Admixtures And Special Concretes

Prof. Manu Santhanam

Indian Institute of Technology Madras

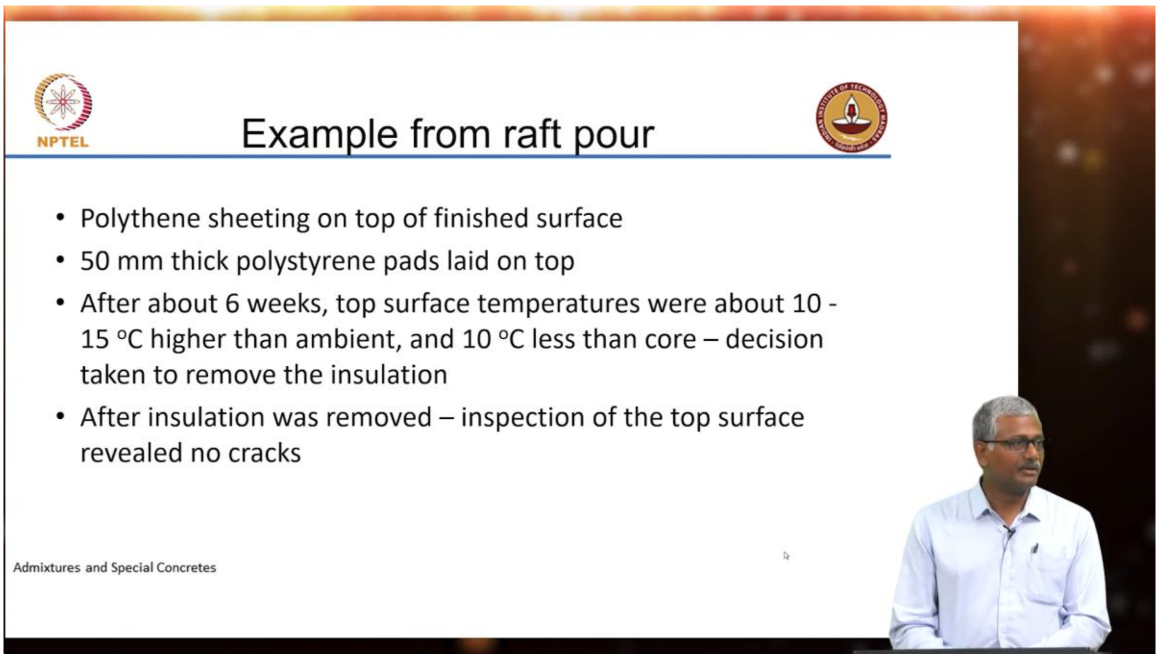
Department of Civil Engineering

Lecture -67

Special concretes - Mass concrete - Heat modelling

Example from raft pour:

(Refer to slide time: 00:19)



So, we were talking yesterday about or in the last class about, for example, the pour that happened for the raft, 4 meters 4-meter-deep raft which is 50 by 50 meters in size. And I was talking about the fact that to protect the surface from cooling rapidly and to prevent temperature differentials from being large, you can try insulation on the top of the surface to ensure that the heat dissipation happens very slowly. So, in this case for this raft which is 4 meters thick, a 50 mm thermocol or polystyrene pad was used on the top. Under this layer, there was also polythene sheeting to ensure that there was no evaporation of water from the raft to prevent any plastic shrinkage cracking. And this insulation was maintained for 6 weeks and from the temperature records that I showed previously, it is clear that the temperatures inside were still substantially high close to 60 to 65 degrees at this point in time. But then the overall differential had reduced significantly and the fact that you already waited 6 weeks, means that the concrete strength also has been gained sufficiently to resist any further shrinkage-related cracking that may happen.

And again, after the insulation was removed inspection revealed no cracking. One thing you need to think about now, nowhere in the process has any curing happened for the concrete. Is that a good thing or a bad thing? Bad because we want curing to be there in the concrete. But here is there a problem of evaporation of moisture from within the concrete? That is not happening now.

