Development and Applications of Special Concretes
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Lecture 10
Curing of Concrete

Namaskar and welcome back to another lecture in our series on development and applications of special concretes. Today we start our third module in this series and the focus of discussion will be curing of concrete.

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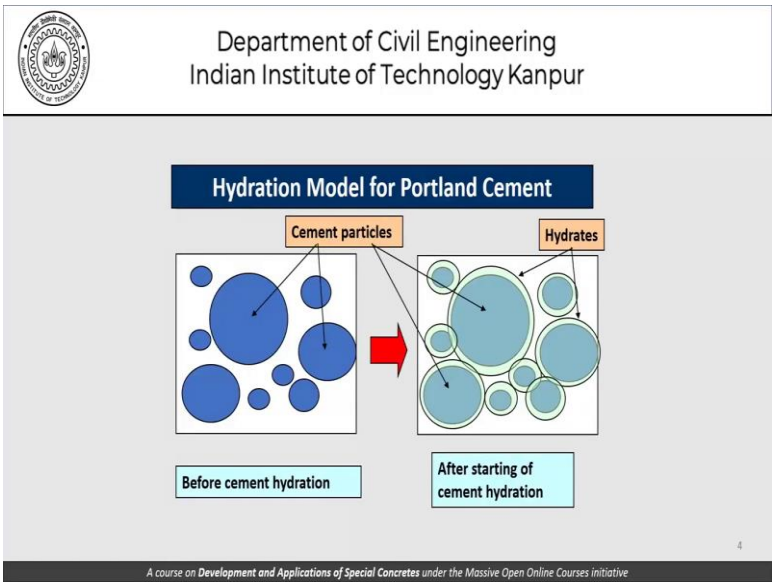

So, before we get started with our discussion of curing in concrete let us try to review some principles in hydration. This slide we have already seen before and what this picture tells you is cement particles surrounded by water and as hydration proceeds hydrates or hydration products are formed around these cement particles. To facilitate this process, we need to do curing. Now how do we facilitate this requires a little bit more understanding of the hydration process which we will just do.

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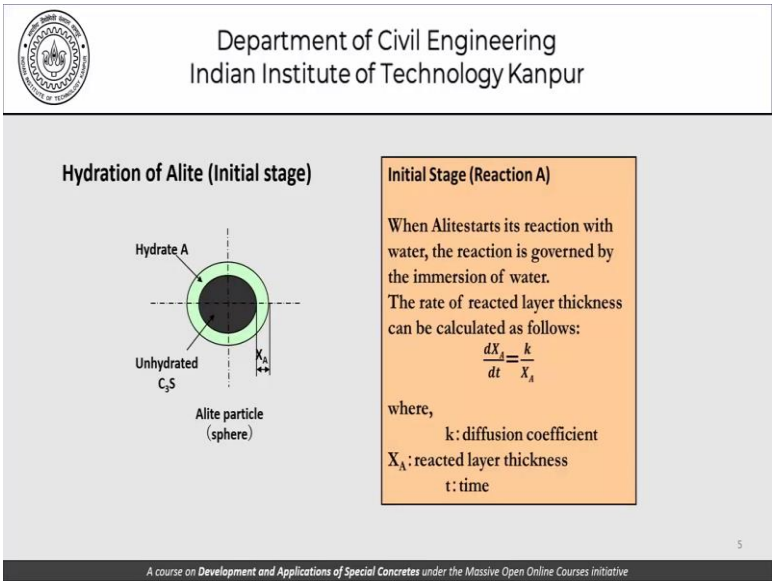

This picture here shows a schematic sketch of hydration of a light one of the constituents of cement. What this equation really tells you is that as hydration of a cement particle of course it is given as a light here. So, let us not bother so much about the light part of it, if it was a cement particle as it hydrates these hydration products are formed and the rate of development of this hydrated product layer is inversely proportional to the thickness of that layer at that time.

So, the rate of hydration of cement can be taken to be inversely proportional to the amount of hydration that has taken place till that point in time. Which means that, water is present outside here and hydration is taking place at the surface here, which means that as more and more hydration happens water has to negotiate through the hydration products to react or to reach the surface of cement where fresh hydration will take place and fresh hydration products will be formed.

This is something which you have to keep in mind to understand what is going on as far as the hydrates are concerned in this layer. There are two things happening initially some hydrates are formed, and as more and more water moves through them these hydrates or these hydration products are refined. More hydration products are formed, that means the hydration products become denser.

In fact, from the porosity point of view we have talked about it before in the previous module that as hydration proceeds the total pore volume in the hydration products that it goes down and not only that but also the pore structure also gets refined. The pore size distribution gets

more and more refined. So that is precisely what is happening if we want complete hydration and when we talked about 25% or whatever that number was, 25% water being required for complete hydration, we have to take this value with a pinch of salt because we really do not know whether the complete hydration will ever happen.

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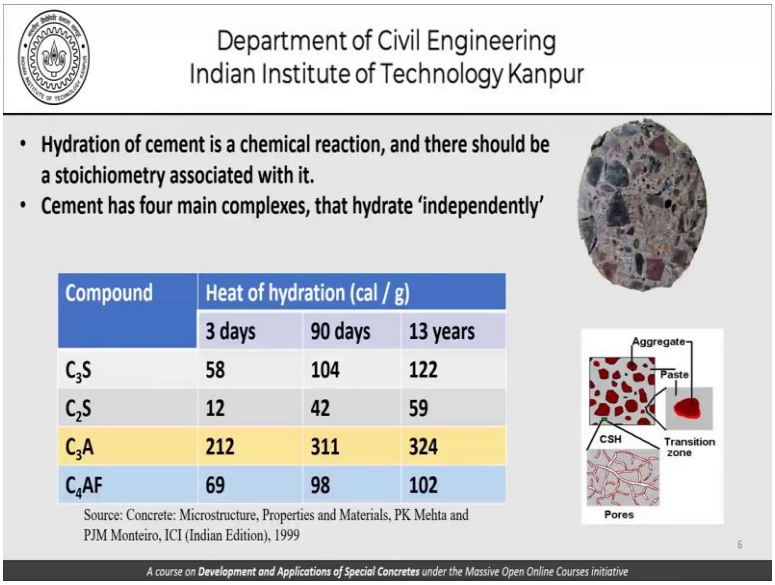

You would recall this slide from a previous presentation and you can see that these four principal compounds of cement hydrate independently showing the following the model that we just discussed. And we can see that the hydration as such continues for a very long period of time. Even at this point here, in 13 years you can see that still heat of hydration in terms of calories per gram is being liberated it could be 13 here it could be 18 here, it could be something else and so on.

