Advanced Concrete Technology
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Lecture - 41
Durability issues in concrete - Part 5

So we were talking about some reasons why anodic sites can form on the same steel surface and corrosion can actually initiate without there being a electrochemically different metal or different piece of steel in the vicinity of the (()) (00:29). So there are several reasons that we discussed yesterday primarily dealing with variances on the steel surface due to composition due to the residual strains or stresses that may be present and sometimes when you have changes in the cleanliness of the river.

By the way, I do not know how many of you noticed when you walk up the stairs here, they are working with rebar which is looking spotlessly clean, yeah it is a spotless rebar, it is totally clean, probably it is just freshly arrived from the factory and they are using it for the construction, so that is very good that is good quality control but in many sites you do not see that.

You see that rebar is lying around in the open for days without being used and because of that it develop some mill scale on top right and that scale is usually a problem not really a good thing.

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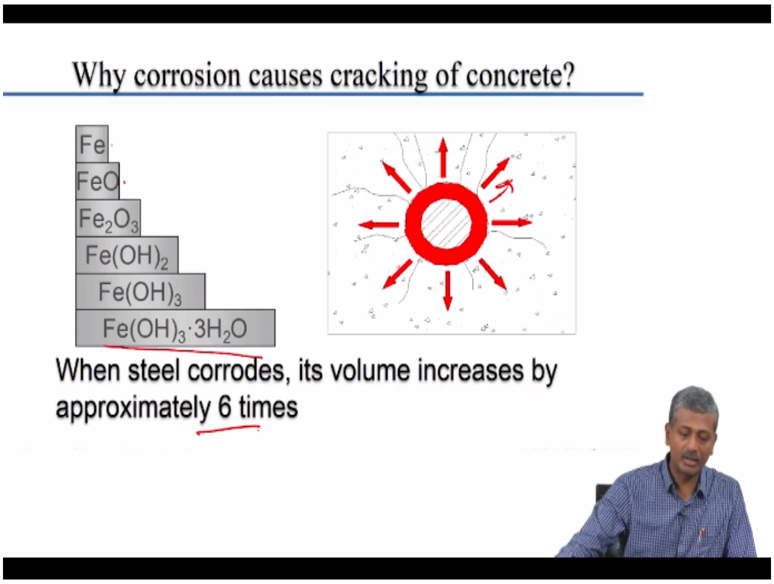

Why corrosion causes cracking of concrete?

Fe
FeO
Fe_2O_3
$Fe(OH)_2$
$Fe(OH)_3$
$Fe(OH)_3 \cdot 3H_2O$

When steel corrodes, its volume increases by approximately 6 times

Now obviously when rebar gets converted to its oxide or hydroxide forms, there is a change in volume that is associated with that process. So when iron changes to iron oxide there is a slight increase in volume but the hydroxides are the ones which are having a very large volume as compared to the original steel. So when you have an increase in volume of the rust because of different forms of hydroxides and oxide that forms obviously there will be an expansive pressure on the surrounding concrete.

And this expansive pressure is of the order that can easily exceed the tensile stress of the concrete and that causes cracking in the concrete. So in most cases the concrete surrounding the rebar tends to crack at very late stages of the rebar corrosion when you have substantial amount rust products forming you can have expansions because the volume increases approximately 6 times.

So volume increases when steel converts to its oxide and hydroxide forms is nearly 6 times I mean the peak hydroxide is 6 times as voluminous as the original steel. Now because of this there is expansive pressure, concrete cracks around it and the cracking and further deterioration of the concrete around the steel further increases the rate of penetration of your chlorides or other aggressive agents that are coming from the external environment.

So obviously this will lead to a further acceleration of the attack. Attack will happen faster and faster once the concrete is cracked and the chlorides are able to get in much easier.

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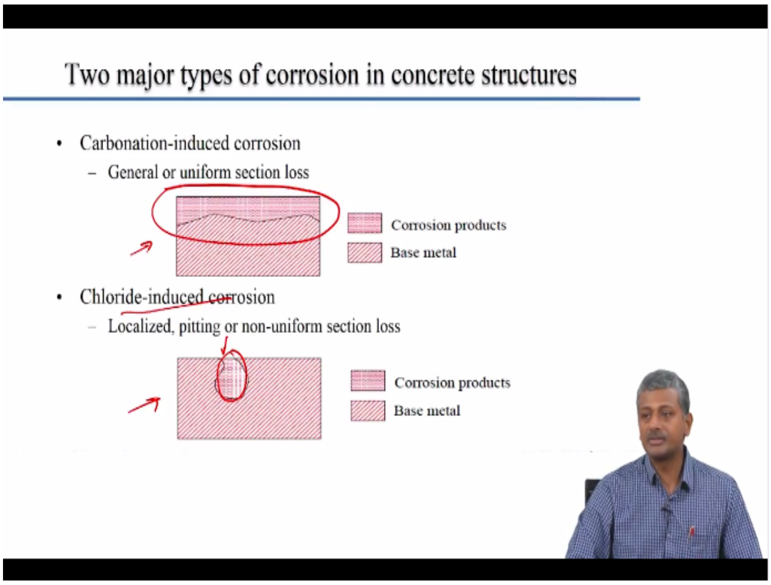

Two major types of corrosion in concrete structures

- Carbonation-induced corrosion
  - General or uniform section loss
- Chloride-induced corrosion
  - Localized, pitting or non-uniform section loss

Now mainly we deal with two different types of corrosions with respect to the mechanism of the corrosion itself. One is arising due to carbonation and we talked about this earlier that the carbonation is happening because of carbon dioxide penetrating the surface of the concrete and reaching the level of the reinforcing steel where the pH is brought down to suboptimal conditions.

So when we are reducing the pH to<11 there are some concerns about what that number exactly is, some people say 11.5, other say 10.5 and so on and so forth. So when you reduce the pH to<11 you are actually creating conditions for corrosion or depassivation that means the stable film that is forming around the steel surface in an alkaline environment can get unstable when you have carbon dioxide penetration leading to a loss in pH okay.

But one thing you need to remember is when carbon dioxide related corrosion actually happens, you get a uniform section loss that means you have a slow and steady loss of the steel cross section starting from the surface inverts whereas when you have chloride induced corrosion there are local spots on the steel whether chloride concentration may exceed the other spots in the steel right.

We know that chloride is not going to uniformly diffuse, it is only going to come in where there is a substantial concentration gradient where there is an interconnected network of porosity available and so on and so forth and again the nature of the reaction of chloride with the passivating layer that forms in the steel surface is such that there is a pitting type corrosion that actually happens when chlorides actually attack the concrete okay.

So when chlorides attack the reinforcement, it forms a local area where the cross section can be significantly reduced, so it is called pitting type of corrosion and truly speaking this one is a lot more disaster as compared to the carbonation-induced corrosion because that is more uniform you have a slow and steady loss of cross section, here you have a sudden loss of cross section at a single point and you know very well that a steel rebar if it has a localized defect can lead to the failure of the entire system okay.

So the chloride-induced corrosion which leads to pitting type corrosion because of non-uniform section loss is a lot more dangerous as compared to the carbonation-induced corrosion.

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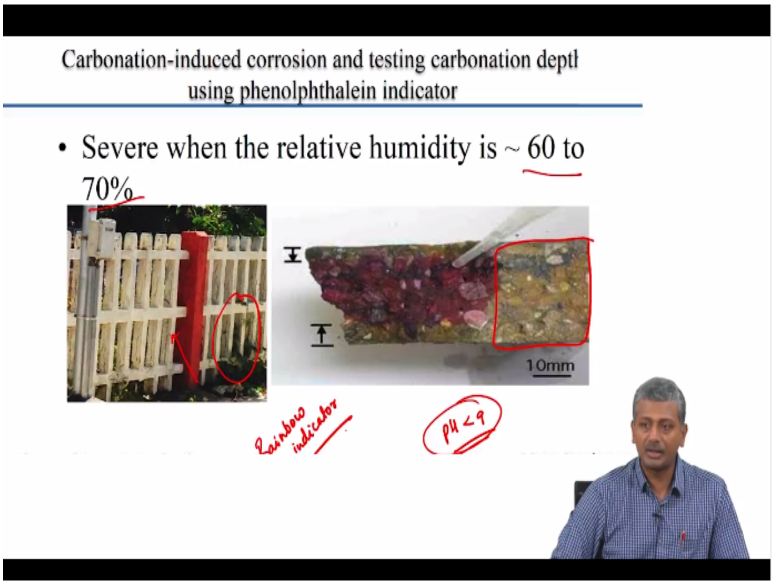

Carbonation-induced corrosion and testing carbonation deptl
using phenolphthalein indicator

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

So again this is carbonation-induced corrosion which we talked about the fact that carbonation or carbon dioxide penetration into the concrete is extremely severe particularly for certain ranges of relative humidity between 60 and 70% okay. So for example structures like this compound wall which is standing on the outside direct exposure to the atmosphere.

And again in these walls obviously the cover of the reinforcing steel will not be very much right where it is not a major structure so we do not really provide a large cover to the reinforcing steel and so you start getting corrosion of the steel in such cases quite easily and as we discussed earlier the corrosion or the propagation of carbon dioxide diffusion into the concrete is detected by the phenolphthalein test.

So phenolphthalein is an acid-base indicator, so when the concrete is alkaline phenolphthalein spraying on the concrete will induce a pink color. When the concrete becomes acidic and actually when the pH becomes<9, the concrete will show up to be colorless when phenolphthalein is sprayed on it. Now this is often a problem in detecting what is the critical level of carbonation that has happened in a system.

If you use phenolphthalein test, the discoloration will happen only when the pH crosses the barrier of 9 but most researchers tend to believe that that is already a little bit too late okay when your pH is reaching<11 itself the stable passive film around the steel has already started deteriorating. So there has to be other means to actually understand what the depth of the carbonation front is without really relying too much in the phenolphthalein test.

So today many people use what is known as a rainbow indicator. Now as the name implies rainbow indicator will indicate different colors for different pH levels okay. So you can actually track the actual carbonation front into the concrete by detecting minute changes in pH by a factor of 0.5, 0.5 and so on so you have very many different colors based upon the actual pH that is inside the concrete okay whereas phenolphthalein wants that pH to be much<9 to create the colorless condition.

So indication of carbonation depth could be a critical factor in looking at concretes which are in the field and trying to understand their propensity for getting corroded okay.

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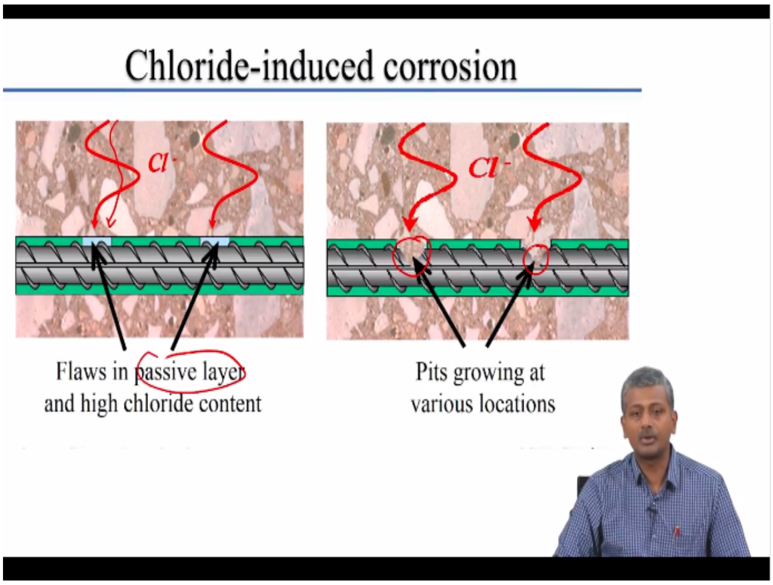

Chloride-induced corrosion

Flaws in passive layer and high chloride content

Pits growing at various locations

Chloride-induced corrosion as I said chlorides are propagating through the cover layer of concrete and reaching the steel surface again when high chloride content is present the passive layer gets broken down and then once the corrosion initiates the pits start growing in the steel okay. So once corrosion initiates, the pits start forming and when the pits form you have a local loss of cross section that leads to a loss in structural capacity of the steel.