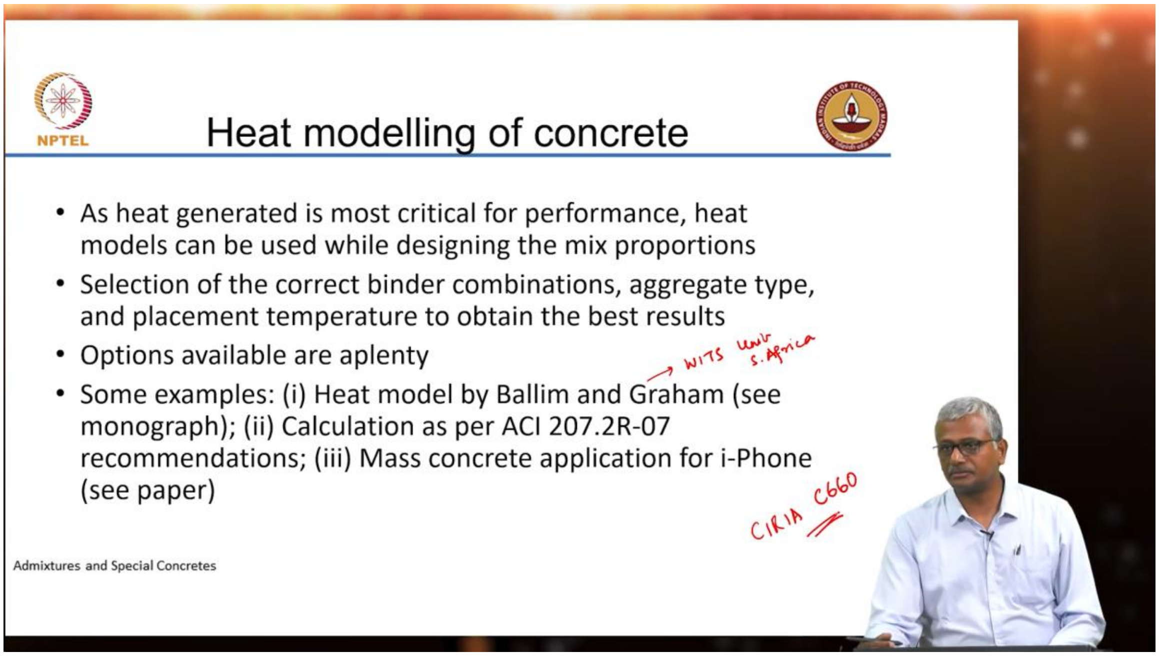
So, if that is not happening, your system is undergoing some level of curing. The difficulty arises when it is high-strength concrete. Why? Because, we talked about this previously that in high-strength concrete, water-to-cement ratios are very low, and in such cases, you can get internal self-desiccation or autogenous shrinkage. In such instances, it is always advisable to have an external source of water for curing the concrete. Otherwise, if you take a concrete mass and then simply encase it in plastic, prevent any evaporation that is as good as curing.

Essentially you are sealing the material and preventing any evaporation that is as good as curing. But to avoid excessive strains because of autogenous shrinkage, the provision of external moisture is always a good thing to do for concrete structures that have high-strength concrete. In mass concrete that is the reason why high-strength concrete and mass concrete do not necessarily go very well together. Because you are not going to be able to sort out the problem of autogenous shrinkage when you seal the concrete and prevent evaporation. When you insulate or seal the concrete, you are okay, you are protecting against drying of the moisture from inside but internal drying is not prevented.

So, you have to assess what the best solution to your particular situation is. But in general, when you go with mass concrete water curing needs to be avoided in the beginning phases because that is when the temperature differential between the core and the surface is going to be quite high. So, if you are sure about how fast your heat is dissipating then you can do something about it.

Heat Modelling of Concrete

(Refer to slide time: 04:04)



So now let us just briefly look at what we can do to model the heat development in concrete. So, it is important as I said, during the mix design process to also understand what extent of heat can develop inside the concrete and how do we tackle the problems that are associated with this heat development.

So, if we know already how much heat is getting developed, and what the temperature of the concrete is going up to then we can devise appropriate strategies for concreting and change our methodology to ensure that we do not get the problems that we are likely to get because of the thermal differentials, because of the high temperatures and so on. So again, all of these will dictate the choice of material for your concrete. So, there are several options available. I will give some examples here. One is a heat model developed by Ballim and Graham from the University of Witwatersrand in South Africa.

