Hydration, Porosity and Strength of Cementitious Materials
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Lecture – 36
Curing of Concrete

[FL] and welcome to this lecture 36 in the course on Hydration, Porosity and Strength of Cementitious Materials and today we will concentrate on Curing of Concrete.

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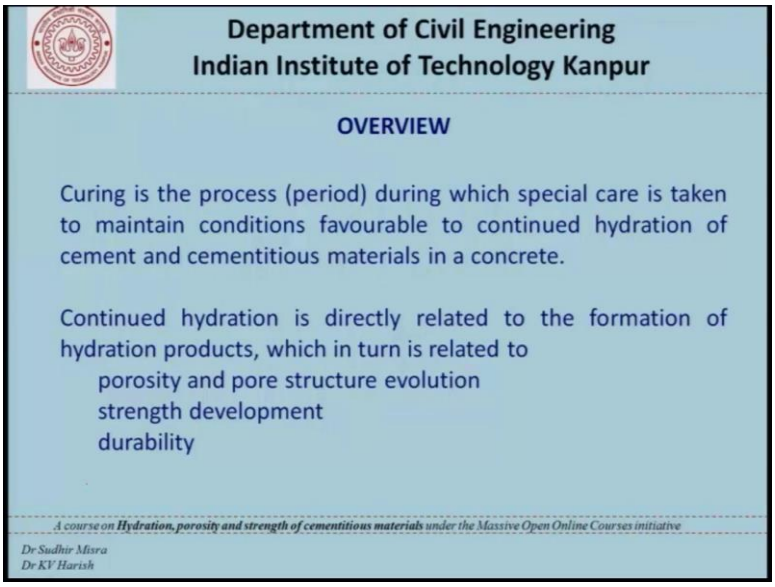

Curing is the process or the period during which special care is taken or needs to be taken to maintain conditions which are favorable to continued hydration of cement and cementitious materials in a concrete. We have in this course talked extensively of cement and cementitious materials and how cement reacts with water and the supplementary cementitious materials they react with the calcium hydroxide that is formed in the primary hydration to form CSA gel, but that reaction continues over long period of time.

And the period during which that special care needs to be taken is the curing period continued hydration is directly related to the formation of hydration products which in turn is related to aspects such as porosity and pore structure evolution in the hardened cement paste strength development whether it is the hardened cement paste or the mortar or the concrete system that we are talking about and finally, durability and permeability related issues. So, you must remember at the outset that curing is an extremely important

aspect of ensuring durable concrete construction. This again is the slide that we have been talking about extensively and repeatedly.

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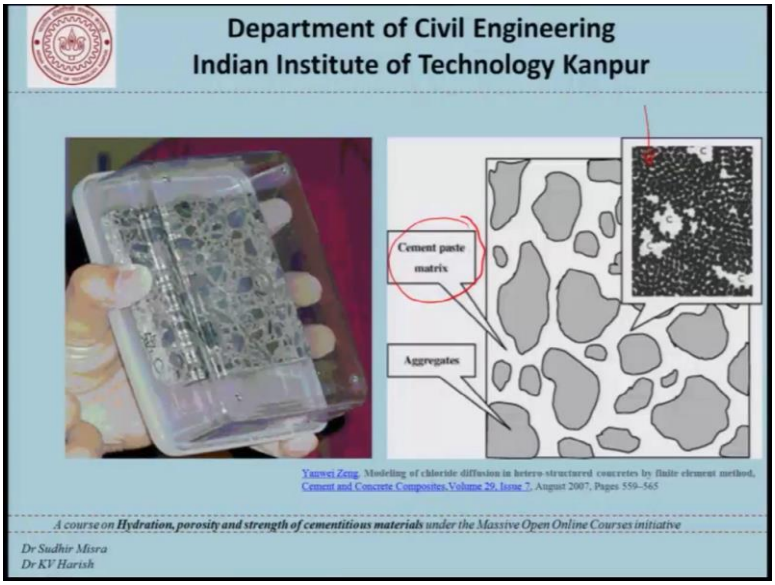

The concrete consisting of aggregate phase and the cement paste matrix and through thus curing process we are essentially trying to ensure that the cement paste matrix indeed develops into a very dense structure where as much as possible of the calcium silicate hydrates are formed and we have as lower porosity as we possibly can get.

So, in the last class we have talked about factors that affect the compressive strength of concrete the materials, the curing and the testing.

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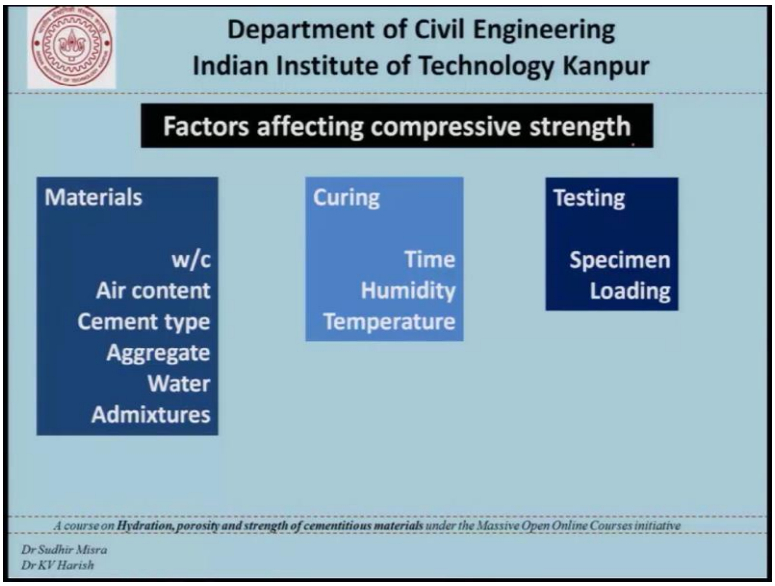

And today we will concentrate on curing.

