Maintenance and Repair of Concrete Structures
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Lecture – 35
Service-Life Estimation-2

Good morning, good afternoon or good evening wherever you are at and whatever time you are watching this. Welcome to the MOOC class at IIT, Madras. My name is David Trejo. I am here to present on corrosion on service-life of reinforced concrete structures. I really want to focus on the influence of input variables. In my last lecture I spoke about the basics of corrosion, I talked about the physical system, I talked about thermodynamics, I talked about the kinetics of the system and then I actually wrapped up with little bit on service-life and I talked about the importance of service-life and how would affects our society today if we construct structures or they short lived or they deteriorate quickly that there is a significant problem with that.

And so one of the things that I want to focus on today is, I am going to pick up the service-life, I am going to reintroduce it briefly then I am going to talk about the input variables that we need to predict the service-life. And one of my arguments is that we have been very good with modeling and computational power that we have now to model the service-life, but what we have not done is the input parameters or the input variables that we need to predict that. I will talk about this, I will talk about the influence, and I also talk about the need to a standardized some of the testing.

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What I am going to do is I am going give a brief review of a service-life of reinforce concrete structures, I am going to talk about influencing variables, about four influencing variables is another one that it is just a field measure, it’s the the concrete cover and I want to address that. I want to talk about the chloride surface concentration, I am going to talk about the critical chloride threshold, I am going to talk a little bit about the admixed chloride content that is interesting because it seems it just a laboratory test and we should be able to do fairly easy, but there is quite a bit of controversy on that, so I will talk about some of those controversies and what we have to do. I will talk about the apparent diffusion coefficient and this is really just talking about the need we have not actually started addressing this, there are several tests out there, but those test are not representative of field conditions and so we need to make changes to that and then I will go ahead and summarize.

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So my objective for the presentation is really to show that input variables for predicting the service-life of reinforced concrete structures can significantly influence the prediction and I will show some data. The second thing is that significant research is needed in the standardized testing to better asses these input variables. So these two big takeaways that I want to talk about today.

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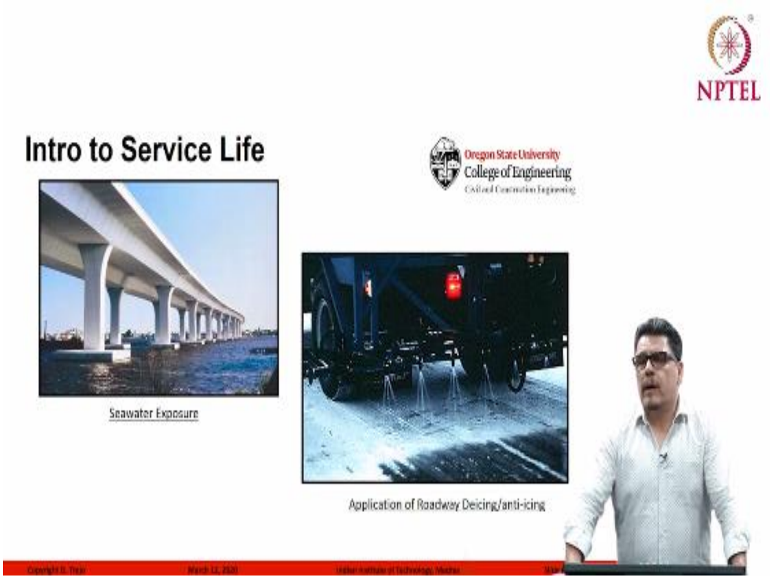

Let us go ahead and look at the brief review of service-life. I showed this slide yesterday, how do we go about predicting the service-life and what do we need to do and why. Well, the reason that we need to predict the service-life is because we spent lot of money on these structures to design and construct them and we put them in aggressive environment and these aggressive environment are can be ocean, if there is freezing it can be salt application in roadways, but we are putting our structures in much more severe environments and so because of that we need to look at the service life.

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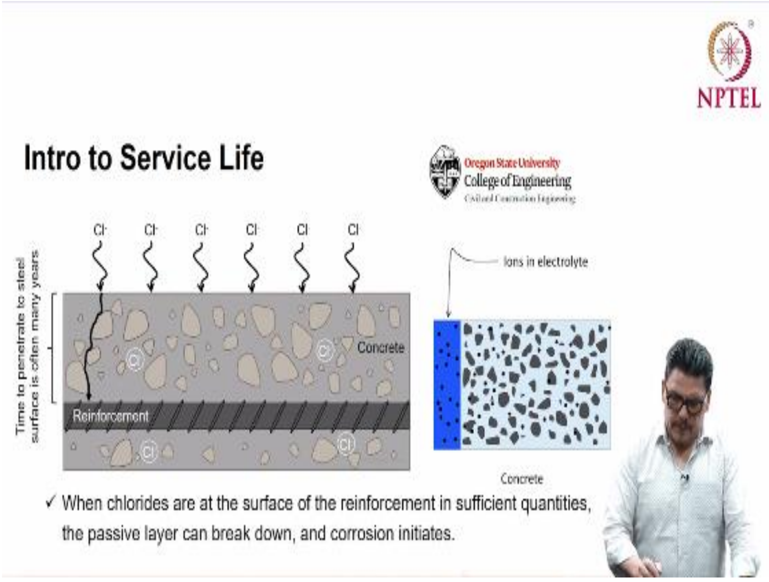

I will do a brief overview again, why do we expose it to chlorides, chlorides are transported into the structure and into the concrete and it takes some duration to get there. So what we do is we model the transfer of chlorides into the concrete and the key point is how long does it take and I did little cartoon here is that we have chloride and surface for the concrete, you could see there to the right, I think it is going to show here to the right. These ions in the electrolyte and the surface of the concrete they are typically transported into the concrete.

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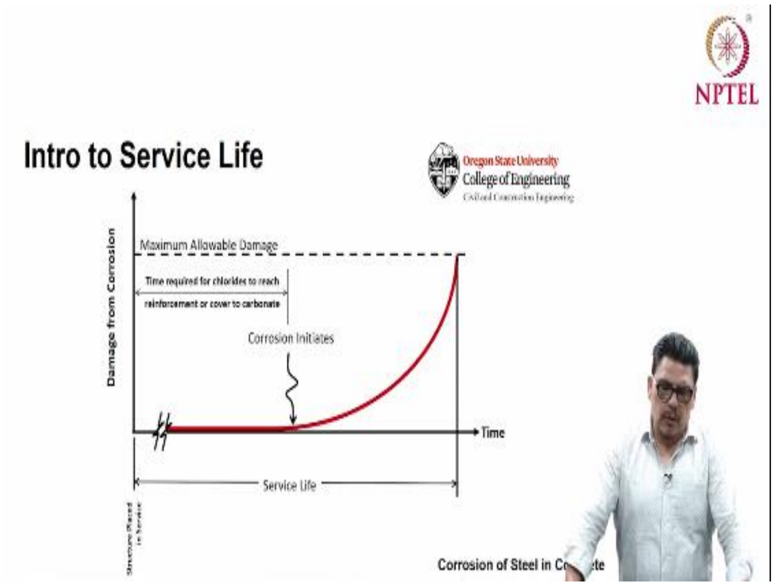

How do we look at the service-life. The service-life is really a function of the damage the structure experiences. If we look at the damage as a function of time, what we can do is when you construct something like in the picture, we have no damage at the beginning and then with time it increases and there is maximum allowable damage and we call that the end of our service-life.

And so what is critical for us is, we are looking at especially chloride induced corrosion, that at some point in the structural life corrosion starts, it initiates and what we do is we want to determine that time, from where we put in service to when that corrosion initiates. There has not been a whole bunch on propagation phase, the phase after it starts initiating, but there is a more starting now and we should get a better handle on this. Right now the time after corrosion initiates we typically give it to 6 to 10 years and then we take it out of service or we do a major repair. So that is what service-life is and time required to start the corrosion process is really what we are interested in here.

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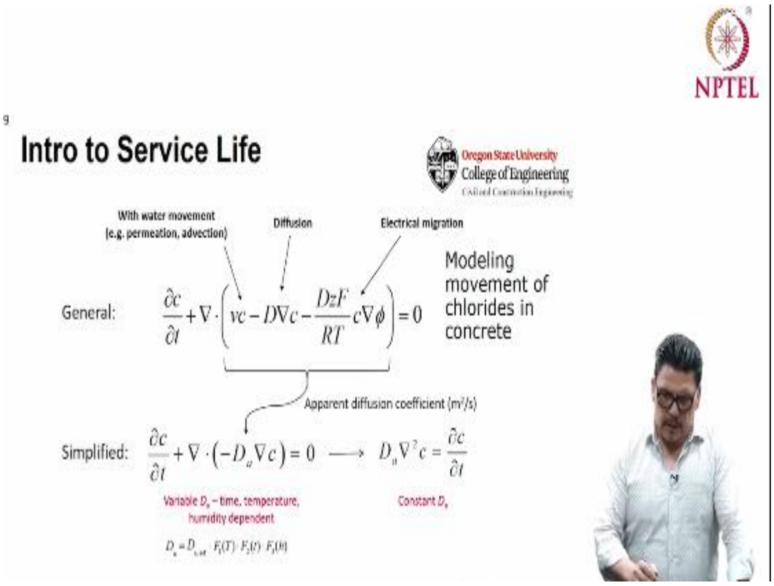

I talked in my last lecture a little bit about the process, we talk about advection and diffusion and permeation and then migration of chlorides. We have all these different mechanisms, but what we do is we simplify it and we make use of the apparent diffusion coefficient.

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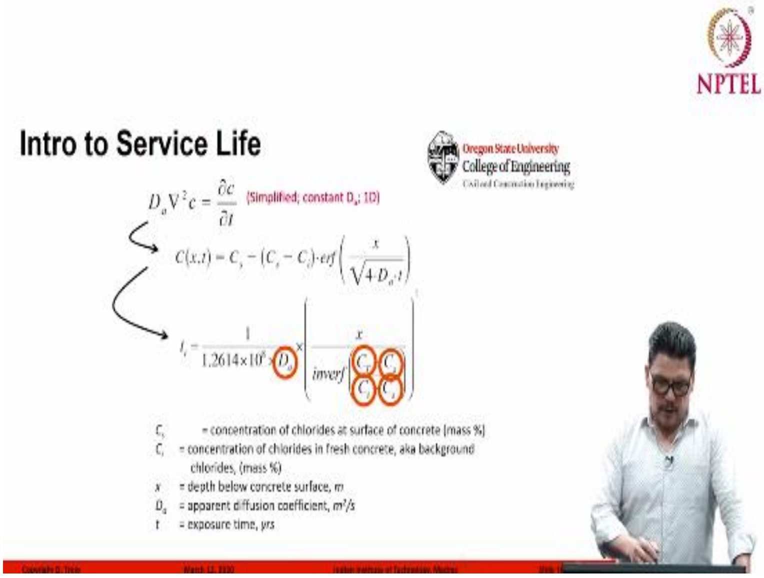

Using that we actually solve for that, we come up with an equation for looking at the chloride transport at the time and then what we do is we make some assumptions on the chloride concentration at the surface of the steel and what we do is we come up with a time and we call this service-life that is it. That 't' right there is that time to corrosion initiation and there is four key variables that I want to talk about. And I am going to show here is that those are the variables the apparent diffusion coefficient, the critical chloride threshold, the admixed chloride content (Ci) and the surface chloride concentration. Now why do we care about this? Well we have the equation and we have input variables, is that it is important to understand how significant those can affect the output and the output in this case being the time, the time to corrosion or service-life, the major part of the service-life.

