# Maintenance and Repair of Concrete Structures
**Prof. Radhakrishna G Pillai**
**Department of Civil Engineering**
**Indian Institute of Technology Madras– Chennai**

## Module No # 01
## Lecture No # 01
## Embedded Metal Corrosion

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Outline of
Module on Embedded Metal Corrosion

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

Hi, welcome to this module on embedded metal corrosion. We will have 5 lectures in this and the outline will be first lecture we will cover what is the significance of corrosion and some fundamentals of corrosion in which we will talk a little bit about what happens in concrete also. And then in lecture 2 we will cover in detail what is carbonation induced corrosion and chloride induced corrosion.

Then 2 lectures on different type of steel reinforcement and what are the precautions to be taken when we use latest type of steel reinforcements which are available. And then lecture 5 we will cover corrosion exclusively what is happening in pre-stressed concrete system both pre and post tension systems we will be covered. Now let’s talk more about the significance of corrosion and fundamentals of corrosion.

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## Sunshine Skyway bridge, Florida

- In 1980 this bridge was hit by a cargo ship and a 1200-ft section of bridge fell into the Tampa Bay.
- Replaced with a segmental, post-tensioned (PT) bridge in 1987.
- Only 13 years later,
  - PT tendon of the new bridge failed.
- If two tendons fail,
  - PT bridge can collapse (Pillai 2009).

- https://www.tampabay.com/resizer/bRh2m43Q1mwAMKB0N9uh5Rh9pGk=/1370x0/smart/filters:quality(60)/arc-anglerfish-arc2-prod-tbt.s3.amazonaws.com/public/MJX74QLL5VDCHE63H3MSTIPFAU.JPG
- https://study.com/cimages/multimages/16/sunsky.jpg
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I am going to give you some examples of corrosion related failure or premature failure that means prematurely the steel started corroding or before the design life or the target design life was achieved the structure started corroding. So this is one example where on the picture on the left side you see that at the far end there is a ship it actually hit the pillar and then the bridge collapsed and what they did is after that they reconstructed another bridge right next to it

In which, in about just 13 years you can see this pillar over here started severe corrosion and then you can see that the severe corrosion of the post tension systems in the vertical tendons.

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Golden Gate Bridge, San Francisco, CA

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And another example of premature corrosion is golden gate bridge. We spend a lot of money on this bridge to maintain the structure every year there is lot of corrosion related issues and maintenance is a big job there.

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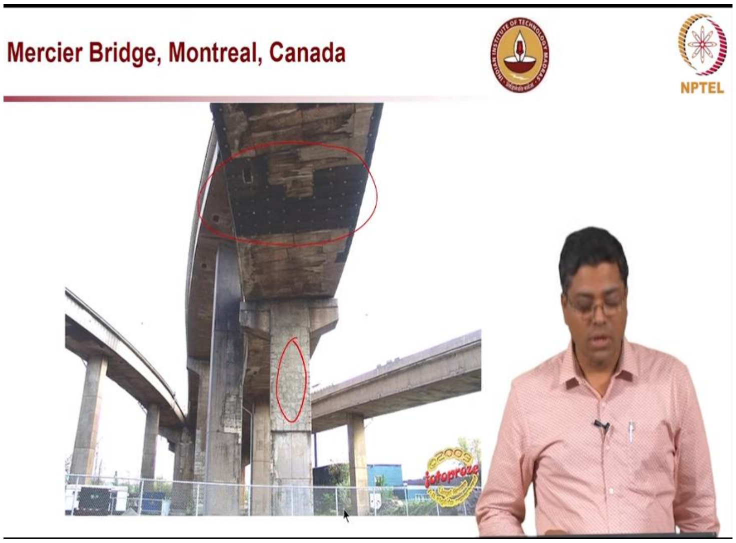
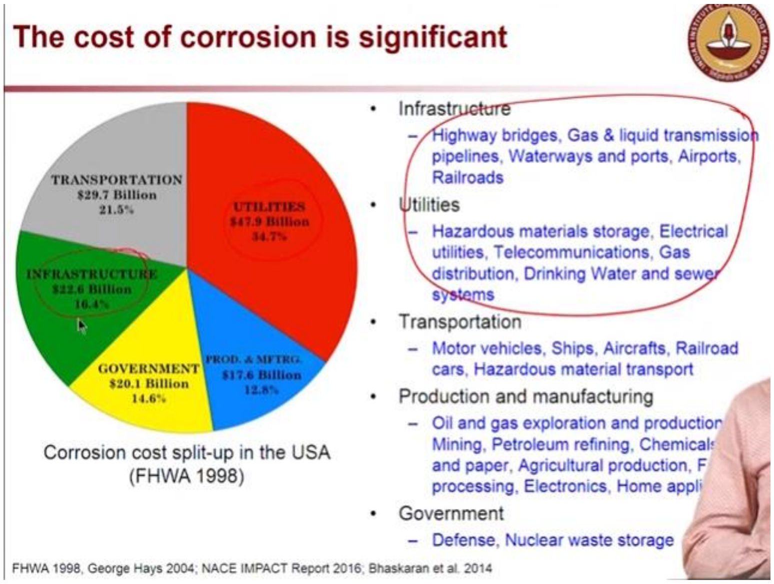


Mercier Bridge, Montreal, Canada

Another structure again in the developed world is in Canada. This is the Mercier Bridge, couple of decades old bridge. But you can see that the bridge is severely corroding the net which you see here is actually to protect it from falling down and then you can see here it looks like ASR type of problem there. So, different type of deterioration mechanisms happen, I mean deterioration happen in many of these structures. **(Refer Slide Time 03:04)**



The cost of corrosion is significant

Corrosion cost split-up in the USA
(FHWA 1998)

- Infrastructure
  - Highway bridges, Gas & liquid transmissio pipelines, Waterways and ports, Airports, Railroads
- Utilities
  - Hazardous materials storage, Electrical utilities, Telecommunications, Gas distribution, Drinking Water and sewer systems
- Transportation
  - Motor vehicles, Ships, Aircrafts, Railroad cars, Hazardous material transport
- Production and manufacturing
  - Oil and gas exploration and production Mining, Petroleum refining, Chemical and paper, Agricultural production, F processing, Electronics, Home appli
- Government
  - Defense, Nuclear waste storage

FHWA 1998, George Hays 2004; NACE IMPACT Report 2016; Bhaskaran et al. 2014

And what we are trying to tell here is corrosion is leading to huge cost and what is that cost? It's about 3 to 4% of GDP before getting into that this Pie chart which is showing the cost of corrosion and this is made for USA. But more or less which will be similar to many other countries. So, I thought this will be a good example to show, what you see here is, if you look at the infrastructure which is the green pie here. You can see it is covering highway bridges, gas and liquid transmission pipelines, waterways, ports, railroads etc.,

Utilities which is this one which covers about 35% of the cost of corrosion. That covers different hazardous material storage facilities, electrical utilities, telecommunication, gas distribution, drinking water and sewer systems. What I want to focus here is there are many concrete elements are there in these two. And if you put them together that utilities and transportation infrastructure that is coming to be about 35+ % another 15% if you add that's about 50% of the total cost of corrosion. So, we have a big job here to reduce this cost of corrosion associated with concrete structures.

