Concrete Engineering and Technology
Prof. Sudhir Misra
Department of Civil Engineering
Indian Institute of Technology, Kanpur

Lecture - 26
Reinforcement corrosion in concrete

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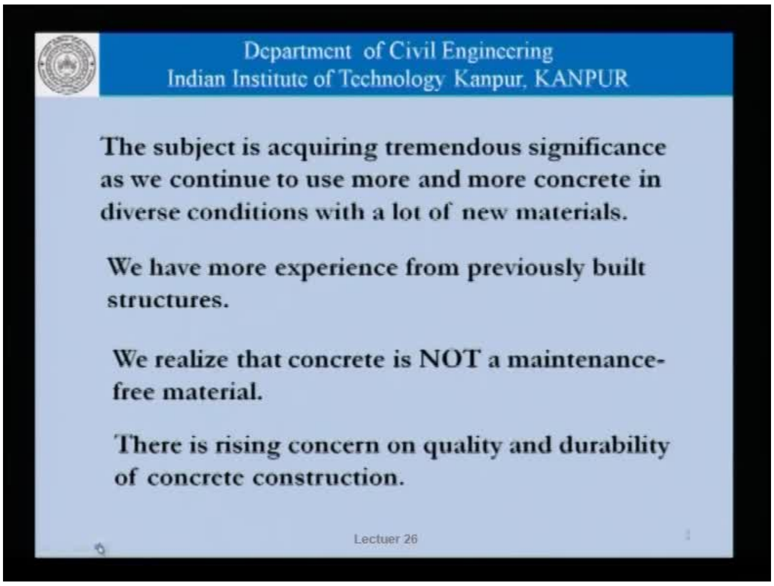

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The subject is acquiring tremendous significance as we continue to use more and more concrete in diverse conditions with a lot of new materials.

We have more experience from previously built structures.

We realize that concrete is NOT a maintenance-free material.

There is rising concern on quality and durability of concrete construction.

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[FL], and welcome back to another lecture in this series of concrete engineering in technology. As we have been talking the subject is acquiring tremendous significance as we continue to use more and more concrete in diverse conditions, and with the lot of materials. We have also now got a lot of experience from previously built structures in different environments. And know how those structures have behaved structurally and also from the point of view of materials, the kind of degradation that we have seen, the kind of deterioration we have seen.

We also have some experience now with maintenance and repair rehabilitation of concrete structures. And we have realized that concrete is not a maintenance for a material. Depending on the environment that the concrete structure is in, the concrete of the structure undergoes certain changes it may deteriorate. And that is what we need to study, there is a rising concern now on the quality and the durability of concrete construction.

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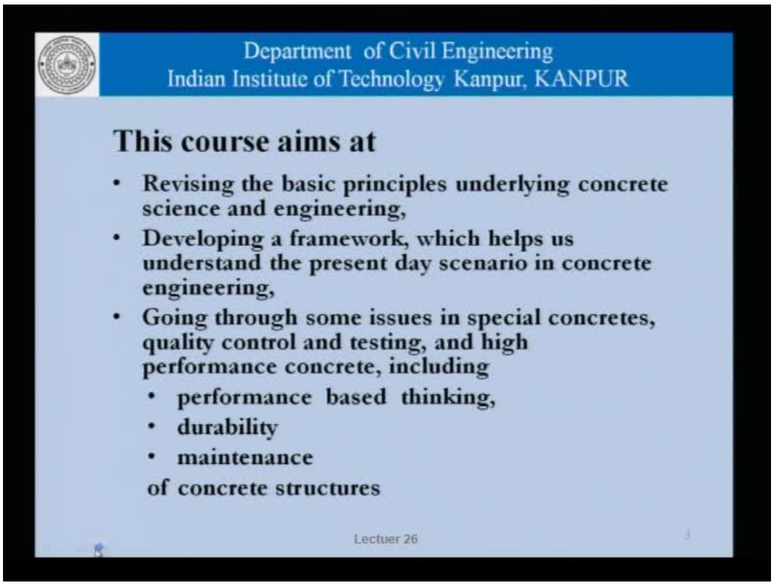

This course aims at

- Revising the basic principles underlying concrete science and engineering,
- Developing a framework, which helps us understand the present day scenario in concrete engineering,
- Going through some issues in special concretes, quality control and testing, and high performance concrete, including
  - performance based thinking,
  - durability
  - maintenance

  of concrete structures

All this has lead to increased awareness and calls upon the concrete engineers to know something about deterioration durability and so on. This course aims at revising the basic principles underlying concrete science and engineering, develop a framework which helps us understand the present day scenario in concrete engineering. And we are trying to go through special issues in what we can call special concretes, the quality control and testing. We have talked about high performance concrete and also performance based thinking durability and maintenance of concrete structures that is what we are doing now.

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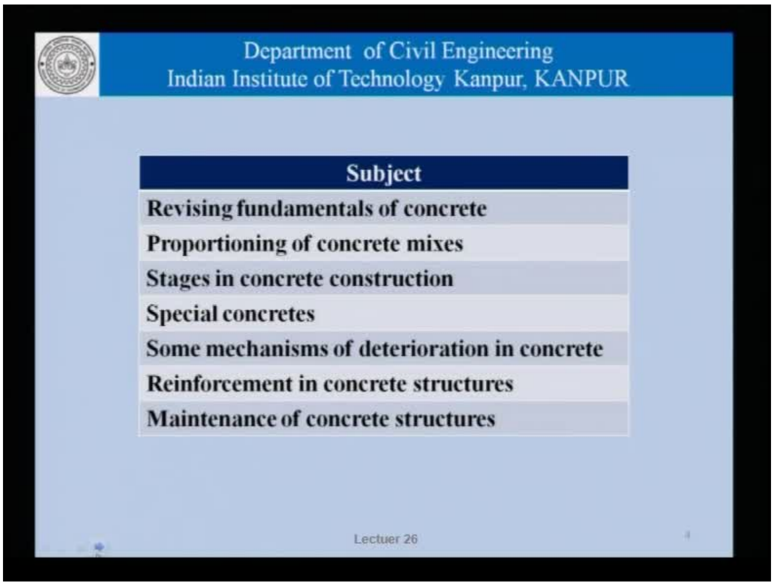

Subject
Revising fundamentals of concrete
Proportioning of concrete mixes
Stages in concrete construction
Special concretes
Some mechanisms of deterioration in concrete
Reinforcement in concrete structures
Maintenance of concrete structures

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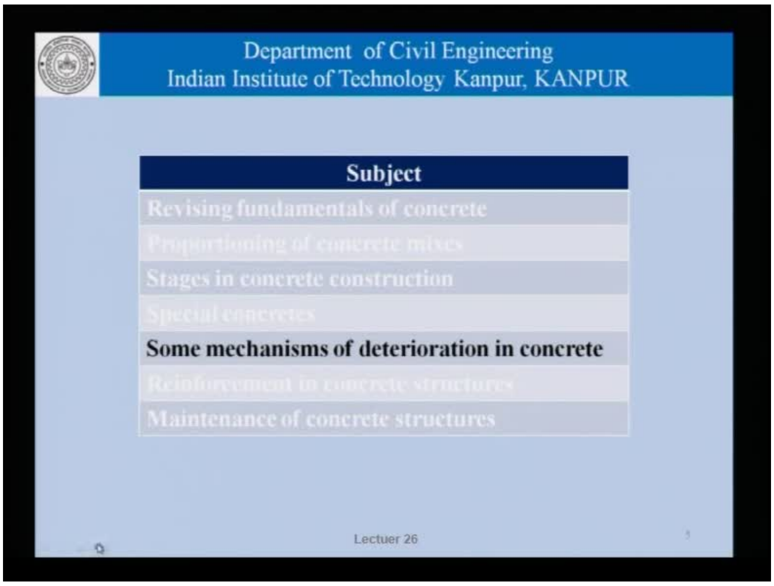

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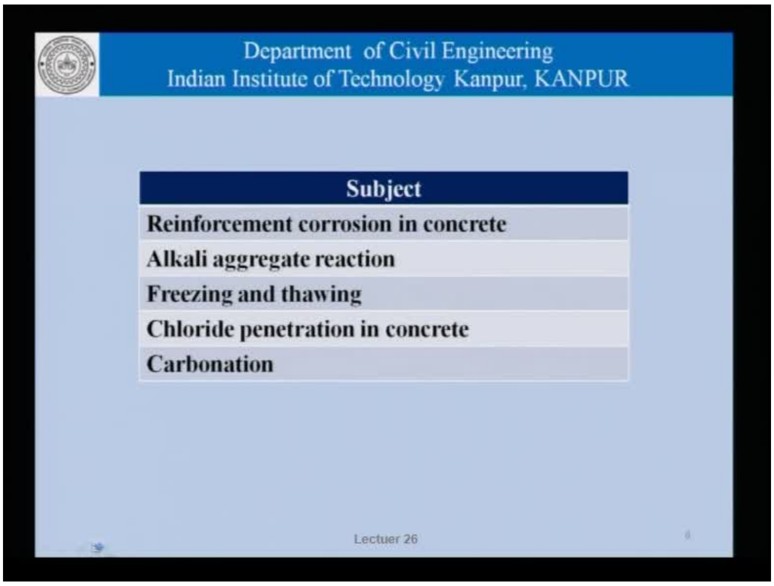

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Subject
Reinforcement corrosion in concrete
Alkali aggregate reaction
Freezing and thawing
Chloride penetration in concrete
Carbonation

This slide is familiar to you and outlines the different subjects that we are dealing with in this course. Now, having gone through a little bit of background in durability studies in the larger sense of the word, we will now commence our discussion on some mechanisms of deterioration in concrete. And what we will talk about is reinforcement corrosion in concrete, alkali aggregate reaction, freezing and thawing, chloride penetration and concrete and carbonation of concrete.

Chloride penetration and carbonation are not necessarily causes for deterioration of concrete parse. But they play a very important role in inducing reinforcement corrosion in concrete. We know that reinforcing bars are an integral part of any reinforce concrete construction. And what we are going to study today is how they deteriorate, what is a mechanism and so on. And we will study the importance of chloride penetration and carbonation as a part of the discussion in this course.

