Maintenance and Repair of Concrete Structures
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Lecture No. 18
Surface Preparation and Protective Treatments
(Protective treatments for steel reinforcements)

Hi, this is the third lecture in this module on surface preparation and protective treatments. We will be looking at protective treatments for steel reinforcement in this lecture.

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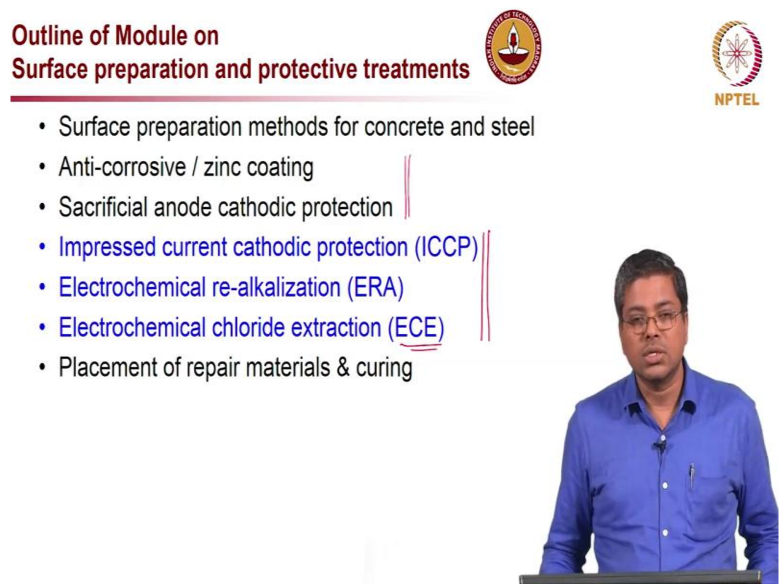

In the last lecture we looked at anti-corrosive coating or zinc coating and at sacrificial anode cathodic protection or galvanic anode cathodic protection. In today's lecture we will look at these three items which are in the blue text. The first one is impressed current cathodic protection, we are going to call it ICCP in the coming slides. The second technique we are going to look at is electro chemical re-alkalization, we are going to call it ERA in the coming slides. And the third one is electro chemical chloride extraction, which is we are going to call it as ECE in the coming slides.

So, if you look at the impressed current cathodic protection, we are directly dealing with the steel and protecting the steel from corrosion, in the electro chemical re-alkalization, we are going to increase the pH level which has dropped in the concrete so that the steel will be protected and in the third case again when we talk about electro chemical chloride extraction, we are essentially removing the chlorides from the concrete or from the surface of the embedded steel so that corrosion cannot continue. So, if you look at the last ERA and ECE, we are working on the surrounding environment of the steel reinforcement whereas in the impressed current cathodic protection, we are looking at reversing the current flow.

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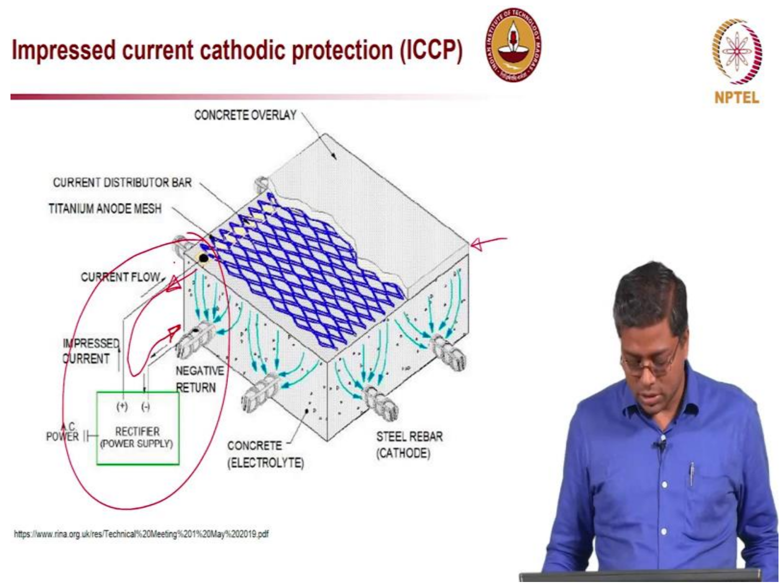