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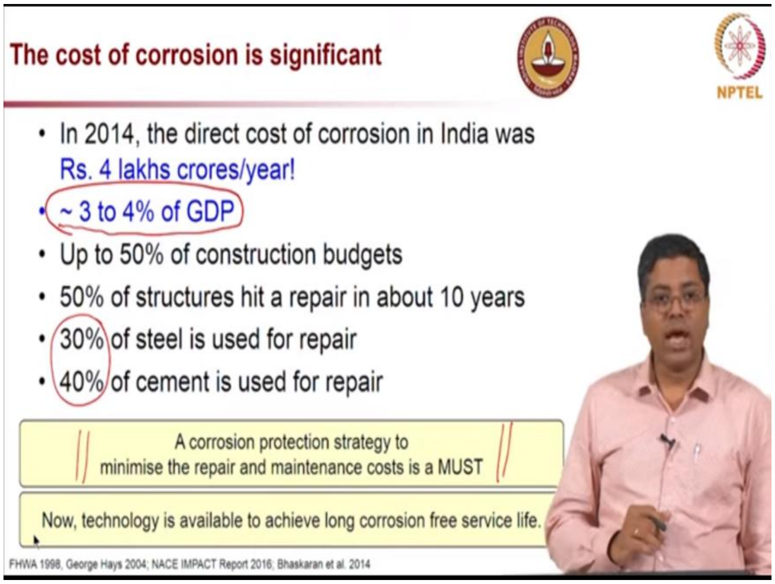

The cost of corrosion is significant

- In 2014, the direct cost of corrosion in India was Rs. 4 lakhs crores/year!
- ~ 3 to 4% of GDP
- Up to 50% of construction budgets
- 50% of structures hit a repair in about 10 years
- 30% of steel is used for repair
- 40% of cement is used for repair

A corrosion protection strategy to minimise the repair and maintenance costs is a MUST

Now, technology is available to achieve long corrosion free service life.

FHWA 1998, George Hays 2004; NACE IMPACT Report 2016; Bhaskaran et al. 2014

So, some statistics on this corrosion in the pie chart I showed earlier; I told that it was 3 to 4% of GDP. Now if you look at Indian case, we spend about 4 lakhs of Crores that's our cost of corrosion, annual cost of corrosion in 2014. As time passes the cost is actually increasing because we are constructing more and more structures. And also we are seeing premature corrosion in many of the structures, much before it reaches its design life.

Now, some other statistics I just want to mention here, to emphasize that this is really a big problem. Up to about 50% of the construction budgets actually is used for some kind of repair and then 50% of the structures they experience a major repair within about 10 years which is probably very short period. And now if you look at the amount of steel and cement which is produced, if you look at the steel, 30% of the steel is used for repair.

And in case of cement 40% of the cement is used for repair. So, maybe these numbers look very large but I have cross checked it with the same steel and cement industry. This is more or less correct the steel that is actually used for replacing the existing steel, cement is also purchased for repair projects. So, these two numbers are really alarming. So this is what we have to really reduce 3 to 4% GDP. We cannot keep on spending this much money on our structures which we are building and the structures which we already have. So, we must have a corrosion protection strategy that's essential to have a protection strategy in other words we should think of how to do a proper maintenance and even in design life how to design the structure so that you will have minimum repair. And do a proper maintenance and repair; the repair itself should be durable. If the repair itself is not durable, then you will end up in doing many repairs which will again increase the cost of corrosion.

So, point is now we have technology, to actually achieve this corrosion free service life of 100 years and all that. But provided we do give more importance on quality of construction.

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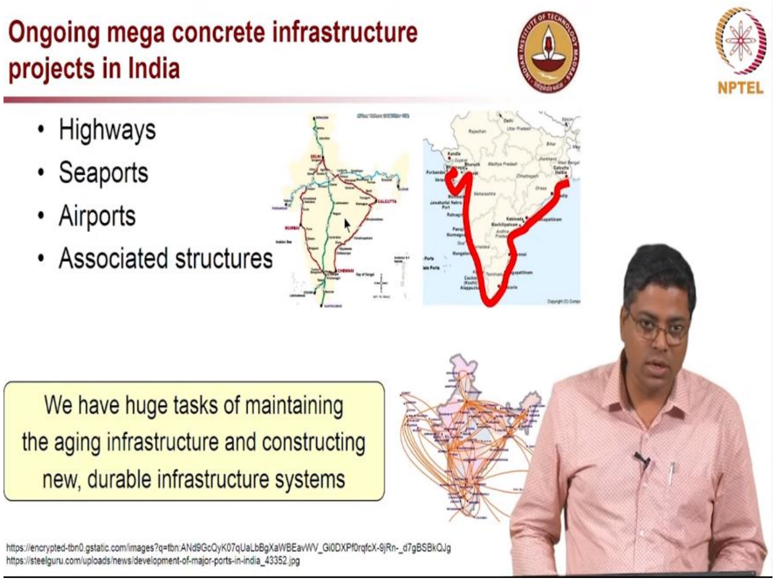

Ongoing mega concrete infrastructure projects in India

- Highways
- Seaports
- Airports
- Associated structures

We have huge tasks of maintaining the aging infrastructure and constructing new, durable infrastructure systems

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https://steelguru.com/uploads/news/development-of-major-ports-in-india_43352.jpg

Now, why the corrosion cost is becoming more important today is because we are constructing a lot of structures today like highway projects, seaports and then airports and also when we talk about these major projects there are also associated structures which are being built. For example: if you are constructing a road, there will be a lot of other structures which will come up all along the roads or on either side of the roads.

So, that’s also very important to have all these structures with quality in mind. Otherwise we will face a huge repair and maintenance cost in the years to come. So the main purpose of this course is to make sure that we construct the current structures in good way with durability in mind. And at the same time, we ensure that the way which we repair this structure or the existing structures are also going to be long lasting.

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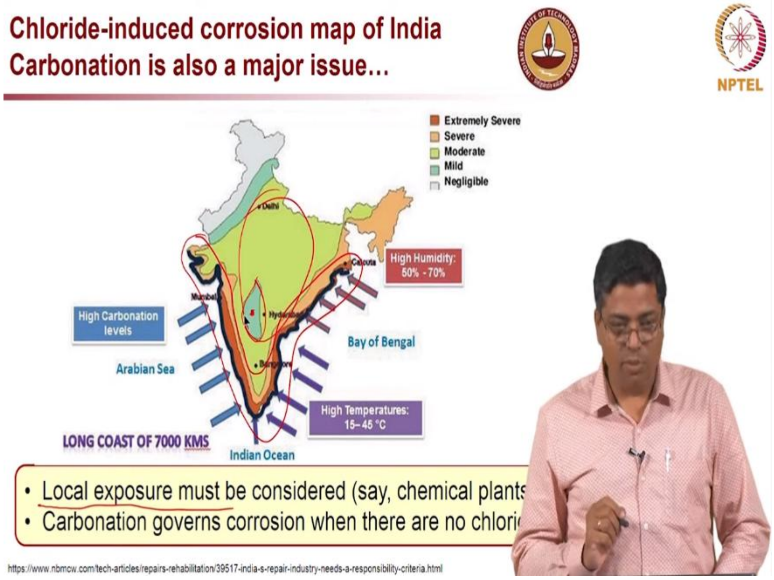

Chloride-induced corrosion map of India
Carbonation is also a major issue...