The fact is that hydration continues for a very long time and it is only an engineering judgment or an engineering decision that we base our quality control procedures as far as concrete is concerned at 28 day and we restrict the curing conditions or the curing duration to three days or seven days or whatever it is. Having said all this, I think you now understand the backdrop of curing. Before we get into the discussion of curing as such let us look at one more picture.

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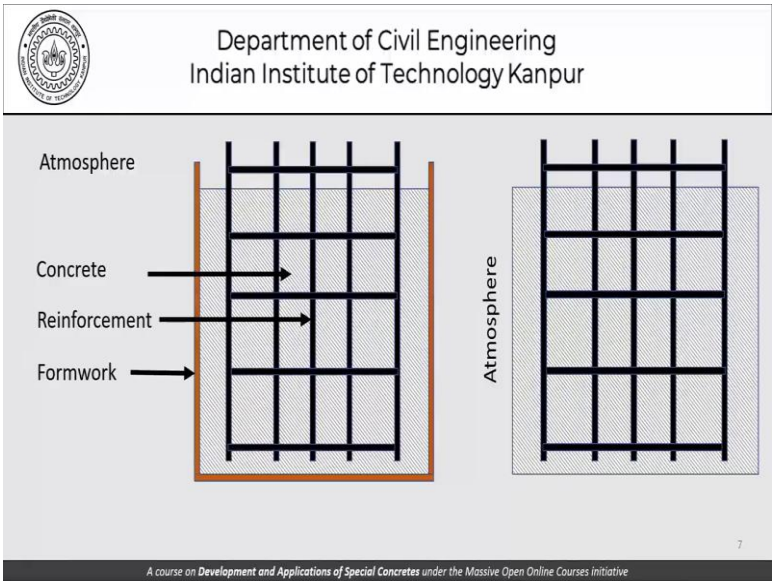

This picture here shows the concrete as is cast in a formwork with reinforcement and this is the cast concrete, and it is very important to note the atmosphere that is we are casting this concrete in atmosphere which is characterized by its own temperature, relative humidity, wind speed and so on. Once the concrete has hardened and has sufficient strength to be able to sustain at least itself weight we remove this form work and we get a concrete which is of this form.

That is the concrete is exposed to the atmosphere in this case here till such time as the form work is there the concrete is protected from the atmosphere at least from direct contact except for the horizontal surface the way I have shown it here. Except the top the other three sides are protected from the atmosphere by way of this form work. This protection does not exist any longer once we remove the form work which we do when the concrete has reached sufficient strength.

In fact, there are reasons to remove the form work early because we would like to recycle the form work and so on and so forth. So, this is precisely the kind of picture that we have to understand and also understand one more thing what is going on in this part of concrete may not be going on in this part of concrete, can you think why? The simple reason is that this concrete here is closer to the atmosphere than here than this concrete.

Therefore, if at all there has to be some moisture exchange that has to happen between these two materials the air here and the concrete here it will be so much easier to occur here than here. The water from here will have to travel all the way here before it can evaporate. But the

water here can quickly evaporate and that is actually true from all sides depends on what kind of atmosphere or what kind of conditions are prevailing on what we can call the top the sides which is this side of the concrete structure and possibly the bottom.

If you want to take an actual example as to what this really represents. If you were to take a column which is like this then if I remove the form work from the four sides all these four sides will be exposed to the atmosphere and the top here is something like this. It was always exposed unless we take definite measures to protect it. The bottom of the column is not really in question because either it will be against a fresh surface of it will be either cast against an existing surface of concrete or it could be coming from the raft or whatever happens.

So that is not really relevant. Having said that, if it were a beam that we are talking about then the bottom and the sides and the top is very much in line with the kind of representation that is shown here. Similarly, for the slabs we have a thin reinforced concrete member with the top being always exposed to the air and the bottom being protected to some extent by the form work for some duration and then exposed and so on.

So, this idea that there is a surface of concrete which is closer to the atmosphere or which comes in contact with the atmosphere at different points in time maybe all the time maybe it comes in contact after the formwork is removed depends on the kind of structure that you are talking about. Keep that in mind and the effort involved in curing or the principle of curing is basically to handle whatever goes on, on the surface of concrete.

We cannot do much about what goes on inside the concrete. And now the difference between the inside and the outside here would be significant if the member thicknesses were large. If the member thicknesses were small, it will not matter so much. Now what is a large member thickness what is not a large member thickness is what is exactly the normal concrete versus special concrete kind of discussion. So that is what we are kind of getting started as far as this module is concerned.

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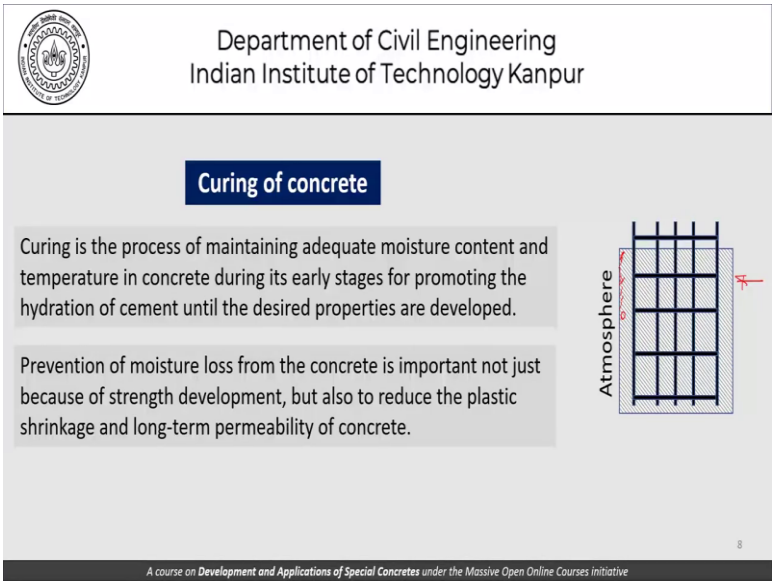

Now this is the formal definition of curing you can see that I have just included this picture here as a reminder from the previous slide to explain to you or for you to better visualize what curing is all about. As far as the definition is concerned curing is the process of maintaining adequate moisture content and temperature in concrete during its early stages for promoting the hydration of cement until the desired properties are developed.

