Advanced Topics in the Science and Technology of Concrete
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Chloride induced corrosion and service life of reinforced concrete structures Part -2

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Welcome to this NPTEL course on advanced topics in science and technology of concrete systems, so this was the part 2 of the module on chloride induced corrosion and service life of reinforced concrete structure. So we will focus as we discussed earlier we will focus on the steel cementitious system and how the interface place a role in enhancing service life.

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So we will be talking mainly about the chloride threshold, so in the previous part 1 we covered chloride diffusion coefficient and today we will talk about chloride threshold. We will be covering mainly how the threshold of the uncoated steel reinforcement can be estimated and then what will be the effect of corrosion inhibitors and what is the effect of coated reinforcement and through these discussion we will also cover different types of test methods which are available, which we developed because all the test method cannot be adopted for all these materials, so we will see what are the challenges associated with different type of steel and then associated testing for chloride threshold. Then we will also cover some tools for service life estimation.

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So in today's market we use different types of chemical inhibitors sorry corrosion inhibitors and supplementary cementitious materials and different type of steels, coated rebars all these are used in today's market as a measure for enhancing service life. However before we start using these materials in large-scale we must do a test on how really the effect diffusion coefficient and chloride threshold, so in this part we will focus mainly on the chloride threshold of these different steels cementitious system.

Chloride threshold testing for various systems

- ACT
  - Systems with plain OPC
- mACT
  - Systems with OPC, SCMs and chemical admixtures
- sACT
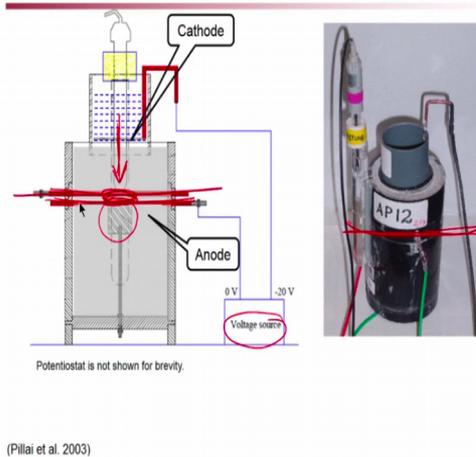 - Systems with OPC, highly resistive SCMs, and chemical admixtures

So first I will talk about accelerated chloride threshold that is the ACT stands for accelerated chloride threshold which was developed or determining chloride threshold of OPC systems without any inhibitors but we found that there were some challenges in using that test method for systems with chemical admixtures mainly corrosion inhibitors and later we found that you know when you talk about highly resistive supplementary cementitious systems.

For example, Limestone Calcined Clay Cement and fly ash in some cases and corrosion inhibitors it will be not clear that easy to adopt this method mACT we had to actually modify the test method and then come up with more suitable test method for determining chloride threshold of highly resistive systems, so I will walk you through these 3 different testing and the results which we obtained from these tests and how those results actually influence the service life.

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ACT test using the linear polarization resistance (LPR) technique

Cathode

Anode

0 V   -20 V

Voltage source

Potentiostat is not shown for brevity.

(Pillai et al. 2003)

Now first accelerated chloride threshold testing this was originally developed as part of my master's thesis then what we used was linear polarisation resistance technique and you have this test specimen how it looks like and then here you have motor filled mould with steel specimen inside and you have anode and cathode system which is connected to a voltage source and when you apply 20 volt across this it is going to drag the chlorides towards the steel from their pond on the top.

And what we do it this will continuously check the corrosion rate using the technique called linear polarisation resistance and when there is a significant change we break this specimen here along this line and then we determining what is the or if you talk about here you will break the specimen along this line and then right at the surface or the motor which is adjacent to the steel we will check the chloride concentration of that motor which will be defined as the chloride threshold. So you drive the chlorides towards the steel keep testing the corrosion rate and then when it initiates break the specimen right here and find what is the chloride concentration of the motor in this region here and that is defined as the chloride threshold of that particular steel in any system.

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Linear Polarization Resistance (LPR) Technique

$$i_{corr} = B/R_p = \frac{B}{(\Delta E/\Delta i)_{E \to E_{corr}}}$$
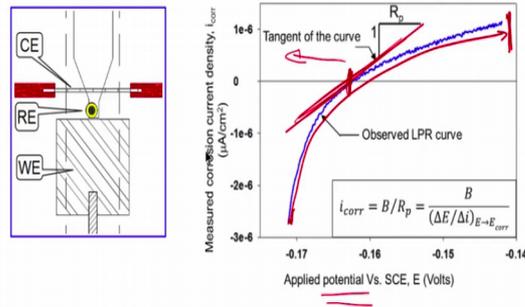
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So here how you do that is how you determining this corrosion rate is by conducting this linear polarisation resistance test or LPR in short where you actually take a specimen and then you apply some potential, very small potential so originally when you talk about specimen you have something called open circuit potential or e core and from there you push the specimen or you induced some potential so that the, Current you will see that as specimen, ideally they should start from here but that is not the real case.

Anyway, so you push the specimen here and then you start sweeping from here till like this all the way up to her and then what you do is you take the slope when it crosses the 0 current line or current density and then that slope indicates the corrosion rate, so higher the slope means that the corrosion rate is higher. So like there is after every application of voltage to drive the chloride towards the steel what you will do is? You will do this linear polarisation resistance test and you will determine the corrosion rate or inverse polarisation assistance 1 by Rp so which is actually equivalent to a corrosion rate.
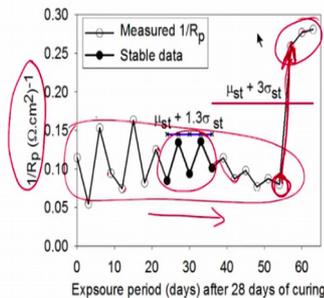
So then you plot this 1 by Rp or corrosion rate. This represents the corrosion rate, so you can see that these are all different corrosion rates which are been obtained after every application of or after driving some chlorides towards the steel using an applied electrical potential and then we came up with the statistical method on how to detect that there is a when there is corrosion happening, so you can see that all these numbers are actually more or less similar and then you also determining there is something we defined as a stable corrosion rate where that means the corrosion rate when there is no significant corrosion happening or when there is only passive corrosion I mean no active corrosion happening.