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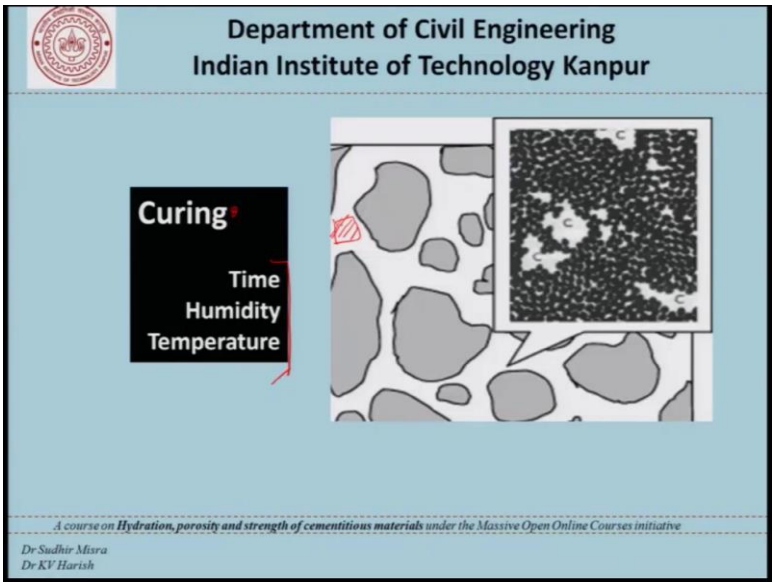

So, when we are talking about curing there is the time of curing, there is the humidity or the conditions that have to be maintained around the concrete and it is the temperature at which the concrete has been cured. These are the kind of things that come to mind. Basically we have to study how these three things or how the curing process affects the hydration or continued hydration that is taking place in this part of our concrete.

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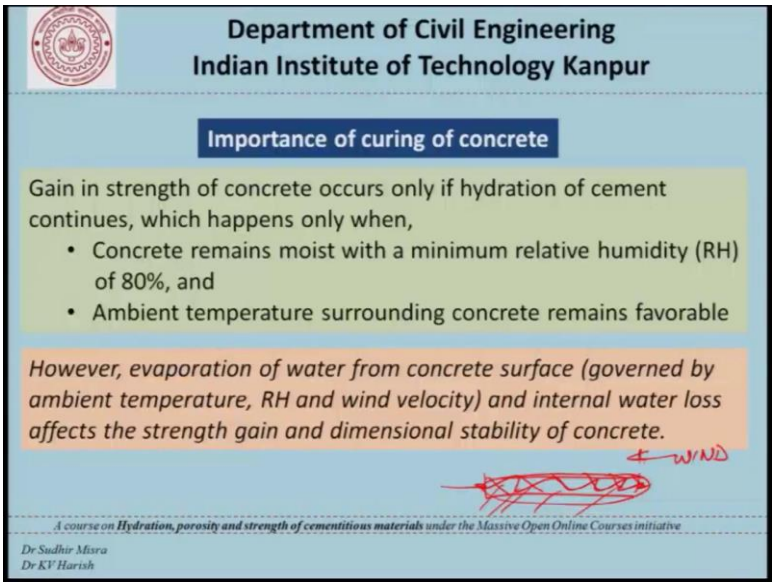

As far as the importance concerned the gain and strength of concrete occurs only if hydration of cement continues which happens only when concrete remains moist with a minimum relative humidity of 80 percent and ambient temperature surrounding the concrete remains favorable. We must remember that evaporation of water from the concrete surface which could be governed by factors such as ambient temperature, the relative humidity and the wind velocity and internal water loss affects the strength gain and dimensional stability of concrete.

Concrete is caused in all kinds of conditions, it could be caused underwater, it could be caused in the desert where the temperatures could be very high during the day, it could be caused in normal atmosphere where the temperature could be in the range of 20 degrees or sometimes 30 degrees a lot of wind no wind and so on. Now after the concrete has been cast the natural forces that is wind, temperature and so on they come into play and try to remove the water from the concrete surface and that is precisely the kind of thing that we would not like to happen because if we cast the concrete to here and there is wind that is blowing, causing drying of this concrete. So, now, this drying will affect the surface of this concrete and this part will be left without enough water for the hydration to continue. That is precisely the kind of thing that we want to address when we talk about curing of concrete. So one of the objective is really to prevent any loss of moisture from the concrete.

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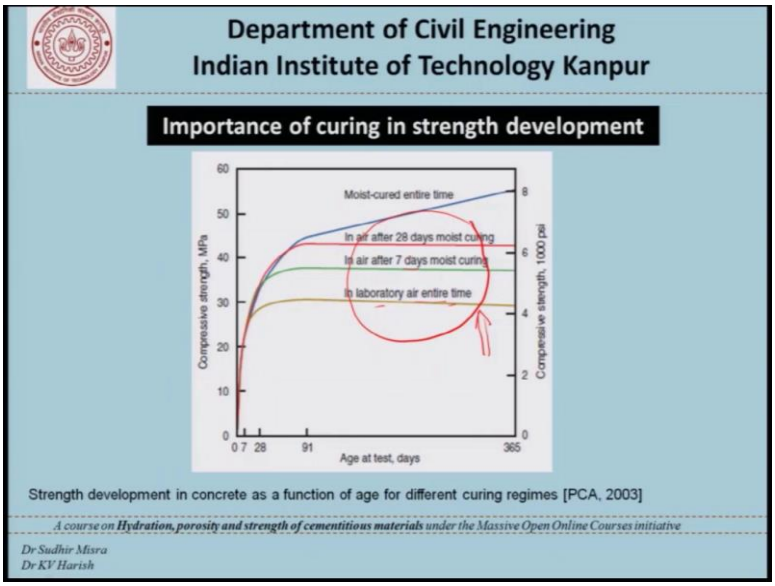

This picture again is also something which we had seen last time and we can clearly see that depending on the conditions that the concrete has after the initial period the strength could be very different.

Usually it can be assumed that hydration is not really a process which can be switched off and switched on depending upon availability of water. So, it cannot be said that we will stop hydration remove the water that is available and after some time if we reinsert the water in the system the hydration will take off as if nothing happened. So, now, if that does not happen we must be prepared that once for some reason hydration stops it will be difficult for any amount of strength gain to happen after that. So, this is precisely what is being shown by this picture here. So, while we are talking about in the laboratory entire time in the air, in the air after 7 days of moist curing or in here after 28 days of moist curing or moist curing entire time. So, we can see that that makes a difference to the ultimate strength that is obtained.