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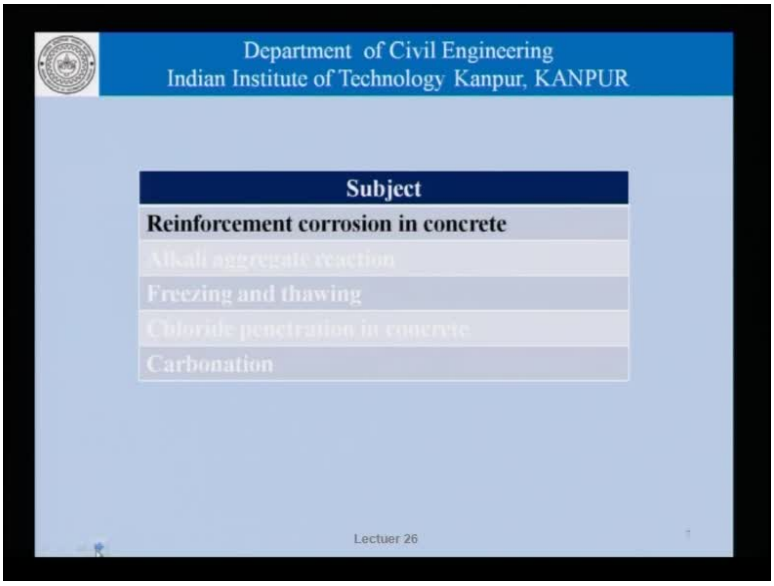

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Subject
Reinforcement corrosion in concrete
Alkali aggregate reaction
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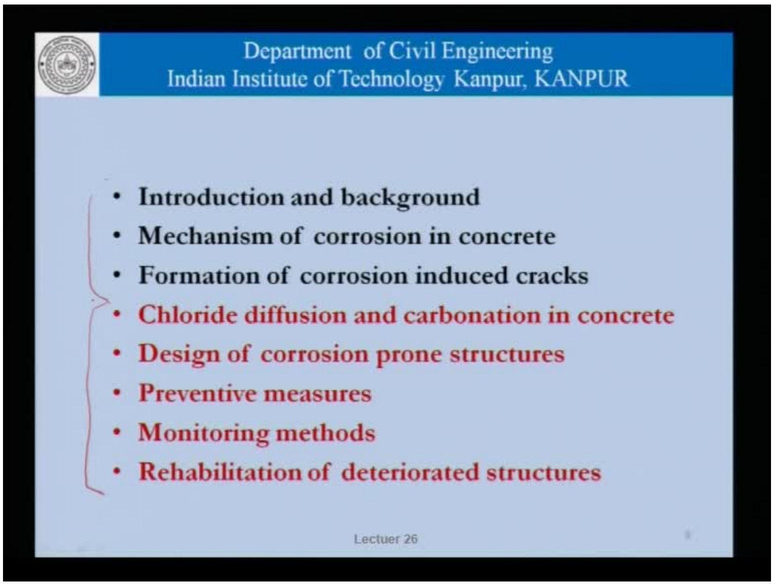

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- Introduction and background
- Mechanism of corrosion in concrete
- Formation of corrosion induced cracks
- Chloride diffusion and carbonation in concrete
- Design of corrosion prone structures
- Preventive measures
- Monitoring methods
- Rehabilitation of deteriorated structures

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So, beginning our discussion with the reinforcement corrosion in concrete we will go through some kind of introduction background, develop the kind of framework that we need to have. We will talk a little bit about the mechanism of corrosion in concrete, what is the science of corrosion? We will talk of formation of corrosion induced cracks.

Most of us know that corrosion in the reinforced concrete structures becomes an issue only when we see some cracks on the surface or we see signs of rust deposits on the concrete surface. And how these cracks are formed is what we will study today. Then there are other things like chloride diffusion and carbonation in concrete, design of corrosion prone structures, preventive measures and monitoring methods and rehabilitation of deteriorated structures. So, this part, we will cover at a later date are concentration today will be on these 3 subjects.

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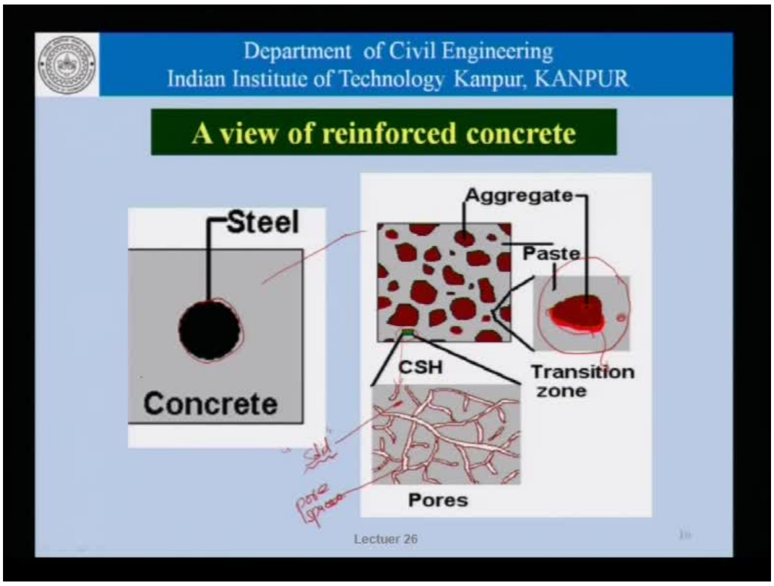

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A view of reinforced concrete

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Coming to the introduction and background let us go back to this picture that we saw early in the course. This is a view of reinforce concrete, we have a steel bar embedded in concrete. This is how we have most of our reinforce concrete structures whether it is beam or a slab or a column or a wall, whatever it is we can always understand or imagine or model that reinforcing bar is embedded in concrete. And that is something which we must keep at the back of our mind. Also we have seen this picture earlier where we say that as far as the concrete is concerned it is nothing but aggregates suspended in mortar. And if we look at a small element here in the mortar or the paste phase, what we see here is the grey area here, we can say is solid hydration products. And these are the pore spaces, depending on the kind of concrete that we have water cement ratio that we have used and so on.

The amount of pores in the concrete will vary and we have seen that when we discussed the hydration of cement. The kind of hydration products that are formed, what is the amount of hydration products formed and so on? Those are an important ingredient in our determination or in our understanding of how durable the concrete is? Coming with that this picture here shows what is called the transition zone, what we have here is at the bottom of the aggregates, coarse aggregates more. So, then fine aggregates there is a small very fine, very thin layer of hydration products where the water cement ratio is much higher than in the main body of the paste. So, basically what we are saying is that as we have the aggregate here we have the main body of the cement paste here in between this is a transition zone where the water cement ratio is much higher. That is this transition zone provides an easier access to the deleterious materials travelling through concrete.

Another thing which we must remember from this diagram is that as far as this steel bar is concerned it is exposed or it is embedded in concrete. And therefore, the environment around the steel bar is that of concrete and there are lots of these pores and pore spaces in contact with the reinforcement bar. And what is the characteristics of these pores? What is that pore space filled with? All these things become very important in our understanding of how chemically or electrochemically to be precise the reinforcing steel behaves from the point of view of corrosion.

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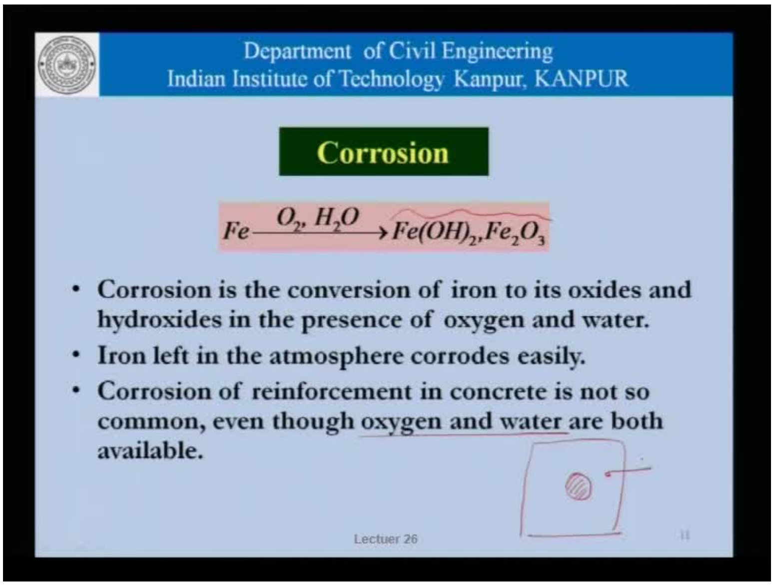

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Corrosion

$$Fe \xrightarrow{O_2, H_2O} Fe(OH)_2, Fe_2O_3$$

- Corrosion is the conversion of iron to its oxides and hydroxides in the presence of oxygen and water.
- Iron left in the atmosphere corrodes easily.
- Corrosion of reinforcement in concrete is not so common, even though oxygen and water are both available.

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As far as corrosion is concerned, what is the most fundamental understanding? We all know that corrosion basically means the conversion of iron to its oxides and hydroxides in the presence of oxygen and water. Of course, these are only two of the corrosion products that are formed there can be any number of hydroxides and oxides depending on how exactly the corrosion reaction proceeds, how much oxygen is there, how much water is there, what is the temperature and so on and so forth? Now, having said that we know that iron left in the atmosphere corrodes easily, we just leave a steel bar in the atmosphere. And very soon we will find a layer of corrosion product deposited on the surface of the steel bar.

However, corrosion of reinforcement and concrete is not so common even though oxygen and water are both available. If we go back to the picture that we had that we had concrete and a steel bar embedded in it there is no dearth of oxygen and water in this environment. Oxygen is present in plenty given that there are lot of pore spaces, water is also abundantly available, because concrete to begin with had a lot of water. And even after the hydration reaction as taken place some amount of water still remains further depending on the environment in which the concrete is there could be a rain there could be marine structure or whatever which will cause the concrete to be saturated with water that is the pore space in the concrete is filled with water. So, there is no dearth of oxygen and water, but corrosion is not a rampant phenomenon even though we see reasonable amount of corrosion in certain cases, but in most cases we do not see corrosion. So, we must understand as to why that happens.

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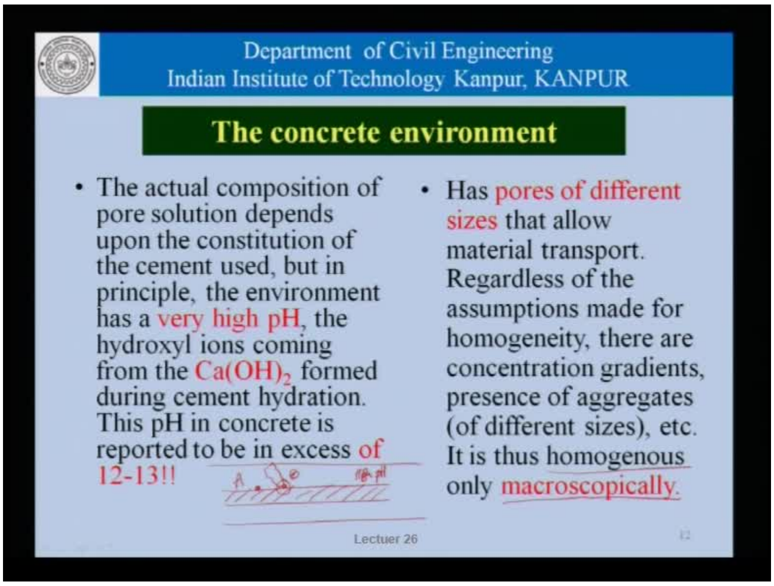

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The concrete environment

- The actual composition of pore solution depends upon the constitution of the cement used, but in principle, the environment has a very high pH, the hydroxyl ions coming from the $Ca(OH)_2$ formed during cement hydration. This pH in concrete is reported to be in excess of 12-13!!
- Has pores of different sizes that allow material transport. Regardless of the assumptions made for homogeneity, there are concentration gradients, presence of aggregates (of different sizes), etc. It is thus homogenous only macroscopically.

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So, let us look at concrete environment that is the environment of the reinforcing bar just around the reinforcing bar more closely. The actual composition of the pore solution depends on the constitution of the cement used, but in principle the environment has a very high p H. The hydroxyl ions coming from the calcium hydroxide formed during cement hydration, the p H in concrete is reported to be in the access of 12 or 13.

We saw the when we saw the hydration reactions, we saw that whether it is the hydration of C 3 S C 2 S C 3 A or C 4 F of any phase of cement when it hydrates leads to the formation of hydration products and a lot of calcium hydroxide. So, this calcium hydroxide when it is deposited within the pore system it dissociates into calcium and hydroxyl ions. And these hydroxyl ions cause the p H to be in access of 12 or 13. So, in principle the bars reinforcing bars are in environment which is extremely basic. Now, though the pores have different sizes that allow material transport.

