Advanced Topics in the Science and Technology of Concrete

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Chloride induced corrosion and service life of reinforced concrete structures Part -1

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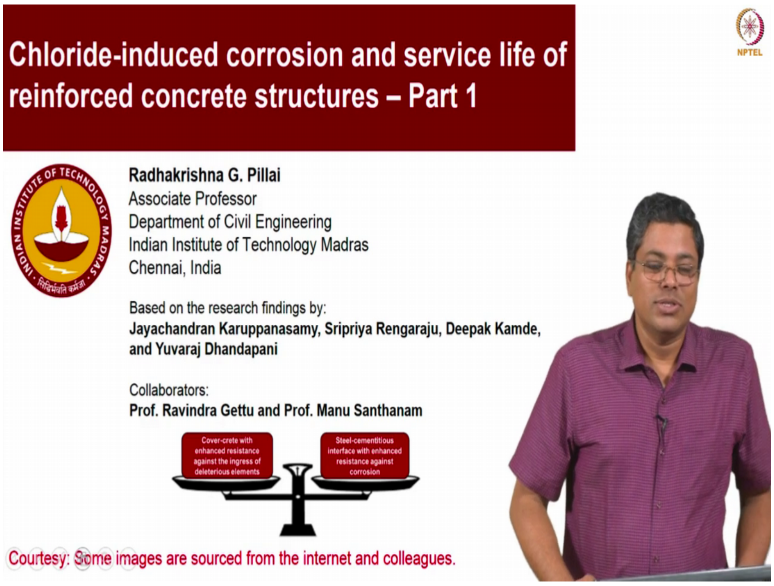

Welcome to this NPTEL course on advanced topics in science and technology of concrete. I am Radhakrishna Pillai I associate professor in Department of Civil Engineering at IIT Madras, Chennai, India and this presentation is mainly from the inputs given by my students Jayachandran, Sri Priya, Deepak and Yuvraj. Also thankful to Prof. Ravindra Gettu and Manu Santhanam for help at various stages, so this molecule on chloride induced corrosion and service life of reinforced concrete structure is split into 2 parts. First part we will look mainly on the issues associated with the concrete systems and the 2nd part we will look at the issues associated with the steel cementitious system or the steel cementitious interface.

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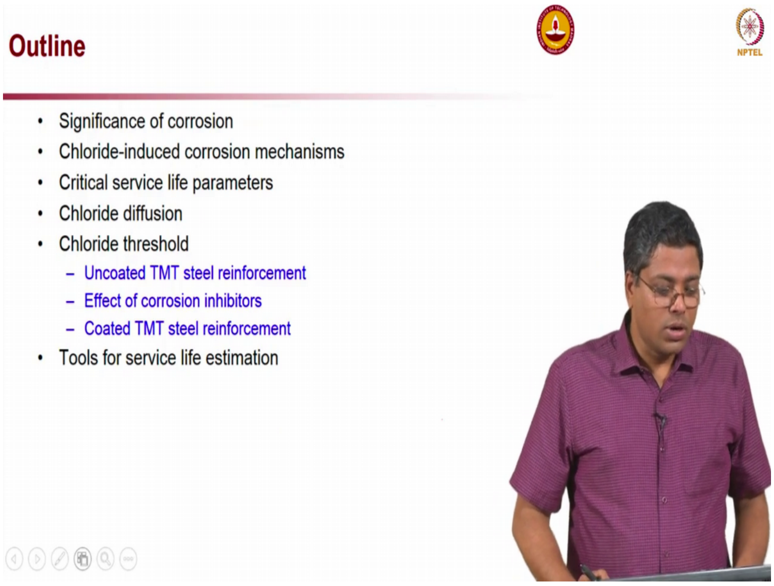

So the outline of the lecture is first we will look at why the corrosion is significant for why we really need to worry about it and then looking at some mechanism of chloride induced corrosion especially in concrete structure and then critical service life parameters and 2 parameters which we will be looking at mainly is chloride diffusion coefficient and the chloride threshold. When you talk about chloride diffusion we look at different cement issues binder system and also when you talk about chloride threshold we will look at how the coated rebars and uncoated rebars and the performance of corrosion inhibitors also. Then towards the end we will show you some nomograms on estimating service life at the very early stages of design phase.

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Now significant of corrosion I am going to show you 3 case studies where premature corrosion has been observed one is the Sunshine Skyway Bridge, Tampa, Florida. This was built in 1980s and in just about 13 years you can see the significant corrosion were observed in the tendons of this bridge, so this is right here you can see that in on the pier, inside the pier you have this scale tendon which were corroded in just 13 years. For a structure of this status it is not expected to have this much of corrosion in 13 years that is why we are actually talking about it.

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Now this another famous bridge Golden Gate Bridge in the US but even on this bridge you can see that this is a severe corrosion there and the reinforced concrete elements are also corroding, so what is… The point here is to maintain this type of structures for long life you are really now forced to invest a lot of money in maintaining these structures, so cost of corrosion is also very high on this type of structures too.

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And another structure is in Canada where you can see that there is actually a wire mesh here is mainly to prevent the falling hazardous prevent the concrete pieces from following on to the people below the bridge. So the point here is there are concrete structures abroad and in developed world where they have actually experience significant premature corrosion and we can easily learn the lesson from that and then make sure that today's structure which you are building today do not experience such premature corrosion.

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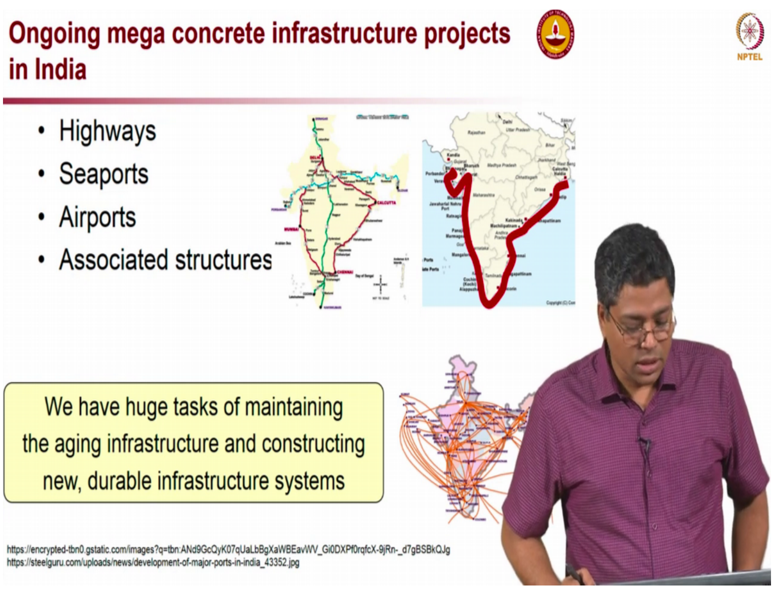

Now what are we building today in India is lot of highways, seaport, airport and associated structures which for example if you are talking about any highway or any seaport you will also construct a lot of associated structure around these main structures and that means if you do not make sure that the structures which you are building today is of high quality. Eventually if they start exhibiting severe corrosion then you will actually have significant repair and maintenance cost. It will be a huge economic burden, so we have a huge task today in making sure that these existing and new structures will actually be able to meet the desired service life or in short they will be durable enough.

