Maintenance and Repair of Concrete Structures
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Module No # 01
Lecture No # 02
Corrosion of embedded metal; Carbonation-induced and chloride-induced corrosion

Hi, welcome to the second lecture on corrosion of embedded metal. In this lecture, we will be covering carbonation induced corrosion and chloride induced corrosion.

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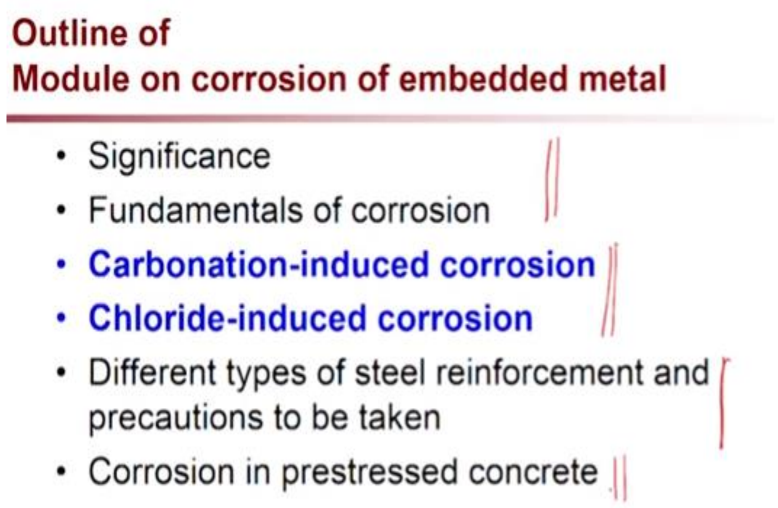

Outline of
Module on corrosion of embedded metal

- Significance
- Fundamentals of corrosion
- Carbonation-induced corrosion
- Chloride-induced corrosion
- Different types of steel reinforcement and precautions to be taken
- Corrosion in prestressed concrete

This is the outline of the module on corrosion of embedded metal. Where, we will have 5 lectures. First, we already covered as lecture 1, which is mainly on significance and fundamentals of corrosion, and then in this lecture, we will be covering carbonation inducted corrosion and chloride inducted corrosion, and 2 lectures on this and 1 lecture on corrosion in pre-stressed concrete.

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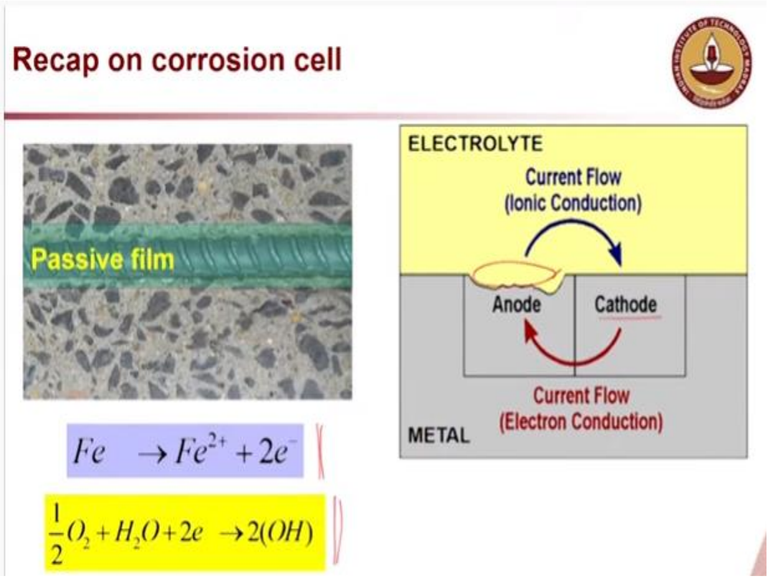

Recap on corrosion cell

$$Fe \rightarrow Fe^{2+} + 2e^-$$

$$\frac{1}{2}O_2 + H_2O + 2e \rightarrow 2(OH)$$

So just a quick recap, on the lecture 1, where we covered basics of corrosion. When we put the steel in concrete, we found that there is something called passive film forms, which, prevents the corrosion of the steel further. And we also looked at 4 components of the electro chemical cell, where you have an anode (the region the corroding region is defined as the anode), then the other region on the metal which functions like a cathode, and then at connection, ionic and electronic conductor.

The metal itself functions like an electronic conductor and the concrete will function like an ionic conductor or any solution to which the metal is exposed to. The anodic reaction which we are mainly talking about is

$$Fe \longrightarrow Fe^{2+} + 2e^-$$

The cathodic reaction is

$$\frac{1}{2}O_2 + H_2O + 2e^- \longrightarrow 2(OH)^-$$

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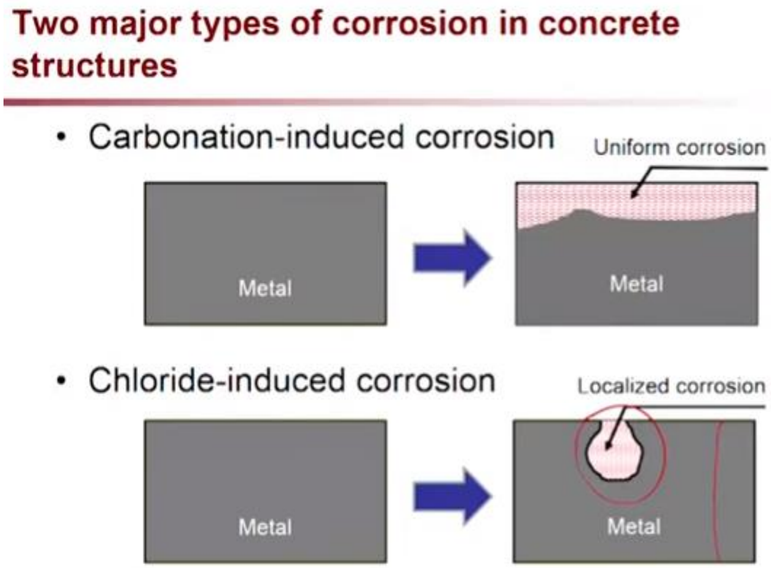

Two major types of corrosion in concrete structures

- Carbonation-induced corrosion
- Chloride-induced corrosion

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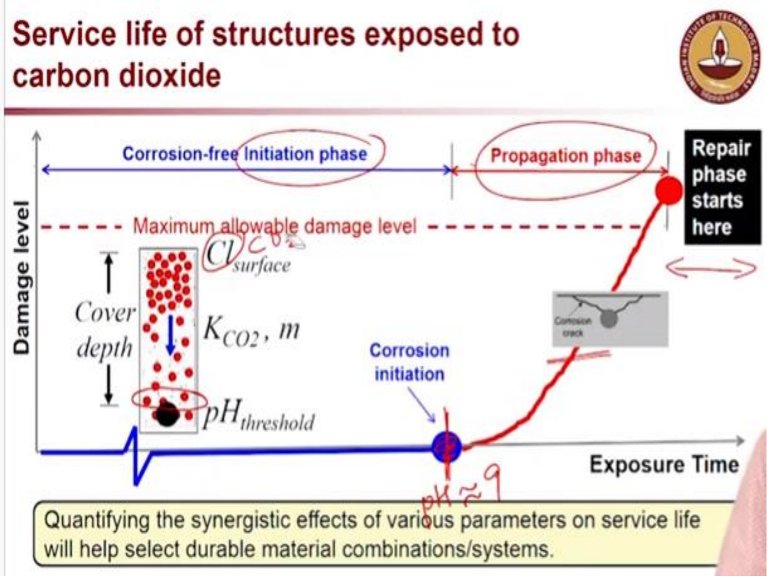

Service life of structures exposed to carbon dioxide

Quantifying the synergistic effects of various parameters on service life will help select durable material combinations/systems.

Now, let's look at how the carbonation influences the life of the concrete structures. What you are seeing here is a schematic of various phases of concrete structure. The blue region indicates the initiation phase, essentially, we can say that is the phase where there is no corrosion happening, because corrosion have starts to occur at this time.

So, during initiation phase there is no corrosion happening. Now what is happening during this initiation phase is that the carbon dioxide in the atmosphere will try to penetrate into the concrete and react with the concrete, and try to reduce the pH of the concrete. When the pH of the concrete in this region (near the steel surface) reaches a value of about 0.9, steel will start corroding, and that is at corrosion initiation point (blue dot on graph).

Now, beyond that point the steel will continue to corrode and it will lead to cracking of the concrete. we call this phase as propagation phase. Now the steel will continue to corrode and reach a particular level where, you have to start doing the repair or the structural safety may be a concern. We start repairing the structure and that is starts from here (Red dot on the graph).

How do we achieve this, is by looking at different factors which effect the carbonation and carbonation induced corrosion and we have to look at various factors, not just one factor to be looked at, all the factors influencing carbonation and carbonation induced corrosion should be looked at and then really we should say okay a particular system will actually have a long life. I want to correct one thing here (in graph), it is not actually chloride please make a change, it is Co2, carbon dioxide concentration at the surface of the concrete.