So the kind of pores that we have around the reinforcing bars they could be of different sizes and that and they allow material transport whether it is carbon dioxide or chloride or any other deleterious material. Regardless of the assumptions made for homogeneity there are concentration gradients presence of aggregates of different sizes and so on. So in principle concrete is homogeneous only macroscopically when a designer sells that the concrete has a strength of 20 m p a 25 m p a. It is assumed that that is the strength of concrete across the structure or across the member. Even though there is macroscopically true as far as the microscopic properties are concerned if we look at one location of the reinforcing bar to another location of the reinforcing bar there concrete is definitely not a homogeneous material.

There are reasons to believe that if we have a reinforcing bar like this which is embedded in concrete. Then electro chemical environment here which is let us say A and the electro chemical environment here could be different, because it is possible that there is an aggregate sitting here and that aggregate changes the microscopic environment around here. And therefore, concrete is only macroscopically homogeneous and microscopically highly heterogeneous. And there could be concentration gradients, that is in terms of let us say the concentration of dissolve oxygen the concentration of hydroxyl ions and so on. So, reinforcing bars in concrete are in an environment which is characterized by a high p H and is highly heterogeneous once we keep that in mind our discussion as far as corrosion is concerned becomes a lot easier.

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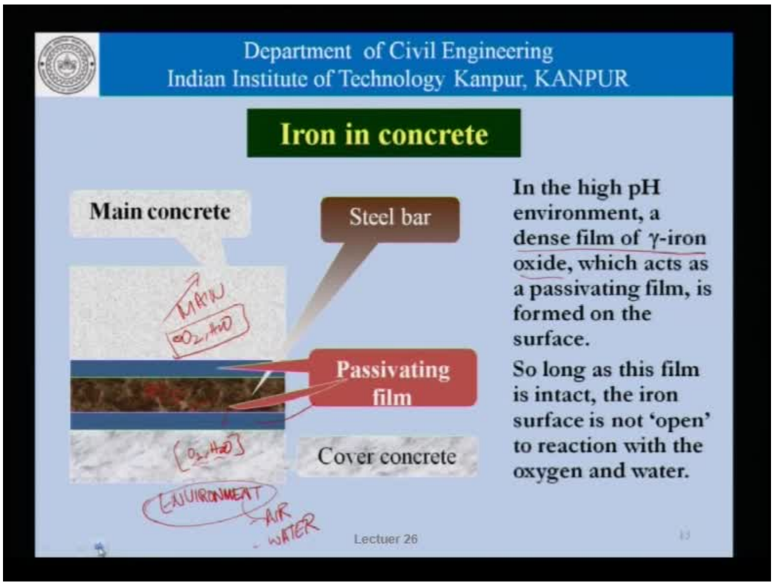

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Iron in concrete

In the high pH environment, a dense film of γ-iron oxide, which acts as a passivating film, is formed on the surface.

So long as this film is intact, the iron surface is not 'open' to reaction with the oxygen and water.

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Now, here is another picture of iron and concrete. So, this is the environment that is on this side of the reinforcement concretes, on this side of the reinforced concrete structure. We have the environment. This environment could be air or it could be water that is what will happen if the reinforced concrete structure is submerged in water or is the water retaining structure and so on. This side is the main concrete and here we have the reinforcing bar. Now, there is something called a passivating film that is shown here the passivating film is here. This is the passivating film the blue one, without getting into the electrochemistry involved or the science majorly involved I would like you to take it for granted though those of you who though those of you who want to find out are encouraged to find out more about this part.

In the high p H environment a dense film of gamma iron oxide which acts as a passivating film is formed on the surface. So, what it says is that this steel bar that we have that is the brown one, once it is embedded in concrete which has a high p H environment, because of electro chemical reasons a very dense film of gamma iron oxide forms on the surface of the steel. And this film essentially prevents a direct contact between the oxygen and water that are present in the concrete whether it is in the min body concrete or it is in the cover concrete and the reinforcing bar itself. And so long as there is no direct contact between the oxygen and water and the reinforcing bar we will have a very little chance of corrosion happening.

So, as long as this film is intact, the iron surface is not open to reaction with the oxygen and water and the iron embedded in concrete does not corrode. So, this basically gives the answer the question that we do not see corrosion in a lot of concrete structures or in lot of reinforced concrete structures. It is because the dense passivating film of gamma iron oxide prevents a direct contact of the iron surface to the oxygen and water that people present in the concrete.

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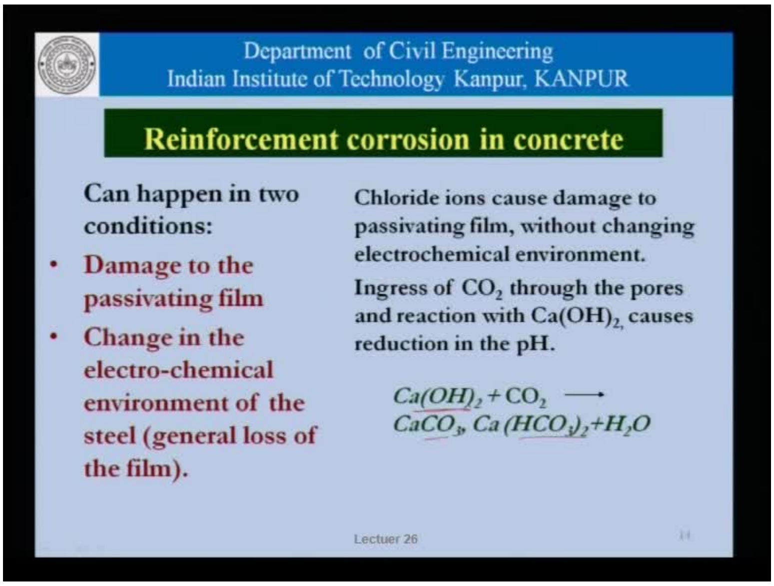

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Reinforcement corrosion in concrete

Can happen in two conditions:

- Damage to the passivating film
- Change in the electro-chemical environment of the steel (general loss of the film).

Chloride ions cause damage to passivating film, without changing electrochemical environment.

Ingress of CO_2 through the pores and reaction with $Ca(OH)_2$ causes reduction in the pH.

$$Ca(OH)_2 + CO_2 \longrightarrow CaCO_3,\ Ca(HCO_3)_2 + H_2O$$

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It stands to reason therefore, that reinforcement corrosion in concrete can happen under two conditions. One case with the passivating film is damaged and the other is a situation where the electrochemical environment of the steel changes in a manner that the film is no longer enable. So, the film is formed basically, because the environment is highly alkaline it has a very high p H. And now if the p H somehow reduces for whatever reason then the passivating film is no longer thermodynamically enable it is no longer stable. And once the passivating film is either lost on account of this kind of a change in the electrochemical environment of the bar or it is damaged for some reason. Then the surface of the reinforcement is exposed to the oxygen and water action which is present in concrete and we have the onset of corrosion.

Now as far as these two mechanisms are concerned, damage to the passivating film is caused by chloride ions. These chloride ions cause damage to the passivating film without changing the electrochemical environment. We shall see a model description of what this means and as far as the in case of carbon dioxide is concerned through the pores and it is reaction with calcium hydroxide causes the reduction in p H. So, the p H is high, because there is a lot of calcium hydroxide in the system. As carbon dioxide goes into the system penetrates into concrete it reacts with the calcium hydroxide as given here calcium hydroxide and carbon dioxide they react to give calcium carbonates and calcium bicarbonates and some amount of water.

So, once these calcium carbonates and bicarbonates are formed we have lost calcium hydroxide. And if this loss of calcium hydroxide occurs to an extent that the amount of hydroxyl ions required to sustain high p H, to sustain the passivating film. Then the passivating film is lost it is thermodynamically unstable.

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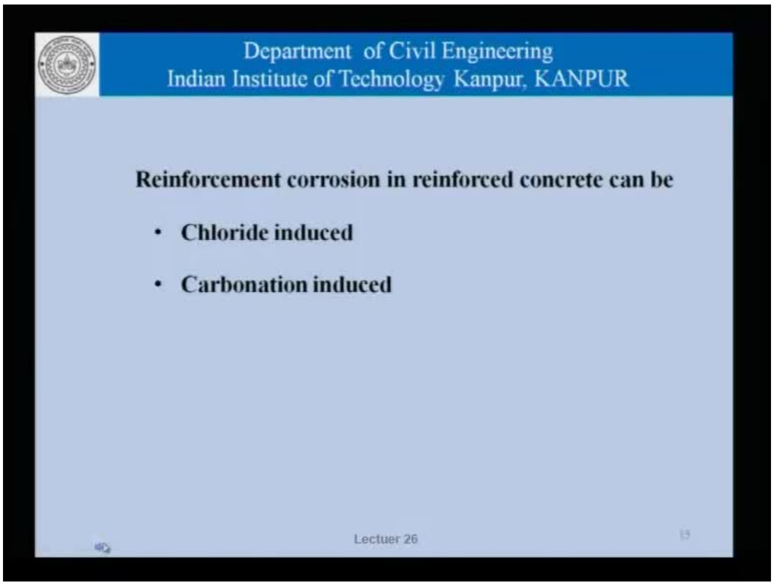

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Reinforcement corrosion in reinforced concrete can be

- **Chloride induced**
- **Carbonation induced**

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So, now summarizing the, the reinforcement corrosion in reinforced concrete can be chloride induced or it can be carbonation induced, what it means is let us in the case of chloride induced corrosion. We will have a damage to the passivating film without change in the electrochemical environment. In the carbonation induced corrosion we will have a change in the electrochemical environment of the reinforcing bar and therefore, the passivating film will simply become unstable.

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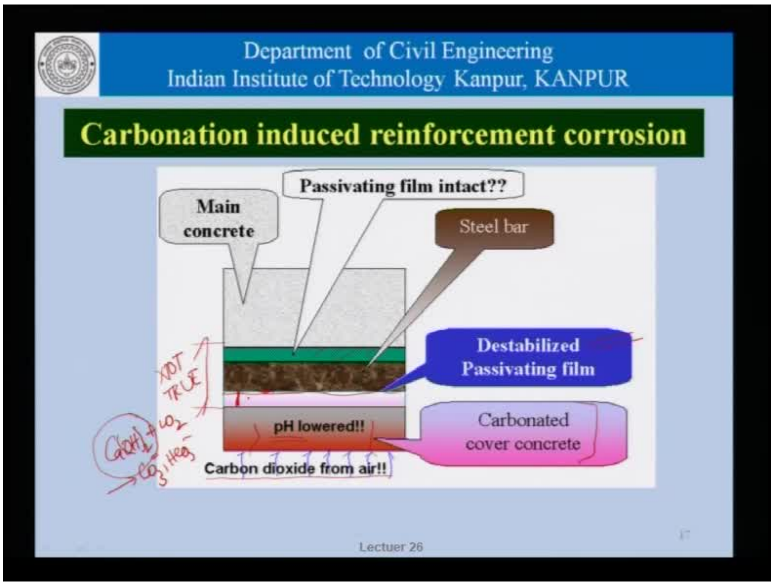

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Carbonation induced reinforcement corrosion

Now, this is what we will see as we go along in our discussion today. Let us look at chloride induced reinforcement corrosion. This is a schematic sketch of what is going on, we have the steel bar and we have a chloride rich environment it could be marine environment and so on. And if it is a marine environment what really happens is that this chlorides form these chlorides find their way into the concrete, because the concrete is after all porous.

So, only the amount of porosity that is different from one concrete to another and as these chlorides move into the concrete gradually they reach the reinforcing bar. And once they reach the reinforcing bar again without going into the science are being very rigorous in the treatment of the subject. We can assume or let us take it for granted that once the chlorides reach the reinforcing bars and are present in a certain critical concentration. They will cause this kind of a disruption in the passivating film. And once this kind of disruption happens the small areas of the reinforcing bar are directly exposed to the oxygen and water in the concrete.