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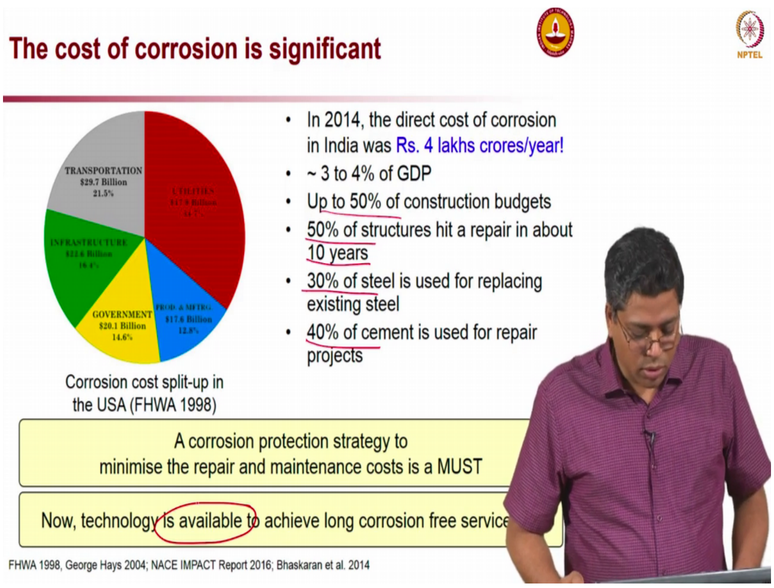

Let us look at why we think that corrosion is very significant? Like this is the statistic on like in 2014 the cost of corrosion was Rupees 4 lakhs of crores per year, so that is very high cost which is proximately equal to about 3 to 4 percent of GDP and some other statistics which I would like to highlight here is you know about 50 percent of the construction budget goes to handle corrosion, not only corrosion but repair related issues okay and some of them are actually you know when you talk about large projects you even see that you know some portions which are built earlier actually experiencing damage because of various tissues. Now another statistics is 50 percent of the structure hit a repair, a major repair in about 10 years, so when they are actually designed for several decades if you are actually expected to repair them in just 10 years it is not something which is pleasing to hear.

Now another thing is 30 percent of the steel including the structural steel which is manufactured is actually used for replacing the existing steel that means that much of repair work is actually happening and 40 percent of the cement which is used is used for repair projects, so these are very large means very large quantity of steel and cement is used for repair projects, so we have really cut down this type of expenses and so we need a corrosion protection strategy to minimise the repair and maintenance cost for the existing and new structures which we are building. Now we have technology to actually achieve this, the point is how successful we are in implementing these technologies that we have to see and we have to educate on that.

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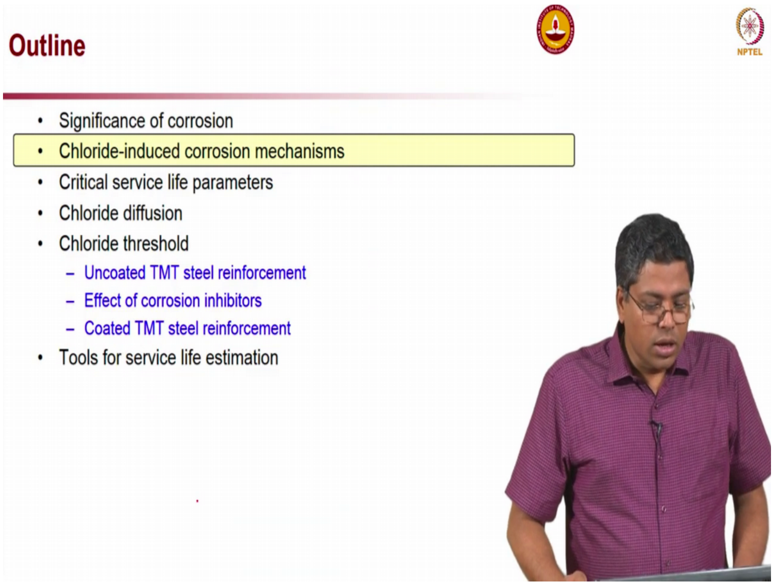

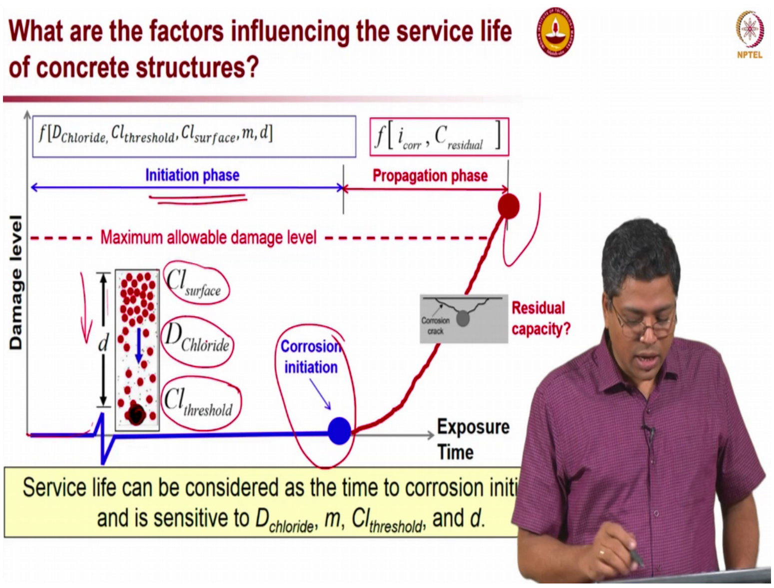

Now what happens when we talk about corrosion in concrete structure, so we will see you know first we will look at what is that service life or how we defined service life usually? So what we do usually is we defined service life as the time taken from the construction until the corrosion initiates, so this is a time when the corrosion initiates. Now if only horizontal (()) (7:17) you have, exposure time and the ordinate you have damage level, so this is the time. Let us say in a typical structure this could be 30, 40 or even 100 years, now after that the structure will continue to corrode and then this eventually you will start seeing spoiling and that is the real end of the service life means without any.

So after that you may also repair the structure here but there will be a time when there is…it is better to replace the structure and not to continue to use that structure or repair. Now this presentation I am going to focus mostly on the corrosion initiation phase which is the blue curve here which will see, blue region or the corrosion initiation phase because where you talk about new structures if you want to enhanced the quality this is the best thing to do is, delay the onset of corrosion. How do we do? Use better quality concrete and better quality steel, so that is the idea here.

So what happens when a structure is exposed, this is a cross-section of RC element or reinforced concrete element, so you can see that this d indicates the depth of the concrete or clear depth for the steel, concrete cover and this black is the rebar and then you have chlorides…the concrete structure is supposed to chloride, so chlorides defuse from the surface towards the steel reinforcement, so 1 parameter to you know quantify that rate of diffusion is this, chloride diffusion coefficient and another parameter which is important is this surface chloride concentration for example if we have a structure which is exposed to directly to sea water you have much more chloride than compared to a structure which is exposed to airborne chlorides which may be or far away from the seashore and things like that.

Then another parameter which is very important if this chloride threshold which is a property of not only the steel but also of the steel concrete interface, so it is very important and it is not just a property of the steel but both the steel and the cementitious system actually influence the chloride threshold. So if we have quantitative estimates of these deficient coefficient, chloride threshold, cover depth and chloride at the concrete surface, we can actually estimate the service life.