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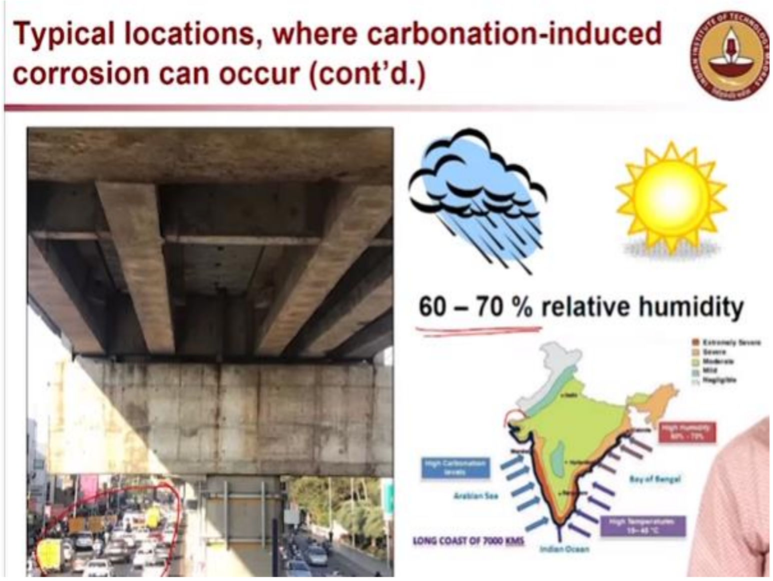

Typical locations, where carbonation-induced corrosion can occur (cont'd.)

60 – 70 % relative humidity

Now, let's look at some typical locations where, carbonation can happen. This is a bridge, you have lot of vehicles here, so the near surface of the concrete elements can actually have very high concentration of Co2, because of the all the exhaust gas from these vehicles. This level could be much larger than atmospheric Co2 concentration.

So, this kind of structures can experience carbonation, especially when the relative humidity is about 60 to 70 percentage. You might see that there are several locations where Relative humidity is very high due to rain. If relative humidity is beyond 70% you may not see that high carbonation but 60 to 70 percentage is very bad for the structure when you talk about carbonation induced corrosion.

And that is also reason for corrosion in the coastal region, usually we think that in the coastal region we see only chloride induced corrosion. But that is not usually the case, carbonation can also happen, but most cases you will see that chloride induced corrosion will be the governing thing but carbonation can also happen. Do not neglect carbonation when you talk about coastal regions.

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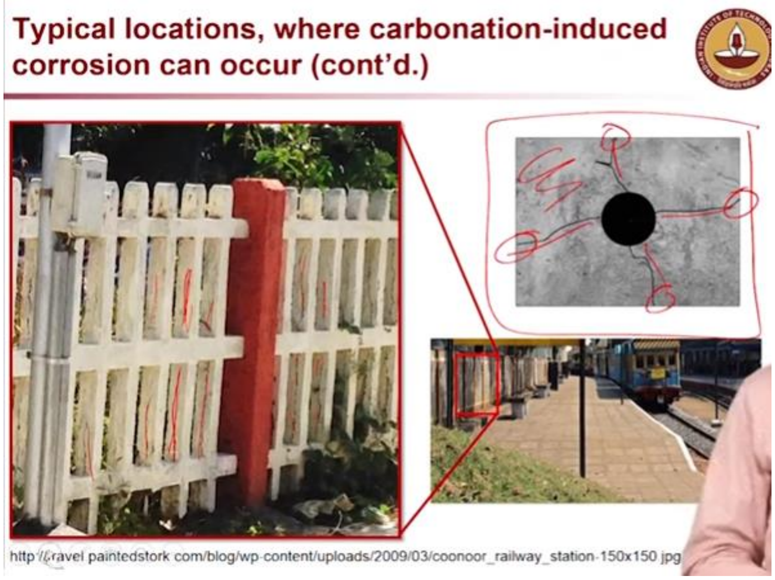

Typical locations, where carbonation-induced corrosion can occur (cont'd.)

http://travel.paintedstork.com/blog/wp-content/uploads/2009/03/coonoor_railway_station-150x150.jpg

Other type of structure where carbonation can happen is typically on railway platforms. At railway platforms or railway stations you will see this kind of fences, look carefully in picture, you have lot of these vertical cracks along this vertical member exactly through the center of it. Actually these members, if you look at the cross section of these vertical members it will look something like this (picture in the top right corner), and what is happening is this portion here is actually very porous mortar which they use for making these fences, even if it is concrete but the aggregate size would be very small.

And what you will see is they are very porous in nature and the steel inside there will be one rebar which is inside this fence that will corrode, expand and it will lead to cracking. We looked at in the last lecture that once the steel starts corroding, there is about 6 times volumetric expansion. which will lead to corrosion cracks like this (Picture in the top right corner).

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Mechanisms of carbonation and carbonation-induced corrosion

CO_2

CO_2

$Ca(OH)_2 + CO_2 \longrightarrow Ca(CO)_3 + H_2O$

$pH \approx 9$

Uniform corrosion

Let’s now look at what is the mechanism of carbonation and carbonation induced corrosion. I already explained this, but let me explain once more. As you see here (See picture in the slide), the Co2 can penetrate into the concrete and then it will react with the calcium hydroxide which is present in the concrete. In this reaction what is happening is this calcium hydroxide which gets consumed. If the consumption of calcium hydroxide is too much then it will eventually reduce the pH of the concrete, of course concrete has a high buffering capacity.

However, there may be a case when lot of reaction happen then the pH will reduce. If the Co2 penetrates and reaches up to this level (Steel surface), then the pH of the concrete around the steel reinforcement becomes about 9 then you can see that the steel will start corroding.

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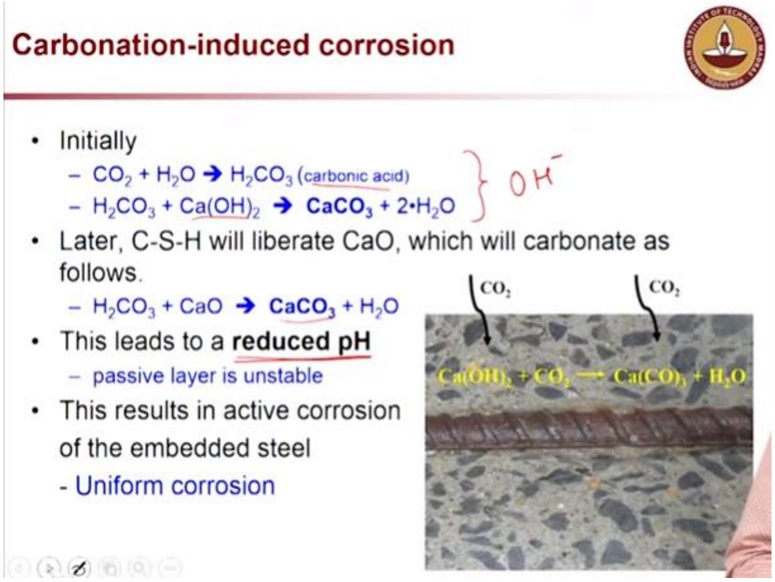

Carbonation-induced corrosion

- Initially
  - $CO_2 + H_2O \rightarrow H_2CO_3$ (carbonic acid)
  - $H_2CO_3 + Ca(OH)_2 \rightarrow CaCO_3 + 2 \cdot H_2O$

  } OH^-
- Later, C-S-H will liberate CaO, which will carbonate as follows.
  - $H_2CO_3 + CaO \rightarrow CaCO_3 + H_2O$
- This leads to a **reduced pH**
  - passive layer is unstable
- This results in active corrosion of the embedded steel
  - Uniform corrosion

This is a more detailed intermediate reactions on this mechanism. What first happens is carbon dioxide will penetrate into the concrete to react with the moisture, and it will form carbonic acid, which then reacts with the calcium hydroxide. So, eventually in this reaction we have consumption of OH-, and then at a later stage, what will happen is CSH or the calcium silicate hydrate will also liberate calcium oxide, and it will also lead to formation of calcium carbonate.

So, if effectively you have a significant reduction in the pH of the concrete, steel is no longer protected.