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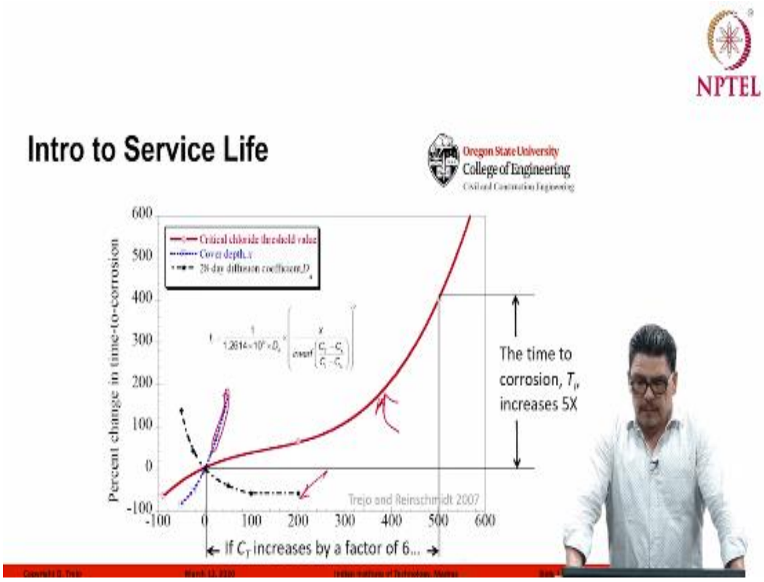

So let us go ahead and see how they influence and then the plot might appear, but if you look at some of the variables what you can do is and this is just the sensitivity plot what I did is I made an assumption, I predicted the service-life for one condition and then what I did is I looked at if I change one variable at a time how much would it change the output or how much would it change the service-life.

And you can see here is that for the critical chloride threshold this is the red line here, you can see that as I change the critical chloride threshold, let us say I am going from a conventional steel to maybe a corrosion resistance steel is that I increase that, you can see that there is a significant improvement in my service-life or my time to corrosion. You can also see, if I increase my cover depth, there is a significant increase.

So really what we want to look at this is that the slope of the line, it is a critical part, the steeper the line the more sensitive this equation is to that variables. And I also show the apparent diffusion coefficient, it is that the black line here, as the apparent diffusion coefficient increases our present change in time to corrosion significantly decrease. So it is allowing the chlorides to be transported to the concrete much more easily.

So you could see, the point that I am making here is that it is very sensitive to the input variables and you can see here that if I increase the critical chloride threshold by a factor of 6, I actually increase the time to corrosion by a factor of 5, it is not linear, but that is what we get out of this. So we are looking at the sensitivity of our variables.

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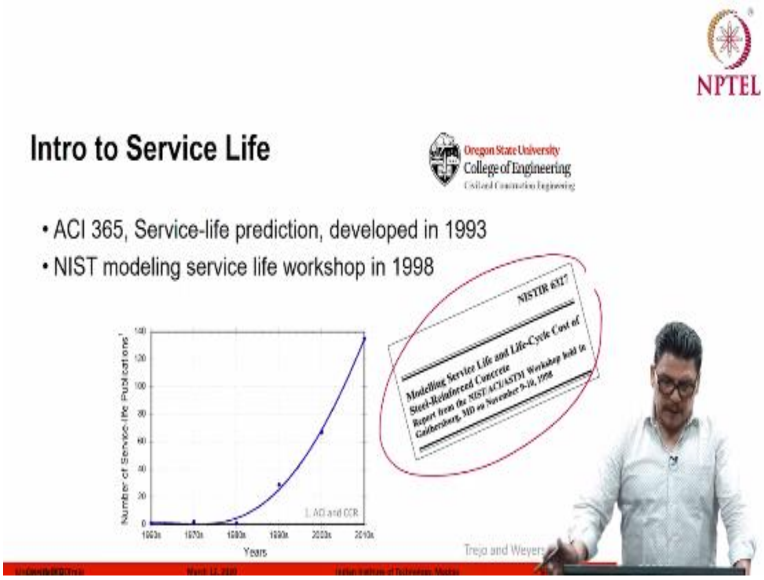

It is interesting to know that we think that we have been looking at service-life for a long time predicting service-life, but if you look at the number of publications, we have our focus on service-life is that in 1980 there was none, in the 1990 there was very, very few, in 2000, less than 20 years ago there was only about 60 publications in service-life. And so what I am trying to show here is that although we seemed to think that this we have been doing service-life for a long time, it is a relatively young time for this and the first meeting on service-life was in Washington DC at the NIST and they were looking at modeling the service-life and that happened in 1998. So we are looking at about 22 years, 25 years and really the point is that we still have a long ways to go and so it is okay to not know everything and let us keep working on in making it better.

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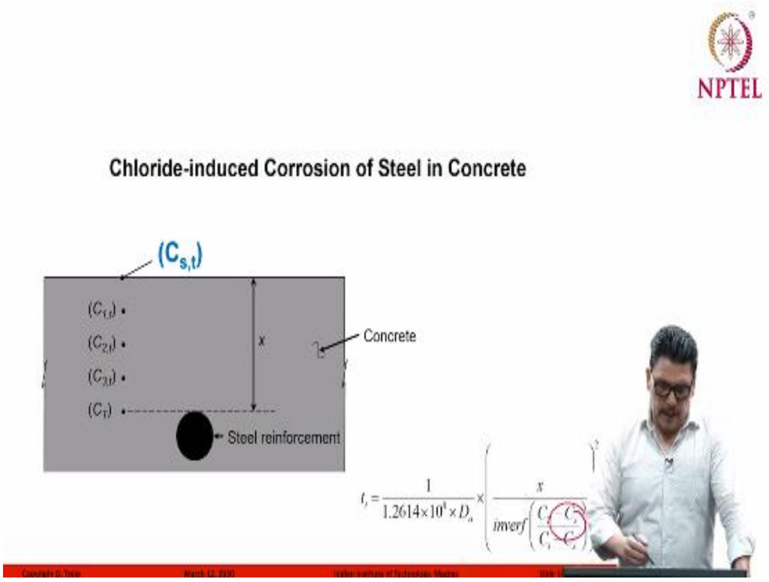

Let us look at the surface chloride concentration. On a surface chloride concentration what happens is, we exposed the concrete to a chloride based solution whether it be the ocean or it be the deicing or anti-icing salts so that there is chlorides build up on a surface and that is going to be input parameters into the model. As you can see down here there is a Cs so that is important. Understand first what do we assume and second is that how can we make it better.

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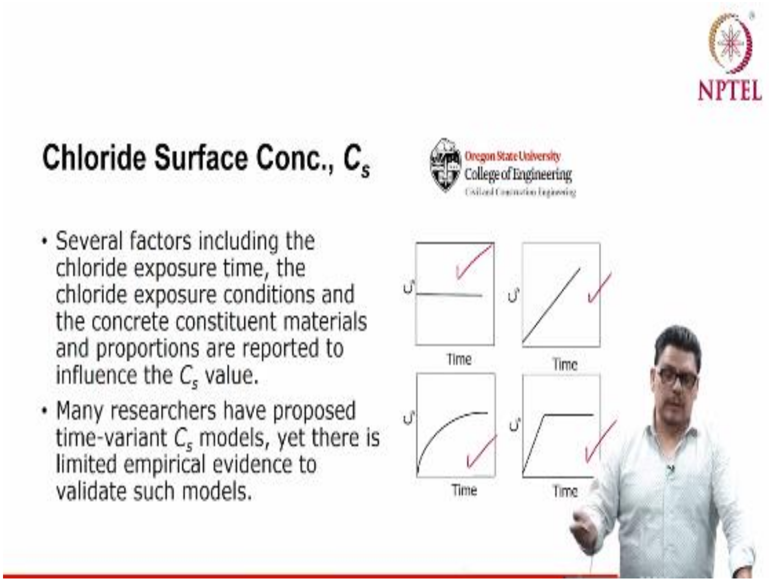

So what do we assume now? We assume that it is constant, we know it is not constant in fact lot of the models assumes it is constant, but there is actually a lot of the publication show that the people have come up with different assumptions. One of the challenges with that is we do not expose every concrete structure in the same way and so we have to look at some variability.

So all these different several factors include the chloride exposure time, the chloride exposure conditions, the concrete constituent's materials, and proportions, those all influencers Cs value. But many researchers have proposed other things all these are different models and I guess you can see that. Some have said that it is constant, like I said earlier there is that some have said is the increase is linearly. We know that is probably valid for a while, but it is not surely not that valid after sometime because that will go up to infinity, some said it asymptotically approaches some value and then of course they do the bilinear, those are all common models in the literature. But really is that the right thing and it really represents field conditions and does not really simulate the real physics that what is going on.

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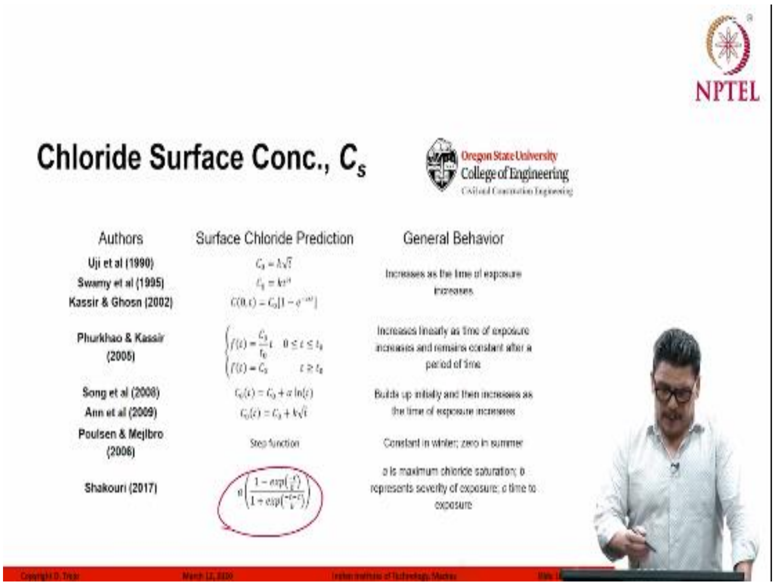

And so look at some of the literature and you can see the different models here there is a wide range of models, but what is best? We can use all these different models, but if it does not represent the actual field performance, it is not realistic and it is not adding any value. I guess it would make significant advances in developing these models, but we made very little advances in coming up with representative input parameters for these models.

So you can see there is a wide range here. One of the things that I am going to do is I am going to talk about this function Shakouri, developed recently and I think it has some parameters that can be changed, that are more representative of the field conditions and I will talk about that a little bit.