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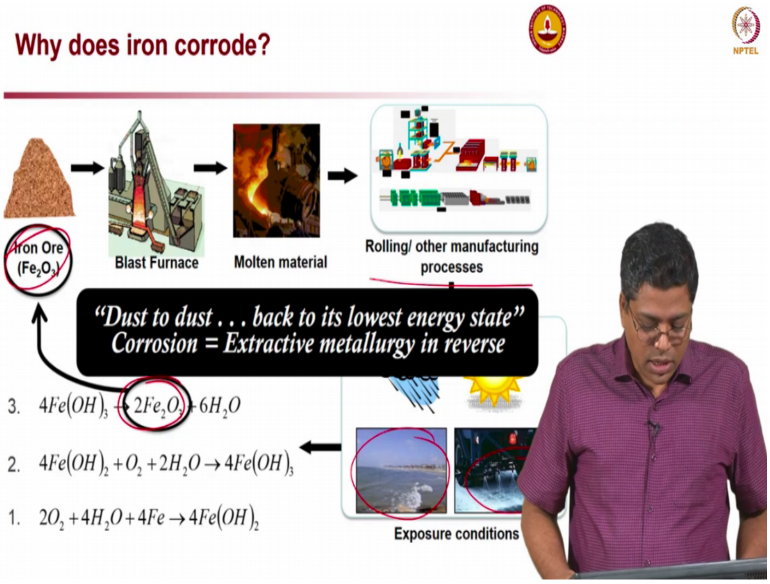

First why iron or steel actually start corroding when we put in the concrete structure? So how do we make iron or the steel, how to make it is from the iron ore you actually take the iron ore and then heat it in a blast furnace that means you are actually introducing more heat energy into the system and after that you actually roll it to a particular shape which you talk about or may be rebar or a structural steel section whatever that is, so you are actually imparting some mechanical energy into the system and after with you who will use the steel in the concrete structures and which will be then exposed to either moisture or sunlight or even chlorides, the focus of this lecture is chloride.

So what you see here is coastal region were you have even airborne chlorides are there and the picture here is basically deicing salt which in some parts of the world they actually especially when you talk about cold weather conditions you have to actually use deicing salts so that you can drive on roads, so when this steel is exposed or steel concrete system is supposed to moisture or temperature or chlorides they undergo some chemical reactions which we can call corrosion reactions like the one which is shown on the screen and eventually the end product of this reactions it will have something very similar to iron ore or Fe2O3 which you can see here, this is very similar to iron ore there, so corrosion can also be explained as extractive metallurgy in reverse or can also be defined as extractive metallurgy in reverse direction.

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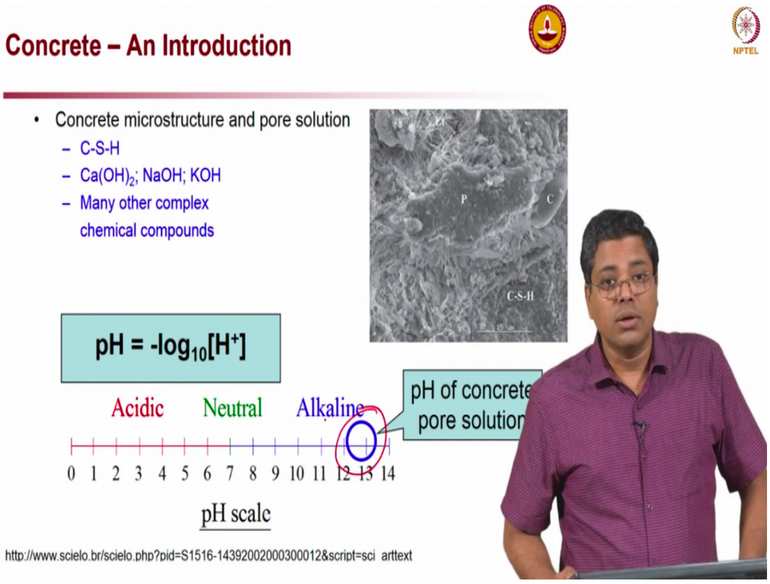

Now why we are able to actually use steel in concrete? Because concrete has a peculiar property that it has a very high pH. An uncontaminated concrete will have very high pH which is about 12 or more than 12 and that is the reason why we are actually able to use steel and concrete because at this high pH steel does not corrode or it is very protective when the pH is very high like this.

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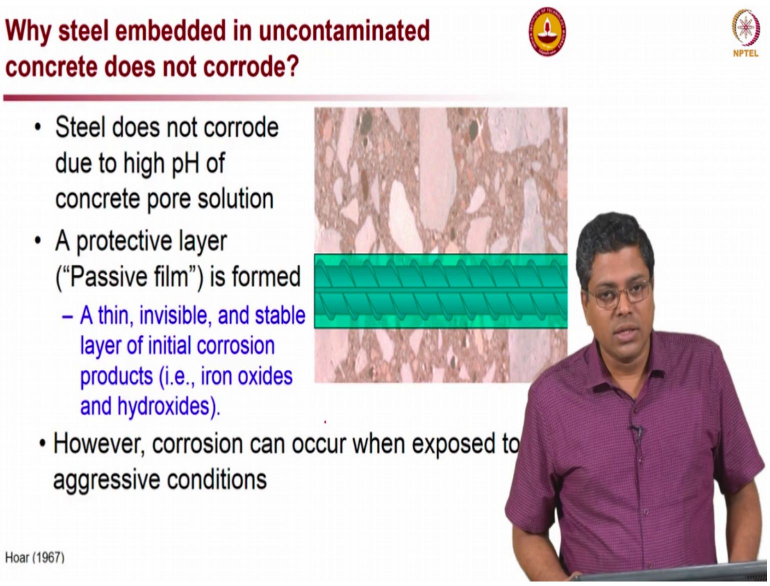

Now what happens is in real structures you will see that there will be some kind of contamination pH will drop or that is when you talk about especially carbonation induce corrosion pH will drop which will lead to corrosion. When you talk about chloride induced corrosion, the chlorides will reach this tale and then damage or break the passive film which is formed at the beginning. So the moment you immerse the steel in concrete or cementitious system you form something called a passive film which is basically the initial corrosion products but that has oxides and hydroxides of the particular metal which you are talking or the steel here in this case and that will be able to protect the steel from further corrosion. Now when you have chlorides coming into the picture that chloride will actually damage or break this passive film which will lead to corrosion.

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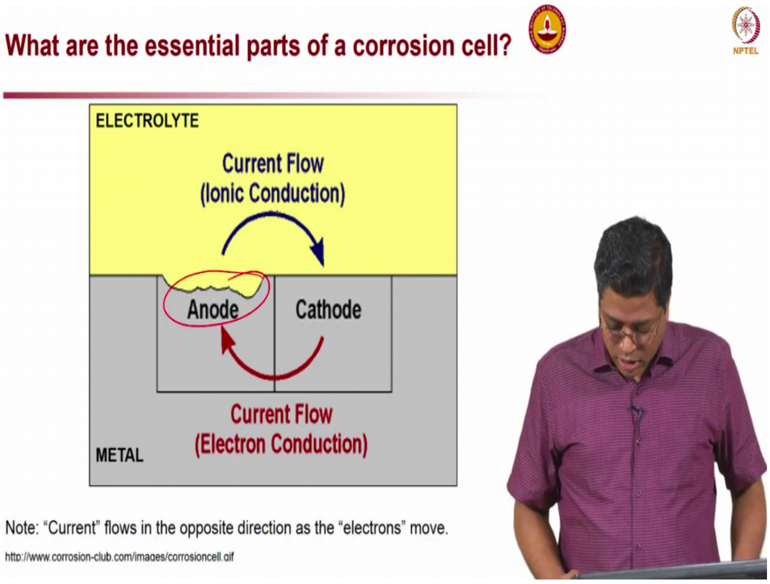

Now what are the essential parts of a corrosion cell? Whenever you talk about any type of corrosion especially in reinforced steel concrete system or (())(13:32) corrosion you have to have these 4 elements one is you have to have an anode which is the part of the metal which is corroding and the cathode which is helping or assisting the anode to road and then you also have to have a conductive component which actually help the electrons charge or the negative charge to pass from the anode to the cathode and then you have current flow for the ions were you are talking about the exchange of ions in case of concrete we are talking about hydroxides ions to move, so you have to have an ionic flow, an electronic flow and an anode and cathode which are electronically connected, so these are the 4 essential parts.

