Concrete Engineering and Technology
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Lecture - 15
High strength concrete

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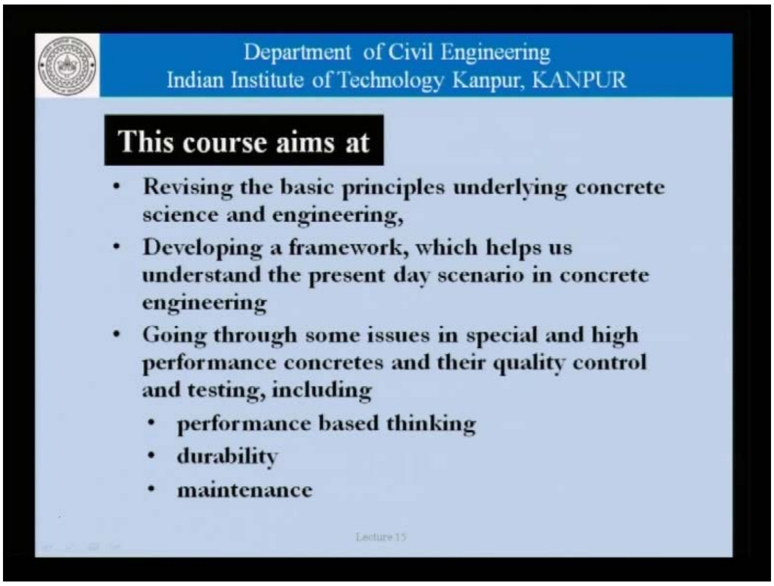

And welcome to this course, this lecture on concrete engineering and technology. In the course as we know, we are trying to study the basic principles underlying concrete science and engineering, developing a framework which helps us understand the present scenario in concrete engineering with the use of different mineral admixtures, different chemical admixtures, and construction technologies and so on.

We are going through some issues in special and high performance concretes and their quality control, testing; which includes performance base thinking, durability of these concretes, and maintenance of the structures made using these concretes.

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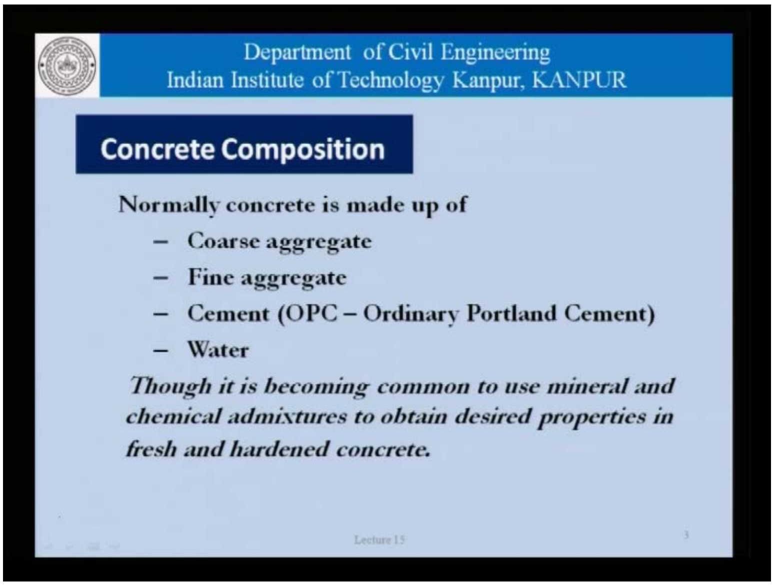

To reiterate; normally concrete can be taken to be a mixture of coarse aggregate, fine aggregate, cement. Ordinary Portland cement is what we refer to most of the time in the traditional sense. And, water even though it is becoming increasingly common to use mineral and chemical admixtures to obtain desired properties in fresh and hardened concrete, and understanding of the basics always helps in building a foundation which is required to understand some of the special concretes which we will be talking about today.

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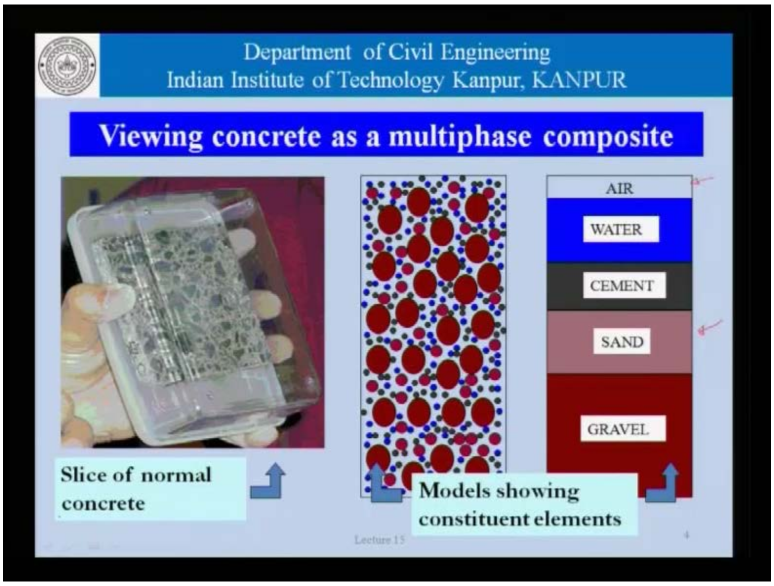

Now, this slide we have seen before. It is again viewing concrete as a multiphase composite which shows that, if we take a slice of normal concrete, what we see is that, concrete can be looked upon as aggregates or well course aggregates embedded in a system of mortar.

Now, if this was modeled to be like this and this was modeled to be like this. Then, concrete is essentially a mixture of gravel, sand, cement, water and air which when mixed gives you concrete. The properties of fresh concrete, properties of hardened concrete are basically determined by the properties of the constituents and the proportion that we use.

We must remember, in proportioning concrete we have seen that, at the end of it all the constituents of concrete should contribute a certain amount in terms of volume to the 1000 liters or a cubic meter. And that is what we get as unit content of different materials.

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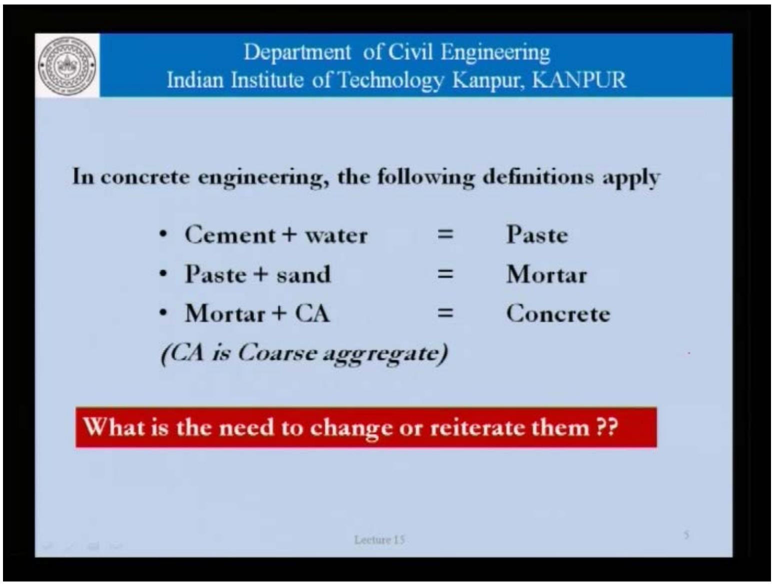

This again is just definitions which we have seen before. Cement and water is paste; paste and sand is mortar; mortar and course aggregate is concrete. There is a reason to look at it once again today. Whether we want to change some of these ideas, whether cement and water alone should be called paste and so on and so forth, we shall see as we go along.