- Local exposure must be considered (say, chemical plants
- Carbonation governs corrosion when there are no chlori

https://www.nbmcw.com/tech-articles/repairs-rehabilitation/39517-india-s-repair-industry-needs-a-responsibility-criteria.html

Now, when we look at India as such we have several geographically different regions and the climatic condition is different for different regions. And usually we think about corrosion when we think about corrosion, we think about chloride induced corrosion. Probably one reason why we think like that is because we have a long coastline. You can see here this long coastline and in this region here looks like a necklace like I showed in the previous slide.

If you have concrete structures along this region then those structures will be exposed to airborne chlorides and at the same also the soil will be rich in chlorides in those structures. So, the foundation also may experience a severe corrosion. So we have to be very careful when we construct structures along the coast line. So, this is along the coast line and also for carbonation we usually think carbonation is not a major problem.

But, carbonation is also a major problem because at about 60 to 70 % humidity you can have very high carbonation. But, again on the coastal zone we usually see that chloride is governing in most of the cases. However we should also give enough importance for carbonation. Another thing is, if you are talking about any other structure in the interior or not on the coast but away from the coast. We should also think about the local exposure condition, because let’s say for example you are building a chemical plant where a lot of salt is being used. So that air next to this structure or the immediate to the concrete elements will have enough chlorides which will diffuse into the concrete element and can cause corrosion. So, even though in this map for example: if the Delhi is coming to be moderate condition or if some structure over here which is mild and if I am actually constructing my chemical plant here, I may actually have very high chloride condition.

So, we have to really think about local environmental condition not just the global conditions. This is very important to consider that.

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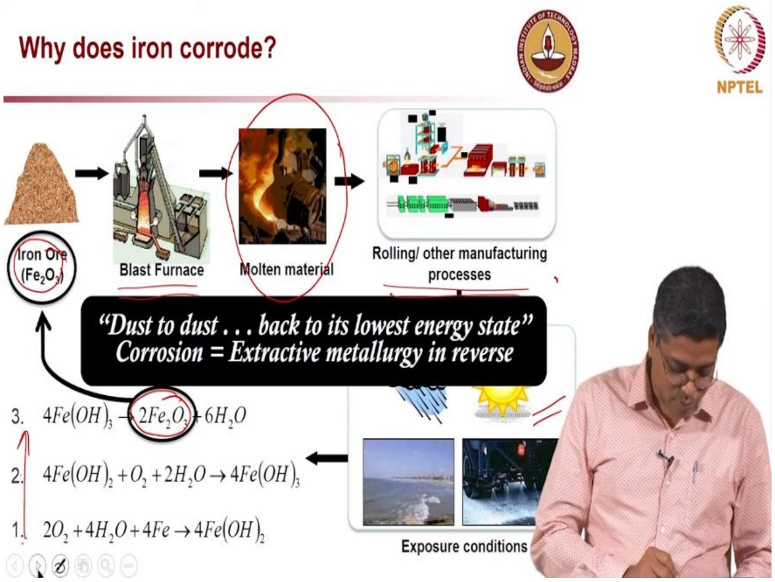

Why does iron corrode?

*"Dust to dust . . . back to its lowest energy state"*
*Corrosion = Extractive metallurgy in reverse*

3. $4Fe(OH)_3 \rightarrow 2Fe_2O_3 + 6H_2O$
2. $4Fe(OH)_2 + O_2 + 2H_2O \rightarrow 4Fe(OH)_3$
1. $2O_2 + 4H_2O + 4Fe \rightarrow 4Fe(OH)_2$

Now, let's look at what happens when iron or how iron corrodes? So, I am going to show you this, see how do we make steel for example: we make steel from iron ore and then we heat the iron ore in a blast furnace and then you get the molten material. Then you mold it into a particular shape. Let's say if you are talking about a rebar you mold it into a cylindrical shape, if you are talking about a structural steel you may have I section or L angle section.

So, whatever it is you mold that into a particular shape and pass this steel through dye. So, here we get in this stage essentially. Here, we are actually giving more heat energy to the system or the material. And here in this process we are giving or using more mechanical energy. So, essentially at this stage the material will have higher energy than the iron ore. Now, once you have this higher energy material that tendency for that material to corrode will be more than when it converts to the iron ore.

So, in short steel will corrode at a faster rate than iron. Now, once your steel is made then you expose that steel to these different conditions. For example: if it is exposed to rainwater you have moisture then this indicates temperature and then you also have chloride environment. If you are talking about the coastal line, you have chloride and if you are talking about luckily in India we don't use de icing or anti icing salts. But, abroad if you go, especially in a cold climate region you will see that during the winter they pour this chloride solution or sprinkle chloride solution on the road. So that the ice flakes can be melted. And then when it is exposed what happen are these chemical reactions or the steel undergoes these chemical reactions which go from 1 to 3.

So, eventually you get this $Fe_2O_3$ which has very similar structure like the iron ore. So, NACE defines this corrosion as Extractive metallurgy in reverse direction. So, essentially from here to here the rate at which it goes can be controlled. If you use stainless steel, I can reduce the rate of corrosion from steel to iron ore or if I am using mild steel it may be higher rate. So, that is only all what we can do is; we can do things so that the rate of corrosion can be reduced. I don't know if we can make it zero but we can make it slow so that we reach the desired life of the structures.

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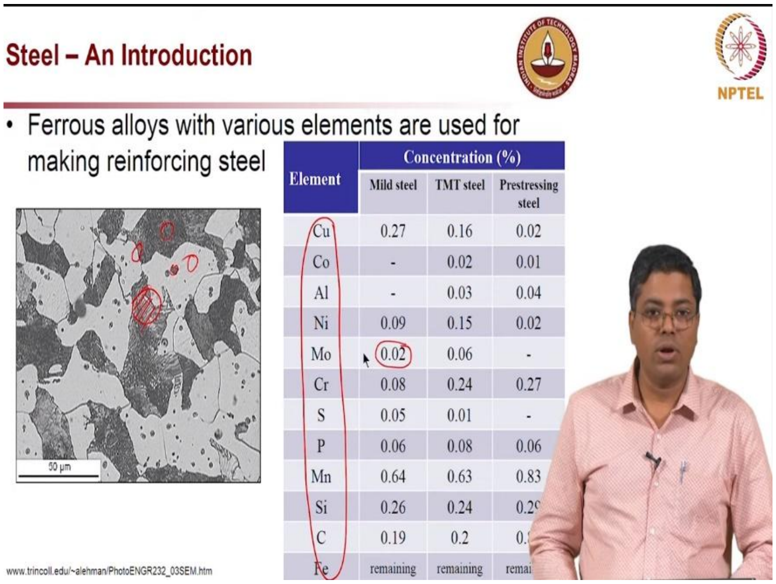

Steel – An Introduction

- Ferrous alloys with various elements are used for making reinforcing steel

| Element | Concentration (%) | | |
|---|---|---|---|
| | Mild steel | TMT steel | Prestressing steel |
| Cu | 0.27 | 0.16 | 0.02 |
| Co | - | 0.02 | 0.01 |
| Al | - | 0.03 | 0.04 |
| Ni | 0.09 | 0.15 | 0.02 |
| Mo | 0.02 | 0.06 | - |
| Cr | 0.08 | 0.24 | 0.27 |
| S | 0.05 | 0.01 | - |
| P | 0.06 | 0.08 | 0.06 |
| Mn | 0.64 | 0.63 | 0.83 |
| Si | 0.26 | 0.24 | 0.2 |
| C | 0.19 | 0.2 | 0. |
| Fe | remaining | remaining | remai |

www.trincoll.edu/~alehman/PhotoENGR232_03SEM.htm

Now, when you look at steel, usually we think it's a homogenous material. But if you look in microscope this is how it looks. So, you have these different phases in same steel and you can see some laminar structure here. So all these actually lead to some kind of local corrosion cell over there or in between here this. So, one of the phase might be corroding in preference to the other. And that’s what metallurgists do like to modify these things. So that, we can actually have better quality steel.