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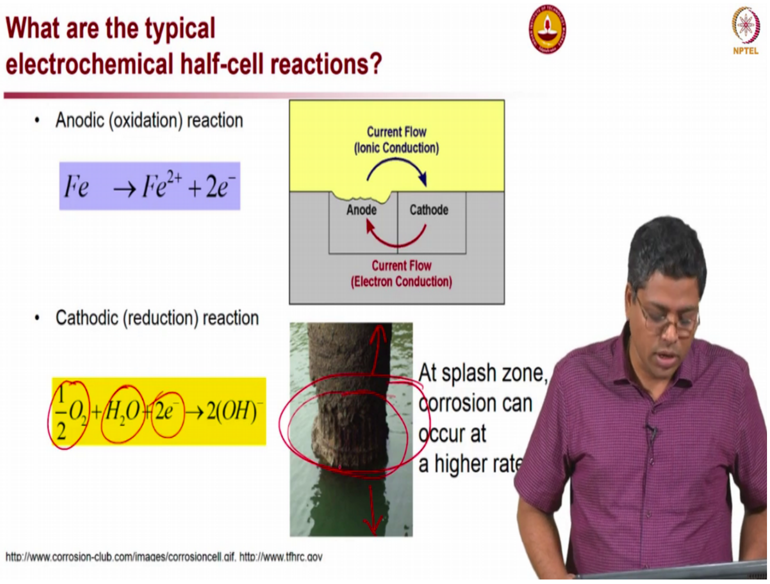

Now what happens when we talk about corrosion, what happens at the anode and what happens at the cathode? The blue equation over there it shows the dissolution of metal ions, so you have the iron atoms which is dissolving into Fe2 plus and 2 electrons are released and what happens is these 2 electrons are absorbed at the cathodic site where you have sufficient supply of oxygen and moisture, so you can see oxygen, moisture and 2 electrons that forms the hydroxide ions at the cathode side.

Now the picture here I showed in most concrete structure what you see is this is a pile coming out of water body you can see that the more corrosion is happening right where the pile comes out of the water body. Why is it happening is that is a lot of wetting and drying action happening there and plus because of the wetting and drying you actually ensure that both the oxygen and moisture are available at this location. Sufficient amount of moisture and oxygen are available because of that you have accelerated corrosion there.

As you go deeper into the water body you will see that there will be less oxygen and more moisture because of the deficiency of oxygen there will be less corrosion as you go up you will see that there will be more oxygen available and less moisture available, so you see less corrosion on either, as you go away from the water body you will see less corrosion, so the splash zone or this interface region where it just comes out of the water and that is the region which we have to really focus on because that place like a critical section for any concrete structure which we talk about.

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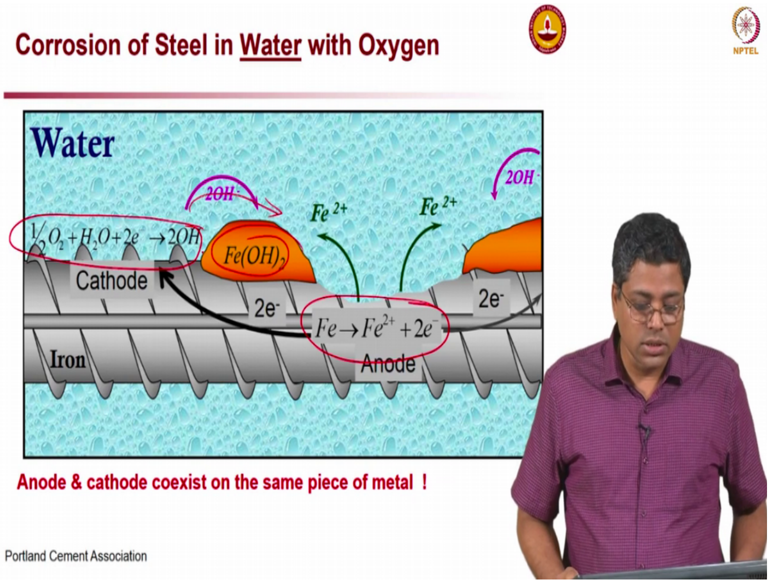

Now corrosion of steel in water with oxygen here you have a steel rebar immersed in water just to explain the same equation which I explained in the previous slide what happens can see here the anodic reaction and see here the cathodic reaction and then you can see the hydroxide ion more towards the anodic side through the water and then you have rust forming right next to the anode right there rust is getting deposited, so this is same equation what we just discussed in the previous slide.

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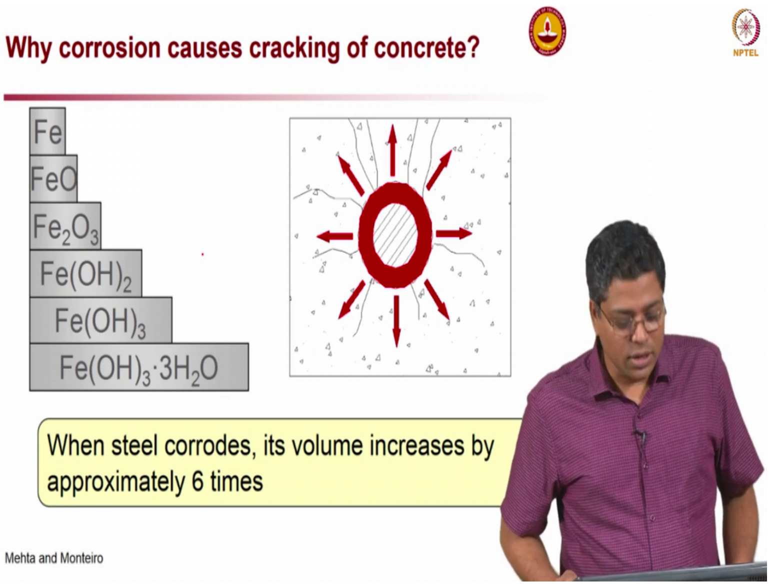

Now when you have corrosion in concrete you always see that there is a lot of cracking, concrete gets cracked. Why it happens is because steel when it corrodes it expands by about 6 times. Now the concrete has very low tensile strength because of which it tends to crack, so you have this expansive force and if the pressure exerted by the steel is more than the tensile strength of the concrete it will start to crack and this is very common and this is one reason why we are actually sometimes able to see corrosion or dictate corrosion visually because you start seeing the cracks and then through the crack the rust will ooze out and then you can actually see that, so one way it is good but other way it is bad because then whence you have the crack then more chlorides or moisture can penetrate into the concrete all so but anyway there is expansion following which the concrete starts cracking.

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Now demonstration of this picture which we can very clearly see there is a lot of bulging of the concrete over here, concrete is bulge there because of the expansive forces by the steel inside, okay.

