Hydration, Porosity and Strength of Cementitious Materials
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Lecture – 35
Concrete –Behavior Under Load-

[FL] and welcome to this lecture number 35 in this course on Hydration, Porosity and Strength of Cementitious Materials where we will be talking about Concrete - behavior under load basically aspects relating to compressive strength of concrete.

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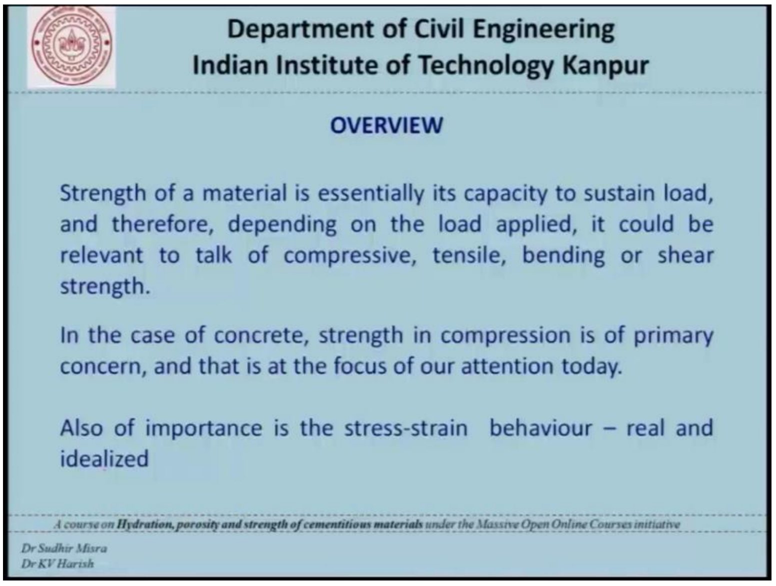

Well the strength of a material is essentially its capacity to sustain load and therefore, depending on the load applied we can talk in terms of compressive, tensile, bending or shear strength.

In the case of concrete, strength and compression is of primary concern to us and that is at the focus of our attention today. Also of importance is the stress strain behavior of concrete, the real stress strain curve of concrete and also the idealized curves which we will also touch upon as we go along in this discussion today.

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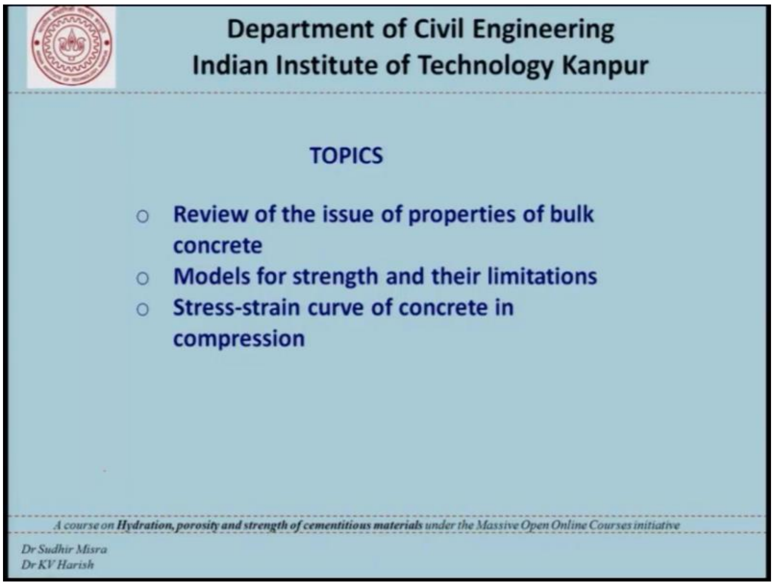

So, what we will talk about is review of the issues of properties of bulk concrete which we already done when we talked about the permeability and the measurement of permeability of concrete, we will talk a little bit about the strength of concrete the models that we have and the limitations, we will talk about stress strain curve of concrete in compression.