Now these are some, one chemical composition for different type of steel. The main reason why I put this here is you can see the number of elements present in one particular steel. Yes, iron is very large in quantity. But there are other very small like, this one very small quantity. But so these are all very important in ensuring different properties of the steel.

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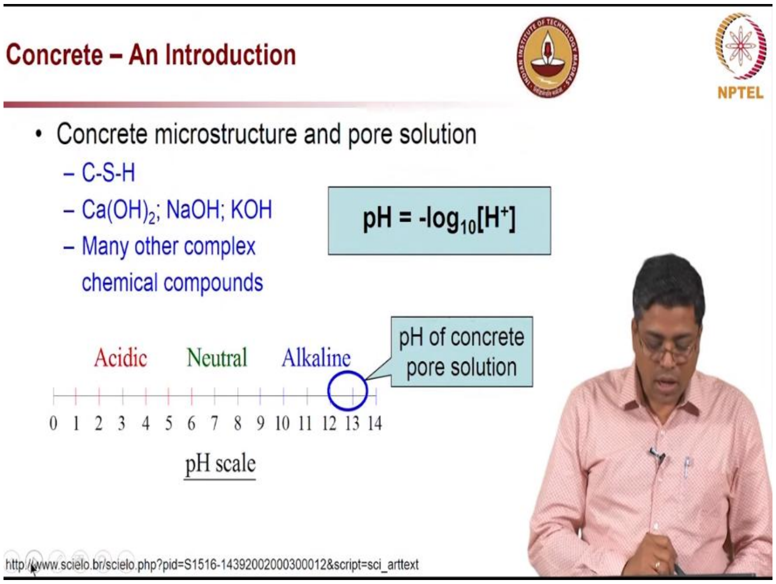

Concrete – An Introduction

- Concrete microstructure and pore solution
  - C-S-H
  - $Ca(OH)_2$; NaOH; KOH
  - Many other complex chemical compounds

$pH = -\log_{10}[H^+]$

pH of concrete pore solution

http://www.scielo.br/scielo.php?pid=S1516-14392002000300012&script=sci_arttext

What about concrete? Concrete is also very complex; I mean you know that calcium silicate hydrates is a binding agent or it gives the strength to the concrete. And we also have a lot of hydroxides in the concrete which give the high pH. Now, where is the pH? It will be somewhere 12+; this is the region where we are going to talk about, when you talk about the pH of the concrete pore solution. Now this high pH really helps us in ensuring that we can actually use steel and concrete together.

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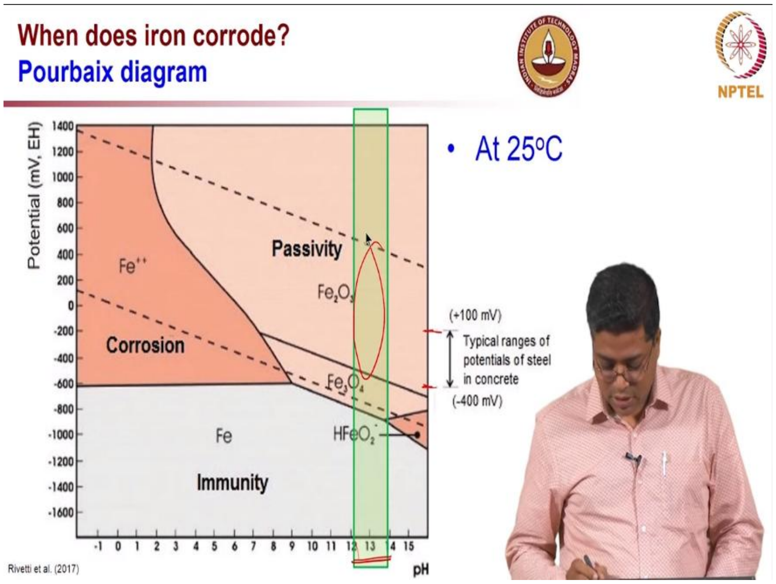

When does iron corrode?

Pourbaix diagram

- At 25°C

Rivetti et al. (2017)

This is the Pourbaix diagram where you can see that, if you talk about the steel this is about 100 to -400. So this is typical region where, when you take measurement or the potential measurement of steel embedded in concrete mostly you will see something in this range. And point here to be noted is, if I put steel in a material with 12 to 14 or more than 12 pH then I can actually have a region where there is a passive region. That's what, so this region I can really have a passive region. So, this is the reason why we are able to use steel in concrete and keep it there for long time without any corrosion.

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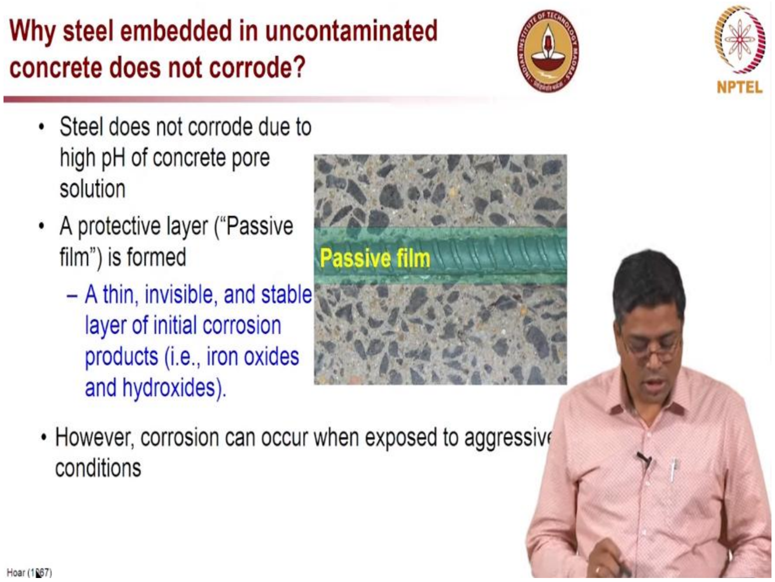

Why steel embedded in uncontaminated concrete does not corrode?

- Steel does not corrode due to high pH of concrete pore solution
- A protective layer ("Passive film") is formed
  - A thin, invisible, and stable layer of initial corrosion products (i.e., iron oxides and hydroxides).
- However, corrosion can occur when exposed to aggressive conditions

Hoar (1967)

So, what happens is you put the steel in concrete this is the photograph showing steel embedded in concrete and I have drawn here small green patch which indicates that some passive film or a protective layer gets formed on the steel surface the moment you immerse the steel into the concrete. Now, you cannot see it in the case of steel we cannot see it. It is very dense and colorless but it protects the steel below that from further corrosion. Now, if steel has to corrode, something has to break this passive film then steel will start corroding.

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Depassivation/corrosion can occur when exposed to...