Then after sometimes you will see that these are all, as you go towards the right the amount of chloride at this steel surface is slowly increasing, now at this point you will see that there is something happening and you have a significant increase in the corrosion rate and what it means is there is something happened to the amount of chlorides at the steel surface and we define that is happens when the chloride concentration at the steel surface achieved or reached the chloride threshold then so what we do just 2 - 3 extra test you have to do so that you can form that this is actually, you know corrosion has initiated and it is continuing to corrode. At this point you take you open the specimen or autopsy the specimen and determining the amount of chloride at the steel surface.
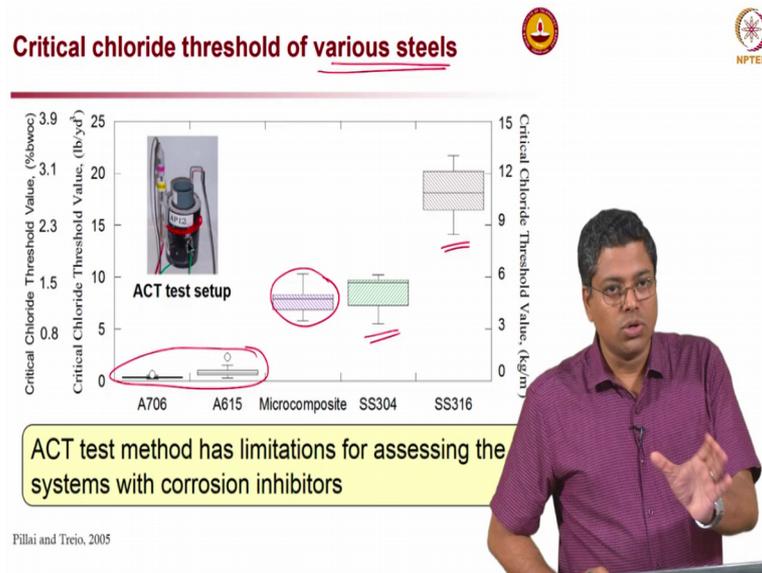
So for example you open the specimen right here and then you open it and determine how much is the chloride and that surface. So by that way we determining chloride threshold and you can see the chloride threshold for different types of the can be very different for example these 2 are the typical steels which are used in the market and then we also had special type of corrosion resistant steel which we called micro-composite steel and then you also have stainless steel rebar of different types. In India we do not use the stainless steel rebar much but mostly we use these type of you know A706 or A615 type steel or steels which has very similar chloride threshold.

So point of this slide is that the type of steel which we use will definitely is an influencing parameter on our service life because they will exhibit different chloride threshold, so if we do not use stainless steel because of the cost implications we can at lease use some type of corrosion resistance steel which will actually provide a larger chloride threshold and exhibit a larger chloride threshold and hence longer service life.

However this method you know in uses that potential application to drive the chlorides towards the steel hence it has some limitations when you talk about systems which has corrosion inhibitors or any complex system where there is lot of negatively charged ions which actually helps in controlling the corrosion or in other words when you do a test, the test itself should not change the property of the steel and cementitious interface.

If you apply the voltage that means it is actually driving more chlorides towards the steel surface and in that process it is also driving other negatively charged ions towards the steel
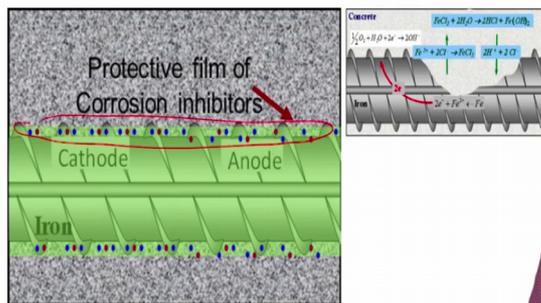
surface and if you do that what you are doing is at the beginning of the test you have different steel cementitious interface, the property is different and after some time you will see that the material has changed because of the application of the voltage which is not a right way of testing. In other words the test method should not alter the steel cementitious system.

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So we went, then also there are requirements of accessing the chloride threshold for the effectiveness of different type of inhibitors which are available in the market. So this is just a picture showing how this inhibitor works, corrosion inhibitors mainly used for new type of structures where this chemicals or corrosion inhibitors are mixed with the new concrete and then they are supposed to form a protective film at the steel surface or they are supposed to control the rate of half-cell reaction.

What they do is they consume the oxygen and then if sufficient oxygen is not available for the half cell reaction then you will not have corrosions, so that is 2 different ways of protecting the steel by use of different type of corrosion inhibitors. Now there are a lot of inhibitors available in the markets and when you talk about service life you have to guarantee that these inhibitors will work after some period of time that means they will work when there is a possibility of corrosion initiation which is probably after 20 or 30 years or in other words these metres start functioning after 20 – 30 years, so there is a need for…we cannot wait for 20 - 30 years to check whether an inhibitor will work. So we have to have a short-term test method which could be let us say 2 - 3 months or even up to 6 months during which time we can actually see whether their inhibitors are of good quality or are they really effective in controlling corrosion or in extending the onset of corrosion.

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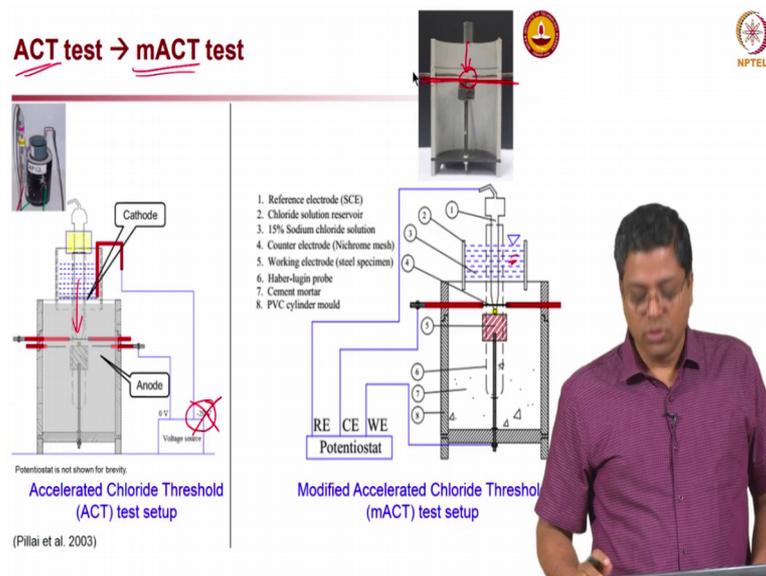
Now so what we did was from ACT accelerated chloride threshold we went to modified ACT, what are the modifications which we did? So this is on the left side you see a sketch or schematic of the ACT test setup where we used to have 20 volt application of 20 volt to drive the chlorides towards the steel from the reservoir this blue line indicates the reservoir. What we did is, we wanted to avoid this application of voltage to drive the chlorides, so we reduce the cover depth a little bit and we did not use the voltage and this is mainly from Jayachandran's work and so what we did was reduce the cover, avoid the voltage and at the same time increase the concentration of chloride in this solution.
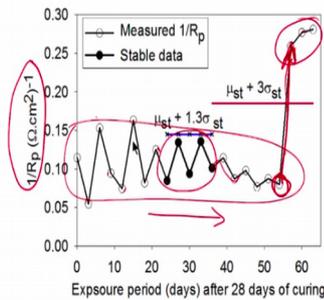
So with all these we could actually get the testing done in $2 - 3$ times. One more thing to note here is when you talk about corrosion inhibitors you are talking about a system which will resists corrosion for a higher amount of chlorides that means it is going to take longer period of time for achieving that time, and test method will actually be longer if you compare with a system with no corrosion inhibitors, so this was the challenge and we have to do everything in short period of time, so here you can see so the chloride will penetrate from here through diffusion it will penetrate, steel is here and then we will have the testing and then once the sufficient chlorides reached you will be monitoring like in the ACT test method we will be monitoring the amount of chloride at this plane at this plane here and then do the same test.