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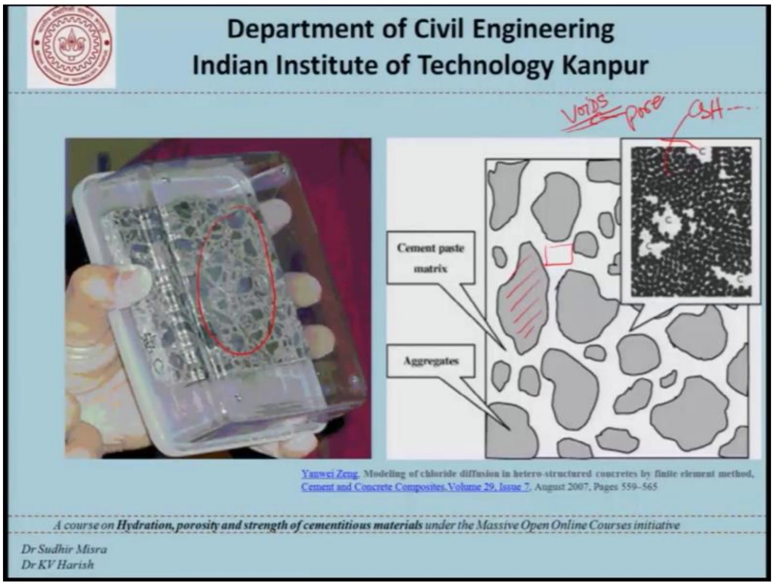

Now, moving forward this is the picture that is being used as a basis for all our discussion for the bulk properties of concrete or concrete or the properties of bulk concrete. We have repeatedly said that concrete which is shown here can be represented as aggregate and HCP or the hardened (Refer Time: 02:18) which itself has CSH and so on which can be looked upon as solids and it has certain amount of pores or voids. So, this matrix of concrete which basically is aggregate suspended in HCP is what is the focus of attention when it comes to strength.

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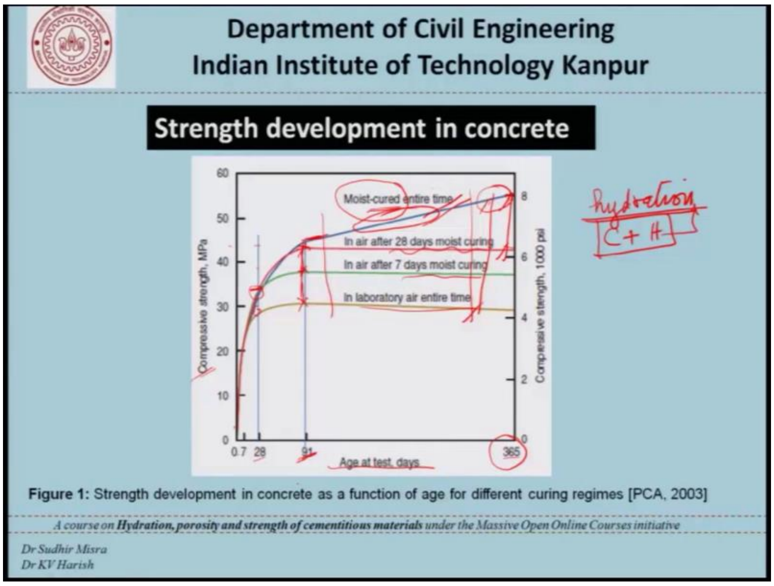

Now, this is another graph which we have studied in a different context, this graph or this picture shows how the compressive strength of concrete varies with age. It can be seen that at 7, 28, 91 and 365 which are very commonly used ages at which the exercise to carry out the determination of concrete strength is carried out as far as engineering factors is concerned, how does the strength of concrete vary. It can be seen that the strength gain starts relatively early, but it takes a long time, it could take even one year maybe even more for the strength to develop fully.

Now, we also discussed when we were talking about phase systems that this strength development is essentially related to the process of hydration because at the end of it we have repeatedly emphasized that as far as concrete is concerned cement and water are the only reactive components in this material, and their hydration and their continued hydration is a matter of fact formation of more and more CSH gel and other hydration products that is what is contributing to strength.

So, the issue of strength development cannot be looked upon in isolation from that of hydration. So, now, what promotes hydration is something called curing. Even though we are not talking about curing today we will spend some time talking about curing its importance and the different methods that we have, but the fact of it remains that curing is a process by which we try to provide conducive environment to cement particles so that they can continue to hydrate. Hydration is a slow process to that extent and continues over a long period of time.

Now depending on the kind of curing that is carried out that is how careful we are in terms of maintaining those conditions for curing that kind of strength development that we see could be very different. So, here we have a situation where we are talking about concrete being cured in the laboratory in the air at entire time we have in air after 7 days of moist curing, 28 days of moist curing and so on. So, we see that well depending on when we take the concrete out from the curing tank and leave it in air. The ultimate strength that we get could be different this concrete here which should really be serving as a basis for our discussion is moist cured entire time. So, that is we keep the concrete in water all the time. So, this shows that depending on whatever the parameters are the water cement ratio the type of cement the kind of aggregate and so on, whatever those conditions are the moist cured concrete could have a lot more strength then what we get in actual practice and that is something which we must keep in mind when we talk of the strength of concrete, the design of concrete structures and so on and so forth.