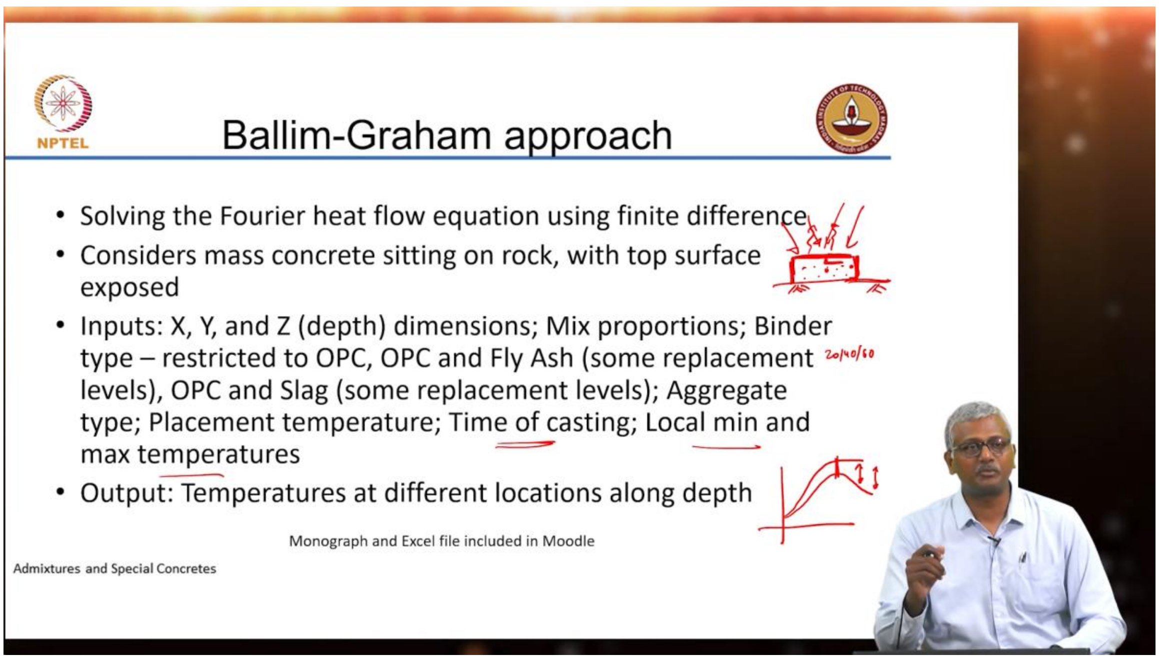
Heat flow is defined by the Fourier equation and the solution to the heat flow equation gives you the rise in temperature in the segment that is undergoing this early hydration. Again, a lot of mathematics is involved here but, in this case, Ballim and Graham used what is called a finite difference approach to try and estimate temperatures at different segments or different parts of a block that is subjected to early hydration. There is also a recommendation given in ACI report 207 on mass concrete which helps you calculate the adiabatic temperature rise inside the concrete given the heat of hydration of your cement. On plain cement or for cement paste we can conduct heat of hydration studies using isothermal calorimetry and use that data to estimate the adiabatic temperature rise. I will go through that formula also.

There is also a mass concrete application available for iPhones. I mean, of course, the application was developed for iPhones. I am not sure if it is there for Android also but this again is a very simplistic assessment based on the heat flow equation. All these are essentially at the beginning of your mix design process you get an estimate of when you use cement or a combination of cement and fly ash or a combination of cement and slag what kind of temperatures are you likely to see in your member given the dimensions of your structural member- 2 meters, 3 meters, 4 meters whatever the case may be. The other approach is obviously to look at the recommendations in CIRIA C660 which is the one I had talked about previously.

It is a very good guideline to follow for designing concrete for applications where thermal gradients and thermal effects can be quite significant.

Ballim- Graham Approach

(Refer to slide time: 07:09)



So, the Ballim-Graham approach as I said solves the Fourier heat flow equation using a finite difference approach. It considers that your mass concrete is sitting on a rock. Just for example as in a dam, a dam basically is massive concrete sitting on a rock. The top surface here is exposed which means drying can happen from the top surface and your side surfaces are basically protected by the shutter.

And the shutter removal will also determine how fast you are likely to expose the side surfaces to the environmental conditions. Alternatively, you can also say that instead of steel shutters, I am using plywood shutters then the heat flow happening through the steel is going to be much greater than the heat flow happening through the plywood which is an insulating material. So that will also affect the rate at which your temperatures in the different segments go up. So, you need to give as inputs X, Y, and Z dimensions. You need to give mix proportions, whatever mix proportions you have chosen.

The binder type, here the combinations are restricted. You can either have just plain OPC or OPC and fly ash. Replacement levels given are 20, 40, 60, and again similarly for OPC and slag. There are no other mineral additives given in the Excel macro that is provided by Ballim and Graham which operates their model and does the calculation of your temperatures. Then the other input is the placement temperature.

