Development and Applications of Special Concretes
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Lecture 14
Special Topics: Heat of Hydration of Cement and Thermal Stresses

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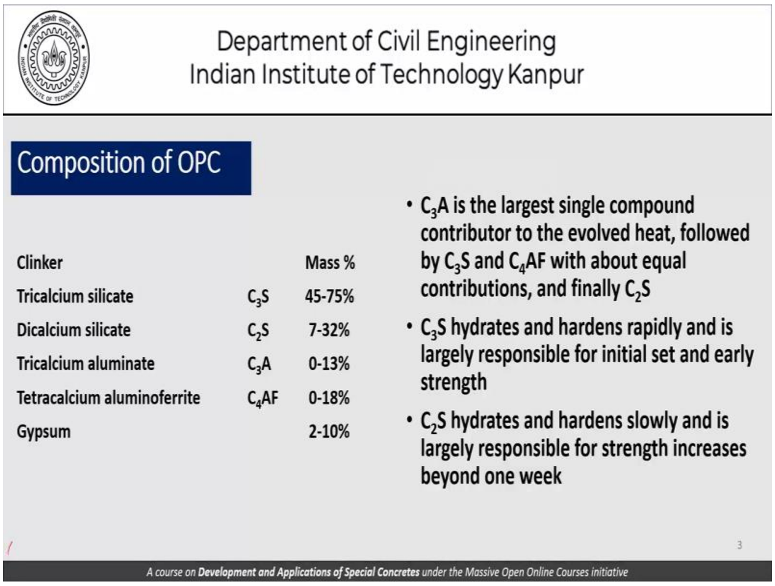

So, as we begin the discussion on heat of hydration the first thing that comes to mind is the composition of cement. Now we know that as far as clinker is concerned in ordinary Portland cement it consists of dry calcium silicate C_3S, C_2S the dicalcium silicate C_3A and primarily C_4AF and the mass composition in terms of these 4 principal components is given here of course gypsum also contributes about 2 to 5% or 7% of the cement mass.

Now from a heat of hydration point of view C_3A is the largest single compound contributor to the evolved heat followed by C_3S and C_4AF with about equal contributions and finally C_2S. C_3S hydrates and hardens rapidly and is largely responsible for the initial set and early strength. C_2S on the other hand hardens slowly and is largely responsible for the strength increase beyond one week.

Now these are some things which we know from our background in cement and hydration of cement.

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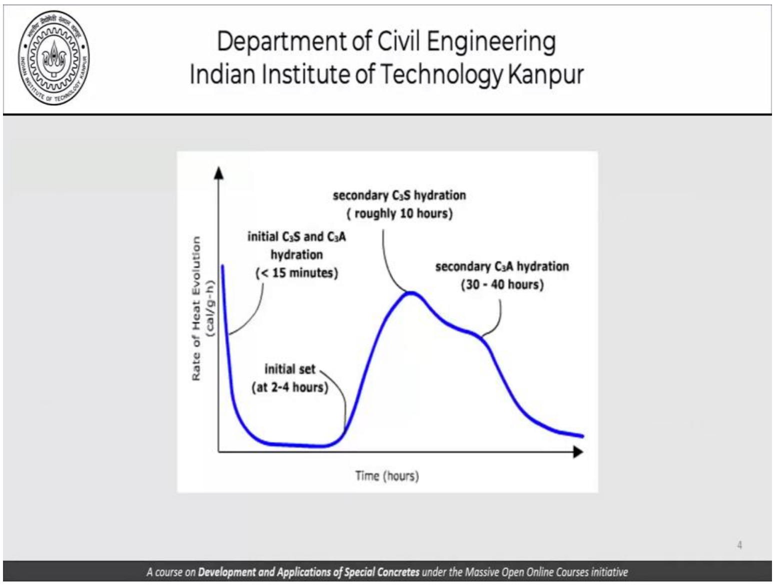

Moving forward this picture here shows the rate of heat evolution over a period of time after the cement has been brought in contact with water. So, there is a rapid number here there is a large number here which goes down as a matter-of-fact initial set sets in somewhere here this part is accompanied by the initial C_3S and C_3A hydration and lasts for about 15-20 minutes. Then we have another burst of heat evolution which is coming primarily from the secondary C_3S hydration and then we have the secondary C_3A hydration which goes on for a much longer period of time.

Now this discussion is very relevant from the point of view of the total heat evolved during hydration of cement and how it is managed as far as concrete construction is concerned.

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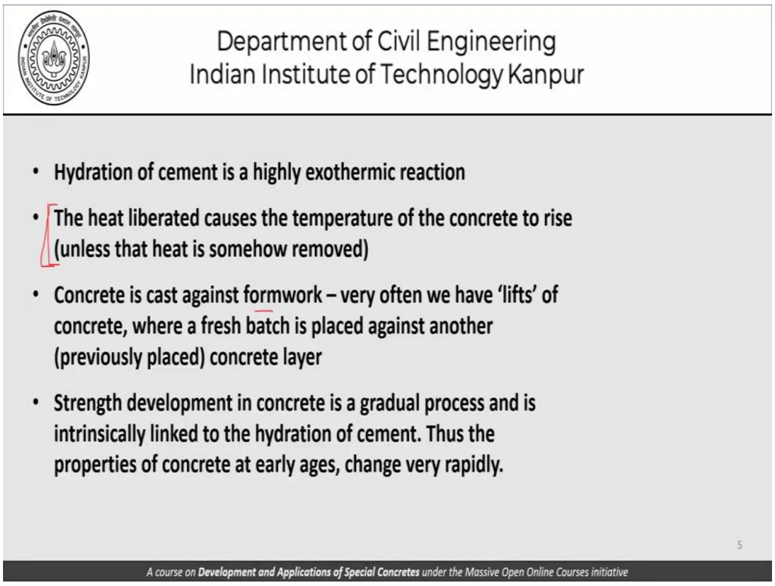

Let us recall some fundamentals hydration of cement is a highly exothermic reaction the heat liberated causes the temperature of the concrete to rise unless the heat is somehow removed and this is the crux of our discussion today. This is something which we will examine in great detail in the different slide's subsequent slides of today's lecture concrete is cast against form work very often we have lifts of concrete where a fresh batch is placed against another previously placed concrete layer.

The strength development in concrete is a gradual process and is intrinsically linked to the hydration of cement and thus the properties of concrete at early ages change very rapidly.

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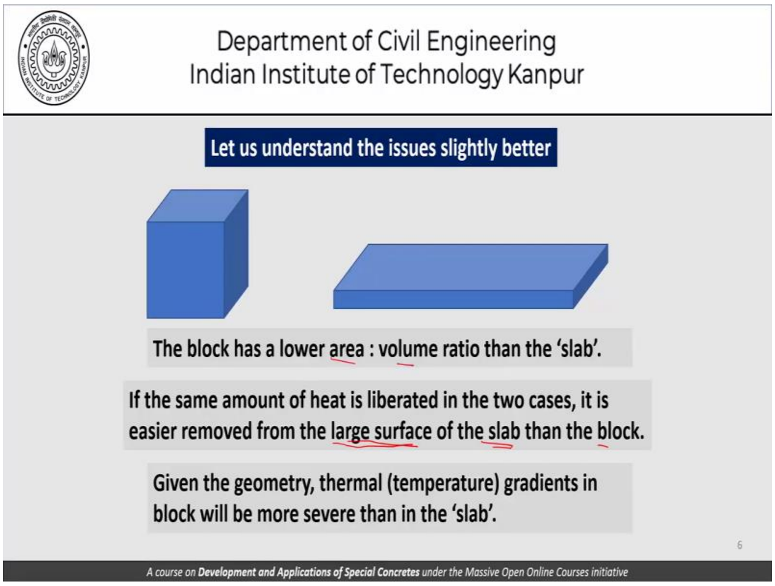

So now in this context let us try to understand a few things slightly better and from a different perspective. Let us talk of this block it's a cubicle block, if that is cast compared to that if the same volume is cast as a slab. What is the difference between these 2? The block has a lower area to volume ratio than the slab and that is something which we will see just now. If the same amount of heat is liberated in the 2 cases.

It is easier removed from a cast where we have a large surface area that is in a slab than in this block given the geometry the thermal or temperature gradients in the block will be more severe than in the slab. Now if you are able to understand this intuitively things become a lot easier to follow as we go and make a treatment of this subject in this class.

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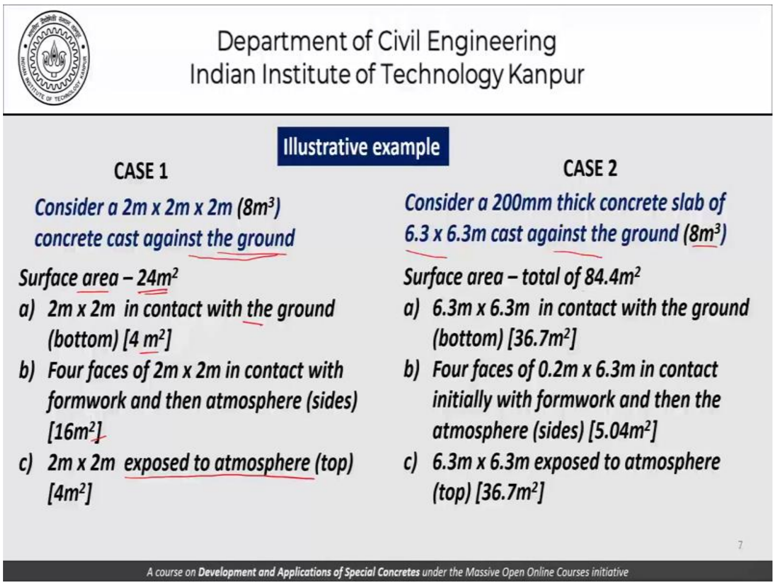

The first case let us consider a 2 meter by 2 meters by 2 meter which is a total of 8 cubic meter of concrete cast against the ground this is very important cast against the ground. Now if this was being cast then the total surface area involved will be 24 square meters, 2x2 which is four square meters is in contact with the ground 4 faces of 2 meters and 2 meters which is a total of 16 square meters is in contact with the formwork initially and then with the atmosphere after the formwork has been removed.

And then another 2x2 that's 4 square meters is exposed to the atmosphere. Some of this discussion is also relevant from the point of view of hot weather and cold weather concreting that is where in those discussions also we had seen the importance of this exposed to atmosphere concrete surface which has a major role to play when it comes to the evaporation of concrete is concerned.

Of course, here we are not concerned about the evaporation we are concerned about the total heat generated and its dissipation and management. Now let us consider a second case that of a 200 mm thick concrete slab being cast measuring 6.3x 6.3 meters again against the ground here also. The dimensions have been so chosen that the total volume of concrete is still 8 cubic meters.

And here we see that the total surface area is 84.4 square meters that is 6.3x6.3 in contact with the ground that is about 36.7 four faces which are quite small 0.2 meters x 6.3 in contact initially with the formwork and then with the atmosphere giving your total surface area of about 5.04

square meters and 6.3x6.3 exposed to the atmosphere which is at the top this is the bottom and this is the top both measuring 36.7 square meters.

Now as far as a block is concerned the distance from the centre to the exposed surface if it was a 2 meters block will be one meter. So, the core will be at least one meter away from the surface whereas in the case of a concrete slab which is 200 mm thick it is something like this. So, the core here which is anywhere here the core part here is only 100 mm or 10 centimetres away from the surface.

So, whether the surface is the atmosphere here or it is the ground surface here. So, this is what we need to bear in mind when we talk of the management of the heat generated within these blocks is concerned that is something which we will discuss a little bit today.