So, in the impressed current cathodic protection, this is a schematic showing how the system works. As you see here there are the blue color mesh is placed on the surface of the concrete and you can see the concrete cover, the region where these arrows are shown, that is the concrete cover and steel reinforcement is protected and on top of that, an overlay is provided which is this and the mesh is provided in between the overlay or sometimes even inside the overlay and the concrete substrate. Now, you can see here the electrical circuit which we are talking where the current or the electrons are drawn from the mesh and supplied to the reinforcement which is embedded inside the concrete. So, electrons will flow like this towards the steel and then it will protect the reinforcement from further corrosion even though the environment of the concrete is highly contaminated. And this technique is widely used in large scale structures where you can actually monitor the system very well because one of the major challenges in this is making sure that the systems are put in place and they are not lost or vandalism happens etc. So, we will cover that later. But, there are some challenges and then some benefits also about this technique.

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Now, what are the things which are required for the materials which are used for this technique? First thing is the anode the mesh, which we use should be corrosion resistant, it should not corrode, because after the installation, the overlay will again be exposed to the same chloride rich environment and in short period of time that material should not get corroded. So, if you just use a steel mesh, it may not work because the steel mesh will corrode very fast and it will not be able to function for a long period of time.

So, usually we use activated titanium or something which is very highly corrosion resistant material and which is also a very good electrical conductor. And so, what is this titanium, it says activated titanium. So, the idea is we don't really use titanium or the pure titanium, but we coat the titanium with mixed metal oxides typically they are called as MMOs and why we coated with that is so that the mesh which is used is highly conductive and at the same time electro catalytic. In other words, it provides sufficient corrosion to happen or sufficient electrons it provide because if you use pure titanium, it is very corrosion resistant, so the amount of current which is required also may be higher for driving the same amount of electrons from the anodic mesh. So, this kind of metal with mixed metal oxides coating on the titanium which provides us both the corrosion resistance and at the same time sufficient corrosion or sufficient amount of electrons are available with the reasonable voltage which we can apply.

This comes in different shapes also, or sizes, it is a mesh, ribbon, tube, wire, or rod. So different types as you see on these pictures on the right side, you can see this is a ribbon over here on the top right and then a tube on the bottom right and also a mesh on the center picture.

Now, also the cementitious material which used as overlay also should be reasonably good, so that you did not really create a highly corrosive environment for the mesh itself. So everything is very important, the steel, the anodic material, and the overlay material.

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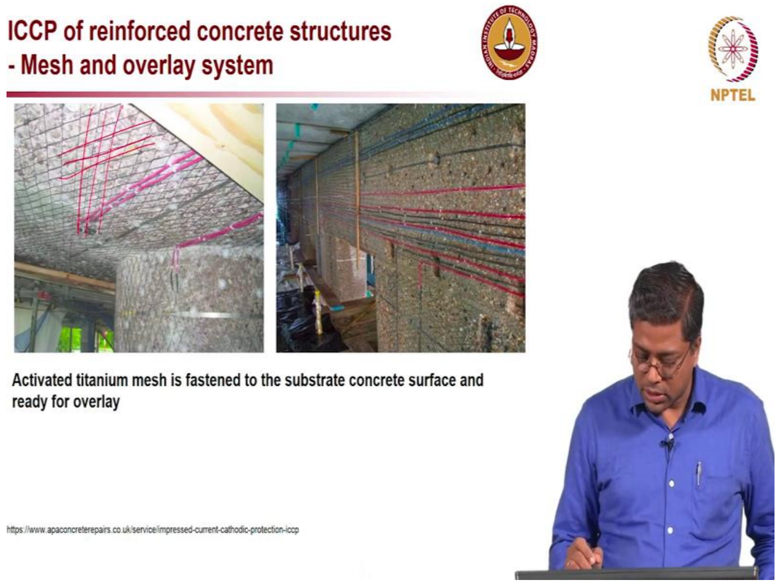

I am going to show you some examples where this is done. You can see here very nicely this mesh on top of this concrete cover region and on the right side also you can see it from similar structure, just to show you how this system works and then it is electrically connected.