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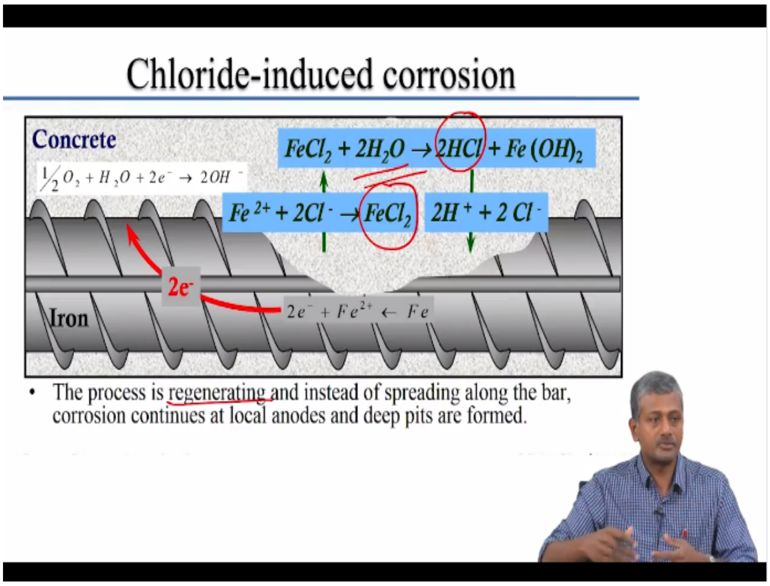

Chloride-induced corrosion

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

Now when you look at the reactions involved with this, the passive layer is actually going to be reacting with the chloride ions lead to the formation of iron chloride okay and this iron chloride may actually again get transformed into an acidic phase like hydrochloric acid and that may lead to further deterioration. So actually this reaction is self-sustaining so once the reaction of the chloride with the external film happens it can be a self-sustaining reaction that leads to more and more damage of the steel happening in the system okay.

So you need to be a very careful about how concrete in a chloride-induced environment will perform because ultimately the reaction that starts with corrosion can be a self-sustaining reaction and that will lead to more and more progressive kind of damage which will happen. So the process is regenerating and it does not spread all along the bar, it tends to localize and forms the pit.

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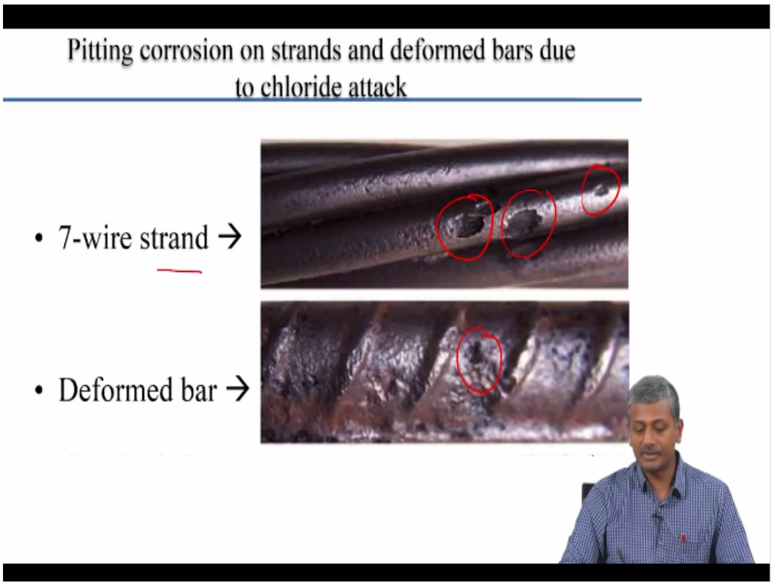

Pitting corrosion on strands and deformed bars due to chloride attack

- 7-wire strand →
- Deformed bar →

So again these are examples from different kinds of steel systems, this is a 7-wire strand which is used for prestressing. You can clearly see the pits forming in the system and of course in a regular deformed bar also you can see several signs of pits formatting due to corrosion of the reinforcing steel.

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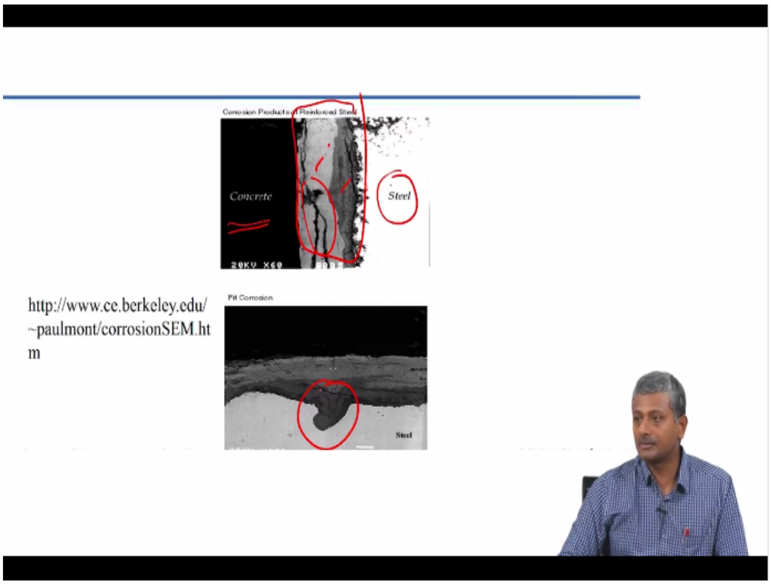

http://www.ce.berkeley.edu/~paulmont/corrosionSEM.htm

This is a microscopic image of a uniform layer of corrosion products on the steel surface. You see here this is uniform layer of corrosion products in the steel surface. This is done with microscopic imaging where the binarization has been done, concrete has been made entirely black and steel because of its much higher density as compared to concrete has been made completely white.

The intermediate rust products which are having a lesser density than steel are showing different shades of grey and you can see here that you are forming different forms of rust. There is one darker grey rust and one lighter grey rust, so different densities of rust are actually forming in the system and there is lot of cracking which indicates that there is some volumetric changes that are happening in the system.

Again this is an example of chloride-induced corrosion, you see that there is a pit locally forming in the steel and that is leading to a greater removal of cross section from that location.

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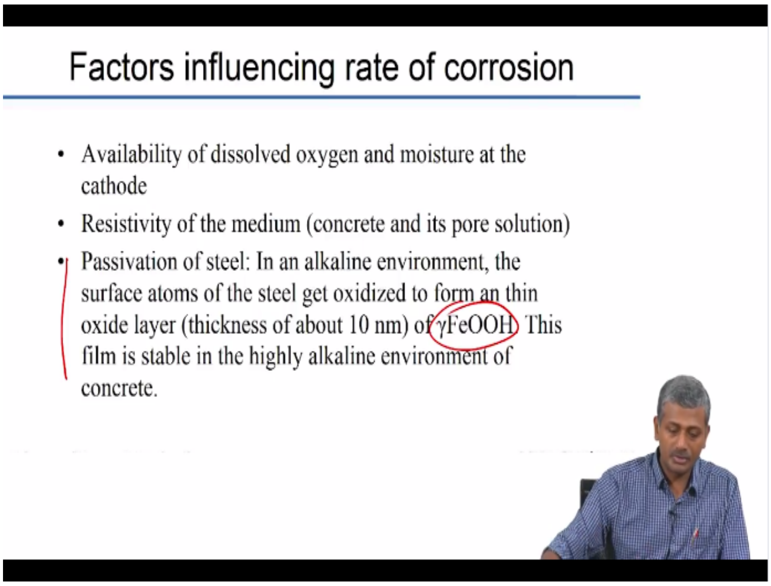

Factors influencing rate of corrosion

- Availability of dissolved oxygen and moisture at the cathode
- Resistivity of the medium (concrete and its pore solution)
- Passivation of steel: In an alkaline environment, the surface atoms of the steel get oxidized to form an thin oxide layer (thickness of about 10 nm) of γFeOOH. This film is stable in the highly alkaline environment of concrete.

So what are the factors that influence the rate of corrosion? We have talked about this before but just to reiterate we need oxygen moisture for the corrosion reaction to propagate. So we need the oxygen moistures availability at the cathode for controlling the rate of the reaction. The resistivity of the medium is very important because your ionic transfer happens through the electrolyte that is concrete in this case.

So if concrete is highly resistive, it will resist the transfer of ions, so it will slow down the rate of corrosion and of course the passivation of steel is something we have already discussed. In the alkaline environment, you are forming this iron oxide hydroxide layer that is leading the steel to be passive in an alkaline environment with time as pH conditions change or when chloride penetrates the system and attacks the passive film you start initiating the corrosion process.

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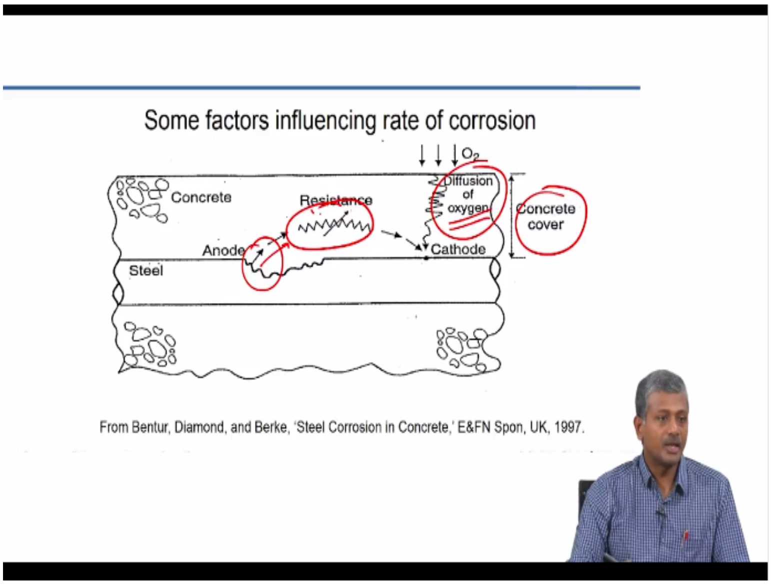

Some factors influencing rate of corrosion

From Bentur, Diamond, and Berke, 'Steel Corrosion in Concrete,' E&FN Spon, UK, 1997.

So if you look at this in a schematic diagram, so you have your steel here we have the anode which is formed inside the steel and the ionic flow is happening through the concrete. So the resistivity of the concrete has a critical factor and what does resistivity of the concrete depend on, the moisture content of the concrete and interconnectivity of the pores right because of conductive concrete would mean that you have a saturated concrete and the pores are interconnected which leads for a high conduction possibility in the system.

If the pores are not interconnected, then your resistivity is going to be extremely high and ionic transfer will be impeded. For example, if you have a system with mineral admixtures, you can expect your resistivity to be much higher than that of regular concrete. So in a chloride-induced corrosion environment, you might actually get a very positive response when you use mineral admixtures as replacement for cement.

In a carbonation environment, we discussed earlier you have greater porosity after carbonation in the systems with supplementary cementing materials. So you may actually end up causing a lot of these pores to get interconnected when the carbonation process happens but the other factor that is the availability of oxygen in moisture may still be restricted in a system with supplementary cementing material.

So there are a number of factors that can actually influence the rate of corrosion once the concrete is carbonated but with chloride you can definitely be sure that all these factors like concrete cover, the diffusion of oxygen and moisture into the system as well as the resistivity, all these factors will be positively affected when cement is replaced by supplementary cementing materials.