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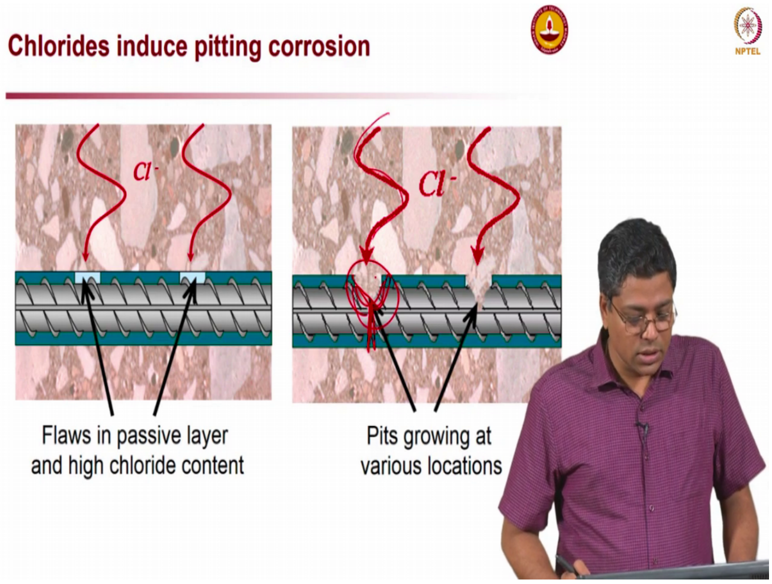

So now other very peculiar phenomenon of chloride induced corrosion is that it leads to pitting corrosion where, that means the corrosion is very localise and you can have pits form on the steel surface for example here you can see the chloride is penetrating towards the steel and the significant section loss right here. Now when you talk about structural analysis you have only this much amount of steel left, so the remaining this much is lost actually so it is not that good thing to see because if you have uniform sectional loss then it is relatively easier to detect the problem and you can actually do an assessment and here it is very difficult to assess what is the residual capacity of the structures because you have this pitting which is happening at random locations, so it is very difficult to assess the residual capacity because of this.

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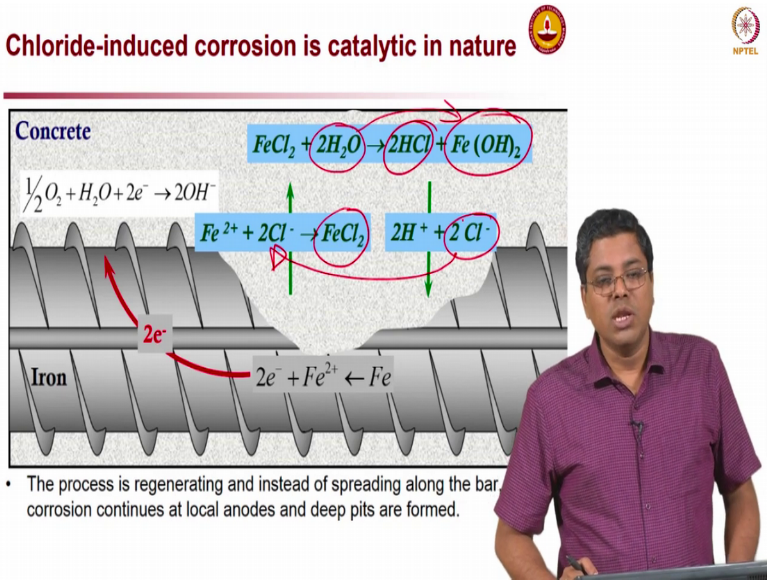

Now how this pitting happens or what is the reason for this is when you have no rights reaching the steel you will see that they actually. Once the amount of chloride available is more than the chloride threshold they will react with the steel and then you have this ferrous hydroxide which is formed right here. Now what happens is along with this ferrous hydroxide you also have HCL which will precipitate near the steel surface and then you will have the same chlorides will be available for the steel for further reaction.

So in other words this chloride is again used by another you know iron atoms and you have ferric chloride which is again ferric chloride which will then if there is sufficient moisture available react to produce more ferrous hydroxide, so you have this more and more ferrous hydroxide forming using the same chloride ions available, so that means that once the corrosion start you do not need additional amount of chlorides for continuing this reaction, so because of this it makes it very important to prevent the chlorides from reaching the steel because once it reaches then there is a difficult to stop unless you use techniques like cathodic protection and other like chloride extraction and things like that but for when you talk about new structures we should think of how to minimise the entry of chloride towards the steel.

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Now this is an example showing how this pitting corrosion looks like, so here you can see that these are the pits on a prestressing strands very clearly there is a significant corrosion here but as you move little bit away there is no corrosion here, so it is very clearly shown that it is not uniform corrosion, pitting corrosion happens and that is much more dangerous than other forms of corrosion and here on the deform rebar also you can see some region where there is significant corrosion and here there is no corrosion, so there are different…so you have to see where pitting is happening and then you have to assess or analyse with that thing in mind.

Now other thing which I would like to explain here is how the corrosion induced cracking happens in prestressed concrete structures and in reinforce concrete and the picture on the top right, this one this is how it will happen in prestressed concrete structure, what will happen is first the initial corrosion which is formed will actually fill these spaces between the wires of the strand and then only after that it will start exerting pressure, so it will take significant amount of time before you can actually see the rust coming through the concrete cover and so visual observation should not be or will not be a reliable tool to see corrosion when you talk about prestressed concrete structures whereas in this case of reinforced concrete structure you have the rebar and as soon as a little bit of corrosion is happening it tends to crack the concrete, so you can actually see the rust stains from outside, so that is a good thing about reinforce concrete but it should not be used as a tool for corrosion detection in prestressed concrete structures.

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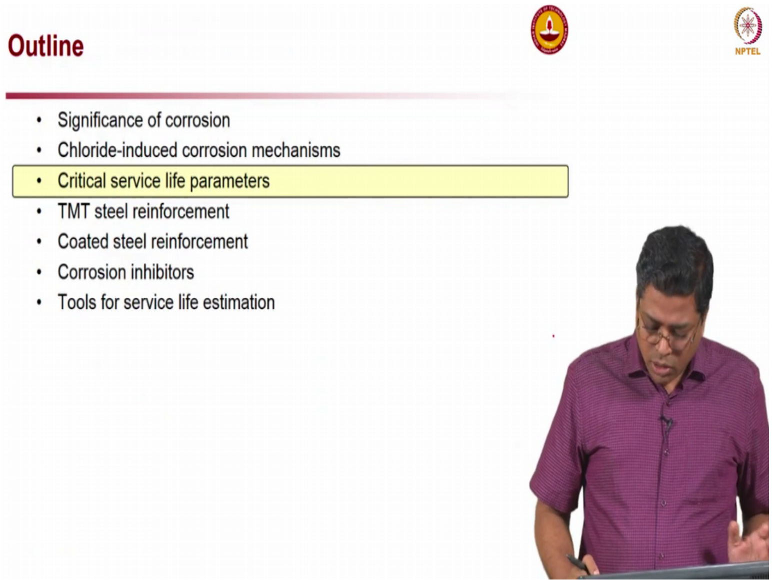

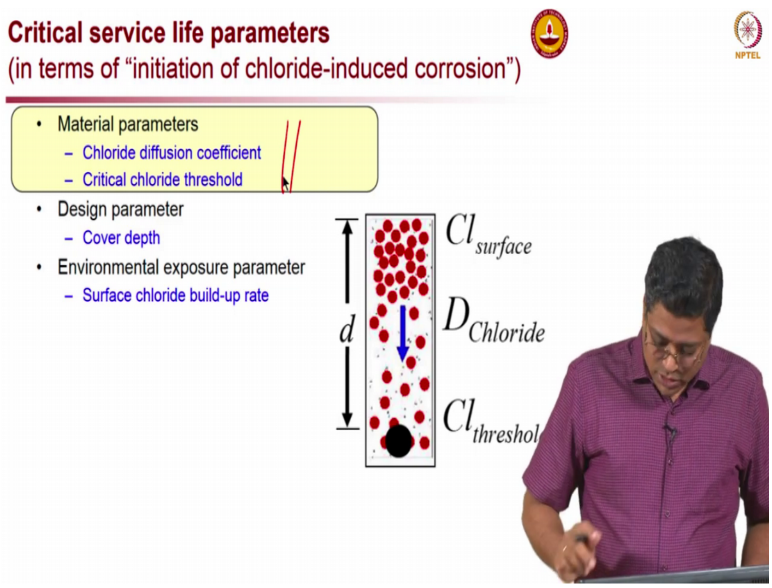

Now let us see what are the critical service life parameters? So it is associated with the… Either it could be a material parameter or it could be your design parameter on an environmental parameter. Material parameters are the focus of this module here where we will talk more about chloride diffusion coefficient and chloride threshold or critical chloride threshold and design parameters are covered depth and how fast you know the surface chloride build up happens on the concrete surface. So those 2 we are not going to focus on but we will focus on these 2 parameters in this module so 1st we will talk about chloride diffusion coefficient.