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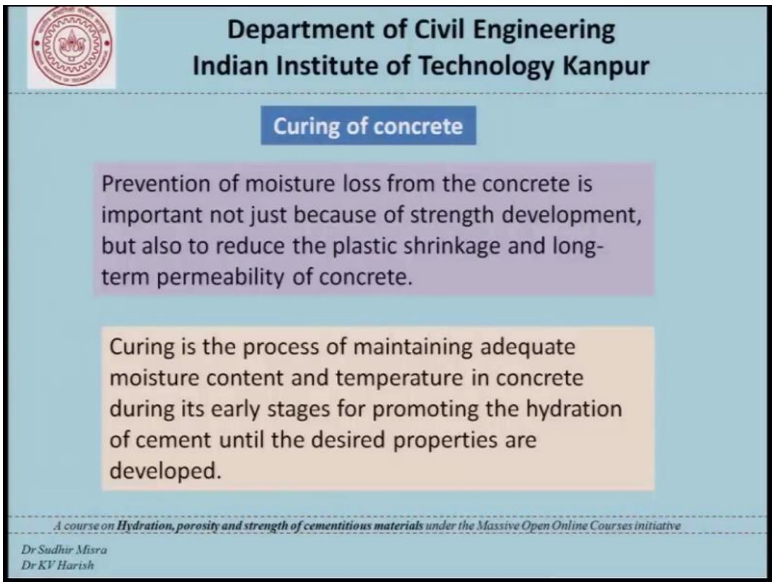

Prevention of moisture loss from concrete is important not just because of strength development, but also to reduce the plastic shrinkage and the long term permeability of the concrete and therefore, we can define curing is the process of maintaining, adequate, moisture content and temperature in concrete during its early stages for promoting the hydration of cement until the desired properties are developed. So, this is a very formal way of writing what are the precautions that we need to take in order to ensure that hydration continues for at least some time.

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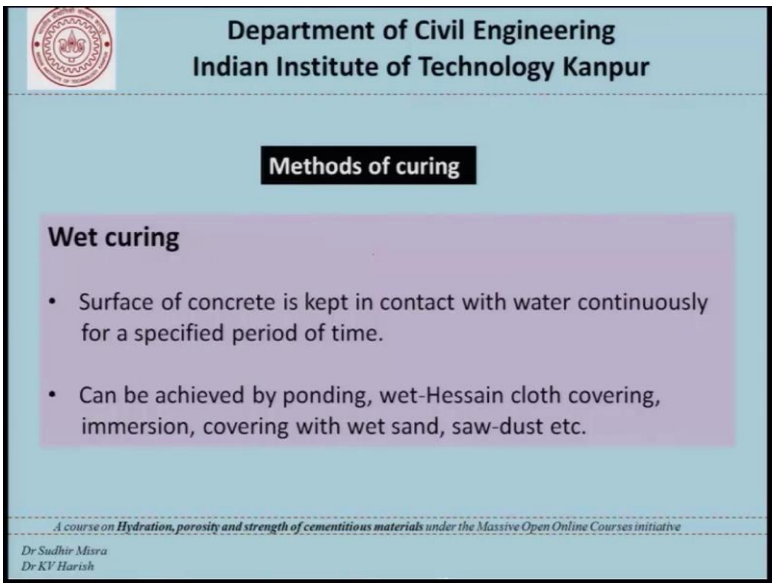

Now, coming to the methods of curing one of the obvious methods would be wet curing which is surface of concrete is kept in contact with water continuously for a specified period of time. We must remember that the concrete structures cannot be kept wet all the time a structure which is in the atmosphere has to be left to dry after a certain amount of time and therefore, it is only the initial period that we will try to provide the water, we will try to provide the right kind of environment. So, that the hydration continues after the hydration has reached a certain level and a certain amount of strength has developed that is what we said when we said desired properties are achieved then we can indeed remove our paraphernalia for providing the water and so on and let the concrete stand on its own.

The wet curing can be achieved by methods such as ponding which means that we just let the water stand wet hessian cloth covering which could be gunny bags or any such cloth which is wrapped around the concrete structure and that cloth is kept wet either by sprinkling or pouring water over it, immersion, we must remember that as per as quality control is concerned the cubes or the cylinders that we take are often kept immersed in a curing tank and the temperature of that curing tank is maintained at a specified level as given by the relevant codes. Covering with wet sands or the sets etcetera. So, these are some of the methods that we use to ensure wet curing of concrete.

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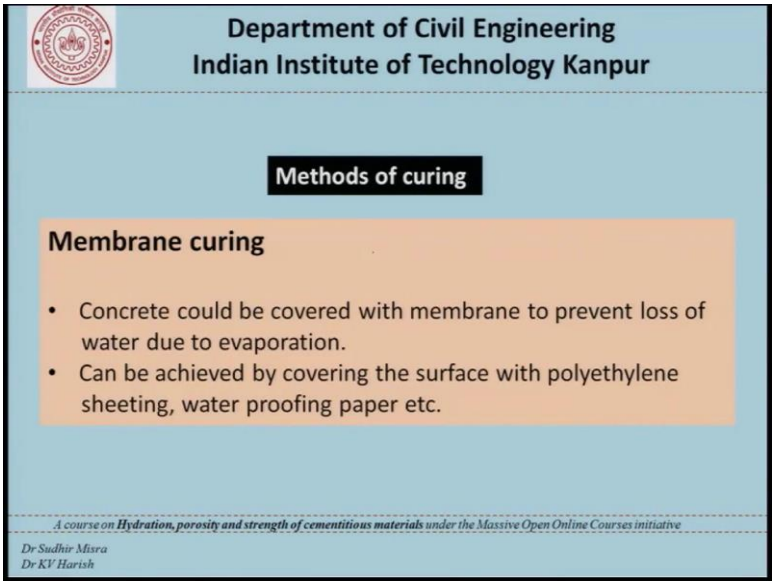

Then there are other methods such as membrane curing. Now what happens in this case is concrete could be covered with a membrane to prevent loss of water due to evaporation this can be achieved by covering the surface with a polyethylene sheet or waterproofing paper and so on.