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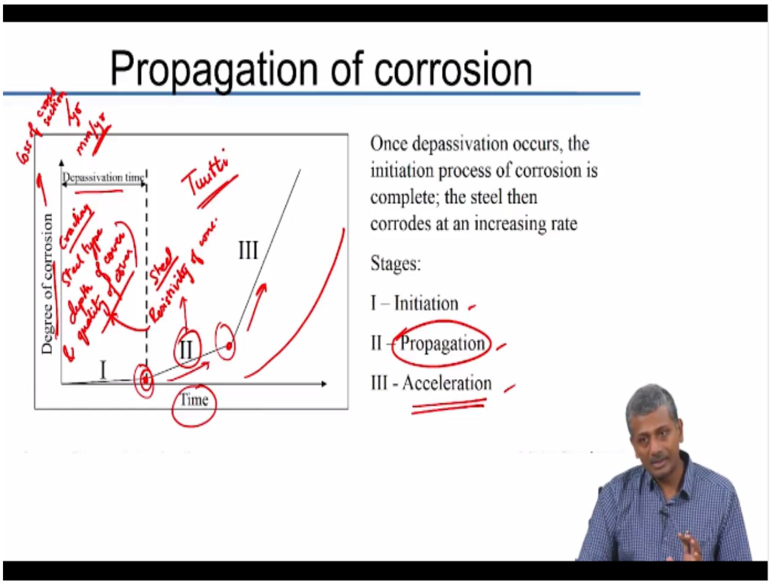

Propagation of corrosion

Once depassivation occurs, the initiation process of corrosion is complete; the steel then corrodes at an increasing rate

Stages:

I – Initiation

II – Propagation

III - Acceleration

Now if you look at the propagation of corrosion as to how once corrosion initiates how does it propagate, if you look at the degree of corrosion, extent of corrosion that is happening with time you will see that initially for a long time the steel although it is actively undergoing the process of corrosion because of increase of carbon dioxide or presence of chloride, steel does not really get damaged because the chloride take some time to reach the steel surface or the carbonation front take some time to reach the steel surface and cause a reduction in the pH.

So that is determined by what? Now diffusion is a phenomenon leading to the penetration of chloride or carbon dioxide but what is the primary factor that is governing that, the cover concrete right, the extent of the depth of the cover and the quality of the cover, quality in terms of permeability of the cover right. So cover being deep or the cover being less permeable would tend to increase the time it takes for depassivation to happen.

So a lot of protection strategies against corrosion are obviously based on improving the concrete cover characteristics. Now beyond this process we call this as the depassivation time okay or the initiation time, so the steel corrosion starts getting initiated at that point and from here on the rate of damage to the steel increases, so degree of corrosion is typically measured in terms of loss of cross section per year so like millimeters per year like that okay.

That is typically the unit of degree of corrosion, so when you look at stage 2 which is the propagation phase right you have an increase in the rate of damage that is happening to the steel. Now you see that there is a transition here from stage 2 to stage 3 and you see that there is an increase in the rate of deterioration of your concrete not concrete of the steel okay why do you see that because of acceleration of your damage.

Why does damage acceleration happen because the steel rusting leads to cracking in the concrete and more cracking implies this further ingress of aggressive species in the concrete and the rate of acceleration of damage happens. So you have initiation stage, propagation and acceleration stage. So this was originally proposed by a scientist name Twitti so that is called Twitti’s diagram okay.

Of course, you will not be able to make out these transitions very clearly mostly what you will see is a more gradual increase in the rate of the corrosion okay but then it has been simplified into this trilinear sort of a diagram so that you understand what are the different phases, so here the first phase is obviously governed by the depth of cover and the quality of the cover.

What else can determine the length of this passivation time, what about the steel itself, will the type of steel matter in terms of the depassivation time, obviously it will matter because if you have regular steel versus stainless steel, the quality of the passive film that is forming will be quite different. In stainless steel, the passive film that forms remain stable for a very long time.

So because of that the corrosion process does not yet initiated itself in a stainless steel okay. Now once a process initiated when you move to the stage 2 what do you think are the factors controlling the propagation of corrosion? One more thing that I forgot here, cracking, if there is cracking of the cover concrete obviously there will be a faster initiation of the corrosion process right.

So cracking will lead to quicker ingress of your aggressive agents and that will lead to a faster initiation of corrosion. So we were talking about the second phase, so what are the primary characteristics of the concrete that are controlling the second phase? You see the type of steel will again be important no doubt, the rate at which steel deteriorates could be different for different types of steel no doubt, what else what is happening in the second stage?

The corrosion is initiated, so there is ionic flow happening in the system. So what is controlling that ionic flow, the conductivity of the medium or the resistivity of the concrete? Now this resistivity of concrete again is linked to the quality of the cover right, impermeability of the cover again determines the resistivity of the concrete. So the primary factor really that affects the rate of corrosion with the initiation or propagation is the quality of the cover concrete.

And in most cases, the economically feasible solutions to prevent corrosion or to extend the period of corrosion to beyond the service life of your structure are related to improving the quality of the cover concrete. Now of course that may include several different things reducing water cement ratio, using supplementary cementing materials in case you are designing against chloride-induced corrosion right.

Alternatively, you could also use corrosion inhibitors okay which can prolong this length of the passivation time. Of course, corrosion inhibitors can act in many ways, one of the ways that they can act is by making the concrete more water tight. So that means your ingress of aggressive species will be getting slowed down when you have corrosion inhibitors in the system, certain types of corrosion inhibitors okay.

So all those factors can affect the kind of cover concrete that you actually have, so most critical parameter that determines the rate of corrosion of your steel is still the cover concrete quality.

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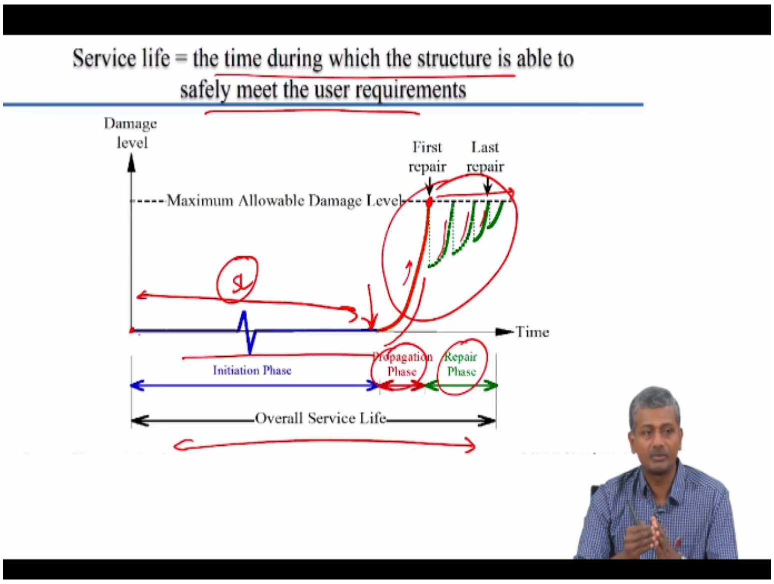
Service life = the time during which the structure is able to safely meet the user requirements

Now the concept of corrosion initiation and propagation can be combined into understanding the service life of a reinforced concrete structure because most researchers tend to agree that the kind of durability mechanism that really deteriorates concrete the most or affects the service life the most is obviously the corrosion of the reinforcing steel because that leads to a loss of structural capacity okay.

So service life is obviously defined as a time during which the structure is able to safely meet the user requirements. Of course, this may mean different things to different people for example when you are defining service life or serviceability limit, for example when you do the highest 4, 5, 6, base design, the serviceability limit for a slab may indicate the extent of deflection that happens in the slab or the amount of cracking that happens in the tensile zone of the slab right, crack width for example.

But here we are talking about the time taken for the initiation of corrosion as the end of the service life. Truly speaking that is not the end of the service life because even after corrosion initiates there may still be some useful performance left in your building okay and if you really look at it, the initiation phase is where there is no damage happening, the propagation is where the damage actually happens if it reaches the critical level we say that that is the end of your service life.

But then if you identify that and do a repair, we can then extend the service life further okay so corrosion mitigation often involves a proper management of the inspection of what is happening to your reinforced concrete and then putting in timely repairs to ensure that you can actually further extend the service level for your building. So this is the propagation phase and finally you have the repair phase, so actual service life is coming all the way till the end here.

The problem is this part is not as easily predictable as this part here given the choice of your binder systems given the water to cement ratio of your concrete, given the type of steel, there are models that you can use for fairly accurately predicting what is the end of the initiation phase that means what is the point where the steel actually starts corroding significantly but the problem is this next part is not that easy to model because of which most service life models will tend to treat only the initiation phase as the end of service life.

So in most cases this is taken as the service life of your structure now that is if you want to have it in a deterministic sense, if you want a probabilistic service life that means you need to account for the fact that your structure may not be free of defects in the beginning itself, you may actually have some defects there because of which you need to do a probabilistic analysis.

So the probabilistic service life will have a range of values of the service life. It would not be one single deterministic value of the service life okay.

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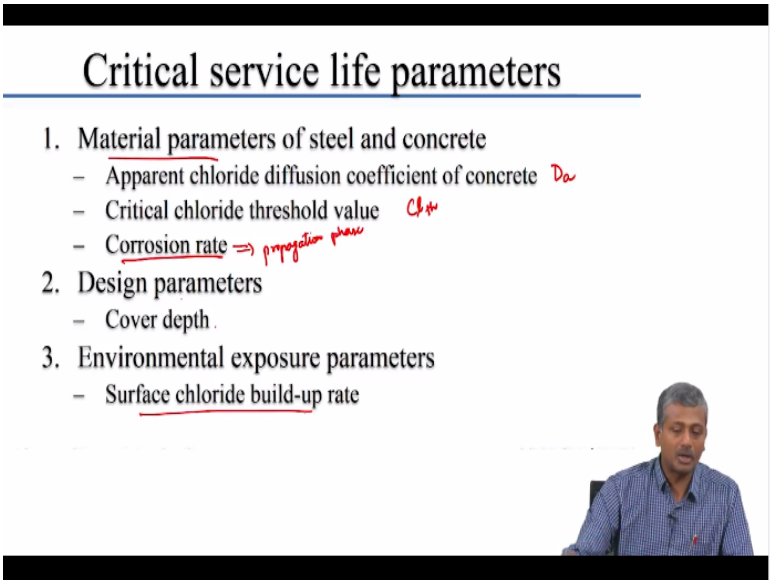

Critical service life parameters

1. Material parameters of steel and concrete
    - Apparent chloride diffusion coefficient of concrete D_a
    - Critical chloride threshold value Cl_{th}
    - Corrosion rate ⇒ propagation phase
2. Design parameters
    - Cover depth
3. Environmental exposure parameters
    - Surface chloride build-up rate

So all that actually is captured in several service life models one of which we will see in just a minute. Before that let us look at some critical service life parameters, one is the material parameters of steel and concrete. So again we are talking about the apparent diffusion coefficient of the concrete, the critical chloride threshold value and the corrosion rate okay. So these are all the critical parameters affecting the service life.

Now we are considering corrosion rate implies that we are also looking at the propagation phase right. If you do not consider corrosion rate, we are only looking at the initiation phase of the reaction. Now design parameters include cover depth because you can always vary the cover depth to check whether your design is satisfying the requirement or not and then the other aspect is environmental exposure parameter, how soon does the chloride buildup at the surface of the concrete.

The critical or surface chloride build up rate will depend on the kind of environment your concrete is in. For example, if your concrete is directly exposed to marine conditions then the chloride is immediately building up in the beginning. If your concrete is setting inside the chloride infested soil, it will take some time for the chlorides to actually build up to a large concentration on the surface of the concrete which will lead to an increase in the level of diffusion.

But this state of very high chloride concentration of the surface will take some time to actually happen. So some of these models actually account also for the time it takes for that build up to happen.