Now, on this graph if I draw a line at 28 days which is the commonly used time for carrying out quality control exercise for most of our concrete structures even the quality control of cement we find that depending on the kind of curing that we do we will have different levels of strength that is one thing. The second thing is this strength here is not so close to the strength that we ultimately may get. So, these are things that we have to keep at the back of our mind when we are trying to evaluate a concrete. Similarly if we extend this discussion to the 91 day age then we find that apart from this strength here which is for concrete which is moist cured for all the time most of the cases we have more or less 100 percent strength that we get or we are likely to get in future. That does not mean that the hydration has been completed because here is the proof of the fact that hydration has not been completed, but whatever hydration had to happen has happened and we do not expect any more strength development beyond this point in time.

Of course this age of 91 days would also be related to the kind of cement or the kind of mineral admixtures you are using, the environment in which we are and so on and so forth.

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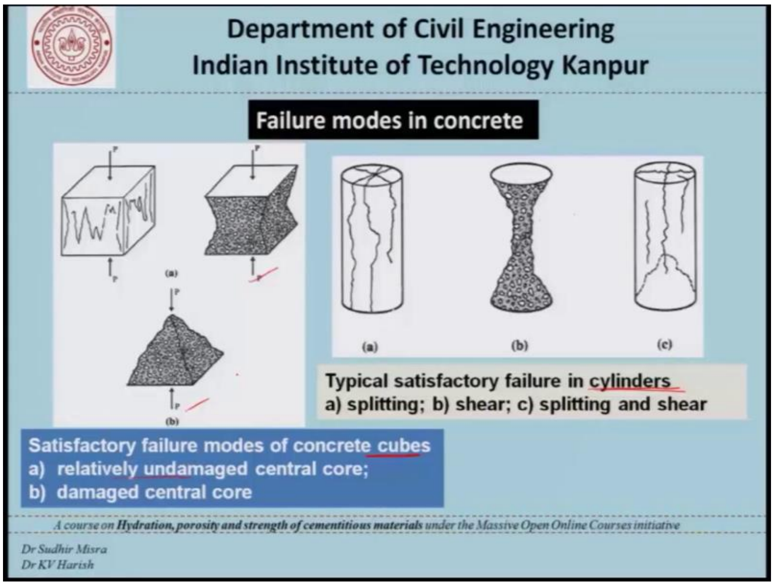

Now with this background let us try to take a look at the failure modes in concrete this is a picture from one of the standard text books. We often carry out quality control of concrete using either cubes or cylinders in India we use cubes US, Japan and some other places they use cylindrical specimens of different sizes. If we test a cube in compression we have two satisfactory modes of failure one where we have a relatively undamaged central core which is here and damaged central core which is here, similarly for the cylinders we have splitting shear and splitting and shear. So, we have different modes of failure that we get and we must ensure that the concrete when we tested fails in one of these modes. If the failure happens in an unacceptable mode or an undesirable mode which is sometimes possible on account of poor specimen preparation, poor loading conditions or whatever that reading or that observation has to be discarded and not taken into account when we are trying to estimate the strength of concrete

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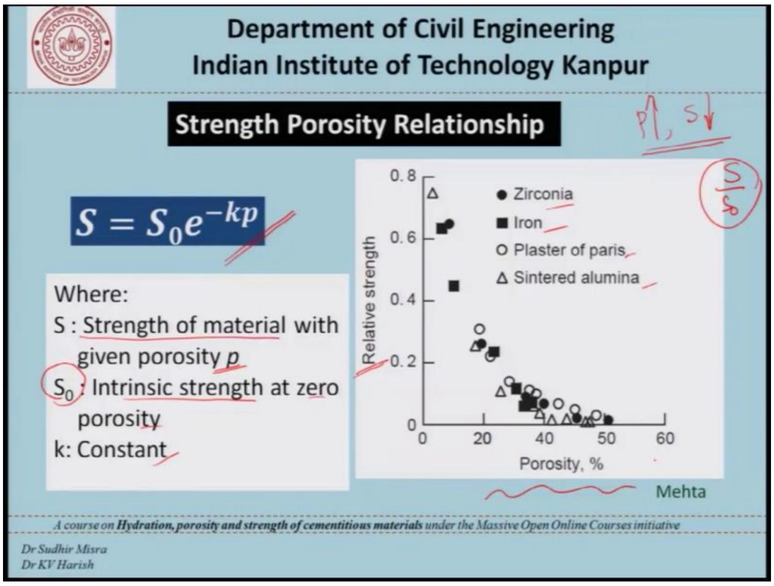

Now, let us look at some of the models that are available to us, some of the thought processes that we can use to understand concrete strength in relation to let say porosity. It is intuitively clear that if the porosity increases the strength will decrease and that has been represented in this equation which says S is equal to S naught times exponential of minus kp where S is the strength of a material having a porosity p, now S naught is the intrinsic strength at 0 porosity of that material and k is a constant.