A statistical approach to detect the corrosion initiation
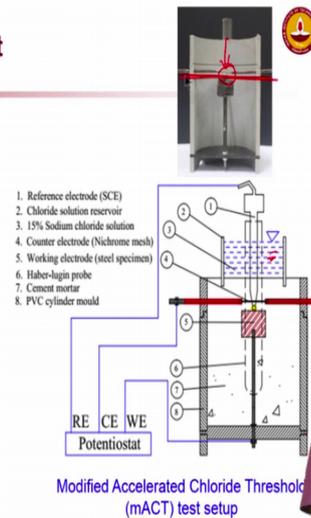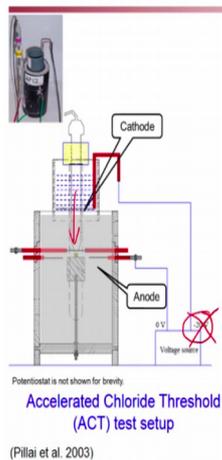
- $(\mu_S + 1.3\sigma_S) \rightarrow$ stable data
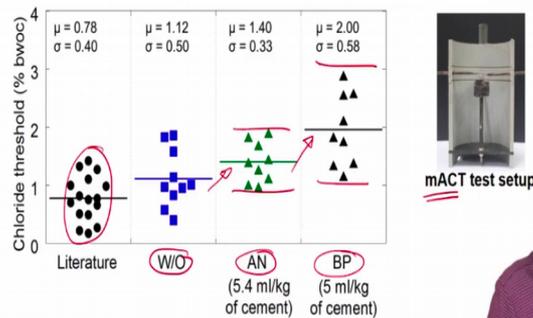- $1/R_p > (\mu_{st} + 3\sigma_{st}) \rightarrow$ corrosion initiated

ACT test $\rightarrow$ mACT test

1. Reference electrode (SCE)
2. Chloride solution reservoir
3. 15% Sodium chloride solution
4. Counter electrode (Nichrome mesh)
5. Working electrode (steel specimen)
6. Haber-lugin probe
7. Cement mortar
8. PVC cylinder mould

Accelerated Chloride Threshold (ACT) test setup

Modified Accelerated Chloride Threshold (mACT) test setup

(Pillai et al. 2003)

I am going to show you how, similar method as we did in the, like this so similar way we will do the same test and then you see when that significant increase, the significantly reason in the corrosion current or inverse polarisation resistance and based on which you will do… Similar test after that, after this we will just do some chemical test on the motor powder which is collected from adjacent to the steel in the specimen. So motor powder from this level and then do the test.

So with this we determining the chloride threshold of without any inhibitor that is plain motor which is more or less similar to the values reported in literature not that different from this blue 1 black I would say look at these scatter also and then you have anodic inhibitor and bipolar inhibitor which are widely available in the market today so we tested and we found that anodic inhibitor exhibits slightly higher average value and also when you talk about bipolar that is also slightly higher in the chloride threshold.

You can see that there is a band if you look at here this is the band so there is an increase in the chloride threshold when we use bipolar inhibitors which is widely used in the market today. Now…so idea here is we have now a test method which can determine the chloride threshold for systems in about 3 to 4 months, so that 3 to 4 months for the systems with corrosion inhibitors and this was done in OPC base system or ordinary Portland cement based system. Now there are other systems available in the market which I will show you later.
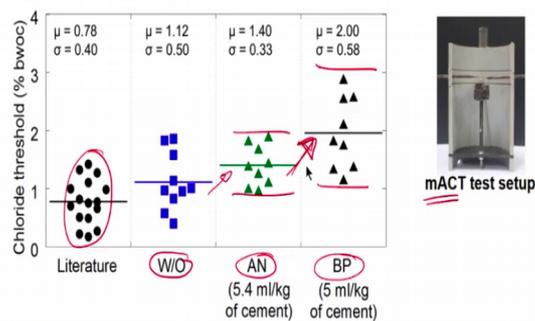
Effect of corrosion inhibiting admixtures on corrosion initiation time (say, service life)
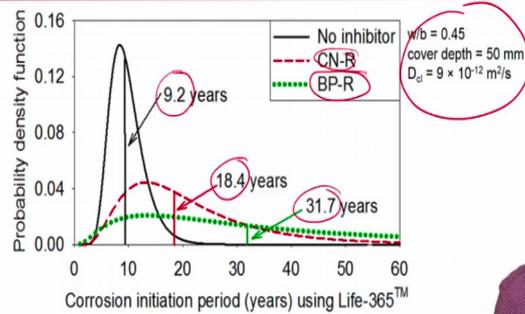
The appropriate use of corrosion inhibitors can increase the corrosion initiation time by about 2 to 3 times

Change in $Cl_{threshold}$ of TMT/QST steel with the addition of corrosion inhibitors

mACT test setup

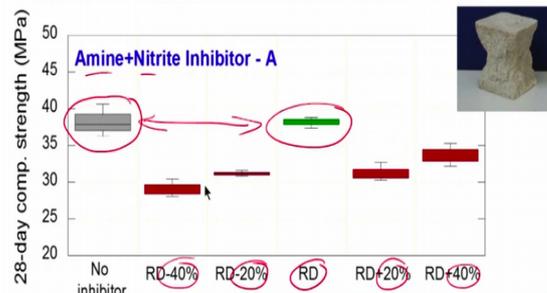Cl_{th} ranges from 0.8 to 2 % bwoc with an average of 1.5 % Test duration ~ 3 to 4 months

% bwoc : % by weight of cement

Now with that OPC system with corrosion inhibitors how this increase in chloride threshold here what it means to the service life or how it as influencing the service life, so you can see here if you have an OPC system without any corrosion inhibitor you may have 9 years of service life. Remember that there are some assumptions for the entire analysis, so it is not, for the same system how it is different that is what the point here is and if you use of calcium nitrite based inhibitor you can have a life of about 18.4 years which is almost doubled compared to 9.2 years and if you use bipolar inhibitors you can have life of about 30 years, so it is a significant increase from in using a corrosion inhibitor, you can easily get about 2 to 3 times. Only catch here is you have to make sure that this inhibitors are actually used in the right dosage.