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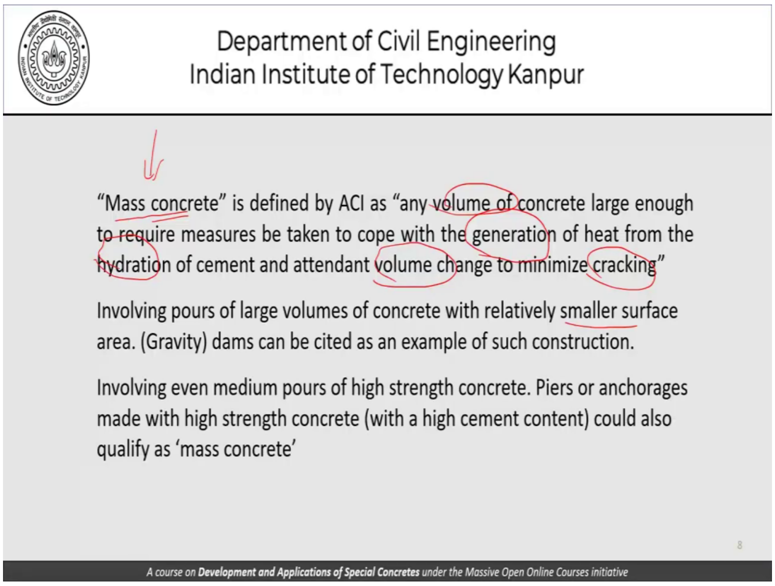

Now this understanding of the heat of hydration and the need to manage it takes us to mass concrete. Now mass concrete is defined by ACI the American Concrete Institute as any volume of concrete large enough to require measures to be taken to cope with the generation of heat from the hydration of cement and the attendant volume change to minimize cracking. So, there are lots of keywords here, one is generation of heat hydration of cement volume changes and cracking.

And of course, the volume of concrete such that all this becomes necessary, is called mass concrete. Now where do we see such concretes, they usually involve large volumes of concrete being poured with relatively small surface areas, gravity dams can easily be cited as an example of such construction. Of course, now even medium sized pores of high strength concrete would qualify for such treatment.

Piers and anchorages made with such concrete with a high cement content could also qualify for mass concrete because the amount of heat generated in this kind of constructions is also such that it requires treatment. It requires management of that heat in order to minimize the risk of cracking.

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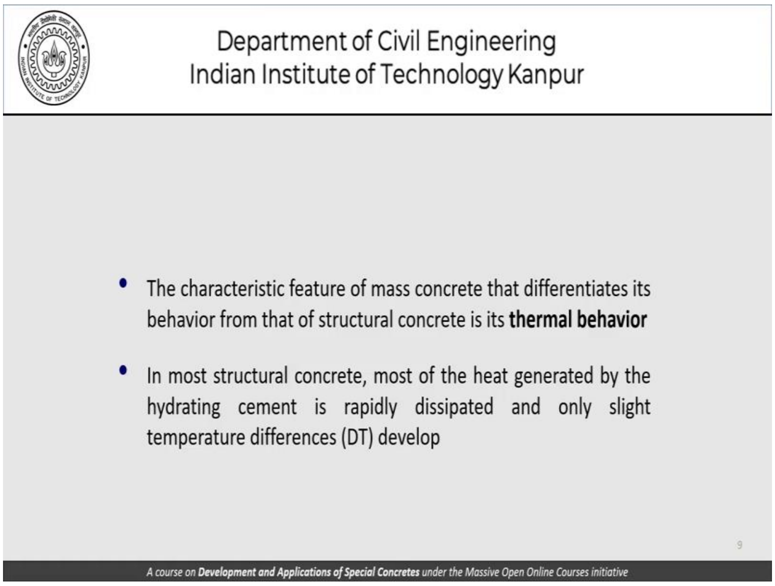

Now what is the difference between structural concrete, the normal structural concrete and the mass concrete. The characteristic feature of mass concrete that differentiates it from the behaviour of structural concrete is its thermal behaviour. In most structural concrete most of the heat generated by the hydration of cement is rapidly dissipated. And only slight temperature differences develop.

What are the temperature differences we are talking about we are talking about the difference in temperature at the core of the concrete and the surface? So, the temperature at the core and temperature at the surface so this difference T_c-T_s is reasonably small for most structural concretes because the heat that is generated here in this block or this member is quickly dissipated.

But that is not the case in the mass concretes where for various reasons this T_c-T_s has significant proportion and needs to be consciously taken care of.

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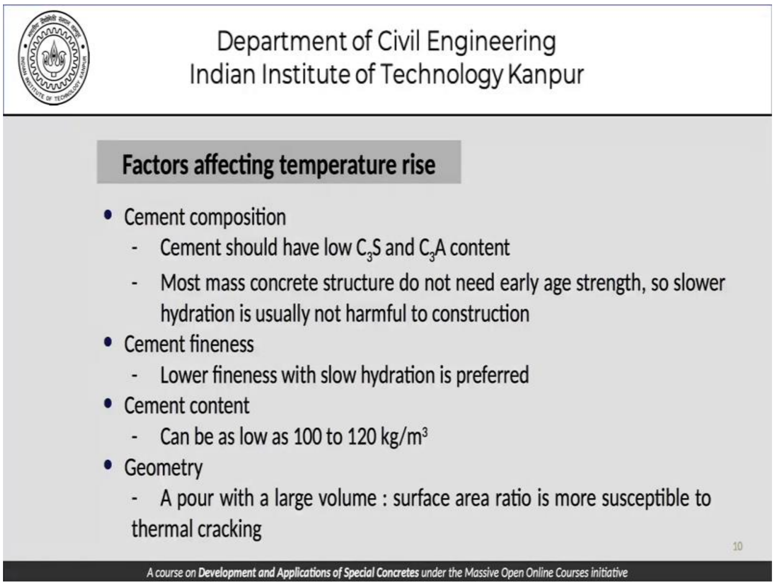

Once we agree that after we place the concrete there will be a temperature rise what are the factors that affect this temperature rise? One factor is cementing composition and the cement should have low C_3S and C_3A content and since in mass concrete most of the times we do not need early age strength we can make do or we can live with slower hydration in the beginning and that does not harm our construction.

The fineness of cement is another part lower fineness with lower or slower heat of hydration slower hydration to begin with that would be preferred. Content of cement is another factor it should be as low as possibly in the neighbourhood of 100 to 120, 130 kgs per cubic meter. The geometry of the pore is a very important factor when it comes to temperature rise. A pore with a large volume to surface area ratio is more susceptible to thermal cracking that is it will have a larger amount of heat generated which will be difficult to manage.

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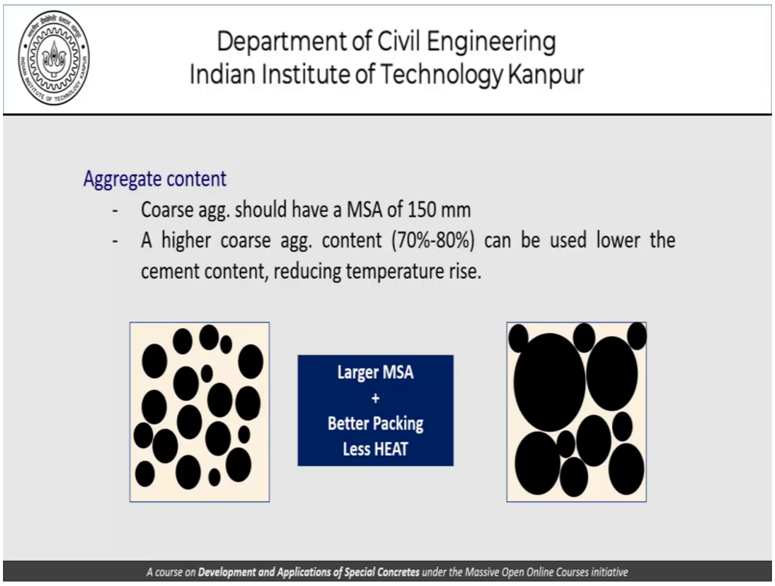

Aggregate content in the concrete obviously is yet another factor the coarse aggregate should have a minimum size of about 150 mm if it can be managed. A higher coarse aggregate content is another important requirement which will help us control the amount of temperature rise that we have if we can get to about 70 to 80%. That will be very useful because that will reduce the cement content and therefore the temperature rise.

So, this picture here in fact tells you a graphic representation of that large aggregates here with a proper distribution of smaller aggregates that. It is not all large aggregates but we need to have better packing that is a better distribution a better size distribution or a particle size distribution and aggregates with the large maximum size of the aggregate that will help us get less heat in this concrete.

Because on the one hand it reduces the amount of cement consumption and also contributes to the total amount of heat being evolved to be reduced.

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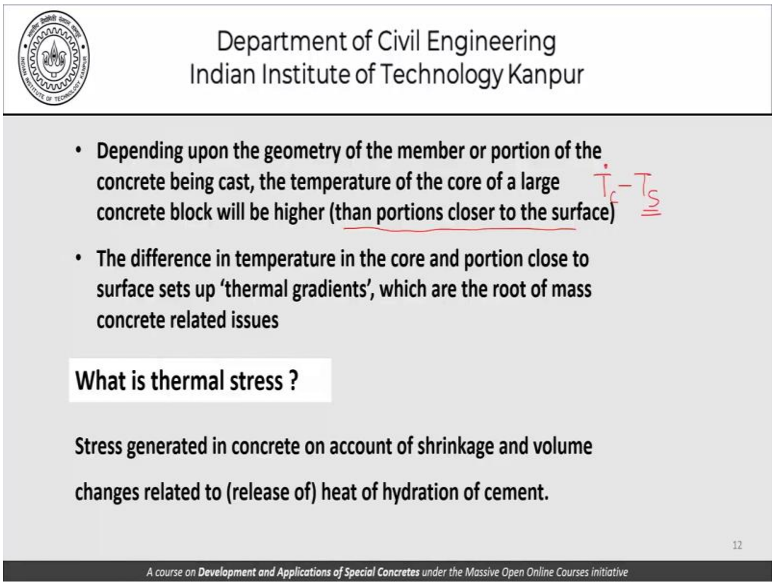

Now depending upon the geometry of the member or the portion of the concrete being cast. The temperature of the core of a large concrete block will be higher than portions close to the surface. This is what I was telling you earlier T_c-T_s this T_s is the temperature at the surface and T_c is the temperature at the core of the concrete block. And the difference in temperatures in the core and the portions close to the surface set sub thermal gradients which is at the root of the mass concrete related issues.

What is thermal stress? This is something which we hear all the time. Stresses generated in concrete on account of shrinkage and volume changes due to or related to the release of the heat of hydration of cement. This is the simple definition of thermal stress. Stresses in concrete which are generated on account of shrinkage and volume change as a result of the heat of hydration of cement.

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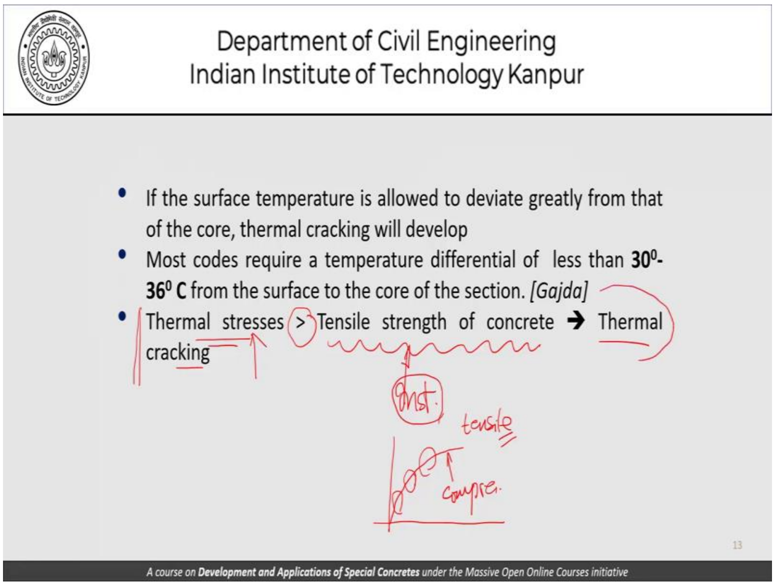

Now reiterating this fact in a different way if the surface temperature that is T_s is allowed to deviate greatly from that of the core i.e., T_c thermal cracking is more likely to happen. In fact, most codes require the temperature differential to be less than 30 to 35, 36 degrees from the surface to the core of the section. yet another thing which is very important for us to understand is if we have thermal stresses which are greater than the instantaneous tensile strength of concrete, we are likely to get cracking.