At what temperature you are placing the concrete? Again, please remember we discussed earlier if you place the concrete as an X temperature then the expected core temperature will be X plus 12 into how much your cement content is there divided by 100. So that is the approximate thumb rule that you follow. So that is why you need to have a starting temperature. Interestingly they also have time of casting as a prescription here as an input to this model because if you cast at midnight in the night as opposed to 10 a.m., in the initial phases your concrete is getting subjected to a different environmental condition and obviously that environmental condition also is an input to the model with respect to the local minimum and maximum temperatures.

Of course, when you do a project that is long over a duration of 1 year or 2 years the minimum and maximum definition itself will change and in the winter, it will be one thing, and in summer it will be one thing, and so on. So, you need to have multiple versions of the model created for different seasons where your temperatures are likely to be quite different. And then the output it gives is at any particular location in your structure what is the actual temperature at any given time. So, it gives an output in terms of at t equal to 0, at t equal to 20 hours, at t equal to 40 hours, 60 hours, and so on. It will give you the actual temperature profile or actual temperatures at different points of your concrete element.

So, you can use that to figure out what the core temperature is and you can probably plot the core temperature. You can also figure out what the temperature close to the surface is either horizontally or vertically. So, you start from the same placing temperature possibly that may happen for the point that is close to the surface. It may reach a certain maximum which will not be equal to the same as the core. If you have insulation, it may be equal to what you get in the core also.

But otherwise, it may be less than what you get in the core and then you will start cooling. The problem really happens in mass concrete beyond this point. So, your temperature rise phase is not a critical phase with respect to cracking. It is the temperature drop phase where the surface temperatures start dropping while the core temperatures are still maintained. That is where you get the maximum differential.

So, you must be very careful at that point of time. In one more project we had the use of plain concrete and in this project, it was seen that there were cracks that were appearing in the structure after about 10 to 11 days of placement. There was no cracking until then. Top surface was insulated, side shuttering was done with plywood shutters so no heat. The heat was retained quite well.

Temperature was coming down quite slowly because of the plywood. But despite that there was a differential created that led to cracking. Later of course we found out that cracking was not just because of the temperature differential it was also because of base restraint because these members were planned as very long rectangles. So, they were planned as rectangles of 27 by 9 meters and they nicely cracked into 9 by 9 meters. So, it gave us a clear idea that when we cast the new slabs, they should be 9 by 9 meters.

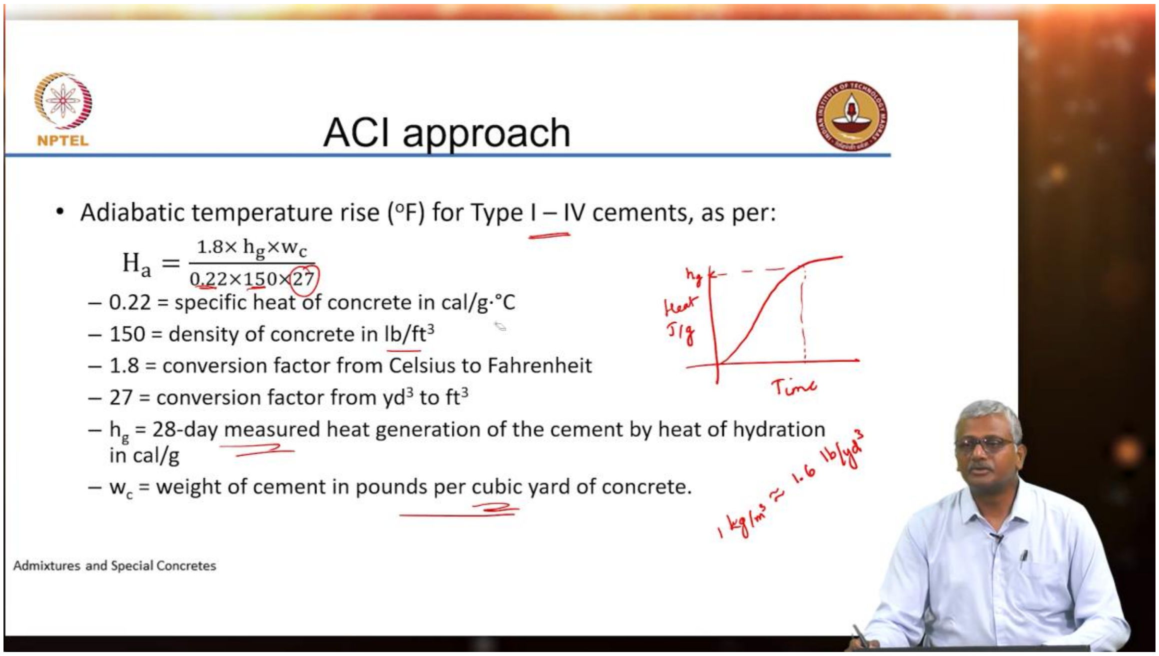
After that we took all 9 by 9-meter slabs everything was perfect, no cracking happened later. Plain concrete, no steel at all. So, in such instances, it is very important for us to understand apart from heat, so we were expecting all the time that heat is going to be the major cause of cracking. So, all the efforts were taken to restrict temperature differential and indeed there was no random cracking on the surface also seen. But what we were able to see is this almost like somebody takes a cake and cuts into 3.

