Maintenance and Repair of Concrete Structures
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Lecture 7
Deterioration of Cementitious Systems
(Frost attack, Freeze-thaw attack and Alkali-silica reaction)

Hi, this is lecture 7, which is actually second lecture in the module on deterioration of cementitious systems. In lecture 6, we covered introduction for the durable concrete systems.

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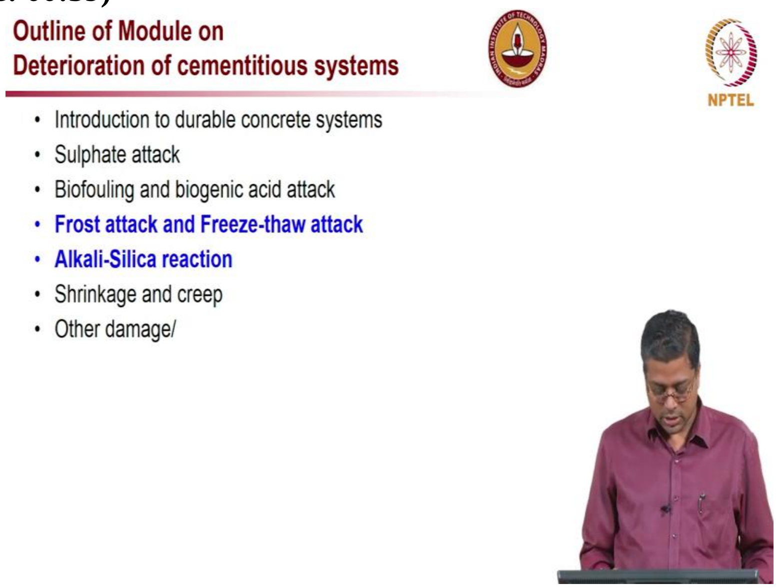

Also sulphate attack and acid attack. In this particular lecture, we will cover frost attack, freeze-thaw attack and also alkali-silica reaction in concrete systems.

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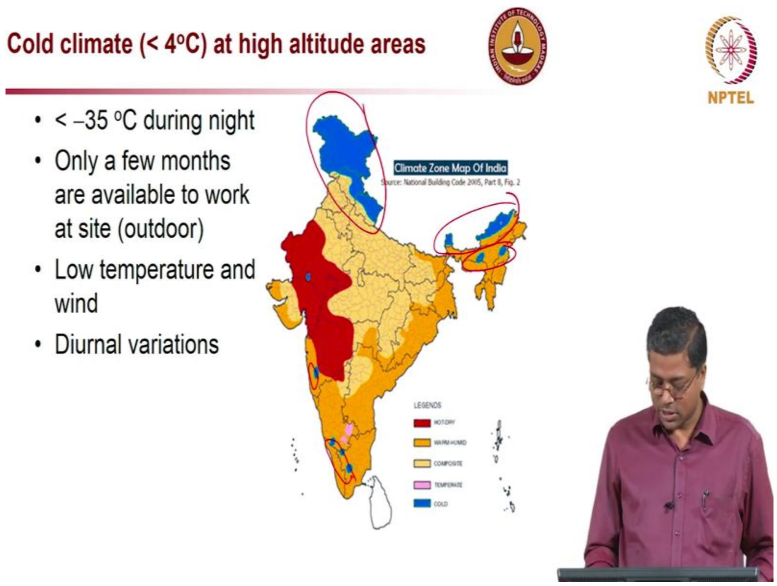

Before talking about the frost attack the first thing is where that will actually happen? We have a lot of regions in our country where the ambient temperature could be less than 4 ^{0}C. So we define that as cold climate. On the map you can see that, all this blue region are regions where cold climate is experienced even in other parts of the country, you can see some hill stations etcetera where the temperature could be very low, can be defined as cold climate.

And if you really talk about the northern border, you have places where the temperature during the night could be -35 ^{0}C or even less than that. And eventually what happens is for construction purpose, we get only few months per year, like 2 to 3 months per year, to work comfortably in an outdoor environment. It is not only temperature we also have to consider the wind chill factor.

Also you might have diurnal variation that is daily variation of temperature. So all these have to be considered when we talk about good quality concreting and it is not very easy to construct during that cold climate because, we ourselves won't feel much comfortable in that climate.

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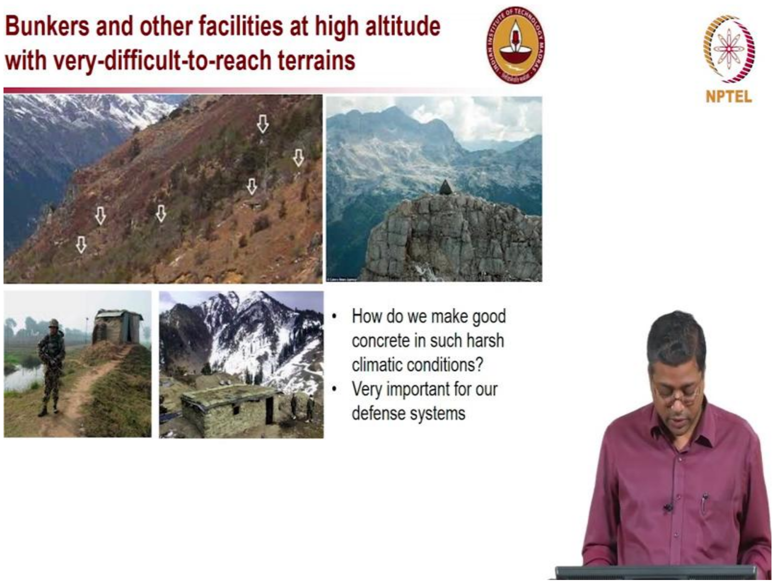

Definitely we have a need for good quality concreting in places like what you see on the screen, especially on the border regions, very high altitude regions with terrain which is very difficult to reach. How do we do good concreting in such cases, which is very important for our defense systems, because we might have bunkers and other facilities, which need to be in good quality. So, in this lecture, we will kindly focus on how to do good concreting in such harsh and very difficult to reach environment also.

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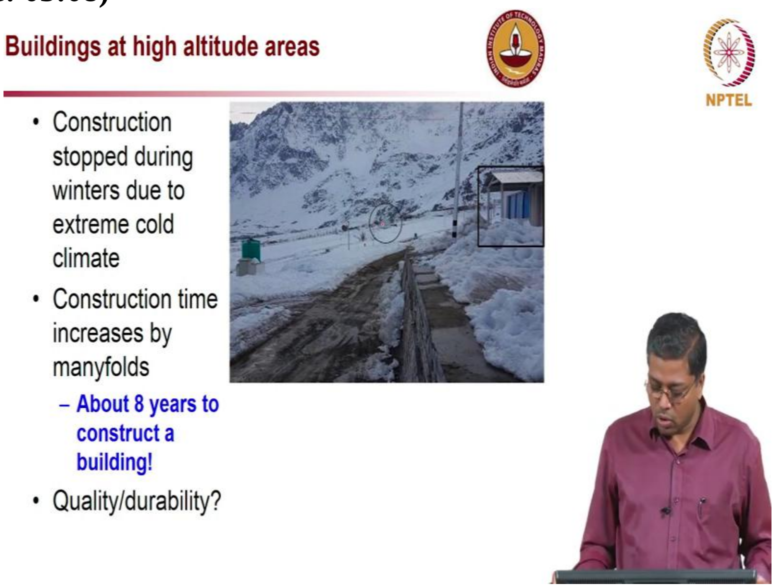

You can see on this picture completely snowcapped region and towards the center of the picture, you see a black circle and there is actually a home which is being built. And this example, I just put here because that particular building took about 8 years to construct because of the harsh weather conditions. So, this is very important to consider. We need good quality and good construction practices so that we can reduce the duration of this construction from 8 years to maybe a couple of years.

So, we have to really think and also another point is even if we take 8 years to construct how long that particular facility will last. Can it be durable? All that also have to be considered when we talk about because first of all in these conditions it is very difficult to construct. So, our objective should be when we do it, it should be of good quality so that we don't have to go on and repair also in this difficult terrains and harsh climatic conditions.

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Now, this slide shows picture of transportation systems or you have a bridge and an asphalt road which is heavily damaged because of moisture attack and also the poor quality asphalt and then which leads to severe damage when vehicles run over them. And then on the right side, you have an image showing a wheel with metallic chains which are sometimes necessary to ride these vehicles in very harsh climate.

So, what these chains do is, as the wheel is rolled, this chain breaks the ice and then makes it easy for driving on ice cap pavements. And the picture on the bottom left, you can see towards the center of the picture there is actually a highway in that region and all this have to be of good quality and how do we really achieve that good quality and long lasting. Again, let me emphasize the point, construction itself is very difficult in these locations.

So, if you do not pay attention for durability, the constructed facilities may not really last long. So we must ensure that the quality of construction is also very good. Once constructed, it should last for as long as possible.

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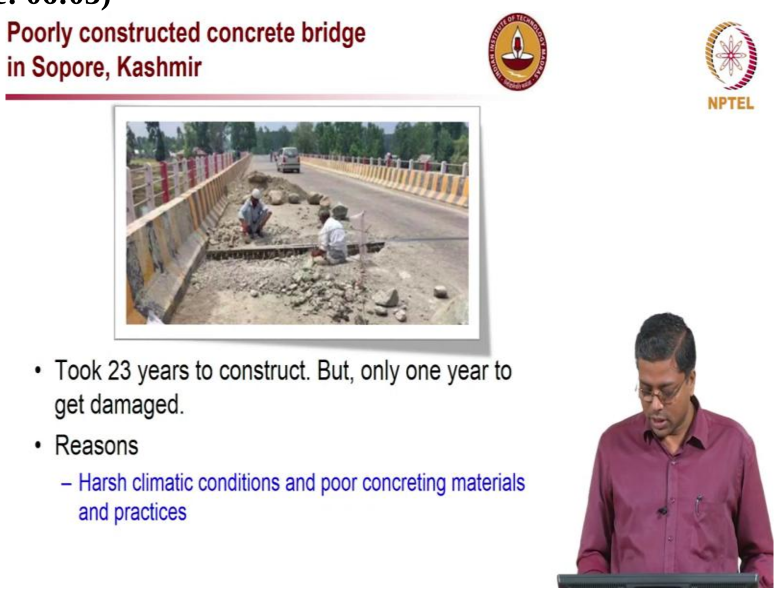

This picture shows that in most cases the construction is not good; day on which this picture was taken was probably a relatively sunny and nice day. But this particular region experiences very cold climate and probably the construction was not done with good materials and practices. Of course, there could be other reasons also non-technical reasons, but at the end; the concrete was not treated well.

It took 23 years to construct, because of various other reasons also, but only 1 year to get damaged. It’s the irony here. Now, what are the reasons? Mainly harsh climatic conditions, poor concreting materials and practices. So, this is not something that is acceptable, especially when we talk about very difficult to reach terrains and very harsh climatic conditions. So, objective of the concreting in cold weather should be like, you do it and do it in a proper way so that you don’t have to go back and then the structure doesn’t really experience a lot of repair but we are having a lot of structures where repair is needed.