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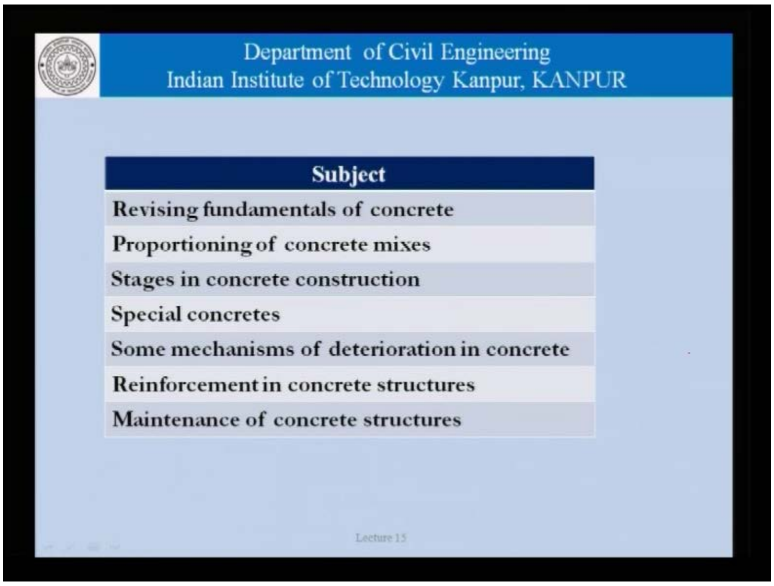

This again is the broad outline of the course which talks of fundamentals of concrete, proportioning concrete mixes, stages in construction, special concretes, mechanisms of deterioration, reinforcement, material used in concrete and maintenance. And today, the discussion focuses on special concretes.

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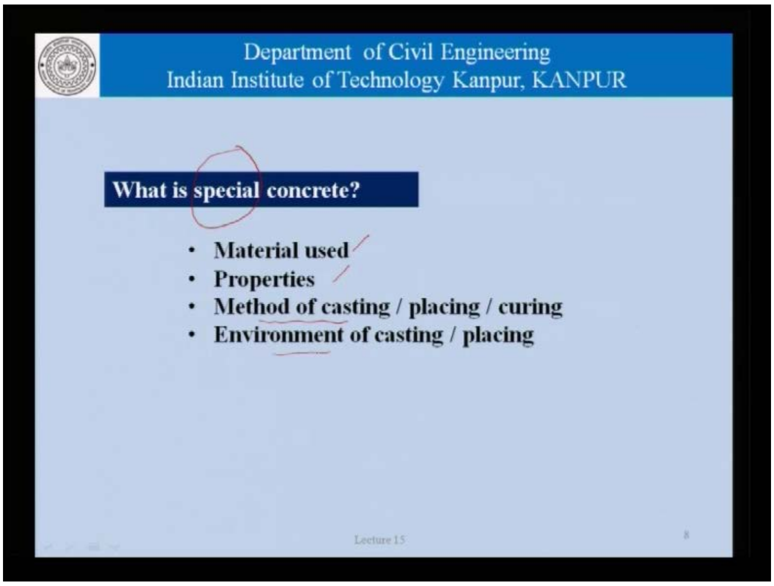

What is a special concrete? And, we have tried to answer the question before. It could be based on materials that we used in the concrete, it could be based on the properties of the concrete that we are talking about. A concrete could become special because, the method of placing or casting or curing of that concrete is something different; or the environment in which the concrete is cast or placed is different.

What this clearly shows is that, in order for a concrete to be special it has to be different from normal. And therefore, for the materials, properties, the method of casting, the environment of casting. For each of these issues we must have what we will define or what we understand is normal. If any of those conditions changes then, the concrete becomes special, the concreting method becomes special.

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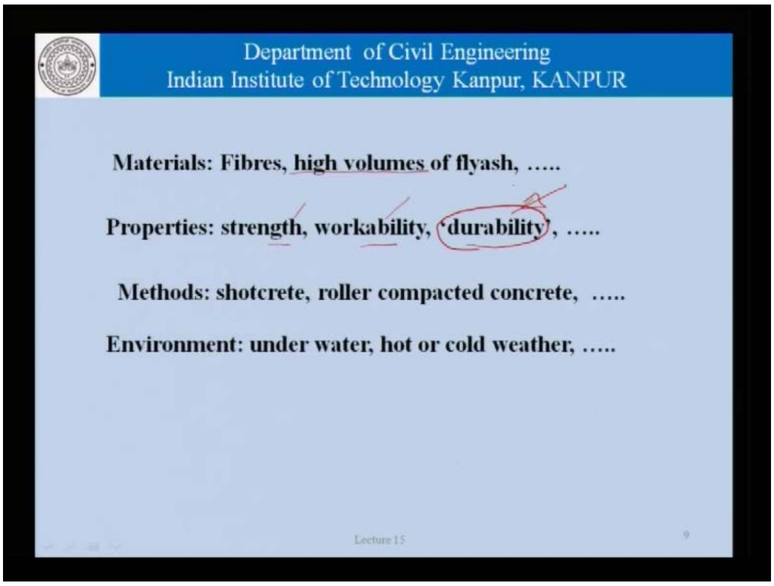

Now, as far as material is concerned, apart from course aggregate, fine aggregate, cement and water. We could use fibers, we could use mineral admixtures. Even if we assume that using mineral admixtures like flyash or blast furnace slag has become common practice either, in the form of blended cements or as additives in concrete itself. There is a special issue involved when we use high volumes of flyash and that is possible and is done in certain specific applications.

Similarly, properties: We talk of properties of concrete in terms of strength, workability, durability. Now, strength is the property that is supposed to be representative of concrete. Most concrete engineers or designers, they talk in terms of characteristics strength of concrete and they say well m 40, m 50 and so on.

So, what is the normal range? And if it is higher than that then, it is special concrete in terms of high strength concrete. At times we also try to develop low strength material that need not be used for reinforced concrete construction but, has certain other applications. So, that again is a special concrete.

Similarly, workability: Depending on the method of construction that we use. If we are using normal methods where, concrete is carried by wheel barrows or in pans manually then, we need a certain amount of workability. But, if we are trying to pump the concrete then, we need another kind of workability. We need the concrete to be flowing sometimes. So, that is what makes it special.

Durability is a very different kind of property. And attention on durability as a property of concrete is not all that hold. Even though the importance of the different parameters such as, the water cements ratio or the cement content, type of cement used and their relationship with the environment in which the concrete structure is placed, is age-old. Specifications did say, what are the limits of water cement ratio? What are the strength requirements from the point of view of durability? Off late however, there is an emphasis on trying to test durability more directly rather than depending only on strength as an indirect measure of durability.

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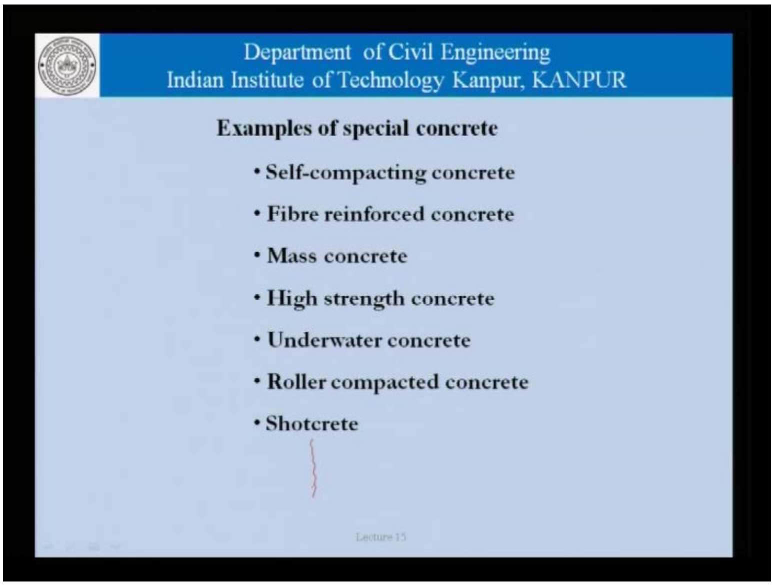

So, this again high durability concrete is a special concrete. As far as methods of construction are concerned: Shortcreting where, the concrete is gonited on to a surface without a formwork. Where the concrete is compacted using vibratory rollers. For example, in the construction of roads. These are concretes which call for a special attention. As far as environment in which the concrete is placed under water, hot weather, cold weather, these are situations which call for a special attention as far as concrete and concreting procedures are concerned.

Now, let us look at examples of special concretes. Several of them: self-compacting concrete, fiber reinforced concrete, mass concrete, high strength concrete, underwater concrete, roller compacted concrete, shotcrete and that list can go on and on. Now, these are all different concretes or special concretes because of one or more of the reasons that we discussed in the previous slide; in terms of materials used, in terms of the method of construction, in terms of the properties or in terms of the environment.