So, this tensile strength is the instantaneous tensile strength it is not the final tensile strength of concrete. Please remember that as far as the strength development in concrete is concerned it starts and it goes on like this. So as this strength development is happening over a period of time so is the tensile strength also developing. Typically, we draw this curve for compressive strength development what we are interested here as far as cracking is concerned as far as thermal stresses are concerned.

We are concerned about the tensile strength. And the tensile strength also develops with time and if the stresses at any point in time exceed the tensile strength at that time obviously, we have a risk of thermal cracking. So that is what we are talking about here thermal cracking is likely to develop or will develop if the surface temperature T_s is far in excess of that at the core that is. This is what is going to cause thermal gradients and finally there will be cracking as we will see subsequently.

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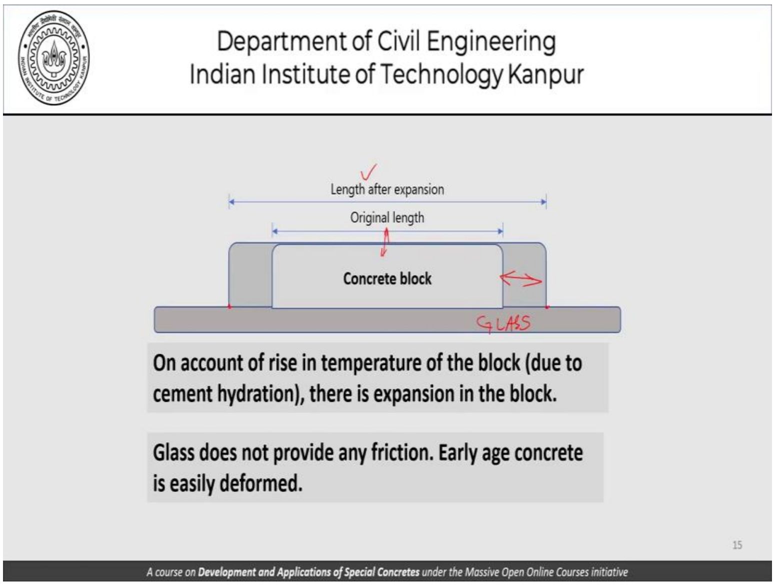

Let me explain this in a very simple way it is almost simplistic try to take it with a pinch of salt we cast a concrete block on a glass plate with this as the original length. Why glass plate? We will see the minute. Now as hydration goes on and heat is evolved some temperature rise will happen and concrete block will seek to expand. Let us not bother so much about the expansion in this direction, we are more concerned about the expansion in this direction.

So, this here shows the length after expansion. Now the class plate comes in because this does not offer any resistance to expansion. So, this smoothly slides over and reaches this point here at the end of the expansion process. On account of temperature rise of the block due to hydration there is expansion in the block. And glass does not provide any friction early age concrete can be easily deformed. So, from this original length it goes to this expansion or expanded length.

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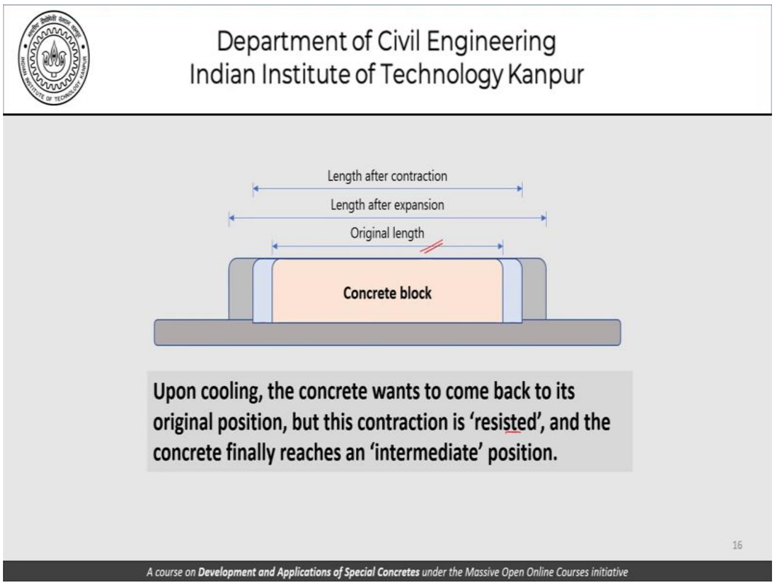

Now what happens after the temperature cools the concrete cools the block wants to return to its original position. Now that is going to be resisted because the concrete is no longer as easy to deform now. Upon cooling the concrete wants to come back to its original position but this contraction is resisted and the concrete finally manages to reach only an intermediate position. So, this is the position that we are showing here this is the intermediate position. Now what does this intermediate position tell us?

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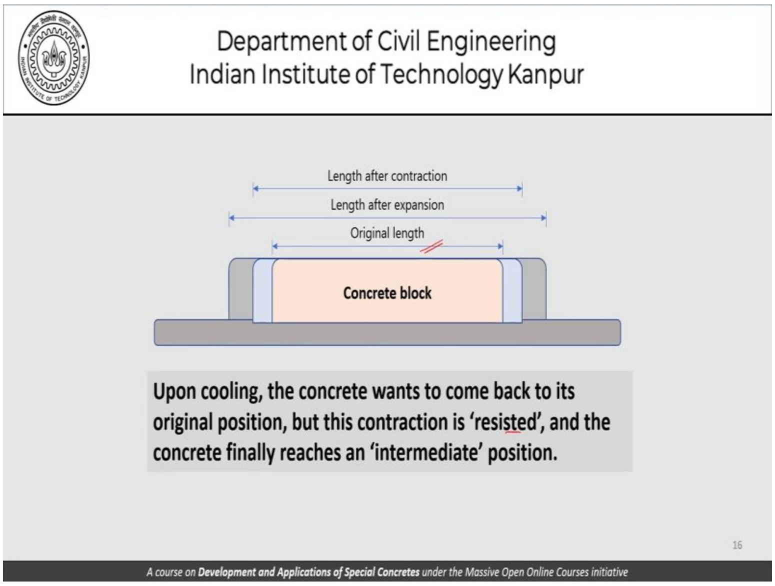

Basically, this is my original length and this is my final length that is what we call the intermediate length because the expanded length was somewhere here. Thus, the concrete would be under a virtual tensile strain. Now this virtual tensile strain is this amount of tensile strain. So, the concrete would believe or would think that instead of being here this is the place where it is and this amount of deformation or strain is some kind of a stress which is acting on it.

This is my tensile strain you can call it a virtual tensile strain but that is what the concrete will feel. So, the concrete is under a virtual tensile strain which can also be looked upon as caused by a virtual tensile stress which is related to the strain and the modulus of the elasticity of concrete at that point in time.

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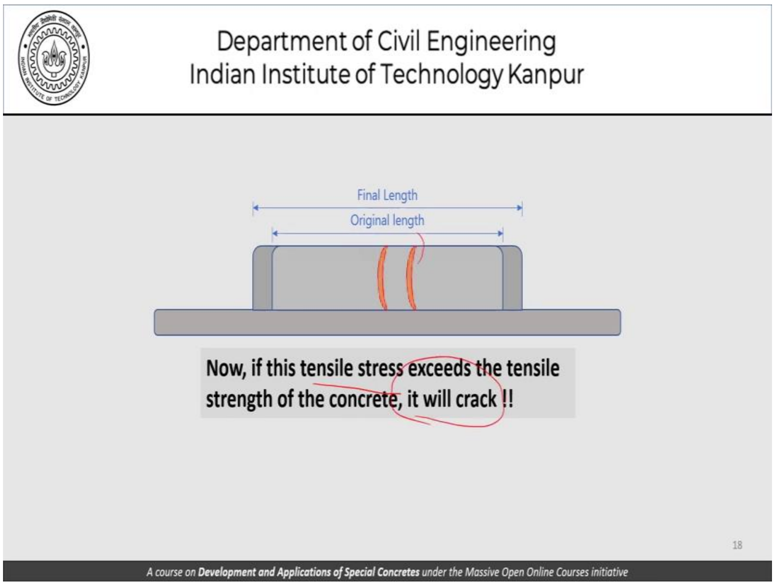

Moving forward if this tensile stress exceeds the tensile strength of concrete at that time it will crack and we will have thermal cracks induced in concrete the way they are shown.

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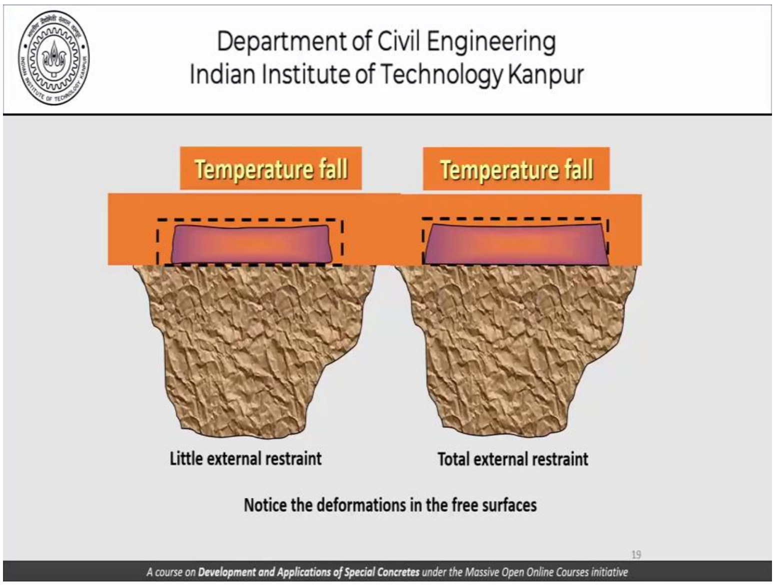

Now what happens when the concrete is cast against a real surface here is the ground against which it is being cast. Go back and think about the picture which I showed you of the block being cast or the slab being cast against the ground. There are pictures we have seen of concrete being cast against the ground when we are talking about hot weather concrete cold weather concrete.

We talked about the treatment of the ground surface before the concrete was placed. So now under those kinds of conditions there is a situation that the ground may offer little external restraint to deformation or total external restraint to deformation. So, when the temperature falls or the concrete cools in this case the portion which is in contact with the ground simply cannot move because the restraint is total.

And the top here will deform the way it is which means that even this direction here there is some amount of differential that builds up and the concrete takes this very difficult kind of a shape. It is not the rectangular block that we cast against the glass plate and try to idealize it. As against that if there was little external restraint this block will also move a little bit but surely unless it is zero the way I showed it in the class plate.

There will be a difference in the contractions which is observed at the top and that which is observed at the bottom which is against the ground. Of course, concrete need not be cast against the ground all the time concrete can be cast against the concrete surface itself. And that will have a certain temperature. So that kind of a discussion is something which you must keep in mind when we try to do an actual plan of concreting where several lifts of concrete have to be cast.

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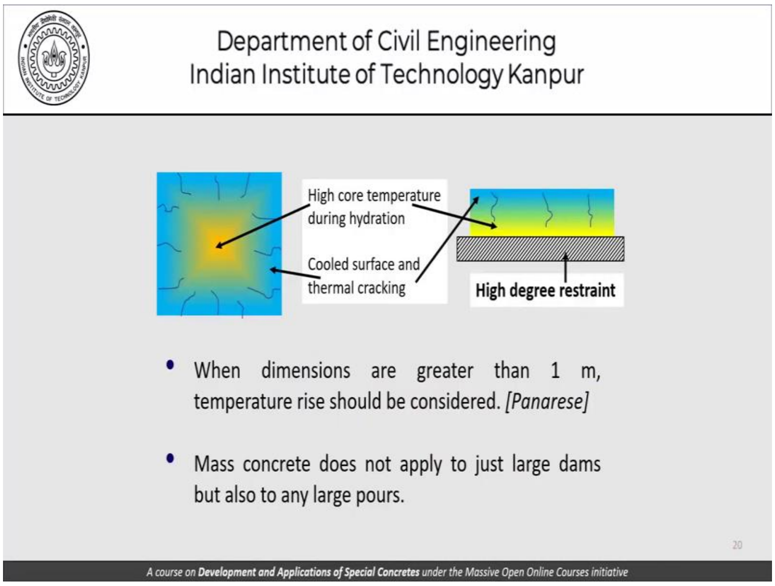

This again is just a review this is the high core temperature during hydration cooled surface and thermal cracking which we have here. Because the surface here has cooled this has not cooled yet. It is much easier for the heat to dissipate from here high degree of restrained that means the concrete does not move from here. Here we have some movement it is not shown here but you understand what we are trying to do.