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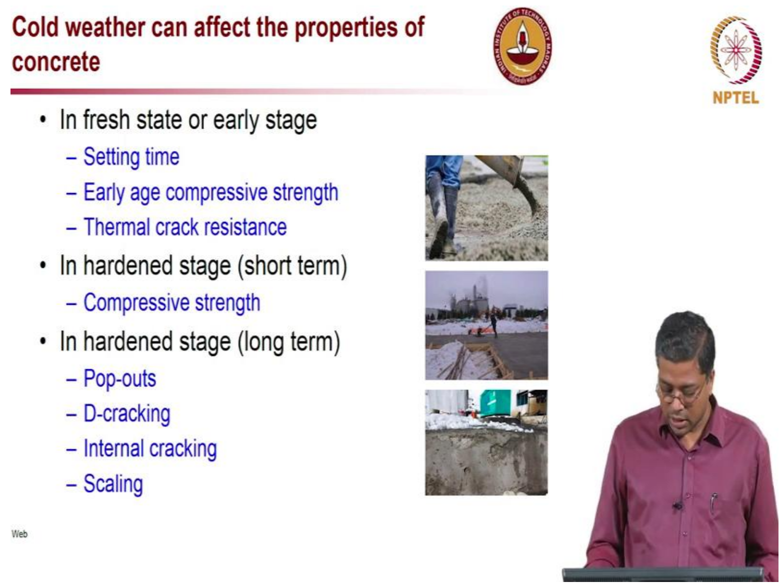

I am going to talk about what are the various mechanisms by which concrete in cold weather conditions deteriorate? What are the difficulties associated with concreting in cold weather conditions? Now, if you say in fresh state or early state of concreting, there are 3 parameters which are important to consider, the concrete should set very fast or as early as possible. And early age compressive strength also has to reach a significant, I mean reasonable level.

Typically, we say 3.5 MPa and then thermal crack resistance is also very important. So, all these can get affected when the temperature is very cold. In hardened state also, compressive strength may not reach the desired strength if the temperature is very cold and if concreting is not done with adequate measures. And other things which can happen in the long term are pop outs, D cracking, internal cracking, scaling, etc., so, we will cover all these in the remaining slides which are upcoming. What are these different mechanisms?

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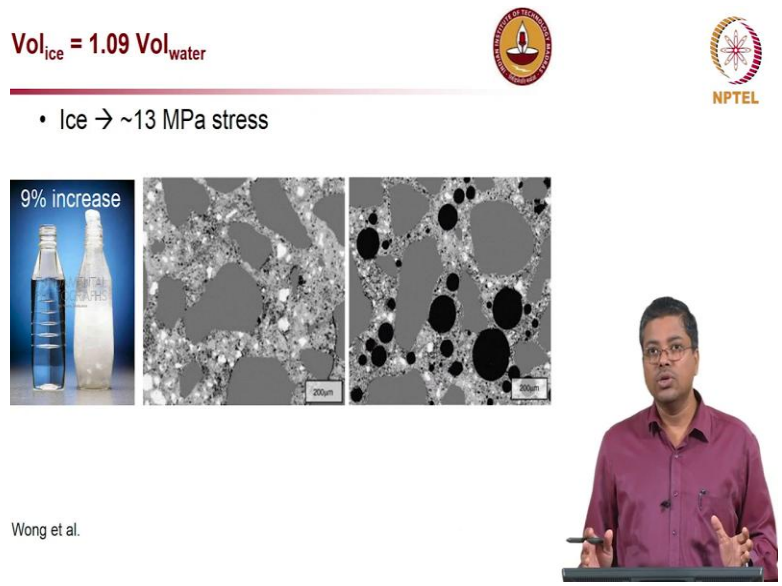

First thing when we talk about cold weather or frost attack is there is ice formation which happens in concrete. If the temperature is very low, the water which is used for mixing the concrete will become ice. As we know, ice formation means an increase in the volume which significantly, 9% increase in the volume, which leads to significant expansive stresses in the concrete

So, the first picture shows that 9% increase and the second picture shows a system where there is not enough space available inside the concrete which will eventually lead to cracking because of the this ice formation and the third picture is basically showing how can we control this scenario of cracking? The black circles which you see there in the third picture is basically the air voids which are introduced or entrained air voids, not entrapped but entrained air voids. In other words, its air added as an ingredient in concrete.

And we typically use about 5 to 6% of air, by using some chemical admixtures that is air entraining admixtures. So, the idea is these air voids will help to provide space for this ice formation without inducing any expansive stresses. So this is the main idea of how to handle cold weather concreting.

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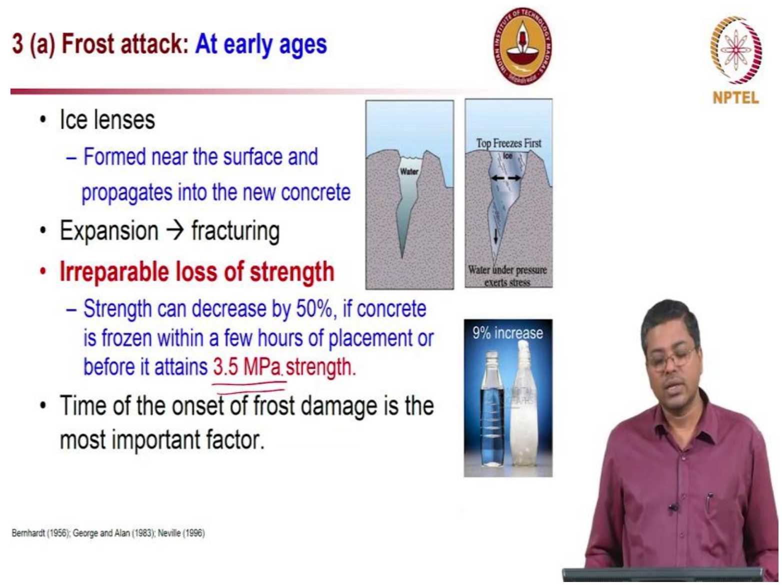

Let us see in particular some more details of frost attack which happens mainly at early ages. So these ice lenses are formed or ice is formed at the surface of the concrete first and then as it expands like you see on the picture on the top right, you will see that there is wedge like ice is formed and as it expands, it pushes into the interior concrete and which leading to cracking. Essentially they end up in fracturing the concrete or leading to cracking.

In fresh state itself this can happen and also in fresh state when this happens the mixing water is actually consumed which becomes ice and the sufficient water is probably sometimes not available for the hydration reaction also and what it ends up in is. You have an irreparable loss of strength which is very important, because if you do not get that strength, then that means it is irreparable loss. What it means is you cannot really gain it at a later stage and the strength can decrease by about 50 percentage.

If the concrete is frozen within first few hours of placement or before it attains 3.5 MPa strength, this 3.5 MPa strength requirement is given in most of the codes. So, in cold weather concreting, we have to first ensure that the concrete gets 3.5 MPa then you go for protecting that concrete further by ensuring adequate moisture and temperature. We will cover that later, but remember this number 3.5 MPa. It’s very important.

Time of the onset of frost damage is also most important that means if the frost damage is happening after 3.5MPa strength has attained then we can still manage to get sufficient strength later.

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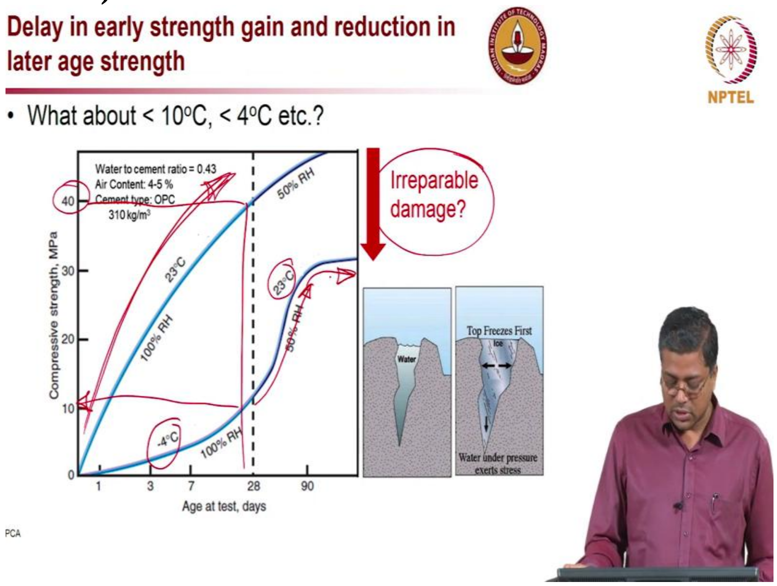

Let us look at delay in the early strength gain and reduction in the later age strength. So, this top graph, it shows strength gain of about 40 MPa in 28 days which is this line here, you get about 40 MPa, but the same concrete when the ambient temperature is -4 ^{0}C, it gains only about 10 MPa strength in 28 days. Thus there is significant reduction in the strength. Another important thing to notice here is after that when the temperature is maintained at about 23 ^{0}C, still it is not able to reach the strength which the other concrete which was exposed to 23 ^{0}C from the very beginning.

So, there is a significant reduction in the strength which I am going to call as irreparable damage. That strength you cannot gain even after about 90 days because you can see that the curve is almost flat. So, there is no significant strength gain after that. So, you have an irreparable damage when we are talking about very low temperature. This is something very important and let us see in the coming slides how to take care of these issues when you talk about cold climate.

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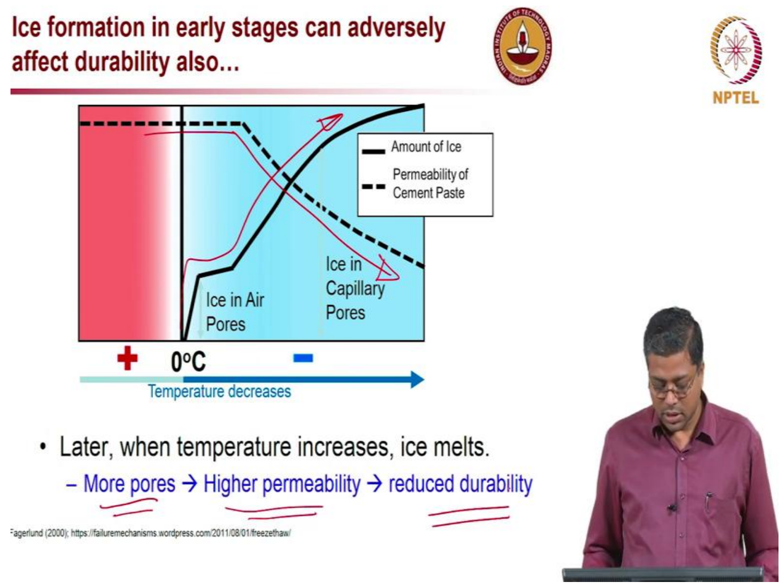

In the previous slide we were talking about strength, very low temperature can also affect durability of concrete. How it affects durability is, if you look in the graph here, this is the solid curve indicating the amount of ice formation and the dashed curve indicates the permeability of the cement paste or let us say concrete. You can see that the permeability decreases as more and more ice is formed.

In reality what will happen is, later once this mechanism is over, after some time, if there is an increase in temperature, and then the ice which is contained within the concrete will melt to become water. And that water might also evaporate at a later time anyway you will end up in having more pores or voids, which leads to higher permeability and definitely you will have reduced durability in such cases. Hence this frost attack is very important to consider not only for strength but also for durability.