So, we have a damaged passivating film a cover concrete which is contaminated with chloride ions of course, part of the passivating film can remain completely undamaged. And there is no reason for the damage to be uniform across the reinforcement bar there is also possibility that the chlorides may be present in the concrete to begin with. And that is what happens when we are trying to use sea sand in the construction in which case the chlorides are initially present. And that is something which could be deleterious from the point of view of reinforcement corrosion, because they will cause damage in the passivating film in the initial stages itself.

Now, as far as carbonation induced reinforcement corrosion is concerned what is happening is that carbon dioxide from the air moves into the concrete and reacts with the calcium hydroxide present there as we saw earlier. And we have carbonates and bicarbonates deposited in the concrete, but there is consumption of calcium hydroxide. And the, if there is consumption of calcium hydroxide we can assume that there is a lowering of the p H in the cover concrete. And what we call this region is carbonated cover concrete this process of ingress of carbon dioxide into concrete is called carbonation. And we have the carbonated cover concrete and if the extent of this p H lowering reaches a level at the reinforcing bar that the passivating film is no longer thermodynamically stable. We have a destabilized passivating film that is a passivating film as simply vanished. And this entire surface of reinforcement is susceptible to corrosion in the presence of oxygen and water which may be present in the concrete.

Of course, like in the case of chloride induced corrosion it is possible that parts of the passivating film may be completely impact. And that is what is caused by the microscopic heterogeneity in the concrete I would also like you to remember that this scale is not at all true that is the thickness of this passivating film is nowhere near the thickness of the reinforcing bar thickness of this passivating film is at best a few microns. But it is so dense that it actually prevents the contact of oxygen and water and the reinforcement surface. So, this scale is not true and it is not that there is a major layer or very thick layer of the passivating film.

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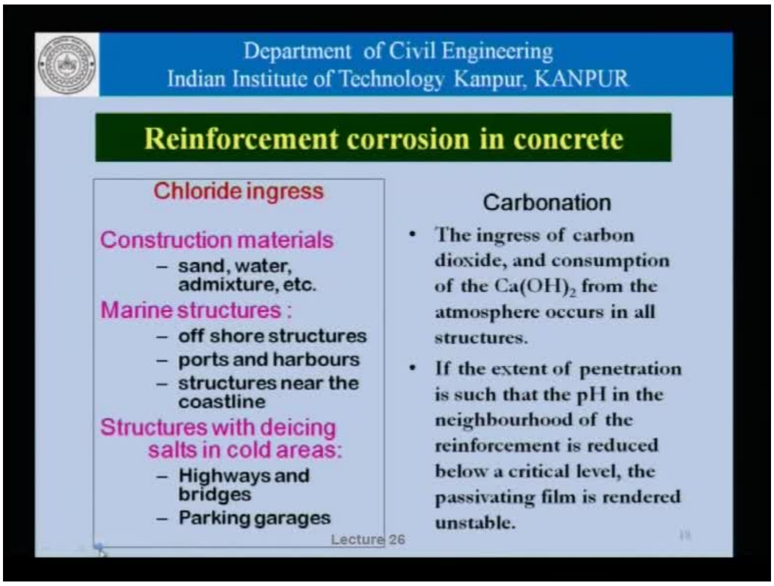

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Reinforcement corrosion in concrete

Chloride ingress

Construction materials
  - sand, water, admixture, etc.

Marine structures :
  - off shore structures
  - ports and harbours
  - structures near the coastline

Structures with deicing salts in cold areas:
  - Highways and bridges
  - Parking garages

Carbonation

- The ingress of carbon dioxide, and consumption of the $Ca(OH)_2$ from the atmosphere occurs in all structures.
- If the extent of penetration is such that the pH in the neighbourhood of the reinforcement is reduced below a critical level, the passivating film is rendered unstable.

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Now, let us look at a summary of the reinforcement corrosion in concrete. As far as chlorides in concrete are concerned they could be coming from the construction materials I mention that if we are using for example, sea sand or a chloride present in the chemical admixtures. Then in the very first place, we have introduced chlorides in the system in the concrete and they could become an deleterious from the point of view of reinforcement corrosion in concrete sand water or admixture. In the case of marine structures it could be offshore structures ports and harbors and structures near a coastline.

All these structures are susceptible to chloride ingress, because of the sea water, the sea water present as such or may be even salt which is carried by air and deposited on concrete surfaces at a certain distance from the coastline. Then there are structures where we use deicing salts in cold areas for example, highways and bridges parking structures what happens is that in regions which have a very, very heavy snow fall. Then in order to keep the highways open for movement deicing salts are spread on to the concrete surface or on the highway.

And this salt which is paid finds its way into the concrete structures and is just like any other chloride it causes a disruption in the passivating film. Also the cards that move on these highways in their tires and on their underside they carry the salt water. And once your parking them in a parking garage then they drip and parking garages and the parking garages are also susceptible to the action of deicing salts or salt action is as far as chloride penetration and finally reinforcement corrosion is concerned. As far as carbonation is concerned the ingress of carbon dioxide and the consumption of calcium hydroxide from the atmosphere occurs in all structures of the atmosphere. If the extent of penetration is such that the p H in the neighborhood of the reinforcement is reduced below a critical level the passivating film is rendered unstable

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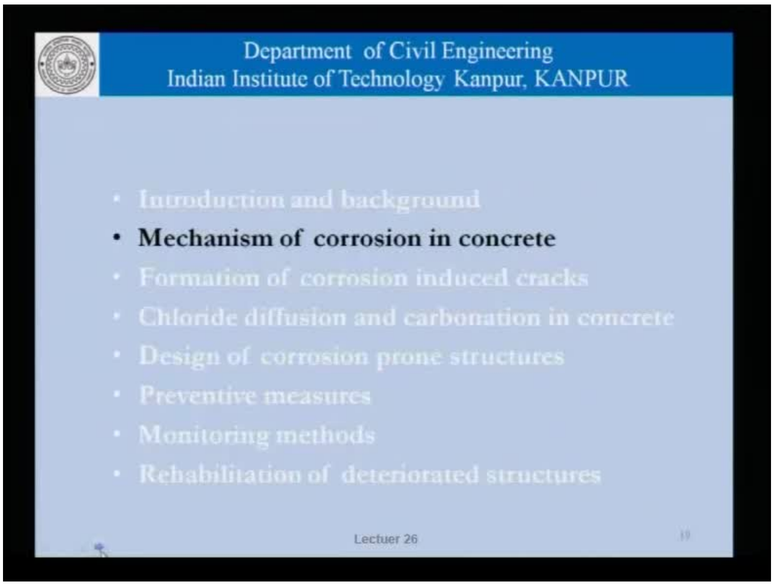

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- Introduction and background
- **Mechanism of corrosion in concrete**
- Formation of corrosion induced cracks
- Chloride diffusion and carbonation in concrete
- Design of corrosion prone structures
- Preventive measures
- Monitoring methods
- Rehabilitation of deteriorated structures

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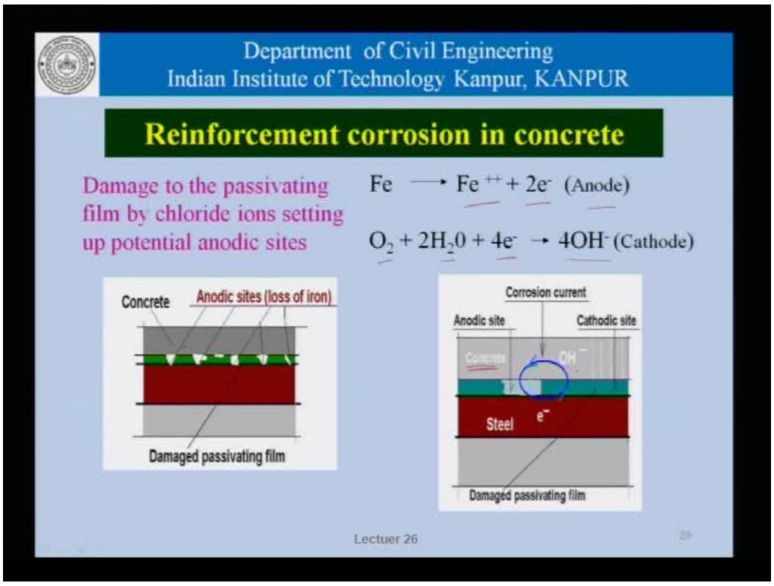

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Reinforcement corrosion in concrete

Damage to the passivating film by chloride ions setting up potential anodic sites

$Fe \longrightarrow Fe^{++} + 2e^-$ (Anode)

$O_2 + 2H_20 + 4e^- \rightarrow 4OH^-$ (Cathode)

Now, let us try to take a closer look at the mechanism of corrosion and concrete. We know that there is a damage to the passivating film by chloride ions setting a potential anodic sites. Now, what are these anodic sites? Anodic sites are those where the loss of iron occurs we also have the setting up of a corrosion current. Please remember that at the end of it corrosion is an electrochemical process it involves setting up of anodes and cathodes. And the passage of a corrosion current between the anodes and cathodes and the concrete really serves as an electrolyte as we can see here. So, we have this is concrete and this current is passing through the concrete and concrete is acting as an electrolyte. As far as chemical reactions are concerned iron is going to the iron ions and release of electrons at the anode and oxygen and water in the consume the electron to form hydroxyl ions at the cathode. Now, once this is happening then between the anode and the cathode there is this corrosion current which is set up and we have propagating reinforcement corrosion.

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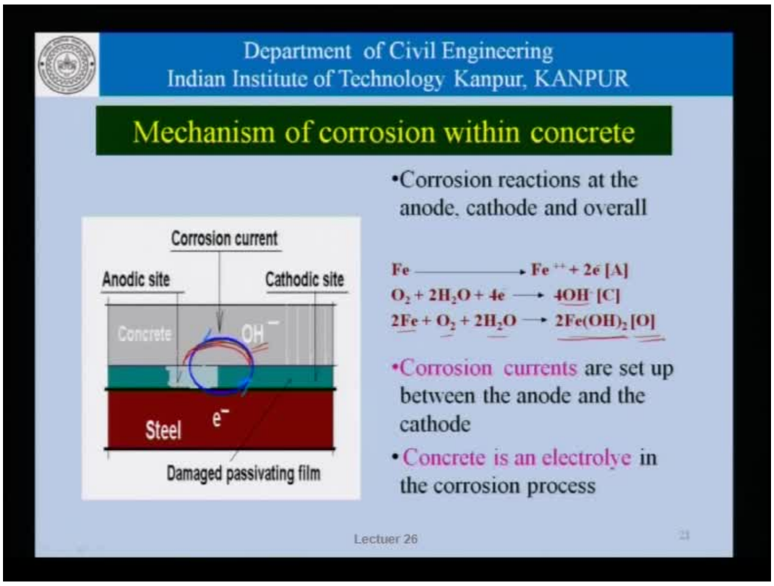

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Mechanism of corrosion within concrete

- Corrosion reactions at the anode, cathode and overall

$Fe \longrightarrow Fe^{++} + 2e^{-}$ [A]
$O_2 + 2H_2O + 4e^{-} \longrightarrow 4OH^{-}$ [C]
$2Fe + O_2 + 2H_2O \longrightarrow 2Fe(OH)_2$ [O]

- Corrosion currents are set up between the anode and the cathode
- Concrete is an electrolye in the corrosion process

This is what we had seen is the reactions iron going to iron ions and two electrons being released at the anode. The electrons being consumed in the presence of oxygen and water to form hydroxyl ions in the cathode and over all what we are has seeing is that iron oxygen and water gives us some kind of hydrate some kind of a corrosion product.