This picture here shows the heat is still very much there here we have cooled concrete so again there is a situation of thermal gradients having developed. What literature suggests is that when dimensions are greater than one-meter temperature rise should be considered. Calculations need to be carried out to ensure that the thermal stresses will be under control and there will be no cracking on account of these thermal stresses.

Mass concrete does not apply to just dams but also any large pore. We saw that in the previous slide.

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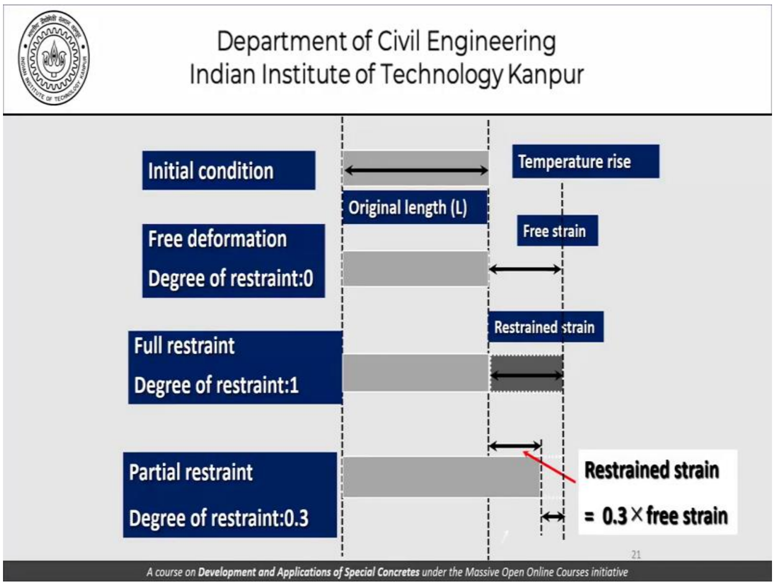

And here is a final summary of what we just talked about the initial condition is this that is my original length l. After the temperature rise the concrete moves somewhere here. Now if it was zero restrained the concrete would come back to a position somewhere here. If the restrain was one that was complete then the concrete will remain here and this will be the restraining strain that the concrete will feel.

It wants to come back here it is been held at this point and therefore this entire thing is the restraining strain that the concrete will feel. If it is a partial restraint let us say 0.3 or something like that then this much deformation will happen which is 0.3 times the free strain and this is the amount of restrained strain that the concrete will feel. So, this is the schematic simplified representation of volume changes that are important on account of the heat of hydration of cement.

So that is what we talked about heat of hydration volume changes stresses and cracking that is the crux of the discussion today. hat is heat of hydration and related problems.

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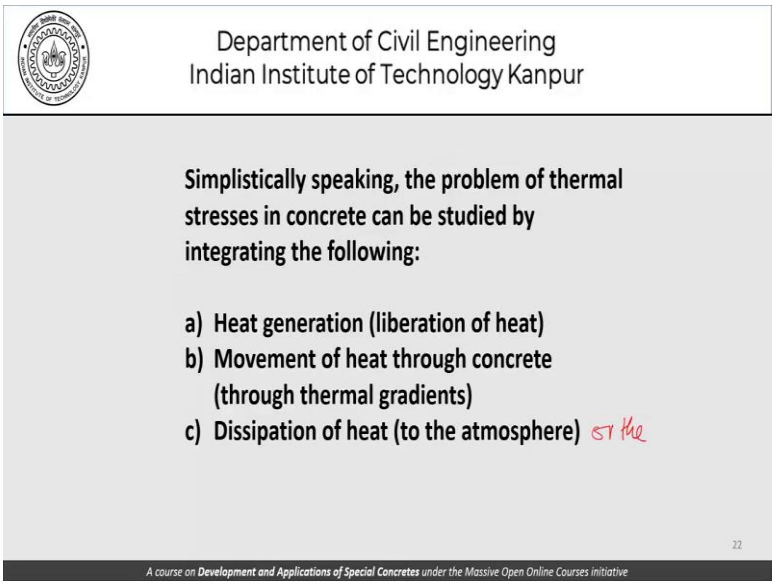

Simplistically speaking the problem of thermal stresses and concrete can be studied by integrating the following. There are 3 processes involved heat generation that is the liberation of heat, movement of heat through concrete through thermal gradients and finally dissipation of heat to the atmosphere or to the ground.

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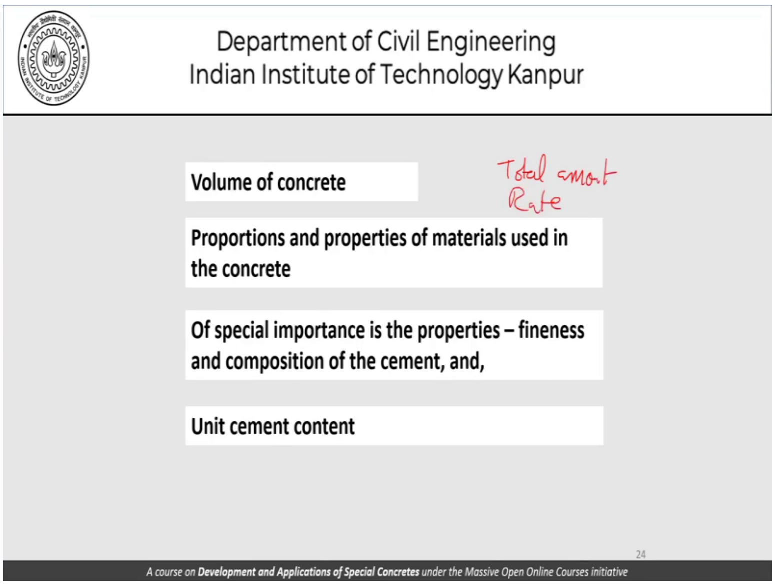

Coming to the first part of it that is heat generated one factor is the volume of concrete. The next is proportions and properties of materials used in the concrete it is not only cement but cement is the principal player of special importance is the properties that is fineness and composition of the cement. The amount of cement of course and that is what it is. Unit cement content these are the principal players that determine the amount of heat that is going to be generated.

Of course, it is not only the total heat that is generated but also the rate at which it is generated both these things are very important the total amount and the rate of generation. So, this rate of generation. And as a matter of fact, is the one that is determined by the composition and fineness of the cement if it has more C_3A the rate of generation is rapid in the initial part compared to some cement which does not have so much C_3A.

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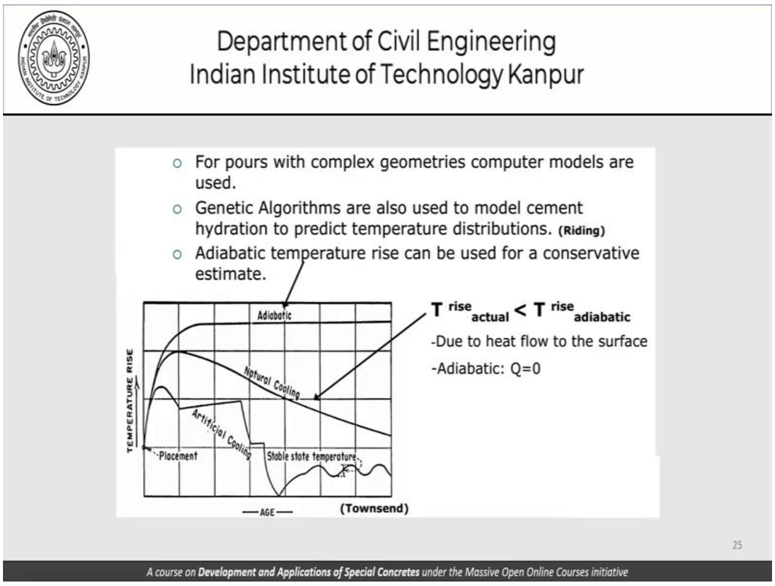

Here is an example of how we handle this situation for pores with complex geometries computer models need to be used genetic algorithms or any such modern tools can be used to model cement hydration to predict. The temperature distributions, adiabatic temperature rise can be used as a conservative estimate to check or determine for design purposes how much is the likely temperature rise?

So, if we have temperature rise here and the age that is what we are trying to plot adiabatic values are like this natural cooling goes here artificial cooling. If we do something this is how it goes and this is the place where the whole thing starts this is the temperature at the point of placement. And this is a very, very important parameter that governs our thought process as we try to understand this whole idea of temperature rise.

The actual rise in temperature here will always be less than the rise that we determine from the adiabatic conditions. But this discussion here when we are talking of adiabatic rise it is not for cement it is for the concrete. That means if we were to do mass concrete kind of construction and we want to do this exercise as to how much is the likely temperature rise. Then for a particular mix proportion we need to carry out this adiabatic temperature rise test and find out what is the actual value.

And then try to figure out how much will be the value under natural conditions or the kind of actual pouring conditions that we use.

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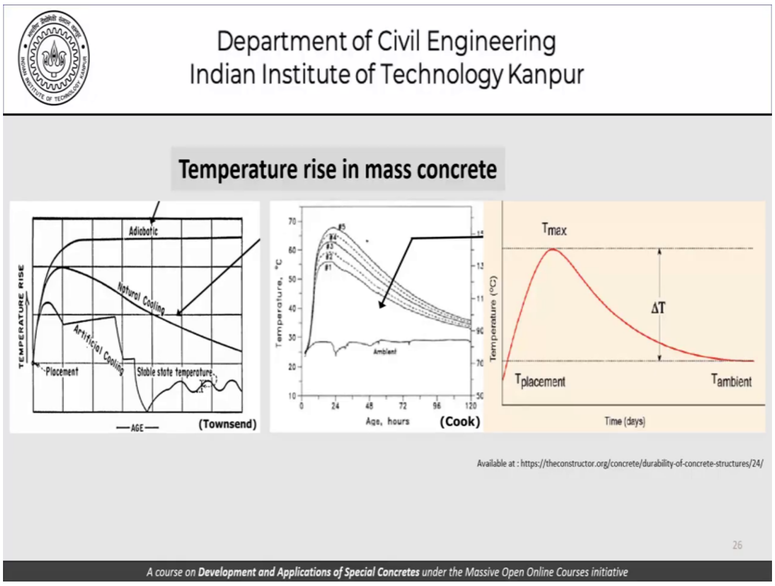

This is another representation this is the same picture that we saw just now. These are for different mixes and this is how we try to model this graph temperature in degree centigrade time in days goes back to $T_{ambient}$ it starts with $T_{placement}$ and this is the ΔT which we talk about so there are 2 parameters here. One is the maximum temperature that comes around and the time at which this happens.

Both these parameters are equally important when it comes to management of this heat of hydration issue in mass concretes whether it is dams or high strength concrete or any other.