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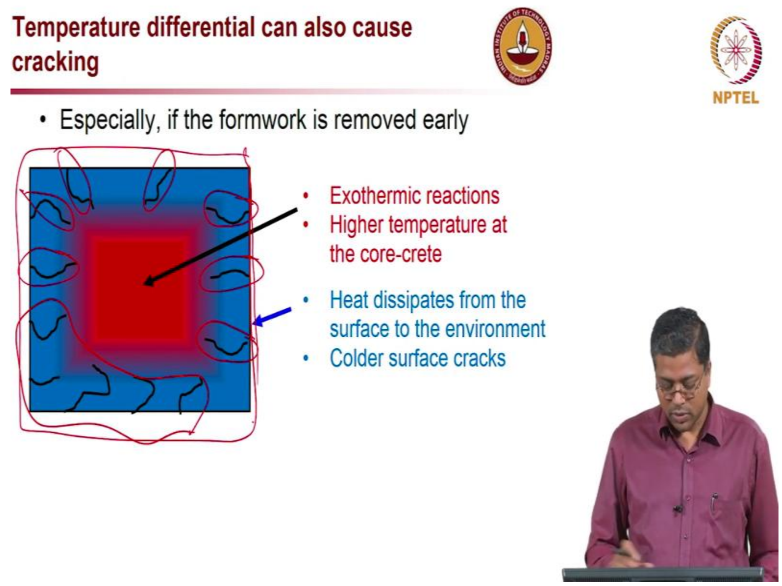

Now, other effect is temperature differential induced effect. You can see here, this is a schematic diagram showing mass concrete. Imagine this is a cross section of a concrete column and when the formwork is removed, the heat generated in this blue or the peripheral region is lost into the immediate environment which is actually cold. But at the same time at the core of the concrete you will still have reasonably high amount of heat. So, there is a temperature difference or differential temperature between the core and the peripheral region of the concrete.

Because of this differential temperature, you will end up in having the concrete which experience significant cracking near the peripheral region. All these black lines this indicate the cracked region. So, the cracking might happen at the peripheral region. And imagine our case if you have cracking and if you have reinforcement near the cover concrete, you will also have corrosion related problems at a later stage.

You don’t want the concrete to crack. So, how do you ensure that this does not happen is making sure that the heat generated inside is not lost into the atmosphere. So, you have to maintain a good formwork and a good insulation around the peripheral region something has to be covered. The concrete has to be covered with a good blanket or some measures.

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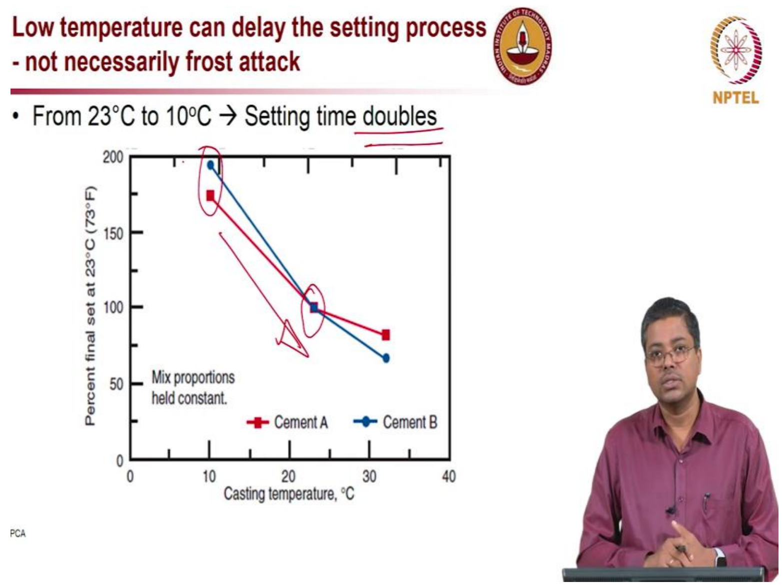

Now, talking about not that cold, but reasonably cold environment, which is like let us say, if the temperature is about 10 ^{0}C, what happens to the setting time? You can see here setting time is increasing almost by twice. You can see, final set there is doubled or 2 times increase in the setting time as you go from 23 ^{0}C to 10 ^{0}C.

So, this is the 23 ^{0}C data and this is the 10 ^{0}C data and it is a significant difference. So, you have to really consider various measures on how to ensure that the concrete is actually setting fast enough.

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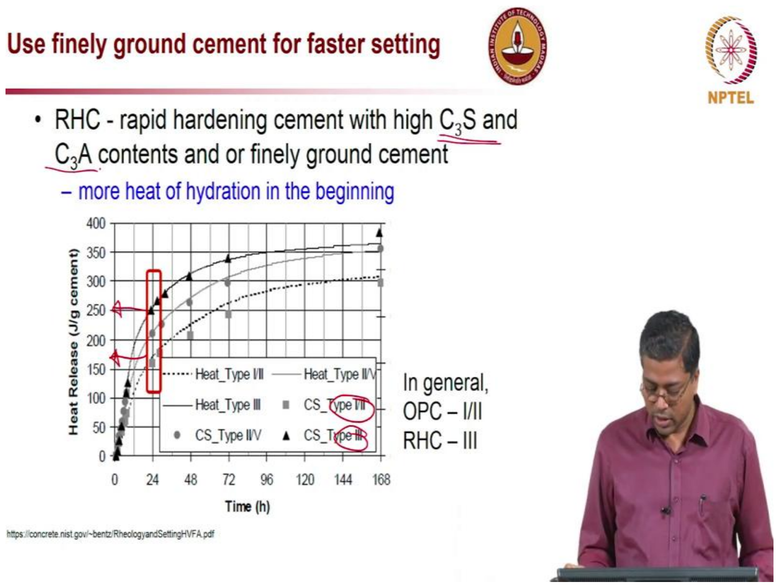

So, one way to achieve that is by using finely ground cement. Basically the idea here in the graph you will see type 3 cement, which is the designation used in the US and you have type 1 or 2 cement, which is the normal cement. So, you can see here that normal cement (type 1 or 2) which is the Square markers and the triangular one which is type 3, which is the finely ground cement.

So, definitely in 1 day that is 24 hours you see a difference in the heat release from 175 to about 250 that is about 75 joule per gram of cement. So, that much heat release difference is there, when you talk about different type of cement itself. So, that heat is necessary for the concrete to get cured better or in an accelerated manner.

And also we can use high C_3A and high C_3S cement which will actually help in making sure that there are more and more reactions especially in the early stages of curing or hydration.

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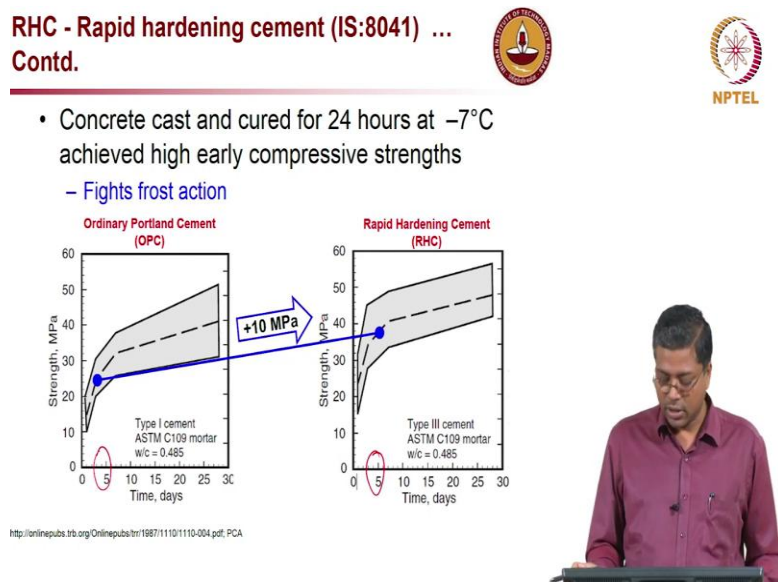

Now, this image here a graph shows, how the use of this rapid hardening cement can help in increasing the strength gain in the early period. So, let us look here about 3 to 5 days. And here also about 5 days, you can see that there is about 10 MPa strength gain or increase in the strength when you come back from OPC to rapid hardening cement. So, definitely the type of cement which you use definitely matters.

And the content like if the cement has high C_3A or C_3S and at the same time if it is finely ground, then definitely you can resolve some of the issues which happened at the early ages of curing.

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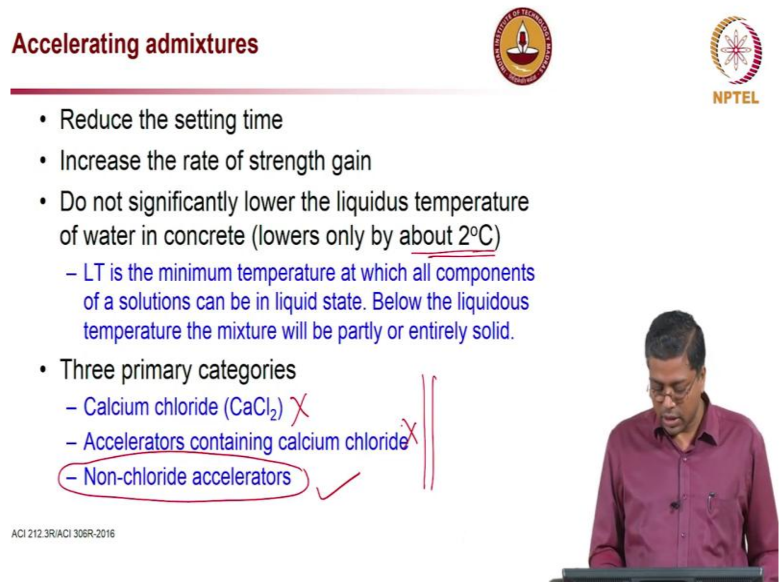

We also have accelerating admixtures until now we were talking about the cement or the mineral admixtures and how selection of cement can help in reducing the setting time and gaining early strength. Now, let us look at accelerating admixtures which can help in reducing the setting time and increasing the strength gain, especially at the early age and this accelerating admixtures they also actually reduce the liquidus temperature, but not significantly reduce the liquidus temperature or reduces only by about 2 ^{0}C.

What is this liquidus temperature? It is the minimum temperature at which all the components of a solution can be in liquid state and that means below the liquidus temperature the mixture or the concrete will be partially or entirely solid. So, we have to have some admixtures or some way by which we can ensure that the mixing water is available for reaction. I will come to that later.

But, before getting there, let us see this accelerating admixture. What are the 3 main categories? They use calcium chloride and accelerators which contain calcium chloride and also non chloride accelerators. So, I would prefer to use this non-chloride accelerators, probably we may have to avoid the use of calcium chloride and calcium chloride based accelerators because that might eventually lead to corrosion which is not a good idea. So, it is better to go for accelerators without any chlorides in them.