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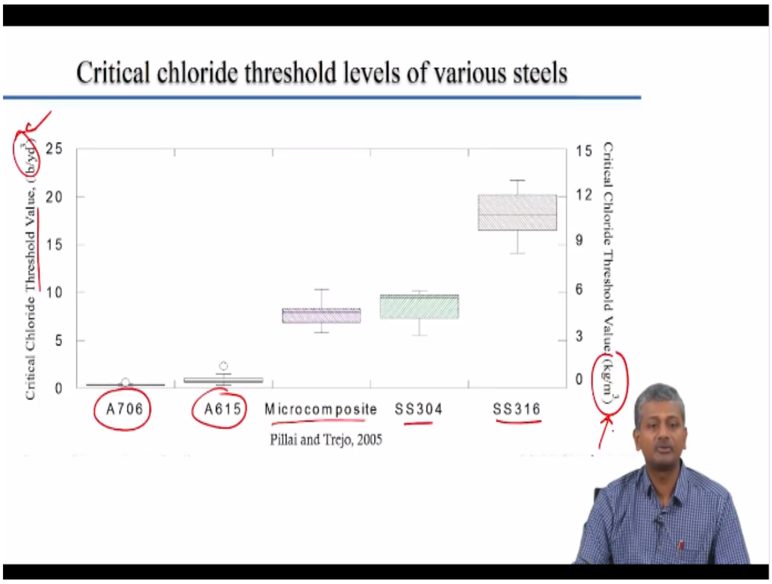

Critical chloride threshold levels of various steels

Pillai and Trejo, 2005

Now looking at critical chloride threshold levels of various steels, these are stainless steels SS304 and SS316, there is a microcomposite steel and you have your regular brands of reinforcing steel. You can see the range of performances quite different, so this critical chloride threshold value in pounds per cubic yard and this is in kilogram per cubic meter. Of course, when you work in the US you have to put both these values.

Because Americans will not understand anything other than this, other world people cannot understand anything other than this. So you need to put both these values so you get totally different results when you test different types of steel. So critical chloride threshold will vary with the type of steel that you use in the concrete.

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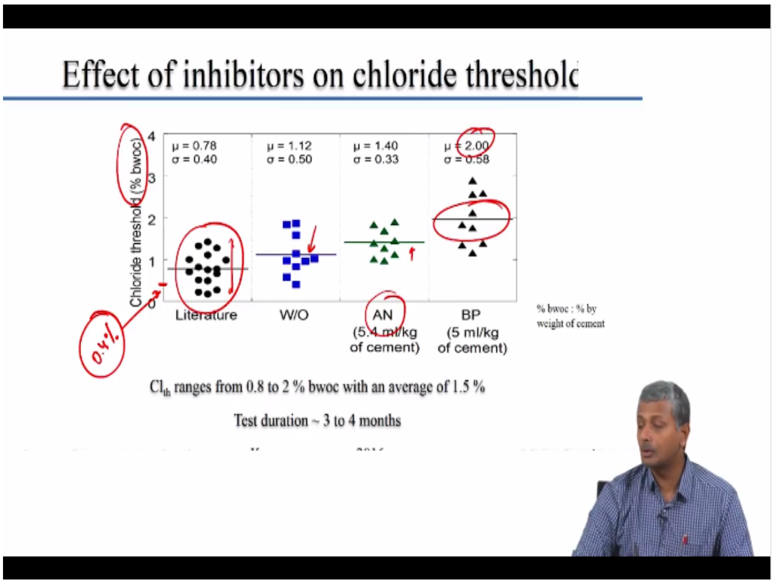

Effect of inhibitors on chloride thresholc

% bwoc : % by weight of cement

Cl_{th} ranges from 0.8 to 2 % bwoc with an average of 1.5 %

Test duration ~ 3 to 4 months

Now interestingly when you use corrosion inhibitors, you can again lead to a change in the critical chloride threshold of the concrete. So the data from literature for concrete without corrosion inhibitor seems to indicate that the chloride threshold is varying significantly. Look at the extent of variation all the way from 0.2 to about 1.5 okay but generally this is percentage by weight of cement okay.

Chloride threshold or chloride concentration is measured in terms of percentage by weight of cement. The generally accepted value is 0.4%, it is a very conservative value because often it turns out that it is much higher than that okay. Now in an experimental study done by one of our Ph. D students, it was found that for concretes that we tested in our lab, the average was about 1.1 without inhibitor.

And for an anodic inhibitor okay which basically works towards suppressing the anodic reaction that is conversion of Fe to Fe2+ for that type of inhibitor it was pushed up marginally but for a bipolar inhibitor that means which works both on the anode and the cathode your results were much more better so the actual mean was around 2, so the inhibitors can have an influence in the chloride threshold.

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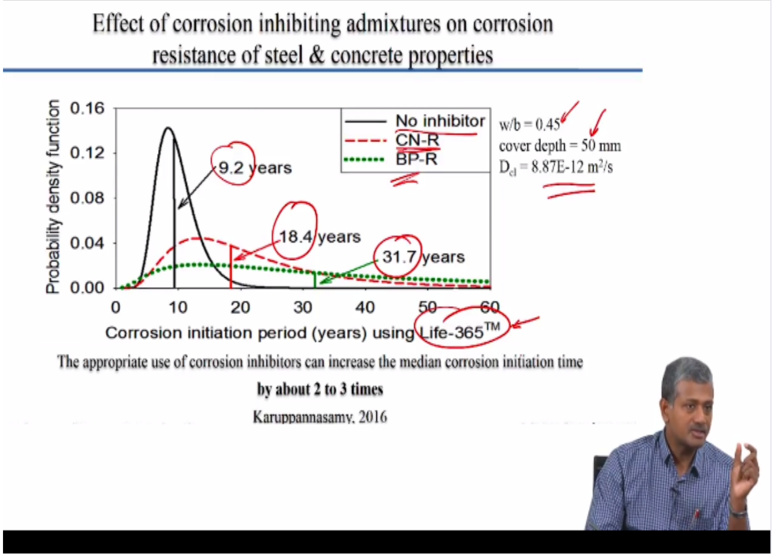

Effect of corrosion inhibiting admixtures on corrosion resistance of steel & concrete properties

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

Karuppannasamy, 2016

Now based on these parameters and analysis of the service life of the concrete was done using a software called Life-365 about which I will explain in just a minute. So for this of course there were certain things that were resumed one is the cover depth was assumed as 50 millimeters, this concrete was designed with the water binder ratio of 0.45 and the diffusion coefficient of the concrete was 8.87*10 power -12 square meter per second.

So based on this what Jeychandran who worked on this Ph.D thesis was able to show was with no inhibitor the probabilistic service life had an average of 9.2 years okay. So of course this distribution is a probability density function of the service life. So if you are taking 50% of the mean, it is about 9.3 years in the case of concrete without any inhibitor. When you use the calcium nitrate which is anodic inhibitor you extend it to almost double 18.4 years.

And for a bipolar you are taking it to more than 3 times the service life predicted without the inhibitor okay. So again inhibitors can have a significant influence on the service life. Now Life-365 for the most part takes only the initiation phase for determination of service life, it takes a little bit of propagation phase. What it does is it takes the initiation phase and adds a certain number of years for 10% damage level to happen in the steel.

That means the cross sectionality of steel reduces by 10% and that is taken to be a point where your service life is considered to be over okay. So they are just adding a small quantity to indicate that 10%. So most of the measurement is only for the initiation time, it only takes a small bit for the propagation time.

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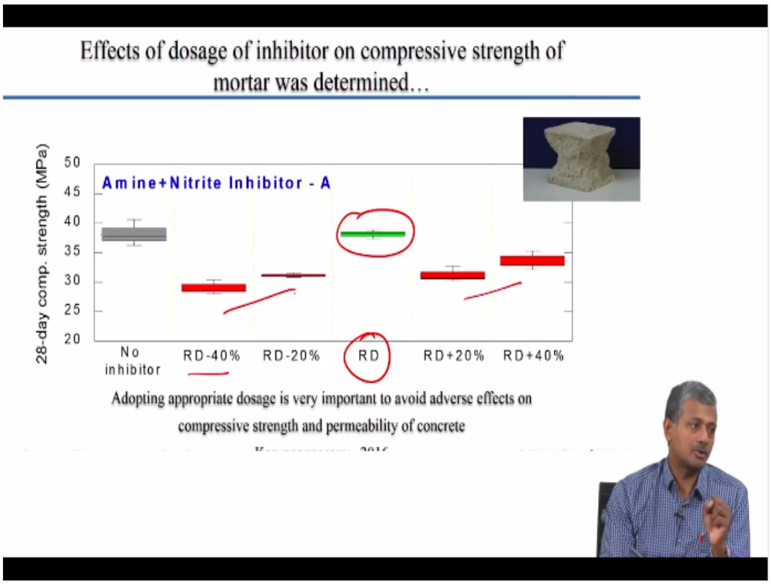

Effects of dosage of inhibitor on compressive strength of mortar was determined…

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

Now interestingly when you use corrosion inhibitors, the concrete properties also seem to get affected. So for example here without any inhibitor the concrete that was designed for this project had a strength between 35 and 40 megapascals. When the actual dosage of the inhibitor was used, the same strength level was achieved but when different dosage that means 20% and 40% below the actual or 20% and 40% above the actual were used, there was a significant difference in the compressive strength performance of the concrete.

That seems to indicate that one of the parameters that you should check when you put in corrosion inhibitors in your system is also its influence on the mechanical properties of the concrete.

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Tools are available to estimate the service life of concretes with various SCMs

http://www.life-365.org

So Life-365 is a freely downloadable service life design software, it is not that difficult to use. There are tutorials which will help you actually determine what you need to do for different kinds of systems that you are choosing to look at.

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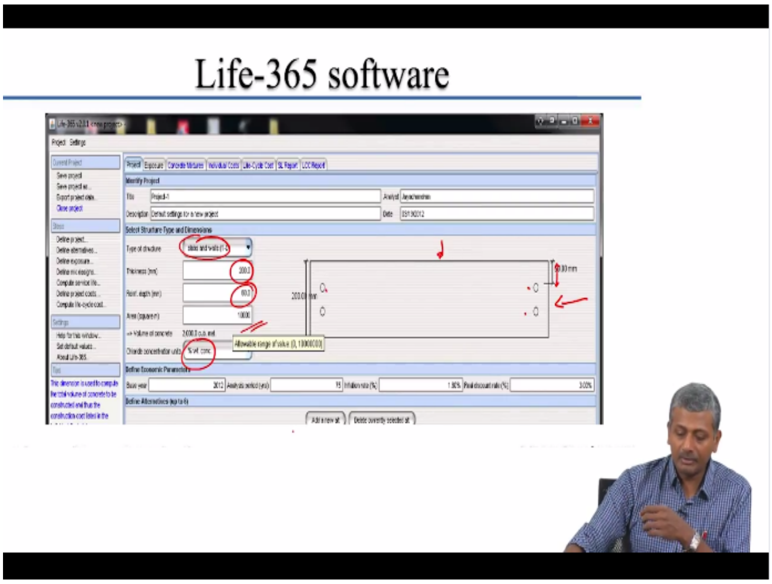

Life-365 software

So just to give you a snapshot of what this software has, there are pages where you can actually enter the details of the kind of element that you are trying to test, for example slabs and walls there is 1-dimensional diffusion or if you have a column, it is going to be a 2-dimensional diffusion right. You can put the thickness of the member, the reinforcement depth or the cover depth and the area that is exposed to the chloride okay.

And chloride units can also be given in terms of percentage weight concentration, it gives you of course this is the details of the structure you can see, this is the slab with the cover thickness of 60 millimeters and there are two layers of reinforcing steel here okay and what you can also enter are the local environment details, for example temperature and relative humidity for the local environment.

There are preset environments created for North American cities because this software is developed in North America. The easiest way is to find a city which closely resembles what you are trying to investigate for example Chennai, the closest cities in North America would be cities in Florida like Miami for instance. You can choose a city like that and put or you can have your own temperature and relative humidity data fed into the system.

The chloride data can also be included in terms of how much chloride has been found in the sea water or the ground water which you are designing for. You can also decide on how long it takes for the chloride to build up to its maximum level in the surface of the concrete. In a marine condition, it is immediate okay. In soil, you can assume it will happen over several years and early after that you will have the real increase in the process of diffusion.