So, if we look at this picture once again what is happening is there is an anodic site where we have the iron is going into solution that is iron is getting converted to iron ions.

And at the cathodic sites the hydroxyl ions are formed and these kind of move within the concrete. So, this corrosion currents which are set up between the anode and the cathode are a very critical part of our study of reinforcement corrosion, concrete in number serves as an electrolyte in the corrosion process. So, if this concrete which is serving as an electrolyte in a corrosion process has a very high resistance then it will not allow free passage or it will offer a greater resistance to the passage of these corrosion currents. And we could control the extent of corrosion or the rate of corrosion and so on.

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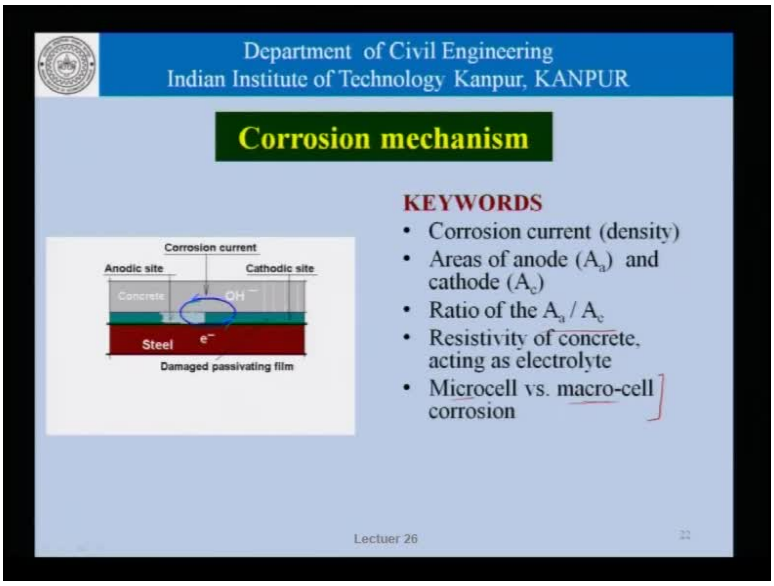
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Corrosion mechanism

KEYWORDS
- Corrosion current (density)
- Areas of anode (A_a) and cathode (A_c)
- Ratio of the A_a / A_c
- Resistivity of concrete, acting as electrolyte
- Microcell vs. macro-cell corrosion

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Now, if we look at this picture once again the keywords really are corrosion current or corrosion density or the current density there is an area of the anode involved there is an area of the cathode involved. And there is a ratio of the area of the anode to the area of cathode. That is if this ratio was very small or very large that will alter the rate at which the corrosion currents are flowing, resistivity of the concrete which acts as an electrolyte. There is discussion in literature on microcell versus macro cell corrosion. Now you can imagine what microcell macro cell is.

Microcell refers to a situation where the anode and the cathode are very close to each other. And they could even be interchangeable that for a certain amount of time, a certain area acts as an anode the corrosion there being supported by the neighboring areas in terms of the cathode. And after certain time something else happens the electrochemical environment changes and that area becomes a cathode to some other anode. So, this is happening in the microcell corrosion where the anodes in the cathodes are very closely spaced, whereas in a macro cell corrosion the anode and the cathode are very different are at especially different locations. And it is easy to find out which area of the cathode or which area is acting as a cathode to support or sustain the corrosion at a particular anodic area.

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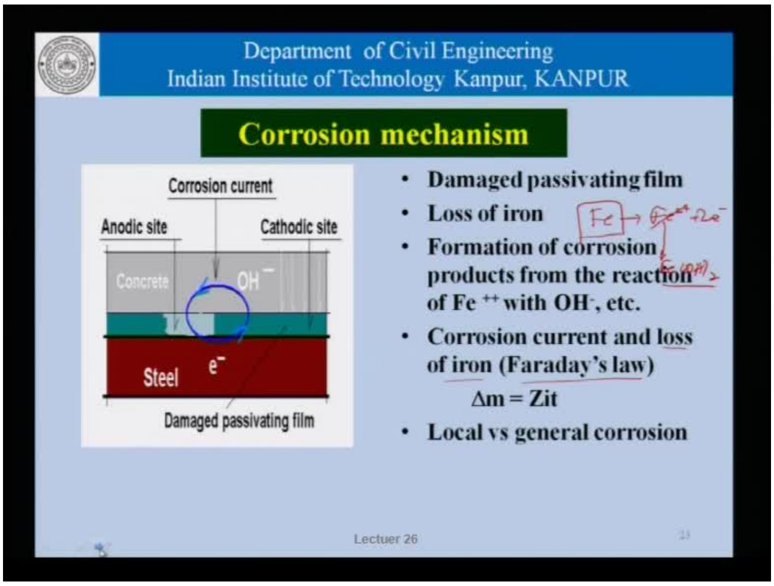

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Corrosion mechanism

- **Damaged passivating film**
- **Loss of iron** $\boxed{Fe} \rightarrow Fe^{2+} + 2e^-$
- **Formation of corrosion products from the reaction of Fe $^{++}$ with OH $^-$, etc.** $Fe(OH)_2$
- **Corrosion current and loss of iron (Faraday's law)**

  $\Delta m = Zit$
- **Local vs general corrosion**

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As far as the corrosion mechanism is concerned we are reiterating that there is a damaged passivating film. There is loss of iron, because once the iron is gone to F e 2 plus and electrons are released and this goes and gets converted to F e O H 2 and so on. Effectively the amount there is a loss in the iron and this is effectively there is loss of iron in the reinforcing bar. And we recall that corrosion current and the loss of iron is something which we can study using the Faraday's laws that is we have delta m is equal to Zit.

Now, without getting into the complexities of these equations let us proceed and say that the corrosion can be local or general local is a corrosion where the corrosion is localized. And a lot of corrosion takes place at a relatively smaller area that is the anode has a very small size, whereas general corrosion means that the corrosion is spread over the entire reinforcement or the entire reinforcing system.

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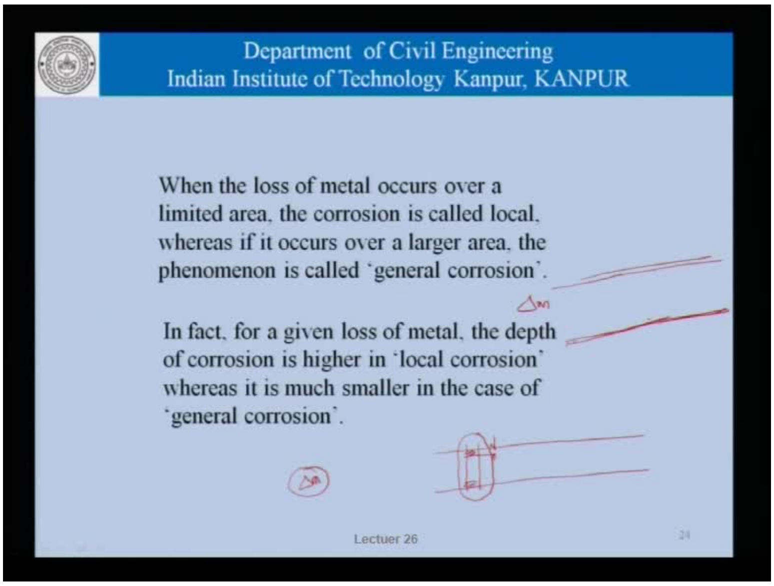

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When the loss of metal occurs over a limited area, the corrosion is called local, whereas if it occurs over a larger area, the phenomenon is called 'general corrosion'.

In fact, for a given loss of metal, the depth of corrosion is higher in 'local corrosion' whereas it is much smaller in the case of 'general corrosion'.

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When there is loss of metal over a limited area the corrosion is called local, whereas if it occurs over larger area the phenomenon is called general corrosion. In fact, for a given loss of metal the depth of corrosion is higher in local corrosion, whereas it is much smaller. In the case of general corrosion what we are really saying is that if we have a reinforcing bar like this and a certain amount of delta m has to occur here. That is a certain amount of total corrosion is involved. Then if this corrosion occurs over a very small area and the rest of the bar does not get affected by the corrosion process. Then this here represents the loss in thickness of the bar. And therefore, if the corrosion is local, this depth of corrosion is very large.

Whereas in another system where for the same reinforcing bar and the same loss in weight for the iron in terms of the total corrosion. If it was distributed over a very large area the corrosion, the loss in thickness of the reinforcement will be very small. This is something which we must keep in mind that at the end of it the loss of matter or the loss of material that is a loss of iron actually translates to a loss in thickness. The thickness becomes smaller if we have a 16 m m bar and the corrosion occurs in a manner that the diameter of the bar is reduced by 1 m m that is an extreme case then the bar will remains only 15 m m in diameter.

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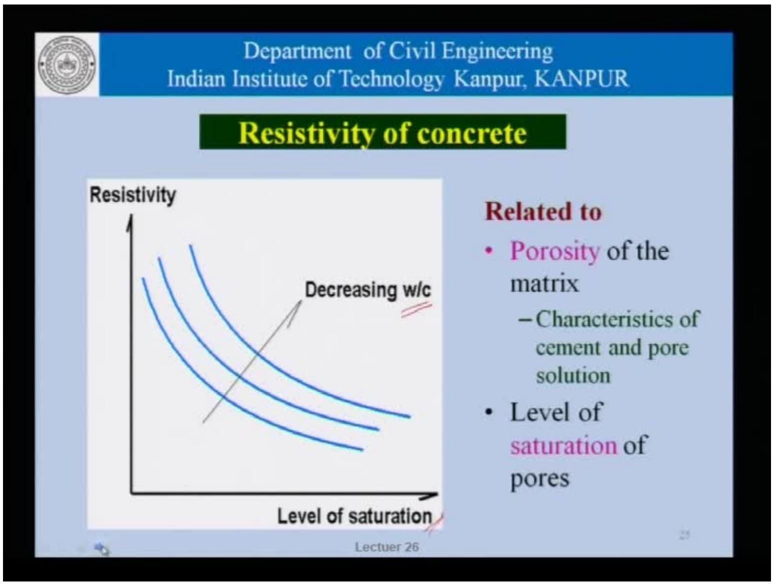

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Resistivity of concrete

Related to

- Porosity of the matrix
  - Characteristics of cement and pore solution
- Level of saturation of pores

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Now, let us look at the resistivity of concrete which is another important controlling parameter as far as the reinforcement corrosion is concerned. This here is the schematic representation of resistivity versus level of saturation and the water cement ratio. So, the resistivity which is the specific property of concrete depends on the level of saturation that is if the concrete was saturated with water. Then the resistivity will be very small and the same concrete if it was try it will give you a very large resistivity.

Whereas of course, it also depends on the water cement ratio that is if the concrete had a high water cement ratio that is it had more pores. Then we will have lower resistivity, but primarily it is been it is suggested in literature that the level of saturation is a very important parameter as far as the resistivity of concrete is concerned and that is something which we must remember. For example in the case of as can be seen in this picture the resistivity is related to the porosity of the matrix which is depending on the characteristics of cement and the pore solution and also on the level of saturation of the pores. Now, we must relate this to the, to the chloride induced and carbonation induced corrosion.

In the case of chloride induced corrosion most likely the concrete is in a marine environment or a deicing salt environment and so on. And there the concrete is likely to be saturated with water a lot of times. And therefore, we are working with the system or we are likely to work with the system where the resistivity of the concrete is very low. In contrast to this as far as carbonation induced corrosion is concerned that occurs in the atmosphere and there it is quite likely that the concrete is not highly saturated with water. And therefore, we are working with a concrete system which is low on saturation and therefore, has a relatively higher resistivity. So that is how we relate the importance of resistivity of concrete to chloride induced or carbonation induced corrosion.