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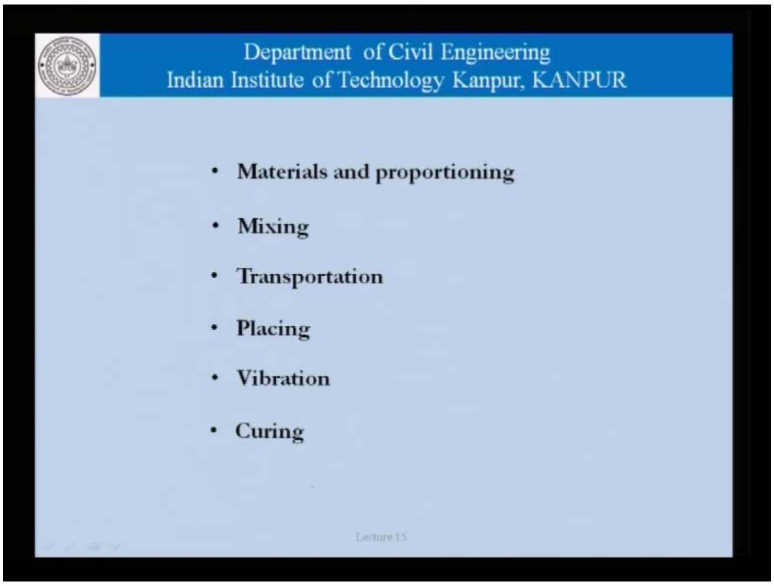

Having said that, it is not possible to develop a special concrete purely based on one of the issues involved or is just not that if we material. Concrete engineering involves from another point of view several aspects. One of them is materials and proportioning .What is the kind of materials we use? What is the proportion that we use? What is the process of mixing the concrete? What kind of mixture, volume of mixer, method of mixing, time of mixing? How is the concrete transported, agitator truck, conveyer belt and so on? How is it placed? How it vibrated, form vibrated, internally vibrated, not vibrated at all? How it is cured, curing compounds, membranes, gunny bags, under water and so on.

So, these considerations are important when we talk of concrete. Now, when we talk of special concretes. This whole thing is interrelated. So, if we are talking of a special concrete from the point of view of strength then, not only the materials and proportioning of materials is different but, that has implications in terms of mixing, it has implications in terms of placing, it has implications in terms of vibration and curing. So, only a comprehensive way of all these issues will help us properly handle special concretes.

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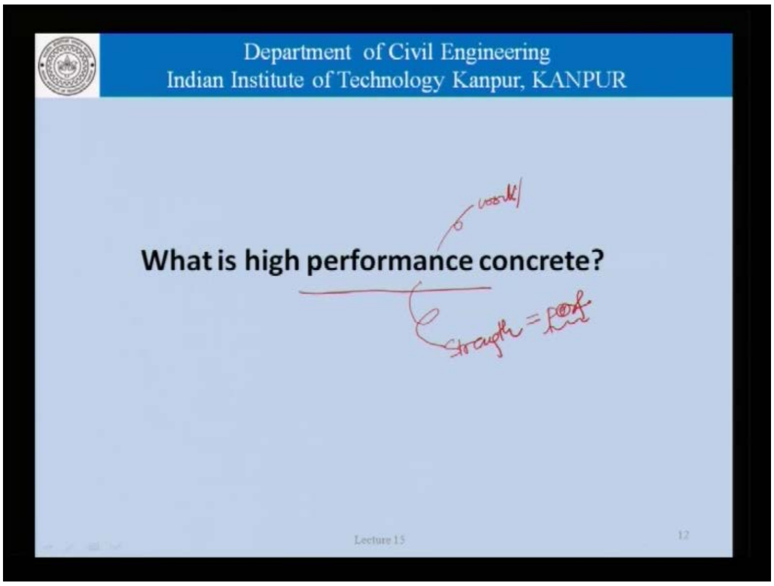

I have not even talked of, what is high performance concrete. Let me share with you a small diagration. In the late 80s and early 90s that is 1980s and 1990s, the high performance concrete has a term in concrete engineering been being widely touted and there was a school of thought that at the end of it the performance of concrete is basically strength.

So, high strength concrete is the high performance concrete. So, performance and strength were related, were supposed to be almost synonymous. But, there was another school of thought or another school of research as engineers who were working on other parameters. Workability or a concrete which did not require to be vibrated and that was going to help us produce concrete of a more uniform quality. That was touted as performance.

So finally, what has happened is, that no matter what parameter we use, it could be workability, it could be strength, it could be durability. So long as the performance of that concrete is higher then, what is normally expected on that parameter, the concrete can still be called high performance concrete. Now, we have talked of these examples as of special concretes. And today, we will focus on high strength concrete.

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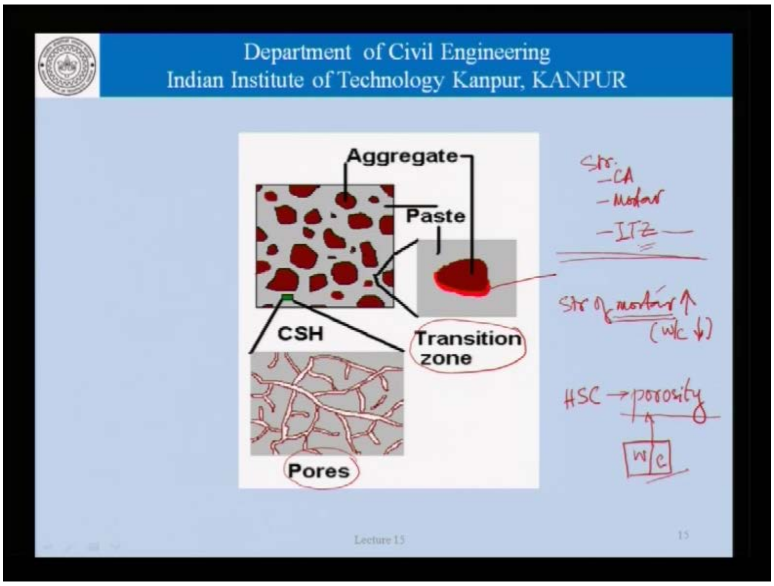

Now, let us take a look at this picture once again. Concrete as we said is a coarse aggregate embedded in mortar. Now, what is happening as far as strength is concerned? In normal concretes, the strength can be determined by either the strength of the coarse aggregate or the strength of the mortar or the strength of the intermediate transition zone. And that is what is shown here. And that forms just around the aggregates. That is the interface between, the aggregates and the mortar.

Now, as the strength of this mortar phase is increased. And, how do we increase it? We know that the only way that, that strength can be increased is by reducing the water and cement ratio. That is, either put more cement or useless water. So, as we increase the strength of the mortar, we get higher and higher strengths. So long as the ITZ does not become a bottleneck. So, in high strength concretes, we are talking of a situation where the mortar phase is very strong. Now, the strength of the mortar phase itself depends on the porosity and the pore size distribution. More porosity than the pore size distribution perhaps.

So, in high strength concretes we try to control the porosity, which we know is related to the water cement ratio. Once we keep this in mind, that in high strength concretes we have reduced porosity because we use very low water cement ratios. The strength of mortar phase is much larger or much more than in traditional concretes. The ITZ is also stronger, there is less bleeding in the concrete. And therefore, the ITZ found is not that higher in water cement ratio. Then, we will be able to appreciate and discuss the properties, the construction method, the proportioning and so on of high strength concretes with the lot more ease.

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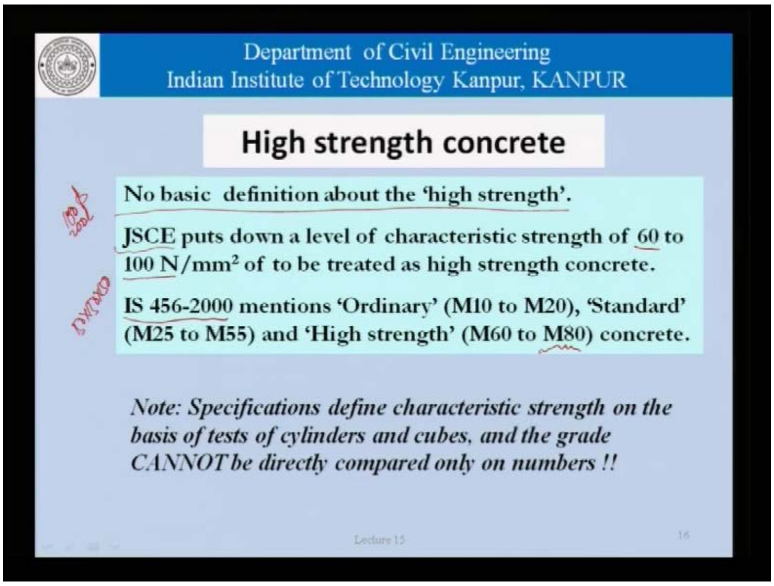

Now, once we talk of high strength concretes, we must remember that there is no universal definition of high strength. High strength simply means high strength. But then, there are different norms of what will be called or what may be called high strength. For example: Japan society of civil engineers puts down a level of characteristics strength of 60 to 100 Newton's per millimeter square to be treated as high strength concretes. IS 456- The code in India mentions 3 categories of strength: Ordinary, which is M10 to M20 or well m 10 to m 20; standard, which is M25 to M55 and high strength, which is M60 to M80 concrete.