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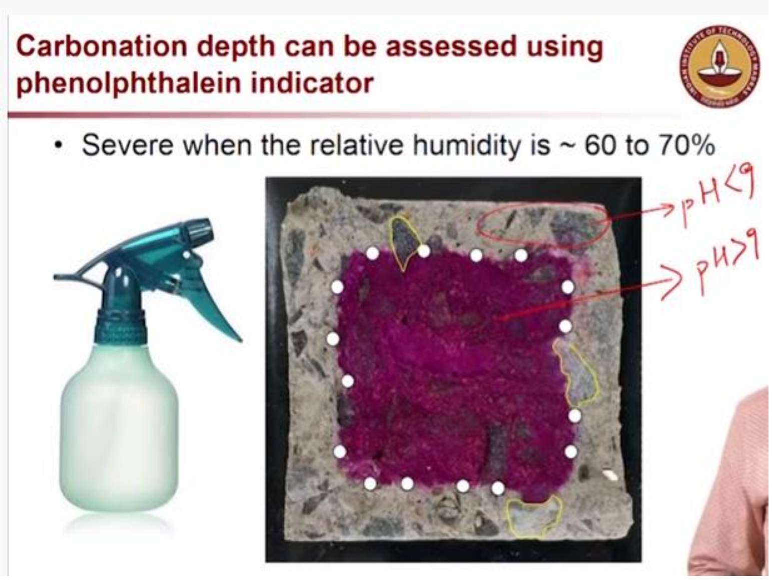

Carbonation depth can be assessed using phenolphthalein indicator

- Severe when the relative humidity is ~ 60 to 70%

Let’s look at how this carbonation depth can be measured by using simple test. If you remember, earlier college time in the chemistry lab you might have used phenolphthalein indicator to see a change in the pH. So, as in the same way we do, we can spray this phenolphthalein indicator onto the concrete surface and depending on the pH of the concrete surface it will change the color.

For example, here this colorless region (Picture on the right side) or when this solution is sprayed, there is no change in the color. This region, indicate that pH of that region is less than 9, and whereas in this region the pH is greater than 9. That means, the region with pH less than 9 is highly carbonated, and the region with pH greater than 9 is uncarbonated region. Of course, you can also think like, Co2 penetrates from outside to inside. So, of course, the outer or the peripheral region will be carbonated before the interior.

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This steel is about to start corroding

Carbonated concrete
pH < 9

Uncarbonated concrete
pH > 9

NOTE: Rebars should NOT be cut while extracting cores for condition assessment

Now, if you take a core from the concrete structure (you can see there is a rebar), actually by looking at this image, I can say that this rebar is going to start corroding very soon, because the carbonation front is almost reaching the steel surface.

Now, if you wait for longer time, you will see that the region at steel surface will also becomes colorless and that means the steel is gets exposed to carbonated concrete, and pH is low so it will start corroding. However, I want to mention one very important thing here, we should never extract a core with rebar, you should do a proper check, whether, there is any rebar present in the area where you are going to core, you should not damage the structure. Because, by cutting the rebar you are actually damaging the structure which should not be done. So, it is very important to check whether there is a rebar before you actually take a core.

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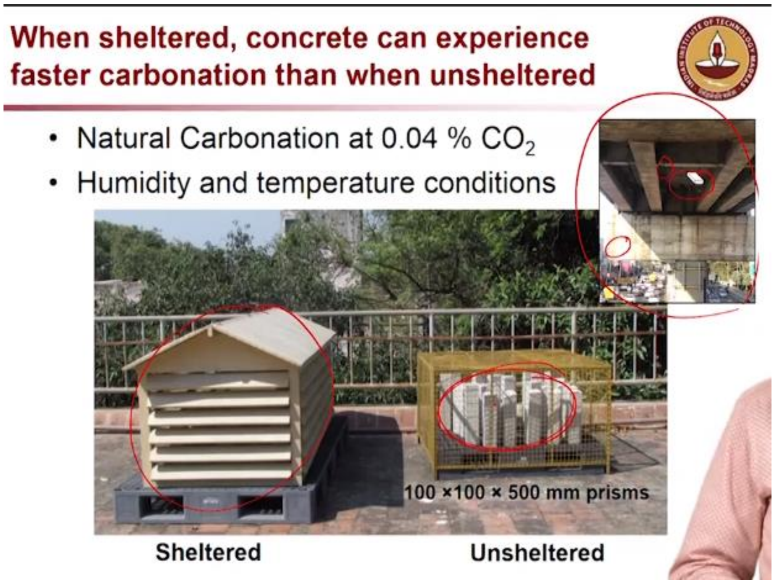

When sheltered, concrete can experience faster carbonation than when unsheltered

- Natural Carbonation at 0.04 % CO_2
- Humidity and temperature conditions

Now, this is a photograph of some experiments which we are doing in our lab. What we are doing here is looking at how exposure condition influences the rate of carbonation in a particular concrete. We have similar kind of specimens inside this shelter also. What we found is when you have sheltered specimens or the specimen where it is not directly exposed to the sunlight, you can actually have more carbonation.

So, in other words, specimens inside this shelter will have more carbonation than those specimens which are exposed directly to sunlight. If I relate that to a real structure imagine that this particular bridge (Picture in the top right corner) is actually having same concrete in all the elements, however, I would expect that the region here (Between girders) will have more carbonation that this region over here(Pier cap), because, most of the time pier cap is exposed to the direct sunlight.

So, you have a very low internal humidity over there (Pier cap), whereas in this case (Girders), it is very difficult to change the relative humidity, so, that leads to more carbonation in this region (girders), than in this region(pier cap).

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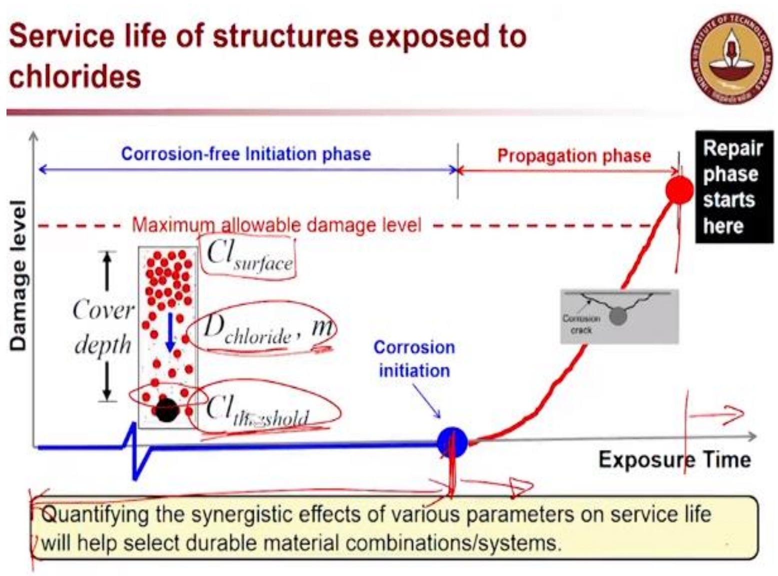

Service life of structures exposed to chlorides

Quantifying the synergistic effects of various parameters on service life will help select durable material combinations/systems.

Now, let’s look at chloride induced corrosion. What is happening is very similar to the carbonation induced corrosion. what you will see is there is also an initiation phase which is indicated by blue region. These are the factors which influence, you have chloride surface chloride concentration, and then you also have the rate diffusion coefficient, which indicates the rate of penetration of the chloride into the concrete.

And, there is also another term which is called decay constant, in other words this is very important when you talk about new type of concretes and because which keep on hydrating for longer period of time, and then you might see that the diffusion coefficient keeps changing as a function of time. So, we have to consider that also when we talk about service life estimation and all that.

In other words, you should not just look at 28-day diffusion coefficient, and then compare different concretes, it is not the right way to do. More details on this will be covered towards the end of the course. When we talk about service life estimation, there is a very important parameter which we say chloride threshold, which is the amount of chloride required to initiate the corrosion, when we talk about chloride induced corrosion.

Now, what is happening here is the corrosion initiates at this point (Blue dot in the graph), so the chloride penetrates through the concrete cover reaches the steel surface, and it is keep on building up at this steel surface. And when the chloride content over there reaches the chloride threshold value, then you can say that corrosion will initiate at that point of time. Now the time from the beginning until this point (blue dot in the graph), we can say it is corrosion initiation time, and beyond that we can say it is corrosion propagation period.

Again, as we discussed in the carbonation induced corrosion case, we start doing the repair work right here (red dot in the graph). Now, we have to see how to build durable structures, which is mainly a phase from here to here (Corrosion-free initiation phase + propagation phase), or some people say it is up to here (Corrosion-free initiation phase), and then you have propagation phase. we also have to worry about durable repair, that is also very important to look at how to ensure that the repair, which we do is also durable, which is main focus on this course.

We have to really look at synergistic effects of chloride diffusion coefficient, chloride threshold, and surface chloride concentration. How all these have to be looked at and the service life should be estimated. Then only we should decide which material combination or system should be selected. We should not make comparison just based on diffusion coefficient or just based on chloride threshold, the synergistic effect on service life should be considered.

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Typical locations, where chloride-induced corrosion can occur.

- Seawater, marine conditions

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Now, let’s look at where we usually see chloride induced corrosion. I mean we see in many places, I am going to show you some examples, where, it is more prominent. Main, first of all, it is sea water or marine conditions, where whatever structure, which is exposed to either seawater may be in direct contact with seawater or very close, proximity to the sea water you can have chloride induced corrosion.

So, here, this is a concrete pier (1st picture in top row), or a pile, where you can see significant corrosion at that wet dry region, here also (2nd picture in top row) splash zone all this you can see lot of corrosion on all these elements, because you have very rich chloride environment, and here also (3nd picture in the top row), it's again a port structure you can see lot of corrosion here. In fact, this particular structure there is a lot of repair also being done, but we found that those repairs also were not lasting long enough, so lot of repeated repairs have been done on this particular structure.