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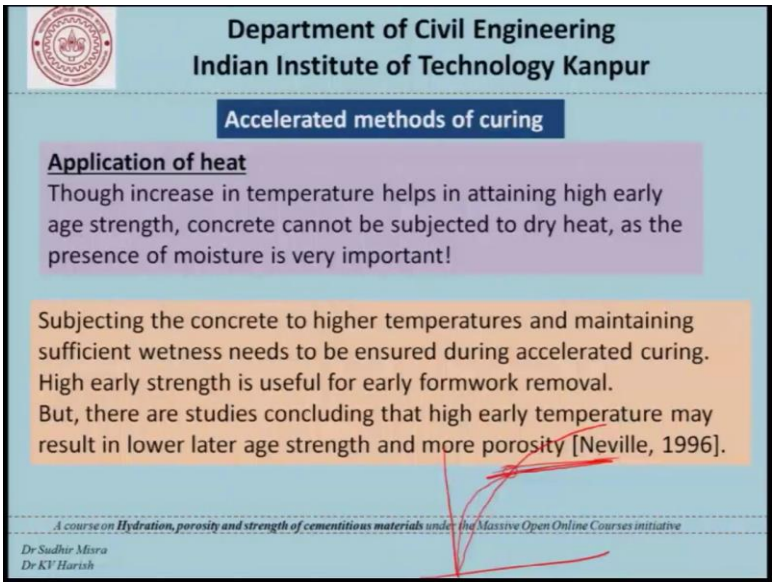

Moving further there are other methods such as application of heat. We must remember that though increase in temperature helps in attaining high early strength concrete cannot be subjected to dry heat as the presence of moisture is very important to ensure the right kind of hydration and strength development. Subjecting the concrete to higher temperatures and maintaining sufficient wetness needs to be ensured during any accelerated curing.

High early strength is useful for early formwork removal and there are studies; however, where it has been found that high early temperature may result in lower later age as far as concrete is concerned and greater porosity. So, what is being said is essentially that if we try to accelerate the curing process we can accelerate it by application of heat. The steam curing is a standard technique which is used we will talk about that in a few slides we can use steam curing and other methods, but we must remember that first thing provide enough moisture and the second thing is to be aware of the fact that it is possible that high early strength even if we get it could impede or make it difficult for the concrete to achieve very high strength later on.

Basically if this is the strength that we get for normal hydration and normal curing steam curing can help us get here, but it is possible that the tapering will take place after some time. So, we may get a lower final strength in the case of accelerated curing. We use accelerated curing extensively in situations such as making precast products because at that place we would like to have an early turnaround of the formwork.

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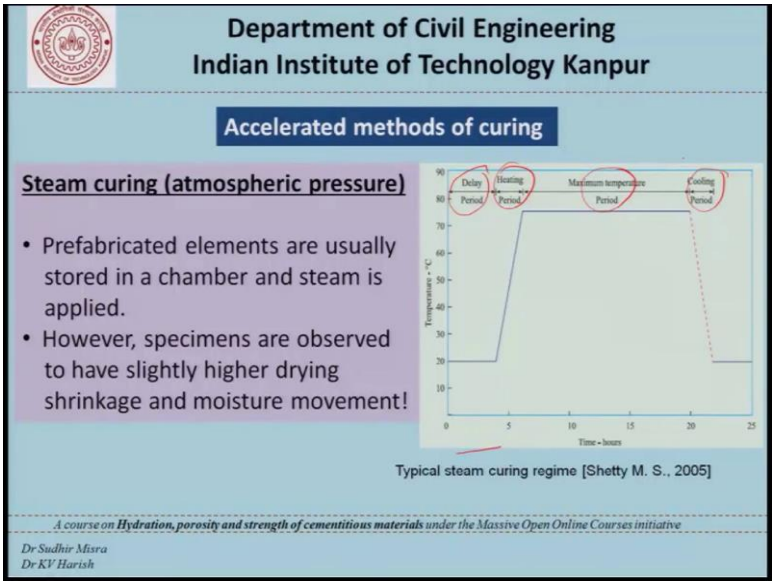

Discussing this whole idea of steam curing a little bit this picture here shows the cycle that is followed there is a delay period, a heating period, a maximum temperature period and then a cooling period. So, all these times have to be carefully decided depending on the type of cement and the type of product, the type of strength that we want and so on.

Prefabricated elements are usually stored in a chamber and steam is applied; however, the specimens are observed to have a slightly higher drying shrinkage and moisture movement. So, these are things that we need to understand and keep in mind when we use steam curing. Now steam curing can be carried out at atmospheric temperatures as has been suggested here or it can be carried out at higher pressures.

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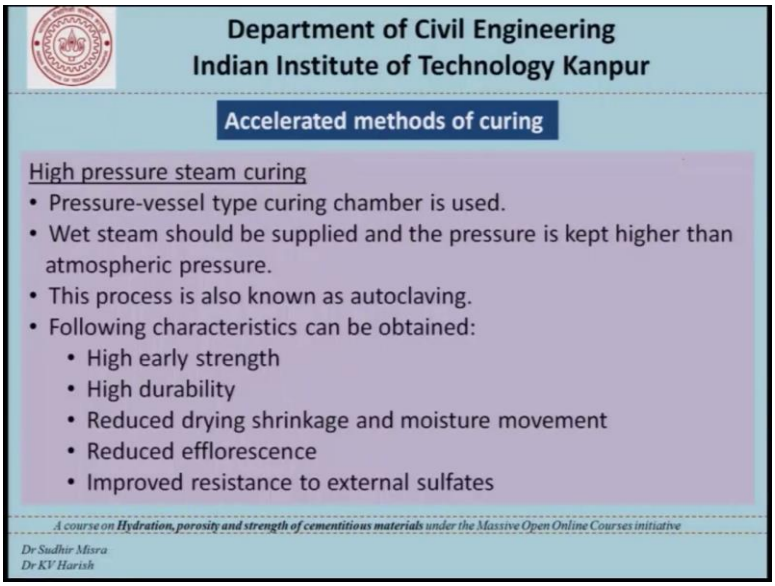

In this case there is a pressure vessel type curing chamber and we use wet steam and pressure is kept higher than atmospheric and this process is also known as autoclaving. The following characteristics can be obtained if we use this autoclaving curing process high early strength, high durability, reduced shrinkage and moisture movement, reduce the efflorescence improved resistance to external sulfates and so on.