So that is something here where we looked at how change in the dosage which will influence other properties of the concrete because when we talk about corrosion inhibitors usually the trend is to check the effect of inhibitors on the corrosion properties but we also should look at how that material which is mixed with the concrete is influencing the properties of the cover concrete or the core crete also because you are going to mix that with everything about cover and core concrete are going to be having this corrosion inhibitors.

So one example here is an inhibitor with both Amine and Nitrate it was mixed and then this box here indicates with the inhibitor at the recommended dosage, as recommended by the manufacturer and when you do not have any inhibitors this is the graph more or less these are same there is no statistically significant difference between the grey box and the green box it is more or less same compressive strength, however when the recommended dosage was changed to less than, to minus 20 and minus 40 percent than of the recommended dosage and plus 20 and plus 40 of the recommended dosage there was significant difference or reduction and not just difference, significant reduction in the compressive strength. Now this is not something which is good, so you must check the effect of integral inhibitors on the properties of the concrete. The first property which anybody would check it as compressive strength, so to that test first.

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But we also found that there are, it may also affect the durability related properties or transport properties, one example here I am showing is the water Sorptivity Index, so here how we do is you take a disk of concrete and then you place that in a small water bath not immersed but just place like this what is shown in the picture and then you see how much water is absorbed by the, because of this option by the concrete disk.

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So what you see here this you have the control that means without any inhibitor and the recommended dosage of inhibitor for this case of inhibitor A you see significant increase in the Water Sorptivity Index, so this is not something which is good, so you have to see and we could find some other inhibitor where there is no change, so for example here you can see no

change in the Water Sorptivity Index but it is not in a good category concrete anyway, so you have to see all these things have to be thought through and tested before we really accept and use corrosion inhibitors but definitely it has an improvement and it can actually enhanced the corrosion resistance or chloride threshold in particular okay.

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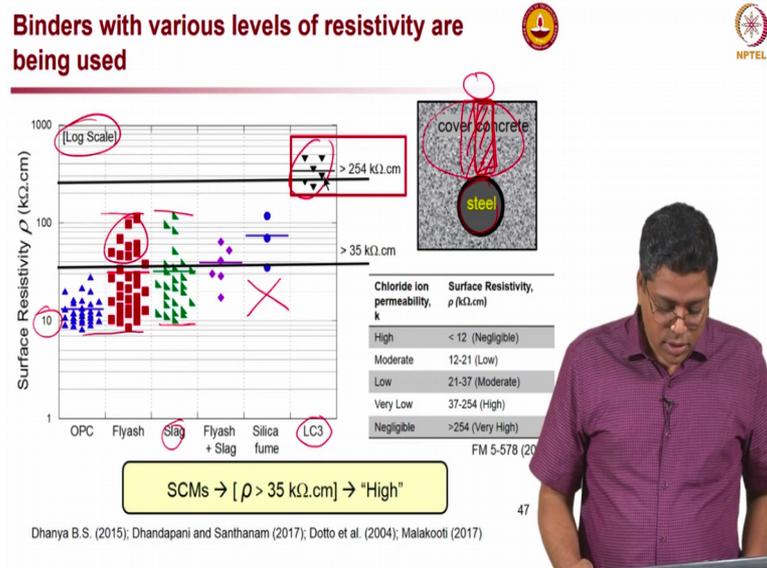
Now today, so that was about the first talked about ordinary Portland cement system without any inhibitors then we talked about how we can check OPC system with inhibitors. Now the new trend in the market is using a lot of SCM's okay and also low water cement ratio, SCM's low water cement ratio and maybe we will also use SCM with corrosion inhibitor, so things are becoming more and more complex. Now here when you talk about SCM the main property which is changing is the resistivity of the concrete system, so you can see her steel and then you have a cover Crete which is now with SCM.

If you have very high and most of the time when you do the testing your testing systems are kept here outside the, or the electrodes we talk about it as all actually outside the concrete. Now what the property of this concrete here will actually influence the measurements which you take when you talk about electrochemical testing, so what we are looking at is how this resistivity of this concrete here actually affects the testing and results, so what we found was the earlier test method were not able to reliably estimate the chloride threshold, so there was a need for a development of a new test method which will kind of take care of this resistivity of the concrete cover.

So here you see OPC, this is in log scale so here OPC concrete you can see about 10 kilo ohm cm is the resistivity, fly ash you have something from there but a large range you know that means there are fly ash concrete which can have high resistivity and most OPC concrete, it will not really, I mean it will be very difficult even if you use a very low water cement ratio you may not see very high resistivity for the OPC-based concrete.

If you talk about slag again you have something very similar to fly ash and if you talk about silica fume actually the lower band is there is no…the resistivity is much higher compared to fly ash or slag. If you talk about LC3 it is all in a completely different range your one order of magnitude different, so you have very wide range of resistivity when you talk about different type of SCM or concretes with different type of SCM, so we are trying to develop a simple test method where you can actually catch the specimen in a relatively easy manner and at the same time get a reliable estimate of chloride threshold, so SCM lead to high resistivity

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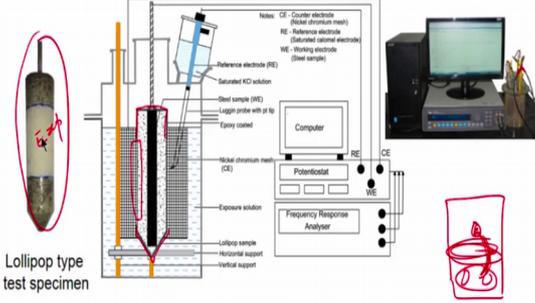
So we started with ACT and then we modified that for corrosion inhibitors and now we are modifying the tests for incorporating highly resistive SCMs concrete with highly resistive SCMs. Now you can see this is a simplified specimen just as a lollipop type specimen, cylinder specimen with one single rebar, now you may be aware of test method called ASTM G 109 which is having a specimen will be something like this which has 3 rebars like this and then you look at what happens between this rebar and this rebars so where you talk about a macro cell corrosion but what we have found recently is that you know when you talk about highly resistive systems you do not have you know exchange of you know current across these because this material here is highly resistive in nature.