Now if we use this equation or this kind of a thought process and try to plot a relative strength, relative strength means some kind of an S by S naught kind of a variable, then for different kinds of materials we find that well more or less it is valid. The question to us now is, is this equation valid for concrete.

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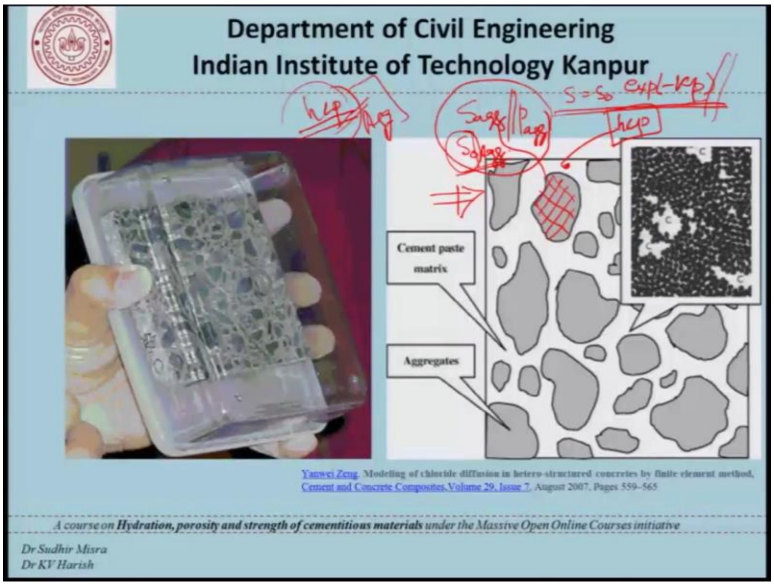

Let us go back to this picture for concrete this equation which is S is equal to S naught times exponential of minus kp to my mind or to the mind of a lot of us is not applicable because of the simple reason that indeed there is a porosity involved, there is a strength involved, we know that the strength of concrete goes down as the porosity reduces the strength goes up, but the fact that the concrete is a composite material of the nature shown here is proof enough that this equation will be very difficult to apply. If we are talking only of aggregates, these aggregates have their own strengths and their own porosity of aggregates. This is something which is of interest to somebody who is studying geology or who is studying the properties of rocks from that point to view indeed this equation could be very useful to relate the properties of a particular rock and try to compare the properties of different rocks with different porosity and so on.

In our case it is not only this S naught because these guys will definitely have an S naught, we can think in terms of an S naught for the aggregate phase. Even though the aggregate phase will have an S naught, what about the composite whole? When it comes to this HCP and indeed for the hardened cement paste there have been efforts to relate the strength of the hardened cement paste using an equation of this nature, but when it comes to a composite where the HCP and the aggregates come together in varying volume proportions, it is very difficult to apply equation of this nature.

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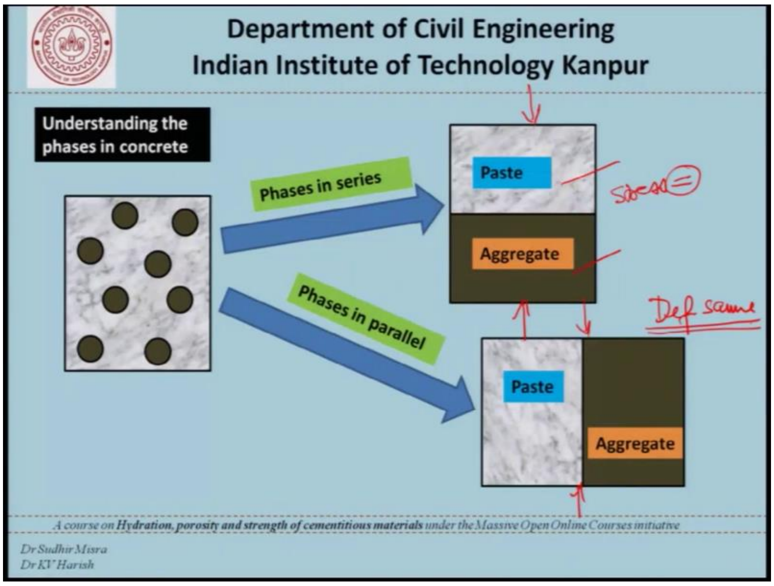

Now, we have already seen this picture which is in terms of trying to understand the application of load whether the paste phase and the aggregate phase is to be taken in series where we are talking about their stress being equal in both the cases whereas, in this case if we apply the load it is the deformation which is the same in both the cases we had some discussion on these pictures and models. And if we move forward we have this kind of a relationship which is very often used to explain or to model the strength of concrete which basically says that the strength of concrete is inversely proportional to the water cement ratio.