So, what we are saying is that no matter how much water is added to the concrete here some water will tend to escape from the concrete into the atmosphere unless we take some preventive measures. And that will leave the cement especially in the surface or near the surface of concrete un-hydrated. And that's a very undesirable or an unwelcome kind of a prospect. And therefore, through curing what we try to do is to maintain favourable conditions within the concrete.

So that all cement particles or the entire cement content in the concrete is actually able to hydrate and hydrate fully. Prevention of moisture loss from the concrete is important not just because of the strength development but also to reduce plastic shrinkage and long-term permeability of concrete. Now this really is just a corollary of this and follows what is being said is, that we have to create conditions the surface of concrete such that the water does not escape.

If water escapes or what is allowed to escape from the surface that is an undesirable thing that is what we do not want to happen. And we try to create conditions around the surface. Now the question obviously remains that we can create conditions around the surface which will

facilitate the complete hydration of concrete in the proximity of the surface that is at the near the surface conditions what about deep inside.

Now deep inside we cannot really do much as far as promoting hydration is concerned it is impossible to provide water in fact it is not even needed. Because in any case the amount of water that we have added is in excess of that required for complete hydration. So, it is only the prevention of water escape that has to be our focus as far as curing of concrete is concerned.

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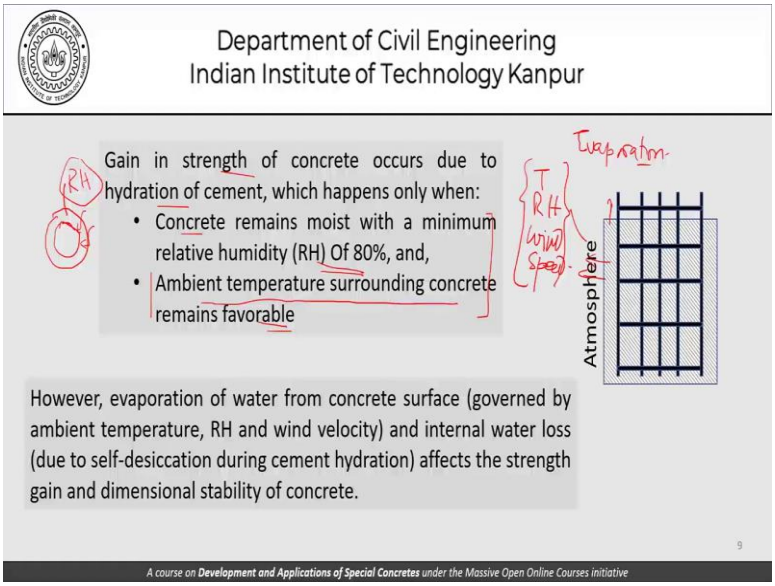

Now gain in strength of concrete occurs due to hydration of cement which happens only when the concrete remains moist with a minimum relative humidity of 80% and ambient temperature surrounding concrete remains favourable. Now this is the kind of picture that gives us an inkling of what is coming in the next lecture and possibly the next one. Ambient temperature surrounding the concrete remains favourable.

Now if this temperature here this atmosphere is after all characterized by a temperature relative humidity and let us say a wind speed. Now you imagine that all these factors could determine how much water will tend to run away from here or escape through evaporation. Now if evaporation was not allowed things will be good for us as far as concrete is concerned and that is what is being said here that the strength development in concrete will happen which is coming from hydration of cement.

And that will be good only if the concrete remains moist with a relative humidity of more than 80% which is a favourable condition for the hydration reaction which we saw just now to move forward that is a cement particle with hydration products here. If the relative humidity around here within concrete falls below 80% becomes drier then less water is likely to move inside these hydration products come in contact with a fresh surface of cement and promote more hydration that is the stoppage of hydration and stopping of gain and strength.

And that is something which we want to prevent to the extent that is possible. However, evaporation of water from concrete surface governed by the ambient temperature relative humidity and wind velocities and the internal water loss due to self-desiccation during hydration affects the strength gain and dimensional stability of concrete.

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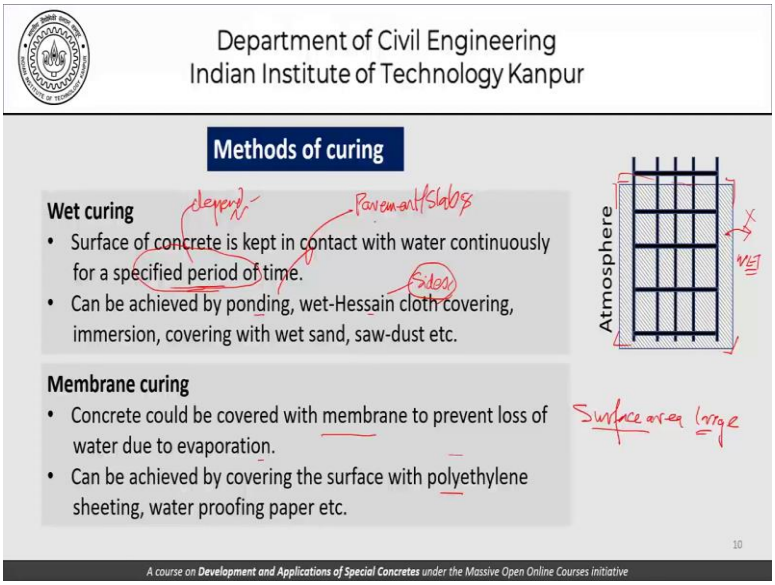

So far, we have talked about the principles of curing why we need to cure? Basically, we said we need to cure because, we want to have complete hydration of cement especially in the neighbourhood of the surface which is in contact with the atmosphere. Now we come to the methods what are the methods of curing that are available to us and we use them? The first method that comes to mind is wet curing.