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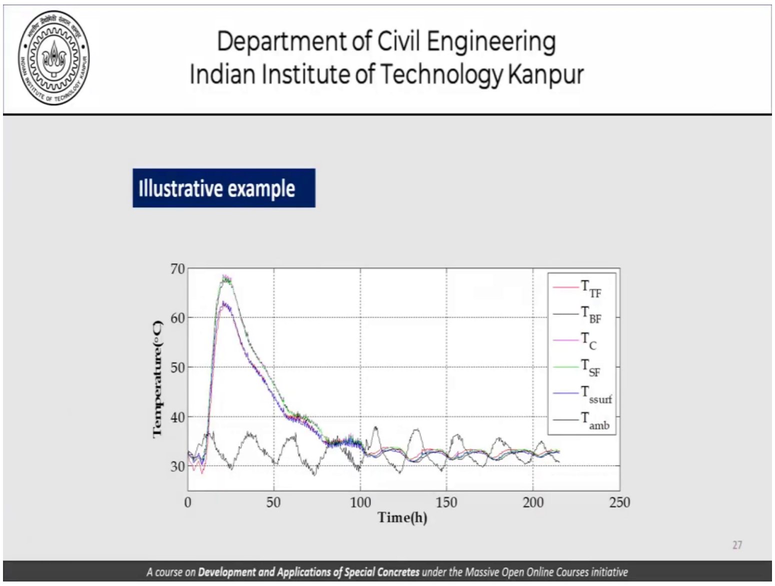

Here are some actual values where these are the temperatures which have been recorded at different parts of a concrete block cast in the lab. The core the surface the bottom and so on so it started here this is the ambient temperature and it went all the way up to 67, 68 degrees centigrade. So, if we have this point here, we have this point here this is my ΔT this is the rise in temperature on account of hydration and this peak occurred here which is somewhere around 20 to 25 hours

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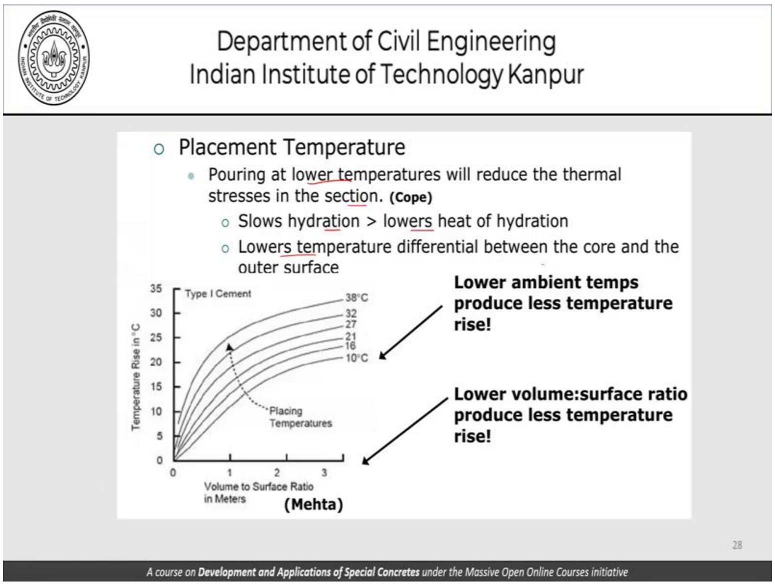

I mentioned to you the placement temperature is a very important thing. Pouring at lower temperatures lowers the thermal stresses in the section slope hydration lowers the heat of hydration. Lower temperature differentials between the core and the outer surface lower the heat of hydration. Take off this entire explanation for this slide and start once again. I told you that placement temperature is a very important parameter.

The pouring at lower temperatures will reduce the thermal stresses in the section. Slows hydration lowers. Heat of hydration lowers the temperature differential between the core and the outer surface. So, if we see from this graph lower ambient temperatures produce less temperature rise. These are the ambient temperatures that we are talking about and on the x axis we see the volume to surface ratio in meters.

See the volume will be in cubic meters the surface area is in square meters and therefore we are talking of volume to surface ratio in meters. If that value increases the temperature rise increases. So, the lower volume to surface area ratios produces less temperature rise. So as far as design of lifts is concerned and that is something which dam engineers always do. As far as the lift design is concerned these are the kind of factors that they play with how much should be the length breadth and height of the lift.

At what rate it should be placed and finally what should be the placement temperature. Lower placement temperatures are always an advantage.

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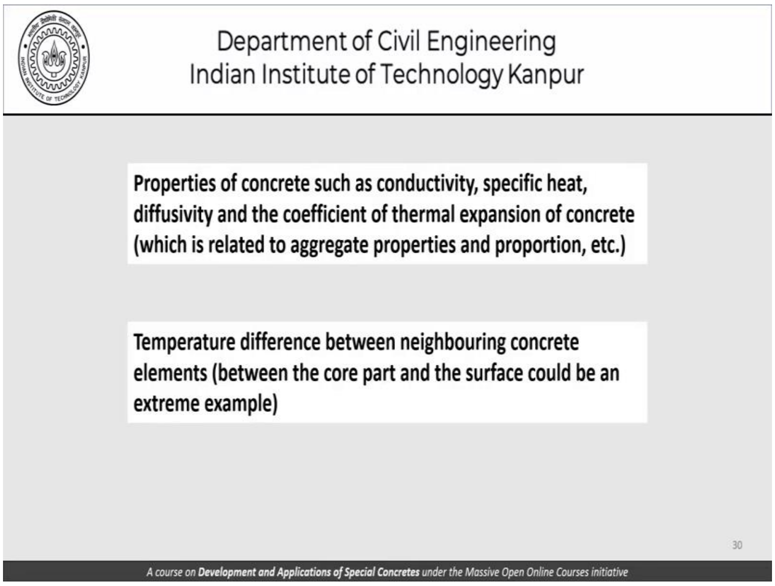

Now let us come to heat movement through the concrete properties of concrete such as conductivity, specific heat diffusivity and the coefficient of thermal expansion of concrete which is related to the aggregate properties. And proportions come into play here when we are trying to determine the movement of heat through the concrete from the core which has high amount of heat been generated temperatures are high.

And the heat is being conducted away towards the surface from where it is being radiated into the atmosphere. The temperature difference between the neighbouring concrete elements between the core part and the surface could be an extreme example. So, this temperature difference drives the amount of heat or the rate at which the heat is being conducted through the concrete.

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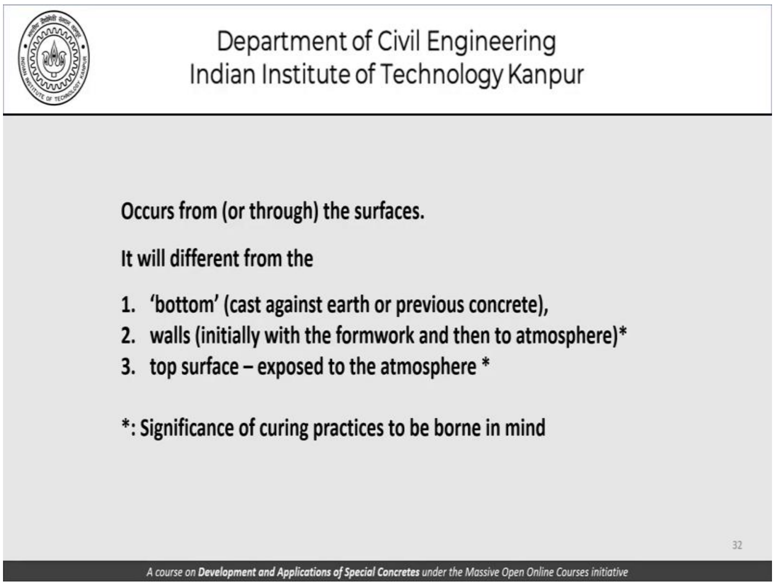

And lastly, we come to the heat removal dissipation of heat that occurs through the surface of concrete and it will be different from the bottom because it is cast against the earth or the previous concrete which has certain properties in terms of its thermal behaviour is concerned. Walls initially with the formwork and then to the atmosphere. So, there is the bottom of the cast there are the walls and then there is the top surface which is exposed to the atmosphere.

Now in both these cases that is the walls and the top surface we need to significantly understand the curing practices. Because curing practices can help us control the temperatures in the walls and in the top surface, they cannot help us much with the bottom temperature but the walls and insides, yes.

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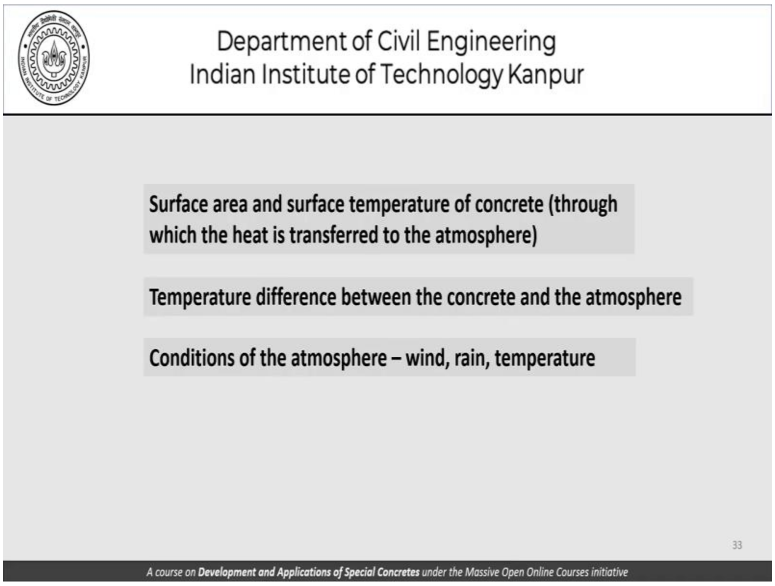

Surface area surface temperature of concrete through which the heat is transmitted or transferred to the atmosphere. The temperature difference between the concrete and the atmosphere. The conditions of the atmosphere that is wind, rain and the temperature. All these things matter when it comes to the radiation or when it comes to the dissipation of heat from the surface.

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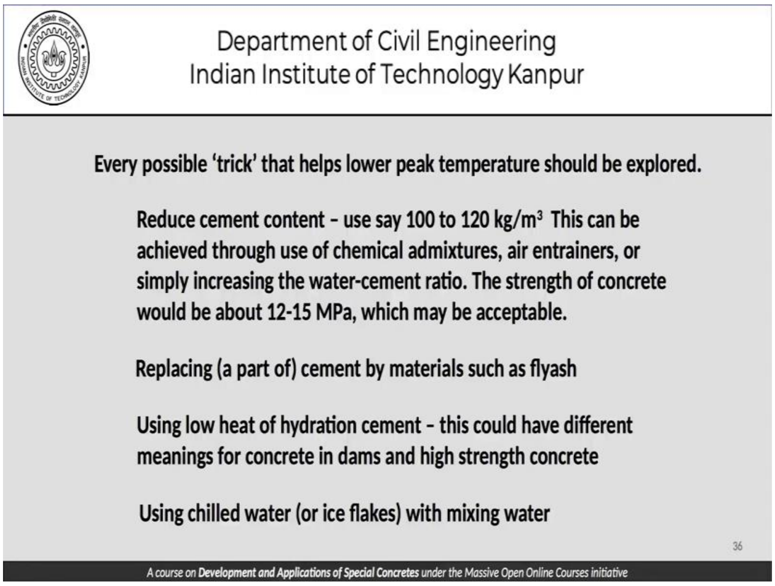

So, having quickly gone through the 3 principal components of the heat of hydration issue that is the heat generated, moved and dissipated. Let us talk quickly of some principles about working with mass concrete or working with concretes which is vulnerable to such treatment which calls for such treatment first thing that comes to mind is materials and proportioning of such concretes.

Every possible trick that helps lower the peak temperatures should be explored and what are some tricks? Reduce the cement content to say 100 to 120 kgs per cubic meter this can be achieved through the use of chemical admixtures air entrainers or by simply lowering the water cement ratio. For most of the mass concrete applications even if the strength of the concrete is about 15 to 17 MPa that would be largely acceptable.

Replace a part of the cement by materials such as fly ash using low heat of hydration cement this could have different meanings for concretes and dams and high strength concretes. Using chilled water with ice flakes as mixing water or with the mixing water to lower the temperature recall that we had prescribed a similar treatment when we were talking of a special condition of placement.

Hot weather and cold weather kind of concrete there also we had suggested that if we want to reduce the temperature of concrete use of chilled water would be one of the things that could be used.