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And also this mesh is anchored to the concrete as it is shown here on the right, you can see here the mesh is actually anchored to the concrete substrate, surface preparation should be done properly and then you place the mesh on top and anchor it properly onto the surface and then on top you apply an overlay cementitious material, you can see here on the right side that shotcrete is applied. And what you see here is a water body probably like rich in chlorides and very corrosive environment. In such an environment this technique works very well, only problem is it has to be monitored properly and continuously. If you are saying at 20, 25 years of life, you need to ensure that for the entire time period, the amount of current is actually supplied because sometimes what happens is the electrical connections are lost and then the system will stop functioning.

So, that is one advantage when we talk about the galvanic anode sacrificial system is those systems those systems work without continuous monitoring, in other words, it is a dynamic system. So, once installed and secured inside the concrete, they will continue to supply the current as it is demanded.

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Now, this is again another example, for a ribbon anode, you can see how a ribbon looks like and slots are cut on concrete, then inserted into the concrete cover region and which then is covered so, that it can protect the steel reinforcement inside. So, whenever you talk about ICCP there is an electrical unit or a rectifier which is controlling the amount of current to be supplied to the mesh or ribbon or tube or whatever anode system which you are talking about. Even though the anodes are embedded, for the system to work, you need an electrical current which is externally applied, unlike what is in the sacrificial anode system where it there is no external electrical unit. Here ICP you have external electrical unit which is supplying a known amount or a predefined amount of current. In the case of SSCP, there is no predefined amount of current, it is a dynamic system. So, the depending on the demand of electrons, it will supply that much electrons. That is the main difference between the two.

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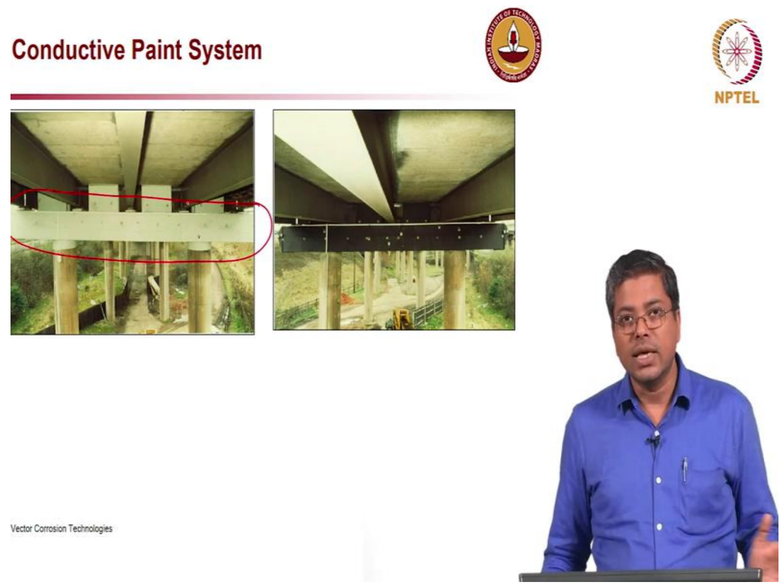

This is another example of where on surface you apply a conductive paint system, you can see on the right side is the preparation and on the left side a painted system., It is a completed work where you can see conductive paint on this. So instead of providing a mesh, it is basically a paint layer, a layer of paint which is actually conductive in nature.