Perfect cut happened just like what you see in pavements or in slabs where you forget to put the construction joints. So, this almost appeared perfectly. Luckily that was not really a problem in this case. So, this is an instance of understanding what your structures likely go through but this is only an approximate characterization of what is going to happen in your system because you will have changes to the system also sometimes you cover the top by insulation in which case the temperature differentials are going to come down. But also, you must think about the fact that the solar radiation is also falling on the surface.

So that will also result in some heating up of the surface and when the insulation is there probably greater heat-trapping may happen inside which may lead to top surface temperatures exceeding the core temperatures also. So, this must have a proper evaluation done before you really can proceed with a proper understanding of what kind of construction methods you will put into place to avoid cracking.

ACI Approach

(Refer to slide time: 14:18)



The ACI approach is rather simple. It predicts the adiabatic temperature rise in degrees Fahrenheit for most cements.

Here they say type 1 to 4. Type 5 is sulphate-resistant cement which is very low C_3A. So, that is not considered in this equation. So, it just says adiabatic temperature rises in degrees Fahrenheit. Of course, the Americans are still far behind in terms of catching up with the rest of the world. They still deal with pounds per square inch, pounds per cubic foot, cubic yard all those kinds of things they still use whereas the rest of the world uses SI units.

So here they still use Fahrenheit, in the US when you go, the temperatures are always indicated in Fahrenheit. Never in degrees Celsius. So as per this, the adiabatic temperature rise is given as 1.8 times h_g multiplied by w_c where h_g is the 28 days measured heat generation of the cement.

$$H_a = \frac{1.8\ \times\ h_g \times\ w_c}{0.22\ \times 150\ \times 27}$$

So, do you remember the heat profile? Usually, it starts off and there is an S-shaped curve that is how it goes. The heat profile of any cement goes like that. So, at 28 days what is the heat generated h_g. So of course, in India, we would be using joules per gram but this equation uses it in calories per gram. w_c is the weight of cement in pounds per cubic yard of concrete. Just for simplicity in calculation, 1 kg per cubic meter is equivalent to about

1.6 pounds per cubic yard approximately. So, let us say your concrete has 500 kg of cement which means it has 800 pounds per cubic yard of cement as per the conversion. Now here at the bottom, you multiply the specific heat capacity of the concrete by the density of the concrete and a factor to convert a cubic yard into cubic feet because there is a cubic yard coming here at the top. So that cubic yard needs to be converted to cubic feet because the density 150 is in pounds per cubic foot, the density of concrete. What is the density of water in this archaic system of units? In SI units, we know the density of water is 1000 kg per cubic meter.

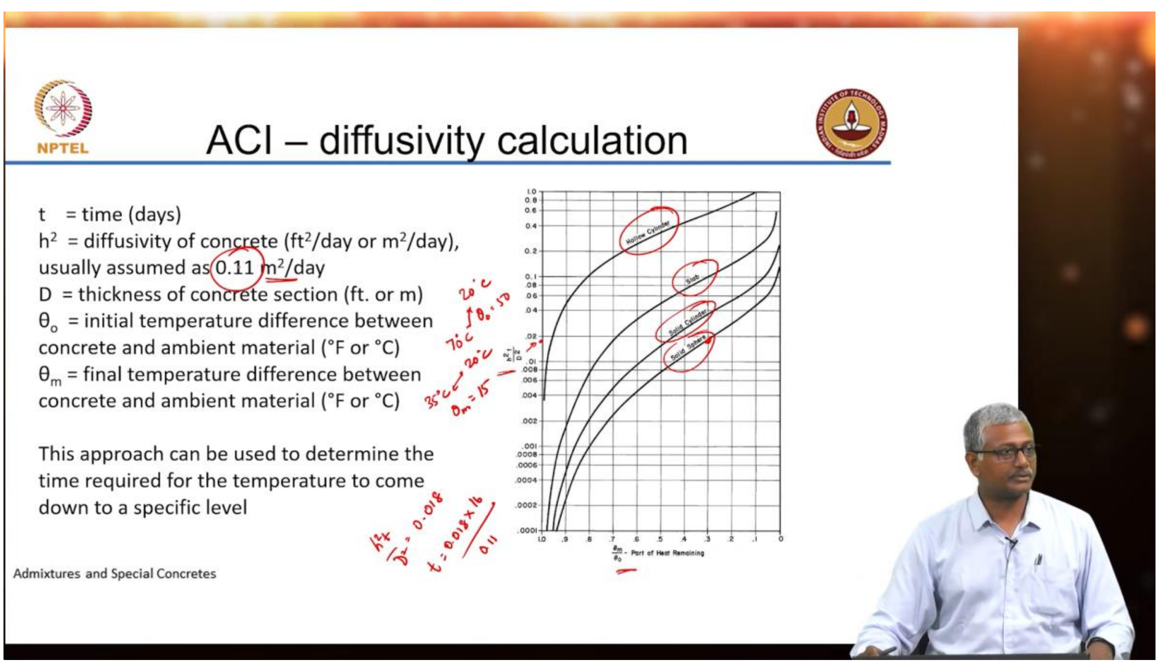
Here it turns out to be 62.4- pounds per cubic foot. So concrete density is 150 pounds per cubic foot which is equivalent to 2400 kg per cubic meter.