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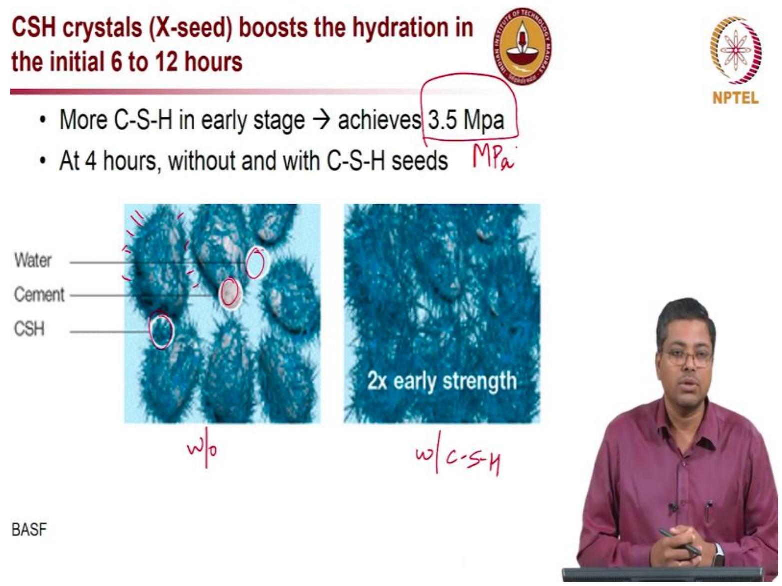

Now, there is also another technology where the admixtures contain seeds of CSH which function like nucleation points for further reaction to happen and help in setting. So, what you see here is you will have the CSH seeds, cement grain and then you have water and these are also the CSH, ettringite needles etcetera. You will see the needle shaped structure. So, here the picture on the left side is without the CSH seeds and whereas here this is with CSH seeds.

Now, this will help in gaining the early strength and reaching this 3.5 MPa. So that, 3.5 MPa strength criteria is achieved, especially for cold weather climates this is very helpful because the seeds provide the nucleation point for the cement hydration that is the technology.

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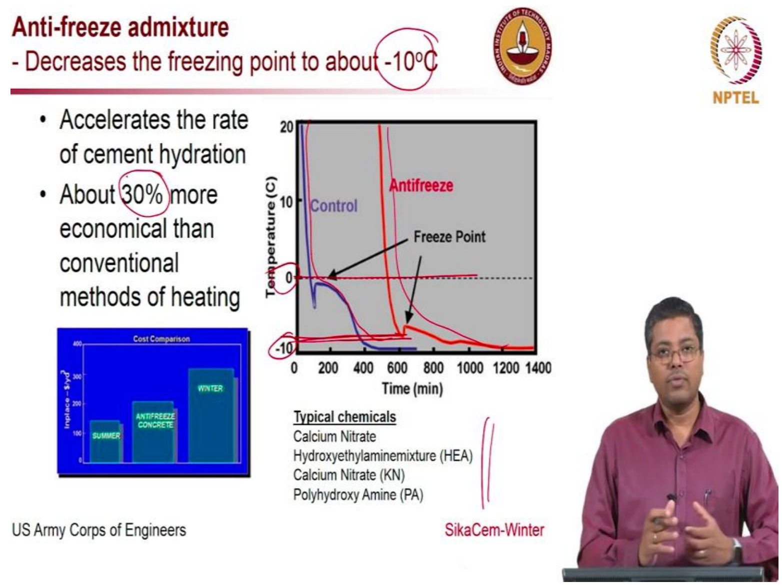

Antifreeze admixture is another technology where the addition of this admixtures reduces the freezing point of the mixing water by about 10 ^{0}C. From 0 it might go to – 10 ^{0}C. So, because of that reduction you have more water available for the hydration reaction. And you can see in this graph here when you have a controlled case where there is no antifreeze admixture this graph here.

And the red one with antifreeze admixture, you can see that there is a drop from 0 to about – 10 ^{0}C. So, that is the reduction in the freezing point of the 2 systems without and with antifreeze admixtures. So, essentially what it means is during the cold weather conditions or cold climatic conditions, you can have more time for construction. Also, that means we can pick a time and even if the temperature is up to – 10 ^{0}C, you can still do concreting with these admixtures.

These are some of the examples of chemical family which are used. And people have done some studies on how economical is this methodology of using chemical admixtures for mixing concrete. People have seen that there can be about 30% savings instead of going for heating or other conventional methods of cold weather concreting. So, just use a chemical, which will be added to the concrete and which can reduce the freezing point of the mixing water in concrete. So, that is the idea here.

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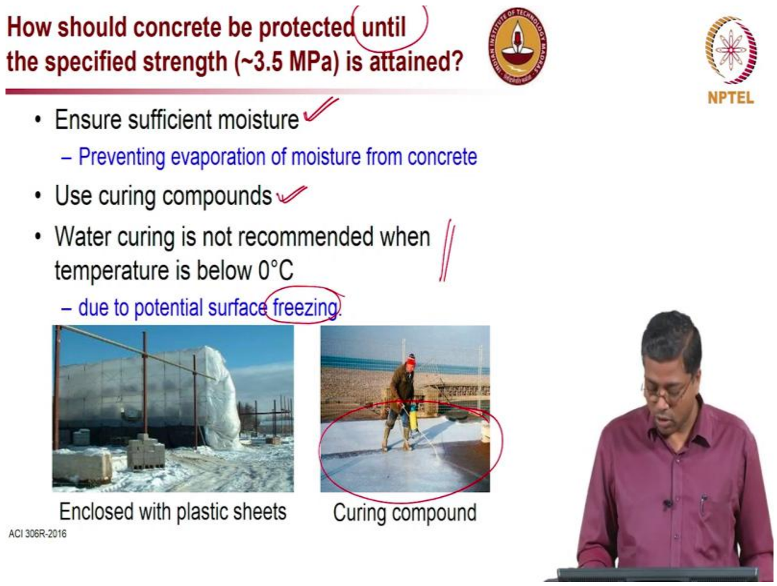

Now, how should concrete be protected until the specified strength of 3.5 MPa is attained, until that 3.5 MPa is attained that means very early stages in the concreting. First thing we have to ensure that sufficient moisture is available and how do we ensure? By preventing evaporation of moisture from concrete, because when you mix concrete based on your water cement ratio you already have the amount of water which is required for the hydration. All what we need to do is preventing them from getting out of the concrete that is prevent evaporation.

We can use curing compounds also to prevent the moisture loss from the surface. And one important thing to note here is, when the temperature is in the freezing range like less than 0 ^{0}C, it is not recommended to use water curing because that water which you use for curing will stay on the surface of the concrete which eventually freeze and which will lead to further damage to the concrete.

So, water curing is not a recommended idea. Main thing to do here is first protect your concrete structure with a plastic sheet or something like that. So, that water evaporation does not happen and then another way is providing a membrane, which is basically the water curing compound.

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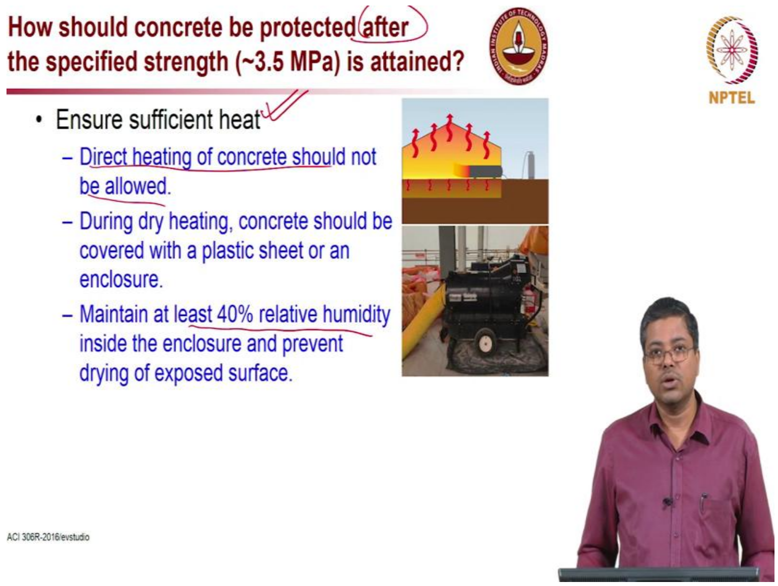

How should concrete be protected after the specified strength has attained, not in the very early stage, but after that. How do we ensure? Mainly by ensuring that sufficient heat is available or the heat which is coming from the concrete is not lost into the environment and also you can provide external heating to the concrete in this slide we are talking about external heating, which is direct heating of concrete, should not be allowed, directly we should not.

So, as you see in the picture on the top right you can see that there is a flame and then there is an enclosure on top of the concrete surface which provides hot air uniformly on the concrete surface. So, the uniform heating is essential, not direct heating or a localized heating and maintain at least 40% relative humidity inside the enclosure because if you keep it too dry then concrete will dry and it will not have enough moisture for hydration to happen, especially near the surface.

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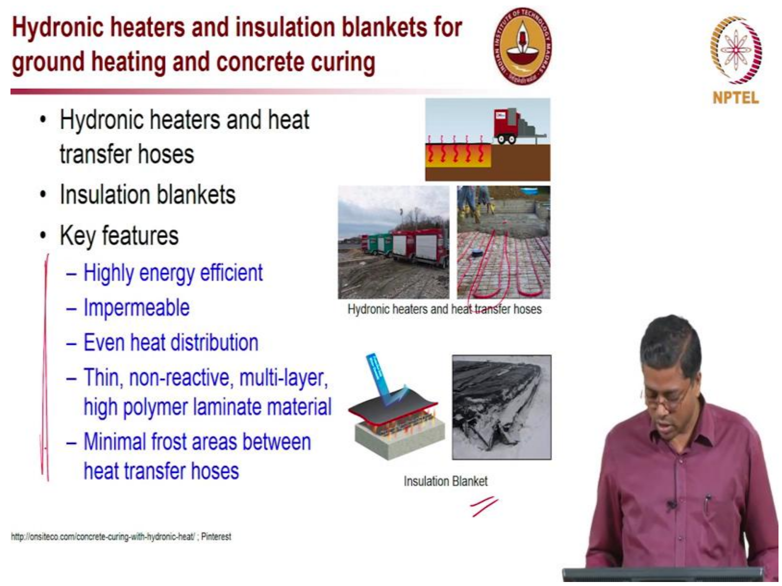

The other way is by keeping the environment hot or by providing external heat. Providing external heat by using hydronic heaters or heat transfer hoses and also by providing a blanket. So, two ways, one is the heat which is generated from the concrete has to be contained and other is, you can maintain immediate surroundings of the concrete whether it is air or the ground below has to be maintained at a reasonably higher temperature so that, the heat from the concrete is not lost into the environment. Here are some key features which you can read later on looking at what are the qualities to look for when you talk about this concrete blankets or insulation blankets.

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So, good quality concrete is possible, this picture very clearly shows that you can see that all around the concrete slab which is being constructed you have snowcapped region, I mean trees and the job site is very clear, there is no snow on the concrete surface. The concrete is well protected in this picture that plastic sheet which you see around and also the blanket it is going to keep the concrete well protected from losing the heat which is generated because of the exothermic reactions.

At the same time the immediate environment of the concrete can be maintained at a reasonably high temperature. So, protecting concrete is also very important. It is not only the materials which you put like finely ground cement or cement with high C_3S or C_3A and chemical admixtures like antifreezing chemical or accelerating admixtures, all that is fine when you talk about the material aspects.

Then you have to place the concrete properly and make sure that in the initial stage you have sufficient moisture available as water, preventing frost attack and then make sure that 3.5 MPa strength is gained and then protect the concrete by preventing further moisture loss and also heat loss. So, if you do all these things I think we can really have good quality concrete like we see in normal climatic conditions.