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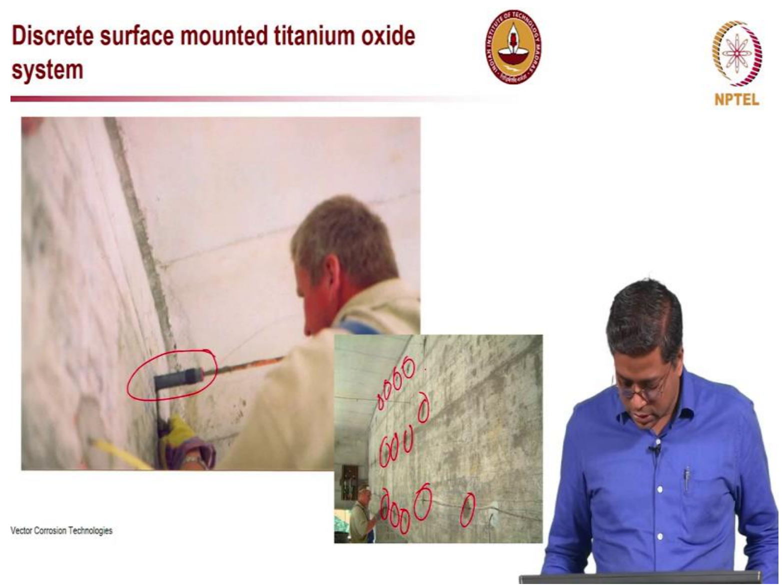

Now here its discrete surface mounted anodes. As you see here a lot of these anodes drilled into the concrete wall and then they are all electrically connected to make the system work. And that is that is how this system works.

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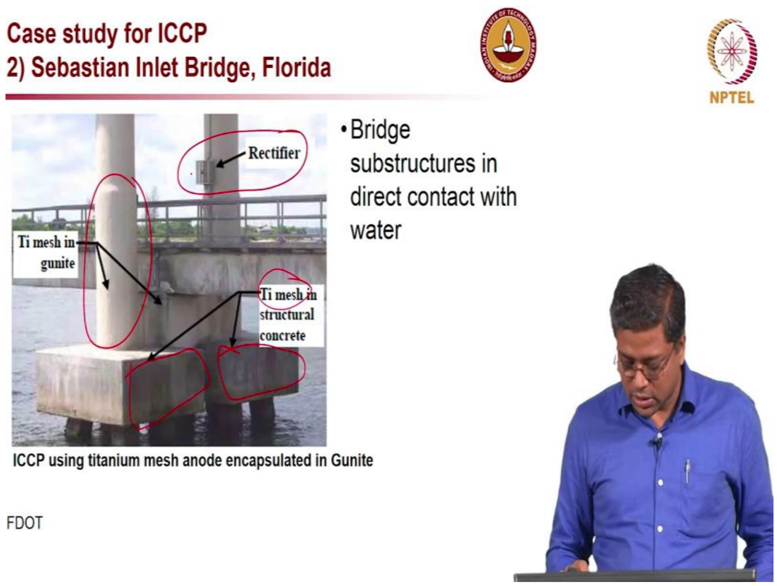

Now, this is another example where again exposed to water, you can see titanium mesh is embedded here inside this concrete, this portion here and after placing the titanium mesh it is covered with cementitious material and then you have a rectifier which provides the small amount of current which is required and continuously for a long period of time.

And that is the challenge which I was telling you earlier, how we have to make sure that this rectifier is well protected and it is active or functioning or in very good condition until the structure needs to be protected, without that functioning, the structure will not get any current.

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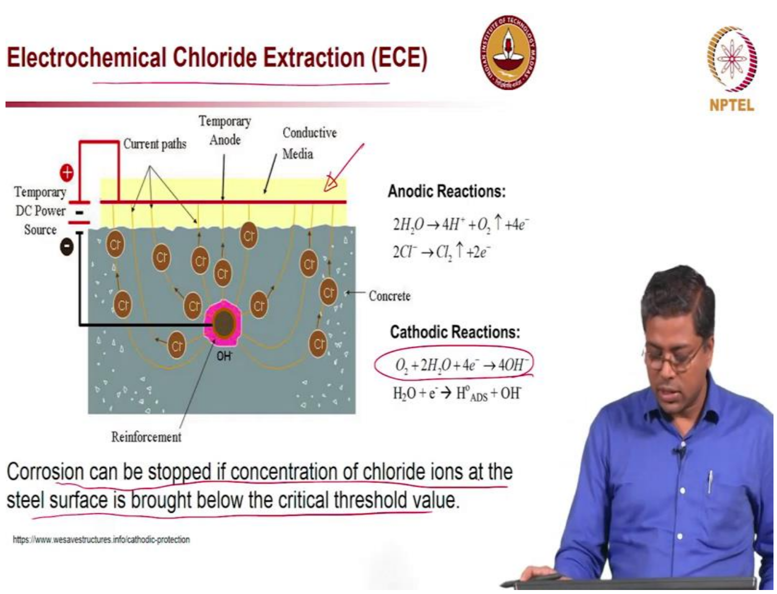