So what you do is, you usually see microcell or corrosion will be happening on the same bar there is no electrical circuit between different bars when you talk about highly resistive system, so this specimen with single rebar will really work for testing highly resistive system, so this is how the specimen looks like so you have some portions here are coated for defining the expose region which is this portion here which is this, so this is your exposure region okay. Now similar test setup but the technique used is different here we are using electrochemical impedance spectroscopy instead of linear polarisation assistance because linear polarisation assistance even though it is difficult to, there are some techniques which are not really working when you talk about steel cementitious system but in an aqueous system it might work.

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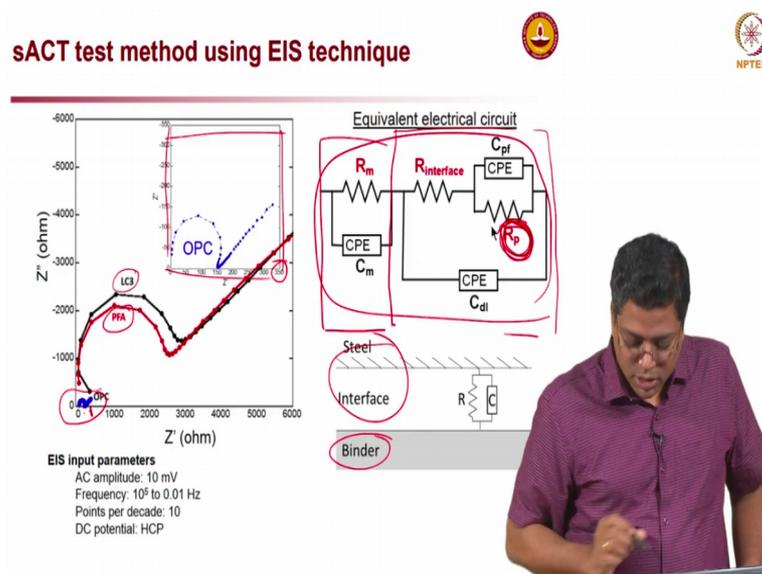
So here we found that our assistance is very different so this is the electrochemical impedance spectroscopy technique and how the Nyquist plot look like you can see here this is the plot very small plot for OPC type systems. This is expanded here, this portion here you can see that the changes only up to 350 over here it is about 350. Now we talk about fly ash-based concrete or LC3 based systems you are seeing much different, the curve is completely different than range you are talking about this also completely different because of the high resistivity of the binder system.

Now how do you use this technique to determining the corrosion rate, so essentially in the previous slide also I have told that invoice polarisation resistance is what we try to obtain and which is related to the corrosion rate. So here you have an equivalent circuit which has one of the compound and as polarisation resistance, so from this what you do, you collect this CIS

data and then fit for this particular equivalent electrical circuit and then we determine by curve fitting to determine what is the Rp. Once you determining the Rp then you can use the other methods statistical approach on determining whether the corrosion has initiated or not, so here you can see a schematic of this diagram here. This portion here as much is actually representing the binder and then this right side of this is representing the steel cementitious or that interface region okay and then by curve fitting you determining what is the polarisation resistance.

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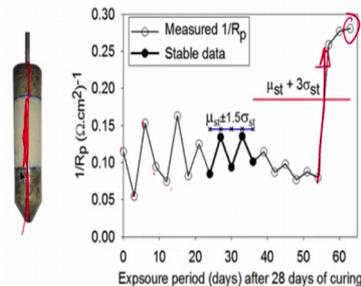
Now once you get the polarisation resistance like that like the same curve I showed earlier you in mind when there is a significant increase in the Rp and then at this point you break the specimen and then you split the specimen across this line and then you will see the rebar there and then you take the motor from inside the… or the motor which is just touching the steel rebar and then you determining the chloride threshold of that motor powder which is defined as the chloride threshold.

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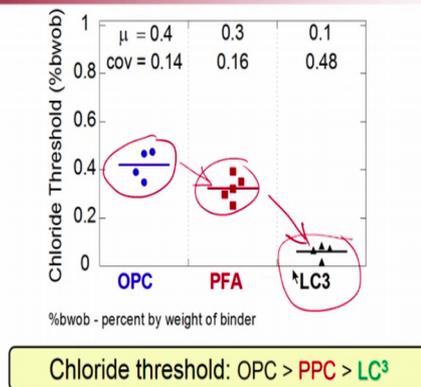
And likewise we determining chloride threshold for OPC. It was important we have to determining this because you to get something which is to verify the testing procedure, right? So you have OPC which is 0.4 which is kind of widely accepted number for OPC system and PFA or fly ash base system are slightly low chloride threshold and LC3 has much lower chloride threshold when you talk about… Using this SSET method I am calling S for simplify. So now if you are actually looking at only the chloride threshold what you will see is that you may end up in not using this concrete and not using this concrete which is not a right way because we have to use these 2 concretes for looking at the long live and more greener approach because industries is changing from OPC to other types of cement systems.

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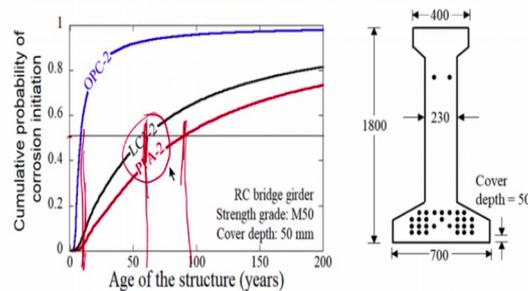
Now we have determined the chloride threshold we have determined the diffusion coefficient for various types of systems and using the determined values we looked at how these things actually affect the service life of a real structure, so we picked up one example and then look that actual cover depth which is there in the real structures and then we put in these input parameters and also m was also used diffusion coefficient and chloride threshold, m like a mentioned 0.2, 0.5 and 0.7 for these 3 types of OPC, PF fly ash and LC3 based systems. Chloride threshold also for this systems were used.
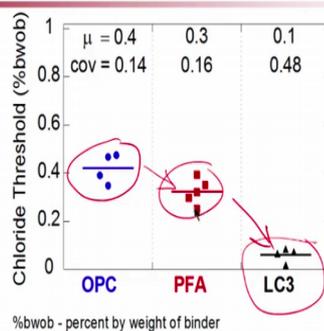
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And we found that service life can be very significantly different for these 3 types of systems and so here you look at although the chloride threshold of LC3 was significantly lower than that of PFA that is not much difference between the service life of fly ash and LC3. What it
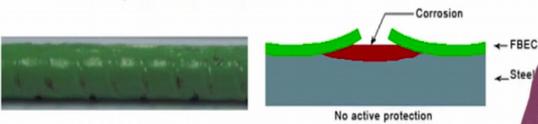
means is you should not discard a particular cement just by looking at the chloride threshold you have to look at how the threshold and the diffusion coefficient influence the service life because here LC3 system has much lower diffusion coefficient and low chloride threshold but the synergistic effect like the positive effect due to a lower diffusion coefficient and a negative effect due to a lower chloride threshold you know you had to see what is that net effect, so that can be seen through this cumulative distribution curves.

