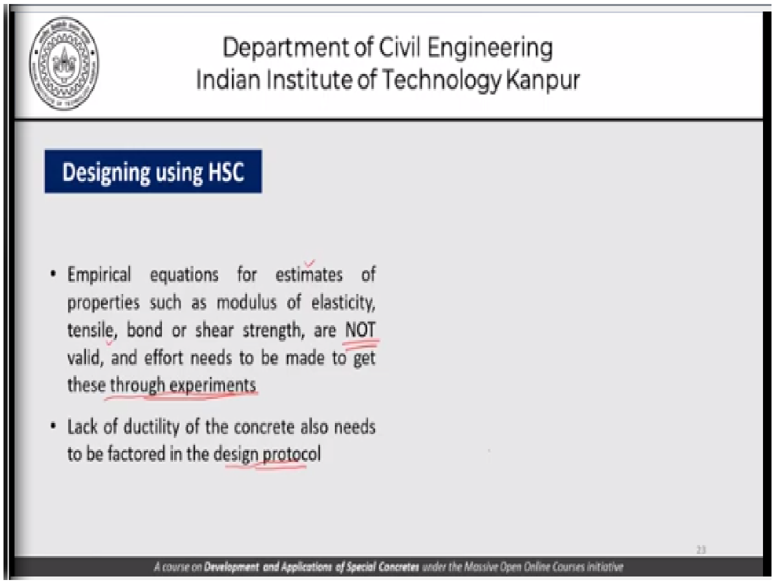

When it comes to designing using high strength concretes, empirical equations for estimates of properties such as the modulus elasticity, tensile or bond or shear strength. These empirical relationships are not valid and effort needs to be made to get these values whether it is E or it is the tensile strength or it is the bond strength of the shear strength through direct experimentation. Lack of ductility of the concrete also needs to be factored in the design protocol that we follow when it comes to designing with high strength concrete.

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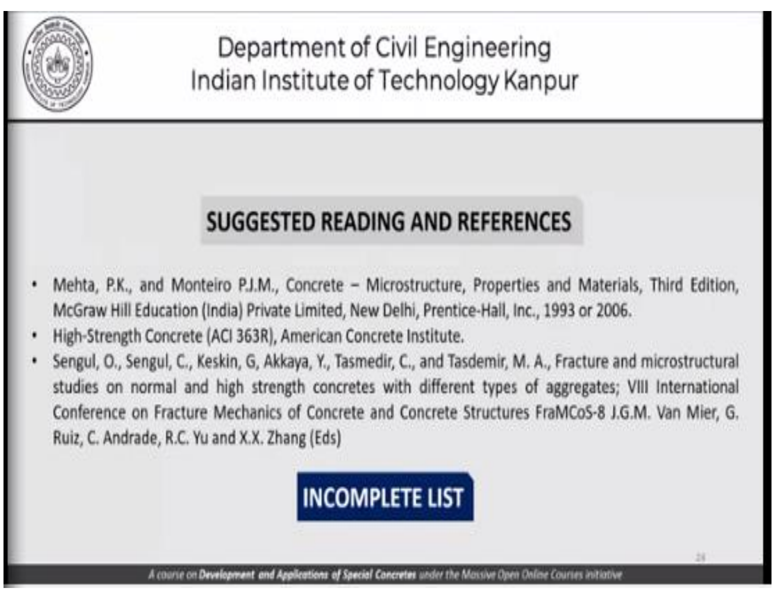

With this we come to an end of a brief introduction to high strength concrete. And this lists some of the literature which you could be probably referring to understand a little bit more about high strength concretes. And as usual the list is incomplete, and you are expected to do more and more reading to be more familiar with the principles of high strength concrete.