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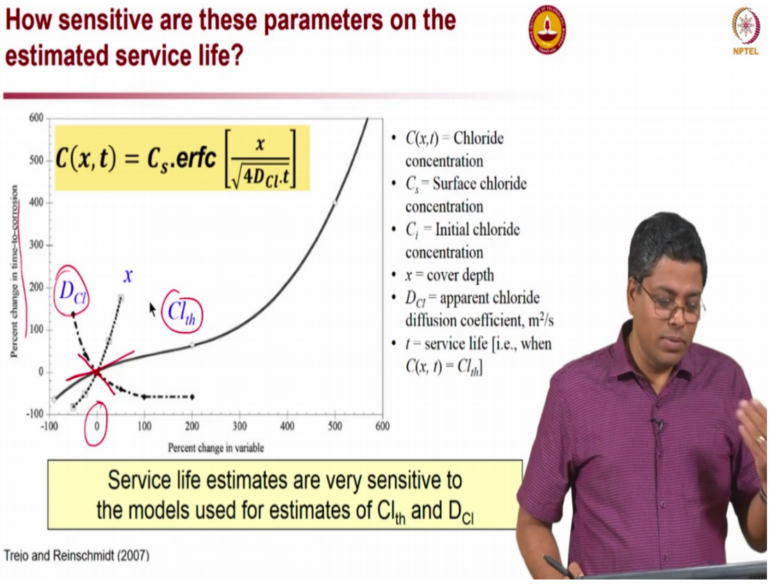

Before that let me also tell you how sensitive this parameters are, so here you can see the chloride threshold, so how you read this graph is? If you have a particular point here let us say 0, so if I deviate let us say if I talk about the slope of each of these curve about 0 for example this chloride threshold if the slope is smaller than the slope for the deficient coefficient here okay do not look at the direction there but the magnitude of the slope if you look at, so what it means is the effect of chloride threshold is actually less than the effect of deficient coefficient in this particular case.

So in other words if it moves a slight change from this point, any of the parameter you will see a significant percent change in the time to corrosion initiation, so slope of this curve above that 0 axis that is what about this origin we can say, that is what it is supposed to be looked at, more the slope more sensitive that parameter will be, so in these 3 cases you can see that covered depth is very sensitive, then the deficient coefficient and then the chloride threshold.

However when you talk about different systems you cannot keep on increasing the cover, so you have to really look at this and this which are more or less in our control when you talk about materials for choosing, even we can do this at the design stage there is towards the end of the lecture, we will show you some slides were we can show you some tools by which we can actually see how sensitive these parameters are for the particular cases you are dealing with and that way you can decide the materials during the design stage itself.

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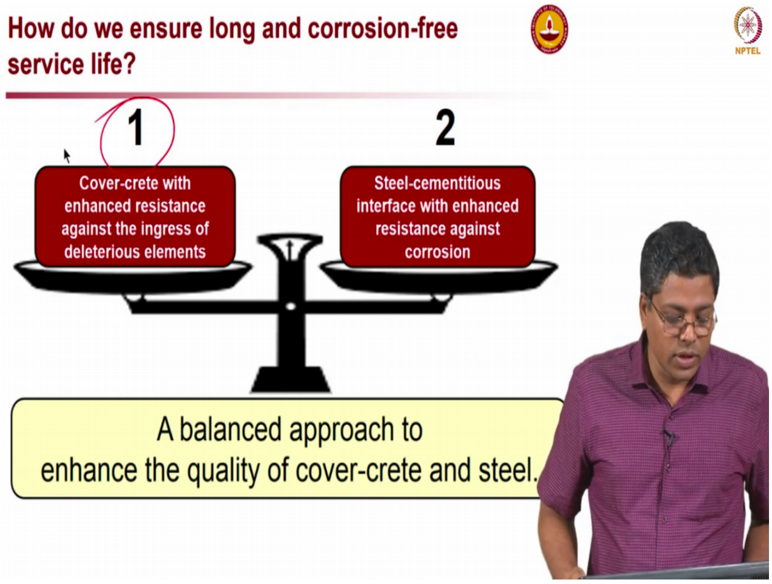

Now how do we ensure, so like I discuss from the very beginning you have to worry about both the concrete and the steel, so when you talk about concrete cover it is the deficient coefficient of the concrete cover and when you talk about the steel and cementitious system it is the chloride threshold of the steel. So we have, for achieving a longer life you cannot just focus on only one of this thing, you have to worry about both and what we recommend is a balanced approach to enhance the quality of cover and steel. So we will focus on the 1st part which is mainly on the diffusion coefficient of the concrete, chloride diffusion coefficient.

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So here how we can determine this chloride diffusion coefficient, so the 1st picture shows that you can take the chloride powder sorry take the concrete powder from the concrete structure, you can see there is a plastic bag here, so in which the powder is being ground and collected and then you can do some chemical test on that powder and then you can determining how much chloride is available at various depth within the concrete which will then be used to determine the diffusion coefficient.

I will show that how to do that in the coming slides and then on this…if you are not talking about an existing structure if you talking about the new structure or even if you are talking about concrete course which are extracted from the existing structure we can determine the diffusion coefficient by immersing them in some chloride solution and immerse them for about 35 days and then after that you determining the chloride profile, so what you do is you take the cylinders, either it could be a lab prepared cylinder or it could be a cylinder which is core from the structure, immerse it in chloride solution then you grind and collect this powder at various depths in the concrete.

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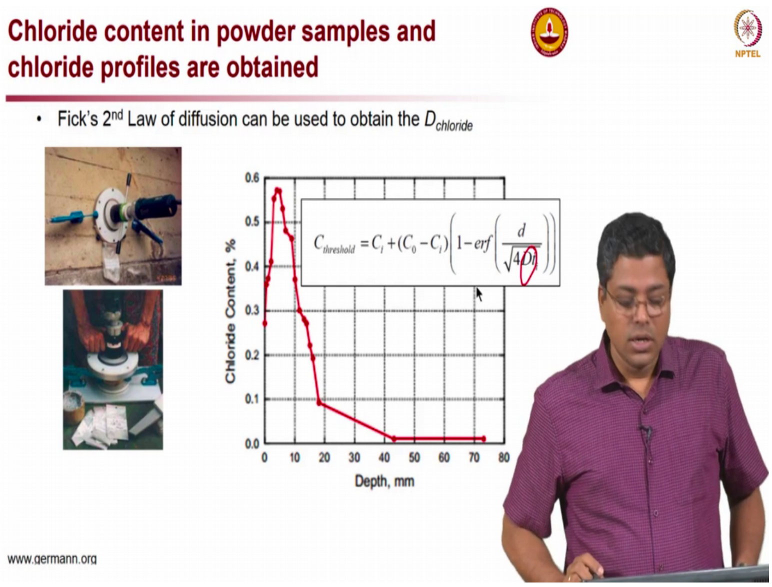

Then you determining, you plot the chloride content versus the depth in the concrete then this is Fick's second law, you Fick this curve to this whatever the data which you collect, you Fick that to the Fick's second law equation and then you determining this value here, what is deficient coefficient? Because you know the time at which you are collecting the data, so you can fit it and then find exactly what is the diffusion coefficient?