We can look at also ranking these different materials for M30 you can say PFA will give you longer life than LC3 systems which will be much longer than the OPC system, so if you look here for one thing if you can see like here if I draw vertical lines here, so I can say if you look at an average service life not been a probabilistic sense, so I can draw a line here and I can see this could be around 10 years for OPC where as I can design a concrete system with either fly ash or LC3 and it can have a life for about you know this much may be 60 and 80 years something like that so it is possible to design durable structures even if your chloride threshold could be low. For example, here we see that chloride threshold of fly ash and LC3 are lower than that of OPC but that is not really a concern when you talk about synergistic effect of both threshold and diffusion coefficient.

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Now we also have other ways of enhancing corrosion resistance of concrete systems and one way is by using a coating material, however if you do not use… If you do not apply the coating properly or if you do not handle the coated rebar properly at site you may actually end up in having a lower service life than what you would have without the coating, so I am going to demonstrate some of these issues. Again we should remember that what I am
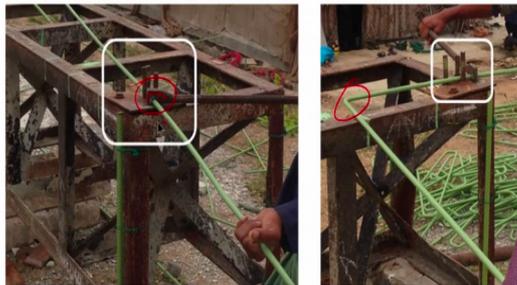
showing is issues where the rebars are handled in a poor way or not in an adequate manner, it is very roughly handled and coatings are not of high-quality but unfortunately this is the case in many construction site, so it is very important to discuss this.

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Now you can see here you are talking about bending of rebars, so we usually bend the rebars at the construction site but you know epoxy coated rebars are not supposed to be bend at the side, they are supposed to be bend before you apply the epoxy coating but as a practice this is not being done, so when you talk about this bending at site you are using a metallic tool and you have a epoxy which will get pinched or damage wherever you actually hold the rebar with this bending tool or liver

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Fusion bonded epoxy coated rebars (FBEC)

- **Fusion** bonding is necessary to ensure quality bond between the steel and the coating material.
- Epoxy should be resistant against scratching, cracking, etc. due to on-site practices
  - Scratching can happen if the bars are dragged at site
  - Cracking can happen if the bars are bent at site
- Major damage mechanism
  - Localized, under-film corrosion

http://www.srmbsteel.com/azar
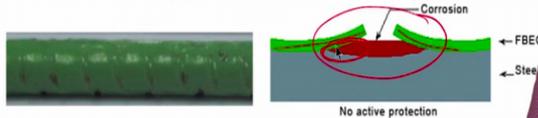
Now also if he quality of the epoxy is not that great then you can actually form cracks wherever it is bend and if cracks is there then definitely this will need to something called crevice corrosion, so this here something like this here you have a cracked epoxy layer here and here and what will happen is this region will form there will be crevice corrosion happening underneath these epoxy layer or we can even call it under-film corrosion. Now if this happens usually the practice is you apply one more coating 1 more layer of epoxy but that is also not really effective to do that.

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Poor quality FBEC steel rebars are being used in many projects...

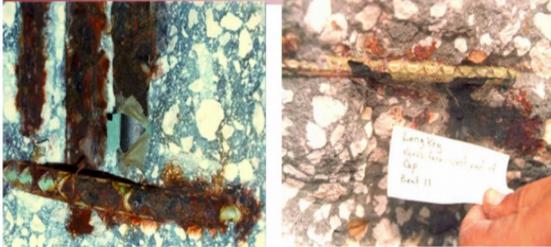It is more dangerous to use damaged epoxy-coated steel than conventional uncoated steel

Now one more picture which shows you can see here in this picture there as lot of scratches on these rebar all along the length this is from a real site and here you can see rebars which are bend and after some days this will get filled up with more concrete and you will have very

serious premature corrosion in this cases, so the takeaway here is it is more dangerous to use damaged epoxy coating steel than conventional uncoated steel because you are actually…and it is also more costly to use this coating, so you put the coating and then get an inferior product which is not really an advisable thing to do.
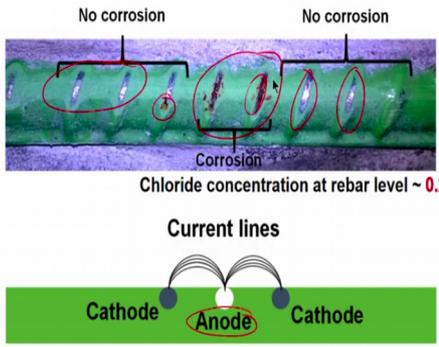
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This is an example from another bridge in Florida where this was just 5 years after the construction you have significantly peeling off the epoxy and then corrosion you can very clearly see that on the picture.

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Now how and why this happens is when you talk about scratching when you drag these rebars at sight you scratch and then you can very clearly this is actually a specimen which is extracted from a motor prism after about 1 year of exposure and you can see that the corrosion happens only on these and a little bit over here but this is very fresh very fresh no corrosion at all on these scratches.