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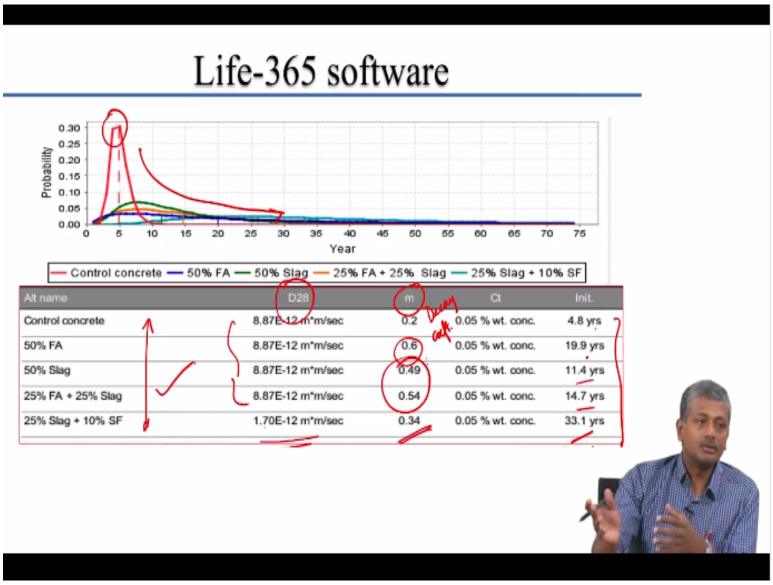

Life-365 software

Alt name	D28	m	Ct	Init.
Control concrete	8.87E-12 m*m/sec	0.2	0.05 % wt. conc.	4.8 yrs
50% FA	8.87E-12 m*m/sec	0.6	0.05 % wt. conc.	19.9 yrs
50% Slag	8.87E-12 m*m/sec	0.49	0.05 % wt. conc.	11.4 yrs
25% FA + 25% Slag	8.87E-12 m*m/sec	0.54	0.05 % wt. conc.	14.7 yrs
25% Slag + 10% SF	1.70E-12 m*m/sec	0.34	0.05 % wt. conc.	33.1 yrs

So based on that you can investigate the potential for different types of binder systems, so the software allows you to test your predicted service life for different types of binder systems because when you change the binder what gets affected is your diffusion coefficient D28. Now please remember D28 is a diffusion coefficient at 28 days, what the software also does is converts this into a time dependent diffusion coefficient by using a factor called m or the decay coefficient.

The meaning of decay coefficient is it is trying to track how the diffusion coefficient will decay with respect to time because concrete gets more and more dense and impermeable, the diffusion coefficient will keep on reducing with time right. So here for concretes which are fly ash or slag, you can expect that your decay coefficients are much larger 0.6 for fly ash, for slag it is around 0.5, for slag silica fume combination is about 0.3.

So the binder will affect not only the decay coefficient but it will also affect the diffusion coefficient at 28 days especially silica fume based binders you see are tremendously reducing the diffusion coefficient at 28 days. For all the other systems, it is assumed to not change the 28-day diffusion coefficient okay but because of the effect of m this diffusion coefficient across the passage of time will change.

So because of that you start seeing that for the control concrete your average service life predicted in this environment is only 5 years whereas the predication of service life keeps on increasing for other binder systems that you are using in the system. So the results are given here about 5 years, 20 years in the case of 50% fly ash, about 12 years in the case of 15% slag, combination of fly ash and slag is 15 years and silica fume and slag combination gives you 33 years so there can be a massive difference.

Of course, this does not mean that your concrete will behave the same way on site. This is just a means of selecting the right kind of material combinations that you have for your project. So this is the selection criteria, it helps you to understand what kind of blend of materials you should select for the construction project without really worrying about the long-term durability in the beginning itself.

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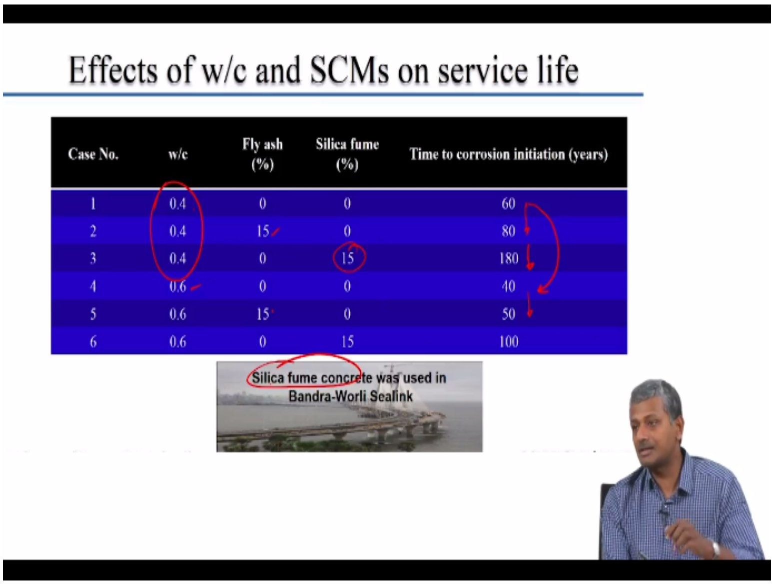

Effects of w/c and SCMs on service life

Case No.	w/c	Fly ash (%)	Silica fume (%)	Time to corrosion initiation (years)
1	0.4	0	0	60
2	0.4	15	0	80
3	0.4	0	15	180
4	0.6	0	0	40
5	0.6	15	0	50
6	0.6	0	15	100

Silica fume concrete was used in Bandra-Worli Sealink

So again this is some examples from water cement ratio and silica fume usage. So for example at 0.4 water cement ratio just inclusion of 15% fly ash changes the initiation time by 20 years. If you have 15% silica fume, it triples the initiation time from 60 to 180 years. Of course, these are only numbers please remember these may not have real life significance because the silica fume concrete will have other problems.

Plastic shrinkage we discussed that will create cracking, there is cracking there is faster initiation. So all that will have to be accounted for when you do the real design okay. So that is why all these numbers have to be taken with a pinch of salt, this is only to do initial material selection.

With 0.6 water cement ratio from 0.4 to 0.6 when you change water cement ratio, you are losing about 20 years of service life obviously because lower water cement ratio implies a better performance. Again here the impact on service life is not as great as the impact at lower water cement ratio. Again for Bandra-Worli Sealink silica fume concrete was used with some considerations of the Life-365 base design to understand whether it would meet the demands of the long service life in an extremely aggressive environment.

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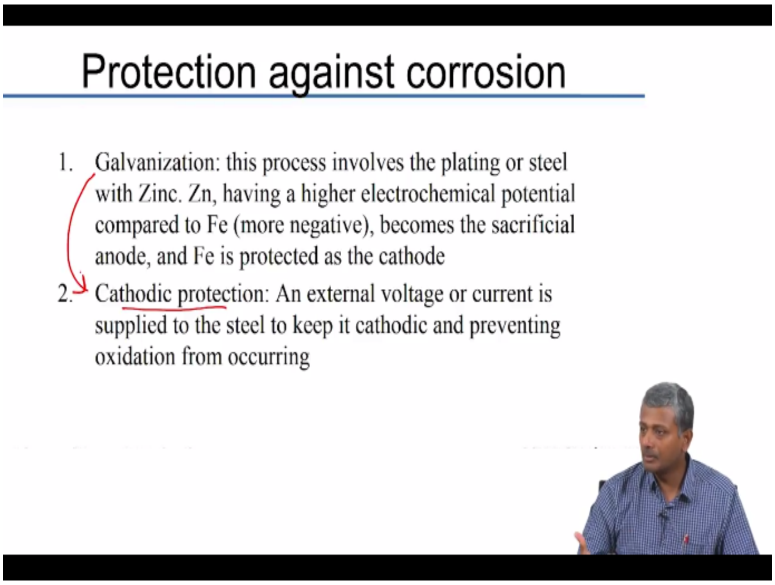

Protection against corrosion

1. Galvanization: this process involves the plating or steel with Zinc. Zn, having a higher electrochemical potential compared to Fe (more negative), becomes the sacrificial anode, and Fe is protected as the cathode
2. Cathodic protection: An external voltage or current is supplied to the steel to keep it cathodic and preventing oxidation from occurring

Of course, you know very well about different protection mechanisms against corrosion. We have been discussing those. Galvanization is a process where you cover the steel with the metal which is more electrochemically active and you can also do a cathodic protection. Galvanization is actually one of the means of cathodic protection. Essentially cathodic protection talks about any process that makes the steel the cathode.

You prevent oxidation of the steel okay, so you can supply current to it, you can cover it with the more electrochemically active material like zinc or you can connect it with another material like magnesium for instance which can corrode while steel remains safe.

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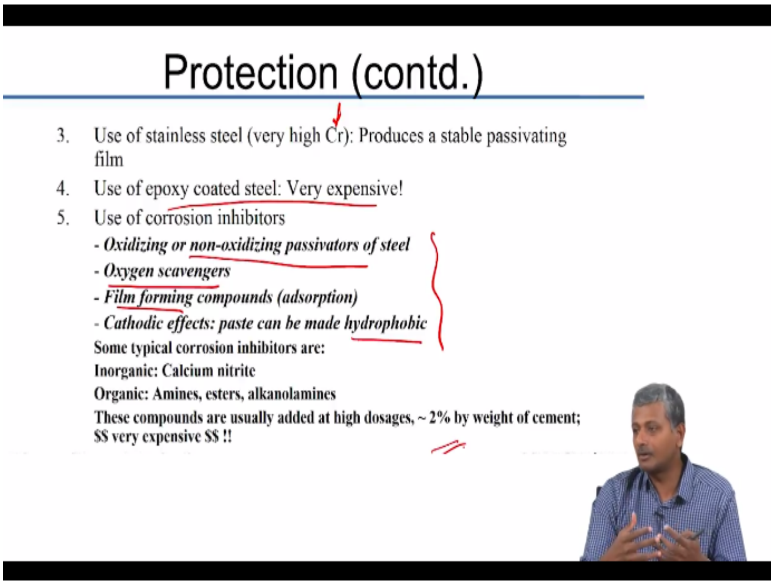

Protection (contd.)

3. Use of stainless steel (very high Cr): Produces a stable passivating film
4. Use of epoxy coated steel: Very expensive!
5. Use of corrosion inhibitors
   - *Oxidizing or non-oxidizing passivators of steel*
   - *Oxygen scavengers*
   - *Film forming compounds (adsorption)*
   - *Cathodic effects: paste can be made hydrophobic*

Some typical corrosion inhibitors are:

Inorganic: Calcium nitrite

Organic: Amines, esters, alkanolamines

These compounds are usually added at high dosages, ~ 2% by weight of cement; $$ very expensive $$!!

Stainless steel has a very high chromium content that makes the passivating film very stable and that prevents further corrosion of the steel. Epoxy coated steel is very expensive. We also talked about the fact that blisters or pinholes in epoxy coated steel could actually make its performance worse than regular steel. Corrosion inhibitors can be of many types, we discussed the mechanism earlier.

Some of these can form, they can be passivators of steel, they can form film in the steel surface, they can make the paste hydrophobic or water proof because of which water will not be able to get in, propagation rate will be reduced, some can be also oxygen scavengers, they can combine or bind the oxygen prevented from reaching the steel surface okay. Again these are expensive materials.

So you have to think quite carefully about how to use them, how best to utilize them. There are migrating corrosion inhibitors also available today in the market, which are spray or brush applied on the surface and they penetrate or diffuse through the concrete to the level of the reinforcing steel and offer protection. It sounds like science fiction; in some cases, it may actually be science fiction.

In most cases, the admixtures that work better are the ones which are admixed into the concrete which are mixed with the concrete itself.