So, using this equation you get an adiabatic temperature rise. So that means that if you are placing temperature is let us say in 70 degrees Fahrenheit, how much is 70 Fahrenheit in Celsius? It is about 21 degrees. So, at that temperature, if you place the concrete this equation will give you what will be the additional temperature rise over that in Fahrenheit. But then when you are using this equation for work in India make sure that you do a proper calibration and conversion of all these units into what is Indian units in kilograms, cubic meters, degrees Celsius, and so on.

So, this is the ACI approach. You could as well use this; it is not that difficult to use this.

ACI- Diffusivity calculation

(Refer to slide time: 18:34)



Now once the temperature is developed in your slab or raft or any other mass concrete structure as it may be how long does it take for this heat inside the structure to get dissipated outwards. If I have a concrete column, cylindrical column or a square column as opposed to if I have a wall, a shear wall, concrete shear wall or a massive slab or a raft the rate at which the heat flows out will be dependent on what is the exposed surface area as a unit of the overall volume of the system. The higher the exposed surface area to volume ratio the faster will be the heat dissipation. So that is what this heat diffusivity calculation helps you.

ACI heat diffusivity calculation- it plots this h^2t/D^2 to θ_m/θ_0. Now, t is the time in days, h^2 is the diffusivity of concrete- it is the rate at which heat flow will happen through concrete. So here it is in terms of, the square of the dimension divided by time so a meter square per day is usually assumed at about 0.11-meter square per day. D is the thickness of the concrete section depending on what units you are using the foot or meter. θ_0 is the initial temperature difference between the concrete and ambient material. So initial temperature difference let us say at peak, so let us say the peak temperature of my concrete is 70 degrees Celsius at that time ambient is 20 which means my θ_0 is 50. θ_m is the final temperature difference between concrete and ambient material. So, in a massive slab, the interior core may never achieve the exact ambient conditions it may still be warmer, and some heat may be still retained. So let us say the final temperature is 35 degrees Celsius in the interior of the slab and the exterior temperature is 20 degrees Celsius.

So, my θ_m is 15. So, here I am dividing $\theta_m$by θ_0 that is indicating the part of heat remaining. The greater the θ_m the greater will be the heat remaining in the system. So, compared to that you are plotting h^2t/D^2 where h^2 is the diffusivity, time is t and D is the thickness of the concrete section. So, for different systems hollow cylinder, slab, solid cylinder, and solid sphere you can then get a point let us say you get a point somewhere here. So, this is for a solid sphere, say a spherical mass of concrete let us say it is diffusing heat outward and you want the sphere to arrive at a temperature of 35 degrees from the peak core temperature of 70 degrees while the external temperature is always 20 degrees Celsius.

So let us say it gives you $\theta_m$by θ_0 of 0.6 maybe we will do the actual calculation 15 by 50 is how much 0.3. Right? 15 by 50 is 0.3. So, I am at that point in a solid sphere if I read out the corresponding number here it is 0.018. Let us say. So, h^2t/D^2 is equal to 0.018.