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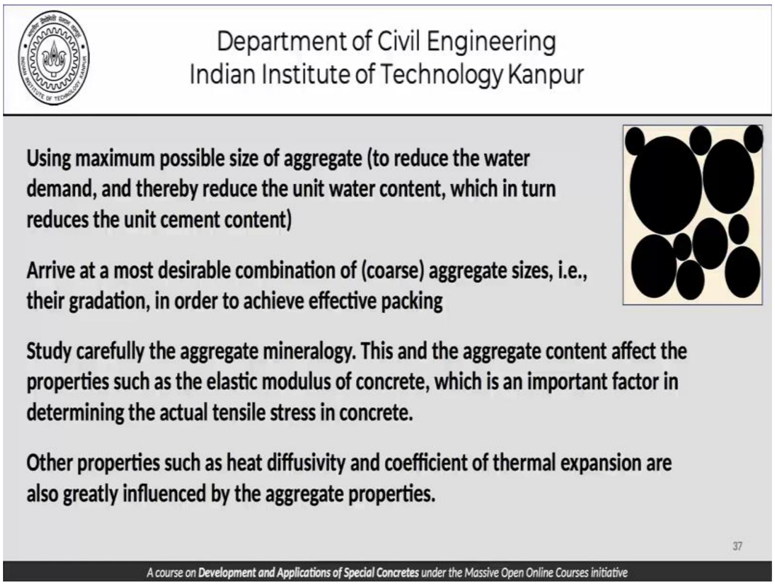

Carefully study the aggregate mineralogy this and the aggregate content we have already seen this picture before affect the properties such as the elastic modulus of concrete which is an important factor when it comes to actually determining the tensile stress in concrete. Use the maximum possible size of the aggregate to reduce the water demand and thereby reduce the unit water content which in turn reduces the unit cement content for a given water cement ratio.

Arrive at a most desirable combination or a particle size distribution their gradation in order to achieve effective packing. These are some of the things or tricks as I call them in the previous slide that need to be used or that can be used in order to reduce the maximum temperature that is achieved during the hydration process. Yet another thing of course is we need to understand properties such as the heat diffusivity and the coefficient of thermal expansion which is also greatly influenced by the aggregate properties.

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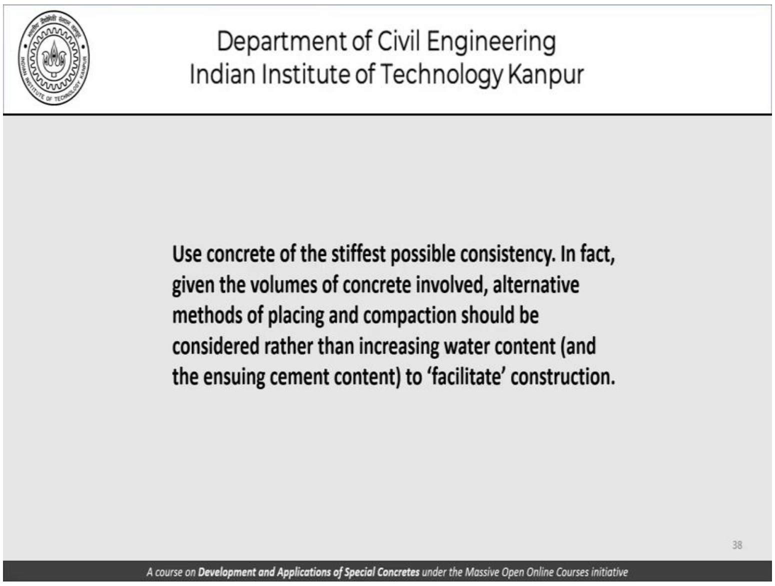

Use concrete of the stiffest possible consistency in fact given the volumes of concrete involved alternative placing methods and compaction should be considered rather than increasing water content and therefore the ensuing cement content to facilitate construction. Now this kind of a thought process is exactly at the bottom of our thinking when we try to develop roller compacted concretes.

We try to use a huge amount of energy to compact the concrete which is not possible perhaps using just internal vibrators or needle vibrators as we normally use them. And therefore, we work with stiff concretes have alternate that is what we are talking about. We use stiff concretes and that is what is being said using stiff concretes will probably call for different methods of placing in compaction.

And that is what needs to be explored and is actually one of the things that we will talk about possibly. In the next discussion when we talk about roller compacted concretes.

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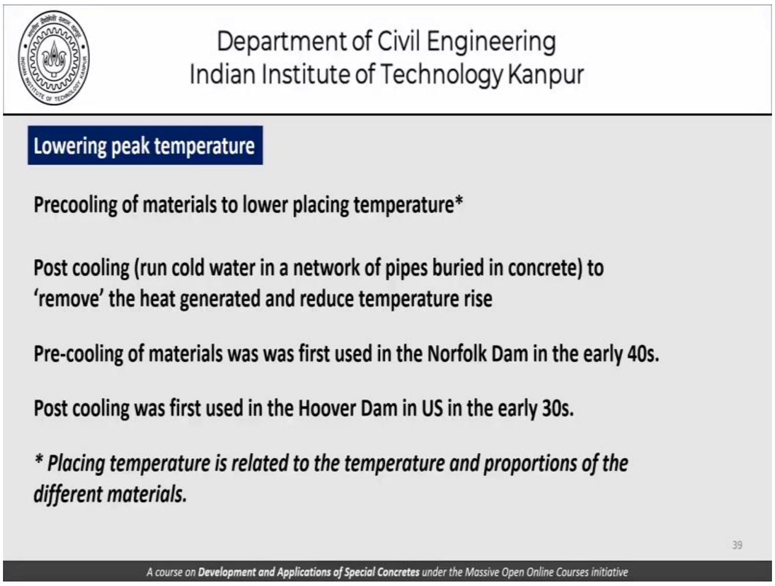

Pre-cooling of materials is another possible option. To lower the placing temperature, I have already given to you as an assignment to find out an equation or look for an equation which helps us determine or estimate the temperature of fresh concrete as a function of the temperature of the constituent materials and their proportions. Post cooling which involves running cold water in a network of pipes buried in the concrete is another way of removing the heat generated and reducing the temperature rise.

This of course is a very interesting way and I would leave it to some of you who are more interested to actually explore this. Find out in which construction projects in the world this post cooling has been used. This method helps us remove the heat from the core directly by running cold water through this network of pipes which takes away the heat from the core directly. So, we do not have to wait for that heat to be dissipated only through the or only from the surface of concrete.

We take it away directly through this water flow. Pre-cooling of materials was first used in the Norfolk dam in the early 1940s. Post cooling was first used in Hoover dam in the 1930s. So, there is a lot of history behind some of these methods and those of you who are interested in the historical perspective would surely find a lot of work to do.

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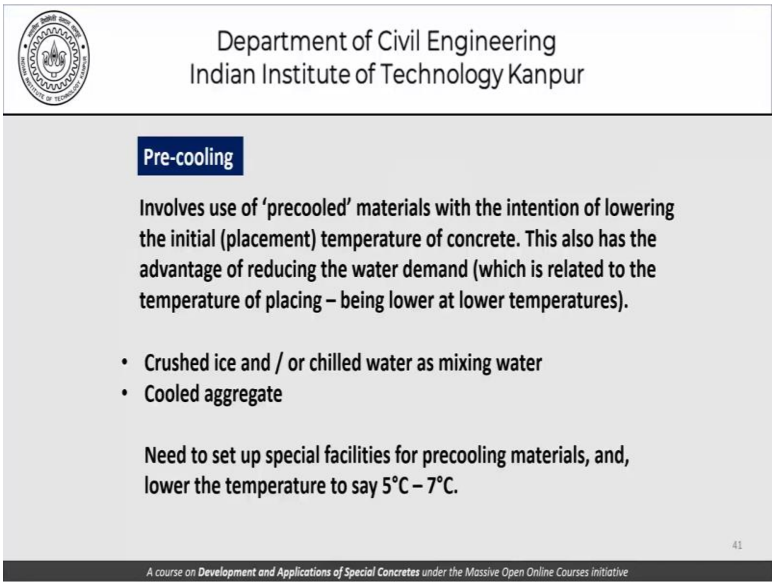

As far as pre-cooling is concerned it involves obviously the use of pre-cooled materials with the intention of lowering the initial placement temperature of concrete. This also has the advantage of reducing the water demand which is related to the temperature of placing being lower at lower temperatures. So, we could use crushed ice or chilled water as mixing water we could cool the aggregates or take any other such step.

Of course, we need to set up special facilities for pre-cooling these materials we have seen some of those facilities earlier when we saw the special collapsible kind of covering for the aggregate storages.

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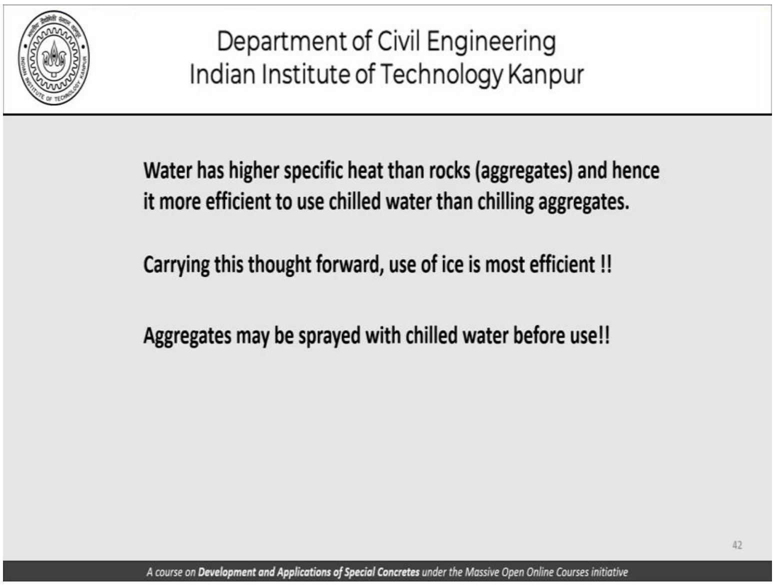

Water has a higher specific heat than rocks and hence is more efficient to use chilled water than chilling aggregates. Carrying this thought forward use of ice is very efficient and aggregates may be sprayed with chilled water before use that will lower the temperature.

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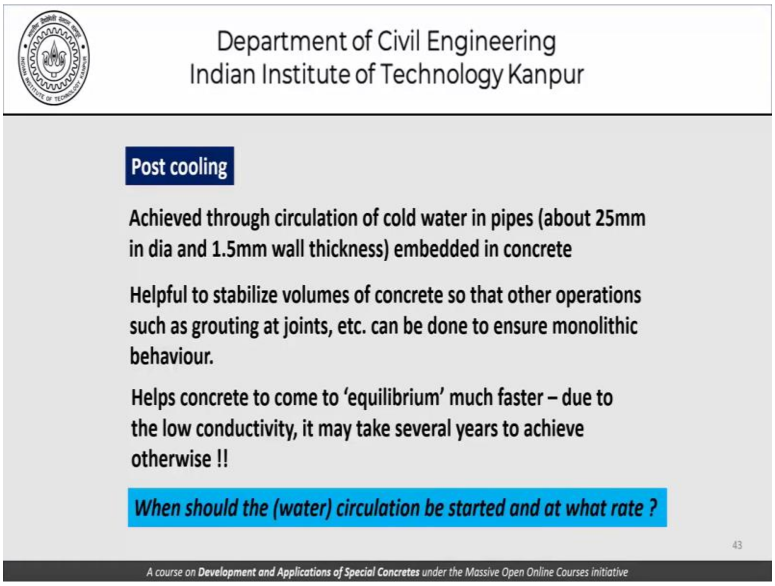

Post cooling is achieved through circulation of cold water and pipes these pipes are about 25 millimetres in diameter and 1.5 millimetres wall thickness embedded in concrete. It is helpful to stabilize the volumes of concrete so that other operations such as grouting at joints etcetera can be done to ensure monolithic behaviour. And helps concrete to come to equilibrium much faster due to the low conductivity concrete may take several years otherwise.

And there is a slide I am going to show you which will bring this point very tellingly. The question in this post cooling scenario is when should the water circulation be started and what should be the rate.