This, is a view of a bridge (1st picture in bottom row), from below. This bridge is located right above a water body. This (2nd picture in bottom row) is an interesting thing where people are tried to actually protect from chloride induced corrosion, you can see a jacket placed right around the columns near the splash zone. Which prevents this particular problem (1st picture in top row) from happening. In this (3rd picture in bottom row) you can see this say temple view actually here, this is very close to the sea and you can see the rebars inside this elements are also severely corroding.

And, actually most of these types of architectural features that those elements will be made out of the very rich cement, rich concrete's, which actually should not be a practice anyway just wanted to mention that, less the cement better the concrete will be.

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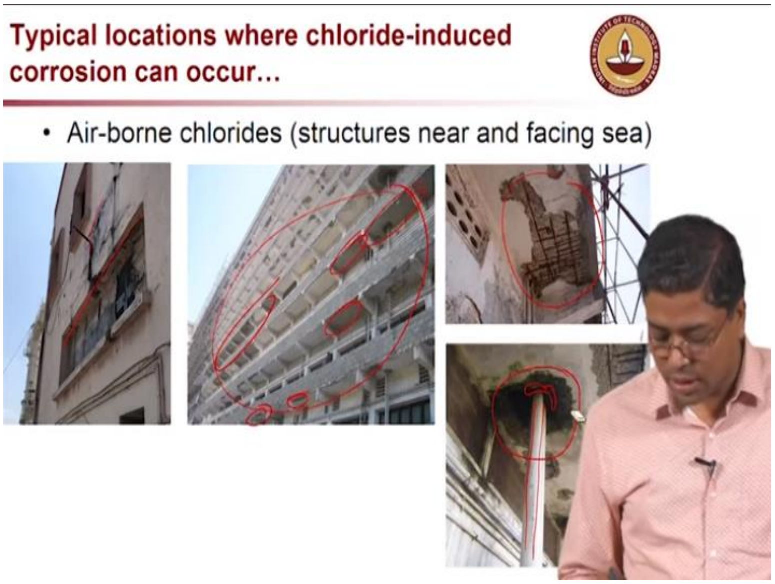

Typical locations where chloride-induced corrosion can occur...

- Air-borne chlorides (structures near and facing sea)

Okay, Now, some other locations we talked about where we talk about direct contact with the sea water, or very close to the sea water, and if you move a little bit away from the sea shore, again you can have a lot of air born chlorides. This is one building (1st picture), where you can see very severe corrosion cracking, this is also very close to the seashore. This is another building again facing seashore (2nd picture) you can see a lot of areas with lot of patchwork happening, you can see all this.

And then, 3rd picture is a close up of one of the sunshades in picture 2, you can see this very severe corrosion and another thing to mention is, I mentioned earlier moisture and oxygen are essential for corrosion to happen, especially, when we talk about reinforced concrete elements. Now, here you can see (4th picture), drain pipe over here, usually what we do is we don't give any space around the drain pipe, when we drill a hole through a concrete element, we pack all that region with mortar.

So, what is happening is, this drain pipe does not have any space to move, and which leads to breaking or cracking of this drain pipe, especially, if it is made of a brittle material. So, we should think about those aspects also and try to provide some cushion you know, over here. So that the pipe will not be broken, when there is some movement. And, in that way we can actually prevent this moisture ingress into the concrete around or moisture attack of the concrete around the drain pipes.

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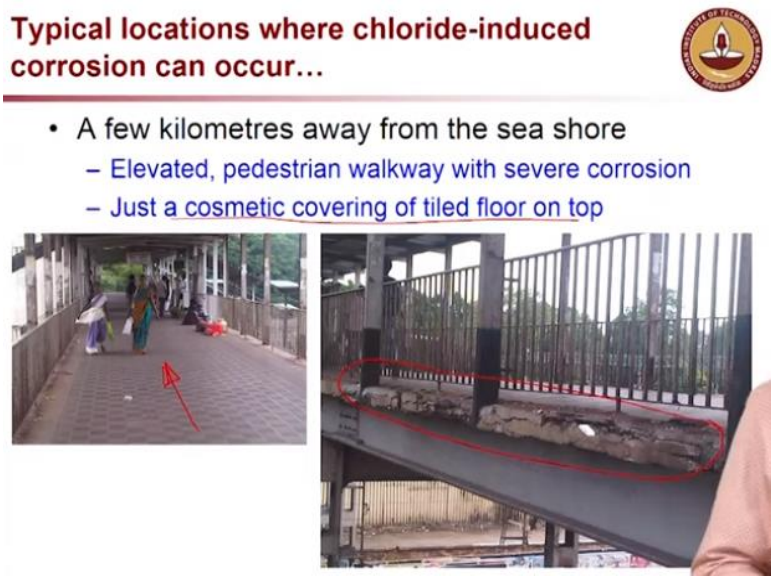

Typical locations where chloride-induced corrosion can occur…

- A few kilometres away from the sea shore
  - Elevated, pedestrian walkway with severe corrosion
  - Just a cosmetic covering of tiled floor on top

Now, other examples which I would like to mention is lot of this pedestrian highways or elevated structures, we usually walk on top of this and then we see that everything is fine, you see nice tile flooring and everything is fine (1st picture), but if you just look below the tiles this is how that looks like (2nd picture). This is from the same structure and this is also located very close to the sea shore, you can see how severally corroded these elements are. So, just by putting a cosmetic, I mean, I would say that this tiling is just a cosmetic thing, it is not really addressing the root cause of this problem here.

So, we should be very careful, just look is not important you have to also address the core concrete, which really gives a strength to the structural element.

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Typical locations where chloride-induced corrosion can occur…

- Chemical plant with chloride-rich local environment

This is another example of a localized chloride attack, this shows picture of a building, where it is a chemical plant, actually this region over here (1st picture), it uses hydrochloric acid for the production of the chemicals here, and because of that chloride rich environment you can see the beams over here (1st picture) has severe cracking here, and unfortunately this is not all a safe practice but I had that photos so I thought of sharing this in the class, you can see this propping (1st picture), it is not really a safe practice, you should replace the beam or do a proper protection.

And, there are many cases where such unsafe practices do happen, and you can see even this tank over here it is also corroding (1st picture), you can see that, so the safety of the workers, who are working here is not really considered in a good manner I would say. That is something which we have to stop from doing. And you can see here cracks all along the structural elements, you can see there is a lot of signs of corrosion, and you can see that they have also tried to do the repair work, install some steel elements structural steel sections over there. severe cracking here through the beams (3rd picture).

So, I just want to show that this structure is not located in a coastal region. I just want to show that it is not just looking at the corrosion map of India, which I showed earlier, where coastal region shows significant corrosive environment. You have to really look at the local exposure condition for the structure, especially this one example is chemical plants.

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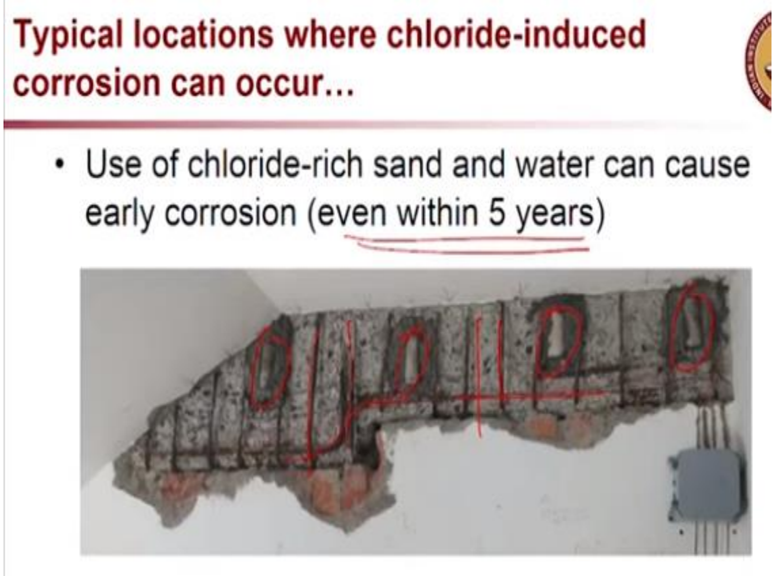

Typical locations where chloride-induced corrosion can occur...

- Use of chloride-rich sand and water can cause early corrosion (even within 5 years)

Now, this is an example where in this particular structure, they used chloride rich sand and chloride rich water, and it could happen in several places that if the sea sand or some sand which is rich in chloride, if that is locally available people will try to use it, but eventually you will see that it was not a good choice to do. We have to make sure that the ingredients which we use in concrete should be free from chlorides or at least with minimal quantity.

Now, if you actually have chlorides within the concrete itself like from the aggregates or from the water you can even see corrosion within 5 years. This particular structure experienced corrosion in about just 5 years, 4 to 5 years they started seeing this problem. All these rebars which you see here are severely corroded and what you see here is there is some cathodic protection being applied. I will discuss more on that technic on a later lecture but I just wanted mention that here.