- Chlorides & Carbon dioxide
- In the presence of moisture & oxygen - essentials

So, what leads to this breaking of this passive film? Chlorides and carbon dioxide. So you can see here this is a bridge passing through marine environment. Chlorides can create problem for the passive film to break, carbon dioxide can also lead to breaking of passive film. And of course moisture and oxygen they are the essentials. So these two are the essential thing for corrosion to happen if I can prevent moisture and oxygen and also keep it very low temperature then corrosion can be stopped.

But which is practically impossible to achieve that in many parts of the world. There may be if you go to North Pole you can probably get rid of high temperature. But most of the place where we live, we have moderate temperature conditions and also you have moisture conditions. Now, this is a picture showing in the one of the metro cities in India, you can see lot of vehicles here they all are actually exhausting $CO_2$.

And you have this concrete structure right above this, is just an elevated corridor. So all these concrete are actually getting exposed to high $CO_2$; locally you will have high $CO_2$. Maybe $CO_2$ will diffuse into the atmosphere but local conditions if you look at those concretes are actually getting exposed to high level of $CO_2$. And also you have high temperature you can see the sun out there.

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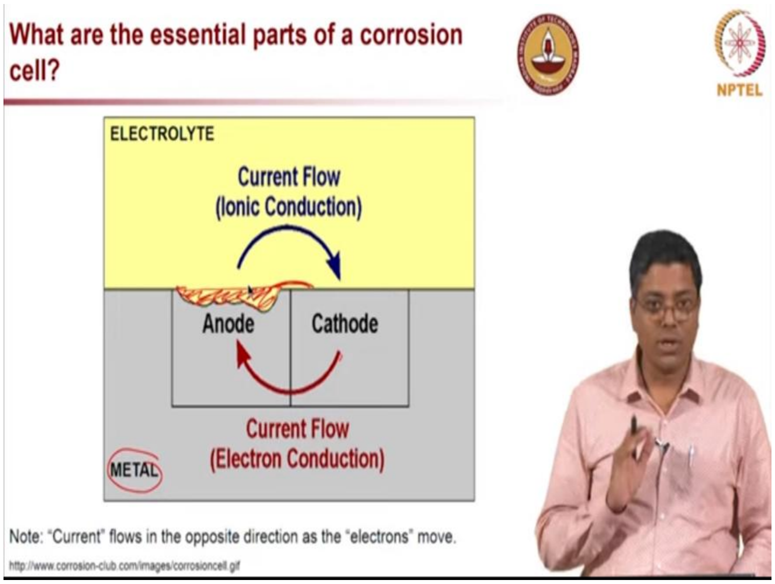

What are the essential parts of a corrosion cell?

Note: "Current" flows in the opposite direction as the "electrons" move.

http://www.corrosion-club.com/images/corrosioncell.gif

Now, when you look at the corrosion as a mechanism there are 4 components or essential parts of any corrosion cell. So there you should have an anode, you should have a cathode and you should have an ionic conductor and an electronic conductor. So here, you can see the region which is corroding from the metal surface. This was the original metal surface so this much metal has been lost.

So this region is what is getting corroded and that we call anode and the remaining region on the steel so here it is the metal, the grey part is the metal. Then the remaining region helps this anode to corrode and the electronic charge actually get passed from the cathode to the anode right through the metal itself. And if you are talking about an electrolyte like a water or even concrete if you want to say.

But water is also electrolyte so if you have it then there is a ionic conduction happening through the water or through the interface between the steel; the metal and the electrolyte. So you have this exchange happening here. So that's electronic ionic conductor. So you should have these 4 components, if I can get rid of one of these I can stop corrosion. But that does not happen.

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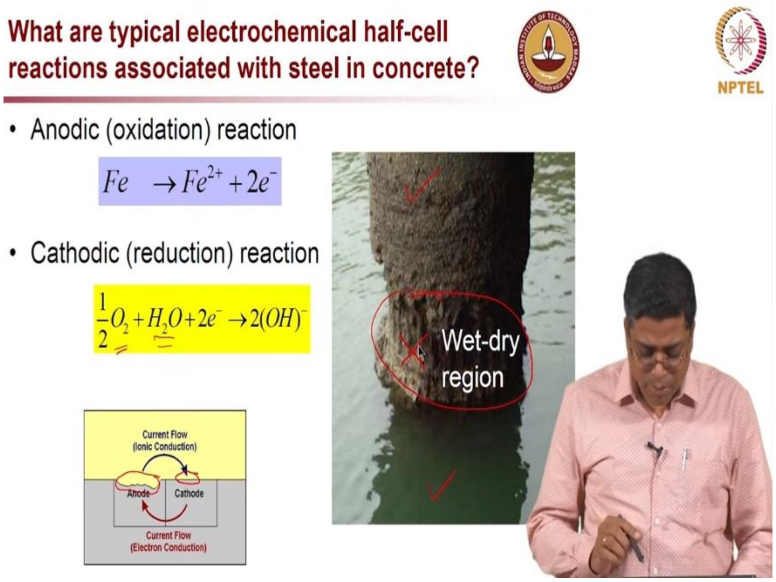

What are typical electrochemical half-cell reactions associated with steel in concrete?

- Anodic (oxidation) reaction

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

- Cathodic (reduction) reaction

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

So, what happens in the steel inside concrete? Again similar thing like you have on the anodic side, you have iron which gets converted into Fe2+ and 2 electrons. So, you have this release of a Fe2+ into the solution. And provided you have enough moisture and oxygen in that environment what will happen is, these 2 electrons which are coming from anode to cathode and they will combine at the cathodic side.

So they will combine here and then you will have two hydroxide ions formed. Now, why I put this picture here is, here you can see that this concrete pier is coming out of the water body and here you can see a lot of corrosion or damage. Whereas here there is no damage and here if you go deeper into this pile there also you will not see any damage. But here you will see lot of damage.

This is mainly because when you go here you do not have enough oxygen when you go above the water body you do not have enough moisture. But here you have both oxygen and moisture available in sufficient quantity. And also this wetting and drying accelerate the movement of the chloride inside the concrete pier. So in combination we have more corrosion at the place where it comes out of the concrete.

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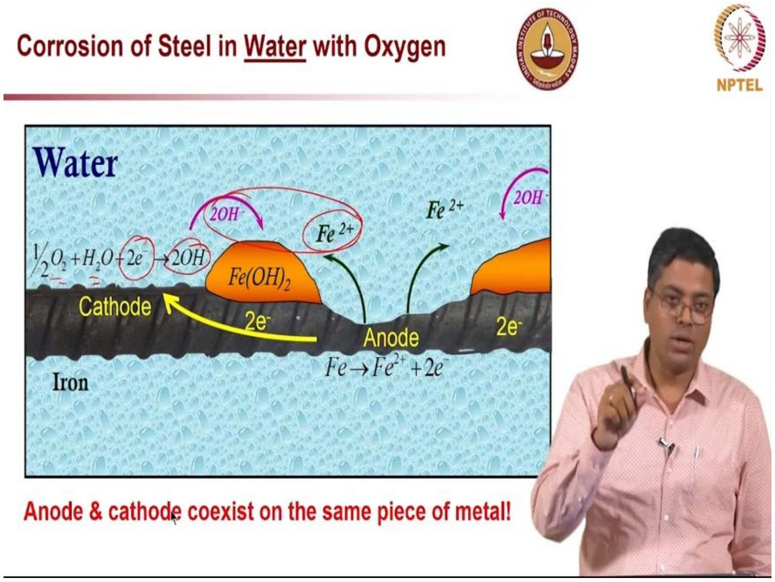

Corrosion of Steel in Water with Oxygen

Anode & cathode coexist on the same piece of metal!