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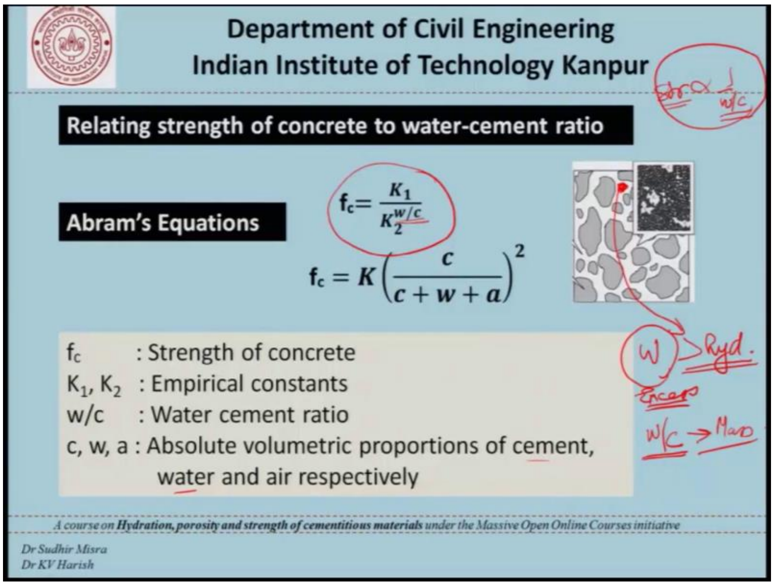

So, if the water cement ratio increases the strength goes down and if it reduces the strength goes up. So, what we are basically saying in this case is that if the water cement ratio of this part here because the water cement ratio really refers only to the proportions of cement and water. So, now, we know that the amount of water that we add is in excess of that required only for the hydration of cement and this excess water as it leaves the pores, leaves behind wide spaces which become the source of porosity and cause a detriment to the strength of the concrete or in fact, this HCP. So, that common knowledge is what is represented in this form.

Please understand that in this equation of course, it is volumetric proportion of cement water and air respectively as far as practice is concerned most of the time when we talk in terms of water cement ratio we are talking about the ratio by mass and not by volume. A few comments on this general statement that as the water cement ratio increases the strength goes down.

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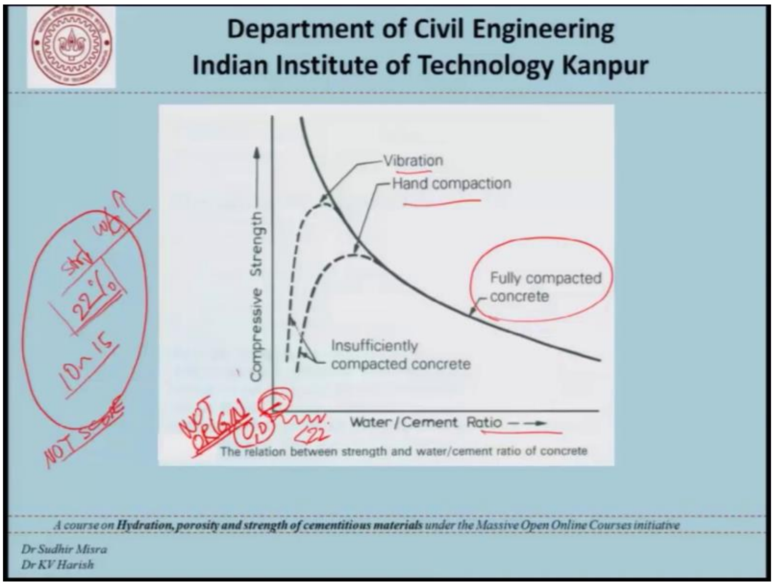

This general understanding is true for fully compacted concrete and for insufficiently compacted concrete with hand compaction and vibration and so on the relationship does not really hold number one. Another thing we must understand is that at the end of the whole discussion this point here is not the origin, in the sense that we are not talking in terms of 0 0 here what is the minimum water cement ratio from which we can say that well the strength will go down as the water cement ratio is increased beyond that point.