We must remember that in principle accelerated curing is something which we often apply to precast products as I said before because this requires a lot more control on the temperature that we use the moisture conditions and the time. It is very difficult to apply, accelerated curing in situ conditions. We must also bear in mind that concrete is used in structures which are very diverse and the diversity makes it very difficult for us to control the loss of moisture from the concrete surface in all the conditions. For example, a highway construction if you are making a rigid pavement using concrete the kind of conditions there are very susceptible to loss of moisture compared to a beam or a column.

The surface areas involved in these constructions are so large that it is very difficult to prevent moisture from being lost and therefore, appropriate curing methods need to be used. Please also remember that keeping the concrete within the formwork also can be construed as a method of curing because by keeping the formwork there we are

preventing or we are at least slowing down any loss of moisture and also we are protecting the concrete of the surface from the action of atmospheric forces.

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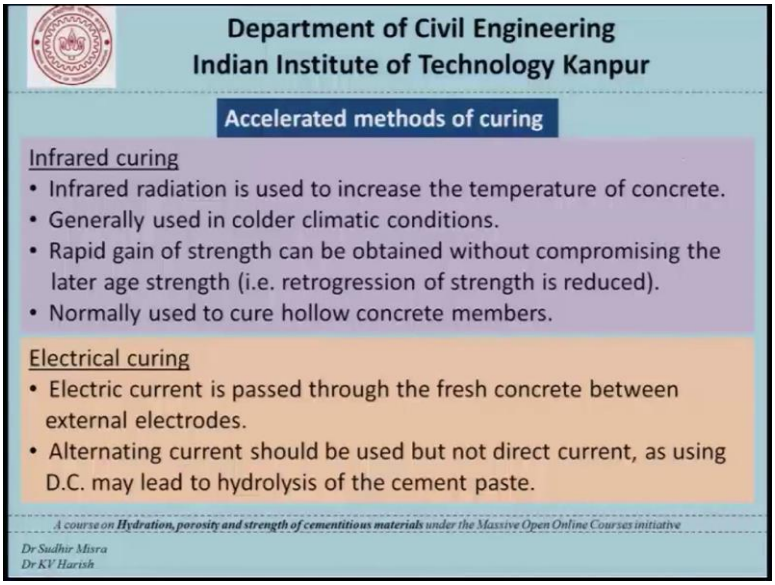

Continuing with methods for accelerated curing there is infrared curing which means infrared radiation is used to increase the temperature of concrete generally used in colder climate conditions, rapid gain of strength can be obtained without compromising the lead age strength and normally used to cure hollow concrete members.

Then there is electrical curing which means electric current is passed through the fresh concrete between external electrodes, alternating current should be used, but not direct current as using DC may lead to hydrolysis in the cement paste. So, these are some of the methods which are in different stages of development few applications, but yes these are possible keys in which we can move as far as promoting the hydration in cement is concerned.

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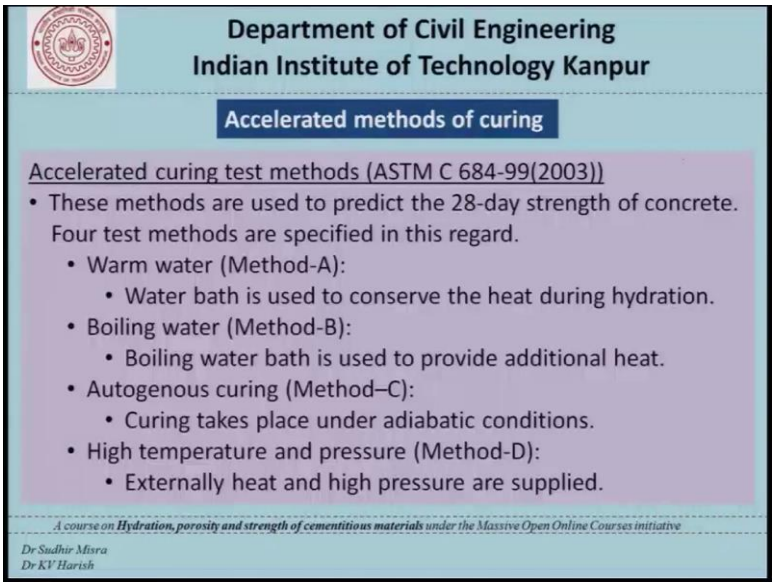

Accelerated curing methods as prescribed in the ASTM 684-99 these methods are used to predict the twenty eight day strength of concrete. Now this is a slightly different viewpoint on accelerated curing. Here the idea is that we want to accelerate the curing with the intent to get an early assessment of the strength that we would get with 28 day cubes or cylinders.

Four methods are specified in this regard warm water, boiling water, autogenous curing and high temperature and pressure. So, these are called methods A B C and D and then the warm water method as listed here warm bath is used to conserve the heat during hydration, in boiling water boiling water bath is used to provide additional heat, in autogenous curing it takes place under adiabatic conditions, and externally heat and high pressure are applied in the method D.

Then there is another method of curing which has emerged and that is the application of curing compounds.

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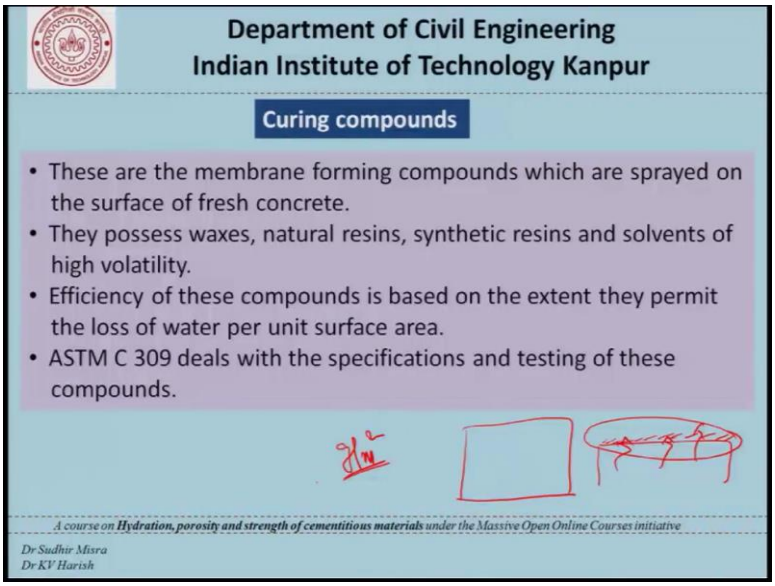