Now, this is a same equation which I showed earlier just showing it in a more easy to understand manner. Here you can see at the anode you have corrosion happening. So, these Fe2+ ions are getting into the solution. And then this negative charge is moving from the anode; electrons are moving from the anode to here. And now what is happening is these electrons are being absorbed at the cathodic side where there is enough oxygen and moisture and it forms OH or hydroxide ions which kind of move and come react with this Fe2+.

So these 2 react and form $Fe(OH)_2$. So this reaction even though in this picture it's very large in scale actually this can happen right in the scale of millimeter or even a smaller scale. But for demonstration purpose we are showing it like this. Now anode and cathode can coexist in the same piece of metal because even if you put one rebar or one steel piece into water or concrete it can actually corrode. So that means both anode and cathode exist on the same steel.

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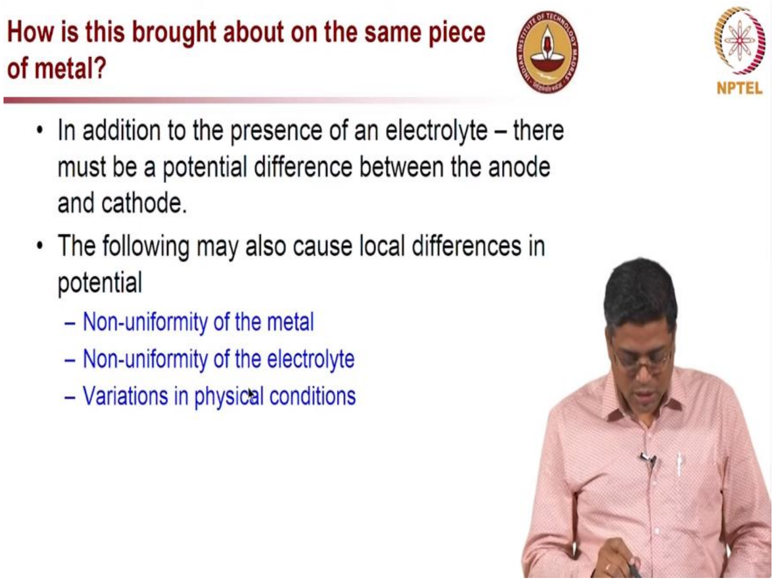

**How is this brought about on the same piece of metal?**

- In addition to the presence of an electrolyte – there must be a potential difference between the anode and cathode.
- The following may also cause local differences in potential
  - Non-uniformity of the metal
  - Non-uniformity of the electrolyte
  - Variations in physical conditions

What is the reason for this? One reason is there could be a potential difference between 2 points on the same metal. So, when there is a potential difference between 2 points on the same metal. There will be a flow of electron from one point to the other to balance it. Now what is leading to this difference in potential is non uniformity of the metal, non-uniformity of the electrolyte and variations in physical conditions. So, I will show you these 3 cases in the coming slide what is this mean non uniformity of the metal.

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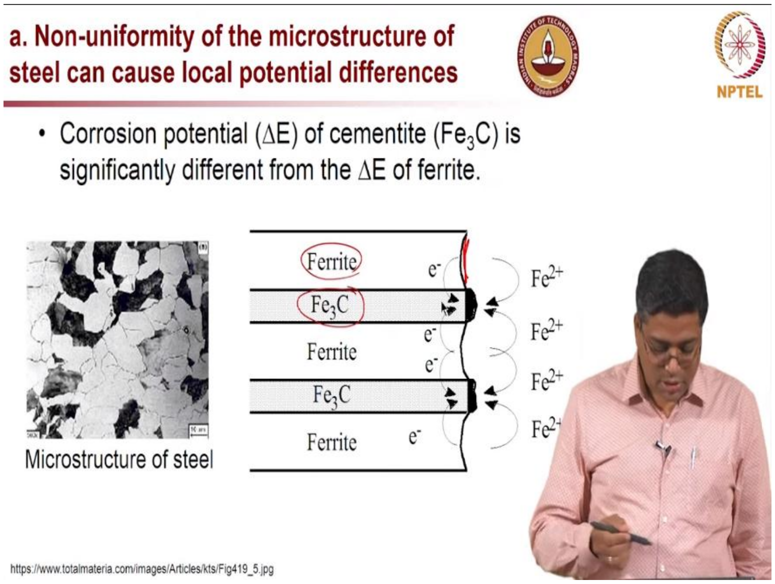

**a. Non-uniformity of the microstructure of steel can cause local potential differences**

- Corrosion potential ($\Delta E$) of cementite ($Fe_3C$) is significantly different from the $\Delta E$ of ferrite.

Microstructure of steel

https://www.totalmateria.com/images/Articles/kts/Fig419_5.jpg

The first one which is here I am saying that why there is non-uniformity mainly because of the difference in the microstructure and different phases available within the microstructure of the steel. You can see here this is a simplistic explanation of this what you see here. You can see this ferrite phase here and cementite phase here and there is a possibility of electrons moving from ferrite phase to cementite phase. Now, here you can see that this portion actually loses iron Fe2+. So this is functioning like an anode and this is functioning like a cathode. So this can happen in any steel which you pick at the microstructure level.

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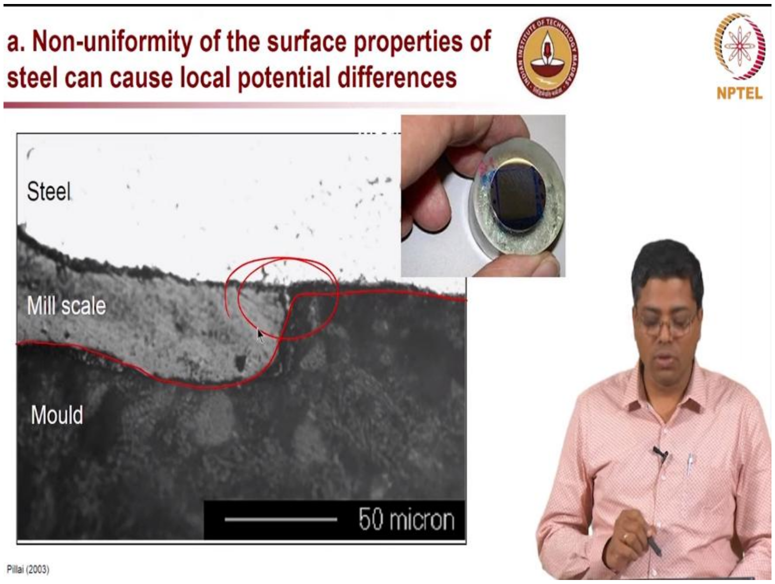

a. Non-uniformity of the surface properties of steel can cause local potential differences

Pillai (2003)

Now, next reason for the difference in potential was non uniformity of the surface properties of the steel or this is another example where mill scale you can see here. Nowadays most of the steel they clean the mill scale but still there will be some remnants present on the steel surface. So this is a picture taken from a metallographic study. You can see here this is the mould, mill scale and steel.