So what is the mechanism here is some of this scratch region will start corroding function like an anode whereas ghee other regions will help in corroding the anode of further or forcing the localised corrosion to happen and in the long run what you will probably see is that once this starts this epoxy layer here will be peeled off and then this corrosion will grow underneath the epoxy and then you will have very significant localised under film corrosion which is not something easy to test because even these specimens when we test it we were not able to detect this corrosion happening by usual methods of electrochemical measurements but when you open the specimen you see that there is significant corrosion happening because that is how…because you have this coating it is much more complex than an uncoated rebar.
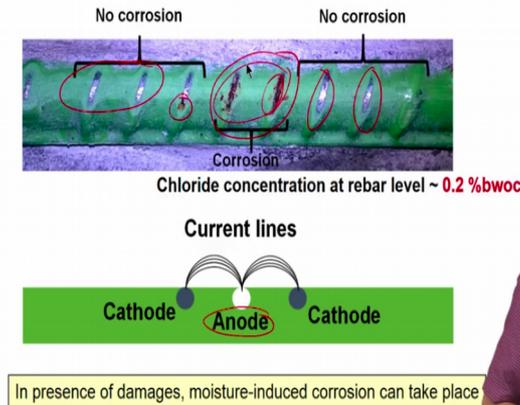
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Corrosion initiation time of systems with FBEC steel rebars

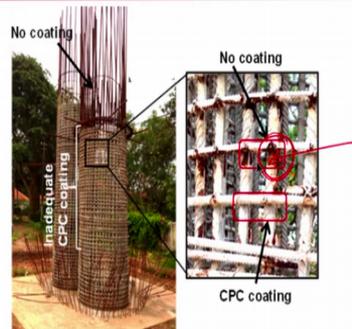• Actual chloride threshold is less than 0.2 %bwoc → overestimation
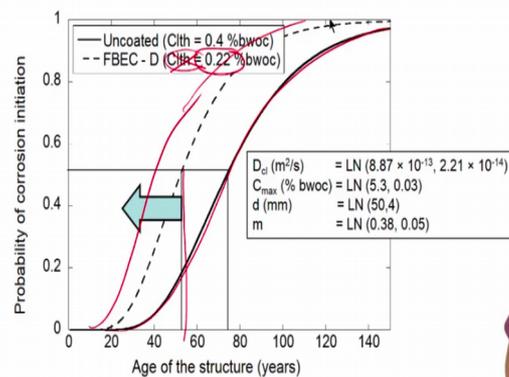
Now with the data what we did is when we open the specimens autopsy then we took the chloride of, determine the amount of chloride at the rebar surface or in the motor adjacent to the rebar and then use that number because the chloride threshold has to be at least sorry it has to be lower than this 0.22, so whatever estimation which you see if you do not use a coated rebar you will get a life of something like this okay with an average life of about 75 years but if you use the coated rebar or poorly ported you know an epoxy coated rebar with poor coating you will get a life of only about 50 years but you should not consider this as 50 because this is not the actual chloride threshold.

This is actually chloride threshold for this system is lower than what we found because when we tested it was corroded this much we could not detect the actual initiation of the corrosion, so significant corrosion was already in place so I would say this graph would be something somewhere to the left of the dash curve, so if that is the case we really have to think on whether we should use this epoxy coated rebars in many of our structures because to me whatever we learn from the lab and literature this is not right approach to use this kind of epoxy coated bar especially when we consider the type of rough handling of these bars at the site.

Now other type of coating which are in the market today is the cement polymer composite coatings, so this is a pitcher from the peer of coastal highway where right next to this, just about 500 meters you have the seashore right on the coast, so you can see that these coatings is actually supposed to be applied on the rebars after the cleaning, they are supposed to clean the rebars or you sand blast the rebar then only this CPC coating should be applied, CPC stands for cement polymer composite.

Now if you do not apply, if you apply without cleaning how it is going to affect the service life, do we really get the life which are supposed to get and another thing also to notice here is when you apply this after the cages are put you will have some regions where there is no coating at all, so here you do not see any coating and right next to it you have regions with coating, so there is a region where you can actually form an anode and cathode, so your battery can be formed right there where there is a damage in the coating. So this is also very important to notice that whenever you talk about any coating for the rebar you are supposed to have good surface preparation otherwise it may not work properly and handle that coated rebar in a delicate manner.

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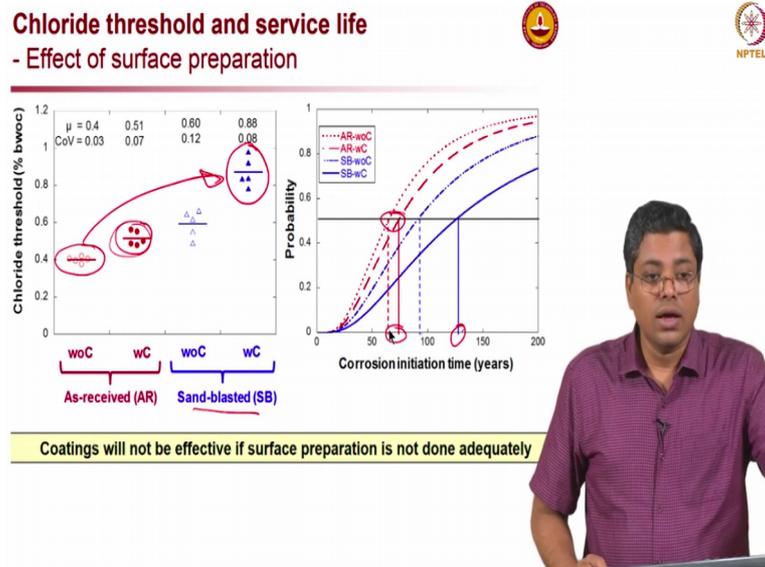
Now we did the similar type of testing for determining chloride threshold and what is showing here is you have the wo without the coating you will have 0.4 which is kind of okay number or very similar to whatever is reported in literature when you have with coating it is becoming 0.5 not much difference but the amount of money you spend and time is spend on putting this coating is significant but you do not really get much higher life because you are actually supposed to get this that means with cleaning I mean sandblasting and then apply the coating.

So ideally when you talk about CPC coating you should get something from here to here but because if you do not apply proper cleaning and proper surface preparation you will have something this which is not really useful thing to do and when you talk about the amount of money invested, so what do you see like there is not significant increase in the chloride threshold. What it means to the service life and in terms of corrosion initiation time.

So if you do a proper job in sandblasting and applying the coating you will let us say a case where you will get about 125 years, what you see is if you apply only sandblasting without any coating you will again get about 100 years but if you do not sand blast or do not clean the rebar and just apply the coating you will get almost half of the life than what was expected, so it is a very significant reduction from about 125 to about 70 - 75 years is what you are actually getting, so it is a significant reduction in the life or you do not really achieve what is supposed to be there okay.

Now some schematic also on how the properly coated rebar if you have sandblasted and properly coated rebar after exposing and then we expose the rebar and then (())(42:45) and then look at it you can see just some spots here and there indicating low level of corrosion but when you apply the coating on the, as received rebar that means there is no cleaning or no sandblasting you see significant amount of corrosion, so this is not something which is expected. If you are using CPC coating we must ensure that proper cleaning is done otherwise it is not really advisable to use it.