So, we should remember that specifications such as JSCE and IS 456, they define characteristic strength on the basis of tests of cylinders and cubes and the grade cannot be directly compared only on numbers. The JSCE defines these values or talks of these values in terms of cylinders with 100 mm diameter and 200 mm length.

Whereas, IS 456 talks in terms of a 150 by 150 into 150 cubes and now for the same concrete, if we take cylindrical specimens and we take cube specimens, the strength determined is different. Cubes are stronger by about 15 to 20 percent compare to cylinders. And therefore, what we are talking of M80 here based on cube strength is at about 15 to 20 percent lower as far as the Japanese standard for high strength is concerned. That is something which we must bear in mind when we are talking of high strength concrete, as to who is talking about high strength concrete.

What specification provisions will apply may depend on the specification from, will depend on one specification to another. For a particular strength, one specification may say that provisions relating to high strength concrete apply. Whereas, another may say no, they do not apply. It is just normal concrete.

As far as concrete strength is concerned, we should also remember that concrete structures are built in the field. They are normally not factory made products. And therefore, the strength we are talking about, even though is based on laboratory tests of cylinders and cubes or whatever is a specification may require. What the engineer keeps in mind is that, finally the strength has to be achieved in the field with conditions of transportation, placing and curing; as may be applicable in the field, the technology which is available in the field.

And that is why different specifications which are drawn by different countries naturally, take into account the kind of construction technology that is normally used. Nobody stops them from using different technologies, modern methods, and old methods. But, their specifications are written from the point of view of normal construction. And that is what is at the back of the mind of people who writes specifications and makes a statement as to whether or not professions for high strength concrete will apply.

So, so much for the definition of high strength concrete. There is no uniform definition; there is no universal definition, and different specifications depending on different conditions that the writers of those specifications feel like they lay down different bench marks which will help us define high strength concrete as far as that specification is concerned.

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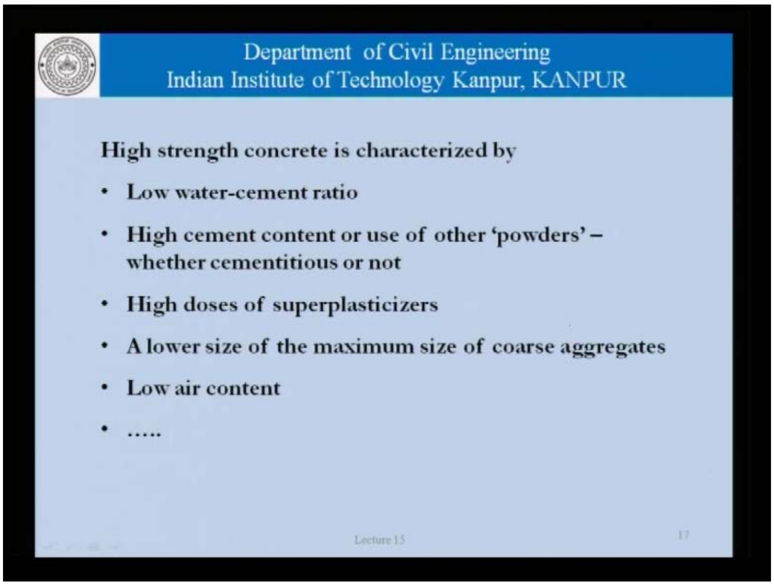

Now, what are the characteristics of high strength concrete? High strength concrete is characterized by low water cement ratio. Naturally, unless we lower the water cement ratio, the water that is available beyond that required for hydration of cement cannot be controlled and that excess water is the one that is responsible for the creation of pore spaces.

So, if we are able to reduce that excess water. We have basically created a framework where, the amount of pores generated is less. And, if the amount of pore generated is less, the porosity is less and the strength is high. So, high strength concrete is characterized by low water cement ratio and these low water cement ratios typically would mean 35 percent and below.

How can we reduce the water cement ratio? One is to reduce the water content but, we cannot reduce the water content below a certain level because that is the minimum required for workability and so on. And therefore, the only other option that we have is to increase the cement content. So, it is the high strength concrete is characterized by high cement content or use of other powders whether, cementitious or not.

Using high cement content has its own implications in terms of heat of hydration, in terms of economy and so on. But, since we need not only need the cement but also we need to increase the paste content, as we will see later on in the discussion. We very often use mineral admixtures such as, flyash or blast furnace slag or silica fume to increase the strength. Some of these products contribute to the strength by the formation of the CSI gel in the secondary pozzolanic reaction or they simply occupy the spaces in the pore space reducing the porosity and else, they just contribute to the paste content by shear presence.

Things like stone dust would bring that category. They do not possibly participate in the pozzolanic reaction but, their fineness is such that they are or they can be counted towards paste content which is also required to be increased as far as high strength concrete is concerned.

One of the options we mention was reducing the water content. Now, reducing the water content can be achieved through high doses of superplasticizers. This we have seen in example in somewhere that if, we are able to use certain amount of super plasticizers, we can reduce a certain amount of water demand for a given level of workability.

So, if we want to reduce the water content for a given amount of workability using super plasticizers is almost the only way out. A lower size of the maximum size of the coarse aggregates. As the maximum size of the coarse aggregate increases their strength tends to reduce. The defects that are formed as a result of the presence of these large coarse aggregates are bigger and they tend to become the weakest link in the whole strength chain. That is why we try to reduce the maximum size of the coarse aggregate as far as high strength concrete is concerned.

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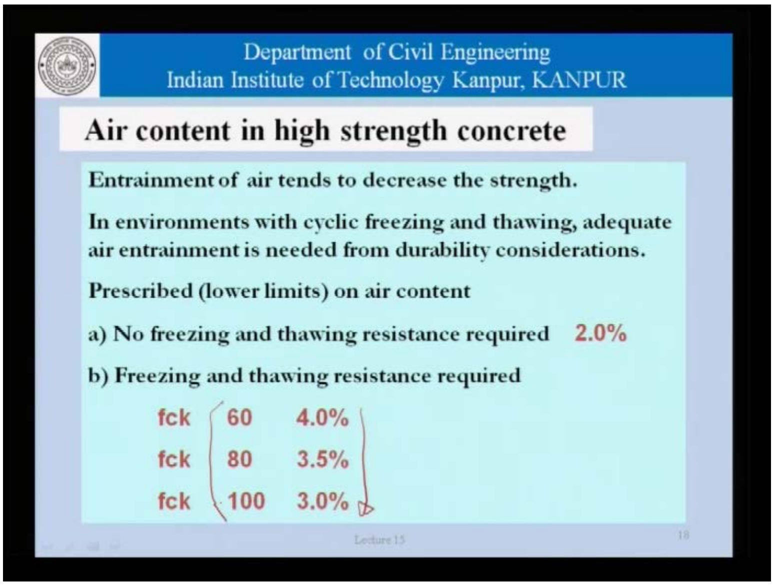

Once we reduce the size of the coarse aggregates, we increase the surface area. And once we increase the surface area, we need more mortar, more paste and that is what relates to the use of mineral admixture and other powders in high strength concretes. Low air content: High strength content is also characterized by low air content. We shall see in a slide, what are the provisions that are related to air content. There could be lot of other properties which we can list and enumerate as far as high strength content is concerned.

Now, coming to the air content in high strength concrete it is known that entrainment of air tends to decrease the strength. Even though when we do air entrained concretes or when we make air entrained concretes for different reasons, we do not explicitly take that into account because of other benefits that follow. But, indeed it is logical that air at the end of it contributes or causes some kind of words which is created within the concrete. And that obviously tends to decrease the strength at least to some extent.

Now, as far as high strength concrete is concerned, that is quite an uncertainty acceptable position. And therefore, we must try to control that. In environments with cyclic freezing and thawing, adequate air entrainment is needed from durability considerations. But, prescribed lower limits on air content could be, if no freezing thawing is there then of course, 2 percent. But, in case freezing and thawing resistance is required.