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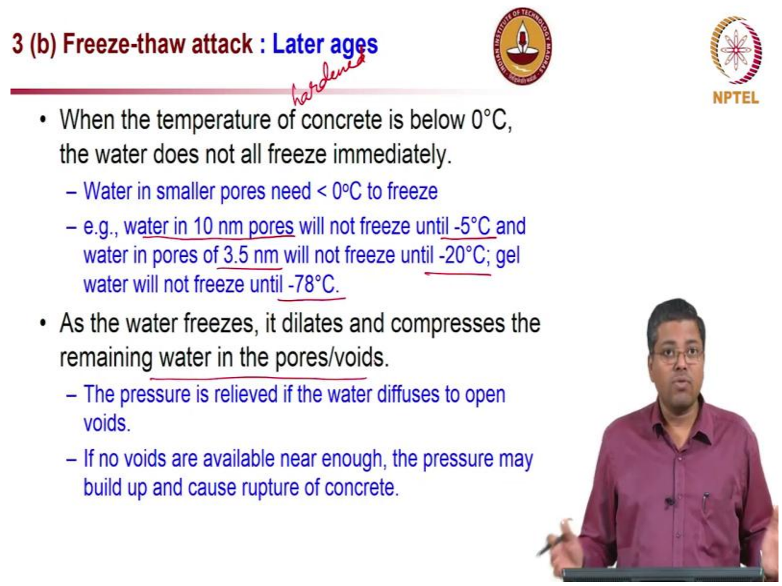

Now, freeze-thaw attack if you talk about which happens at later ages. So, when the temperature of hardened concrete is below 0 ^{0}C, all the water does not freeze immediately. So, the freezing point also depends on the size of the pores. So, water in the smaller pores need less than 0 ^{0}C temperature to freeze. Example if you are talking about water in 10 nanometer pores it will not freeze until – 5 ^{0}C.

If you are talking about 3.5 nanometer pore it will not freeze until -20 ^{0}C and if it is gel water will not freeze until - 78 ^{0}C that is much smaller pore. So, at the same temperature what it means is, there could be some water which is already frozen and some which is not frozen depending on the size of the pore where the water is staying or occupying.

And as the water freezes it dilates or expands and compresses the remaining water in the same pore. What happens is during this process of dilation, it pushes the water and that pressure is relieved if there is sufficient pathway available for that water to move into another pore or void. And if no voids are available in the near vicinity, then the pressure may build up, which eventually leads to cracking or rupturing of concrete.

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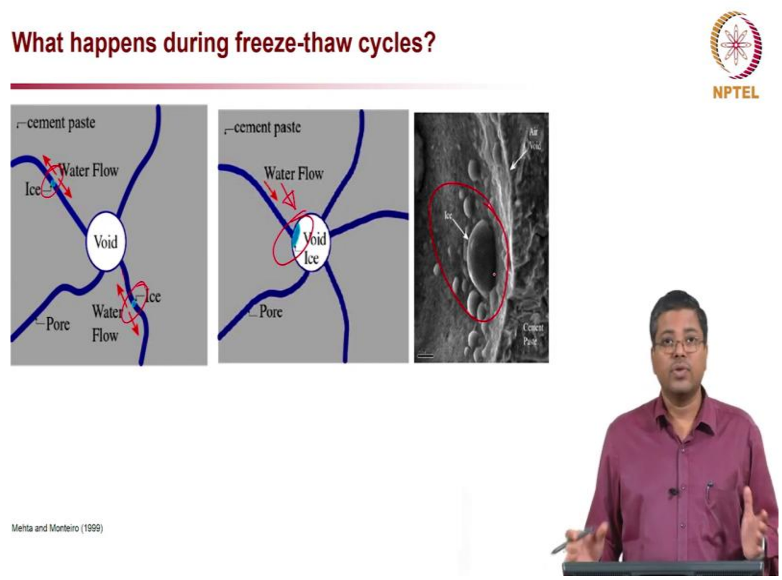

This is what I just mentioned. Here you can see a little bit of ice is formed, that ice will push the water near there and this water can actually flow into the void. And if that void space is nearby, you can see here water is flowing to this and then a small ice is formed. The picture on the right end shows that how this ice is formed. This is one of the classical images from Berkeley where they have captured this ice formation inside an air void in cement paste, a very nice image.

You can see a lot of ice formation happening and so this is what really happens. So if you have an air void, then it will not exert pressure, but if you do not have air void then it will exert pressure and lead to cracking.

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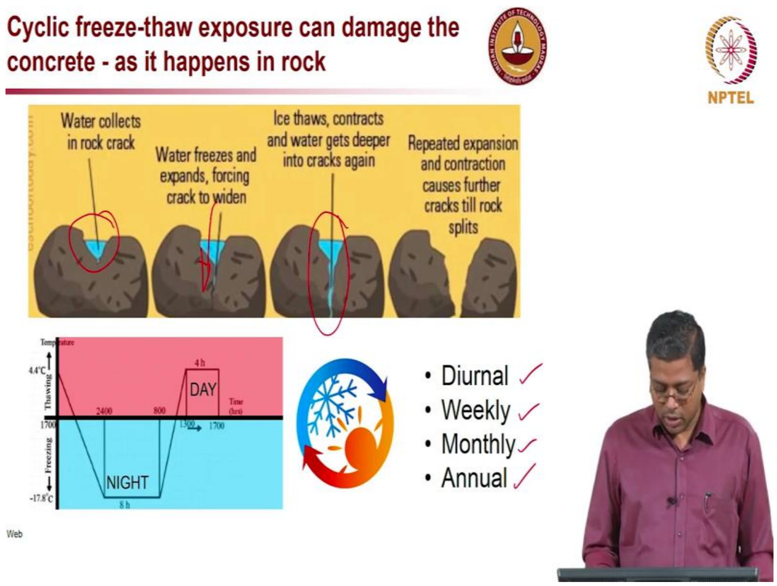

Now cyclic freeze-thaw exposure can also damage the concrete; I am showing an example of what happens in the web. This is a picture from the internet but I thought it is a very nice demonstration. So, thought of using it, you can see here in a small crack in rock, water collects and after some time that water freezes and then pushes down, you can see it pushes down and it expands and like a wedge it pushes in and here that rock is now cracked into 2 pieces.

So, something like this will happen depending on the number of cycles of freeze-thaw. So, for example, this number of cycles depending on the geographic location and climate, I mean, depending on the climatic condition, it could be daily cycle, like diurnal variations or weekly, monthly or even annual depending on where you are. The number of cycles is what matters here not the freezing time.

So, number of freeze-thaw cycles which matters. If it is more then you will have more and more damage induced into the concrete.

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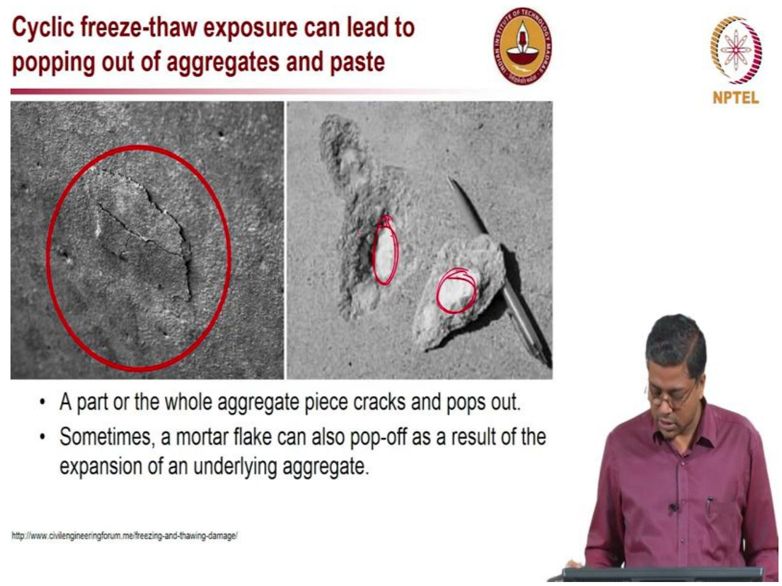

Cyclic freeze-thaw exposure can also lead to popping out. As we discussed this ice will form inside the concrete, it will push the cementitious system and it will lead to cracking and popping out, you can see on the picture on the left it is about to pop and then on the right side you can see that it is completely popped and then you can very clearly see the same aggregate is also cracked. So, the pressure is so much that it can also crack the aggregate. So, as you see this is the aggregate which is cracked.

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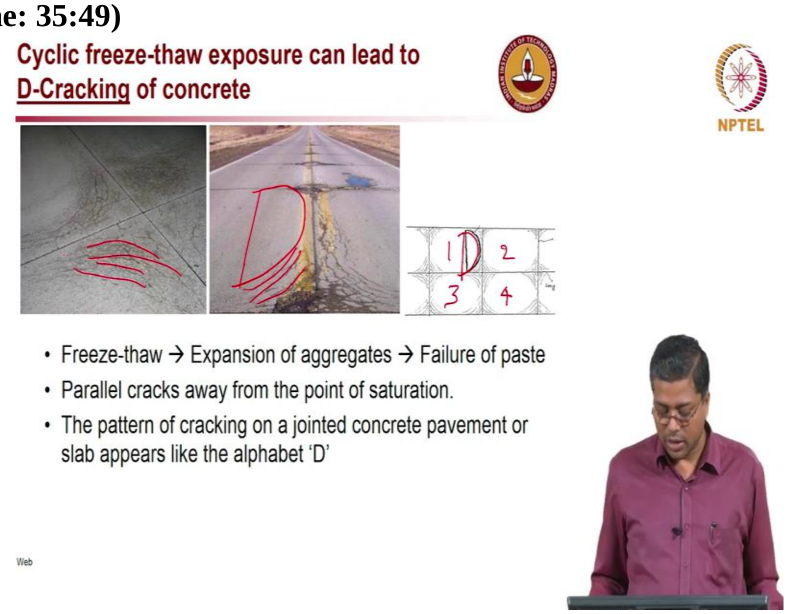

The cyclic freeze-thaw exposure can also lead to something called D cracking of concrete. Why this D cracking name? It comes based on the pattern of cracking on a joint at concrete pavement. You can see here picture on the right side or the sketch on the right side which shows 4 slabs 1, 2, 3, 4 and the joint, this shows like an alphabet D and that is why it is called D cracking.

And which is observed here; if I draw something like this, you can see that D cracking on this highway pavement and what happens during the freeze-thaw exposure? The expansion of aggregate might happen depending on the presence of pores inside the aggregates, it might expand because of the ice formation inside. And also eventually that expansive force will push the paste around and which will lead to the failure of the paste.

Parallel cracks away from the saturation points. So, you can see these cracks, these are the parallel cracks which are actually happening. So, here also you can see parallel cracks, they are actually away from the joint which is the saturation point. So, this D cracking is something which is widely observed especially on this exterior concrete structure, I mean exterior elements such as roads which are directly exposed to the environment.