Where the surface of concrete is kept in contact with water continuously for a specified period of time wet curing can be achieved by ponding, wet-hessian cloth covering, immersion covering with wet sand sawdust and so on. Again, the principle is the same we try to ensure that this surface here is covered by something and we ensure a wet environment. And this wetness prevents any water from here to escape into the atmosphere.

How we keep it is by ponding if it was possible in a horizontal surface like this, we could probably make a pond here there is something which is used in pavement is easy to do this in slabs it is easy to do. But this kind of methods like wet recent cloth covering or wet gunny back curing is something which we often use on the sides. Now how long should this be maintained? Now this is given as a specified period of time.

Now this is specified period of time would depend on what? This would depend on the kind of cement that you are talking about if the cement is such that it is hydrating rapidly you may stop curing quickly just after a day or two days or three days. But if the cement is such that it requires longer period for hydration if you are using porcelain admixtures where the hydration reaction continues for a long period of time there of course the curing period will also have to be correspondingly increased.

So, this is something which has to be determined either experimentally or through specifications or any other thing that comes to your mind. Please try to go through literature and find out what is the specified period of time which is specified or given in literature. Another method that is often used is membrane curing. Now what is membrane curing membrane curing refers that, Concrete could be covered with a membrane to prevent loss of water due to evaporation this can be achieved by covering the concrete surface with a polyethylene sheeting, waterproofing paper or something similar this is something which could be popular where the surface area involved is large. And in certain cases, it may not be possible to pond a large surface because that itself promotes evaporation water may not be available to that extent.

So, in those cases we go for membrane curing. Basically, have the concrete surface here and then try to place a membrane on top of this we see a picture later on of a membrane being placed which prevents water from moving out regardless of what goes on here. This is my atmosphere as I showed you and regardless of what is going on in the atmosphere the presence of this membrane prevents any water from the concrete to escape into the atmosphere that is what is called membrane curing.

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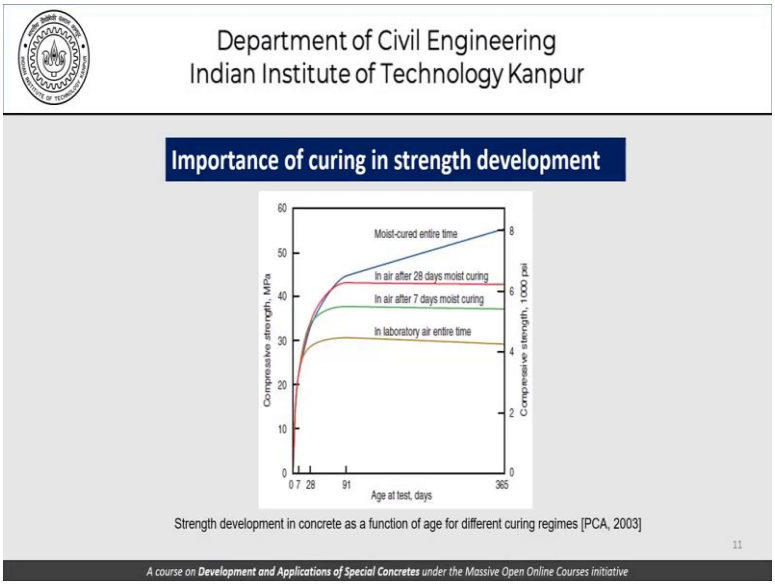

This picture shows you the importance of curing from the strength development perspective based on actual experimental data using concrete with a certain water cement ratio a certain type of cement and so on. What this picture tells you is that if the concrete was left in air all the time this is the kind of strength development that you will see. If it was cured for seven days under moist conditions and then brought to air this is the graph 28 days in moist curing and then air this is the graph and this is what the graph will look like if the concrete was moist cured the entire time.

Please note that the last time on this graph is 365 days which is one year. So, you can see that there is a substantial amount of development in strength that is happening beyond the 28 days period as far as moist cured conditions are concerned. With respect to this the amount of development that is happening at other curing conditions is much smaller that is one thing to note. The second thing to note is that since this graph is drawn in MPa and as I said it is for a particular proportion a particular cement these values would be quite different if I were to change this water cement ratio or the cement content or the cement type.

I am leaving it to you as an assignment to look for literature and try to plot this graph with different curing conditions if you can get it else you can at least try to do the strength development studies for different water cement ratios different cement contents and cement types and see for yourself how much are these ultimate values different. Yet another thing which you should notice is the fact that strength development happens even in air.

So, it is not that if you do not moisture the concrete specimen there will be no strength development. In this case for example it is moist cured only for seven days that means it is taken out from the curing pond somewhere here from here onwards to this point this strength development is happening in air. But if it was moist cured for 28 days the strength development is still there as we can see here.

So that shows you the importance of maintaining favourable environment around the concrete to facilitate development of strength. Please also remember that these kinds of data that we get are produced or are obtained using laboratory studies which are often carried out I should say mostly carried out using specimens. Now this is quite different from the real structure because as we saw in the structure there is a concrete which is close to the surface and there is main body concrete.

So, it is difficult to discuss whether this strength development that we are talking about is here or here. The conditions of moist curing certainly do not represent the conditions of either of these fully so that's another engineering approximation that we make in all of our concrete engineering discussion where we try to study a lot of concrete properties using laboratory specimens under certain conditions which are standard.

And that is why standardization is very important that under standard conditions which for example in India would be under water at a certain temperature for 28 days try to do that. So that really gives you just the potential strength of concrete from a specimen point of view. When it comes to the structure things are quite different and to remember this difference when we are actually carrying out engineering practice when you are working in the field.