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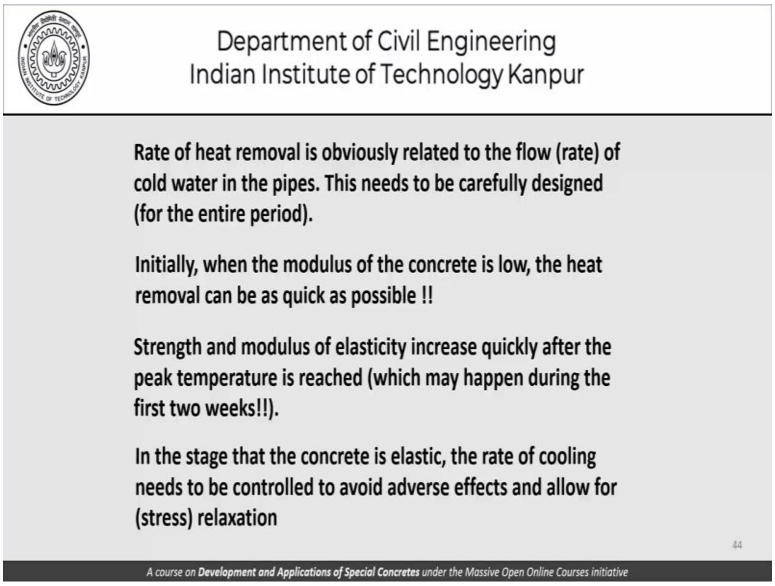

Rate of heat removal is obviously related to this flow rate of cold water in the pipes and therefore there has to be a complete design that has to be undertaken for this purpose. Initially when the modulus of concrete is low the heat removal can be very quick. Strength and modulus of elasticity increase quickly after the peak temperature is reached which may happen during the first week or 2.

In the stage the concrete is elastic the rate of cooling needs to be controlled to avoid adverse effects and allow for relaxation. These are some of the things which are given in specifications or in documents which prescribe certain procedures that can be followed.

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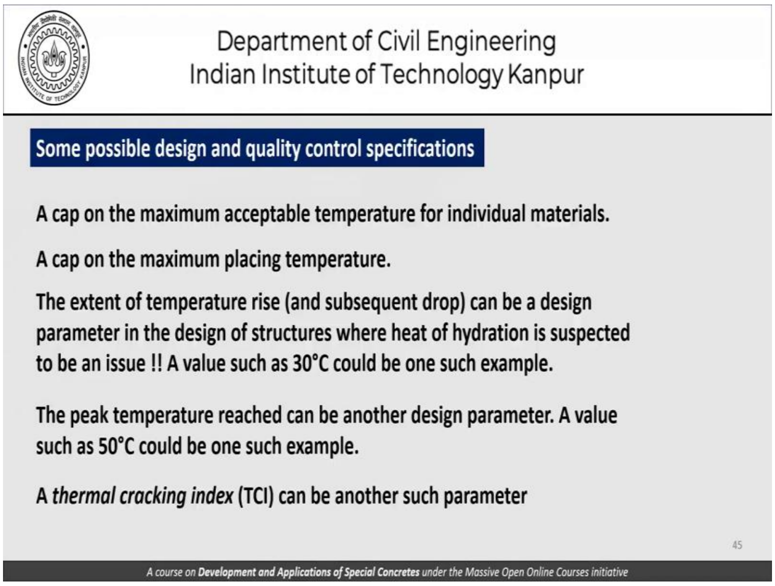

Some possible design and quality control specifications relating to mass concrete or situations when we are hunting this heat of hydration could be a cap on the maximum acceptable temperature for individual materials. A cap on the maximum placing temperature of concrete. The extent of temperature rise or the subsequent drop can be another design parameter where heat of hydration is suspected to be an issue.

A value of 30 degree centigrade could be an example in an earlier slide we have talked about 30 to 35 degrees being prescribed in some of the codes. The peak temperature reached can be another such parameter. We saw in one of the examples that in the lab a peak temperature of 65, 68 degrees was achieved. And there can be a specification that in this particular construction. Steps need to be taken to ensure the peak temperature does not exceed say 55 degrees centigrade.

A thermal cracking index could be another such parameter. Now what is a thermal cracking index.

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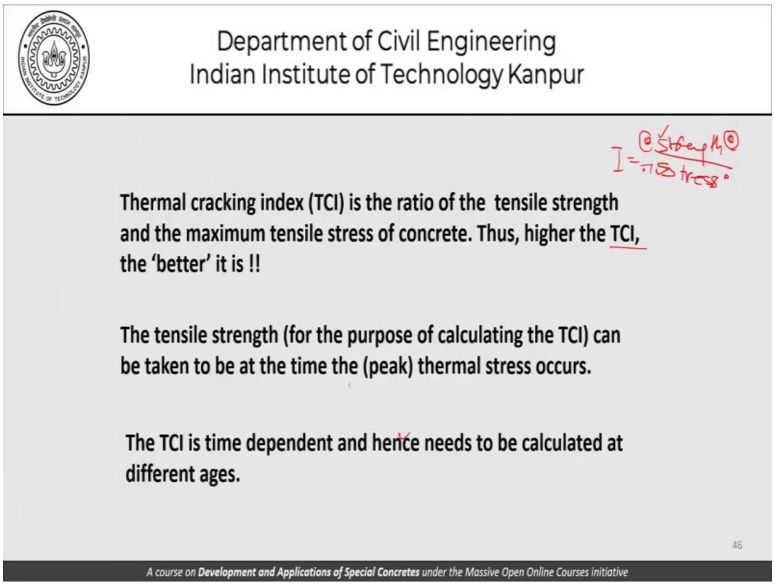

Thermal cracking index is the ratio of the tensile strength and the maximum tensile stress in concrete. Thus, higher the TCI that is the thermal cracking index the better it is the less likely. It is that the concrete will crack to reiterate this index is the ratio of strength the instantaneous strength to the instantaneous thermal stress. So, if we have higher strength here compared to the stress this index is higher and that is what is better for us.

The lower is the risk or the probability of cracking. Remember that strength development and stress development even though they are related they are reasonably independent phenomena. The strength develops on account of hydration and stresses are a complex discussion as we have been doing relating to temperature rise, temperature fall conduction of heat dissipation of heat and so on.

The tensile strength for the purpose of calculating the TCI can be taken to be at the time of the peak thermal stress. And therefore, concepts like the characteristic compressive strength and the characteristic tensile strength or any such relationship that will not really help. The TCI is time dependent and hence needs to be calculated at different ages. Obviously, it is time dependent because my strength as far as concrete is concerned is changing over time at that time and so is the stresses.

So, we need to work out the stresses and the strengths at different points in time and find out which is the TCI which is most critical for our design calculations.

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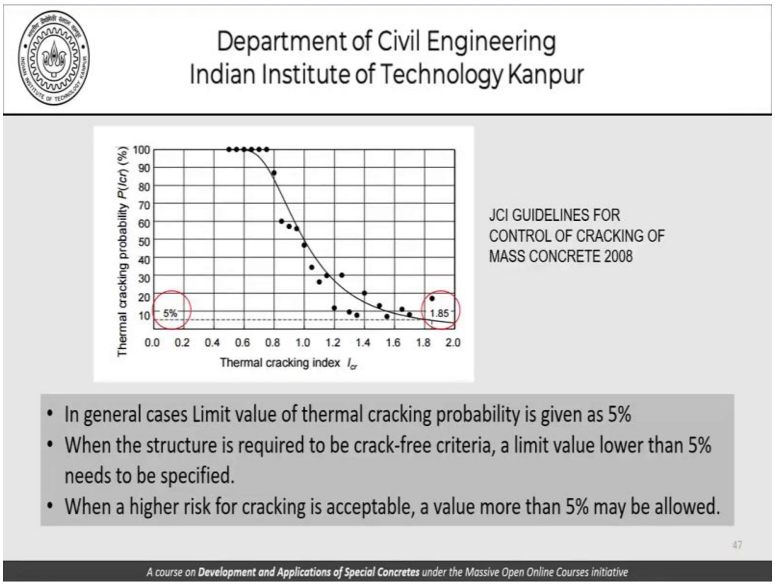

So, here is what a guideline from the Japan concrete institute says that if we plot the probability of cracking on this axis and the TCI on this axis obviously when it is 1 the probability of cracking is 50%. Because obviously once we say that the strength and the stress is the same. We really do not know which is slightly exceeding the other and therefore the probability is pretty close to 50%.

But as we go in this direction the probability of cracking increases and if we go in this direction the probability of cracking reduces. So, in general the limit value for the thermal cracking probability is given as 5%. So, we try to prescribe a thermal cracking index such that we want to control the probability of thermal cracking. Most of the time we try to take a value of 5%.

In certain cases, if we want the crack free criteria to be more stringent, we can work with the value which is lower than that in which case we are going towards a higher TCI. But sometimes we may say that we are happy with something which is having some cracks here and there we can work with the value which is more than 5. In which case we are happier with the TCI value which is let us say 1.4 or 1.2 even though the probability of cracking increases.

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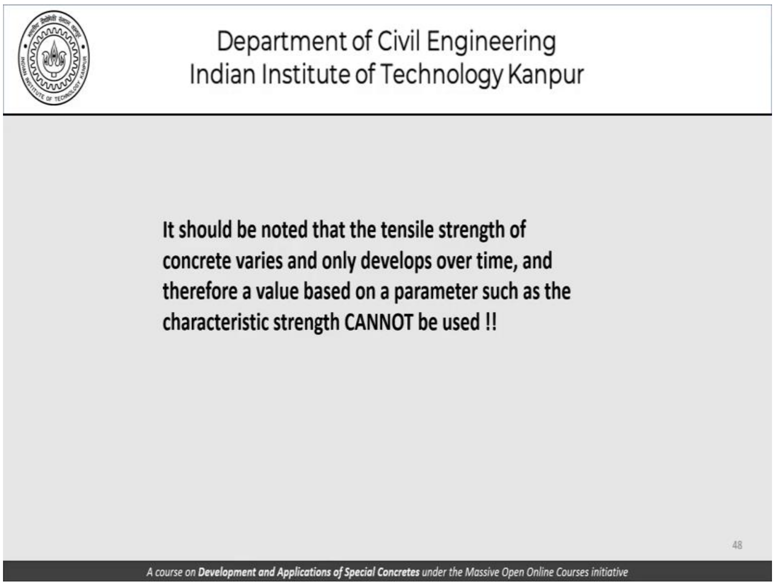

It should be noted that the tensile strength of concrete varies and only develops over time and therefore a value based on the parameters which is the characteristic strength of concrete cannot be used. I mentioned that before because this concept of characteristic strength is defined for the 28-day strength. Now we are not talking of the 28-day strength here at all we are talking of strengths which is developing in the first week, 2 weeks and that is where we need to concentrate and that is why characteristic strength concepts.

Or empirical relationships which relate the tensile strength to the characteristic strength of concrete they will not be of much use.

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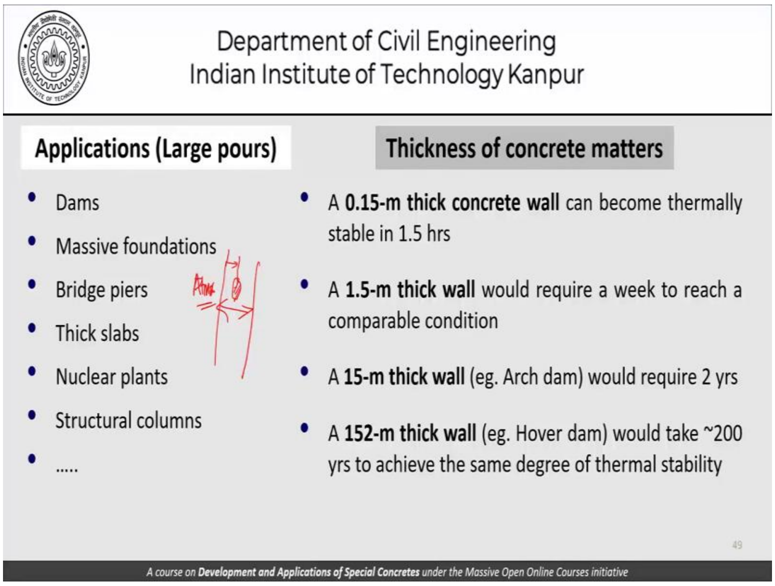

So, reiterating once again towards the close of our discussion today. Where can we use the kind of discussion that we have been having about mass concretes. In dams, massive foundations, bridge, piers, thick slabs, nuclear plants, structural columns with high strength concrete and so on. And here are the details or some kind of numbers about which I had talked earlier. If it was a 0.15 meters concrete thick wall it would become thermally stable in about 1.5 hours.