The second technique we are going to talk in this lecture is electro chemical chloride extraction. So, this is essentially when we talk about chloride rich environment, if the cover concrete has sufficient chloride already there in the structure or the cover concrete is rich in chloride. So, first thing to do is, if we can actually remove that chloride that is the best way to do it. So, this is one way of doing it.

Of course, there are challenges and then we have to see where these types of techniques can be applied and where it cannot be. So, all these techniques which we are talking like, sacrificial anode cathodic protection, impressed current cathodic protection, electrochemical chloride extraction and then one more we are going to talk is electrochemical re-alkalization, you have to make a judgment on which technique will be best suited for the particular type of application you are talking about so that you can have a durable repair in other words a durable repair without much of interventions in future.

So, let us see what is the principle behind is, you have the center rebar, you can see here this is the reinforcement, the center portion or inside the pink region is the steel reinforcement and the steel reinforcement is (the black line you can see) connected to a temporary DC power source where you can apply current or potential difference. And then there is a mesh which is placed that is the horizontal red line on the top and the yellow region is the conductive media which completes the electrical circuit. So when the current is applied or the potential difference is applied between the the red line and the rebar (which is the black line), and in this case the red is the mesh is connected to the, I am going to call it temporary anode or a mesh, the red one, it is connected to the positive terminal of the DC power source. And the reinforcement or the steel rebar, which is embedded inside the concrete, is connected to the negative terminal of the voltage source or DC power source. So, when it is connected like this, what happens is all these chloride ions, which are negatively charged ions, they tend to move towards the positive terminal which is the anodic mesh, which is the red one kept outside the concrete.

And then also you can see this pink color that is because of the cathodic reaction which we are talking here, cathodic reaction which happens at the steel surface, in this case steel is the cathode now, and that generates a lot of hydroxide ions or in other words, that increases the pH of the concrete surrounding the, just in the vicinity of the steel reinforcement. So, that also helps in making sure that even if there is some carbonation that is also highly alkaline.

But that is not the really the primary purpose of this process. The primary purpose is just to move all the chloride from the near the steel surface towards the outside. So, once you remove all the chloride, then we can forget about chloride induced corrosion, may be some other form but that is different, in this case idea is, if you are talking about a structure, which is exposed to chlorides and if you are sure that the corrosion is happening because of chlorides or if the corrosion is going to happen because of the presence of chloride, then this is a very good technique to adopt to remove all the chloride or to extract all the chloride from the vicinity of the steel reinforcement to outside the concrete and then you can say that now the structure is as it was on day one.

So, idea is corrosion can be stopped if concentration of chloride ions at the steel surface is brought below the chloride threshold or brought to a minimum value which was probably at the beginning or during the construction time.

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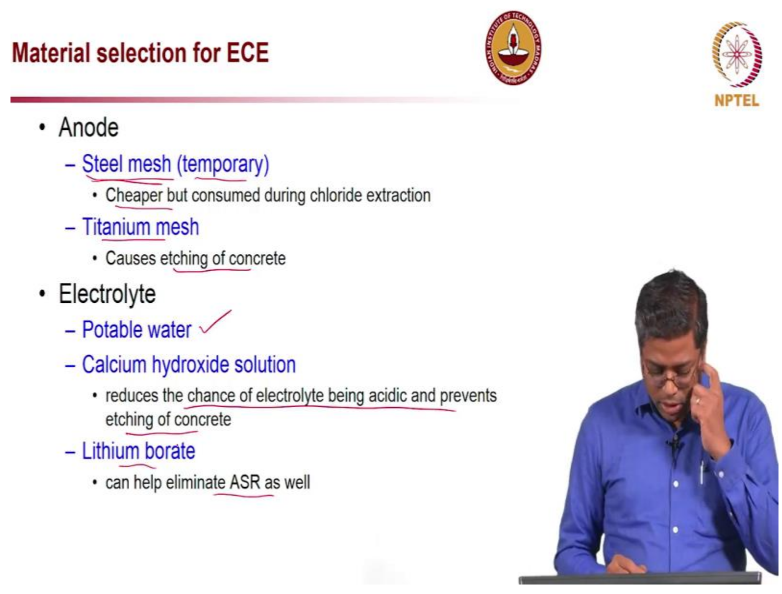