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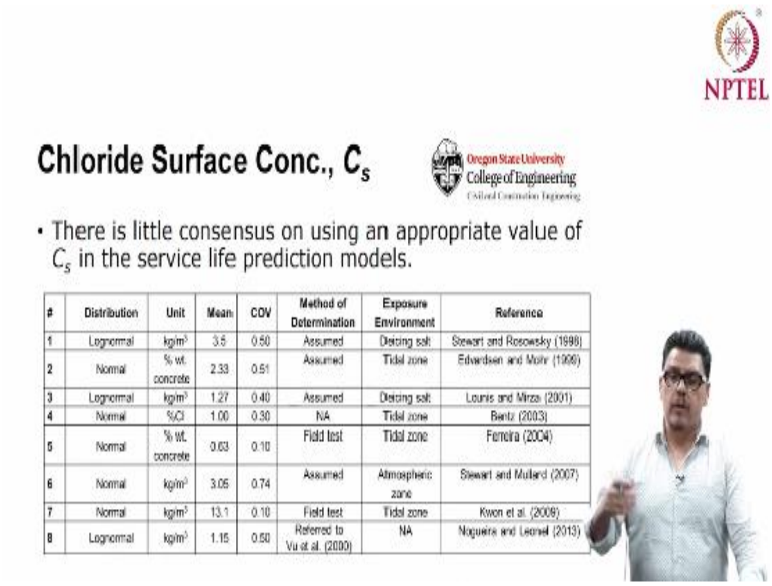

If you look at the literature is that you can see there is wide range of assumptions and on these different surface chloride concentrations, you can see there is a wide range of distributions, you can see there is a wide range of units, there is a wide range of mean values and coefficient of variation. There is different ways that they assume, different ways that they determine these values, some of them they assume and some of them they measure.

But when you do this it actually increases the variability of the model output and so you can see there we have a wide range down and I am not saying those are incorrect what I am saying is that at the time that is what they did, they are now in the literature and if you go and use those values you can actually get a wide range of output.

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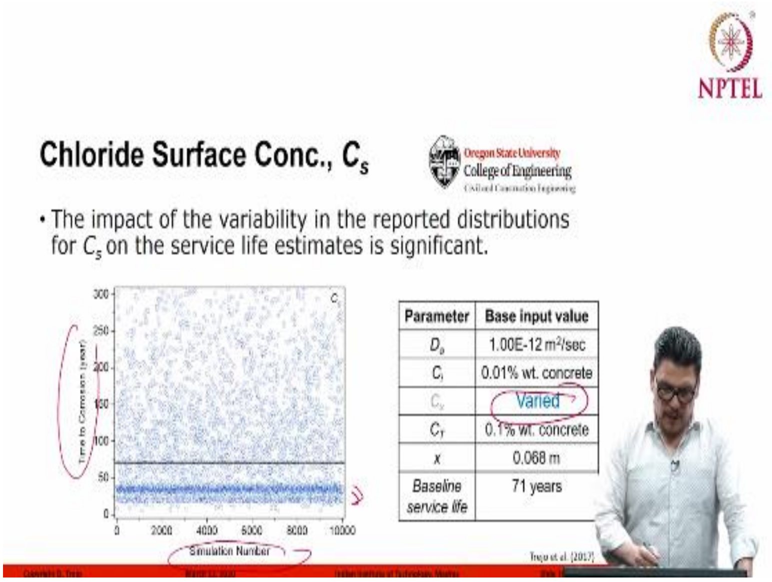

So what we do is this made some assumptions and all the input parameters just made them deterministic or they accepting the one what we did is we varied Cs here. And if you look at this what we did is, we did time to corrosion here and we look at the number of simulation and the only thing that we varied was a surface concentration. And you can see that we there are models it looks like there is some concentration of data between about 25 or maybe 20 and 40 years, but you can get anywhere from 5 to 300 years. And that is a point it is that if we do not have any standardized testing, we are going to get all wide range of service-life or time to corrosion values which provide limited values from this great wok that has been going on and so we have to come up with the standardized test method.

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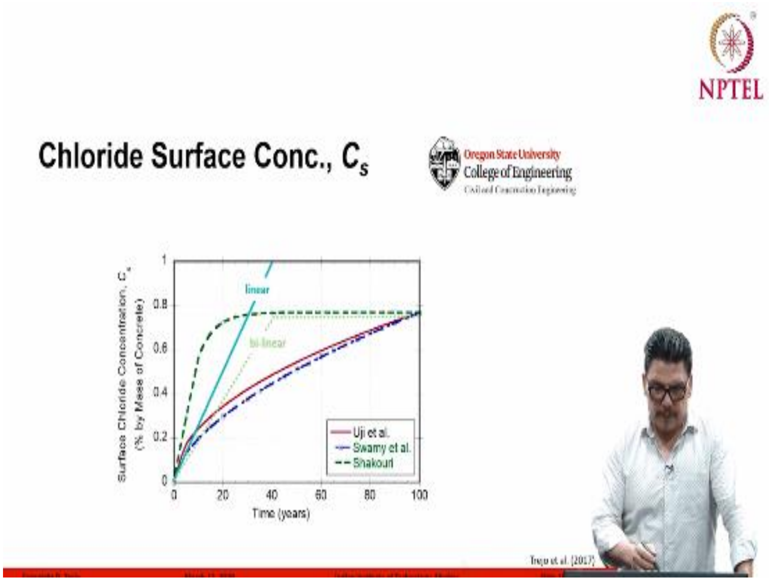

And so I said I was going to focus on the work by Shakouri and here the third one is here, but the nice about Shakouri he let you change the variable. You can see there different surface chloride concentrations and from the different authors, but I am going to focus on the work by Shakouri.

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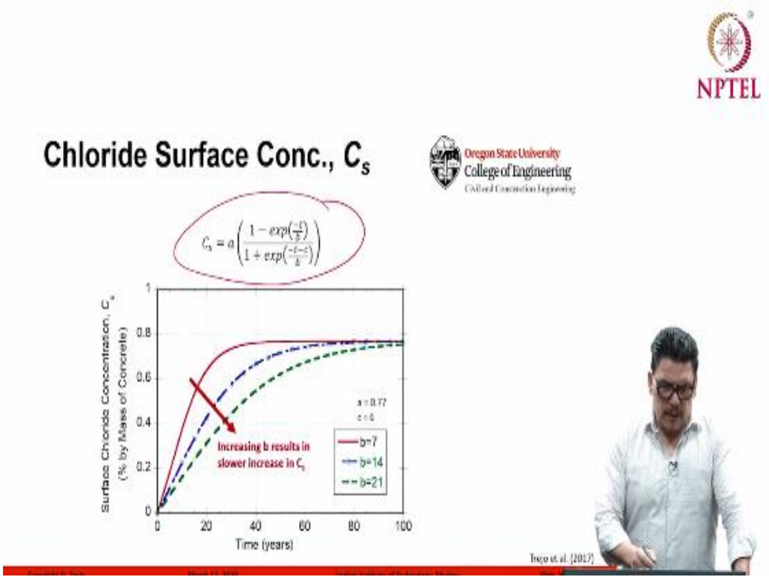

One of the nice things about this you can see the equation that he put up here to predict the surface chloride concentration that is a function of time and it is a function of 2 other constants that he develops and those constants are depended on different things. So the particular one that we are looking at here, we assume that a is 0.77 and we assume c is 6 and we change b that we can see is that the slope of this surface loading decreases.

Now why is that important? Well it is important because even if you are in a very high concentration you are going to have a very high loading rate and the surface concentration is going to increase at a fairly quick rate. However, let us see that you do not have a severe condition and Its builds up is a lot slower where you can adjust this by adjusting this B values.

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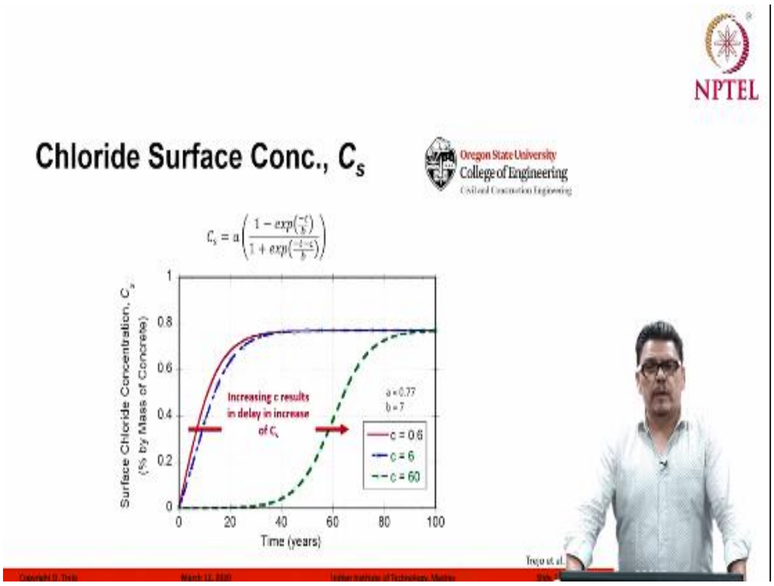

Also I thought, another unique thing that he did is that he changed put a parameter in there where if there is a delay in exposing your structures to chlorides is that you can actually account for this too. And what he did is he put in a C value and you can see that the larger the C value the larger the delay in exposure. So when would this occur let us say that you had a reinforced concrete structure or you put epoxy or epoxy coding on the surface. Eventually that wears off the chloride starts getting into it and you can see there is the increasing in chloride surface concentration, but it increases at a later day. So I think that was a very unique way of coming up with something that realistic in the field. So that some of the works that has been done on surface chloride concentration, he was validated some of this work and that is going to come out soon. But I think this is an interesting and probably a model which is more representative of actual field conditions. So I think there has not been a lot out there, there has been lot of assumptions we are doing some validation now and I think at some point soon we get to looking at the what is the real chloride surface concentration, but we are not there yet.

So let us look at the next variable, critical chloride threshold. I should say quite a work going on this area, but we have not been successful in coming up with what is a real value and this topic I could talk for hours and hours and probably days and days and so we will have to little brief here because we have limited time, but it is a very interesting topic and the one that surely needed, it is a significant variable. Remember earlier I showed, if you change the critical chloride threshold of the steel by factor of 6 you increase your service-life by factor of a 5 or your time to corrosion by factor of 5. So if we went from a, let us say 1 kg cubic meter a critical chloride threshold for conventional steel and we want to 1, still they have 6 which is not that high, 6 kilogram per cubic meter. We could not increase our service-life by a factor of 5, in that example earlier.