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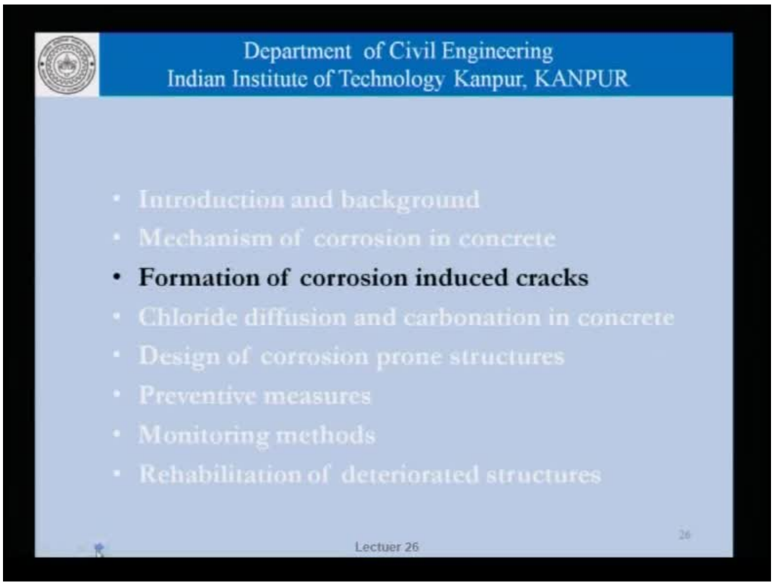

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- Introduction and background
- Mechanism of corrosion in concrete
- **Formation of corrosion induced cracks**
- Chloride diffusion and carbonation in concrete
- Design of corrosion prone structures
- Preventive measures
- Monitoring methods
- Rehabilitation of deteriorated structures

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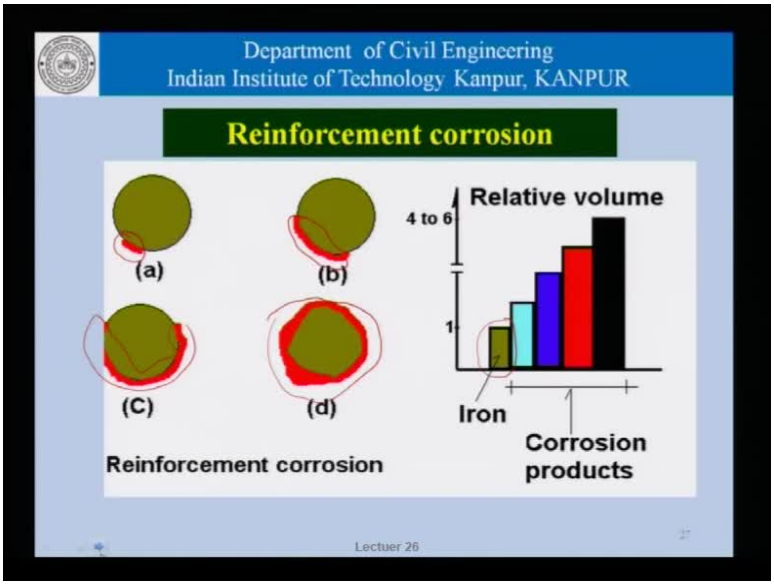

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Reinforcement corrosion

Reinforcement corrosion

Continuing our discussion, let us talk in terms of formation of corrosion induced cracks what causes these cracks. Now, this is a schematic representation of water reinforcement corrosion is all about. We have a bar and we have these corrosion products the oxides and the hydroxides being deposited around the bars. It could be in a small part of the bar or it could be all around the bar depending on what kind of corrosion we are talking about.

Now, as far as the relative volumes of these corrosion products is concerned it is known that compare to iron which is the material which is being lost. These corrosion products have a much higher volume it could be from one and a half to 2 times to about 5 to 6 times, depending on what kind of corrosion products are formed when that in turn depend on how much is the oxygen or water availability and so on. So, now as a result of this understanding where we have seen that the loss of iron is accompanied by formation and deposition of larger volume corrosion products.

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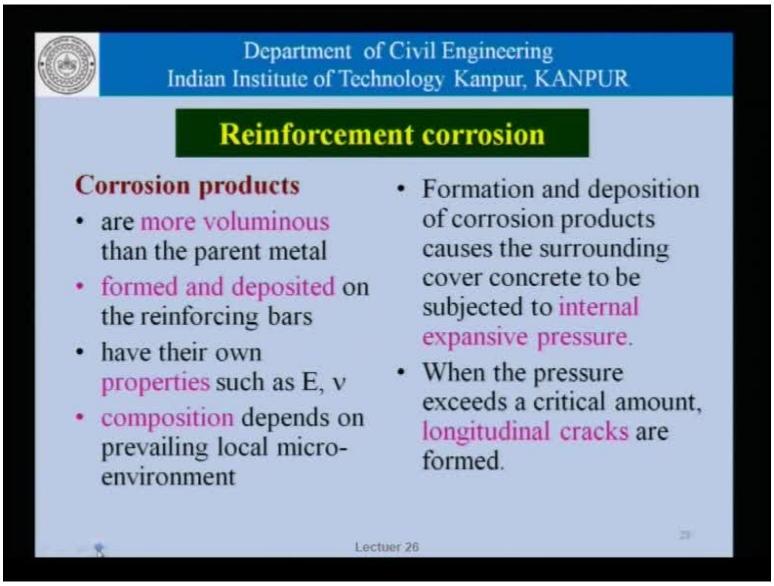

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Reinforcement corrosion

Corrosion products

- are more voluminous than the parent metal
- formed and deposited on the reinforcing bars
- have their own properties such as E, ν
- composition depends on prevailing local micro-environment

- Formation and deposition of corrosion products causes the surrounding cover concrete to be subjected to internal expansive pressure.
- When the pressure exceeds a critical amount, longitudinal cracks are formed.

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What we really have is corrosion products being more voluminous than the parent metal and their formation and deposition on the reinforcing bar. And they have their own properties in terms of the modulus of elasticity and poisson’s ratio and so on composition depending on the local micros environment we have concrete being subjected to internal expansive pressure. So, the formation of these corrosion products which have a higher volume cause the concrete surrounding the reinforcing bar to be subjected to internal expansive pressures. And when the pressure exceeds and when the pressure exceeds a critical amount these longitudinal cracks are formed.

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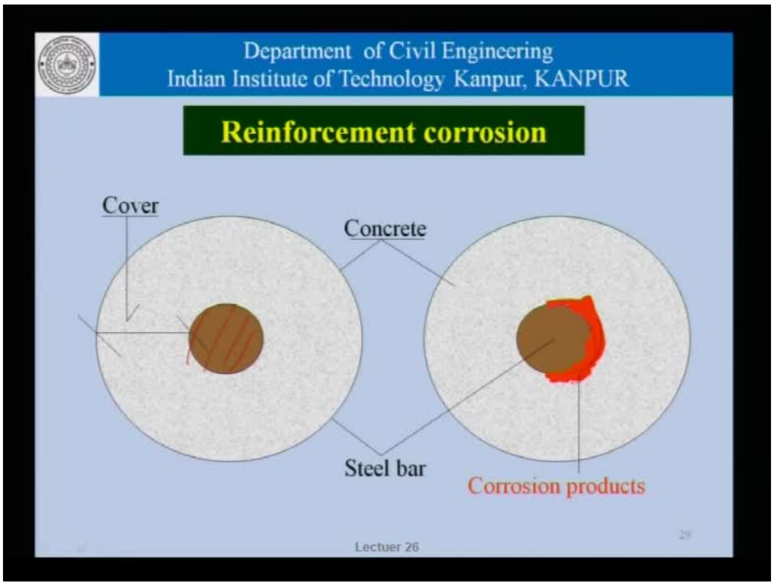

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Reinforcement corrosion

Cover

Concrete

Steel bar

Corrosion products

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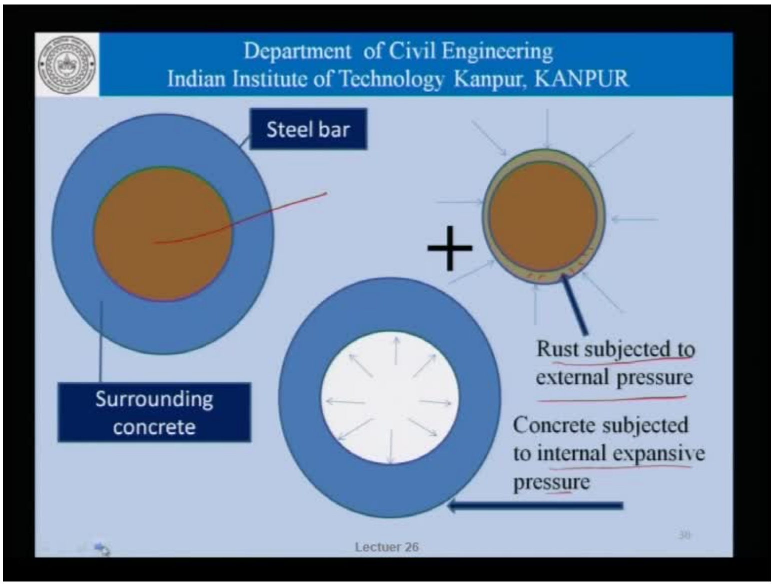

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Steel bar

Surrounding concrete

+

Rust subjected to external pressure

Concrete subjected to internal expansive pressure

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Now, let us look at what is happening, this is what is the cover and there is a reinforcing bar here and if this reinforcing bar was to corrode and a corrosion products were deposited around here. And these corrosion products had a higher volume than the parent metal. Then if we model this, this rust which is deposited here is subjected to confining pressure from the surrounding concrete. And the concrete on the other hand is subjected to internal expansive pressure. So, basically as this bar here corrodes, what we have is a system where if we draw the free body diagrams of the reinforcing bar and the surrounding concrete. The reinforcing bar is subjected to confining pressures from the surrounding concrete and the concrete itself is subjected to expansive internal pressures.

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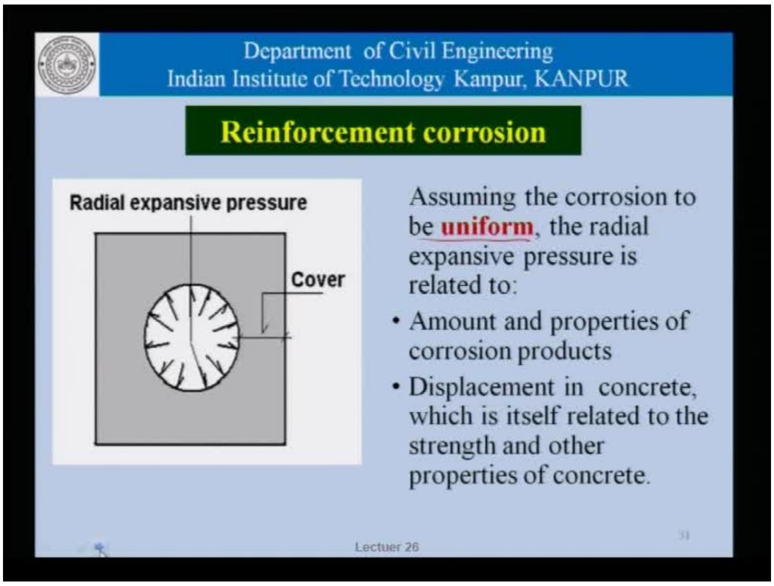

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Reinforcement corrosion

Assuming the corrosion to be **uniform**, the radial expansive pressure is related to:

- Amount and properties of corrosion products
- Displacement in concrete, which is itself related to the strength and other properties of concrete.