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Then, we can see here that, the air content requirement goes down as the strength or the required strength increases. So, basically the designer makes the choice that, if we push the strength higher we have to sacrifice the air content. We cannot get the benefits of air content all the time. So, as far as normal concrete is concerned; yes, we can have 5 percent or 6 percent air sometimes. But, the moment we get into high strength concrete or strength ranges in this range here 60, 70, 80 and so on. Then, air content has to be restricted. Then, let us talk a little bit about some of the considerations that way on the mind of an engineer as far as high strength concrete is concerned.

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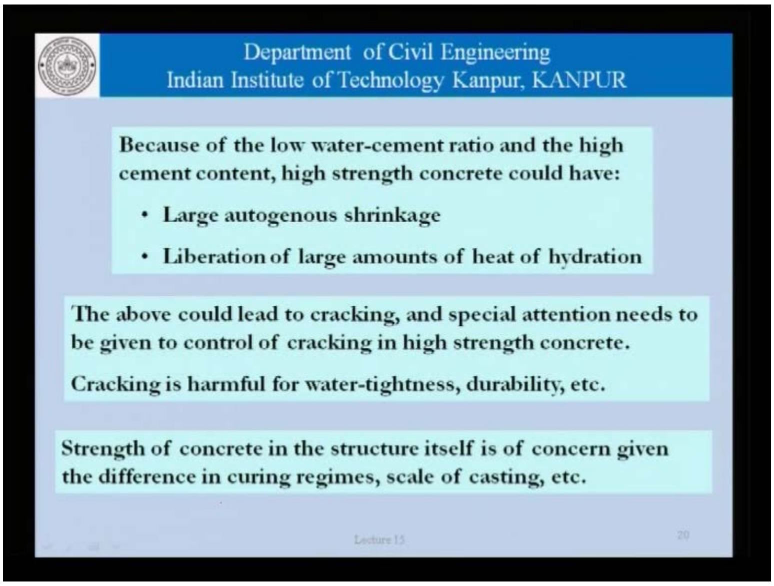

Because of the low water cement ratio and the high cement content, high strength concrete could have large autogenously shrinkage, large amounts of heat liberation on account of heat of hydration. Traditionally, mass concrete was defined as concrete where, the structure was large or the pore volume was large to the extent that the heat dissipation that took place from the surface was not sufficient to handle the heat liberated on account of heat of hydration of cement.

In the case of high strength concrete, even with adequate surface area because the amount of heat liberated is large, because the cement content is high. Even concrete members of the size that would normally be not considered mass concrete, would have to be treated with provisions of mass concrete. Once we have mass concrete related considerations or shrinkage related considerations arising out of the high amounts of cement, we could have cracking in the concrete, non structure but, cracking nonetheless.

And that is something which will require special attention from the point of view of water tightness, durability and so on.

So, high strength concrete is very good as far as durability is concerned from the point of view of the fact that porosity has been reduced. But, if we allow cracks to form in high strength concrete then, the whole purpose is lost. And that is something which as concrete engineers we must keep in mind that, using high strength concrete or having a characteristic strength of concrete has a certain number is not really good enough to ensure high durability concrete. For durability, we need to do a lot other things, other than strength such as, controlling cracks and so on. Further, strength of concrete in the structure itself is of concerned given the difference in curing regimes, scale of casting and so on.

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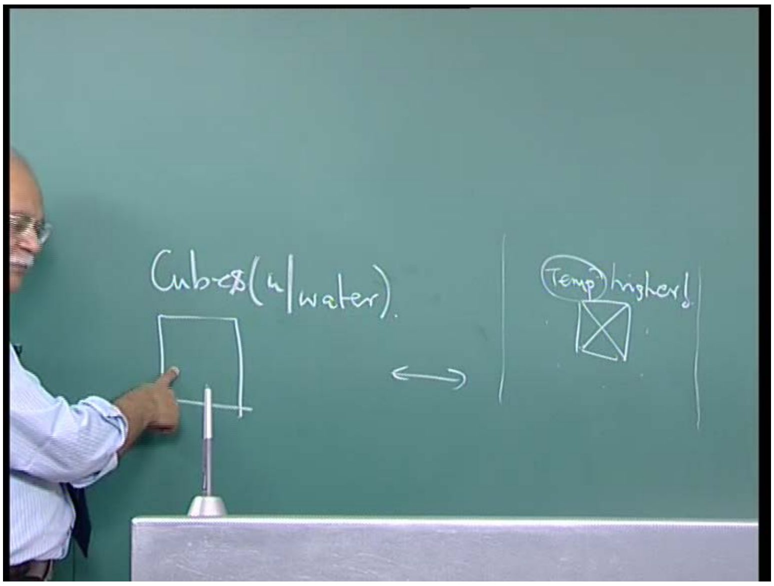

In a normal concrete, if we do the quality control using cubes which have been cured under water versus a situation where a certain member has been cast and the concrete is sitting here. In normal circumstances, the environment here as far as temperature and so on is concerned is not so different from this atmosphere. But, when it comes to high strength concrete, the temperatures here are higher than normal. And therefore, when we cured the cubes here, the curing regime of cubes which are used for quality control is quite different from the curing regime or the environment surrounding the concrete in a high strength concrete structure. And this difference starts becoming prominent and has to be accounted for in our quality control procedure and also, in attempts to actually figure out, what is the strength of concrete in the structure.

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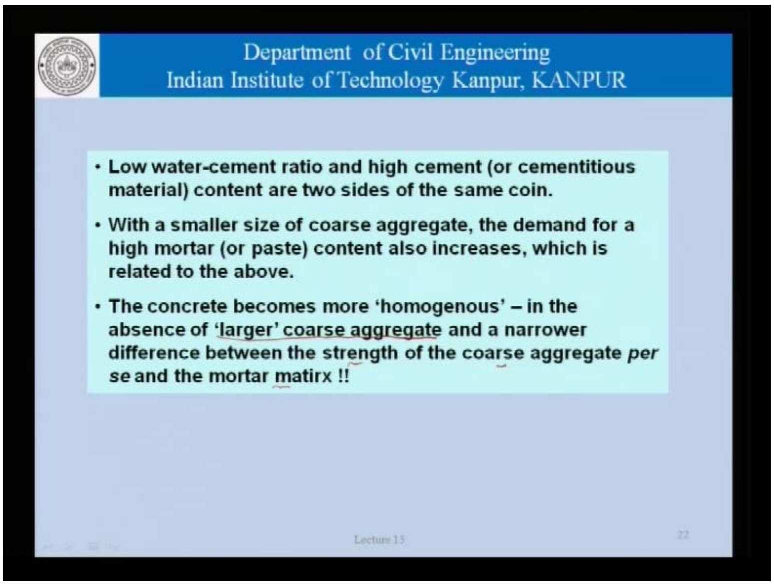

Now, low water cements ratio and high cement or cementitious material content are 2 sides of the same coin. And, we have already talked about that. With a smaller size of coarse aggregates, the demand for high mortar or paste content also increases, which is related to the above that causes us to use more powder in the system. And the concrete becomes more homogenous in the absence of the larger coarse aggregates.

See, concrete is not a homogeneous material at the millimeter levels. It can be considered homogeneous, if we consider reasonably larger sizes or reasonably larger unit sizes. And that unit size which is required to be considered for concrete to be assumed to be homogeneous is related to the maximum size of the coarse aggregate used.

If we are using large coarse aggregates then, we will have to consider a much larger area, in order to say that, ok, if that area is replicated all over the place, the concrete is homogeneous. If those of you who work or who have a background in finite element analysis could understand this concept very simply. In order to assume that concrete is homogeneous, we are making an assumption that the aggregates and the mortar and the ITZ have all the same strength; which is obviously, not true. So, if we are able to remove the larger course aggregates, the concrete becomes more homogeneous. And also, the gap between the strength of the coarse aggregate and the mortar matrix is narrower.

So, from normal concretes or in comparison to normal concretes, high strength concretes are more homogeneous.