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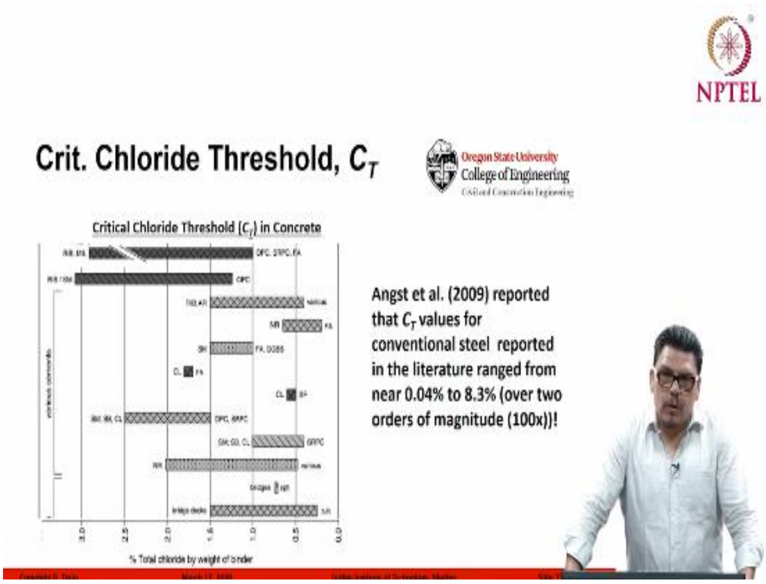

Let us look at the literature Angst did, did a similar paper on 2009, he looked at the critical chloride threshold values and what he found is that the values of range from 0.04 to 8.3%, I mean that is about 200 times of magnitude and so why we are getting this and what is happening with this stuff. One of the things is we have seen is that there are several issues, surely how you test your chlorides, really how you test the critical chloride threshold, I will talk about these now.

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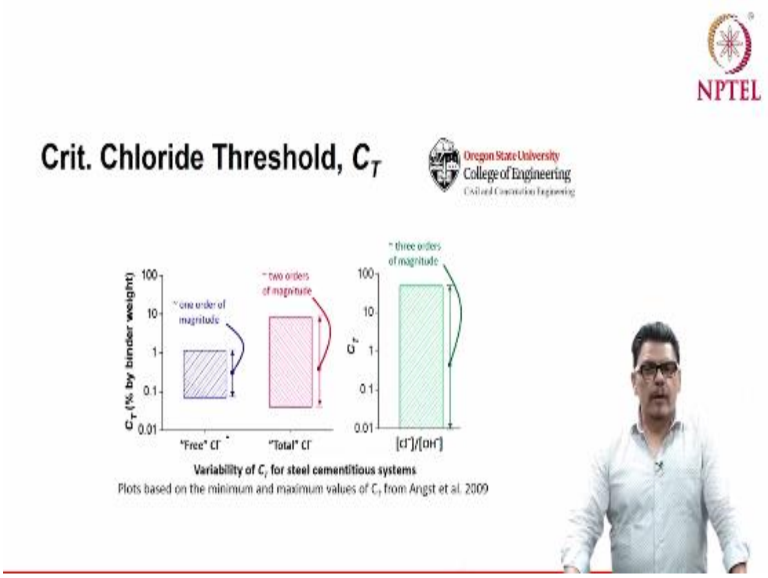

One of the things that we look at is that what test we used to test the chlorides, one could be free chloride which they call when I have free in here in parentheses or I am sorry in quotes intentionally is because free is it could be water soluble, it could be pore extraction, it is really very clear on lot of this what this was. And when we talk about total and we know that acid soluble test it is not total but it is close to total. But you can see there just a range, just from the critical chloride or just from testing of the chlorides. So that is something that we need to think about, should we be testing using the acid soluble test or should we be doing water soluble test. And if you are not familiar with those tests, they are different test and you can see that they will get a wide range of values from the different test. But I think one of the things that we need to do is we need to start standardizing the test and not using both and we will talk about that a little bit later.

Now if we look at the chloride hydroxide ratios, we have not only variability from the chloride test method, but if you look chloride hydroxide ratios now we have even the more variability and so what is right? If we are looking the critical chloride threshold, what is correct and what best represents the actual field conditions? We do not know, we need to test it.

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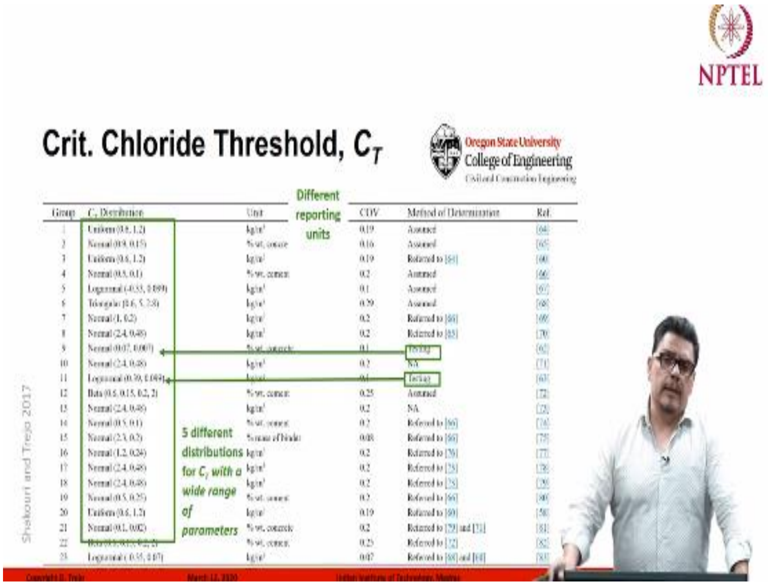

I am going to show you some of the stuff it is in literature. It is a wide range of stuff from the literature, you can see here that is Shakouri and myself actually did look at it. And you can see that there is a wide range of distributions or different types of distribution to use different units and you can see here, they have used some testing to predict this, but some of them just assumed it.

I think one of the challenge is that we have to assume some things early on, once it gets in the literature it can continually being used and if it is used predict the service-life with something that has been assumed, you have to be very careful with that. So I guess the point is that there is a wide range of looking at this variable, it has been a wide range of assumptions and we do not know how they apply to the actual conditions in the field.

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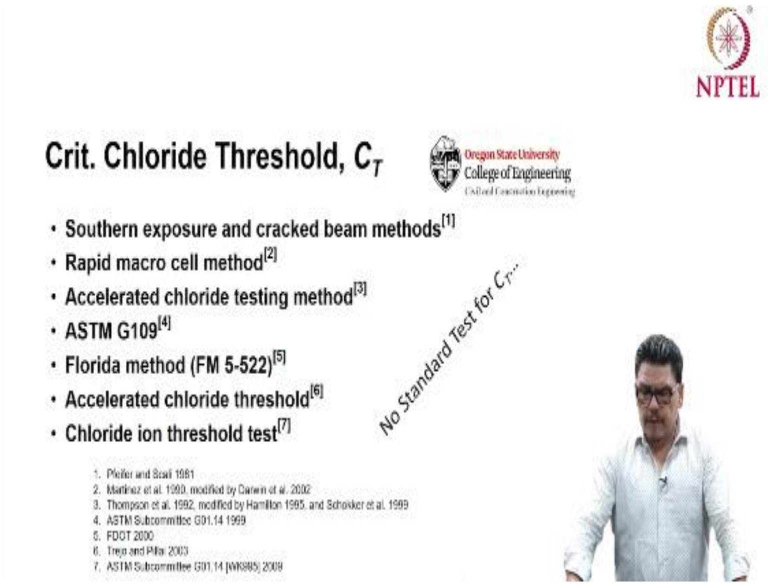

If we look at the test and I am going to focus on little bit here from here on now is that there is a wide range of test to actually estimate a critical chloride threshold. You can see, I listed 7 here, that were in the literature and so we have a different test method, so we are probably going to get different critical chloride threshold values. And Angst when he did his work he recommended that was a critical part, that was a critical thing in evaluating the critical chloride threshold and so we cannot have 7 test if we want to actually get something that is representative of the field.

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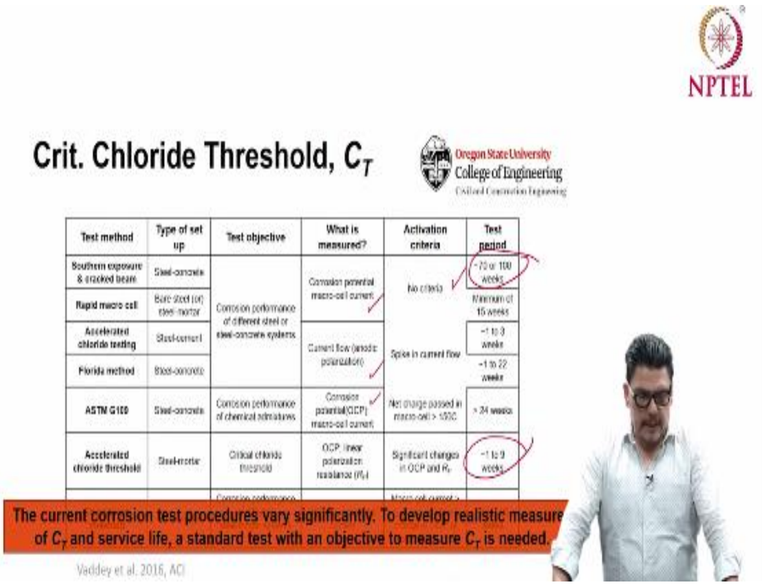

You can see by looking at different test methods, you can summarize in a table here and what was the objective of the original test, even though the original objective may have been different and was not to get the critical chloride threshold, all these are commonly used to get that and so what measured and how do we measure and how we determine what the critical chloride threshold, you can see that they use corrosion potential macro-cell, they use anodic polarization, they use OCP or micro-cell current here again, linear polarization, they used a wide range of different test which will also influence the variability. What criteria do we use to say that now it’s put it from a passive state to an active state. You can see that there is some early work that they have had no criteria, they started cracking maybe pulled that out. There has been some stuff and there has been spike in current, I am not sure spike is the best technical term, but that is what they used and they have a wide range of things.

But what is most important here is that you can see that some of these test period is a 100 week that is too long we can get down to 1 to 9 weeks. There is a wide range of different test procedures and test times, if we want something, if we want to test to the economical and the value adding to the industry, is that we have to develop a test that can be performed in a reasonable amount of time. If I am introducing a new product to the market and new reinforcing bar I cannot wait 5 years to have that evaluate, just not economically feasible, we have to do something in a reasonable time. So that is kind of review of the different test methods, you know the current test procedure is, very significantly they had to develop a realistic measure of C_T and service-life and we need to standardize the test and that is my point here.

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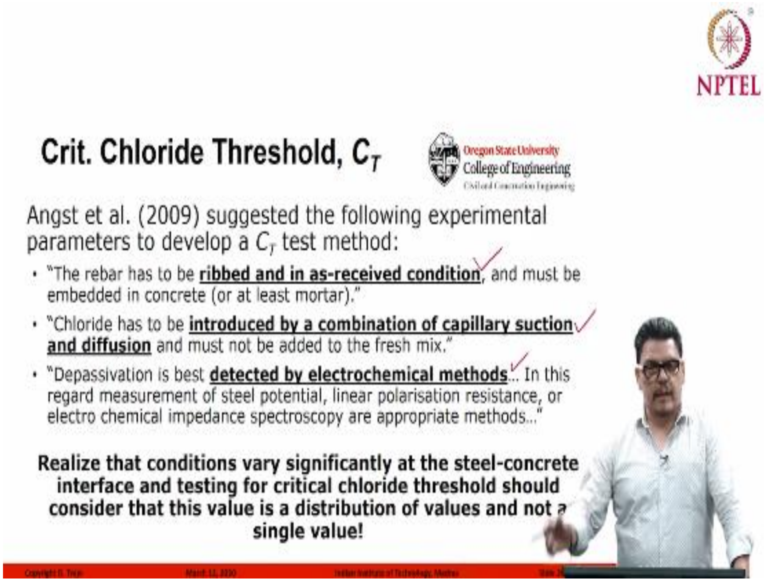

So, Angst made some recommendations on, if we did develop a test, what we should do, there has been some additional publications, but I think this was interesting, he said that if you develop a test it has to be ribbed and in as-received condition. He also said that chloride has to be introduced by a capillary suction or diffusion, I am not sure we could do both, but I do not think we have to do both, one or the other and that is important. The point he is making is that do not admixed chloride in your mix and really we have to use detected by use electrochemical methods. Those are the 3 critical parts that he recommended and we have to also realize that there should be some variability in this, there is still concrete interface it will vary that surely they will vary with the different test, but just different steel products will vary a little bit and different cementitious material will vary a little bit. And so we should see some distribution in our values, but some distribution does not mean orders a magnitude distribution. I think we need to really have a standard test that can be representatives of what is really in the field.