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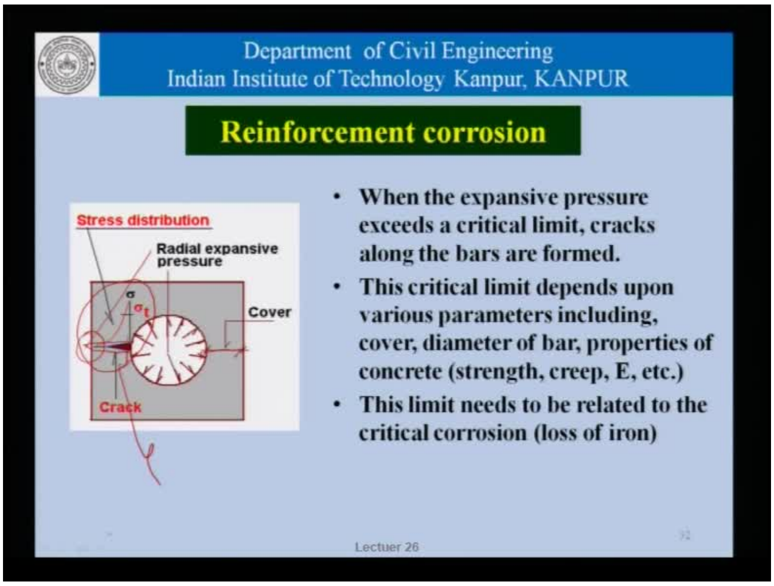

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Reinforcement corrosion

- **When the expansive pressure exceeds a critical limit, cracks along the bars are formed.**
- **This critical limit depends upon various parameters including, cover, diameter of bar, properties of concrete (strength, creep, E, etc.)**
- **This limit needs to be related to the critical corrosion (loss of iron)**

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And once these pressures exceed the certain amount and that is what is shown here. This picture here assumes that the corrosion is uniform that is all around the reinforcing bar. We have certain amount of expansive pressure which depends on the amount and the properties of corrosion products, the displacement in concrete which is itself related to the strength and the properties of concrete. What we really have is once this stress here in the concrete exceeds the tensile strength of concrete. We have the onset of a crack and this crack quickly reaches the surface. And what we have here at the surface is the appearance of a crack which runs along the structure that is along the reinforcing bar when the expansive pressure exceeds a critical limit cracks along the bar are formed. And this critical limit depends on various parameters including the cover the diameter of the bar the properties of concrete strength creep modulus of elasticity and so on.

And it is also related the critical corrosion in terms of loss of iron. And let us go back to this picture; obviously, if we increase the amount of cover that is we increase this thickness. Then the amount of pressure or the radial expansive pressure that the concrete will be able to take were possibly go up which means that that particular system with the increased cover will be able to sustain a higher amount of corrosion before we have the onset of longitudinal cracks.

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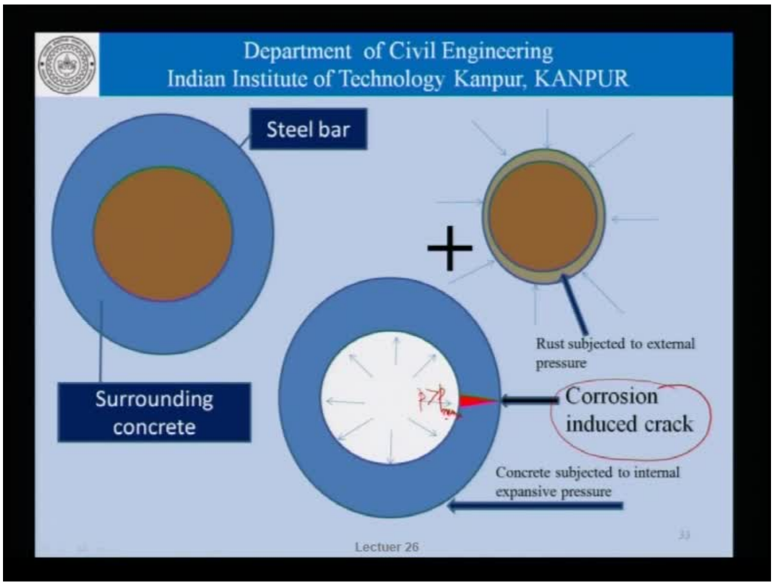

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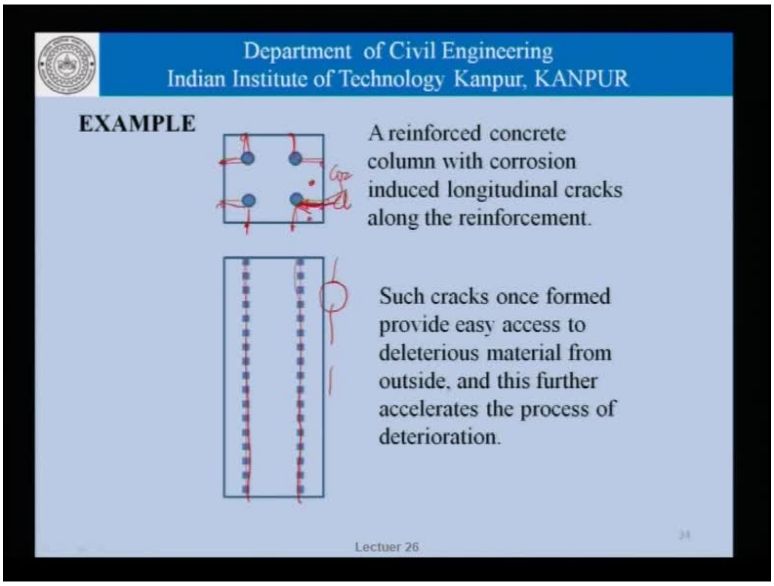

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EXAMPLE

A reinforced concrete column with corrosion induced longitudinal cracks along the reinforcement.

Such cracks once formed provide easy access to deleterious material from outside, and this further accelerates the process of deterioration.

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And this is what is happening as far as the previous picture is concerned. As far as the surrounding concrete is concerned, we have this corrosion induced crack, once this pressure exceeds a certain critical p max which the concrete can sustain depending on its properties in terms of strength and so on. Now, let us take an example as to what is happening as far in a column if we have this as a cross section of the column with these reinforcing bars. It is likely that we will have we will see the onset of corrosion cracks around these reinforcing bars something like. And these points being closest to the surface we will see the onset of corrosion cracks at these points assuming of course, that all the 4 bars are corroding uniformly.

And in the longer section, we will have this as a corrosion crack along the reinforcing bar it is not necessary that it will run continuously it is possible that it may be in certain places you may have a crack then not have a crack and so on. So, this portion here need not be corroding and therefore, it is only and therefore, it is only a matter of understanding that yes once corrosion occurs the cracks are formed along the reinforcing bars here. We have a reinforced concrete column with corrosion induced longitudinal cracks along the reinforcement and such cracks once formed provide easy access to deleterious material from the outside and this further accelerates the corrosion process.

Because once this corrosion cracks are formed whatever is available in the atmosphere whether it is carbon dioxide or chlorides and so on. They find a much easier access to the reinforcing bar. And no matter what the properties of this concrete are the access is really gets governed by the width of these corrosion induced cracks. And we have an accelerated corrosion process after these corrosion induced longitudinal cracks are formed.

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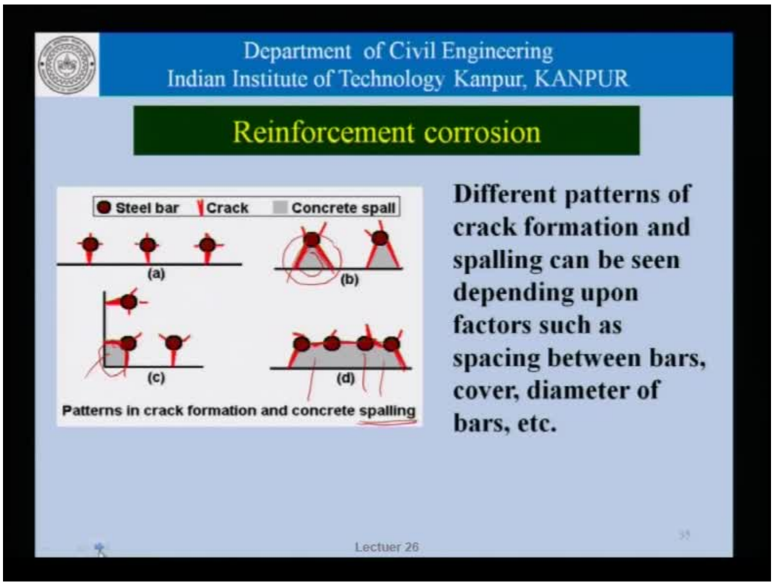

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Reinforcement corrosion

Patterns in crack formation and concrete spalling

Different patterns of crack formation and spalling can be seen depending upon factors such as spacing between bars, cover, diameter of bars, etc.

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This is another example of how the cracking continues to effect the reinforced concrete structure, we have a situation where if these two cracks are formed. Then this part of concrete becomes loose and falls off and that is what is called spalling that is the concrete from the structure becomes loose and falls of exposing the reinforcing exposing the reinforcement. So, this is spalling can happen in different ways it can happen in a corner, it can happen in a situation like this where two cracks are formed along the bar. And this portion becomes loose or this kind of a crack pattern is formed and we have the spalling of a much larger chunk of concrete from the surface. So, basically the cover concrete falls off from the RC structure, the different patterns of crack formation and spalling can be seen depending upon factors such as spacing between the bars cover, the diameter of the bars and so on.

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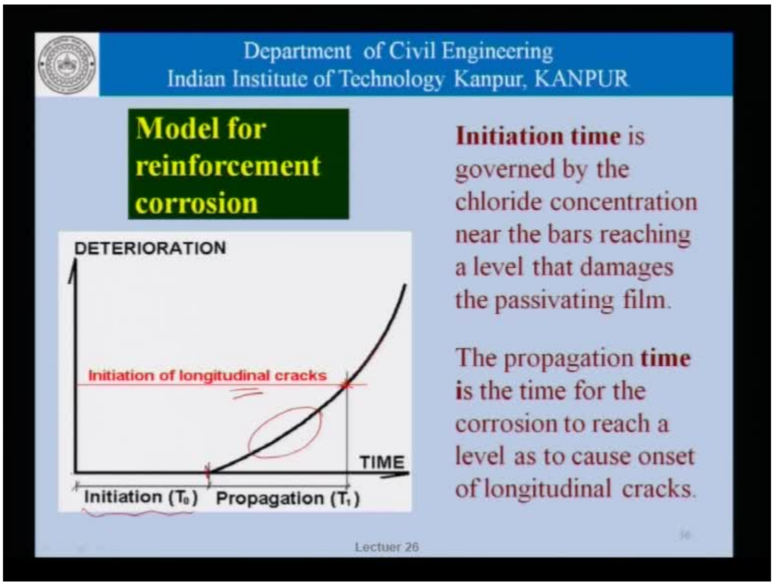

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Model for reinforcement corrosion

Initiation time is governed by the chloride concentration near the bars reaching a level that damages the passivating film.

The propagation **time is** the time for the corrosion to reach a level as to cause onset of longitudinal cracks.