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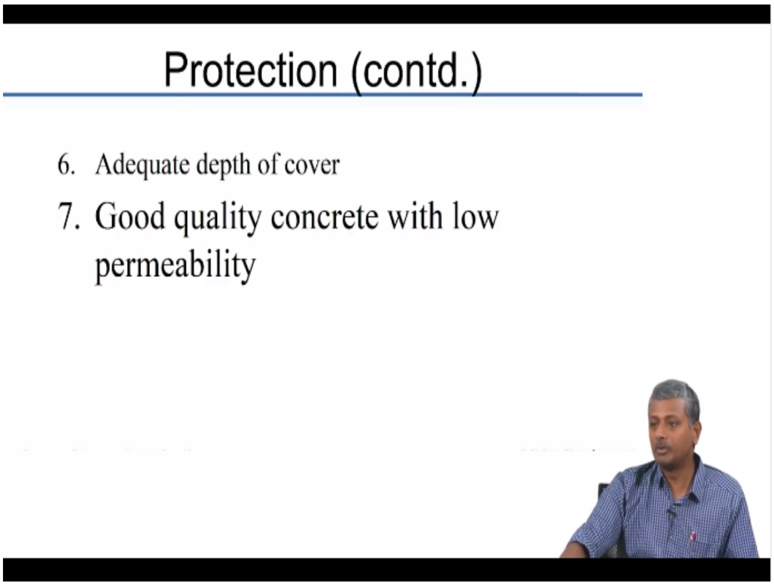

Protection (contd.)

6. Adequate depth of cover
7. Good quality concrete with low permeability

And of course this is the simple mantra but the one which is most difficult to execute on the site is to produce concrete which has the right depth of cover and low permeability.

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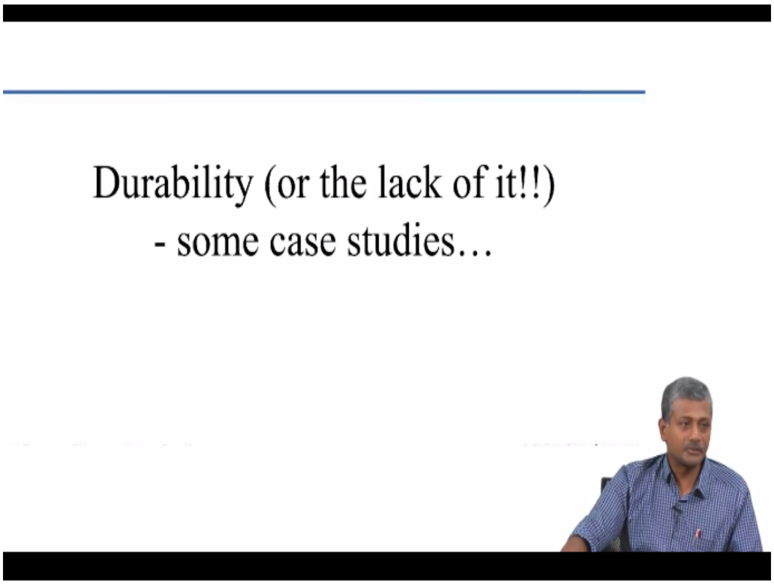

Durability (or the lack of it!!)
- some case studies…

Very quickly, I will show you a couple of cases of reinforcement corrosion which was caused because of different things.

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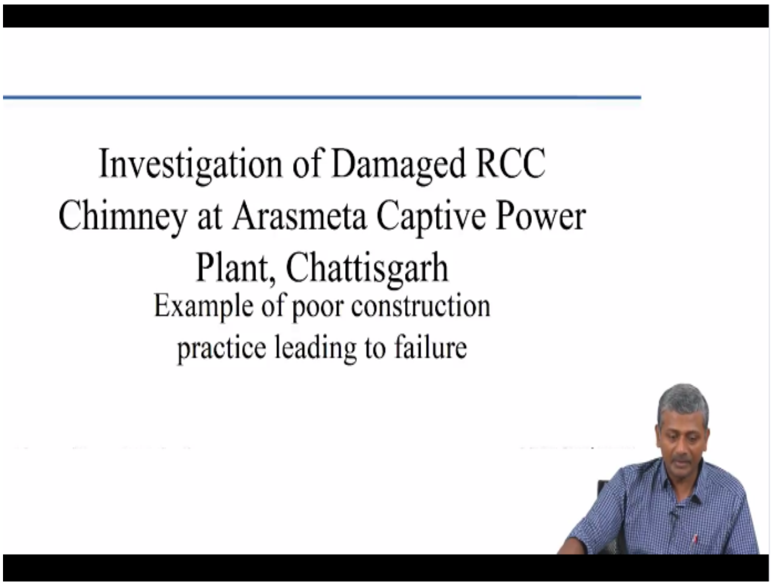

Investigation of Damaged RCC Chimney at Arasmeta Captive Power Plant, Chattisgarh
Example of poor construction practice leading to failure

This first example deals with the damaged chimney in a captive power plant in Chattisgarh. This is an example of poor construction practice leading to failure.

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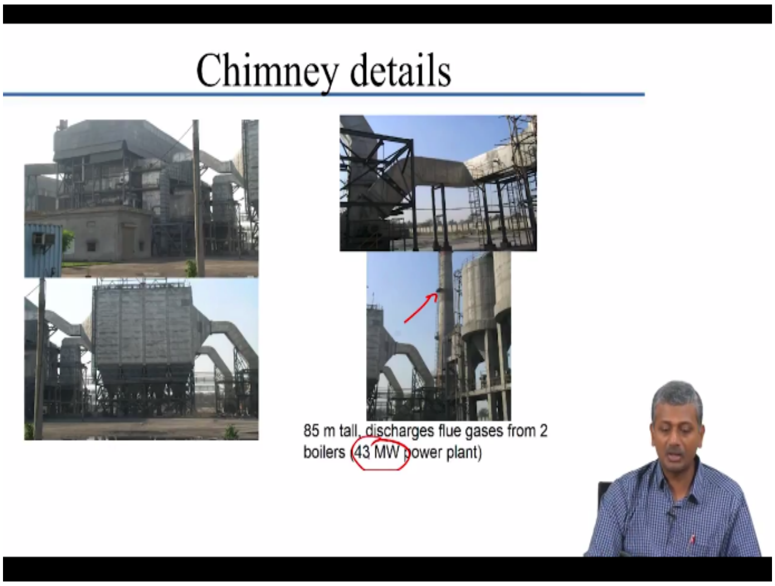

Chimney details

85 m tall, discharges flue gases from 2 boilers (43 MW power plant)

So the chimney basically is an 85 meters tall chimney you see here at the bottom in the power plant. It is a small power plant; it is a captive power plant which only serves the cement company which is right next to it Lafarge Cement Company.

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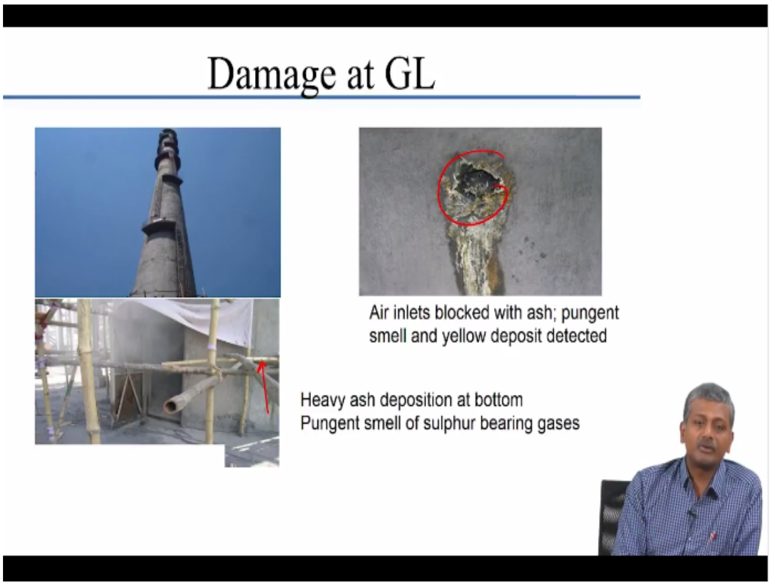

Damage at GL

Air inlets blocked with ash; pungent smell and yellow deposit detected

Heavy ash deposition at bottom
Pungent smell of sulphur bearing gases

And the kind of damage that was seen, this was at the ground level so at around this level 1.5 meters from the ground, there are air holes which are supposed to be open to allow the passage of gases and air out into the system to push the gas up okay. Now here these air holes were blocked and there was this yellowish deposit, again strongly smelling of sulphur. The coal has very little sulphur, it is not very high sulphur.

But then still the sulphur flies out with the flue gas but then lot of sulphur was actually detected in this and this sulphur obviously can be detected in the form of hydrogen sulphide gas.

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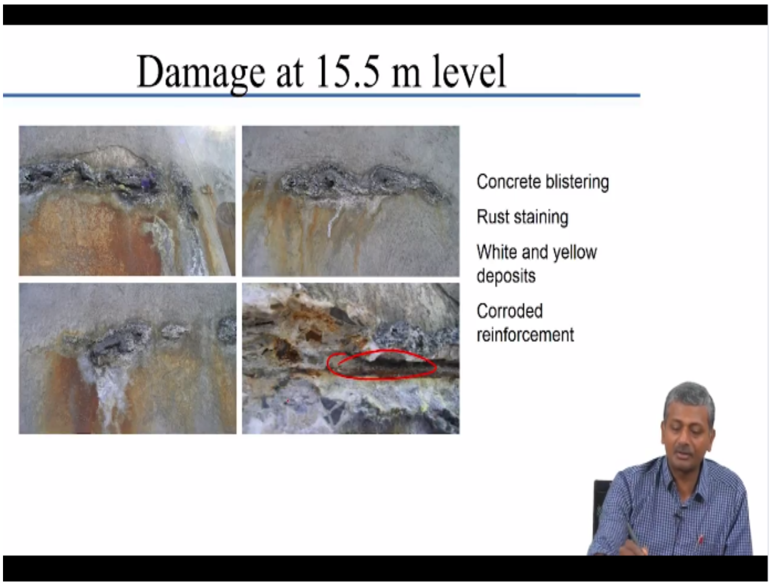

Damage at 15.5 m level

Concrete blistering

Rust staining

White and yellow deposits

Corroded reinforcement

So this is the damage which was at 15.5 meter level, of course that was the level to which they could erect the scaffolding, they could not really go beyond that, otherwise we have to take the rung ladder on the side of the chimney, I was not too excited about doing that. So there was scaffolding at 15 meter level which we climbed and we saw that there was a layer where the concrete that completely got blistered.

You see the concrete has completely got blistered, the steel is very badly corroded inside okay and this sort of a pattern was repeating itself across the height of the chimney. So what is the common construction method for a chimney? Slip forming okay. If you do not do a good job of slip forming, you create joints between the different lifts and very clearly all this damage was actually happening at the joints.

But this was only after about 2 years of construction, so what could have happened here, this gas with hydrogen sulphide was somehow finding its way through the joints and when it was coming to the external surface it was condensing as sulphuric acid. So it is almost like acid attack, you can see the blistering of the concrete surface.

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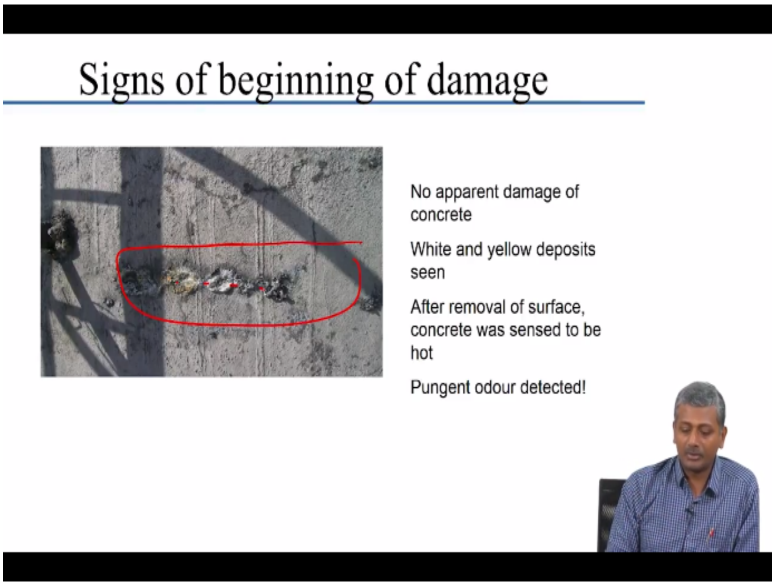

Signs of beginning of damage

No apparent damage of concrete

White and yellow deposits seen

After removal of surface, concrete was sensed to be hot

Pungent odour detected!