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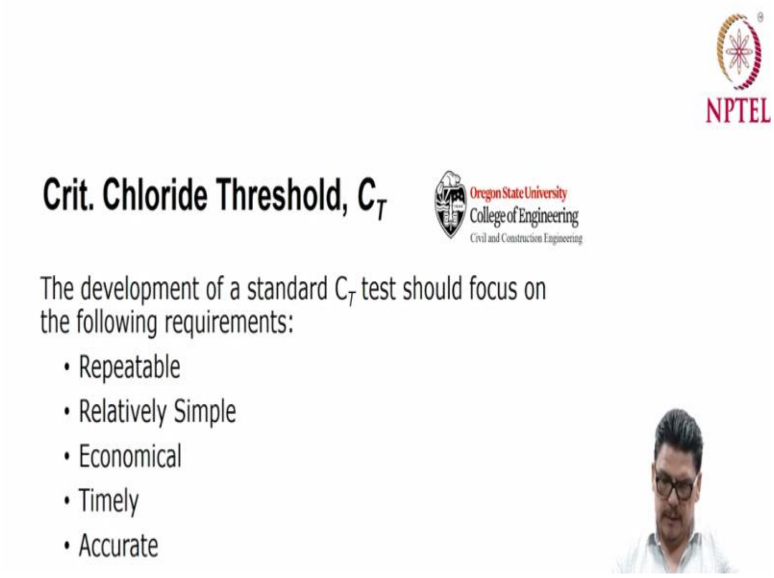

And so what is important if we are going to develop a test, I think needs to be repeatable, I think it needs to be simple, I think it needs to be economical, it need to be timely, and it need to be accurate. I am going to focus on this timely thing now because I think that is a critical factor of course they all are, well we have looked at some of this, but time is critical.

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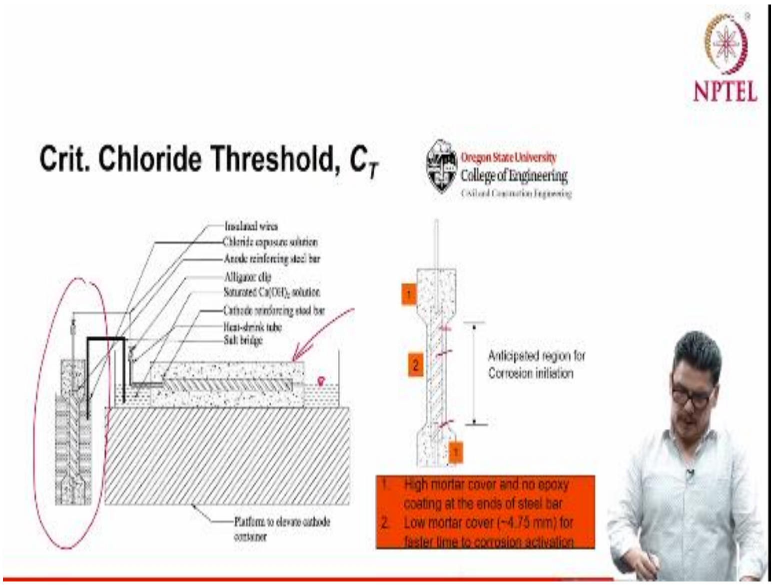

So we did is we developed a test procedure to predict or quantify the critical chloride threshold and you can see here, here is our anode here, it is a relatively small sample, 150 millimeters or something and then we actually have that connected to a cathode here and that of course what we want to do we want to have some driving force. What we have done is we have raise a cathode above the anode, we have a solution here.

We have it only up to the center horizontal bar and we only have the solution in our cathode up to half a bar because we want oxygen to get into our cathode, then we have those connected with both the salt bridge and the wire. You can see here is that here is our anode a little bit more descriptive of it and what we have done is we have intentionally designed it so that we can have a dog bone. But this area in the middle, what we do is we expose this of course chloride is transported in, they will get to the steel in this area first and so once we get activation, we have some criteria for this corrosion activation, we can easily break that off and do the testing, it is very simple. I mean this is one way the criterias make it simple.

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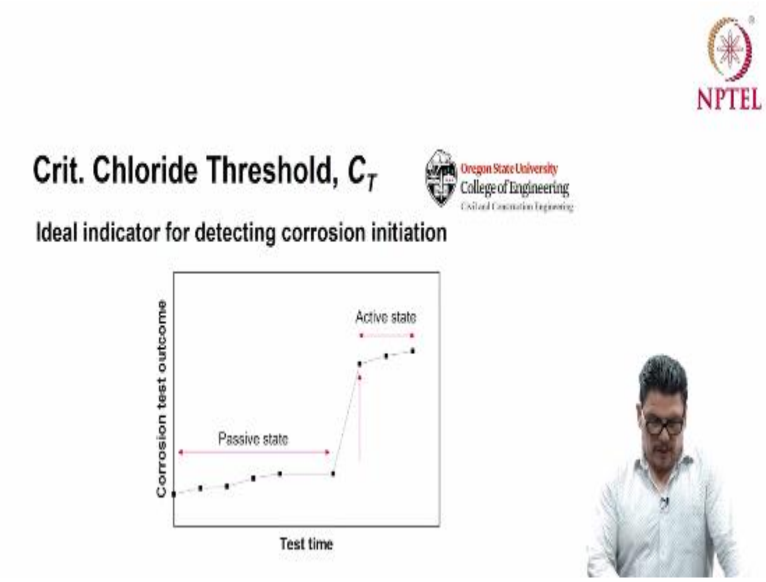

So what we would like to see from this test is, we have some test time and this is not real data this is just kind of simulated data, but we thought about, before we actually developed this test what we want to see. We want to see some passive state at sometime and then at some point when there is sufficient quantity of chloride at their interface, we get significant increases in whatever variable we are measuring and we can clearly see and whether there is an active state. That was one of our objectives to do this and we did, I am not going to show the data, we have lots of data on this and so it is very distinct, but we can see that increase in what we are looking at OCP, open circuit potential.

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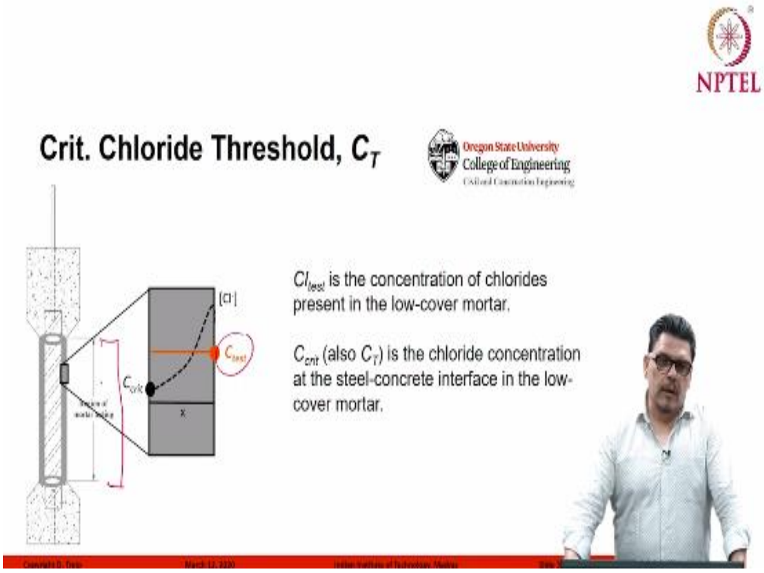

If we look at this region here, we crack this region off, we expose it for some time and typically the test can be done in about 4 to 5 weeks, we cure and then we actually expose 4 to 5 weeks not more than that and you can see the region of mortar testing, it is from here to here. It easily breaks off the sample, that area right there that supposed to be mortar, you can see that this we have this there.

Now what we do is we actually, when we measure this we actually get some C test and this is this value here. We get an average value because we check out the whole cover what we have to do is we have to correlate that with a critical chloride threshold which is less of that. We have done that testing, I am not going to show now, it is very repeatable, I mean it seems to run about 60% to 70% of the average value. So our secret is about 60% to 70% of our C test.

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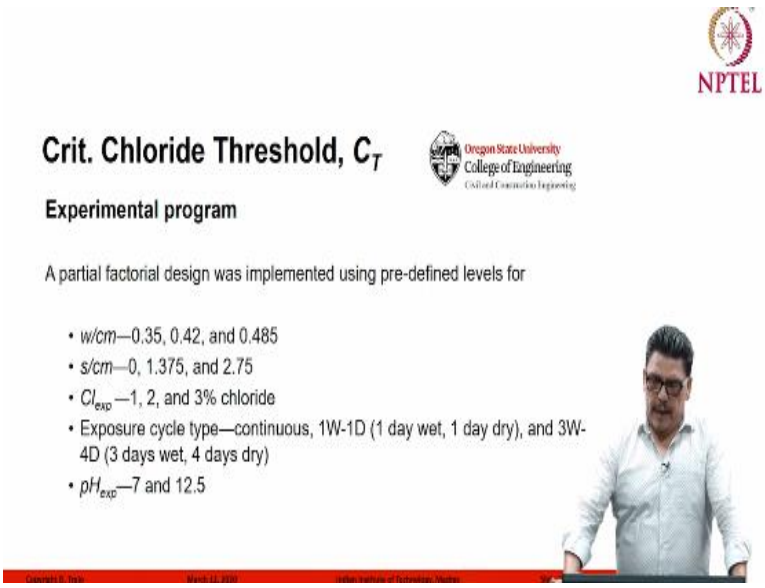

Okay so we did a partial factorial design, you can see our variables, we change the water cement ratio, our sand to cement ratio, and our chloride exposure solution. We looked at different exposure cycles, it was continuously wet. We looked at one day wet and one day dry, we looked at 3 days wet and 4 days dry and we want to see what would be most efficient and timely and would gave the least variability. And then we actually are exposed solution in our anode because we have a small cover what we did is we looked at different pH of our exposure solution and that was 7 and 12.5%.