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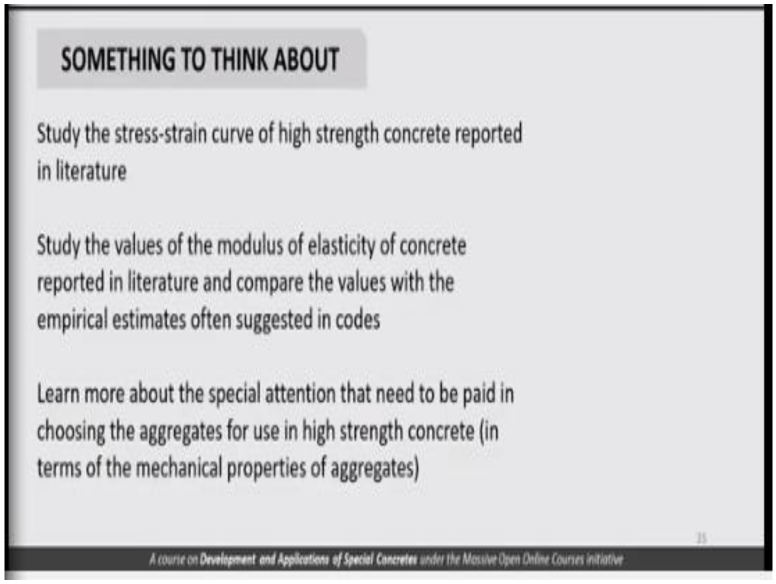

Now let me just end with a few homework kinds of assignments for you, study the stress strain curve of high strength concrete reported in literature. Try to compare it with the stress strain curve of normal concretes. And you can compare it again with the idealized stress strain curves of concrete which are given in the codes. Study the values of the modulus of elasticity of concrete reported in literature and compare these values with the empirical estimates often suggested in codes.

For example, the Indian code suggests the use of 5000 root FCK as a model for calculating or estimating the modulus of elasticity. Try to see whether that formula or that empirical rule is good enough even for high strength concretes. In fact, there is a very clear disclaimer as far as IS 456 is concerned. Cautioning the engineers not to use these kinds of empirical relations for high strength concretes.

Learn more about the special attention that needs to be paid in choosing aggregates for use in high strength concretes in terms of the mechanical properties of the aggregates.

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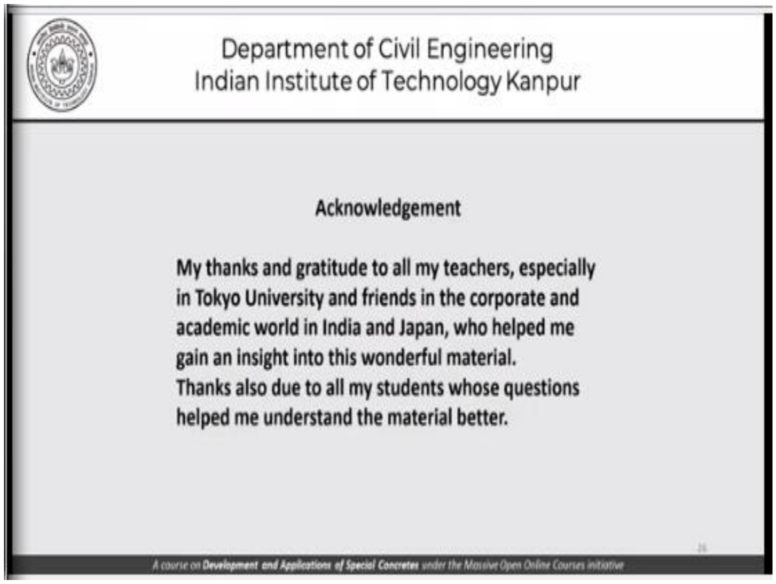

And in the usual manner, I end with my thanks and gratitude to all my teachers especially at Tokyo, my friends and corporate and the academic world in India and Japan who have helped me understand and gain insight to this wonderful material of concrete. And, I thank all the students whose questions have helped me understand the material better. Thank you so much for your attention in this lecture and I look forward to seeing you once again as we continue our discussion in the special concretes next week when we commence module 8, thank you.