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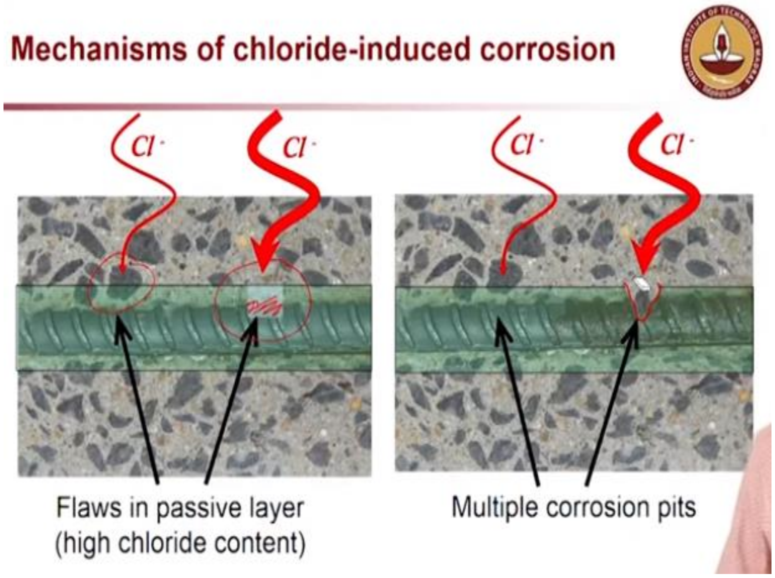

Mechanisms of chloride-induced corrosion

So, we looked at different type of structures or the reasons for, where is the source of chlorides, that is what we looked at, we looked at that marine conditions or even it could be from the airborne chlorides or could be from the materials used for making concrete itself. So, whatever be it like the chlorides are reaching the steel surface. What you will notice is that there will be something called pitting corrosion, for example here, if you look carefully that I have put this one of the arrow as in a thick line, thickness is more indicating that this region might have more chloride than this region, and this will lead to an earlier onset of corrosion in this location.

So, you may see a light pit, they are forming at an earlier time because you have more chlorides reaching the steels of surface over there at an earlier time.

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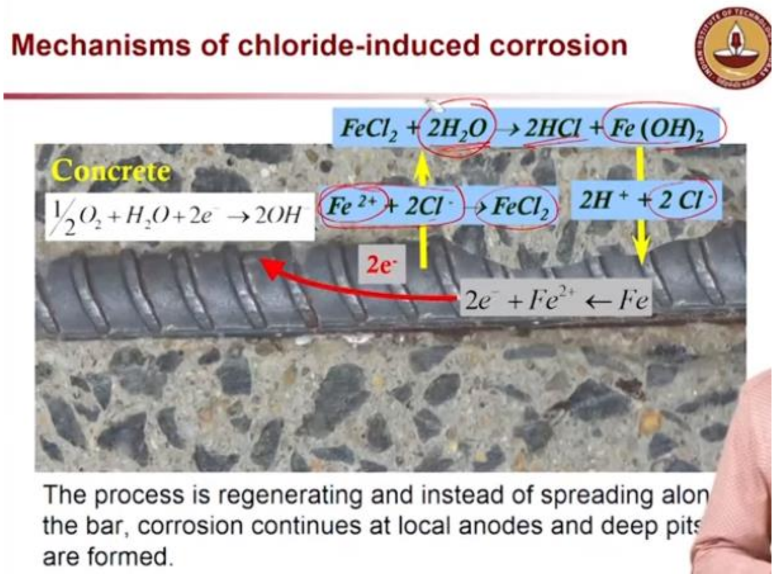

Mechanisms of chloride-induced corrosion

$FeCl_2 + 2H_2O \rightarrow 2HCl + Fe(OH)_2$

$\frac{1}{2}O_2 + H_2O + 2e^- \rightarrow 2OH^-$

$Fe^{2+} + 2Cl^- \rightarrow FeCl_2$

$2H^+ + 2Cl^-$

$2e^- + Fe^{2+} \leftarrow Fe$

The process is regenerating and instead of spreading alon the bar, corrosion continues at local anodes and deep pits are formed.

And, this leads to pitting corrosion, I am going to show you how this happens in a different way. What is the chemistry of this chlorides induced corrosion? So, if you have enough chloride reaching the steel surface, let’s say here somehow you have chloride ions available. And they will try to react with the steel or ion over here and this two will react and form ferrous chloride, which in presence of moisture, will lead to formation of the rust, which is ferrous hydroxide and also you have HCl form.

Basically, you create an acidic environment, and this HCl will precipitate again into two H^+ and Cl^- ions, which can attack this steel further, another iron atoms it can attack and then again it will form. So, this reaction will continue to happen it will form more ferrous chloride which again will in reaction with the moisture, it will form HCl and ferrous hydroxide.

So, this reaction, it will continue to happen, and so the point here is it is a catalytic reaction. So, once you have enough amount of chlorides to initiate this reaction it is very difficult to stop it, unless you can get rid of all the moisture in the concrete, it’s very difficult to keep your structures very dry. Especially, when you talk about very large volume of the concrete elements. So, best practice is to delay the time by which the chlorides can reach the steel, how can we do it?

Either, by increasing the impermeability of the concrete cover, is the best way to do, or, you can also go for the higher quality steel, which will result in a delayed initiation of corrosion.

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Pitting corrosion on strands and deformed bars due to chloride attack

- 7-wire strand
- Deformed bar

Li et al. (2011)

Now, let’s look at how this pitting looks like in the case of a pre-stressing strand, you can see this is the picture showing the pits formed in a pre-stressing strand. So, if you look here very carefully like in this cross section, the area available for taking the tensile stress is different. Especially when we talk about the region with pit there will be less area available that means the structure may fail at an earlier time.

So, this is more dangerous, it is not uniform corrosion. Even in the case of rebars you can see there is a small pit here, there are more corrosion here, but less in this region. So, there is a spatial variation in the amount of corrosion happening and so that is how we say pitting is happening when we talk about chloride induced corrosion.

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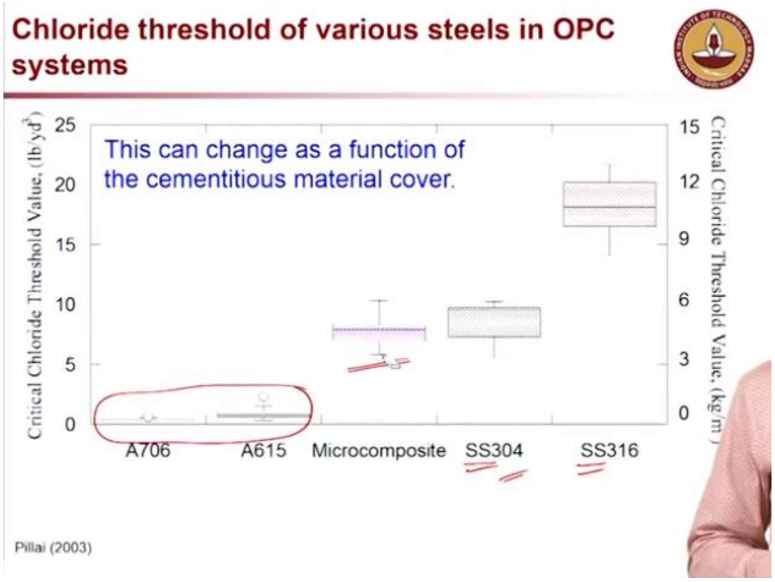

Now, earlier I mentioned that there is a parameter called chloride threshold, which determines the initiation of corrosion, also there are other parameters which influence. I would mention here that this chloride threshold is not just a function of steel, it is also a function of a material in which you put this steel in. Anyway, before discussing that let me show you how that how different the chloride threshold can be for different type of steel.

These 2 are similar to typical steel which we use in the market (A706 & A615), these 2 indicates (SS304 & SS316) that the chloride threshold for this stainless steel, SS indicates stainless steel, it is much higher than what it is for typical conventional steel reinforcement, and among the SS steels you can see SS316 has a higher chloride threshold than SS304. But, in India I do not think we use this stainless steel a lot unless we have a structure which you really want to have completely corrosion free, where we do not want any risk of corrosion, we may go for stainless steel.

And then there are other type of steels also available where they modify the microstructure a little bit, and which gives you higher chloride threshold than the conventional steels. So point what I want to make here is, when you talk about new type of steel which is coming to the market we must check what is it’s chloride threshold, and we must also check the chloride threshold for the particular cementitious environment which we are going to use, and if it is low, one way of improving the chloride threshold is by using corrosion inhibiting admixtures.