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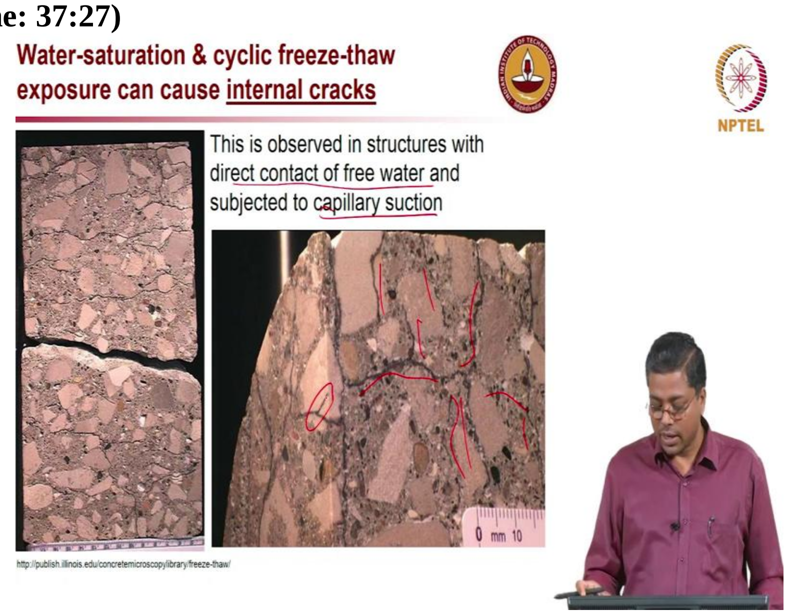

Water saturation and cyclic freeze-thaw exposure can also cause internal cracking especially in cases where the concrete is in direct contact with free water. So, because of the capillary suction the internal concrete absorbs or sucks in all the water from the immediate environment and when the temperature decreases that water will become ice not at the near surface.

But, water inside the concrete leading to multiple micro cracking or maybe in a larger crack also significant cracking you can see on this picture both the images you can see, even the aggregates are also cracked. So, all these expansive behavior, the stress induced because of them is very high, which will lead to cracking of aggregate and eventually of the entire concrete system.

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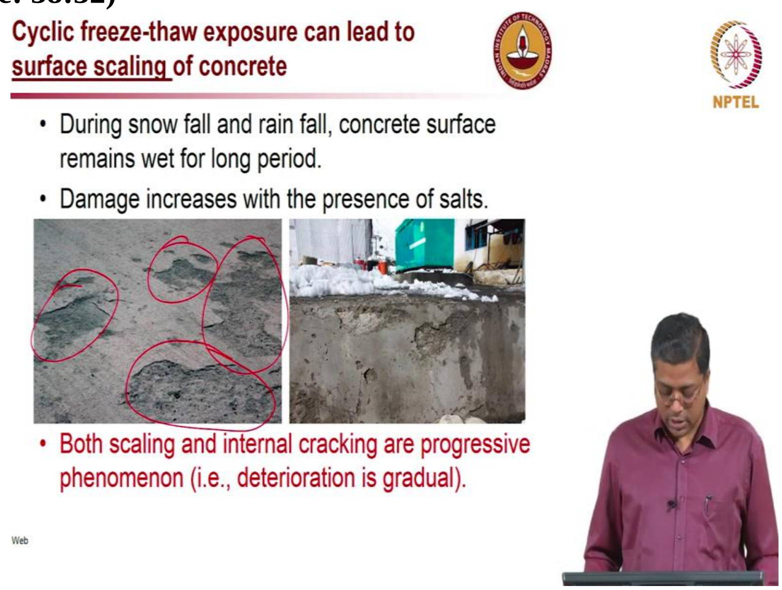

This kind of exposure can also lead to near surface scaling. You can see here, picture on the left side lot of material is lost at the near surface. So, this is again because of the formation of ice because of the absorption of water into the near surface of concrete and then with that ice formation it leads to cracking of the concrete at the near surface.

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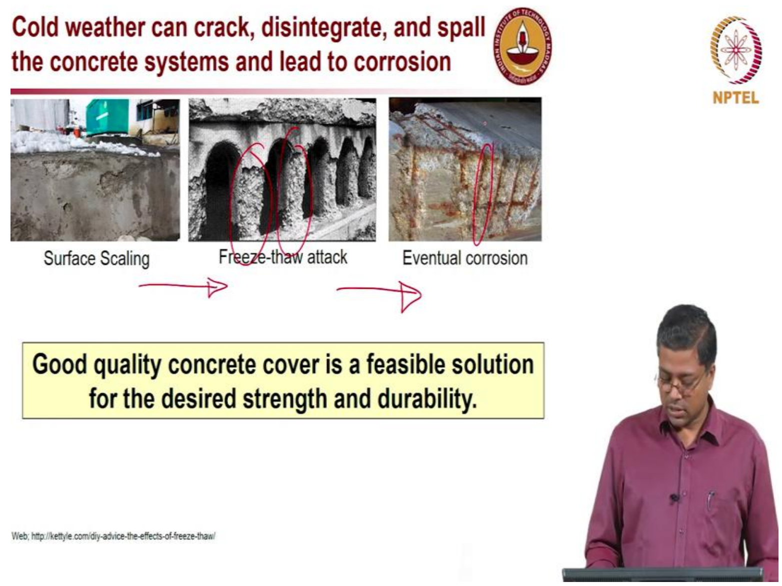

And eventually this surface scaling will happen and then eventually you will have multiple deterioration because new surfaces get exposed and then it leads to significant loss of the material as you see in this picture at the center and eventually the entire concrete cover can be lost due to this kind of freeze-thaw attack and then, once the entire cover is lost, then you will see, the reinforcement getting exposed and corroded which definitely affect the structural capacity of the system.

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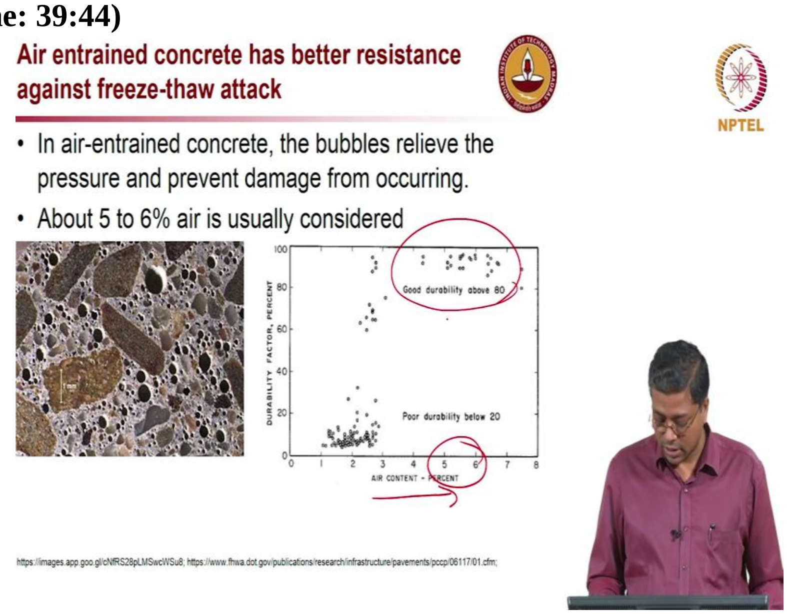

So, how do we handle? The main approach is to use air entraining admixtures. So that you provide enough air voids available in the concrete at which ice can form without exerting pressure onto the surrounding aggregates or the hardened concrete system. So, this picture also very clearly shows that, if you increase the air content about let us say 5- 6% you have good quality concrete or durability factor is increased.

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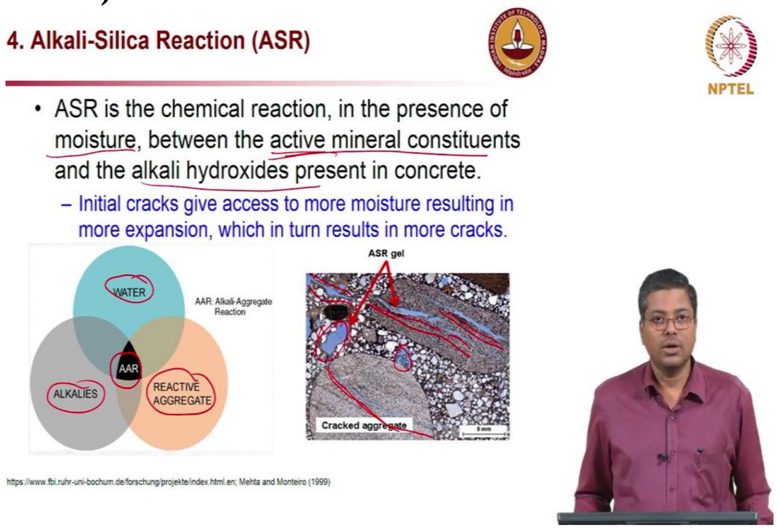

Now, another damage mechanism or deterioration mechanism is alkali-silica reaction. So, ASR is the abbreviation of alkali-silica reaction. Some people also call it as AAR, as you see here alkali-aggregate reaction. Because most of the aggregates are silica rich, we can call it alkali-silica reaction. What it is? It is a chemical reaction, which happens in the presence of moisture. And this chemical reaction happens between the active mineral constituents and the alkali hydroxides present in concrete.

So, what happens when you have water, alkalis and reactive aggregates? This combination leads to alkali-aggregate reaction or alkali-silica reaction, the picture on the bottom right shows an example how it looks like, you can see this all these blue colored region that indicates the gel, which we call ASR gel and this gel induces significant pressure on to the concrete system or it is expansive in nature.

Which leads to significant increase in expansive stresses and it can even crack the aggregate. You can see here, an aggregate is cracked. This is also showing aggregate itself is cracked and also significant cracking in the cement paste. Like we discussed in the sulphate attack, ASR also induces a lot of cracking of the concrete system or the entire matrix gets damaged.

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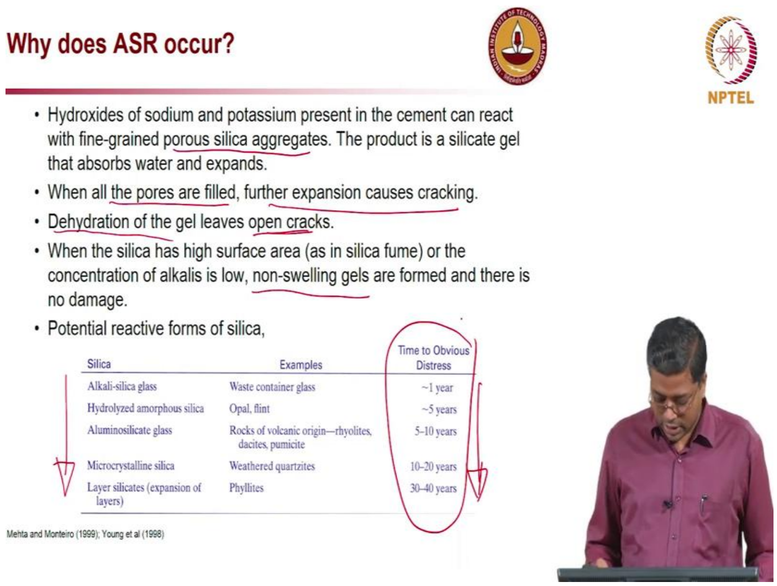

Let us look at why ASR occurs in concrete structures? As we know, there are a lot of hydroxides of sodium and potassium present in cement. And that can react with the reactive aggregates or porous silica aggregates. Especially when they are reactive in nature, they will react and form a gel that can absorb water. When it absorbs water, the volume increases and it induces expansive stresses onto the concrete.

Now there this gel absorbs the water and it occupies all the available pores and once all the pores are filled then further expansion causes cracking means until the pores are filled, there is no stress induced on to the surrounding concrete, but once the pores are filled then it starts inducing stress onto the surrounding concrete and leads to cracking. Let us say there is a dry environment and then all this moisture gets evaporated then it leads to dehydration of the gel and that will leave open cracks or voids in the system.