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So, now as far as the model for reinforcement corrosion is concerned we can talk in terms of something like this. There is an initiation phase that is from this point to this time, there is no corrosion in the reinforcement and beyond this time certain corrosion takes place. And after this point once the longitudinal cracks are formed the deterioration takes off at a much more rapid pace accelerated deterioration is taking place. And initiation time is governed by the chloride concentration near the bars as chloride concentration near the bars reaches the level that damages the passivating film. And this will be governed by controlling the cover thickness and the probability of concrete in terms of the diffusion coefficient of concrete and so on as so as to make the chlorides more difficult so as to make it more difficult for the chlorides to reach the concrete surface. And the propagation time is the time that the corrosion takes to reach a level so as to cause the onset of longitudinal cracks. So; obviously, in this part some amount of corrosion has taken place, but it is not enough to cause the onset of longitudinal cracks at this point the pressure that builds up on account of corrosion is the critical level where the longitudinal cracks are formed.

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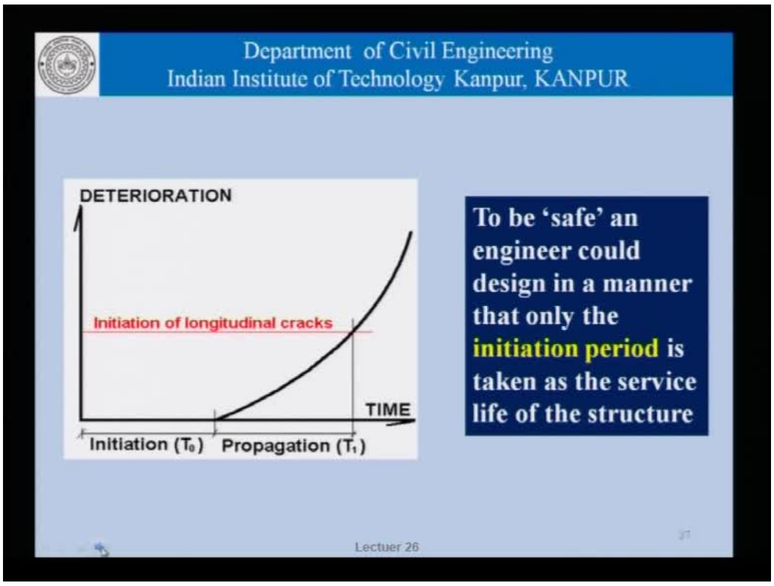

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To be 'safe' an engineer could design in a manner that only the **initiation period** is taken as the service life of the structure

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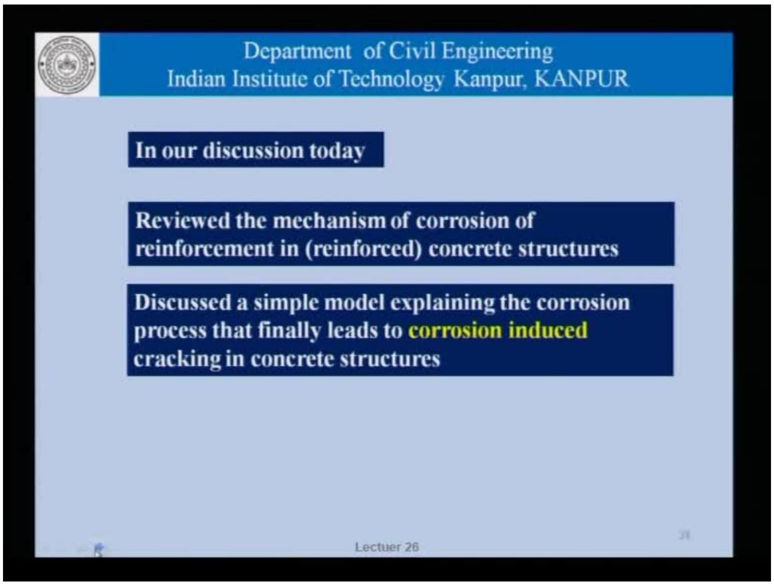

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In our discussion today

Reviewed the mechanism of corrosion of reinforcement in (reinforced) concrete structures

Discussed a simple model explaining the corrosion process that finally leads to corrosion induced cracking in concrete structures

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So, with these two what we really have is that it could be safe as an engineer to design in a manner that only the initiation period is taken as a surface life of the structure. These are this is a this is an idea which we will come back to when we are talking more about the penetration of chlorides, the buildup of chlorides at the reinforcement location and so on in the concrete. Now, so far in our discussion today, we have reviewed the mechanism of corrosion of the reinforcement in reinforced concrete structures. We have discussed a simple model explaining a corrosion process that finally leads to corrosion induced cracking in concrete structures.

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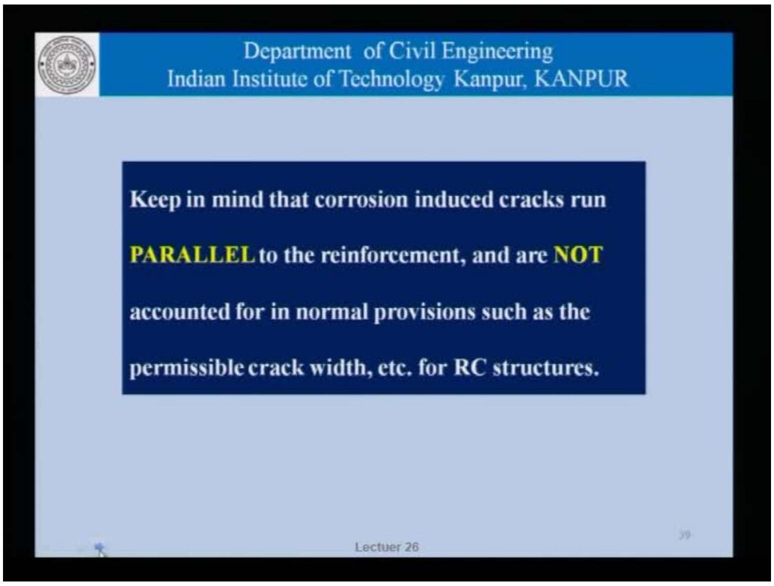

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Keep in mind that corrosion induced cracks run PARALLEL to the reinforcement, and are NOT accounted for in normal provisions such as the permissible crack width, etc. for RC structures.

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And we must keep in mind that corrosion induced cracks run parallel to the reinforcement and are not accounted for in the normal provisions such as permissible crack width for RC structures. We are familiar with provisions relating to maximum permissible flexural crack width.

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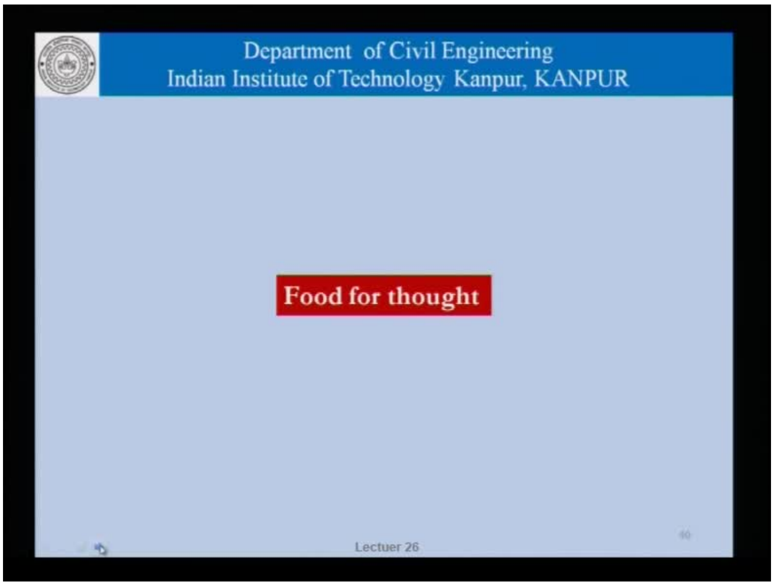

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Food for thought

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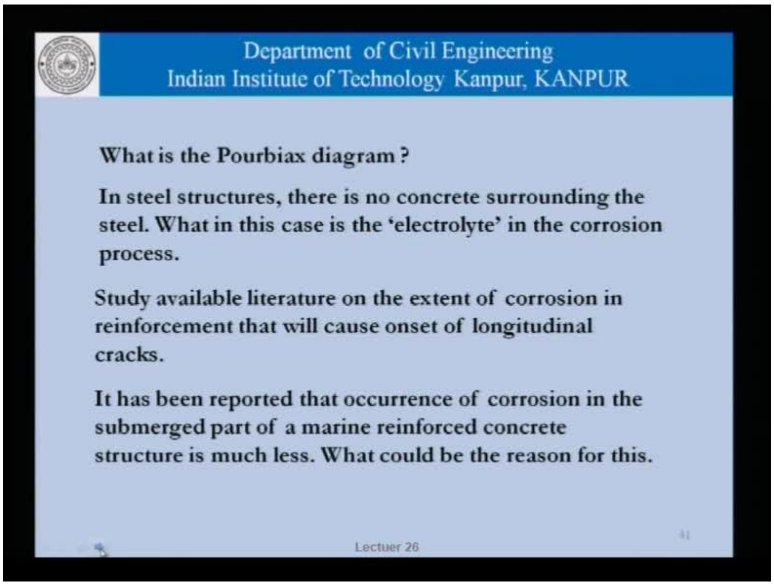

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What is the Pourbiax diagram ?

In steel structures, there is no concrete surrounding the steel. What in this case is the 'electrolyte' in the corrosion process.

Study available literature on the extent of corrosion in reinforcement that will cause onset of longitudinal cracks.

It has been reported that occurrence of corrosion in the submerged part of a marine reinforced concrete structure is much less. What could be the reason for this.

These are not flexural cracks and therefore, the provision for maximum crack width does not apply to them, keep that in mind. And before we close what is something that we need to know little more I would like you to go back and see what is a pourbiax diagram and how is it relevant from our discussion today?

Another question that I have for you in steel structures there is no concrete surrounding, the steel they have steel towers. You have steel pressures there is no concrete surrounding the steel and yet there is corrosion in those structures we try to prevent it by paying ticket and so on. But in this case what is the electrolyte for the corrosion process I would like you to study available literature on the extent of corrosion in reinforcement that will cause onset of longitudinal cracks. This is something which we will also take up in a subsequent discussion.

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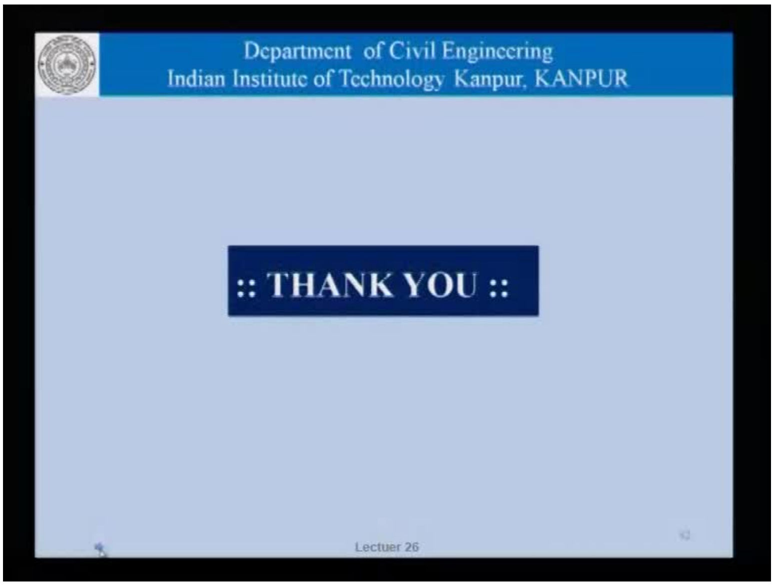

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:: THANK YOU ::

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Now, it has been reported that occurrence of corrosion in the submerged part of a marine reinforced concrete structure is much less than the corrosion in a idle zone or zones which are cyclically exposed to wetting and drying with salt water, what could be the reason for this, with these questions?

Thank you.