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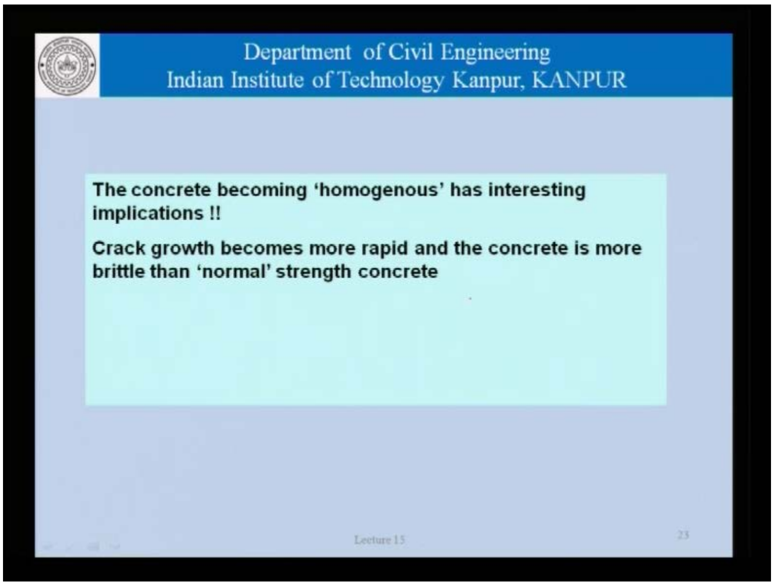

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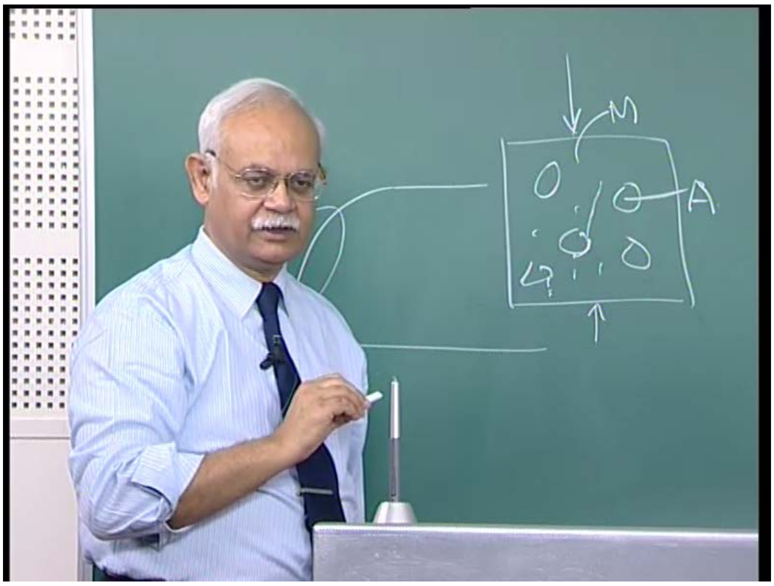

Now, this homogeneous business or this concrete becoming more homogeneous has very interesting implications. Crack growth becomes more rapid and the concrete is more brittle than normal strength concrete. In fact, the crack growth in concrete and the stress strain curve. The stress strain curve is only the relationship or a representation of how the material deforms as stresses are applied. And as stresses are applied, more cracks are found in the system. So, in so indirectly the stress strain curve is representation or can be taken to be representation of the crack formation and crack propagation in concretes.

Now, as far as normal concretes are concerned .If we look at a normal concrete, there are aggregates and we have mortar and these are the aggregates. Now, if load is applied on these, if load is applied on this concrete and we get the stress strain curve. We know that, these are this is one of the model stress strain curves which are used.

Why is it non-linear? Because as micro cracks are formed here initially, they tend to connect at the coarse aggregates. Some kind of crack propagation takes place through the transition zone and then, larger cracks are formed which because the concrete to fail. In the case of high strength concretes, this process where cracks have a stable growth does not exist.

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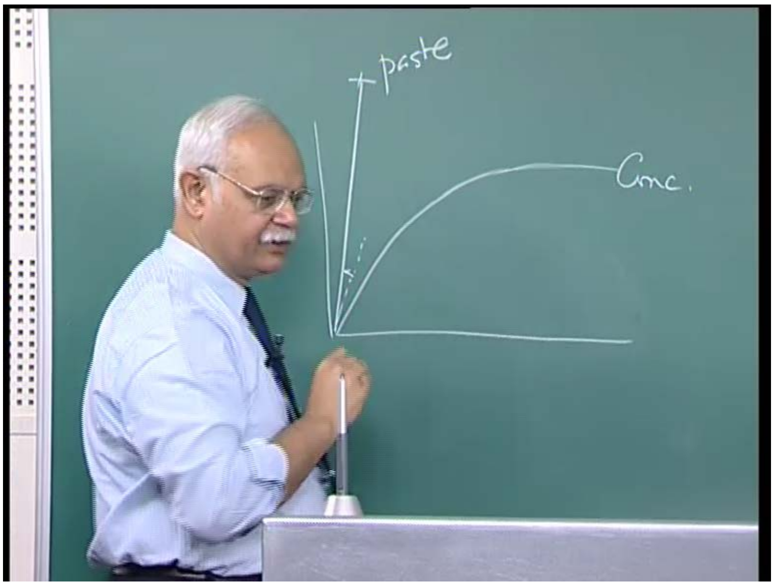

So, if we look at the stress strain curves of concrete and paste. This is the stress strain curve for concrete and this is for paste. Because the material which is paste is more homogeneous, the crack propagation is rapid and the material is more brittle. So, the high strength concrete tends to come closer to paste and therefore. And that is something which we must keep in mind when we talk in terms of properties of high strength concrete.

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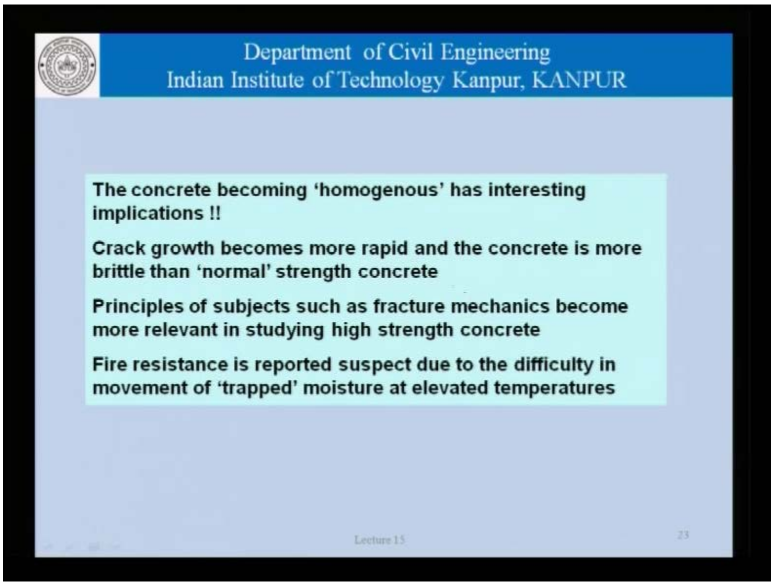

The principles of subjects such as, fracture mechanics becomes more relevant in studying high strength concretes. Fracture mechanics is the science that studies crack formation crack propagation and so on. If you read the literature on fracture mechanics you will realize that the whole assumptions, the whole set of assumptions made in fracture mechanics are more valid when we are talking of high strength materials, more homogeneous materials within concrete than normal concrete.

As far as properties of high strength concrete are concerned, is the fire resistance which is reported to be suspect due to the difficulty in the movement trapped moisture at elevated temperatures. Concrete could have some moisture trapped inside and that moisture must be able to escape in the event of fire because the temperature is rising or the temperature in the concrete rises.

Now, in the case of high strength concrete because of a different kind of pore system, that water finds it difficult to escape. And if the water cannot escape, it gets converted to vapor exerts pressure and causes local well, if you want to call them explosions which damages the concrete. And the performance of concrete at elevated temperatures under fire becomes suspect.

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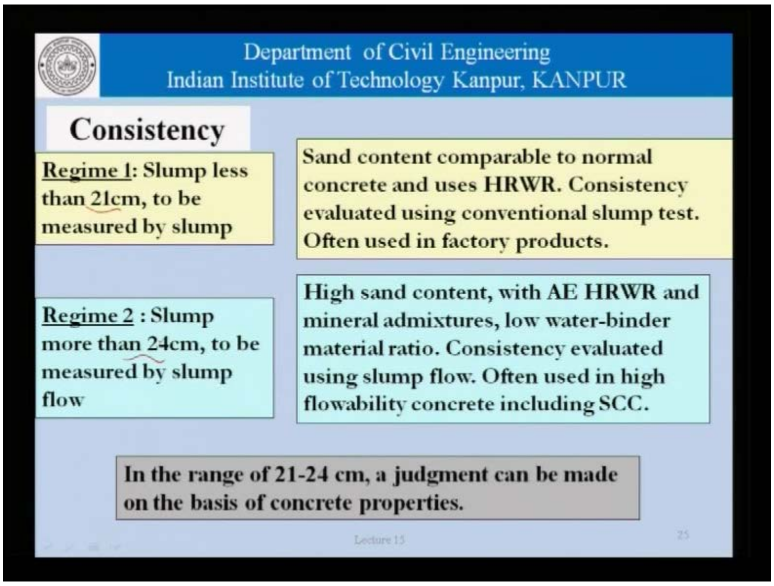

Coming to the properties of high strength concrete, Let us talk in terms of consistency which is property for fresh concrete. Let us talk of a regime where the slump is less than something like 21 centimeters or 200 mm or 210 mm or something like that. At this level, the sand content in the content is comparable to normal concrete. And of course, that concrete has high range water reduces and the consistency can be evaluated using the conventional slump test and that is what is used in factory products.