And later on, you can again have more moisture coming into the system and then further reaction can happen and this can lead to continued formation of more and more gel and leading to significant cracking. Now, when silica has high surface area and if the concentration of alkalize are low then you will have some non-swelling gels which may not induce really significant damage.

So, let us look at which type of silica can be selected. So, in this table as you see on the right side, it indicates if I use a particular type of silica, what is the expected life for that structure? As you go down on the table you get better and better aggregates.

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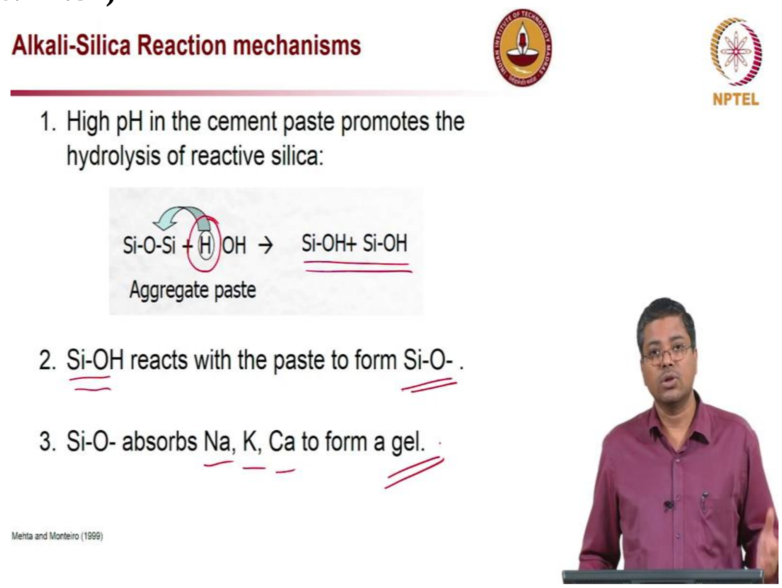

Now, what is the reaction mechanism? So, the high pH in the cement paste promotes the hydrolysis of reactive silica and you can see here hydrolysis of reactive silica and it becomes Si-OH bonds and then this Si-OH bond reacts with the paste to form Si-O and which further absorbs or reacts with the sodium, potassium and calcium to form a gel and this is the gel which we are calling as ASR gel which is expansive in nature or sometimes it absorbs the moisture and expands.

$$\text{Si-O-Si} + \text{H OH} \longrightarrow \text{Si-OH} + \text{Si-OH}$$

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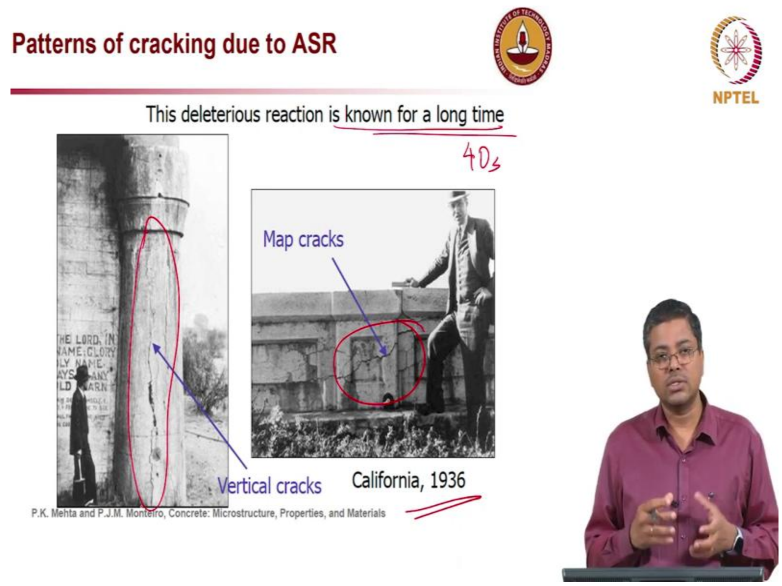

What are the types of cracking which we observe or how can we detect? So, this deleterious reaction is known for long time in 1940s itself people have identified this published in 1940s. This picture you can see in 1936 which is one of the first images showing ASR induced cracks, you can see its map cracking not a specific direction.

And here also you can see, vertical cracks on a column because on the column you have reinforcement and when there is a reduction in the strength of the concrete the reinforcement will try to push the concrete or in other words the crack is along the stress path, but it is not straight line crack, if you look close up you will see that there is lot of map cracks on this column also. So, essentially what it is telling is, the cracking is happening because of this thrust generated from within the concrete system and not because of the corrosion or any other mechanisms..

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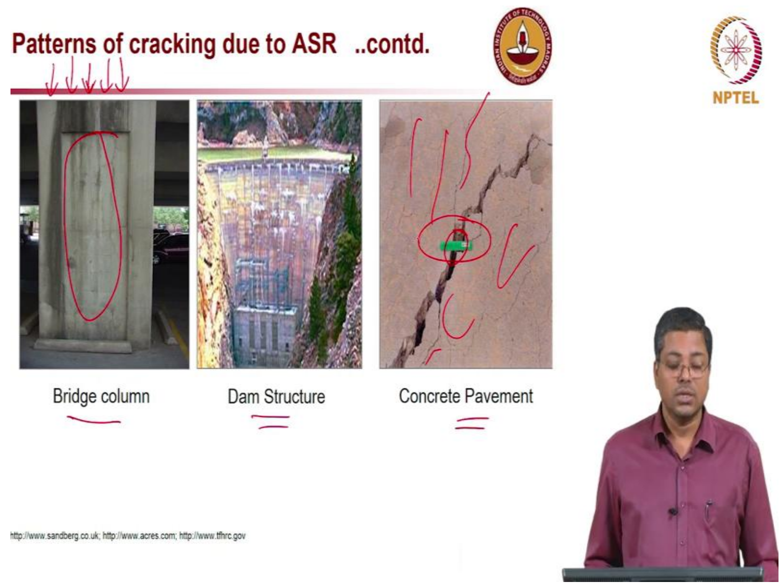

You can see in this picture on the left side you have a bridge column and I have seen this bridge column on the other side of this same bridge; you do not have any cracking. The same concrete on one side you have significant cracking and on the other side you do not have any cracking. Main reason is on this side with a side which is visible to you. Unfortunately, I do not have the photograph of the other side.

But you can see here there is significant cracking and this is mainly because there was a drain pipe and it was giving water or providing sufficient moisture for the ASR reactions to happen. So, as I showed earlier in the bottom left picture, water is also a key factor. So, if you can keep the structure very dry, you may not see ASR induced reactions.

So, there are other examples like a dam structure and concrete pavement where also you can see significant map cracking these are all due to ASR induced cracking or you can see the width this is at least about an inch wide crack there.

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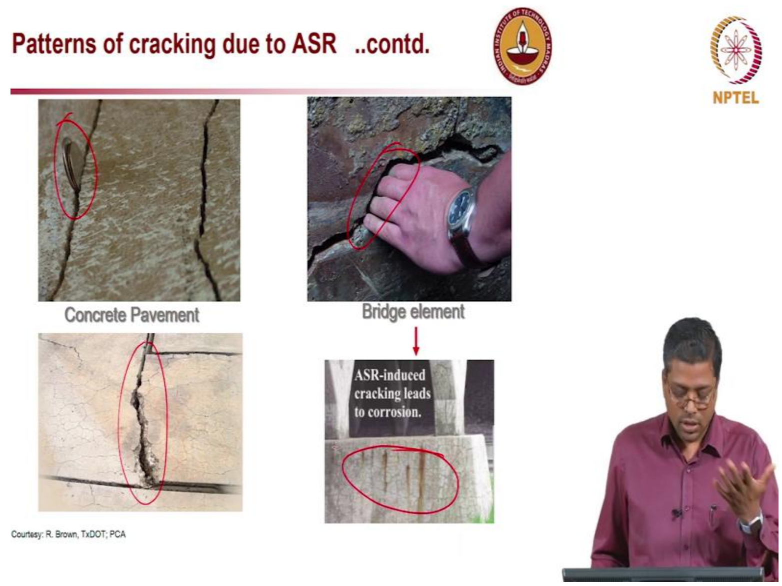

And these are additional examples showing how significant this cracking can be. So, on the left you can see a coin and then the fingers are inserted into the crack and then also significantly wide crack on slab elements. And main point is all these cracks will lead to or will help other deleterious elements to enter the concrete and eventually lead to corrosion of the reinforcement inside which is a big problem later.

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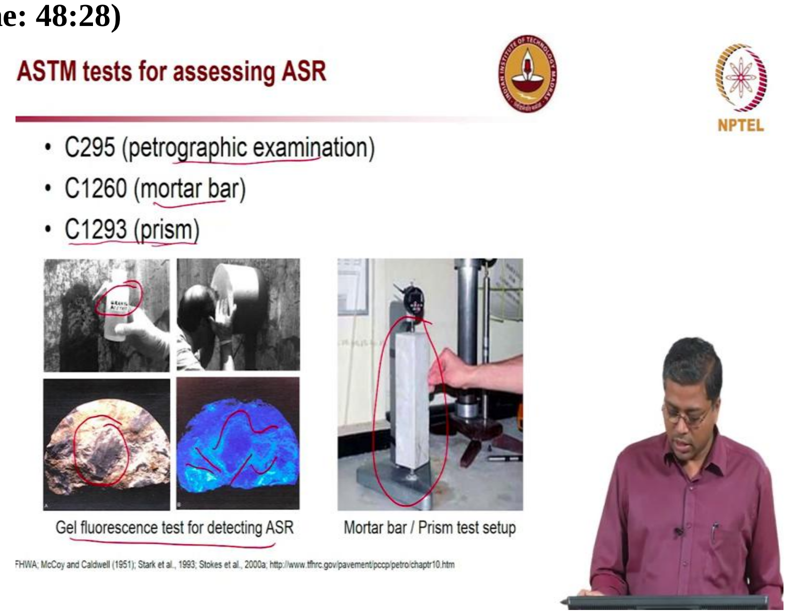

Now, how do we test for assessing ASR? I am just showing multiple tests here. First thing is looking at the type of aggregate or if there is any ASR gel present in the system. So, this is one test where urinal acetate is used. You spray this onto the concrete surface and then you can look through and then see that gel fluorescence test for detecting ASR. So, on this picture you can see this is the aggregate region and you can very clearly see that around the aggregate you have some different color and that is all indicating the presence of ASR gel.

And there are also other tests like mortar bar test and prism test where mortar bar is mainly just to look at the cement paste system or even the mortar system, not the large aggregates presence, but there is also another test which is concrete prisms. So, the picture on the bottom right side is just to show you how both these mortar bar or prism test is done. Basically a prism is made and then we look at the change in the length. If it is expanding, there will be increase in length of the specimen and that will tell you how severe could be ASR. I mean, how severe ASR type reactions can happen

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Now, let us say you already finished the construction of particular structure and then you find that there is ASR type problem and how do we mitigate that? I am going to show you multiple types by which people have tried impregnating the structure with lithium, people say that is the best technology so far.

And here the first one is by spraying lithium on to the concrete surface, these are concrete roads, and this is a barrier you can see there and also vacuum impregnation is also applied here in the first one you spray it. The second over here it is vacuum impregnation where you create a vacuum pressure to suck the lithium solution into the concrete surface but it is probably more expensive to do all these, it is not very easy.