If it was 1.5 meters it will take about a week. What is being talked about is that if this was the thickness of the wall how much time it will take such that the temperature in the core here becomes in equilibrium with the atmosphere. That is there is no substantial difference between this temperature here and the surface of concrete. If it was 150 mm thick wall just one and a half hours.

If it was to become 1.5 meters it will be about a week. If it becomes 15 meters which is something which you would expect something like an arch dam it could take almost 2 years and if it becomes 150 meters then it could take as much as 200 years to achieve the same degree of thermal stability. These calculations of course are simulations using computer programs and the kinds of advanced tools that are now available to model the heat generation, heat conduction and heat dissipation under different conditions for different kinds of mixed proportions.

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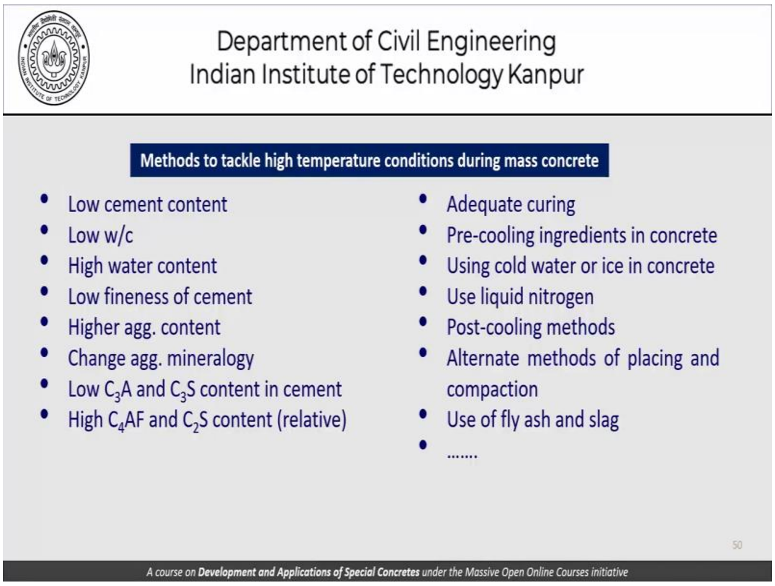

Once again this is a reiteration of the methods to tackle the high temperature conditions during mass concrete. And we have these tools which we could use adequate curing pre-cooling ingredients using cold water liquid nitrogen and so on. Post cooling methods alternative methods of placing in compaction using fly ash and slag. Anything that helps us lower the amount of cement anything that helps us lower the amount of heat that is going to be generated from a cubic meter of concrete that is what is going to help us tackle or manage this problem of temperature rise during hydration.

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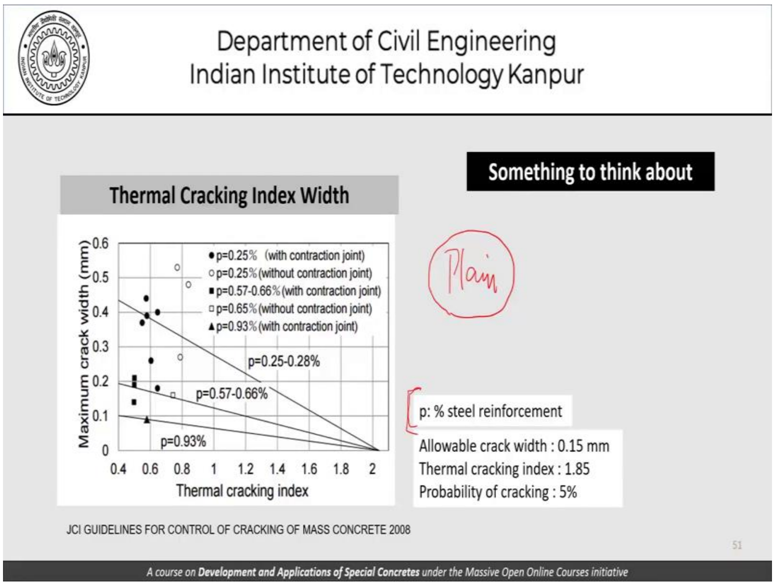

Here is something to think about not all the time we have plane concrete conditions. We have talked about plane concrete conditions as far as today's discussion is concerned. But most of the time even though most of the time mass concrete has a plane concrete connotation. It is also possible that we are talking of reinforced concrete. And when it is reinforced concrete and

P is the amount of steel reinforcement then we really have to think about what happens to crack width.

And how do we control crack width thermal cracking index and how do we attack the problem of maximum crack width and thermal cracking index. This is something which I am leaving to you to think about look at literature the JCI guidelines talk extensively about this. Read that for those of you who are interested.

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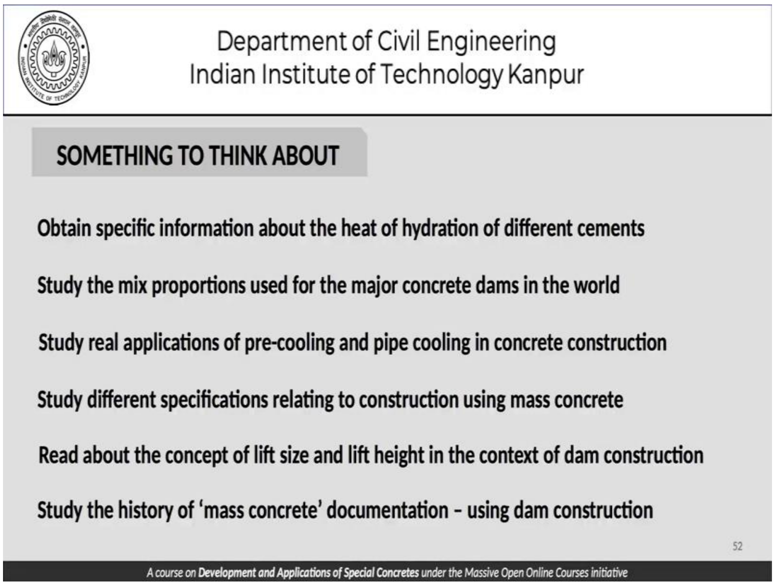

Other things to think about from today's discussion obtain specific information about the heat of hydration of different cements is study the mix proportions used for major concrete dams in the world. Try to study something about real examples of pre-cooling and pipe cooling or post cooling applications in concrete construction. We study different specifications relating to construction using mass concrete the kind of things we talked about the maximum temperature rise.

The max amount of cement content the permissible TCI and so on. Read about the concept of lift size and lift height in the context of dam construction. Planning for dam construction what should be the sequence of operations. At what stage should we cast the next lift because that really determines the temperature of the concrete against which we are casting the next lift. Study the history of mass concrete documentation using dam construction.

These are some of the things that could be very interesting for you to do as an outcome of our discussion which has been largely qualitative. But can be interestingly quantitative as far as heat of hydrations are concerned.

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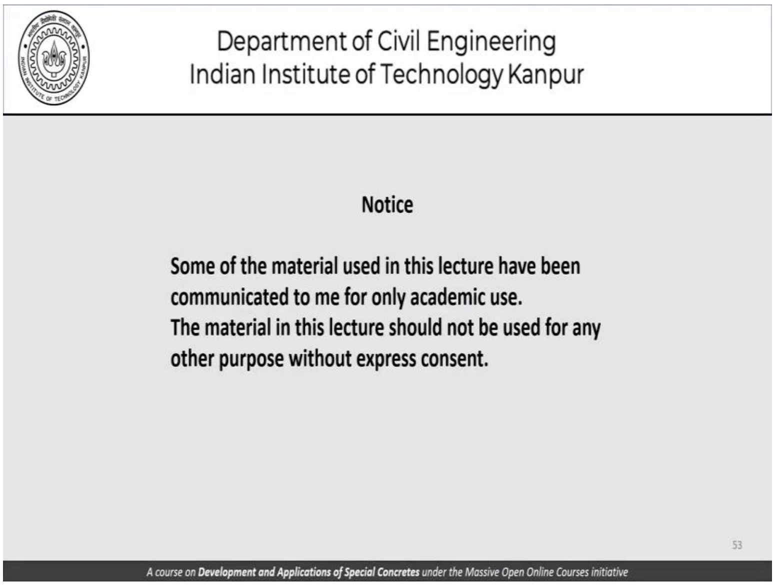

Some of this material which has been used in this lecture has been made available to me for only academic use and I would not like you to use that for any other purpose without express consent.

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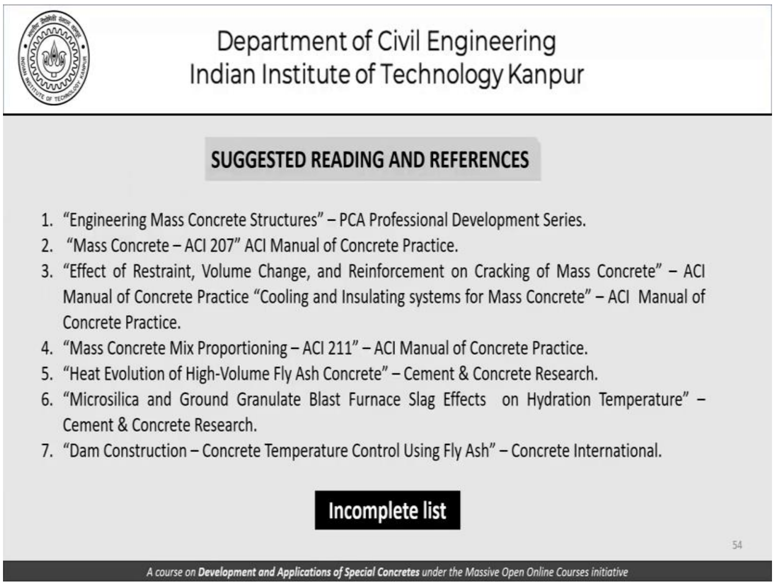

Some suggested reading materials given here but I have always insisted that this reading material is incomplete and I have consciously not given you a very exhaustive list. Please try to make an effort to read more literature on the subject it is a very well-developed subject. And have tried to only give you a glimpse of what goes on when we are trying to talk about heat of hydration issues in mass concrete.

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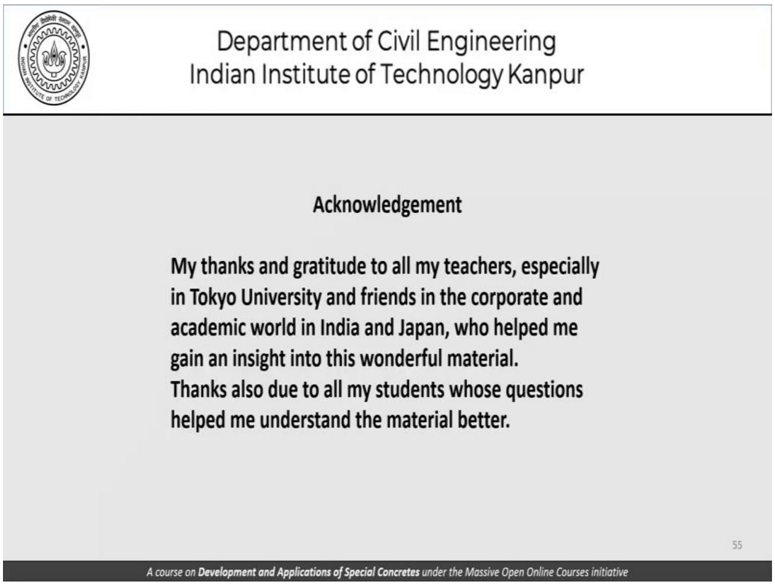

Of course, I acknowledge my friends, my colleagues and my students in helping me understand this issue. And once again I look forward to seeing you in another lecture, thank you once again.