Below that point as the water cement ratio increases the strength is likely to increase because what we are basically doing is providing at least some water just enough water perhaps for hydration to happen. Now to that extent we can argue that if we are working at around let say 22 percent of water cement ratio this is the amount of water let us say which is required for complete hydration of cement.

Now if we are operating at 10 percent or 15 percent of water cement ratio then there is not enough water even for hydration of cement. So, if we give more water there it will promote hydration as a matter of fact and we are able to maintain the right kind of conditions and so on. So, this regime of discussion is not within our scope, we are not talking of the special conditions when this value here in the water cement ratio is less than let us say 22 25 whatever that number is. So, very cleverly when we draw this graph we just draw qualitative graph.

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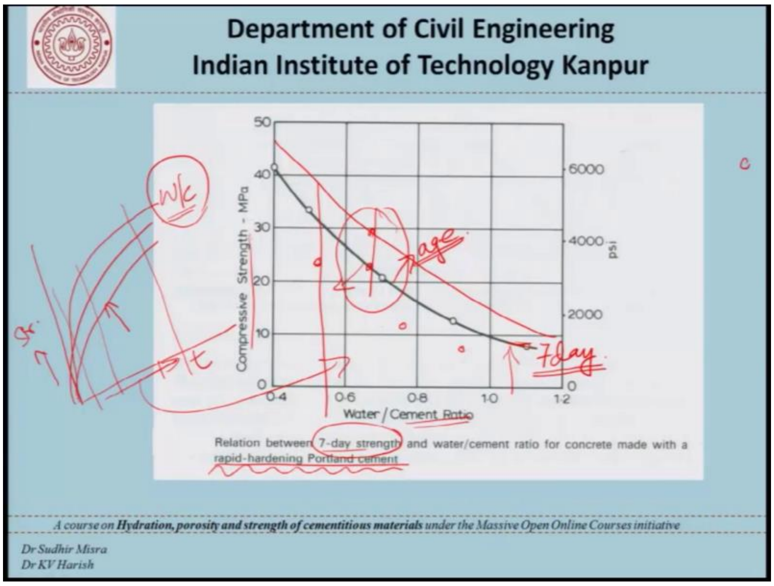

Now, here are some real numbers the compressive strength and water cement ratio if we just plot them depending on what kind of cement or what kind of concrete we have used this is just a 7 day strength with water cement ratio for concrete made with the rapid hardening Portland cement.

Now, if you compare these numbers with some of the other concretes that you may see in literature you will find that these numbers are much higher for the simple reason that rapid hardening Portland cement has been used. If it was simply ordinary Portland cement which way do you think this line will go this line would shift down that is for the same water cement ratio we will get a slightly lower strength that is point number one. Then we have this is the seven days strength now where do you think this line will go at 28 days this is for 7 days. So, at 28 days we are likely to get the line shifting upwards with age and how much it shifts from 7 to 28 days would depend on the kind of cement the kind of curing conditions and so on.

Now, this discussion can be related to our previous graph where we were trying to see how the strength development takes place at 7 days and at 28 days and at 91 days. So, this graph can be transposed into this form here where water cement ratio has been plotted on the x axis and we are talk of compressive strength on the y axis in this case it is the time and on this axis we have the strength. This graph or this line will be different for different water cement ratios this line here is for strength for different water cement ratios at a given point in time, these lines here are for different points in time for given water cement ratio.

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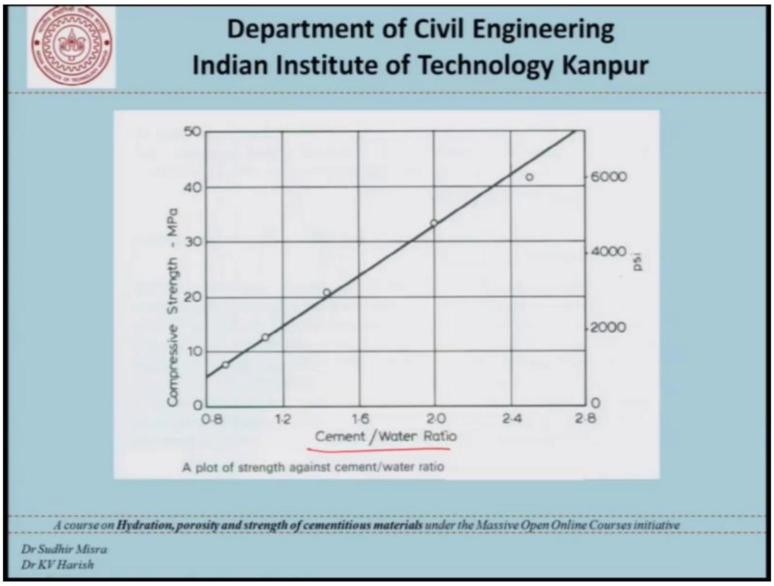

So, once we understand this I think we can move forward. This is yet another way of plotting the strength versus cement water ratio. Now very often engineers and researchers have found this to be a fairly simple way of representing the variation of strength with water cement ratio it is just the reciprocal of water cement ratio and we plot it we get more or less a straight line.