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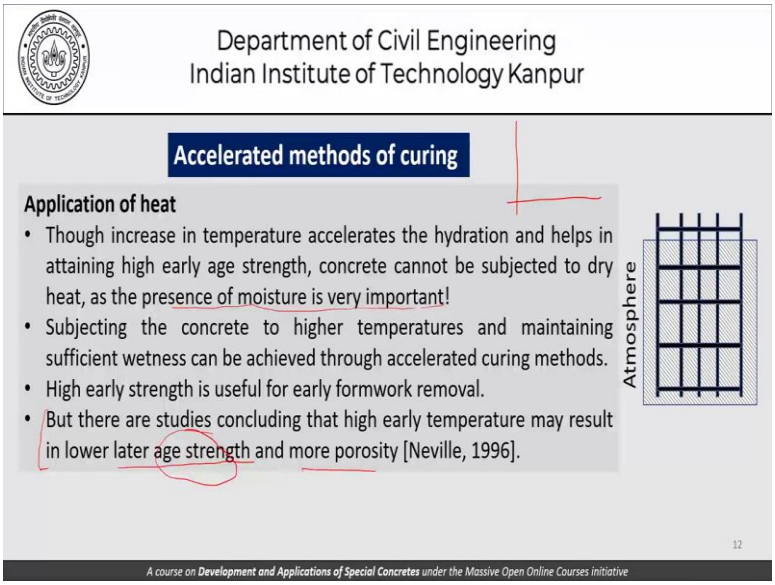

So, having said all this now let us come back to our discussion on methods of curing there are accelerated methods because sometimes we just cannot wait for the kind of normal curing durations to be operating. And in those cases, one of the most common methods that we use is application of heat. Though increase in temperature accelerates the hydration and helps attaining high early strength concrete cannot be subjected to dry heat as the presence of moisture is something very, very important.

So, we cannot really just increase the temperature we have to be very careful that as we increase the temperature the moisture content is still maintained. So, unless that is kept in mind heat application is something which is very dangerous thing to do as far as early age concrete is concerned. Subjecting the concrete to higher temperatures and maintaining sufficient wetness can be achieved through accelerated curing methods and that's what we are talking about.

High early strength is useful for early formwork removal in repair works and so on. There are studies concluding that the high early temperatures may result in lower late age strength and more porosity. So, what it really shows some studies have shown that we may get higher early strength but in those cases the strength development itself is inhibited and the final strength may be lower than what is achieved through traditional or normal curing.

So, if you want to plot a graph it will look something like this that if this is my strength for accelerated curing conditions. This could be my strength for normal curing conditions. So as far as normal curing is concerned at the initial stages the strength could be lower but for

accelerated conditions this will be higher but finally this strength could be lower than what we are getting through normal curing.

So, this is a trade-off sometimes we have to go with this accelerated curing we want to or we have to it is not a matter of we want to but we have to forego this final strength bonus which we can get if we had the luxury of curing the concrete normally.

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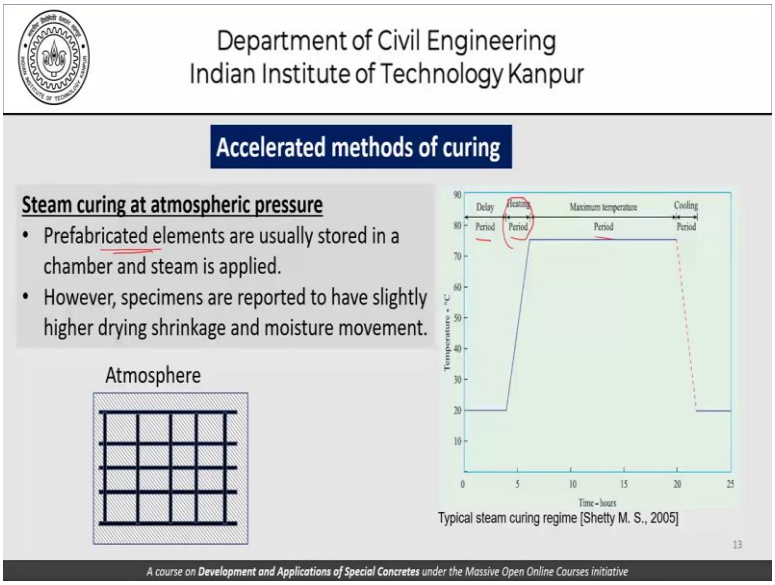

Accelerated methods basically means steam actually, what we really do is have a steam cycle, which says there is a delay period we have to wait for a certain amount of time at least then we heat, it from let us say 20 degrees to about 75 degrees maintain it at this temperature of 75 degrees and then cool the specimen or cool the concrete member back to 20 and let it be where it is. These prefabricated elements are usually stored in a chamber and steam is applied.

Now prefabricated elements this precast prefabricated construction this very often uses steam curing because that is the way to release formwork that is a speedier way of construction. However, the specimens are reported to have slightly higher drying shrinkage and moisture movement. Obviously once you have tried to accelerate the curing process or the hydration process these are some things which you have to live with.

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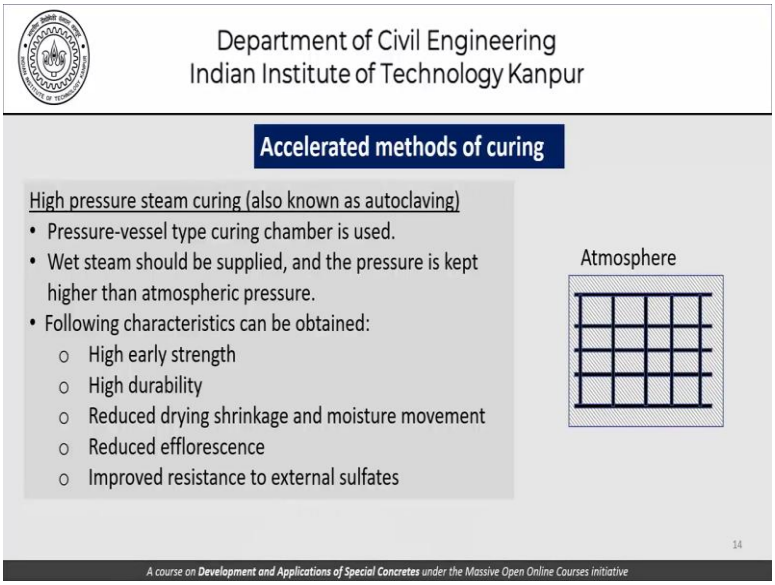

Continuing from there, there is autoclaving which is available to you pressure vessel type curing chambers are used wet steam should be supplied and the pressure kept higher than the atmospheric pressure. In normal steam curing there is no additional pressure as far as autoclaving is concerned there is a pressure element as well wet steam is applied with the pressure kept higher than the atmospheric pressure.