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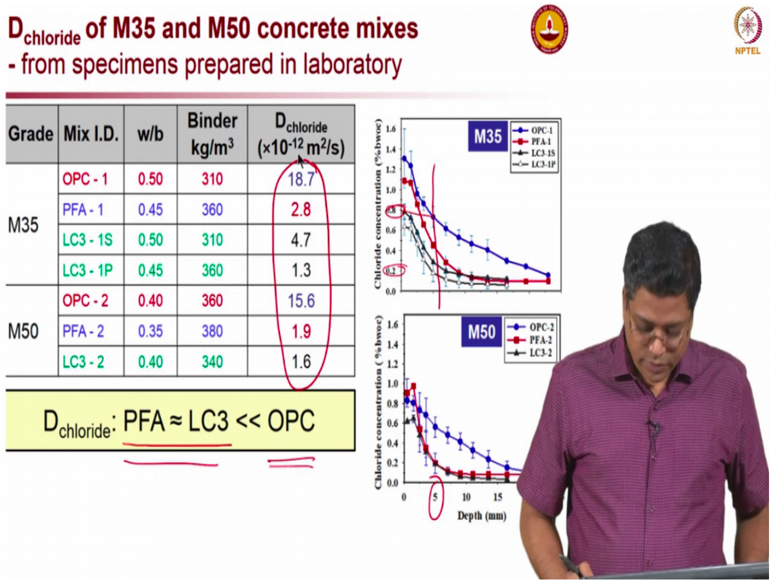

And now this is some examples which we did it in our lab, you can see here the blue curve here is for OPC concrete and then the red curve here is for the fly ash based concrete and then the black curves are for new type of concrete which is made out of LC3 cement Limestone Calcined Clay Cement and you can see that the slope of the curve, the rate of change of the slope is different for this different type of concrete and at the same time the position in other words in the OPC you have much more chlorides than.

So let us say this depth here if you look at in OPC you have about 0.8 is the amount of chloride whereas in LC3you have only about 0.2 at that particular depth of 5 millimetre inside the concrete, so this is very clearly showing that you have actually the type of concrete which you use, the rate of ingress of chloride will definitely change or can definitely be changed, so essence of this graph is that both fly ash and LC3 based concrete you have similar rate of ingress or deficient coefficient whereas in OPC you have much faster ingress of chlorides, so these are the numbers which can be used, these are the deficient coefficient which can be used for predicting the service life. Now I will show because all the time you cannot really determine things in the laboratory or prepare the concrete in the labs, so this could be a case where you are talking about constructing something new where we can prepare the samples in the laboratory and then see how good the concrete can be.

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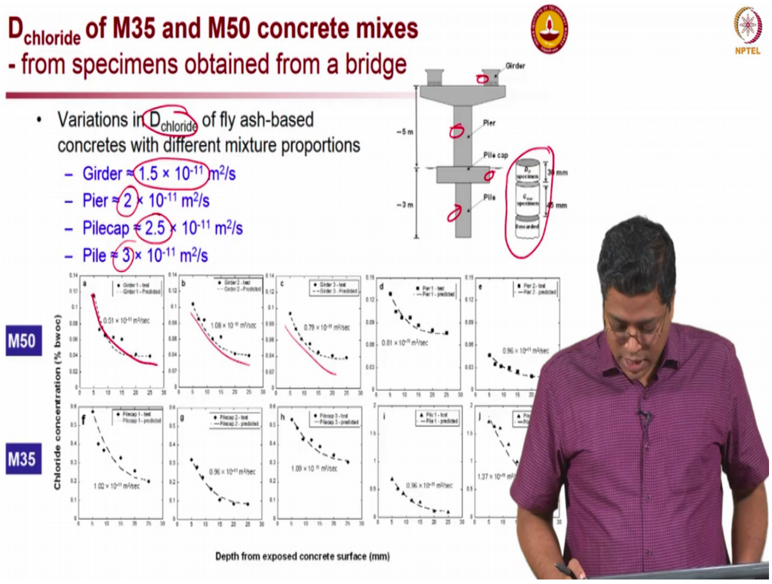

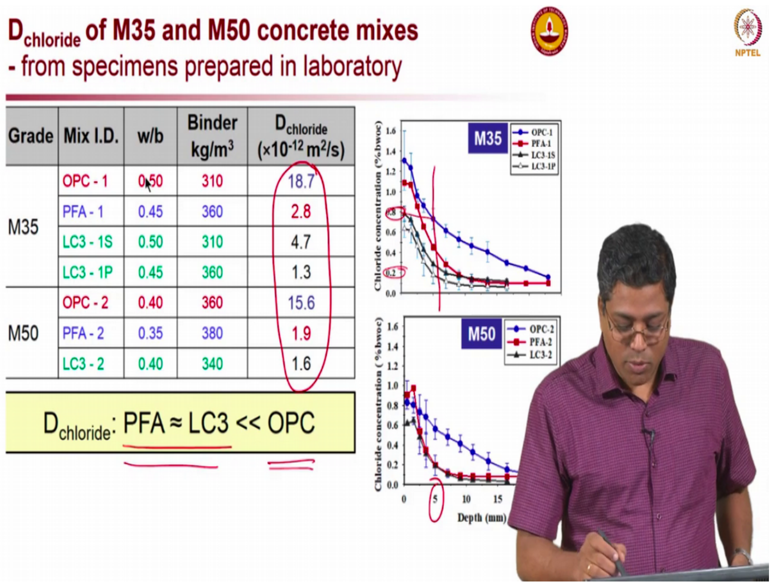

Grade	Mix I.D.	w/b	Binder kg/m³	$D_{chloride}$ ($\times 10^{-12}$ m²/s)
M35	OPC - 1	0.50	310	18.7
	PFA - 1	0.45	360	2.8
	LC3 - 1S	0.50	310	4.7
	LC3 - 1P	0.45	360	1.3
M50	OPC - 2	0.40	360	15.6
	PFA - 2	0.35	380	1.9
	LC3 - 2	0.40	340	1.6

But if we are already talking about some structures which are already existing, how do we do? We first go to the structure and then you can actually core some cylinders from here or from, if you are talking about pile you can go from here, you can go from the girder or even pile cap whichever the structural element you are talking about you can core cylinders and then, so you take cylinders like this from the structure then you do the same test which I talked earlier like this immerse in the chloride solution and then do the grinding and then determine the chloride profile.

So you can see here on the bottom the chloride profiles and then these dashed curves, these dash curve indicates the fitted curve for the Fick's 2^{nd} law of diffusion and then based on that you determining the chloride diffusion coefficient, so these are numbers which you can see, in this particular case which we studied it is actually a bridge in major city in India, so you can say that for the girder your deficient coefficient is this much about 1.5 times 10 to the power of minus 11 whereas in the case of pier it is 2 in the pile cap 2.5 and 3. So what it is showing is there is significant variation so you can design because the cover depth used on these different elements could be different, so you can actually design the structure in a way, the different element of the structure can be designed considering the deficient coefficient and the corresponding concrete cover and so that you really reach the target service life.

Now we also see a lot of scatter and you will notice that if you look at the graph earlier you have much better looking graph here because this is done in the laboratory and with very well controlled specimen preparation whereas here you are talking about the actual data which we get from the structures in the site, so you would expect a little bit more scatter and that is one more important thing is where most of the software which are available today for service life estimation they tend to use a predefined standard deviation or the variation in these properties.