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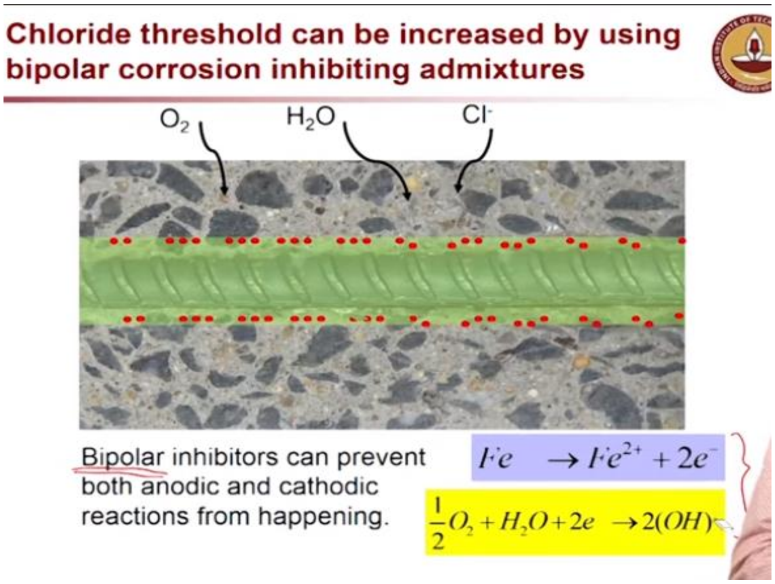

Chloride threshold can be increased by using bipolar corrosion inhibiting admixtures

Bipolar inhibitors can prevent both anodic and cathodic reactions from happening.

$$Fe \rightarrow Fe^{2+} + 2e^-$$

$$\frac{1}{2}O_2 + H_2O + 2e \rightarrow 2(OH)^-$$

So, this picture is now probably familiar to you, you have a concrete and a steel embedded in it, and you have a passive film, so this green patch indicates that passive film is formed. Now, these red dots over here indicate that when the corrosion inhibitors are used, we can make the passive film denser or better passive film which will have more chloride resistance. So, the passive film formed on the steel surface when the corrosion inhibitors are used is much more protective or resistance against the chlorides.

And typical corrosion inhibitors which is available in the market is bipolar corrosion inhibitor, earlier it used to be anodic inhibitors, where it prevents the anodic reaction. But bipolar inhibitors actually help in preventing both anodic and cathodic reaction from happening.

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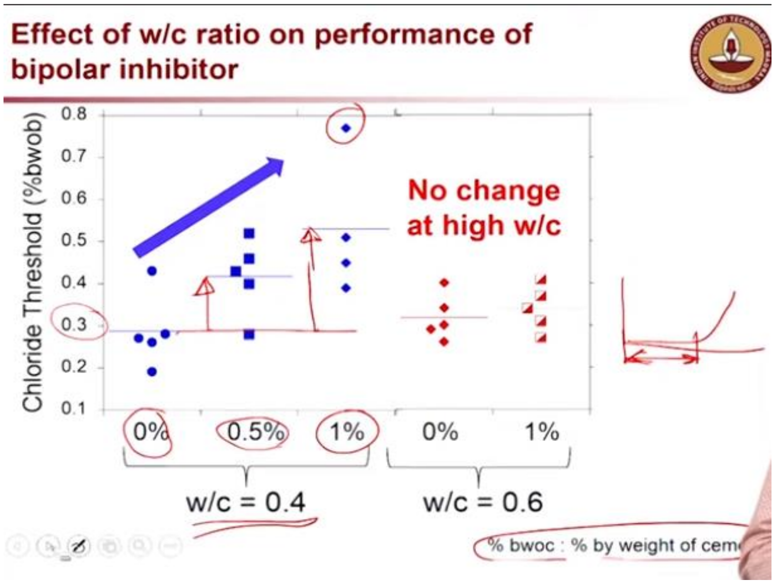

Effect of w/c ratio on performance of bipolar inhibitor

And, I am going to show you some results from our lab, on the effect of corrosion inhibitors on the chloride threshold. First, we looked at the effect of water cement ratio, so if you can see this is 0.4 water cement ratio, you can very clearly see that when there is no corrosion inhibitors that is 0 percentage, you can say that the chloride threshold is around 0.3, that was the value which we have observed, and when we added 0.5 percentage by weight of cement, average chloride threshold is increasing from 0.3 to about 0.4.

And, when we put 1 percent corrosion inhibitor it is further increasing average, but again I must say that there is one outlier probably here. So at least we can say that there is an increase from this point, when the case without the corrosion inhibitor there is an increase. So definitely the use of corrosion inhibitors seems to increase the chloride threshold, when we say it increases the chloride threshold what it means is that the initiation phase, which I showed earlier like in the service life the initiation phase it goes like this.

So, this portion here in the service life chart it is going to be more. So, the initiation phase can be enhanced or increased by using corrosion inhibitors. I will show you later, how much it can be. And also, when we go for a higher water cement ratio, what we are seeing is there is no change in the chloride threshold. So, we have to really see that the effectiveness of this inhibitors is good when the water cement ratio is low.

When the water cement ratio is high, they do not seem to really perform or to be of great use.

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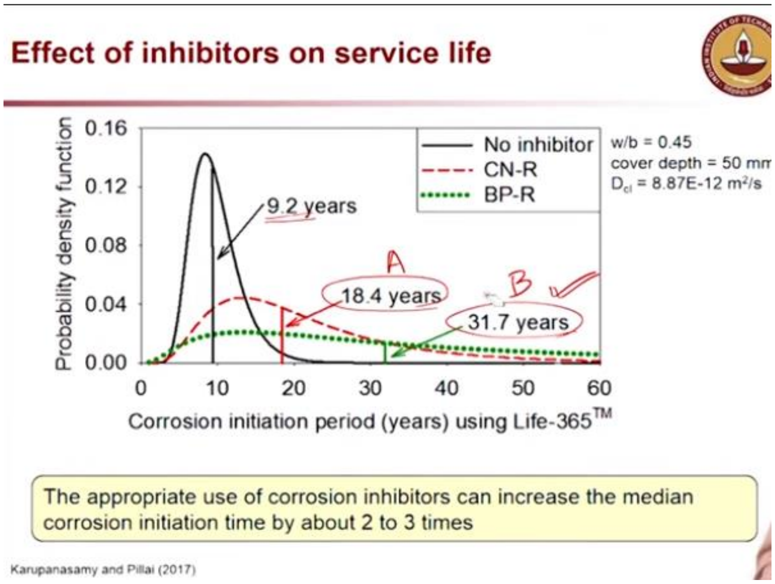

Effect of inhibitors on service life

The appropriate use of corrosion inhibitors can increase the median corrosion initiation time by about 2 to 3 times

Karupanasamy and Pillai (2017)

So, this a PDF indicating that probabilistic service life when we use corrosion inhibitors. So, you can look at these average values here, where you can say 9.2, or about 10 years if you get, when you don’t use inhibitors, when we use inhibitors, we get about 20 years or 30 years. So especially this one is for the bipolar inhibitors, so 3 times increase in the service life is possible by using bipolar type corrosion inhibitors.

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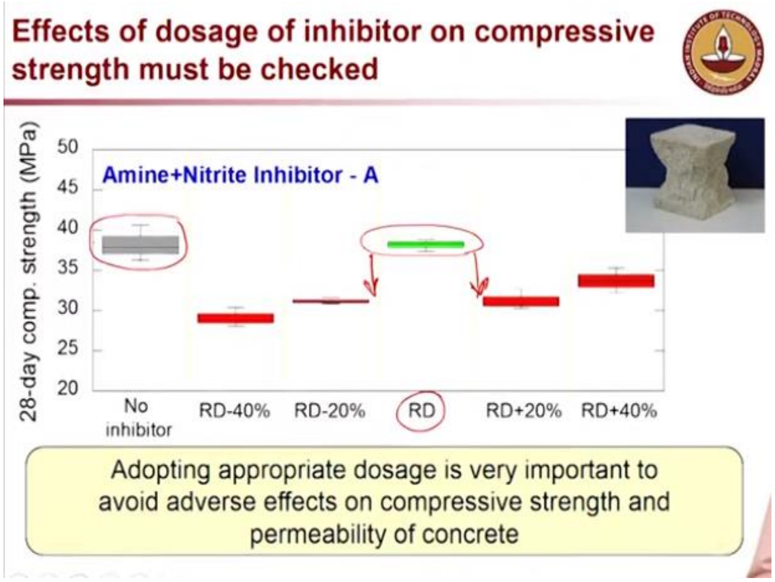

Effects of dosage of inhibitor on compressive strength must be checked

Adopting appropriate dosage is very important to avoid adverse effects on compressive strength and permeability of concrete

Now, when we go for the inhibitors, earlier I showed results on corrosion properties, we can very clearly see that the corrosion resistance can be enhanced or chloride threshold is enhanced.

However, if you do not have an optimum dosage, or if we change the dosage it can actually change the compressive strength and other transport properties of the concrete. I am going to show a little bit of that. So, you can see here, this (Gray color line) indicates when there is no inhibitors used you have about 40 MPA compressive strength.

When the recommended dosage, RD stands for recommended dosage, we got similar compressive strength. When we deviated from the recommended dosage, by about -20, -40 and + 20, + 40, it is very clear that there is a reduction in the compressive strength. So, this thing must be considered while designing the concentrate mix. So, you have to consider an optimum dosage which is able to provide corrosion resistance, and at the same time sufficient strength should be available.