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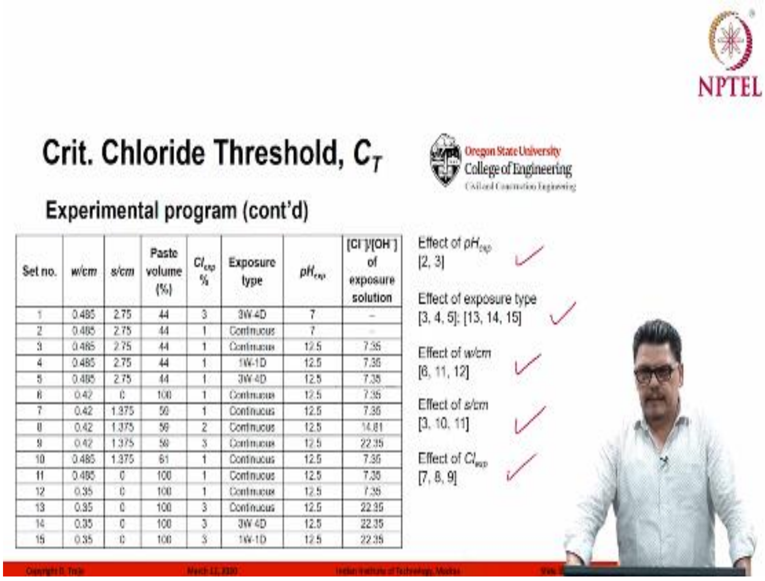

Set no.	w/cm	s/cm	Paste volume (%)	Cl_{exp} %	Exposure type	pH_{exp}	$[Cl^-]/[OH^-]$ of exposure solution
1	0.485	2.75	44	3	3W-4D	7	–
2	0.485	2.75	44	1	Continuous	7	–
3	0.485	2.75	44	1	Continuous	12.5	7.35
4	0.485	2.75	44	1	1W-1D	12.5	7.35
5	0.485	2.75	44	1	3W-4D	12.5	7.35
6	0.42	0	100	1	Continuous	12.5	7.35
7	0.42	1.375	59	1	Continuous	12.5	7.35
8	0.42	1.375	59	2	Continuous	12.5	14.81
9	0.42	1.375	59	3	Continuous	12.5	22.35
10	0.485	1.375	61	1	Continuous	12.5	7.35
11	0.485	0	100	1	Continuous	12.5	7.35
12	0.35	0	100	1	Continuous	12.5	7.35
13	0.35	0	100	3	Continuous	12.5	22.35
14	0.35	0	100	3	3W-4D	12.5	22.35
15	0.35	0	100	3	1W-1D	12.5	22.35

Here is our full experimental program, I do not think we want to get into all of this, but all those variables were assessed, in fact pH was done by comparing set number 2 and 3 and effective exposure type we compared 3, 4 and 5 and then we separately could compare at 13, 14 and 15, then to see effect of water cement ratio we compared set number 6, set number 11 and set number 12, effect of sand and cement ratio is important because it effects the workability of the mortar and the reproducibility of the measurements, we looked at set number 3, 10 and 11 and then of course chloride exposure 7, 8, 9 and that was the concentration of the chloride exposure. Without getting into all that we did a comprehensive study, we actually had about 6 different testing organizations to evaluate this, I mean some round-robin testing.

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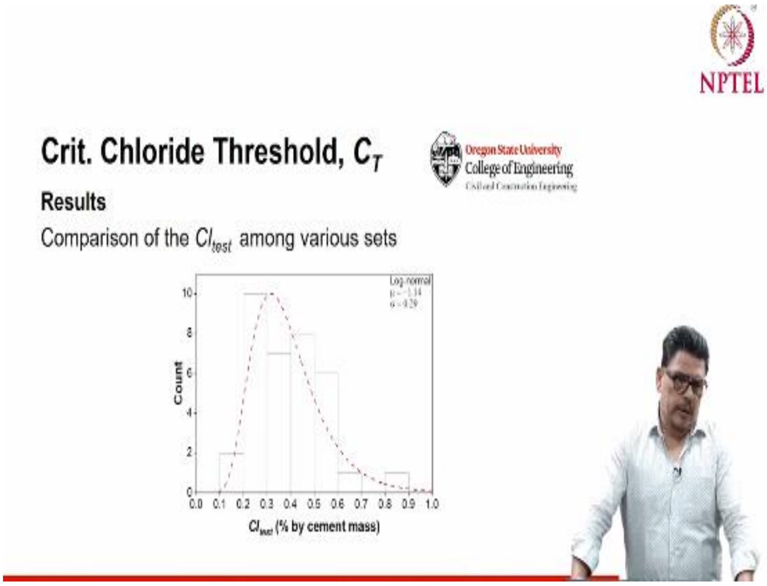

What we did is we came up with some value, some distribution and what we did is this is some preliminary data, we are still getting this is just from one lab, but it is very interesting that we have this range we actually have done some, this was some of the preliminary stuff we have done some more testing and we tied up the test and we do this, this is even getting narrow right now.

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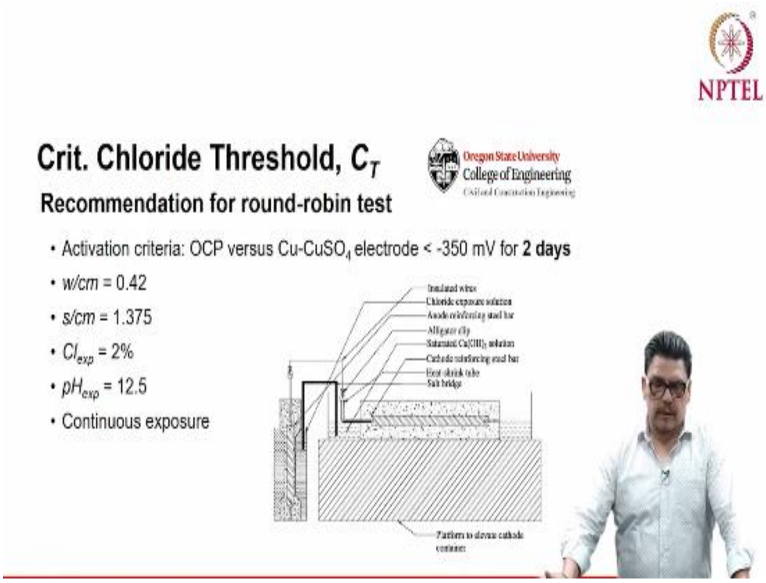

So what we would recommend, we have recommend that the test we perform with a 0.42 water cement ratio and s sand/cement ratio of 1.375, exposure solution of 2%, the pH of the exposure solution for the anode should be 12.5 and we recommended a continuous exposure and we did that for several reasons because first of all it is easier to handle and it is more economical, there is many places where testing is very expensive and so what we did is we decided to do a continuous exposure. We think that we should have results from this very soon, but this is a standard test that we can use for assessing the critical chloride threshold and this is important for reasonably predicting the service-life or time to corrosion and service-life. It is a start.

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Let me summarize here, literature contains a wide range of values of critical chloride threshold. Using these critical threshold value results in a wide range of time the corrosion and service-life predictions. And it is almost provides no value and so we need to standardize, the lack of standardization is the result and we need to standardize. I have showed some preliminary results and hopefully though we will keep going. So now let us look at, should be a very simple thing, we have chlorides and almost all of our constituent.

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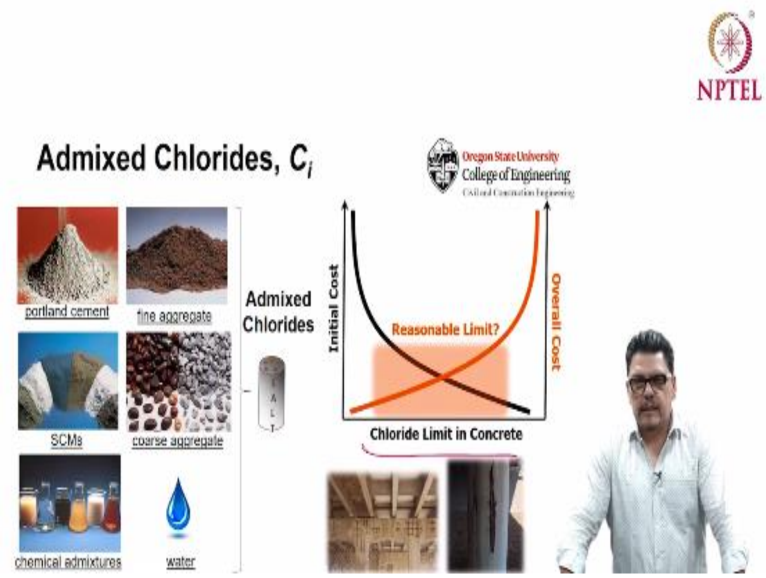

We have Portland cement, we have fine aggregates, we have SCMs, fly ash, slag we have coarse aggregates, we have chemical admixtures and we pour water in our mix and so typically all of those have some chlorides in it and not all the time, but there is almost always find trace chlorides in our concrete.

The question is, if there is too much in there, it could actually initiate corrosion when put the structure in service. The corrosion can start right away, of course we want to keep the corrosion threshold, we want to keep it under some allowable content. These are all referred to as admixed chlorides, the salt and this material are referred to as admixed chlorides and that is very different from transport of chlorides. Admixed chlorides are with the constituent material when the material are mixed fresh, the fresh date. Why do we care about this? If we look at our initial cost and we look at the allowable chloride limit here is that if we actually let allowable chloride limit go high our construction cost will be lower because we do not have to transport any new materials in.

Let us assume that you buy beach and let us assume that you have a great source of sand of course it has very high chlorides and just to be wise, do not use beach sand with chlorides in it, but let us say that you did and let us say it was allowable, you would not have to be transport more sand in, it would be much more economical construction cost. However, there is a cost for that and that cost is the overall cost. Because now if you exceed some level where the chlorides now initiates corrosion early on of course you get corrosion and you get a structure that would not last that long. So we have to find some reasonable time and you can see that would results from, if you actually have too much chlorides in your concrete when you makes it fresh. So we have find what is the reasonable limit. What is it, I mean there is lot of specification to say you cannot have this much, but is this reasonable? I do not know, I do have opinion but I am not sure I know, but let us keep going.

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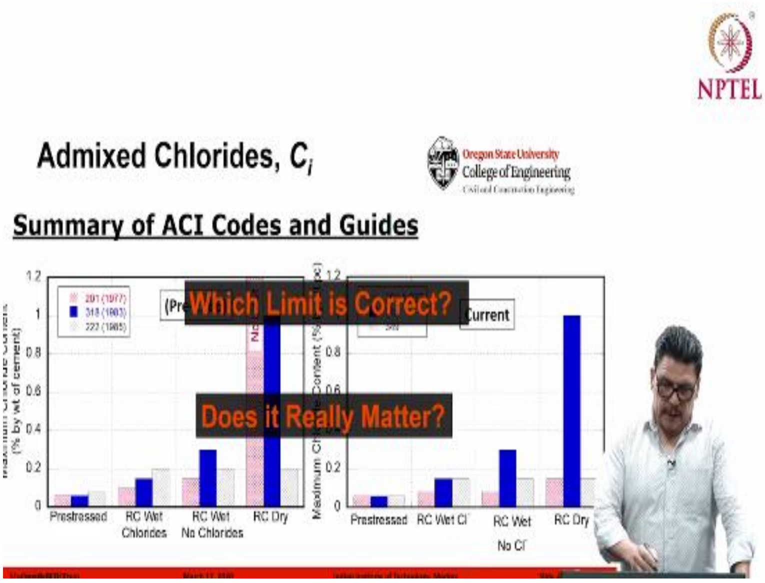

ACI is a leader in looking at these durability issues, but if you look at lot of their stuff there is a wide range of allowable chlorides, how much chloride should you allow in your concrete. We can see here that it varies quite a bit. There was pre 1986 we thought with time we had get a little better, we have not got much better and you could see that there is a still a significant variability, in which document you use and how much chloride you can allow into your concrete. And so it also little bit based on the exposure condition and so we have this current and I guess the question which limit is correct which should we follow the one on the left or should we follow the one on the right. I do not know and really I guess a bigger question it does not really matter, does it matter? I think that I will make a point here that it does matter.