And we could obtain high early strength high durability reduce drying shrinkage and moisture movement reduce the fluorescence improved resistance to external sulphates. So, this is some things which are coming out of autoclaved curing. There are some pluses of course but please remember that autoclaving may or may not be possible for large members is an expensive proposition and is resorted to only when it is necessary.

When the ends justify the additional expense that is incurred in terms of autoclaving that is having a chamber where you can supply steam and maintain a high pressure.

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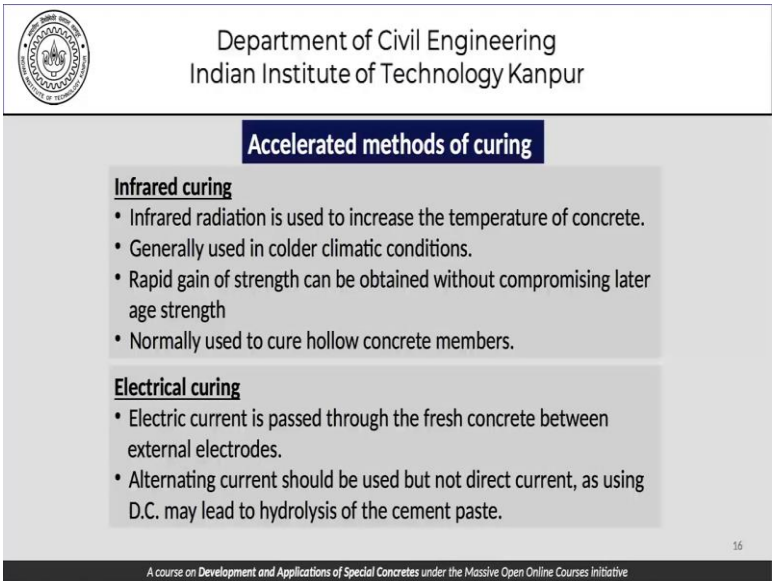

Then there are other methods like infrared curing, which refer to infrared radiation being used to increase the temperature of concrete used in colder climatic conditions results in rapid gain of strength which can be obtained without compromising later age strength and normally used for hollow concrete members. Then there is electrical curing as well where the electric current is passed through fresh concrete between external electrodes and alternating current should be used but not direct current.

As the direct current may lead to hydrolysis in the cement paste. So, there are certain things which we must know about before we try to apply one method or the other as an accelerated method for curing.

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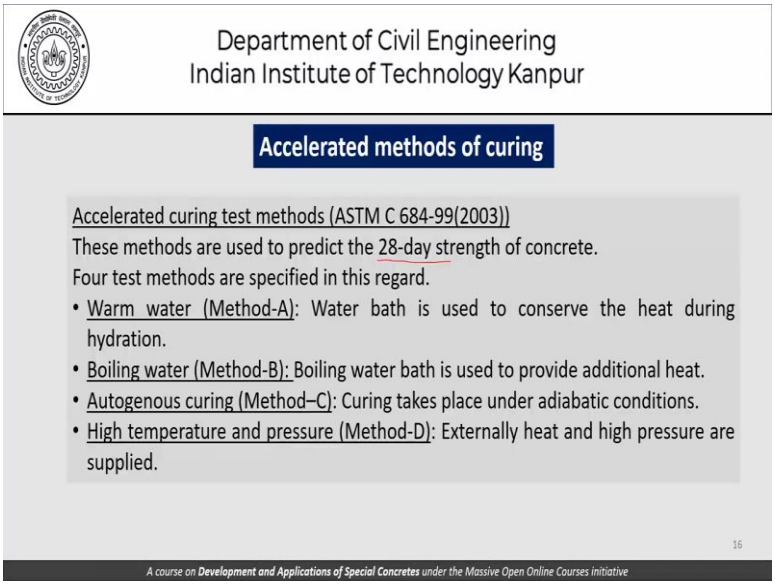

Continuing further there is an ASTM 684-99 2003 there are methods which are used for predicting the 28-day strength. Now these methods have a slightly different approach there are four methods in this regard warm method a warm water method is water bath is used to conserve the heat during hydration. In the boiling water method, a boiling water bath is used to provide additional heat. And auto generous curing method is one where curing takes place under adiabatic conditions.

And a higher temperature and pressure method which is the external heat and high pressure is supplied. So, this is something closer to the autoclaving that we are talking about so these methods have been standardized in ASTM C684 and are used for predicting the 28 days strength. The prediction of 28 days strength is important at times when we cannot wait for 28 days or we do not want to wait for 28 days to know this strength.

We would like to carry out a standard test and try to have a better estimate of the 28 days strength with some other methods and that is where methods such as this would come handy, I am leaving it to you as an assignment to read a little bit more about these methods and see what is the kind of accuracy when we are talking about the prediction of the 28-day strength.