Whereas, if the slump becomes more than 24 centimeters or 240 mm then, we cannot really use slump as the measure for the consistency or workability of the cement or the consistency or the workability of the concrete. And we get involved with the slump flow regime. And it is what happens when we are talking of higher sand content that will obviously imply higher mortar content which is there in the case of concretes with low water binder ratios as high strength concretes have, using air entrained high range water reduces and so on.

And this is the kind of concrete which is used when we are trying to develop self-compacting high strength concretes. So, there are 2 distinct ranges of consistency: One is where by the share use of super plasticizers or high range water reducers we are able to get to a level where, the strength becomes high enough for the concrete to be called high strength concrete.

In another situation, we have gone beyond that range where, slump can be used and we must use slump flow. And depending on where we are using the concrete in the factory. As in the factory for making precast products or whether it is being used at site. We need to make our judgments; we need to proportion the concrete in a certain manner and so on. Now, between 21 centimeter and 24 centimeter we need to make a judgment.

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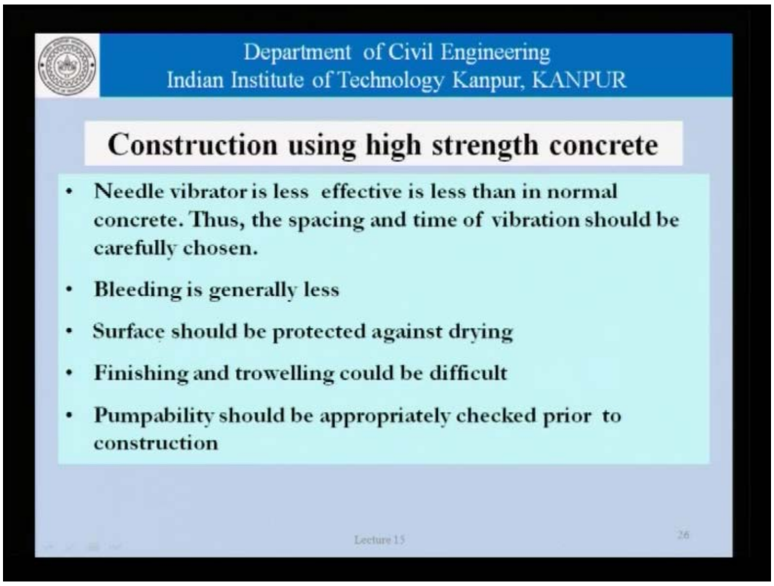

When it comes to construction using high strength concrete, we must remember that the concrete is now characterized by the presence of a large amount of paste or a large amount of mortar which makes the concrete very viscous. And once the concrete has become viscous then, needle vibrators are less effective than in the case of normal concrete. And therefore, the spacing and the time of vibration needs to be carefully chosen.

The bleeding in high strength concrete is less. The surface should be protected against drying because the surface which is susceptible or vulnerable to drying anyway. If that happens in high strength concrete the reduction in strength could be very drastic. And that is why we must make sure that, if a surface is protected against drying. Finishing and travelling is difficult, pump ability should be ensured before construction. Because once the concrete becomes viscous, pumping it is not really the same thing as pumping normal concrete which has a certain amount of flow ability.

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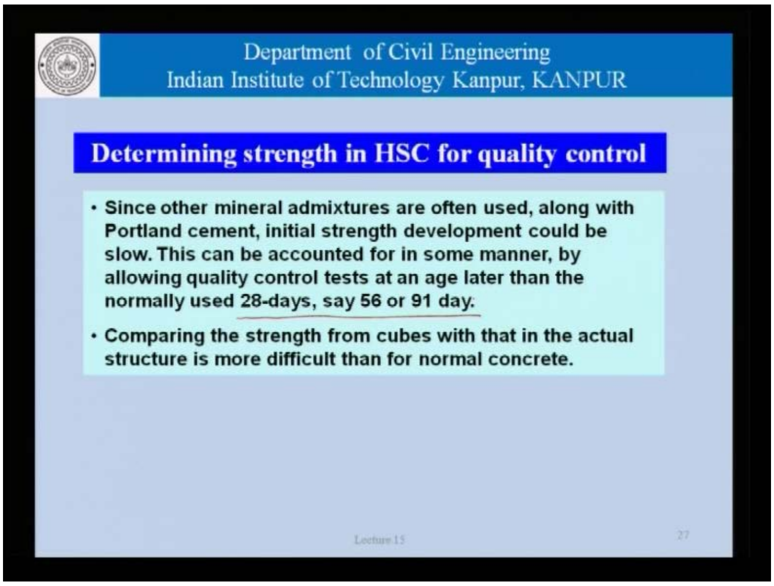

Now, let us talk a little bit about determining the strength for high strength concretes. As far as quality control is concerned. One thing that comes to mind is the age at which the quality control should be carried out. Since, mineral admixtures are often used along with Portland cement, strength development at least in the initial part could be slow. And this could be accounted for in some manner by allowing quality control test at an age later than the normal 28 days, say 56 or 91.

Now, there are 2 arguments which go in the favor of such a treatment. One is the fact that well, we are using mineral admixtures which possibly will have pozzolanic reactions and contribute to strength development at a later stage. And therefore, we should do a quality control at a later day.

Secondly, the structures are very often not really loaded in a month and therefore, there is no harm in saying that we will wait for more strength development to occur over a period of 2 months or 3 months before we carry out a final check as far as quality is concerned.

Now, what is the other side of the story? The other side of the story is that, even though even 1 month is late or 1 month is late enough, if we wait for 2 months or 3 months and then find out that for some reason the strength has not reached the level where we thought it would, the construction process would really been a big ((property)). And therefore, a very careful thought has to be given.

Science or scientifically speaking, yes. There is reason to believe or reason to say that yes in high strength concretes because we are using mineral admixtures, we can go ahead and use a longer time for quality control test. And we already talked about comparing the strength from cubes with that in the actual structure.

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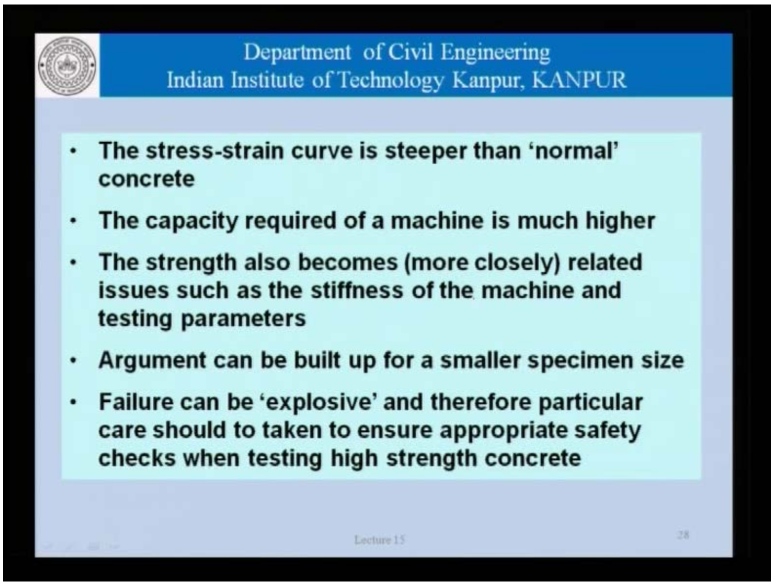

We have talked about the stress strain curve which is steeper than normal concretes. Another thing that happens is the capacity of the machine which is required is much higher in order to carry out the tests. As the strength increases, we need machines of higher and higher capabilities to be able to carry out the compression test cause those specimens whether they are cubes or cylinders to fail. And that becomes a problem in high strength concretes because we do not have so many machines or we may not have so many machines in the neighborhood of that construction site to be able to carry out the test.