Now, let us look at what are the materials required for performing electrochemical chloride extraction. Basically in this in the previous slide, I showed a red line, which is essentially the anodic mesh for that we can use steel, it is sufficient because it is a temporary structure we are not going to keep that mesh permanently in the structure. In fact we are not even keeping it inside the concrete, it is staying outside the concrete as you see here. The mesh is kept outside but in a sponge or in a wet media or conductive media, the yellow region. Now, steel is cheaper and sometimes depending on the amount of chloride which is in the concrete, if have to really apply for a very long period of time, you may consume some of the steel during this process itself because steel is the anode here. So because of this reason, sometimes people also use titanium mesh because if you are thinking about repetitive type of work, maybe you don't want the anodic material to be consumed. So, you go for something which is very corrosion resistant and people are also used to titanium mesh, but which might sometime lead to etching of concrete also in other words removal of the concrete. So, you have to see what is the duration of voltage application required, then look at the cost implications also and then decide whether a steel mesh is sufficient enough, if so, go for it otherwise go for titanium mesh.

Now electrolyte, what is the type of electrolyte is this yellow region in this slide or the conductive media. Now, you need potable water or good quality water for making this calcium hydroxide solution. And which reduces the chance of electrolyte being acidic because when you say calcium hydroxide it gives to sufficiently high pH or a lot of hydroxide ions, and when it is not becoming acidic, it prevents the etching of concrete. Now, also other solution which is used is lithium borate solution, it can have an added feature of even eliminating ASR, if there is a case that both ASR and chloride there, then you can say lithium borate solution, but if you did not have an ASR issue, then you can go with calcium hydroxide or high pH solution can be used.

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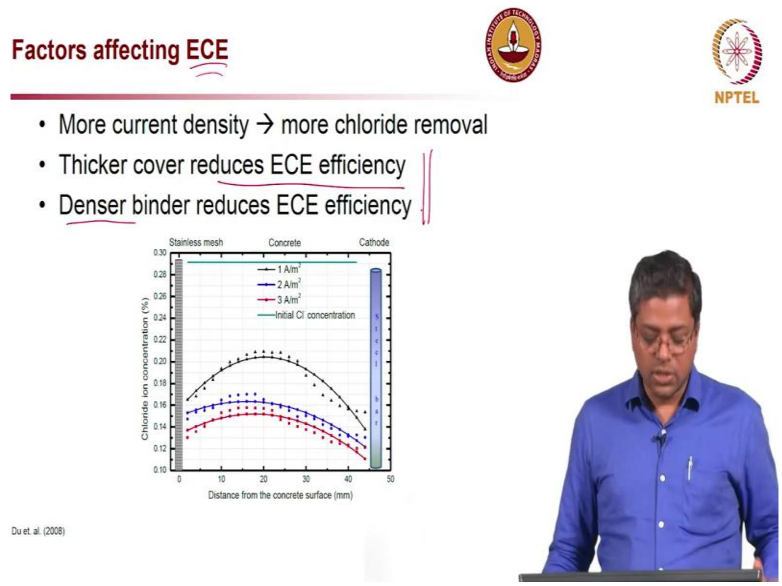

Now, this is an example and some of the factors that affect electrochemical chloride extraction, the more the current density it is logical to think that the more chlorides will be removed in shorter period of time. And, if your concrete cover is thicker, then also it reduces the efficiency of this process. So, in other words, if the concrete cover is thicker, maybe you will have to go for longer duration of the voltage application. And if it is denser, then also it reduces the efficiency then also in that case you may have to go for longer duration. So, in these two cases, you may have to go for longer duration of application of the voltage, but, theoretically this is all possible. The more you apply you can drive chlorides away from the steel and towards the concrete surface. Only thing is you have to really think whether if you apply it for too long period of time, it will create some other problem like what we discussed in the previous slide, etching of concrete or something like that. Possibility of such adverse effect also have to be thought through before you decide on going ahead with this technique. Now, I am going to show this graph here on a larger scale in the next slide.