And we also saw at the same level, there was a location which did not show much damage but there were signs of something initiating and we could actually feel the gas coming out at that location and the smell was also there, the gas was also, you could feel the heat of the gas coming out at that point.

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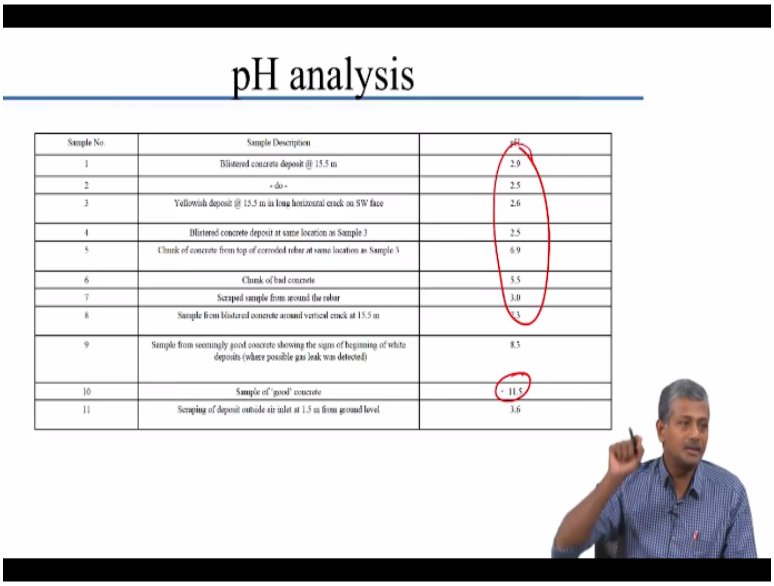

pH analysis

Sample No.	Sample Description	pH
1	Blistered concrete deposit @ 15.5 m	2.9
2	- do -	2.5
3	Yellowish deposit @ 15.5 m in long horizontal crack on SW face	2.6
4	Blistered concrete deposit at same location as Sample 3	2.5
5	Chunk of concrete from top of corroded rebar at same location as Sample 3	6.9
6	Chunk of bad concrete	5.5
7	Scraped sample from around the rebar	3.0
8	Sample from blistered concrete around vertical crack at 15.5 m	2.3
9	Sample from seemingly good concrete showing the signs of beginning of white deposits (where possible gas leak was detected)	8.3
10	Sample of 'good' concrete	11.5
11	Scraping of deposit outside air inlet at 1.5 m from ground level	3.6

So we also took some samples of concrete from the damaged areas, you can see the pH. Extremely acidic pH was determined and we also took a sample of good concrete which had more than 11 pH in this case, so there are clear indications of the acid attack but then why does this gas tend to go through the concrete? So when you have a concrete chimney usually they have a steel tube inside that discharges the gas out.

Or they have an acid brick lining which is protecting the concrete from the gases that are flying out. So here they had the acid brick lining but please remember the acid brick lining has to be supported on corbels that come through the concrete and those locations there are possibilities of gaps being created where the gas can actually stray out and then it starts coming out from the concrete, so that is what we detected was the cause here.

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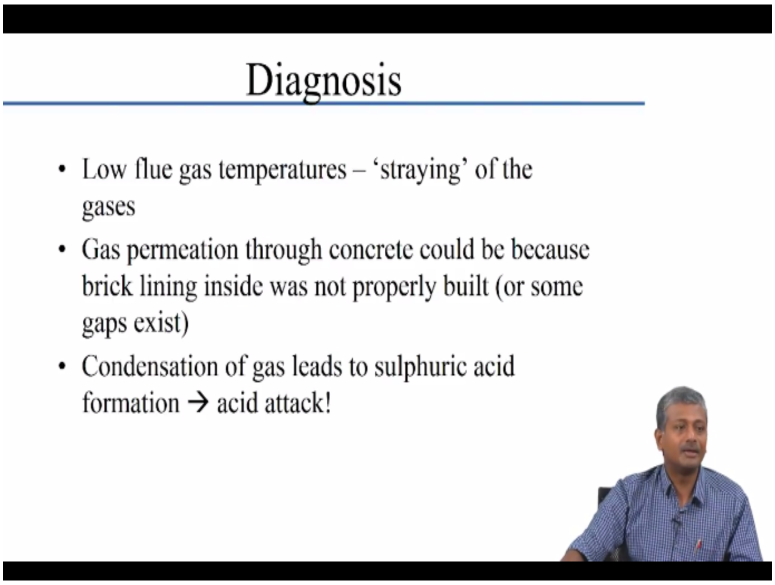

Diagnosis

- Low flue gas temperatures – 'straying' of the gases
- Gas permeation through concrete could be because brick lining inside was not properly built (or some gaps exist)
- Condensation of gas leads to sulphuric acid formation → acid attack!

The problem was the poor quality construction done with the slip forming and that led to the failure.

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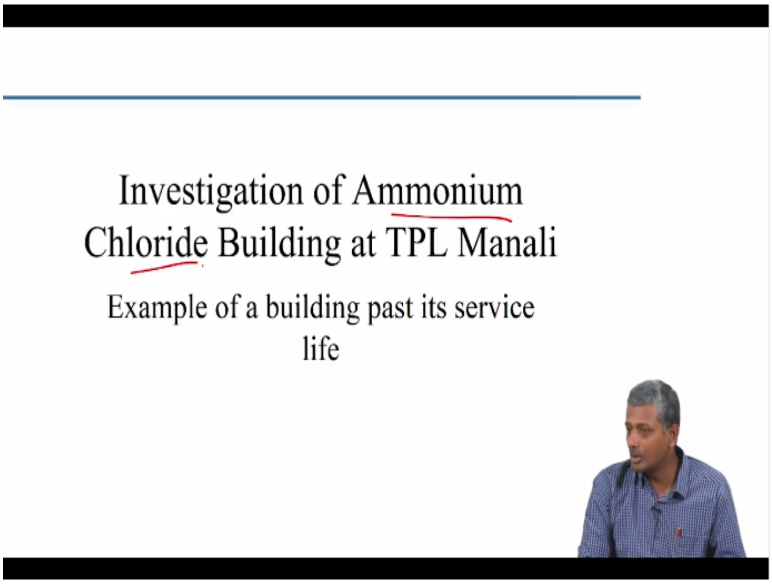

Investigation of Ammonium Chloride Building at TPL Manali

Example of a building past its service life

There is another example of an ammonium chloride building at Tamil Nadu Petrochemicals Limited in Manali, which is at North of Chennai. So this was an example of a building past its service life. So this building was intended to handle ammonium chloride, you can hardly imagine something more corrosive than that. This building was built around 40 years ago. At the time of inspection which was 10 years ago.

So right now it is 50 years, so 40 years ago that building was built and for 40 years possibly 1960s when the building was built the concrete grade would have been very low 20, 25 megapascal concrete, nobody thought about all these issues.

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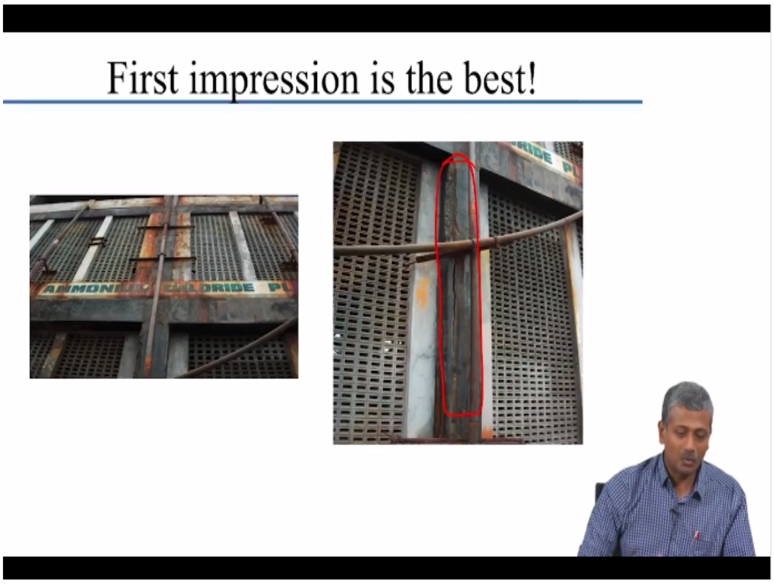

First impression is the best!

So the first impression is the best, the columns are showing vertical cracks. So you obviously do not feel safe entering the building. The workers were complaining for the rightfully so that they were quite scared about what will happen inside the building.

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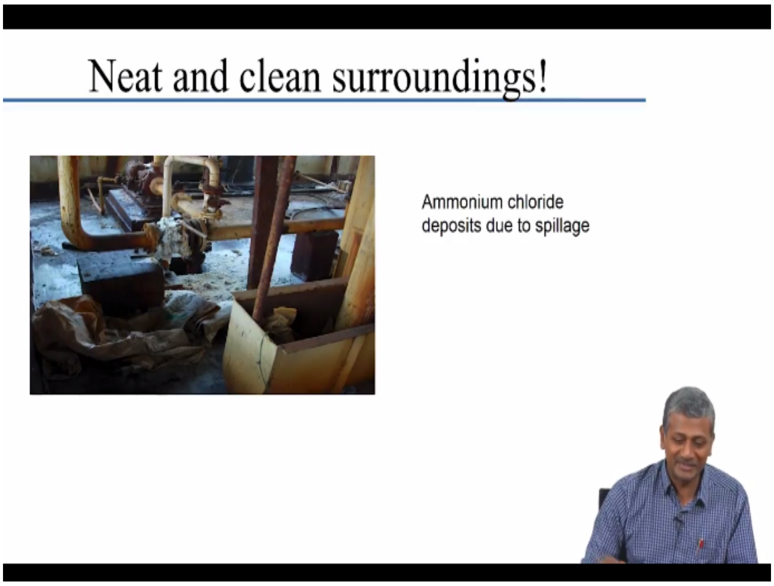

Neat and clean surroundings!

Ammonium chloride
deposits due to spillage

And of course they have also maintained it very neatly and cleanly. There is chloride all over the place.

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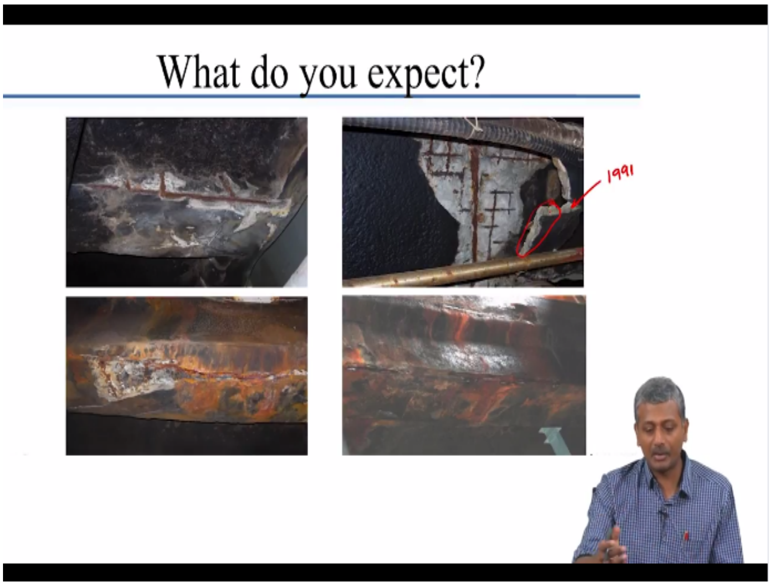

What do you expect?