These are membrane forming compounds which are sprayed on the surface of fresh concrete they possess waxes, natural resins, synthetic resins and solvents of high volatility and essentially form a membrane of their own by sealing the pores of the concrete at the surface. Efficiency of these compounds is based on the extent they permit the loss of water per unit surface area. So, we can imagine that this basically boils down to a method where a certain surface area of concrete is sprayed, if we look at the cross section here we try to spray something on the surface making sure that water does not move out from the concrete. So obviously, the efficiency or the effectiveness with which this application of curing compounds will work would depend on how much let say grams per square meter, how much of this material is applied apart from of course, the characteristics of that material for one material we may need to apply more, for another material we may need to apply less. ASTM C 309 deals with the specifications and testing of these compounds.

What we also need to make sure is that the application of these compounds is not detrimental to the concrete from a functional point of view. For example, in an application where we are trying to apply curing compounds on the surface of concrete like this it should be ensured that the application of these compounds does not alter the surface characteristics of concrete in a manner that it becomes detrimental from a functional standpoint not only immediately, but even in the long term.

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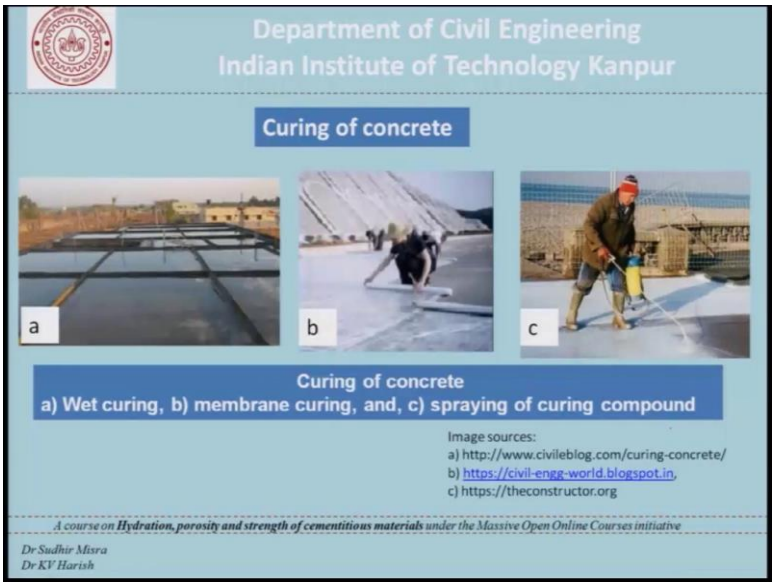

These pictures here show wet curing membrane curing in the spraying of curing compounds. So, we can see that in the situation like this we have the luxury of being able to pond simply pond the surface of a slab and indeed of course, this water evaporates into the atmosphere and is lost. So, from the water conservation point of view indeed this is not a very effective method of curing even though from a concrete standpoint this perhaps the best that we can do when trying to cure a slab.

Here we see the application of a membrane, what this guy is trying to do is to spread something like a polythene sheet on the surface of concrete and thereby preventing any kind of loss of water or loss of moisture which may occur from the surface of this concrete. It can be seen that this method is very effective and is useful only in cases which are having large surface areas or where spreading this kind of a membrane is easily done or doable. Same thing can be said about this application of curing compounds which is like spraying a chemical on the surface of concrete. One of the things that we need to bear in mind is that when we walk on concrete this concrete is definitely not very old when we walk on concrete like this or we try to spread these membranes the concrete should have sufficient strength at least for withstanding that kind of a load.

The person walking here should not leave foot marks on the surface of concrete these are the kind of things that we must keep in mind and there are no specifications that can be

put forward. And this timing of application of the curing compounds or the timing for putting the membrane would depend on the temperature of the atmosphere, the type of cement, the kind of hydration that goes on and all kinds of things so once we understand the principle then it is up to the engineers at site to implement those principles based on local conditions.

Now, carrying forward let me introduce to you the concept of maturity of concrete.

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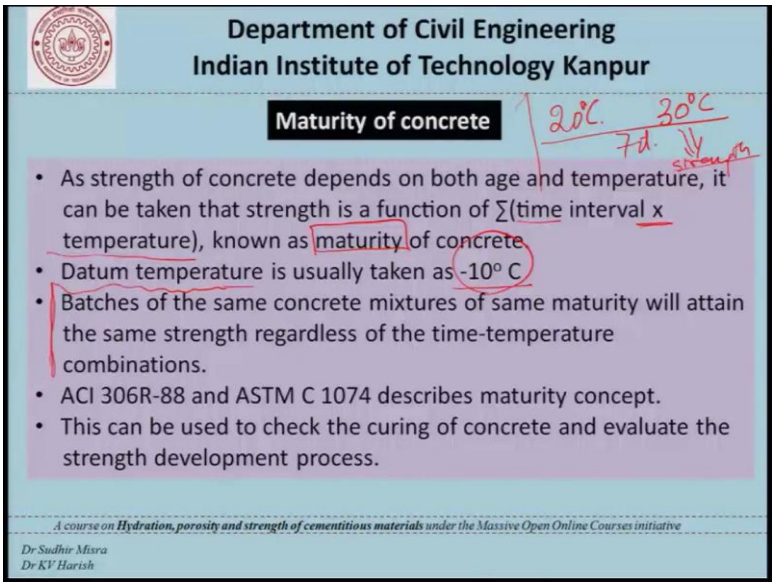

Now, we have discussed that strength of concrete depends on both - the age and the temperature and therefore, we can take that the strength is a function of the time multiplied by the temperature and this product of time and temperature has been referred to as maturity of concrete. In this discussion of maturity in the literature you will find that there is something called a datum temperature and that datum temperature is usually taken as minus 10 degree centigrade. And that datum temperature really means that it is only the temperature above this number which counts towards calculating the maturity of a concrete at any given point in time.