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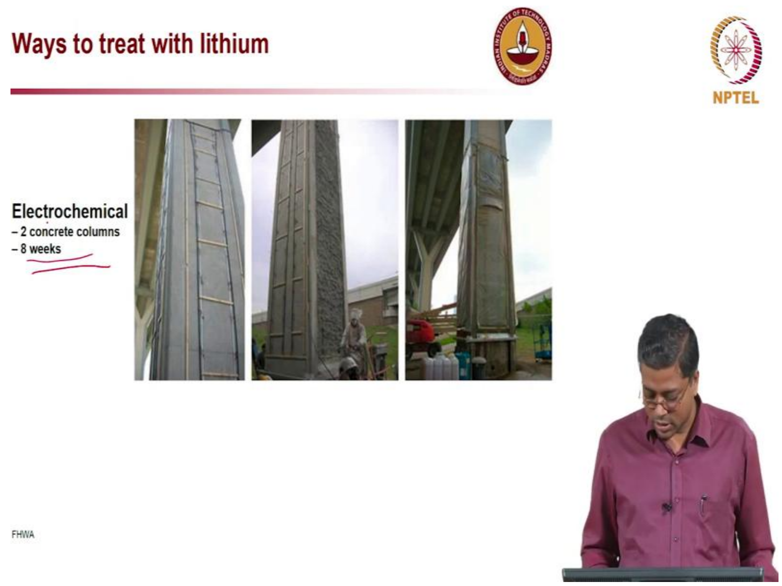

Also there are electrochemical methods where you apply a particular voltage, which will drive the lithium ions into the concrete. But again, just look at here, this particular project for 2 concrete columns, it took almost 8 weeks to impregnate sufficient lithium into the concrete. So, it is expensive but, sometimes you might end up in situations where it is very important and you cannot really look at money but to protect the structure.

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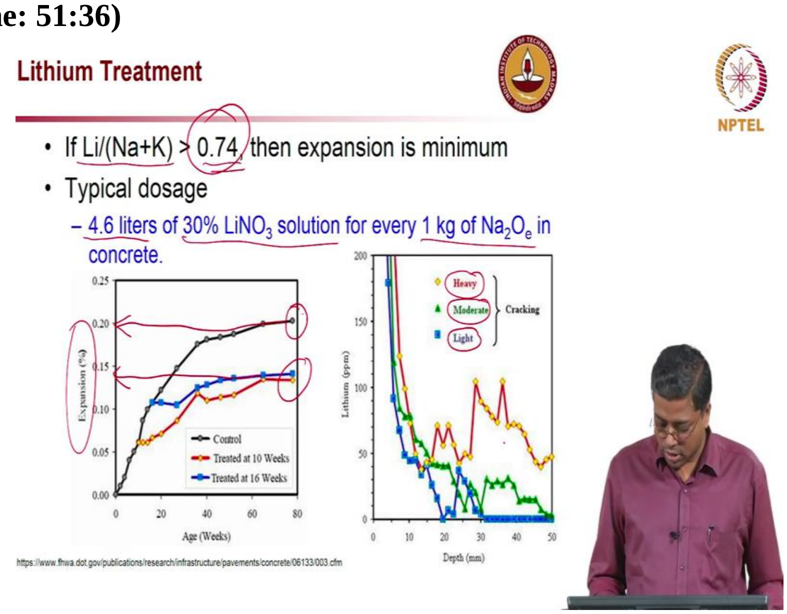

Now, how this lithium treatment? What is the idea behind? So, if the lithium to the (sodium plus potassium) concentration if it is greater than 0.74 then we say the expansion is minimum. So, this is the typical value used, the ratio requirement how much lithium to be impregnated. So, typical dosage is about let us say 4.6 liters of 30% lithium nitrate solution for every 1 kg of sodium oxide equivalent in concrete.

So, the graph here at the bottom left shows the difference between the expansions exhibited by a control system that means no lithium treatment and this is lithium treatment for 10 weeks and 16 weeks. So, point is, you have significant reduction in the expansion from about 0.2 to less than 0.15%. I mean, that is significant reduction that is about 30% reduction in the expansion. And also if you have heavy cracking, moderate cracking or light cracking the amount of lithium requirement is also apportioned accordingly.

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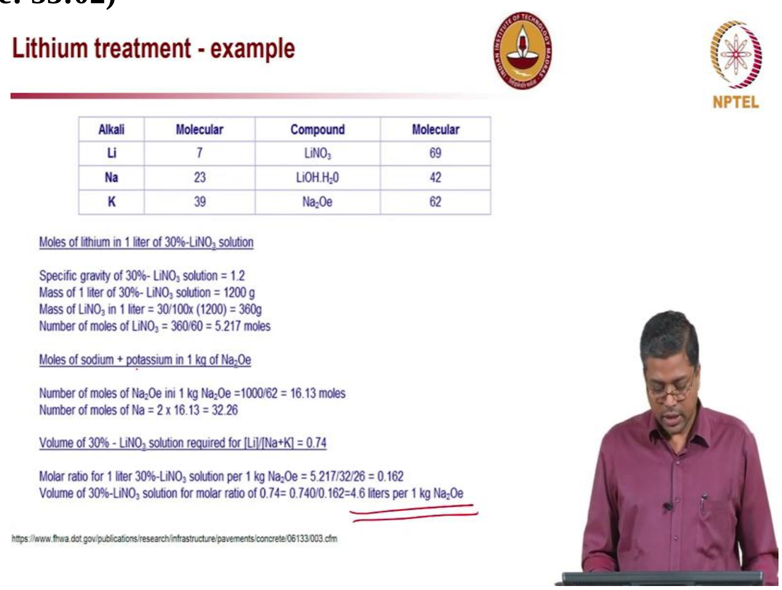

This is an example showing how this amount 4.6 liters per kg of sodium oxide equivalent is come up with so you can go through this more details later.

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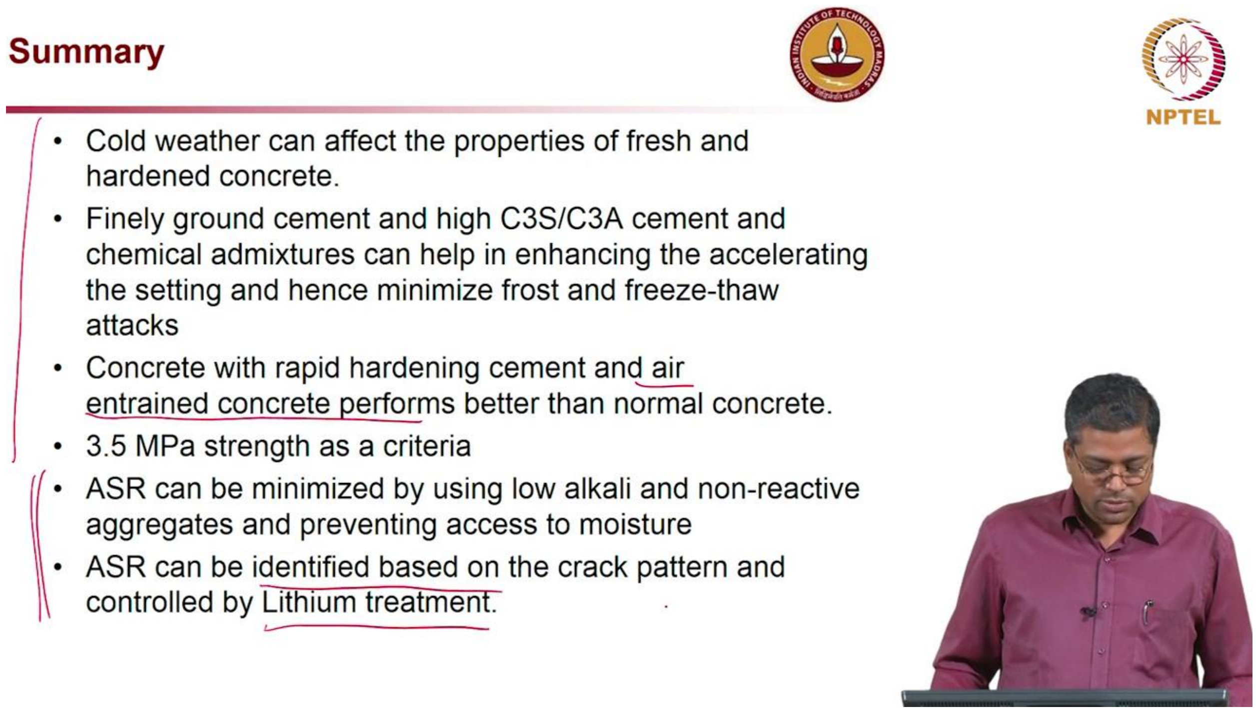

So that's it, for summarizing, we looked at both the cold weather concreting and associated issues and the ASR. So in cold weather we were talking about cold weather can affect the properties of fresh and hardened concrete and finely ground cement and cement with high C_3S or C_3A content and chemical admixtures either an accelerator or an anti-freezing chemical can help in enhancing the setting time and also I do not have it written here but air-entraining admixtures can also help.

Here air entrained concrete performs better than normal concrete and this figure of 3.5 MPa strength. You should ensure that the concrete achieves 3.5 MPa strength and then further protection of that concrete is essential by ensuring that sufficient moisture level is maintained and at the same time sufficient heat is maintained then concrete will continue to develop further strength.

We saw that ASR is basically the reaction between alkali content in the cement and the reactive aggregates and different types of aggregate can have different levels of reactivity and you have to probably choose low reactive aggregates so that such ASR related problems will not happen and ASR can be identified based on the crack pattern typically map cracking and it can be controlled by lithium treatment.

Also, this is not very easy to do, it is very time intensive and expensive method. So best way is again like I mentioned in the last class, prevention is better than cure. So, if we can take care of good quality materials, if we can ensure that good quality materials are used, we can avoid ASR induced problems also.

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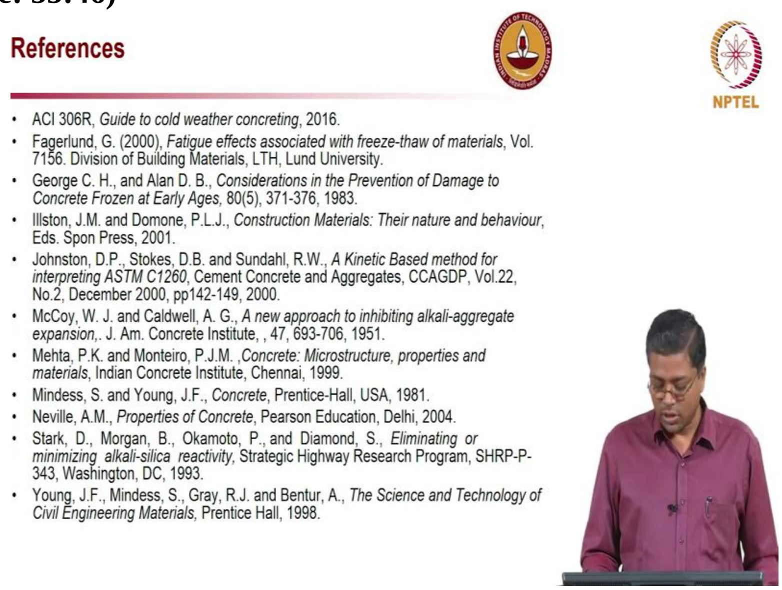

So, these are the references which were used for making this lecture notes. Thank you.