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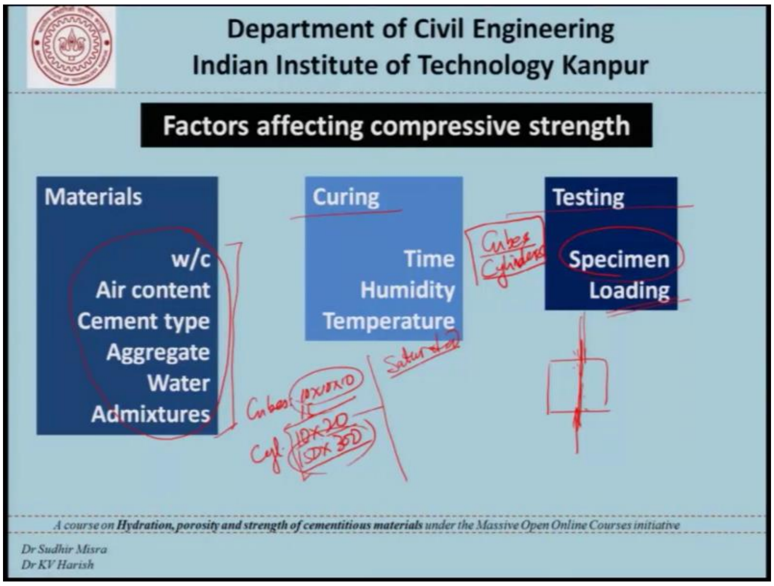

Now, let us spend some time and discuss some factors that affect the compressive strength of concrete. We realize that there are factors which are related to materials and their proportions that is the characteristics of the materials that we use for the concrete and their relative proportions. Then there are issues related to curing or the kind of environment that we provide to the concrete in the early ages which facilitates hydration and thereby strength development. Then there are issues which are related to testing of the concrete, we must keep in mind something simple - the strength of concrete is a material property which needs to be determined in the laboratory using certain tests therefore, we must make sure that the testing conditions and the curing conditions are standardized.

When it comes to quality control this discussion is important for example, for materials obviously, one of the first things that comes to our mind is the water cement ratio, how much is the water cement ratio in a given concrete, what is the air content of the concrete. Air content in principle it can be argued that increasing the air content increases the voids in the concrete and therefore, may tend to weaken the concrete or reduce the compressive strength of concrete. At the same time a certain amount of air and cleaning agency if they are used they also lead to dispersion of cement particles and they increase the area which is available for hydration and therefore, the detrimental effect of air content is partly at least offset by the additional hydration and therefore, we may not see a market change in the compressive strength, but beyond a certain point of your content of course, the air content may be detrimental as far as strength itself is concerned.

The cement type, we know for sure that cement type its chemical composition its fineness that has an important bearing on the compressive strength that we will get for the HCP as well as the concrete made with it. The aggregates though they do not play a part in the hydration reaction and are largely inert fillers when it comes to the larger picture again beyond a certain point aggregates become an important player when it comes to determination of the compressive strength especially in the case of let us say high strength concrete, there the strength of HCP is very high and we need to be also bothered about the strength of aggregates. Similarly if we are using lightweight aggregates or porous aggregates, poor quality aggregates there again the aggregates may become an important source of weakness and we need to be careful about the effect of aggregate properties, it is not only the aggregate properties, but also the gradation of aggregate size or the particle size of aggregates.

Water and admixtures: now admixtures of course, whether they are plasticizers, retarders, accelerators, air and trainers all kinds of admixtures are available as far as chemical admixtures are concerned, if we talk about mineral admixtures again that can be talked along with the cement type if there being used then at what level up they being used what is the level of replacement and so on. So, this set here largely represents the material properties and the proportion of materials the different relative volumes of these constituents which will determine the strength of a concrete.

But that surely is not all there is curing now when it comes to curing we are talking about time, that is how long the curing has been continued, at what age are we testing the concrete, what has been the intermediate curing regime has the concrete being watered all the time, has it been removed from water at 7 days or 6 days or whatever it is and then left in air, has it been protected within the formwork for 1 day or 3 days or whatever it is and so on. Then there is this issue of humidity what has been the humidity of the environment in which the concrete has been left. If the concrete has been left in dry environments versus the concrete having been left in wet environment or high relative humidity environments or submerged in water and so on.