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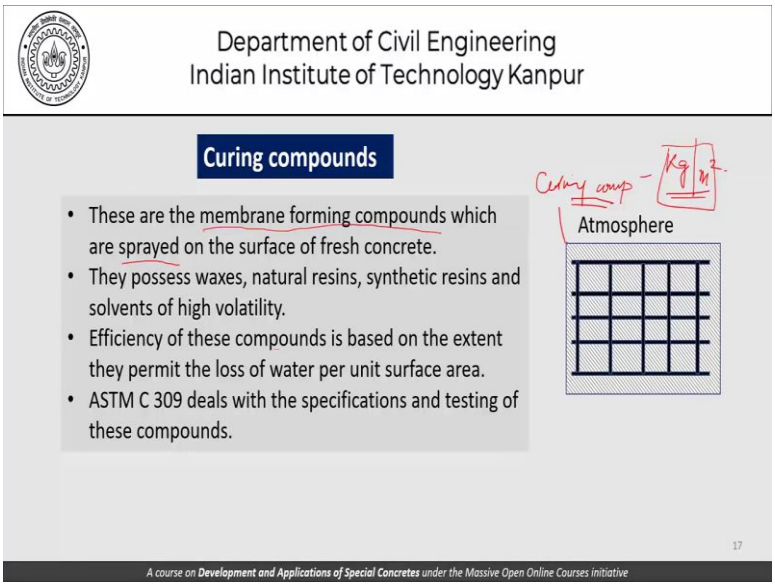

Lastly there are curing compounds, now curing compounds are slightly different from the sheets that we apply. In this case we use membrane forming compounds which are sprayed on the surface of fresh concrete. Now what these compounds do is to really block the surface holes of concrete and prevent any water from the concrete to escape into the atmosphere

through those holes. Now they possess these curing compounds they possess waxes natural resins synthetic resins and solvents of high volatility.

And efficiency of these compounds is based on the extent they permit the loss of water per unit surface areas. Of course, here what will happen is that if we have a concrete surface the way it is shown here on the top you want to apply a curing compound. So, the effectiveness of this curing compound here would depend on how much curing compound in terms of kilograms is applied per square meter of the concrete surface.

If you apply more of curing compound the better it is, very minimal curing compound may not be very effective. Of course, increasing the curing compound beyond an extent will also not help so we have to understand that there will be a critical value beyond which increasing this kgs per square meter spread of curing compounds may not help as far as preventing the evaporation is concerned.

But that is something which needs to be determined and has to be done in accordance with the specifications or recommendations or suggestions from the manufacturer of the curing compound. ASTM C309 deals with the specifications and testing of these compounds. You are free and in fact you are encouraged to go to ASTM C309 and read about these curing compounds try to find out a little bit more about commercially available curing compounds.

And see how they have been used where they have been used. I can almost tell you that most of the time curing compounds are most commonly used in pavement construction in places where you do not want to or you cannot do water curing. This is one of the methods that is available.

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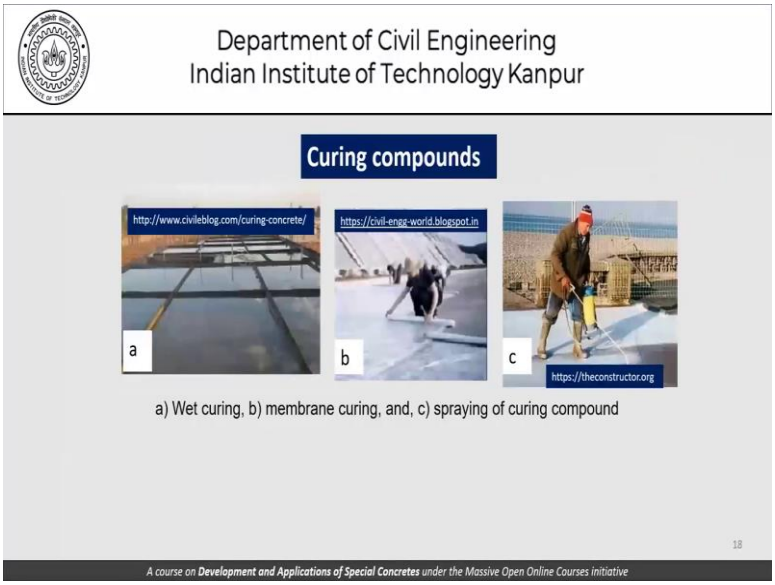

This here is a picture showing wet curing, membrane curing and spraying of curing compound. So, you can see that in wet curing in a horizontal kind of a structure here it could be a pavement. We create these buns and pond this surface with water and this water should be there for the entire duration of curing. So obviously you can see that there will be certain amount of evaporation of this water and it may not be the most favourable method as far as economics is concerned.

From an environmental point of view also there is a lot of water which is required here and that is why we may go for membrane curing or spraying of curing compounds. You can see that membrane curing being done here which means that this sheet that we talked about is being spread on the concrete surface here by this operator. Similarly, this operator here is spraying the curing compound on the surface of concrete.

Now as far as membrane curing is concerned and the spraying of curing compound is concerned there is an element of timing which is involved. How much time should have elapsed before operators can walk around on this concrete surface without damaging it and still apply either it is the membrane that is the polythene sheet or whatever sheet that you are using or apply the curing compound.

So, this is something which we need to be especially worried about when we are trying to use these methods when it comes to the curing compound you can see the discussion that we just had about the kgs per square meter that is the amount of curing compounds being spread on

the surface of concrete that is a relevant parameter here. Similarly, here a relevant parameter could be the thickness of the sheet.

Because if the sheet is too thick it will become very heavy more expensive, if it is too thin it will be damaged and so on. So, these things are more easily told in a lecture but when it comes to the actual practice things a lot more involved and I would encourage you to try to look at the details of the sheets that are available for membrane curing or the kind of curing compounds that are available and also their costs.

Because at the end of it the cost is a very important factor in determining which of the methods will be used for curing.

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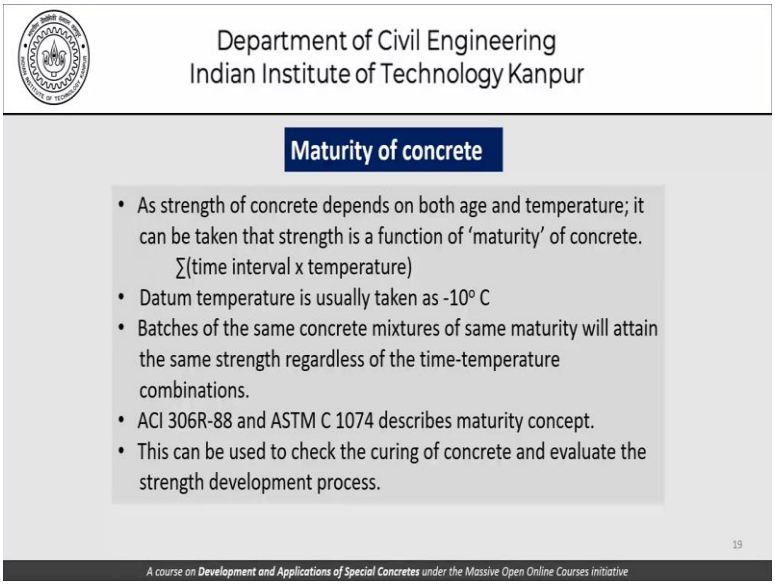