SL-chlor – input parameters

| Input parameters	Standard values for the input parameters(mean)	Is standard deviation considered?	Test methods to arrive at the parameter
Cover depth (d) mm	10 - 100	Yes (User Input)	Fixed by the designer
Ageing co-efficient (m)	0.2 - 1	NA	ASTM C1556-11a at 3 different ages (28, 90, 180 days)
Diffusion co-efficient (D_{cl}) m²/s	1E-12 to 1E-10	Yes (User Input)	ASTM C1556-11a
Chloride threshold (Cl_{th}) %bwoc	0 - 0.3	Yes (User Input)	sACT
Max. Surface chloride concentration (Cl_s) %bwoc	0.6 - 1%	NA	ASTM C1556-11a / NT BUILD 443
Exposure condition	NA	NA	Location of the structure

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Now we will see how we can use all this information for service life estimation not with a sophisticated software but with a simple tool like nomogram, so what we did was we created a Matlab code for using all the input parameters available and the Fick's second law of diffusion and based on…and then one important thing was this code will actually incorporate you will be able to input the deviations in various properties which we are talking about because when you talk about steel and concrete most of the properties are significant deviation.

So some of the existing software which are widely used but they do not have they do not take care of the deviation in other words they have some built-in coefficient of variations not the coefficient of variation which you might see on actual site. So we kind of modified that or developed another code which will take care of this different variation in the input parameters, so it is based on (())(44:31) work and she developed this SL-chlor and based on the sACT test we can get the chloride threshold and then chloride diffusion can be obtained from ASTM C1556 or any other method which is available basically ponding test and then also the M value for which we are considering any deviation, so just a fixed number depending on the type of binder which we use and this is also another thing, there are limitations on the existing software where you cannot go beyond particular number, so here we are trying to cover different types of binder systems.

Cumulative distribution functions were developed for various cases
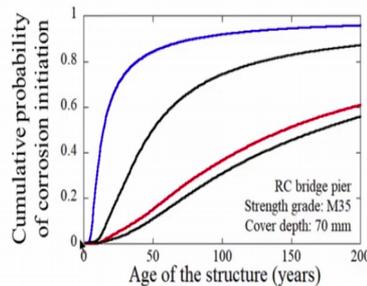
Nomogram for estimating service life during the design phases
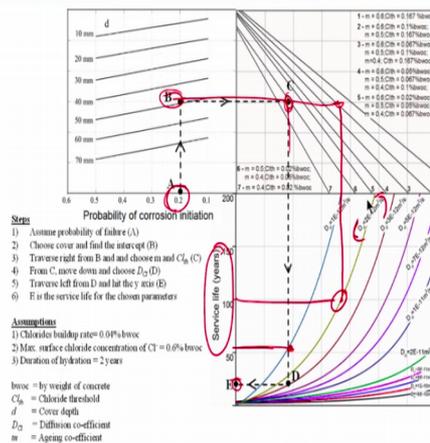
So with all these we developed several CDF Cumulative Distribution Functions for different cases and then generated many graphs like this and then picked up various points from these graphs and then developed a nomogram where if you want let us say I except a probability of corrosion initiation of 0.2 in one case and then I start from here, let me walk you through this nomogram so you have a probability of corrosion initiation then first I will see okay what is my cover depth which is acceptable, so let us say I use a cover depth of 50 mm and then from there I will see which is my chloride threshold and what is my m value, m value I can choose based on the binder which I have and then whichever chloride threshold value for the particular steel cementitious system, you pick that.

Let us say you picked this line 6 and from here to go down and then you can decide for achieving a particular life which type of concrete I should use. So for example here if I pick this concrete, a concrete with diffusion coefficient of 1 e to the power of minus 12 if I use this for this cover depth and this failure probability and the particular chloride threshold and m value picked up, I can get a life of about 50 plus years but if I get a concrete which is of poor quality let us say it is 3 into 10 to the power of minus 12 then I get only life about 20 - 25 years, so this can be used at the design table or design phase where it is relatively simple than playing with the software and entering all the input parameters.

So this is very easy for a design team to because everything all what we are told earlier has been built into this and a nomogram has been made, so I think this will be a good tool and so also we can also do another thing which is, if you have a target life let us say service life is defined, let us say you have a target life of 100 years, so you go from there then you tell what is the concrete which I want to, or which I have want to use. Let us say I pick this concrete and then I have a chloride threshold of this, so if I go from here and then I go to the top I hit here and then I can come here and then pick my cover depth so that I can decide whichever probability of failure or acceptable probability of failure.
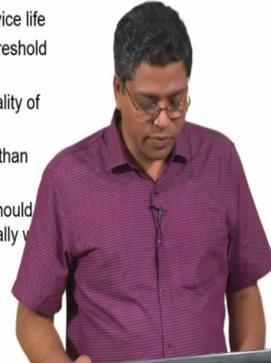
In other words here the probability of failure is probability of corrosion initiation, so this can be used either clockwise or anticlockwise for deciding on what type of material to be used or selected or you can also define a target diffusion coefficient when you talk about new construction and so if I say for whatever case I can say that whatever concrete you use I should have a target diffusion coefficient of this 2 into e to the power of minus 12 then the people at site can actually work on getting that type of concrete or a concrete which has diffusion coefficient of whatever is the defined number, so you can decide what should be the target properties of the concrete.

So conclusion, cost of corrosion is very significant we spend about 4 lakh of crores per year which is very very high number and then chlorides contributes significantly to the cause of corrosion and 2 main parameters which really influences service life or chloride diffusion coefficient and chloride threshold and when you use corrosion inhibitors and appropriate dosage is very important otherwise you may see that the corrosion initiation might, the chloride threshold might be higher but it may adversely affect the other properties of the concrete which is not a good thing so everything has to be tested before we start using corrosion inhibitors and what is the dosage had to be decided.

Then for testing chloride threshold in systems with OPC and systems with corrosion inhibitors or a system with highly resistive SCMs all the techniques do not work everywhere, so you to be able to choose right method for different type of systems and then performance of coating will be achievable like coatings will perform only if they are applied properly, in other words the steel surface should be treated very well before you apply the coating whether it is on-site or off-site and then the coated rebar should be handled properly so that there is no mechanical damage on the coated surface otherwise the performance will not be as expected and other thing is the chloride threshold and diffusion coefficient should be considered before we choose the material or in other words we should look at the effect of the synergistic effect of both chloride threshold and diffusion coefficient on the service life while choosing materials rather than deciding the material based on these are only threshold or only diffusion coefficient.

With that I think that is it, thank you very much. So the main message is when you talk about durability based designs you have to think both about concrete system and the diffusion coefficient or the chloride ingress rate in the concrete system and the chloride threshold for the steel cementitious interface. Thank you.