Then there is the temperature whether the concrete was cured at high temperature or low temperature and so on. So, this combination of time temperature and humidity is really the composite effect of the environment on the kind of compressive strength that we can get from a concrete made with a given set of materials. The story does not stop there the actual strength that we determine is also governed by the testing parameters or by some of the parameters which are typical to testing such as this specimen. I mentioned earlier that in India we use cubes as specimens, in some cases we use cylinders as specimens, it is not only the shape of these specimens, but also the size what should be the size of the specimen. For example, for cubes should it be 10 centimeter by 10 centimeter by 10 centimeter or should it be 15 centimeter a side and so on.

Similarly, for cylinders we typically use 10 into 20 that is 100 mm diameter and 200 mm in height that is the standard cylinder which is used in US and Japan and so many other countries. There is no reason to say that a 150 by 300 cylinder should not be used. In fact, in India we do use 115 to 300 cylinders sometimes in other countries we use it as well. Now the thing is that what should govern the size of the specimen that we use, partly it is the size of the aggregate that we use, partly it is the kind of facilities that we have available and finally, it is a standardization exercise where some professional body decides it well we will use this particular size of specimens. So, it is not only the shape and size, it is also the conditions of the specimen. Conditions of the specimen means whether it is saturated or dry, we can have a cube which is immersed in water taken out just before it is tested versus a cube made from the same concrete cured under identical conditions, but dried before it is tested their strengths are likely to be different.

So, it is the entire picture of what the specimen is in terms of its properties when it is tested and finally, it is the loading conditions how do we load, what kind of an equipment do we use, what is the loading rate that we use. If we are loading a specimen in compression is this axis of loading truly along the axis of this specimen, if there is any mismatch we which could happen because of a misalignment of the equipment and so on the results are going to be different.

So, the moral of the story as far as this picture is concerned is that there are a large number of variables which are involved in determining the compressive strength it is not the compressive strength which is different, but it is what we observe to be the compressive strength that is different. So, we have to be careful about this discussion and understand that concrete properties are only what we determine them to be and that determination is not necessarily extremely objective at one level of thinking. We try to make it objective by standardizing different things, we try to standardize the curing conditions, we try to standardize the specimen we standardize the loading, but then again we must keep at the back of our mind these are still factors which could affect the determination.

So, with this we are more or less at the close of our discussion today what we have covered is some detail of the issues of strength. And strength development in cementitious mixes and we will move forward with our discussion on other related aspects in subsequent classes.

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I must emphasize that in the context of cementitious mixes strength and strength development should be looked upon separately as we must be careful what we are talking about, are we talking about strength which is the ultimate strength that a particular cementitious mix achieves or we are talking of the process of development and that development of strength could be very closely related to the environmental conditions. And that is what we must keep in mind when we discuss this issue of strength and strength development of cementitious mixes as we have done today. This discussion is more or less valid for not only concrete, but also for mortars and pastes.

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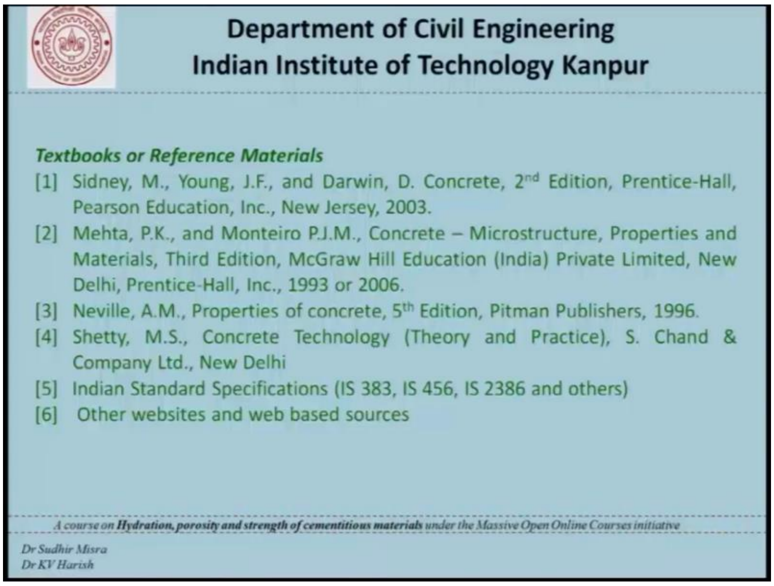

This again is the text books and reference materials which you could refer to, to get a better insight into that subjects that we have talked about today.

Thank you.