So, if necessary, you can over design the concrete, and make sure that the mix after the addition of the corrosion inhibitors is giving you a right strength or desired strength.

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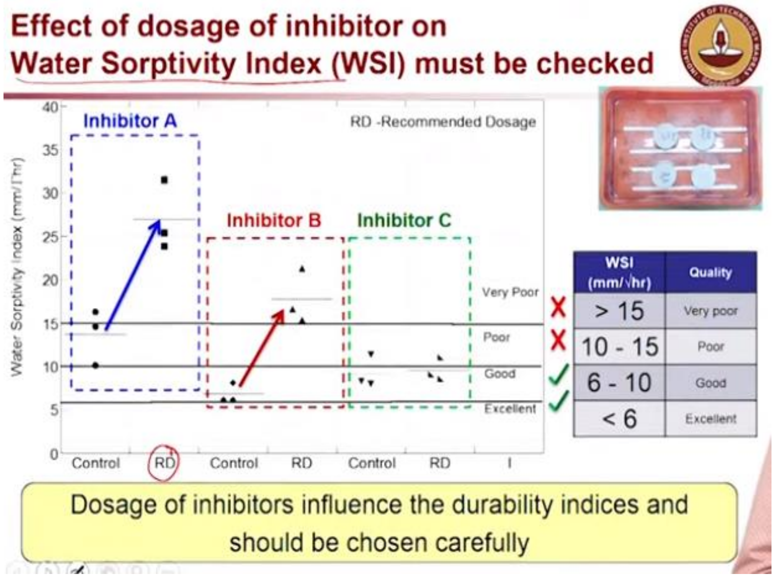

Effect of dosage of inhibitor on Water Sorptivity Index (WSI) must be checked

WSI (mm/√hr)	Quality
> 15	Very poor
10 - 15	Poor
6 - 10	Good
< 6	Excellent

Dosage of inhibitors influence the durability indices and should be chosen carefully

And other thing which this corrosion inhibitors can influence is the transport properties of the concrete. One example I am showing here is the water sorptivity index. We saw that if you use the recommended dosage, there could be an increase in the water sorptivity, that means moisture can ingress faster now into the concrete. So, all these have to be considered when we use corrosion inhibitors, it’s not that you just take this chemical and mix it and it will give you everything what you want.

So, what we have to look at is, what is the right dosage for the corrosion inhibitors, right dosage in terms of corrosion resistance, in terms of strength properties, and in terms of transport properties of the concrete. So, all the 3 things must be considered when we choose a corrosion inhibitor, and this is same thing for all other chemicals also which we now a days mix with concrete.

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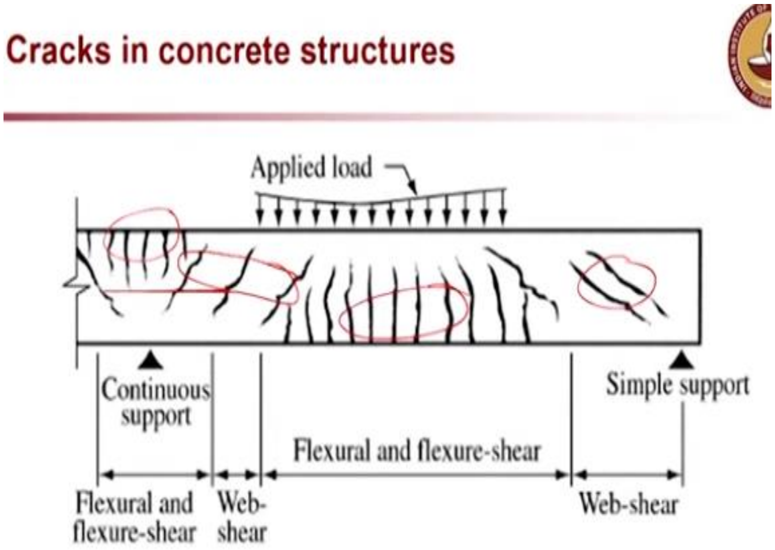

Cracks in concrete structures

Now, let me talk a little bit about the corrosion in cracked concrete. So, this is a schematic showing what different types of cracks which we would observe in concrete structures, flexural cracks here, shear cracks here, this is also shear crack, and this is for a continuous beam element, because the re-bars are at the top. So, these are the types of cracks it is possible to have in many concrete structures.

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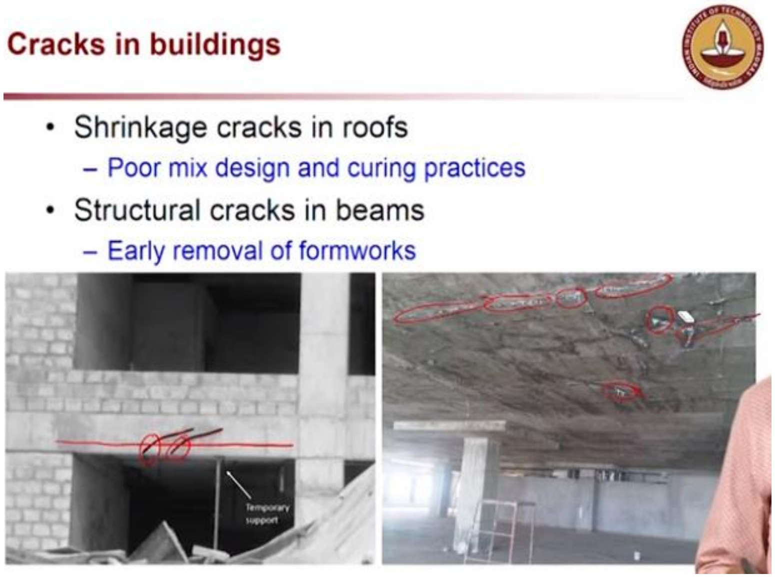
Cracks in buildings

- Shrinkage cracks in roofs
  - Poor mix design and curing practices
- Structural cracks in beams
  - Early removal of formworks

Now, I want to show you some examples of different type of cracks in different type of elements, this is in a building, where this actually what happened in this structure on the left side image is that they removed the foam work before the concrete really attained the strength. So, I draw this black line here because it was very thin hair line crack and so just to show you there was a crack like this on this beam.

Now, imagine there is a rebar, which goes like this (red line), and that re-bar will experience localized attack right when it crosses the crack. Now, another example of crack in a roof element is like this you can see here (2nd picture). Again, here also it could be because of the removal of the foam work at an earlier time, or because of the shrinkage of the concrete either thing can happen.

You can see very clearly the scale formation; all this here is scales very clearly indicating that there is a passage available or a crack available within the concrete element through which reinforcement inside can get attacked.

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Shear and flexural cracks in bridge girders

Now, this is about the example showing cracks in a high way bridge girder, it is actually a reinforced concrete bridge girder, you can see here very fine cracks. So, I am going to draw parallel to the crack (red inclined lines). So, and imagine now what will happen to the reinforcement which is going through these cracks, you know there will be localized attack in these locations and that is what we should be really worried about. You can have a severe localized corrosion attack at an earlier time.

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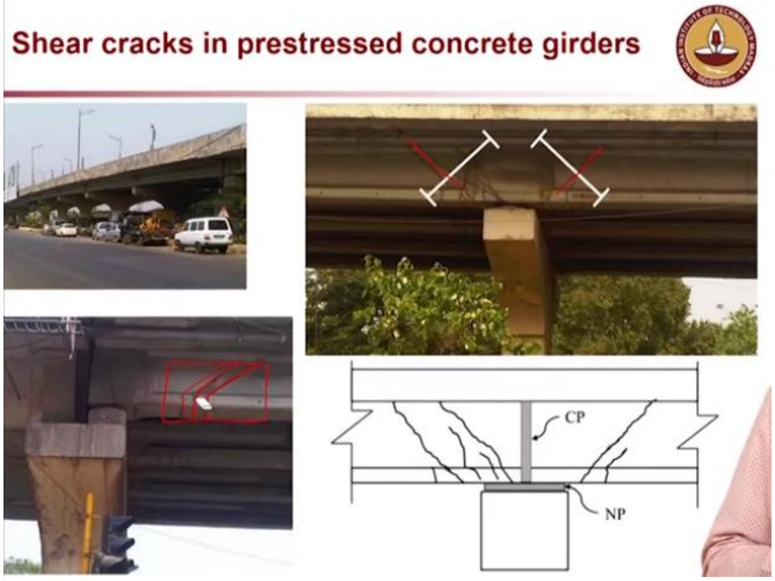

Shear cracks in prestressed concrete girders

This is on a pre-stress concrete girder where again you can see a lot of shear cracks in this direction (red inclined lines), and this schematic is showing very clearly how the shear cracks will look like and in this particular structure you can see that there. Actually the crack was filled with epoxy, you can see this brown patch, it is actually filled with epoxy to prevent. But I don’t know how effective this epoxy injection would be because these structures undergo lot of vibration.