Batches of the same concrete mixtures of the same maturity will attain the same strength regardless of the time temperature history or the combinations of time and temperature. So, this is the essence of this discussion that the strength is related to the maturity of concrete which is a product of the time and temperature basically what we are saying is

that concrete cured at 20 degree centigrade and concrete cured at 30 degree centigrade for 7 days will attain different strength.

Now how much the difference will be can be calculated if we take a product of these two numbers taking into account this datum temperature. Now once this principle is accepted then we can move forward and try to use this concept in checking the curing of concrete and evaluating the strength development process.

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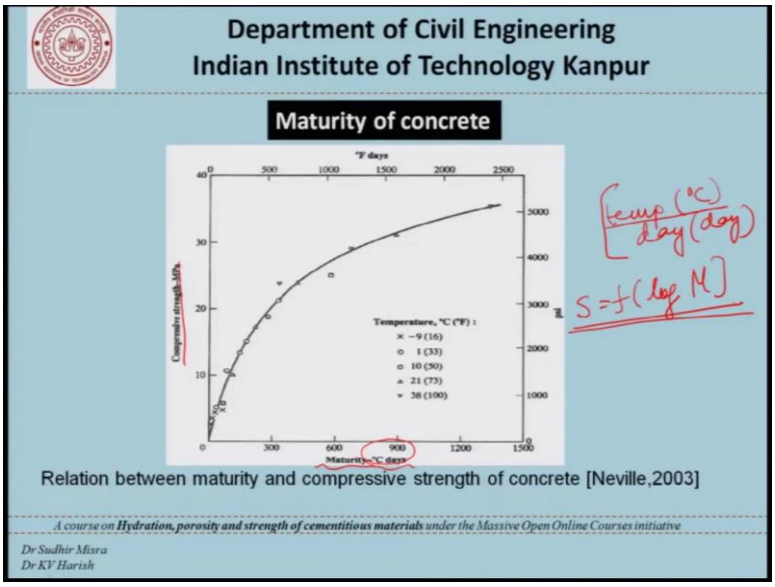

This picture here shows some of the experimental data which is for maturity in degrees centigrade days; so obviously, the unit of maturity will be something like degree centigrade days because we are talking about the product of temperature which is being measured in degree centigrade and the days of curing which will be in terms of days. And this product is maturity related to the compressive strength and we can find that there is a fairly good fit in this relationship.

I would also like to mention that there is literature which says that the strength is related to the log of the maturity and I am leaving it to you to do some homework and find literature where there is more discussion on maturity. This is a very interesting idea which helps us or which will help us at a certain point in time to try to relate the strength to different curing conditions; obviously, this method is applicable or is valid only in the initial periods when the strength development is still taking place.

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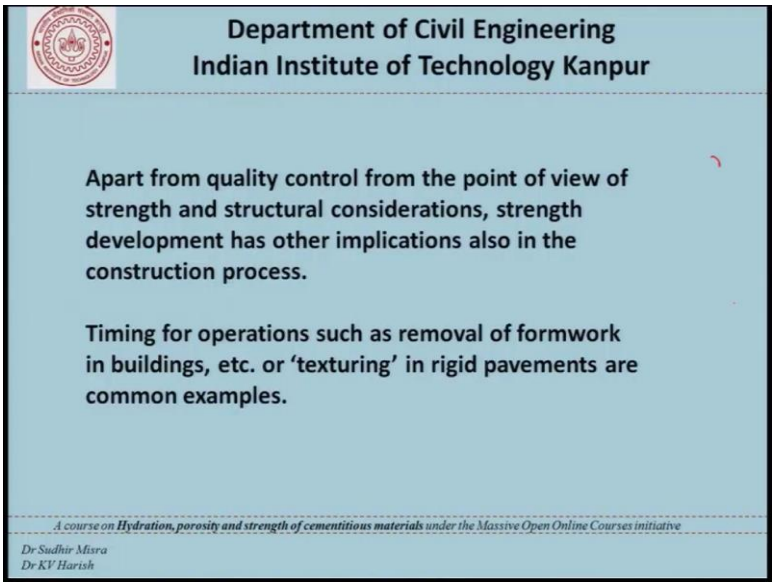

Now apart from quality control from the point of view of strength and structural considerations strength development also has some other implications in the construction process. We are talking of strength development in the initial part when curing is very important. Some of the operations which are important from that point of view are the timing for operations such as the removal of formwork in buildings or texturing in a rigid pavement. Now texturing is the process by which we try to roughen the surface of a rigid concrete pavement in order to increase the friction so that it is easier for somebody who drive on that and of course, in buildings we are concerned with that because we want to recycle the formwork and we want to move forward with the construction process. So, at what time should the formwork be removed?

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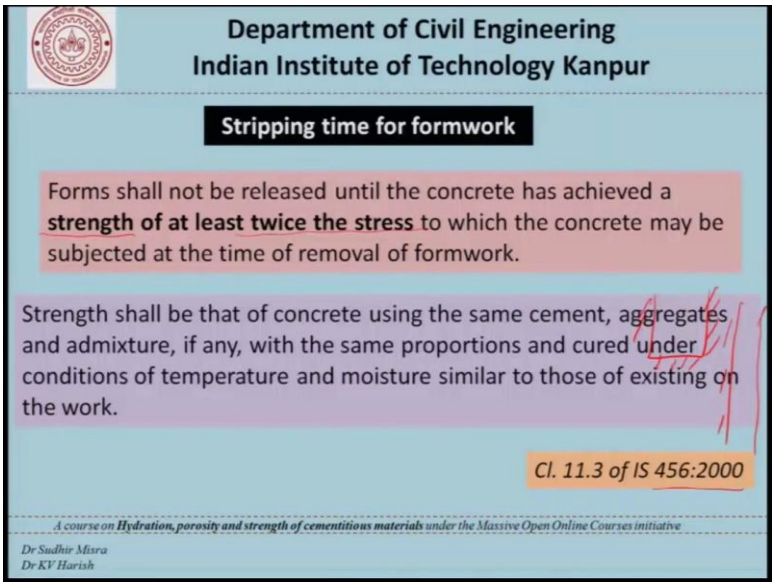

As per as the Indian standards are concerned 4 5 6 2000 when it talks about the stripping time for formwork which is the time for removal of this formwork, it says that form shall not be released until the concrete has achieved a strength of at least twice the stress to which concrete may be subjected to at the time of removal of formwork. We must remember that after a certain member whether it is a beam or a column or a slab it is cast it is a while before these members are subjected to design loads or the full load and therefore, what we are talking about is for the removal of formwork which could be the sides or the bottom of a beam or the sides of a column all these cases we have to only ensure that concrete has sufficient strength.