So now from this what can I get? I can get an estimate of the time, i.e. time at which this will happen I can understand. So, 0.018 D^2, let us assume my solid sphere is 4 meters in diameter. This is like the rock that is there in Mahabalipuram. I do not know if you have seen that, they call it Krishna's butter ball. It is resting on one small area. It is really a wonder that it is not falling, it is perfectly placed there. So that is more or less like I think

4 meters in diameter. So, the thickness of the concrete section, in this case let us consider diameter. So D^2 is 16 divided by h^2 that is 0.11.

$$\frac{h^2 t}{D^2} = 0.018$$

$$t = \frac{0.018 \times 16}{0.11}$$

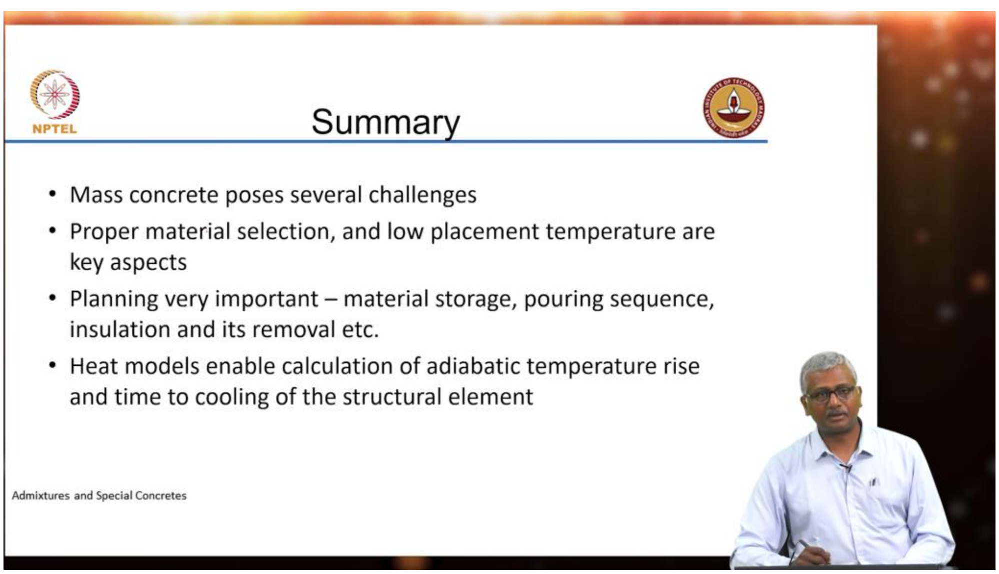
$$t = 2.6\ days$$

So, what does that come to in days? It will be hardly 2 days as per this equation. 2.6 days. So, similarly you can do a calculation for the particular structural member that you are trying to see how long does it take for the heat to dissipate to such an extent that the core is coming down to a particular temperature which is acceptable. This can also be used to understand at what point can I remove formwork for instance. At what point can I but here of course sorry here it estimates that the system is exposed completely. Now the entire curves may change because of the fact that your system is still within formwork because heat is not diffusing out as easily.

So, you may have to get better values for your h square to estimate exactly how a concrete element which is still sitting inside a formwork let us say a plywood formwork is going to be diffusing heat outward. So, this requires some assessment, some understanding of how the system will behave and estimation of heat diffusivity of the material is necessary.

Summary

(refer to slide time: 24:56)



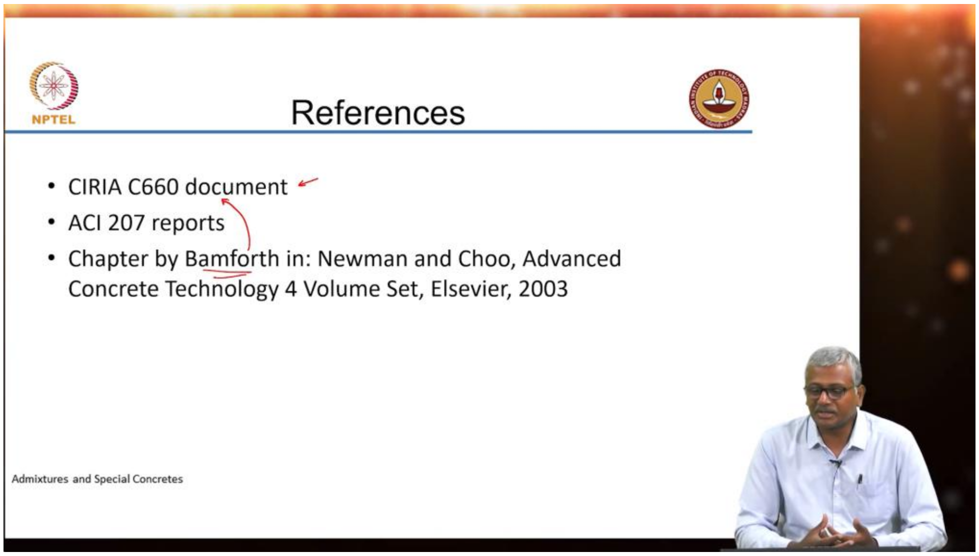
So just to summarize this particular chapter of course mass concrete poses several challenges because very often the demands are quite contradictory especially when you are dealing with modern structures like shear walls which can be massive in size but then they still are required to be extremely high strength because they are usually used in the lower floors of very tall buildings. Proper material selection is important obviously you need to use fly ash as much as possible to reduce heat but lowering placement temperatures by use of ice is possibly one of the best methods to go ahead with mass concrete structures. You need to plan very carefully any mass concrete project has to be planned very carefully how do you store the material right, how do you pour the concrete in what segments, how do you avoid cold joints,construction joints and so on.