Not only the strength or not only the capacity but, also the stiffness of the machines and other tests parameters. The rate of application of load, condition of the specimen, all these things become very important when we are talking of quality control of high strength concrete from the point of view of testing.

Now, there can be an argument which is built up for a smaller size specimen which will help us from the point of view of the capacity of the machine required. We use, for example, in India 150 mm cubes or somewhere we use 10 centimeters by 20 centimeter cylinders. That is related to the fact that most of the time we use 20 to 25 mm kind of aggregates. So, if we are able to reduce or if you do reduce the size of aggregates being used as far as high strength concrete is concerned, there is a case that the size of the specimen used may also be appropriately reduced.

We can imagine that if we are using 15 centimeter cubes, we are talking of area which is really about say 225 centimeter square. Whereas, if you are able to reduce the cube size to 10 centimeters by 10 centimeters, the area of the cube is only a 100 centimeter square. This means that, if that was acceptable from the point of view of the maximum size of the aggregates and so on, we could make do with the machine which has less than half the capacity. So, these are the kind of things that as engineers we need to decide as far as testing of high strength concrete is concerned.

Now, failure could be exclusive and therefore, particular care should be taken to ensure appropriate safety checks when testing high strength concretes. Because of the brittle nature of the high strength concrete at failure the material may explode and particles of pieces of the concrete may fly out. And therefore, we must try to make sure that, people in the neighborhood or the equipment in the neighborhood is not damaged. Which means that, we mean it to have a cage in which these specimens are tested to failure.

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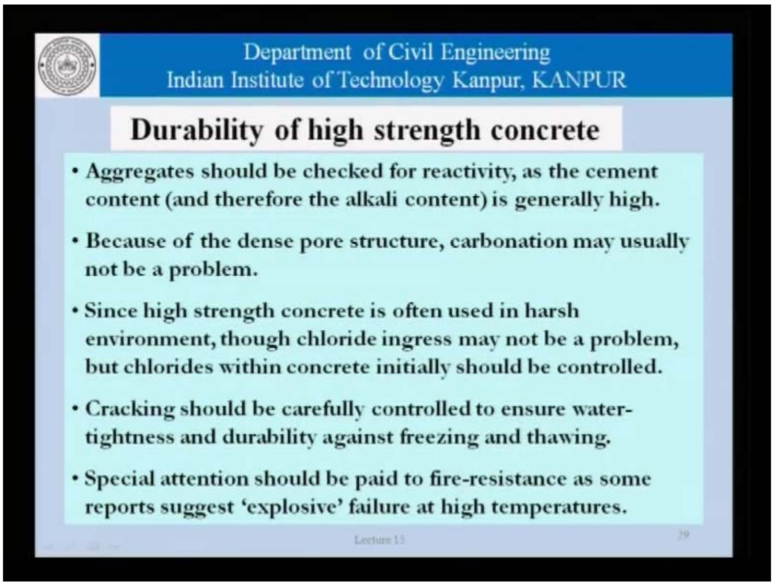

As far as the durability of high strength concrete is concerned, aggregates should be check for reactivity as the cement content. And therefore, the alkali content could sometimes becomes high. Usually aggregates are not rigorously tested because at least from the point of view of strength because the mortar phase is so much weaker than the aggregate. But, not so much in the case of high strength concrete. And therefore, we have to be more careful as far as the choice fabricates, the particles have distribution, the strength and so on are concerned.

As far as reactivity is concerned, again they have to be checked because even marginal aggregates can have problems because the high alkali content in the concrete because the cement content is high. Because the dense pore structure, carbonation is not really a problem. Since high strength concrete is often used in harsh environments though chloride ingress may not be a problem. But, chlorides within concrete should initially be controlled. Because it becomes more difficult to get for, there is no way that anything trapped inside can move out and if there part of an admixture and so on. Then whatever, we use will remain trapped inside. So, that is something which we have to bother about.

Cracking should be controlled to ensure water tightness and durability against raising and thawing which is related to air content. And special attention should be paid to fire resistance as some of the reports just explosive failures at high temperatures.

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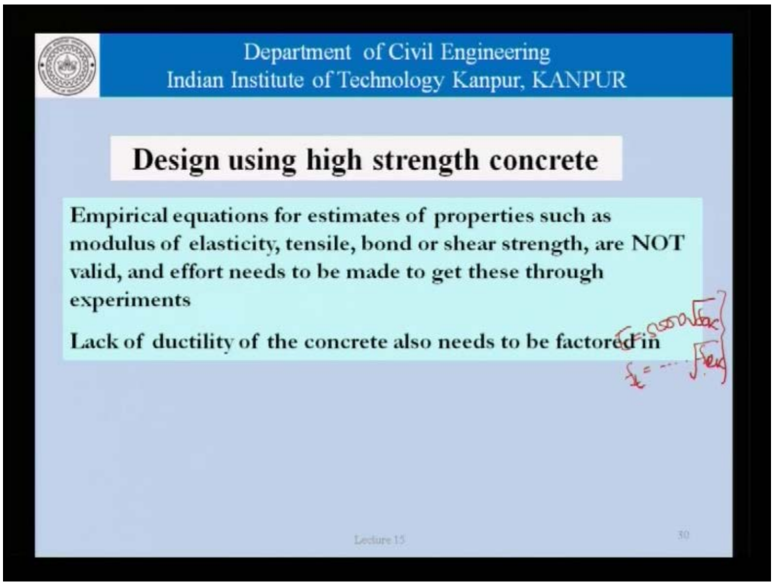

And lastly, coming to some simple things related to design using high strength concretes, we must remember that empirical equations for estimates of properties such as, the modulus of elasticity, the tensile bond or shear strength are not valid and efforts need to be made to get these through experiments.

Very often a specification will tell us that, E can be taken to be 5000 root of f c k or the modulus of rupture can be taken to be something related to f c k or the root of f c k. These equations are valid only for the range in which they have been tested. And since, the data for high strength concretes is not all that voluminous, it is not provident to use these kinds of correlations which exist for normal concretes for high strength concretes as well and that is something which the designers have to keep in mind. Also, the lack of ductility of the concrete needs to be factored in. Before we close, as usual we will have some questions which we should try to answer to improve our understanding of the issues that we have talked today.

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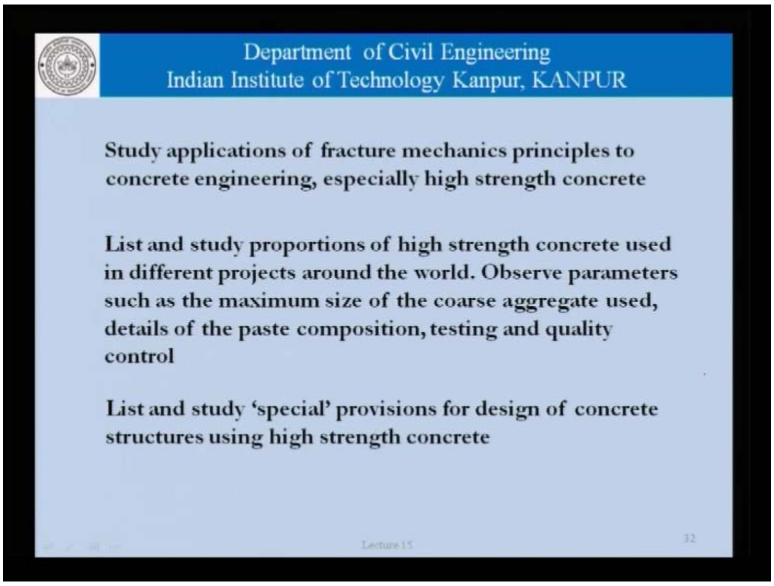

Study the applications of fracture mechanics principles to concrete engineering especially, in the case of high strength concrete. You will find that a lot of researchers have tried to apply fracture mechanics principle to paste and mortar. And in some cases high strength concretes, what are the kinds of parameters that they use, how they evaluate them in fracture mechanics and so on.

List and study proportions of high strength concrete used in different projects around the world. High strength concrete has been used in a large amount of projects across the world where, the quality control has been carried out at different ages, using different sizes and shapes of specimens. So, if we make a list of that, we will observe that there is a difference in the parameter such as, the maximum size of the coarse aggregate used, the details of the paste composition in terms of the supplementary cementitious materials or mineral admixtures used, the super plasticizers used and so on. The testing and quality control procedures. And I would like you to list and study special provisions for the design of concrete structures using high strength concrete. And with this, we come to the end of the discussion today.

Thank you.