So we will show later that we have incorporated how to actually deal with the standard deviations which could be user defined. If you see that a particular type of structure you have much more standard deviation then you can actually plug in of course it will lead to more variation in your predicted service life but that is what is reality, so you have to actually consider the actual standard deviation on this parameters otherwise it will not be realistic.

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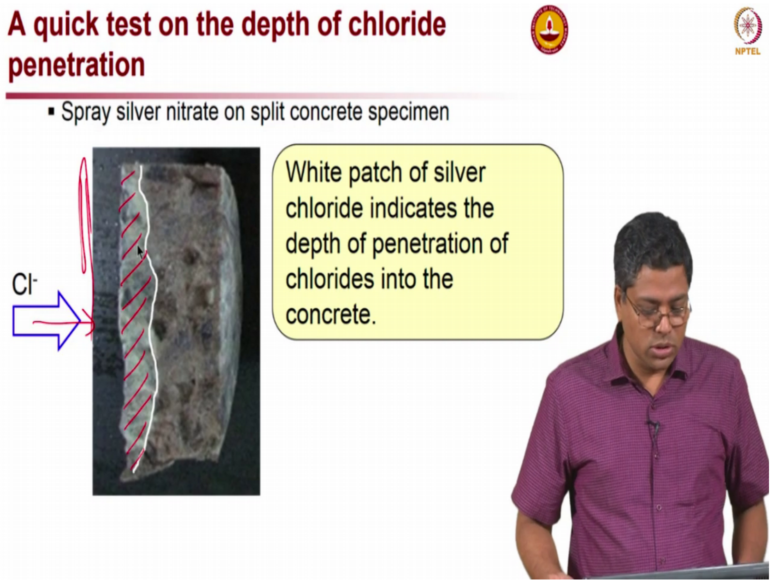

Also sometimes you know you may not be able to lot of chloride grinding testing and all that, so there is a simpler way of how to see how much chloride or what is a depth of chloride penetration, so this is a picture showing a split cylinders were chlorides … Let us assume that this side is the surface of the concrete then chlorides are penetrating towards the right in this and then you take this is a cylinder and split the cylinder into half and then you spray silver nitrate on the fracture surface and what will happen is if there is chloride on the surface, the silver nitrate will react with the chlorides available and it will form silver chloride which has a white color, so you can clearly see that this is the region or the depth to which chlorides have penetrated which is simpler way of checking what is the depth of chlorides in any concrete. Once if you know that there is significant depth then you can actually do more sophisticated studies.

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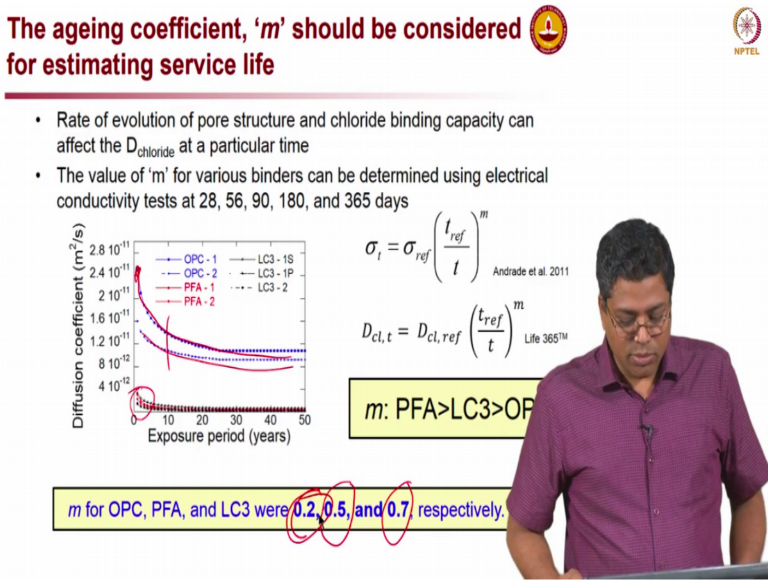

Now one another thing which is very important when you talk about diffusion is this chloride diffusion that value keeps changing as the concrete microstructure keep changing and also it is all depends on how much chlorides can be bound to the concrete or the cementitious system. So what you see here is the blue curve shows how this change in diffusion coefficient for an OPC system would be, so you can see here that when I talk about after about 10 years I see that deficient coefficient is very different than what it was in the year 1 okay for a normal curing condition which you talk about and exposure.

Now but when you talk about the other types of either fly ash or LC 3 type concrete you do not see much difference that means that this decay constant or the ageing coefficient for this 3 types of concrete are different or binders are different. For OPC you can say 0.2 would be a good number but for fly ash based concrete it could be 0.5 and for LC 3 type concrete it could be 0.7. So point here is these numbers are very important or M should be, M we call it aging coefficient, it should be considered when you try to estimate service life. In other words it is not just you cure the specimens for 28 days and then take the deficient coefficient and then along with that you also have to see how the change in the deficient coefficient would be as a function of time which can then be used for service life estimation.

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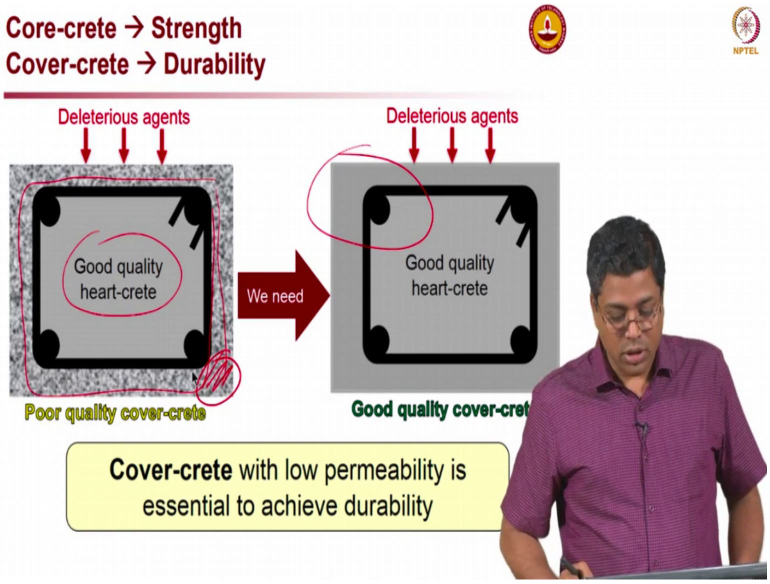

Now we talked a lot about how to estimate chloride diffusion coefficient and you can actually design or mixture proportion come up with a very good mixture proportion which will give you a very good diffusion coefficient in the laboratory. Now in the site when you go and if you do not cure the concrete properly what you will see is, the concrete which is outside the stirrups or this concrete that concrete will be of much poor quality compared to what is inside the stirrups which is good quality.

Why it is happening? Because you are not providing sufficient water for that cover crete to cure and develop the microstructure, so what we need is something like this where both concrete inside and outside the reinforcement cage is of good quality. Now how do we get that by ensuring that you have very good curing practices at site, so that is something very important and it is not just having good quality materials and you know a good mixture proportion it is also a matter of how well you cure the concrete then only you will be able to achieve the desired durability.

So cover concrete with very low diffusion coefficient or very low permeability is what our target should be. When you talk about durability we have to really worry about the cover concrete and not, I am not saying not to worry about the core crete but we must worry about the cover concrete that is very important when you talk about durability. With that we end the part 1 of this module on chloride induced corrosion and service life of reinforced concrete structures.