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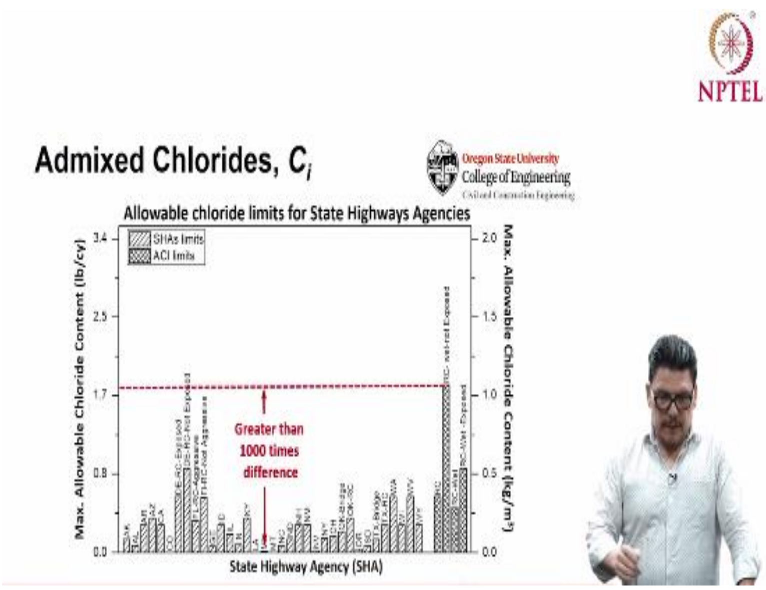

I am also going to show you some data here in the US we have 50 states and what we did is we looked at allowable chloride limit in those 50 states highway agencies and you can see here that they have a wide range of variability is over a 1,000 times difference what they allow in the concrete. So if I am in one state, I am step over that state line between two state, my concrete maybe good, but if I step over the other straight line, it may not any good because they have different allowable limits and so the question is again is which is correct and does it really matter.

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I am going to make a point here, it does matter. So these girders here were produced and what they did is they changed the water source and after several months they realized that the water source had a high chloride concentration. So they did some testing and what they did is they found out that one test was passing and one test was not passing and so you think about okay, no big deal.

But the fact of the matter is, if you do not pass this, these girders have to go and be thrown away. There is a significant investment, there is a significant cost and this is in the millions of dollar and maybe tens of millions of dollars. So you have to think about that how do we measure this, what is the right way to measure it and not only how do we measure it, but what is the correct allowable limit and so we need to do some standardization in this. We have to come up what is a reasonable allowable limit and really how do we test for it. So it does matter.

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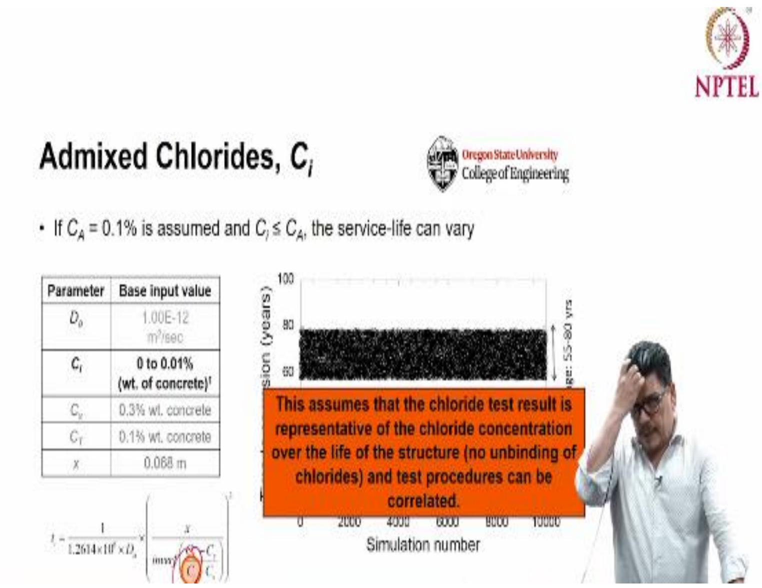

Let us look at if we change our allowable admixed chloride and here we just varied it from 0 to 0.1% by weight of concrete, you can see that this particular one is down here and the time to corrosion equation and if we vary it and you can see it is a pretty tight, ranging from about 55 to 80 years, but that is still a significant difference. 0 to 0.1% by the weight of concrete that is the range we assumed.

If we actually assume different testing and different condition, it could vary even more, but what this really assumes is that the chloride test result is representative of the chloride concentration over the life of the structure. Now that seems known unbinding and the test procedures can be correlated, as I say the test procedures can be correlated, I am talking about the acid soluble test and the water soluble test.

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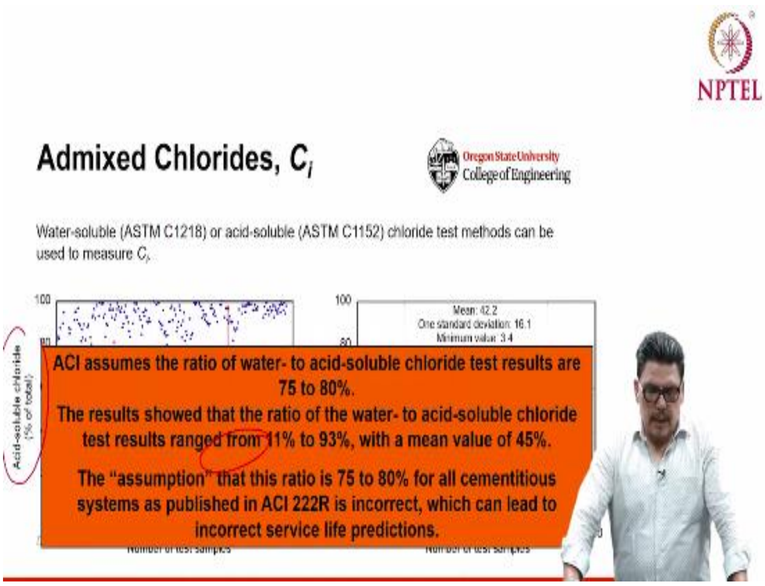

So if we look at one test, the water soluble test is ASTM C1218 and the acid soluble test is ASTM C1152. You can see your acid soluble test here and what we did is we actually looked at 100 or maybe 200 plus samples and we evaluated with a wide range of composition and we evaluated the acid soluble test and it is a percent of total chloride and you can see that the acid soluble test continually go from 80% to 100%. But really it has a mean of 93%, pretty good, almost the total chlorides be this. If we look at the water soluble test, you can see here that there is a huge range and so it goes from about I think 11% or 7% to up to about 75% or somewhere. Now one of the things that standards assume is this water soluble test is 75% to 80% of the acid soluble test. Now you can see here if we took these values here and you divide it by the acid soluble test that would range significantly and that is not correct. So ACI assumes that the ratio of water to acid soluble test is 75% to 80% so that the ratio of water to acid soluble test is anything but that, it ranges from about 11% to 83% with the mean value of 45 and so this is very depended on the cementitious system. So the assumption is incorrect and it needs to be changed and we are working on that now.

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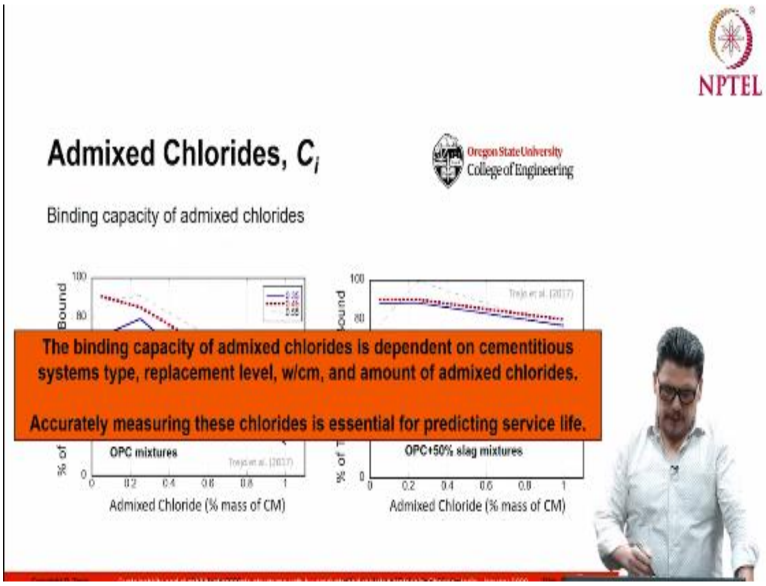

Why is that happen? Well it is really a function of binding is that if we we look at ordinary Portland cement, if you look at as a function of percent of admixed chloride as a function of bind chloride, you can see that the percentages decreases, so as a chloride content, admixed chloride increases that your binding decreases. And if you look at slag, you can see that there is a significant effect of the cementitious material type and so we have to now consider these things when we are doing this. And the question is what should we do? water soluble or acid soluble to determine this and there has been done some more work. It seem to be the case that maybe water soluble maybe be the most applicable, there is some cases where it is not conservative as it is should be, but in large majority of cases it is.

So I guess the point is that the binding capacity is a critical parameter and really what we need to do is we need to come up with one standard test because it does affect the service-life.

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So admixed chloride, there is no consensus on amount of chloride that can be introduced to a new concrete and there is no consensus on which test should be used to measure it. Chloride binding varies with the different cementitious systems and these all will affect the time of corrosion service-life prediction. So although we are making some headway, there is still some mass confusion. We are working on it now, we are hoping to maybe standardize the testing forward and make some progress.