So, what you see here is when you take the steel your steel surface is something like this. There are some local regions where mill scales are present and other region where there is no mill scale. Now this will create a cell here; right here you can actually have corrosion cell. You can have crevice corrosion happening here like; corrosion will actually start here and then go inside. So these kind of mechanisms can happen which leads to again corrosion.

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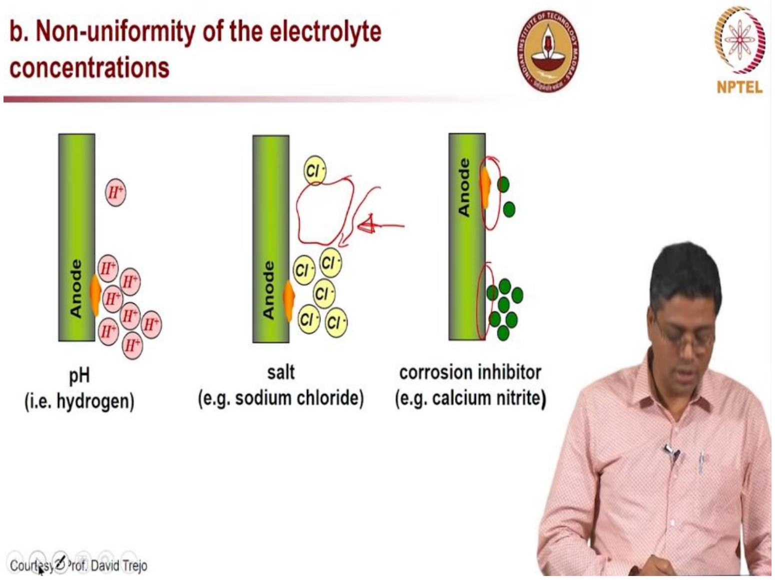

b. Non-uniformity of the electrolyte concentrations

pH
(i.e. hydrogen)

salt
(e.g. sodium chloride)

corrosion inhibitor
(e.g. calcium nitrite)

Courtesy Prof. David Trejo

Now second point was non-uniformity of the electrolyte. Imagine you have some region which is more acidic and some region which is less acidic or more alkaline. So if you have a difference in this alkalinity, the region with lower alkalinity will actually start corroding or it will function like an anode and for example: if you have chlorides it is not essential that everywhere the amount of chloride present in the concrete system will be uniform.

So, you may also see that some region has more chloride than the other region for example: let's say in this case if chlorides are coming from here maybe there is an aggregate here. So chlorides cannot go so they will try to move it this way and then reach this point. So this point gets more chlorides than the one which is next to an aggregate. So this is also causing a differential condition.

Other thing is nowadays you have a lot of chemical admixtures which you put, one of them is corrosion inhibitor and again depending on the non-uniformity in the mixing you may have some region with more inhibitors than the other regions. So this region will at some point in time this region will start corroding before this region starts corroding. So again all this are showing that it is possible to have differential environment even though the steel is embedded in the same concrete. So this differs so the concrete properties are also varying from point to point so that leads to this differential.

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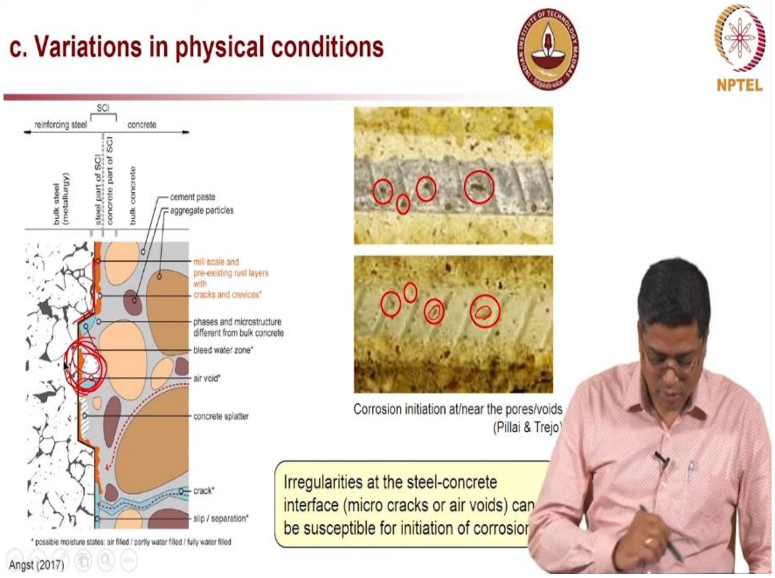


c. Variations in physical conditions

* possible moisture states: air filled / partly water filled / fully water filled

Angst (2017)

Corrosion initiation at/near the pores/voids (Pillai & Trejo)

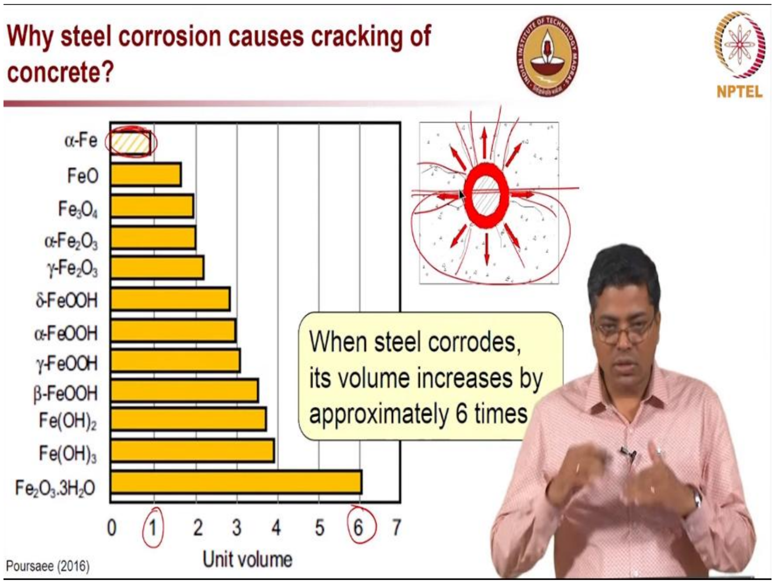
Irregularities at the steel-concrete interface (micro cracks or air voids) can be susceptible for initiation of corrosio

Now, other thing is about the physical condition. So, you know that concrete is a heterogeneous material; steel is also heterogeneous and then we have ribs on the steel which causes some change in the physical conditions the shape itself. So for example this is a detailed drawing showing like what can happen at different points on the steel surface.

So, for example here you can see like if there is a rib here, this is rib here and then you can have the moisture trapped there, you can have an air void in this air void you can see that where the moisture is there, there is no corrosion. But when there is air there is more. So lot of these physical conditions can also lead to lot of variations in the steel-concrete interface. Now for example this is a picture from our own lab where we can see that this, the top picture shows the steel.

So we after casting the specimen we exposed it for some chlorides and then once the corrosion started we open the specimen and then what we can see is like there is a exact match of this thing. So you can see this is a rust spot; this is a rust spot all this region within the red circles they are rust and when you see the imprint of that you can see there was actually a void. There is a void here and everywhere it’s very well matching with.

So very clearly we can see that these very small air voids which may be in millimeter scale they actually lead to the initiation of the corrosion which is matching with this thing what you see here. **(Refer Slide Time 28:47)**



Why steel corrosion causes cracking of concrete?