And the results are therefore you to see, there is corrosion of every possible structural element that is inside the system and one interesting part is we inspected the structure in 2008. In 1991, there was a repair done where they simply removed the crack concrete and put a new layer of mortar, you can see the layer of mortar and this layer is nicely debonded and came off.

Because they have not stopped the corrosion of the steel, they only treated the symptom, they have not really treated the cause. So by putting this new layer again because of the expansive pressures the layer simply came off.

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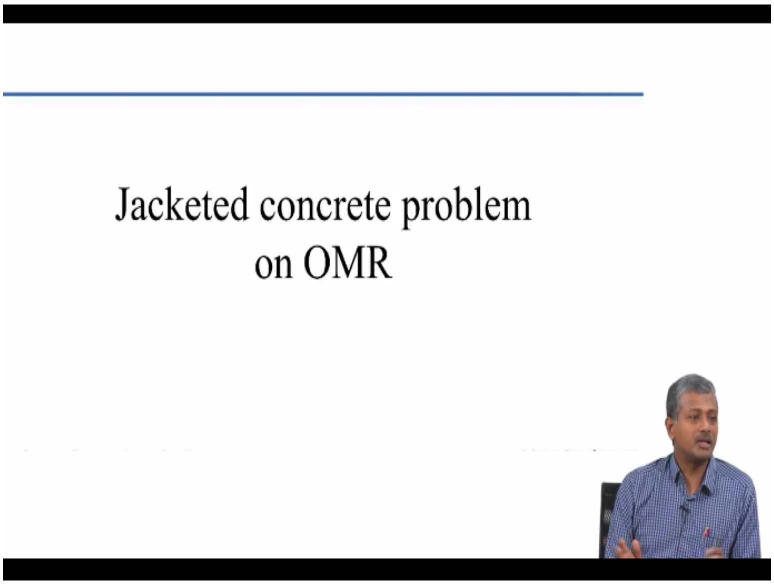

Jacketed concrete problem
on OMR

And this is an interesting problem on Old Mahabalipuram Road where a newly built structure after about 6 to 7 years started showing some corrosion related cracking in some of the columns in the basement. Now this structure was originally intended to be a 3-storey structure ground plus 3 but during the construction process they got permission to extend it to ground plus 7.

So because of that they decided okay they will strength in some of the columns okay, increase the size of some of the columns by jacketing. So about 10 columns were chosen from the basement level to about third floor level to jacket and that was considered sufficiently also built some additional shear walls and things like that. All these jacketed columns where the ones which were showing the science of corrosion, no other column showed any corrosion.

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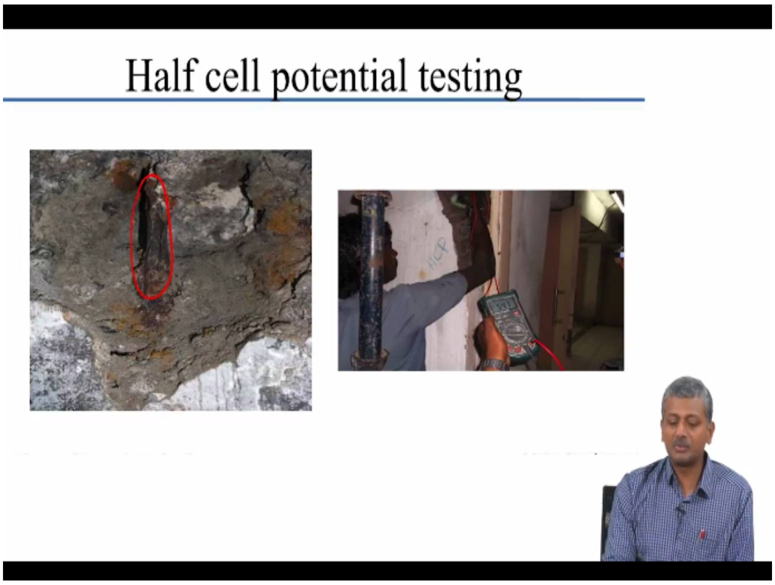

Half cell potential testing

Very interesting, so we started investigating of course you can see the kinds of corrosion that is happening. Extensive corrosion is actually happened, not just small amount of corrosion, we did measurements with half-cell potential studies.

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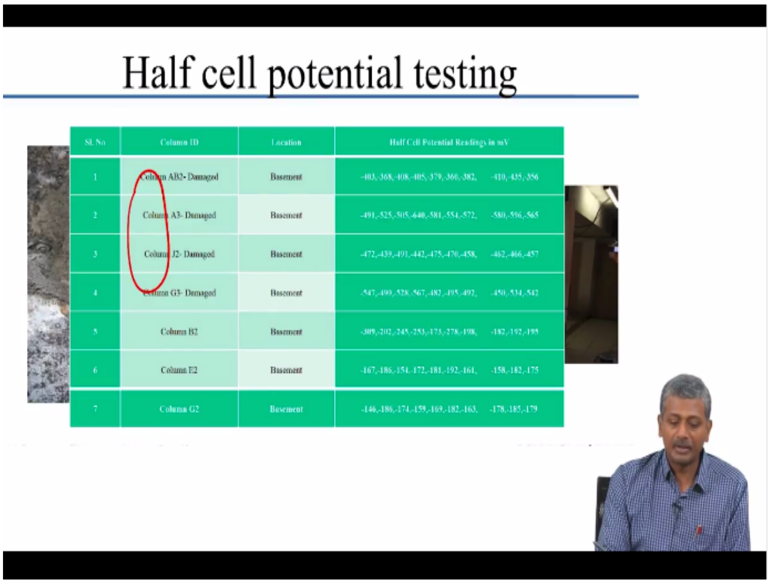

Half cell potential testing

Sl. No	Column ID	Location	Half Cell Potential Readings in mV
1	Column AB2- Damaged	Basement	-403,-368,-408,-405,-379,-360,-382, -410,-435,-356
2	Column A3- Damaged	Basement	-491,-525,-505,-640,-581,-554,-572, -580,-596,-565
3	Column J2- Damaged	Basement	-472,-439,-491,-442,-475,-470,-458, -462,-466,-457
4	Column G3- Damaged	Basement	-547,-499,-528,-567,-482,-495,-492, -450,-534,-542
5	Column B2	Basement	-309,-202,-245,-253,-173,-278,-198, -182,-192,-195
6	Column E2	Basement	-167,-186,-154,-172,-181,-192,-161, -158,-182,-175
7	Column G2	Basement	-146,-186,-174,-159,-169,-182,-163, -178,-185,-179

And we determined that the corrosion potentials were very high that means there most cases all the jacketed columns seem to be showing the damage.

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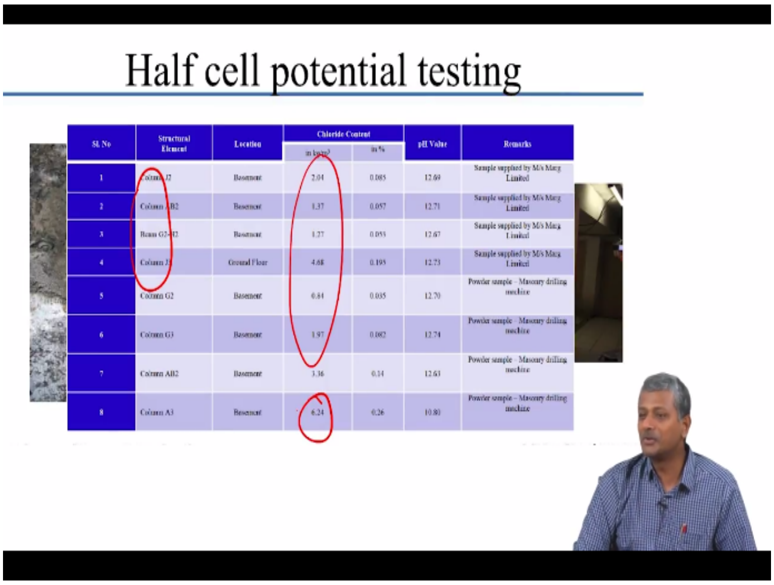

Half cell potential testing

Sl. No	Structural Element	Location	Chloride Content		pH Value	Remarks
			in kg/m^3	in %		
1	Column J2	Basement	2.04	0.085	12.69	Sample supplied by M/s Marg Limited
2	Column AB2	Basement	1.37	0.057	12.71	Sample supplied by M/s Marg Limited
3	Beam G2-H2	Basement	1.27	0.053	12.67	Sample supplied by M/s Marg Limited
4	Column J3	Ground Floor	4.68	0.195	12.73	Sample supplied by M/s Marg Limited
5	Column G2	Basement	0.84	0.035	12.70	Powder sample – Masonry drilling machine
6	Column G3	Basement	1.97	0.082	12.74	Powder sample – Masonry drilling machine
7	Column AB2	Basement	3.36	0.14	12.63	Powder sample – Masonry drilling machine
8	Column A3	Basement	6.24	0.26	10.80	Powder sample – Masonry drilling machine

Chloride contents only in the jacketed columns were extremely high okay. Now chloride content if you look at IS456, in reinforced concrete you are not permitted to have more than 0.6 kilogram per cubic meter of chloride okay. Now that is a conservative estimate, usually at 0.6 we do not really see a problem but then that is taken in a conservative fashion. So here you can see in some cases you have 6% chloride or 6 kilogram per cubic meter chloride, very large chloride loading is there in the system.

Where is this chloride coming from? So we try to analyze soil, nothing is there, there is no leakage, there is no way the chloride could come, what is the answer, is the curing water or the sand that was used in the jacketing portion alone, only for this jacketed concrete, this problem is there. So this OMR not too far from the sea, so you can get sea water, you can get sea sand.

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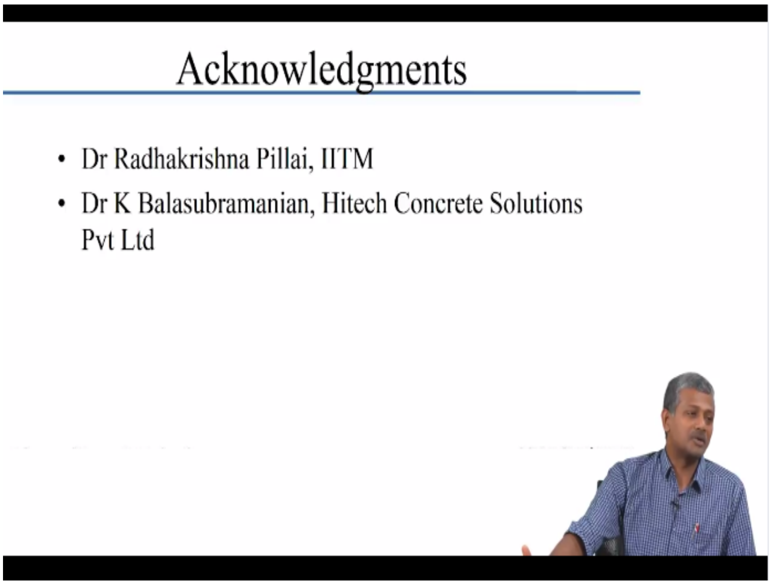

Acknowledgments

- Dr Radhakrishna Pillai, IITM
- Dr K Balasubramanian, Hitech Concrete Solutions Pvt Ltd

God knows what they did, ultimately all the jacketed columns were damaged okay so I have to acknowledge Dr. Pillai for helping me in some of the notes on corrosion and Dr. Balasubramanian for getting access to some of these sites and getting to see the kind of corrosion related damage that actually happen okay. So thanks, with that we finish this corrosion chapter.

Tomorrow the last class of the course, we will take up the issue of alkali-silica reaction and freezing and thawing and with that the theory part will be completed. Thank you.