So, you have to ensure that oxygen molecules or water molecules cannot penetrate through these cracks, that is very difficult to achieve unless, you really provide a proper cover instead of just filling a crack. We may want to go for a proper cover, that might be probably better option than just filling the crack with epoxy. Best thing is to do a better design, so that these cracks do not occur.

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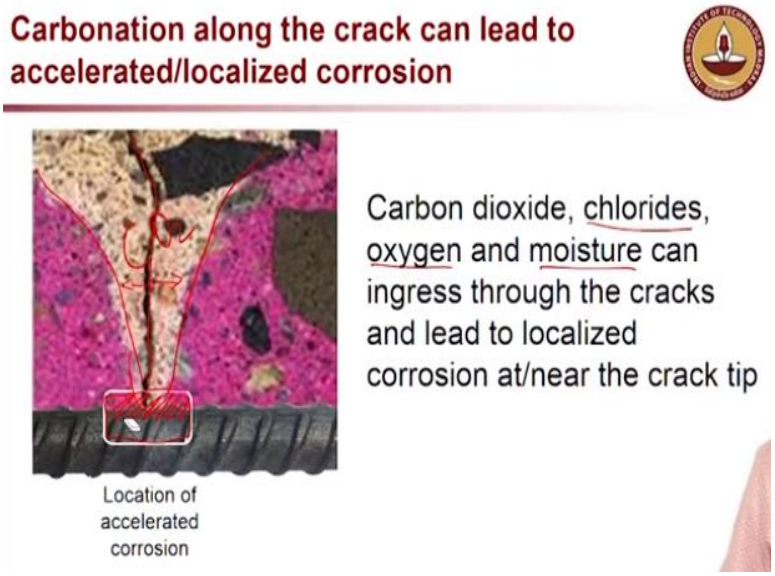

Carbonation along the crack can lead to accelerated/localized corrosion

Carbon dioxide, chlorides, oxygen and moisture can ingress through the cracks and lead to localized corrosion at/near the crack tip

Location of accelerated corrosion

Now, this picture shows how carbonation can happen all along the crack, very clearly earlier we said if pH is greater than 9 then that means concrete is not carbonated, if it is less than 9 then the concrete is carbonated, which is indicated by this region, very clearly we can see this (the region without any change in color) is highly carbonated region..

So, what is the end result, you will have localized corrosion in this region so the steel in this region might experience localized corrosion. Similar is the case it is not just carbon dioxide if there is a crack, chlorides can penetrate through that, oxygen, moisture all this can penetrate through these cracks, and it will attack the steel in a very localized manner which is very dangerous when you talk about structural behavior.

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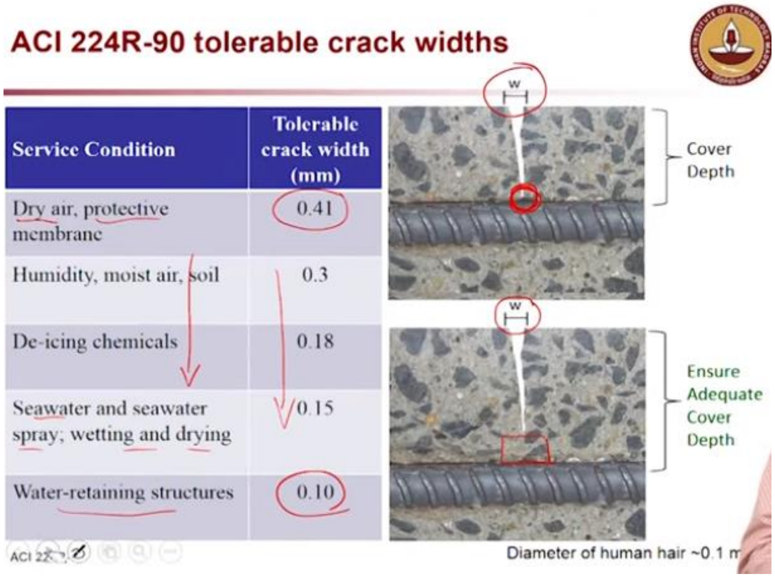

ACI 224R-90 tolerable crack widths

Service Condition	Tolerable crack width (mm)
Dry air, protective membrane	0.41
Humidity, moist air, soil	0.3
De-icing chemicals	0.18
Seawater and seawater spray; wetting and drying	0.15
Water-retaining structures	0.10

ACI 22

Diameter of human hair ~0.1 m

Now, we talked about the crack, and then there is something called crack width. Which is how this problem is addressed in the structural design, as you see here, on the first column you can see different service conditions. If it's dry air or a protective membrane is provided, they allow a crack width up to about 0.4, and as you go down on the left side you will see that the condition is more and more severe, or more corrosive in nature.

Here, you have sea water, sea water spray, wetting and drying, and continuous exposure to water, water retaining structures. So, as you go down the severity of the condition is more, so we try to also reduce the allowable crack width, or allowable or tolerable crack width, it goes all the way up to 0.1 when you talk about water retaining structures. In the pictures on the right side, 'W' is the crack opening width.

Now, if you have a structure like this you can see the cover depth is here, and this there is a high tendency that this region will start corroding very fast (top right picture). Now, what we can do is either design the crack width and have a combination between crack width and the cover death. So, if you have more cover depth even for the same crack width you may not have a condition where the crack is reaching the steel (bottom right picture), there is no crack in this region as you see here no crack (bottom right picture).

So, the steel in the bottom image is better protected than the steel in the top image. so, point what I am telling here is that, I am not telling to keep on increasing the cover depth which of course the structural designer has to look at. What I am saying is whatever is suggested in the design we should ensure that is actually implemented at the site.

Because, sometimes we see that there is a significant variation in the cover depth. so, we must use proper measures on ensuring that the cover depth is adequately provided, good quality chairs can be provided. But at the same time when I mention chair the quality of the chair block should not be inferior to the quality of the concrete. So, it is very important to note down here. So, if you have proper cover that is a best way to ensure durability of structures.

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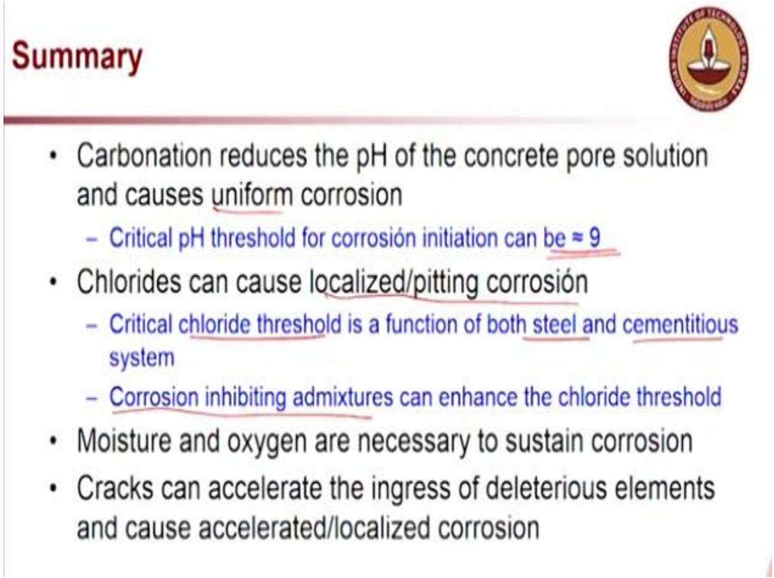

Summary

- Carbonation reduces the pH of the concrete pore solution and causes uniform corrosion
  - Critical pH threshold for corrosión initiation can be ≈ 9
- Chlorides can cause localized/pitting corrosión
  - Critical chloride threshold is a function of both steel and cementitious system
  - Corrosion inhibiting admixtures can enhance the chloride threshold
- Moisture and oxygen are necessary to sustain corrosion
- Cracks can accelerate the ingress of deleterious elements and cause accelerated/localized corrosion

So, to summarize, we looked at carbonation induced corrosion, we found that the carbonation process can reduce the pH of the concrete pore solution, which will lead to uniform corrosion, that is a key feature we looked at, and there is something called critical pH threshold or critical pH at which is if about 9, if the concrete pH reaches about 9, then steel will start corroding.

And the second mechanism we looked at was the chloride induced corrosion, which leads to localized pitting corrosion. And, there is also a critical parameter which we called chloride threshold, the chloride threshold can be enhanced by using corrosion inhibitors and also it is function of both steel and the cementitious material used, not just the steel. The dosage of the corrosion inhibitors used is also very important to consider, it should not affect the other properties of the concrete. For example, if you are using a corrosion inhibitor you should ensure that it's influence on corrosion resistance is more, but it should not influence the compressive strength or the transport parameters of the concrete, or in other words even if it is influencing we should take adequate measures during the design process itself.

Now, cracks can accelerate the ingress of deleterious elements. Through the crack chloride, carbon dioxide, oxygen, moisture all these can penetrate and reach the steel surface at an earlier time, which will lead to localized corrosion.

I think with that we will stop this lecture. In the next lecture we will look at different type of steel reinforcement available and what are the precautions to be taken when we use those kind of advanced steel reinforcement, which claim better corrosion resistance.