When steel corrodes, its volume increases by approximately 6 times

Poursaee (2016)

Now, what happens when corrosion starts? Why our concrete structures are cracking? This is also big concern. When corrosion happens there is a significant volumetric expansion in steel that’s about 6 to 8 times increase in the volume. Now, here you can see this is the uncorroded iron or steel for example we can consider to be steel uncorroded when it expands it is getting from 1 to 6 times increase.

So, this is all happening within the concrete and there is a limit to which concrete can resist this expansive stresses. So, once there is more expansion; when once the stress applied is more than the tensile strength of the concrete it will tend to crack. So you can see that crack radiating outward from the steel, this will happen. Now, if you have a cover concrete this crack may happen only on one side. It may not crack inside because you have much more concrete inside. So the cover region will start cracking faster.

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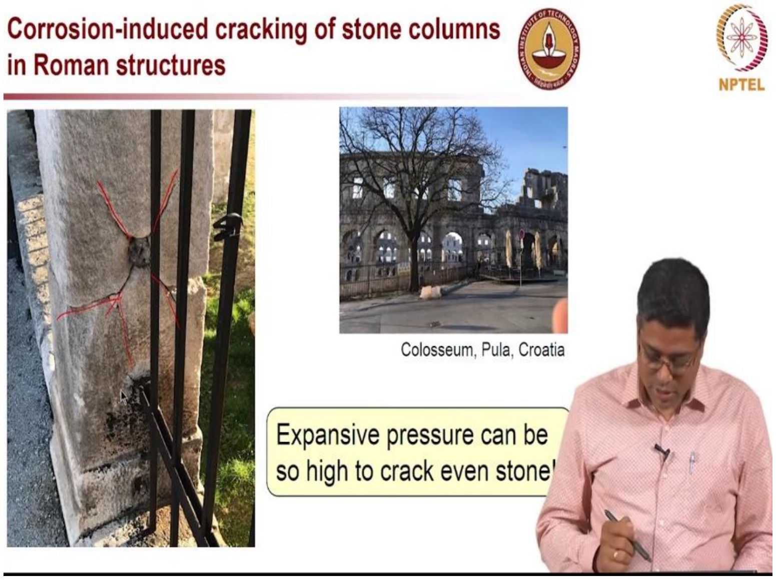
Corrosion-induced cracking of stone columns in Roman structures

Colosseum, Pula, Croatia

Expansive pressure can be so high to crack even stone!

Now, to just show you how significant or how large this expansive stresses could be this is a picture from Colosseum in a Croatia. You can see this is actually a rock. So there was actually a metal piece inside this rock and it expanded and cracked the rock. So if it can crack the rock it can easily crack the concrete which is man made rock. I mean just to show you how significant that force can be.

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Corrosion-induced cracking in buildings

Now, this is again concrete in our own campus, one of the buildings you can see and this is pretty much you might have seen this kind of corrosion happening in many places. You can very clearly see there is a bulging happening here. So this steel rebar inside the concrete is corroding and expanding up to about 6 to 8 times and which pushes the concrete cover outward and leading to cracking and then spalling. So first it cracks then it delaminates and then it spalls.

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Corrosion-induced cracking, delamination, and spalling in buildings

This is another apartment building where you can see that spalling. Actually this is not necessarily because of corrosion I don't know the reason for this. But, based on the experience what we have seen is in this particular locality there are actually buildings when they were constructing they used sea sand or beach sand and chloride rich water. So in addition when you have these clothes drying, they actually drop water on to these beams and you can very clearly see that there is lot of corrosion happening.

Why I put this picture is one more thing to emphasize that we should go for preventive maintenance. Why are we waiting until this happen? We should not let this happen, when we know that there is a possibility of corrosion. We should try to stop it right then and there by adopting a very good repair practice. Not just patch repair means it's not that you just take it and remove it and then fill it with new concrete it is not going to work that way.

You should really have a good patch repair. I mean, it should be done in a durable manner. We will show you, how we can do this repair in a durable manner to ensure that it will actually last long.

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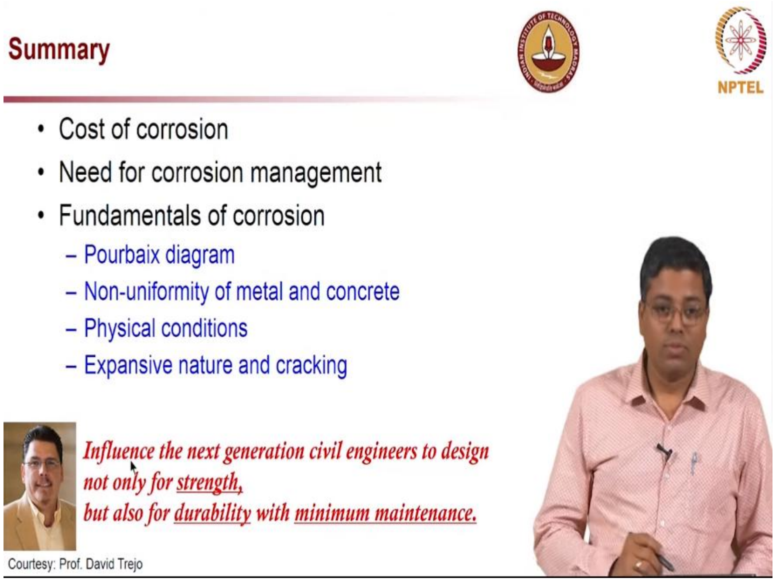

Summary

- Cost of corrosion
- Need for corrosion management
- Fundamentals of corrosion
  - Pourbaix diagram
  - Non-uniformity of metal and concrete
  - Physical conditions
  - Expansive nature and cracking

*Influence the next generation civil engineers to design not only for strength, but also for durability with minimum maintenance.*

Courtesy: Prof. David Trejo

Now in summary what we covered today is cost of corrosion the main or the key number which I would like you to remember is it's about 3 to 4% of GDP today. We really have to work hard to reduce that number. This essentially says why we need corrosion management strategy; main reason is we have large number of structures which we are building today if we do not ensure good quality on those structures they will start facing premature corrosion and then we will have to spend a lot of money on repair.

We also looked at some fundamentals of corrosion mechanism. We looked at Pourbaix diagram and we found that at around 12+ pH steel can actually prevent itself from corrosion. And that's the reason why we are able to put steel in concrete because we have very high pH in our uncontaminated concrete. And then some reasons why steel corrodes even though on the same metal 2 points on the steel one will act as an anode while the other one will act as a cathode.

What is the reason for that to happen and steel essentially is not homogeneous it is a heterogeneous material; concrete is also a heterogeneous material so because of those reasons we have this corrosion happening. Anode and cathode can co-exist or exist on the same metal. One thing I would like to say this is my PhD guide professor David Trejo. This is a sentence from one of his slides. So he tries hard to influence the next generation civil engineers to design not only for strength but also for durability with minimum maintenance.

It’s very important for us to consider this today because most civil engineers when we talk about concrete; one of the important parameter which comes to their mind is strength or to be precise 28 day compressive strength. That’s not going to give you durability for the structure. So you have to really think about how we can ensure durability not by spending a lot of money later on but with minimal maintenance, thank you. So we will see next lecture on chloride induced corrosion and carbonation induced corrosion.