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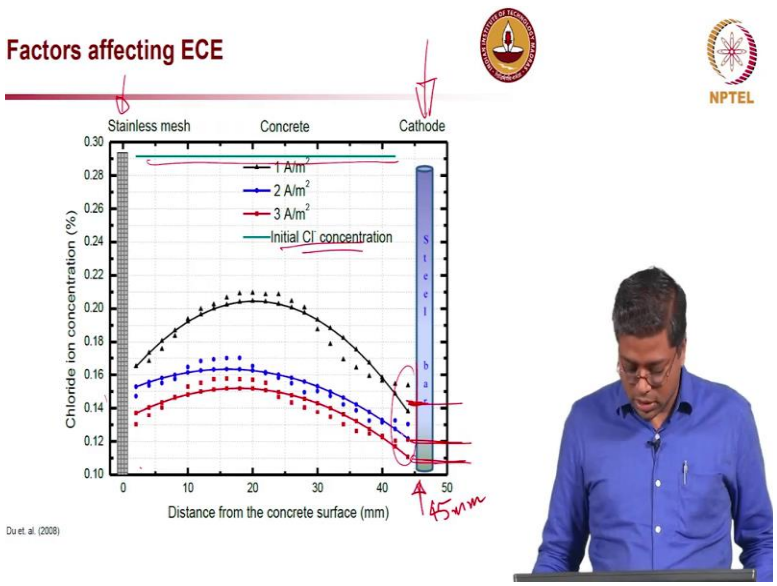

So this is the same graph, as you can see, this line here, on the top of the graph, you have a light greenish line and that is the initial chloride concentration. And on the right side, you see the steel rebar, and on the left side you have the mesh. So you can think the right side is the steel which is embedded and left side is the surface of the concrete where you have the stainless steel mesh or even just the steel mesh, you don't really need a titanium mesh. So, now here it is the on the horizontal axis, you can see the distance from the concrete surface. So, on the left end of the graph, you have the concrete surface, distance is zero. So you can say that this steel rebar on the right side is at about 45 mm deep. So, you can see here this is about 45 mm deep, which is about 2 inches, you can say just a little less than 2 inches.

So, you can see this graph when the current applied was 1 amp per meter square that is a black curve here, near to the surface that is towards the left side, more and more chlorides are removed but as you go towards the center, the amount of chloride removed is less. So this graph is showing the remaining amount of chloride.

So, you can see that in this region less amount of chloride is removed, here maximum is removed and also as you go very close to the steel also the residual or the remaining amount of chloride is less. See, in this case, you must think that the original concentration is uniform you see that this on the top line, it is very clear that original concentration is uniform across the cover depth or across the region from the surface towards the steel. And this method is able to drive the chlorides away from the steel as you see on right here. As you see near the reinforcement near the, the amount of chloride is very less as compared to the original chloride concentration which is about 0.3, this line here, so from 0.3 to about 0.14 or even 1.12, so significant reduction about we can easily say more than 50% reduction in the chloride concentration at this at the steel surface. So from, let us say, 0.15 and from 0.3 to 0.15 that is almost 50% reduction. In this case, if you take this point as the reference, if you are talking about 2 amp per meter square, then it is further less, if you are talking about 3 amp per meter square, it is further less. So the more the current you apply, definitely, the more reduction in the chloride concentration, so it is a good thing, especially when we are talking about chloride extraction.