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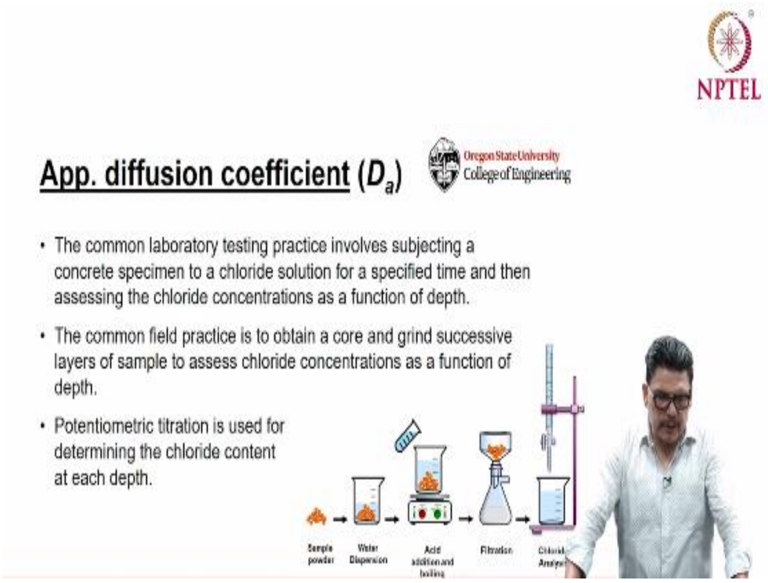

Let us go into apparent diffusion coefficient Da. Actually, what we do now is to assess the apparent diffusion coefficient is we cast the sample and then we subjected into chlorides and we pull it out and we actually asses it using standardized test required, it could be water soluble or acid soluble. The common field practice is to actually go out to the field and take a core and grind it in the lab and do the same thing and we typically use potentiometric titration to determine the chloride concentration.

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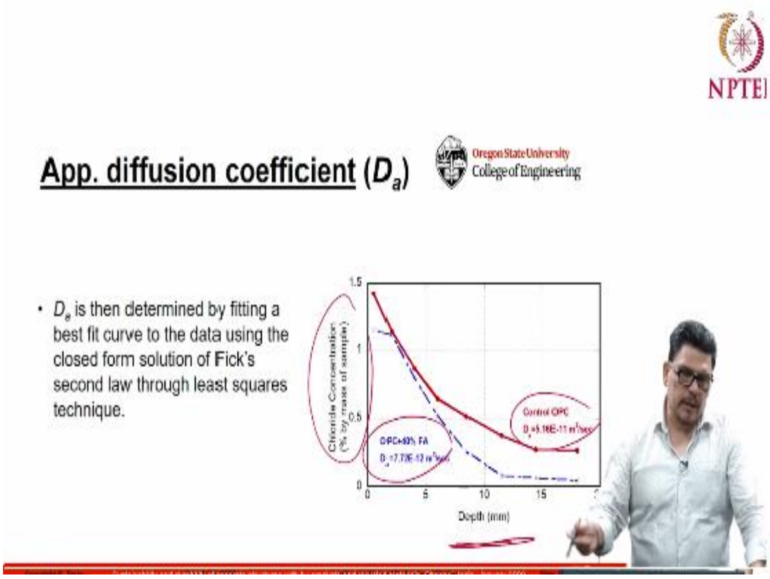

Then what we do is, we determine Da, we actually use the best fit curve, we grind it at different depths, we do the analysis, we look at the chloride concentration as a function of depth here and then we can do a best fit curve and we can get our apparent diffusion coefficient. And you could see that there is an influence of cementitious material type, having fly ash reduces your apparent diffusion coefficient.

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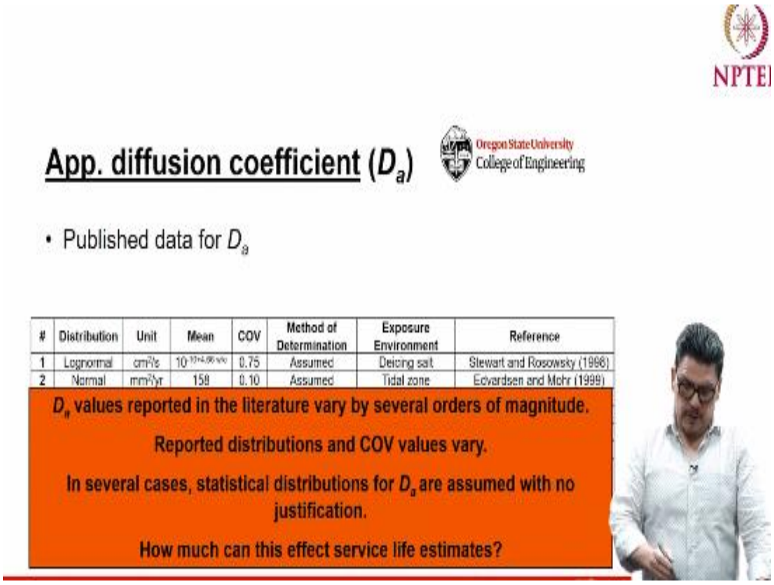

But if we go and we look at literature and what should be the diffusion coefficient, there is a wide range of assumptions, the distribution, the unit, the mean, the coefficient of variation whether it was assumed or was tested or refer somebody else and again I am not being critical of this, what I am saying is that we have to do this, but it is time now to start doing standardized testing to come up with hard data, so we can predict this information.

So the point is there is a significant difference and it can be a significant difference because of course some of the factors that we used to make our concrete changes, but right now some of the predictions they is just too much variability and so the values reported in the literature vary by several orders of magnitude, there is several distribution of coefficient of variations. In several cases statistical distributions are assumed and with very little justification. And so we have to be careful for using this inner service-life prediction and so the question is how much can we use for actually do a service-life of overall structures and again not being critical, just saying we have to be more careful between what we do in the lab and we do in the field.

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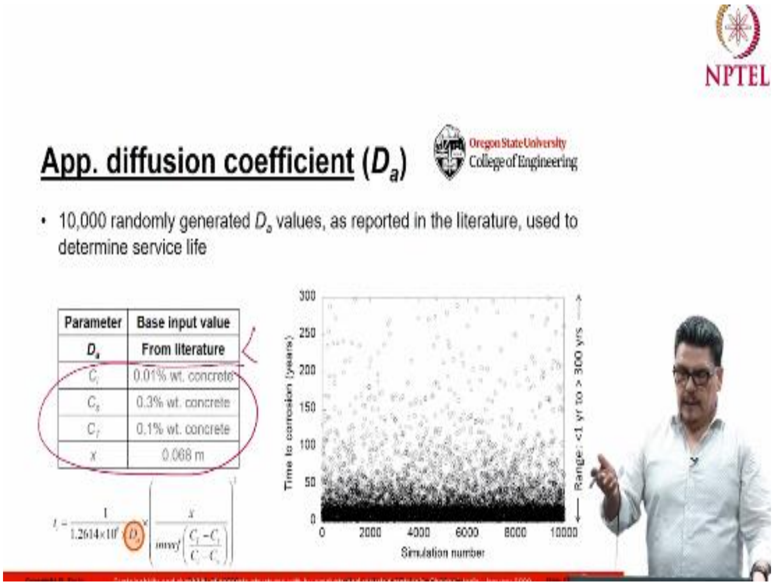

So if we do it again, if we actually vary our apparent diffusion coefficient and we look at again time to corrosion, we do simulated it and we can see here we just took values from the literature and we used to make those assumptions and we assume all the other variables to be deterministic and we can see here that our range is less than one year to 300 years. The point I am trying to make here is that these input variables are significant and they make a significant effect on time to corrosion in your service-life.

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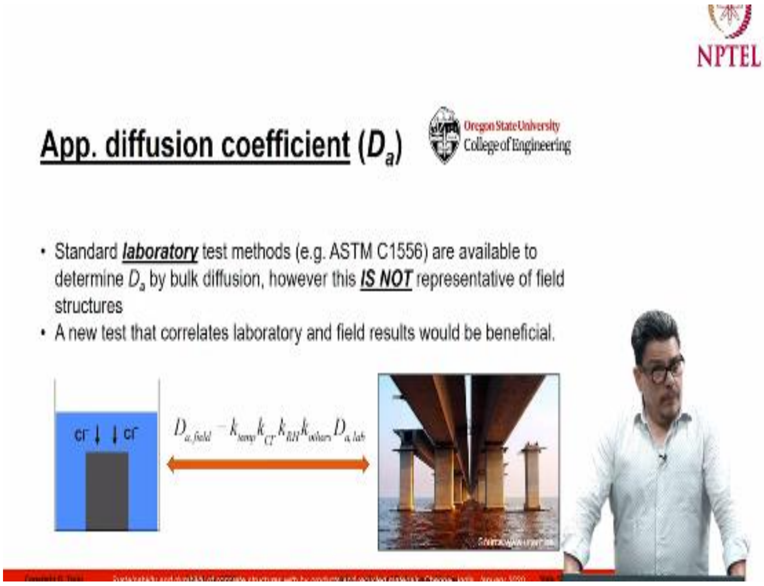

So I guess there are standard laboratory test methods are available ASTM 1556 to determine Da, however this is not representative of what we see in the field structure that is actually diffusion based test but that may not be what we have seen in the field so we have to be little careful and so I think what we need is we need some way to correlate our laboratory test with our field structures and that will make this test better.

So I am going to summarize here, we have to be careful is that there is lot of stuff in the literature that can be used. You can put it into your service-life prediction model, but it is probably not going to be a representative of what you are going to see in the field. So actual service-life or actual time to corrosion from what you see in the field and predicted time to corrosion or service life could be very, very different and so we have to be cautious using your input variables and I believe that we need to standardize these input variables.

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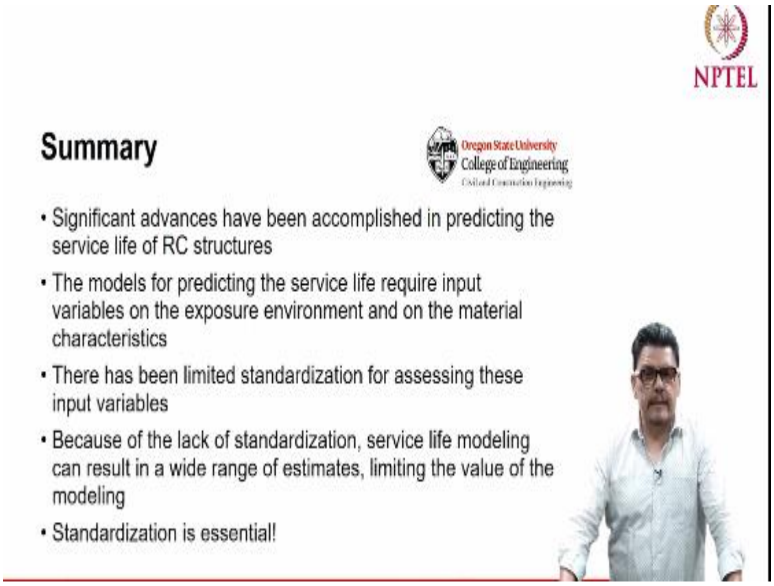

So let us look at the summary, we have made significant advances in predicting service-life and their computational power is increased dramatically, we have the model to predict the service-life of reinforced concrete structures. However, the models for predicting the service-life require input variables and on the exposure environment and on the material characteristics and there has been limited standardization for assessing these input variables. And because of that I think that we can see a wide variation in our predictive time to corrosion. So right now we can get what we want, but it is not going to be representative of what we have seen in the field and so I think that we need to standardize and standardization is essential.

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So well I have for today. Thank you for your time and I guess you can answer any question, but if you did you are always welcome to send them write to trejo@oregonstate.edu.

Thank you.