Now before we close the lecture, I just like to introduce to you a concept which is maturity now as the strength of concrete depends on both age and temperature of concrete it has been found that the strength is a function of what is called maturity which is nothing but the sum of the product of time interval and temperature. The datum temperature is usually taken as -10 this is something which we will come back and revisit in another lecture later on. The idea being that batches of the same concrete mixtures of same maturity will attain the same strength regardless of the time temperature combinations.

ACI 306 and ASTM1074 describe and discuss this concept of maturity a little more and this can be used to check the curing of concrete and evaluate the strength development process. So here is the method the maturity method which helps you engineer your time temperature

combinations in order that a certain strength is reached. There are limitations to it there is a detail in which how this calculation is carried out that is something which will touch upon a little bit later sometime.

For the time being I am leaving it to you as an assignment and a food for thought you can kind of think about it.

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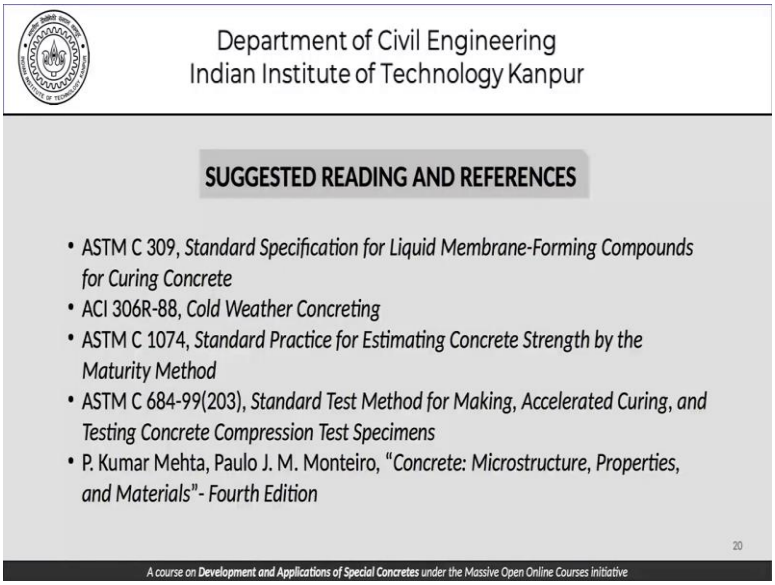

And with that this slide here shows some of the reading that you can do and be more educated.

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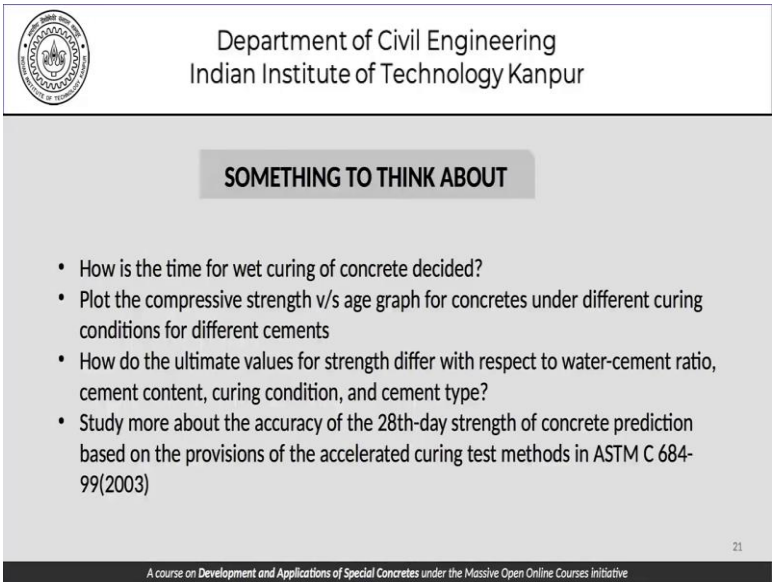

And these are some of the questions which I have said in the class today in the discussion that we had. And some other things which I would like you to answer for yourself.

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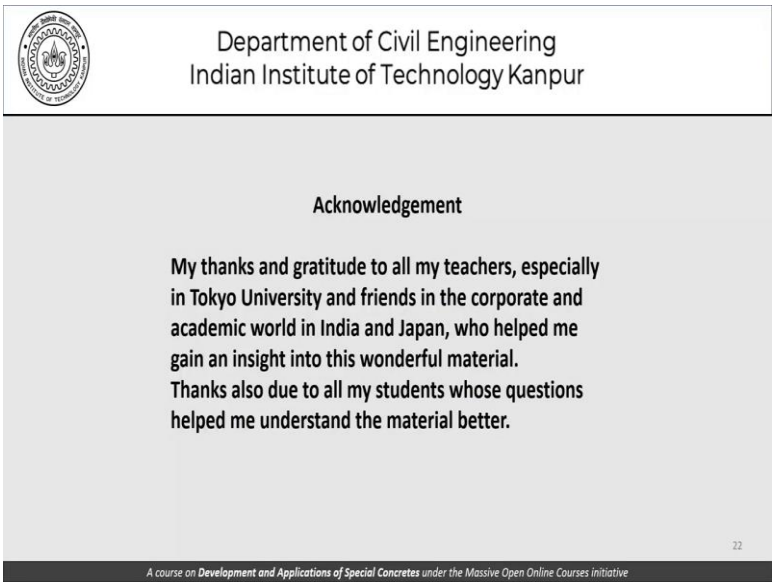

And with that my gratitude to my teachers and my students and friends, thank you all once again and I look forward to continuing this discussion with you on special topics in concrete and development and applications of special concretes bye, bye.