Now, how much is that sufficient is strength is quantified here when it says that it should have strength which is twice the stress that it may be subjected to. Now it is very difficult at site to be able to carry out an analysis and find out which member will be subjected to what level of stress and therefore, try to find out different times of removal of homework. So, what is done and in order to follow the strength development what is suggested is that the strength shall be that of concrete using the same cement aggregates admixture if any, with the same proportions and cured under conditions of temperature and moisture similar to those of existing on the work. So, if we carry out this exercise we will know what is the kind of strength development that is taking place and therefore, for that particular work if we are told that this is the amount of strength that we need then we know at what time should the formwork be stripped, now that is the principle of it.

What it goes on further the code to say is that in normal conditions where ambient temperature does not fall below 15 degree centigrade and OPC is used and adequate curing is done the following striking periods can be used as a guideline. So, instead of quantifying the strength what has been done is some there are some disclaimers.

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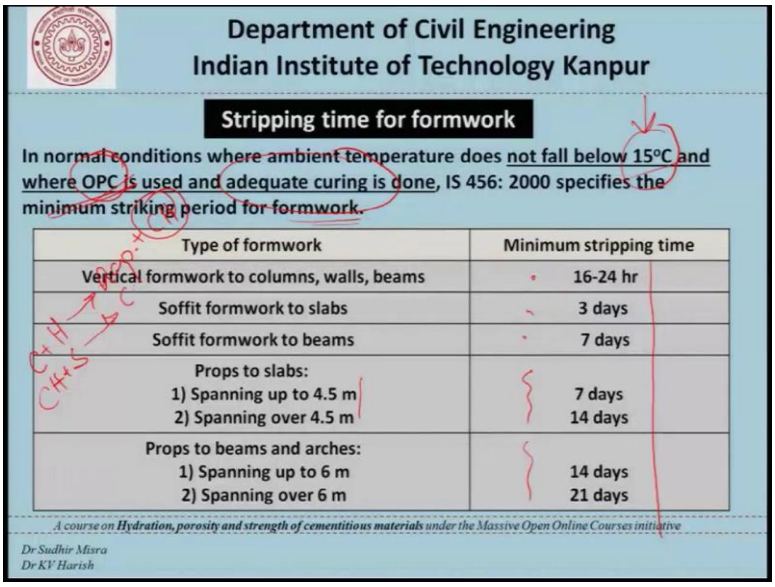

We are saying that the temperature should not be less than fifteen degree centigrade a cement which is OPC is being used that is we are talking of a situation where supplementary cementations materials have not been used and we say that there is adequate curing. Then these are the kind of times that can be used as guidelines to remove different types of formwork vertical formworks to columns beams and walls that can be removed within 16 to 24 hours. Soffits of beams or slabs 3 days, soffits of formwork to beam 7 days and so on and so forth. There is an issue of span longer spans require higher amount of curing and therefore, what is specified is higher amount of time. What it does not specify is the temperature what it lays a stipulation that the temperature should be higher than 15 degree centigrade.

This discussion of OPC versus non OPC that is cement where pozzolanic material has been used is also very relevant from the point of view of appreciating the importance of curing and creating these timings here with a pinch of salt. We remember, we know that cement hide reacts with water to give us hydration products and calcium hydroxide and it

is this calcium hydroxide which reacts with the pozzolanic material to give us calcium silicate hydrates.

So, it is kind of believed in literature that hydration in PPC cements or pozzolanic portland cement is slightly slower that is we have a slightly slower strength gain even though the final strength may be higher depending again on the type of curing that we have done. So, we must be very careful when interpreting any specification or stipulation on removal of formwork as far as curing is concerned, but I hope that we have understood through this discussion the importance of maintaining the right kind of environment around the concrete to ensure that hydration proceeds at least to an extent that is required.

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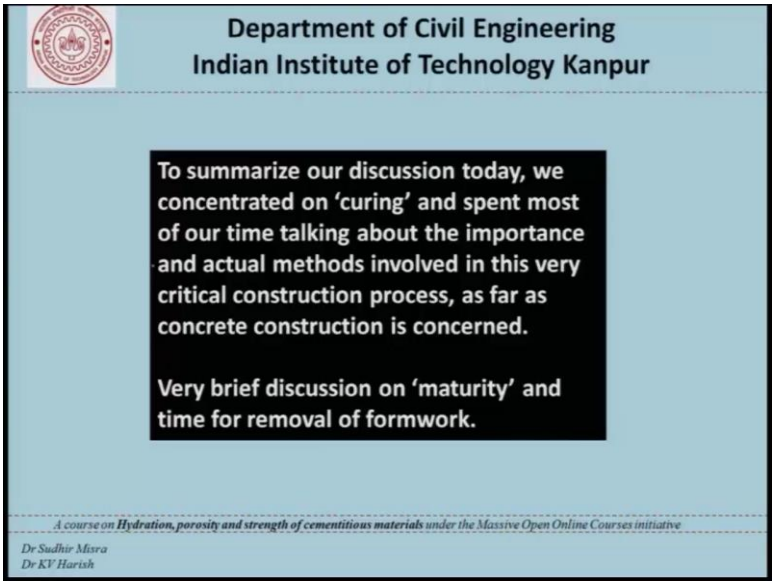

So, to summarize our discussion today we concentrated on curing and spent most of our time talking about the importance and the actual methods involved in this very critical construction process and we also briefly discuss the concepts of maturity and the time for removal of formwork. This as usual is the list of references which may help you better understand the subject.

Thank you.