How do you plan the insulation,how long do you plan it for, when should it be removed to ensure that you are not getting any cracking in your structure and as I said you can help the process by utilizing heat models to calculate the adiabatic temperature rise and also estimate the time that the structure takes to cool down after it heats up to a certain level. Now in usual heat flow studies, all these things have been quite well established. All this calculation that is coming is all from solving the heat flow equation. So that is a subject that has been well understood by people who deal with heat flow like mechanical engineers and so on. So for us we need to ensure that we are entering the correct data in terms of properties of concrete which requires us to also try and estimate these properties as much as possible.

Assuming properties because concrete is changing day to day the materials that we use in concrete are changing, the characteristics of concrete are changing. So, we need to be able to ensure that we are applying the correct set of data to all of these equations to really figure out whether we are getting numbers which make sense. So, it is very important for us to get data that means more research is absolutely necessary.

References:

(Refer to slide time: 27:17)



ACI reports as I said you can download on your own also but I will share it anyway in Moodle. And there is a textbook also which brings about the subject of mass concrete quite nicely. In any case, the person Bamforth who has written that chapter in this textbook is the primary author of this CIRIA document also.

So much of the concepts are covered quite nicely in the document. But for any one of you who are going to be involved with large construction projects, I think it is very important for you to understand how design of concrete needs to be done in cases of mass concrete. So, this is a very important document for you to read through. So, we will close this chapter here.

Discussion:

So, again the general principle is to avoid anything larger than 20 degrees. So here of course we wanted to also ensure that there were not major differences between the core which is at 2 meters from the top and the ambient conditions.

It also helped that the ambient conditions also had warmed up by them significantly. But I do not know if I can put a number there exactly. If you can divide your concrete into 1-meter segments then make sure that within each 1-meter segment the differences are within about 10 to 15 Celsius on a safer side. Again, this is only a thumb 20 degrees also is a thumb rule as I showed you it depends on the type of aggregate it depends on other factors also.

So, one can never be too sure so as much as you can minimize the better. So, your construction scheduling also has to accommodate this. So, as I said contradictory demands are made from the concrete made very high workability. For extremely high workability you need to increase cementitious content. When you increase cementitious content, it increases the heat. When you place restrictions on what type of binder can be used and not allow fly ash that heat is going to be developed even more.

As you increase the grade of the concrete you further increase the heat. There is not sufficient amount of water to take the heat. If you have less water the heat rises much faster. All of this has to be looked at very carefully. So, in such instances of course it is not a subject that has been properly addressed yet but, in such instances, when you are trying to protect the structure from drying internally of course your primary objective is to prevent thermal cracking. But if you want the structure to have sufficient moisture inside that can reduce the extent of autogenous shrinkage people have attempted what is called as internal curing of concrete.

So here there are like in diapers we have these polymers you know the gels which can absorb a lot of moisture. Similarly in concrete people have tried to use what is called superabsorbent polymer. So, there are these polymers when you add to concrete, they take in a lot of water. This water gets slowly released over the time of concrete hardening or over the time of concrete strength gain. So, there is internal release of water which sort of reduces the overall pore pressure that is caused by autogenous shrinkage.

That is internal curing. Internal curing can also be attempted by using some lightweight aggregate new systems. Lightweight aggregate also highly porous it is going to absorb lot of moisture and release it slowly for internal curing. Only problem is when you are using high-strength concrete when you use lightweight aggregate it will cause a drop in strength. So even superabsorbent polymers may lead to a drop in strength. You have to do a proper design in such an instance. It is not easy.