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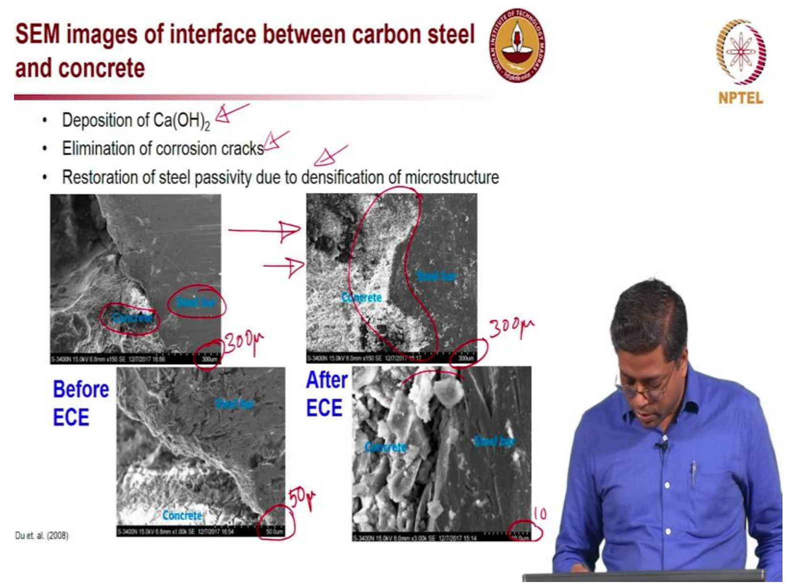

This is some proof on what is happening at the microstructure level, you can see that calcium hydroxide is getting deposited at the steel concrete interface and also some cracks which were present is filled up and the passivity is also reinstated or restored. So, you see here before electrochemical chloride extraction on the top left image you can see concrete here and steel rebar and after is it something like this. So, this is a before case also you can see a zoomed out image this is 50 microns case, these are 300 case and here it is only 10 microns. So, when you compare any micro graphs, you must first look at what is the scale on the micro graph and then only you should make conclusions out of it.

So, now, let us compare the top two graphs here as you go from left to right. So, you can see here, the left one is before the application of ECE or electrochemical chloride extraction and the right one is after the application of ECE, you can see that this region is relatively dense or it is filled with calcium hydroxide crystals and we can very clearly see that there are some calcium hydroxide crystals in the image.

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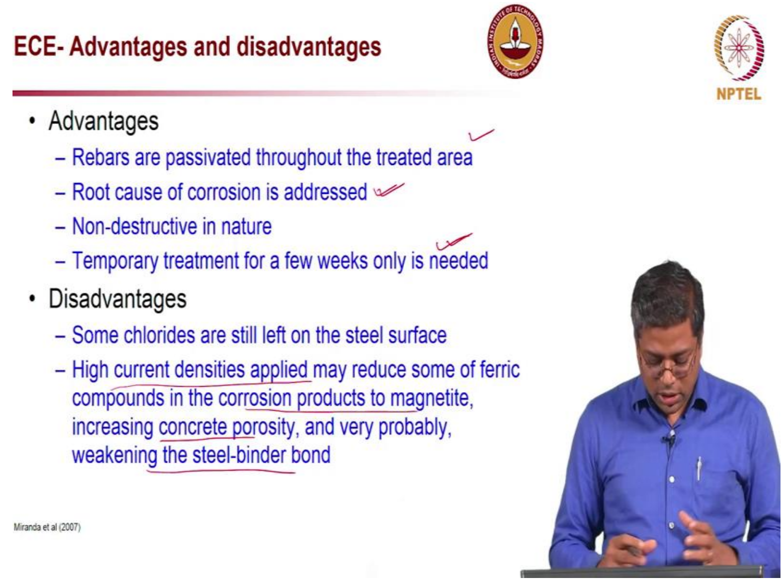

Now, let us look at the advantages and disadvantages of electrochemical chloride extraction. So, some of the advantages are, the rebars are passivated throughout the treated area because you are using mesh to do this, so, almost all the region gets equivalent treatment, and root cause of the corrosion is chloride which is actually addressed, so the chlorides are removed, and then it is non-destructive in nature, it does not really damage the steel rebar, which is embedded or even the concrete. And it is a time required is very less for a few weeks, you can actually extract all the chlorides. So it is a very good repair strategy in a way, if you are able to do this before the corrosion starts, then it is very good thing to do. But the problem is sometimes we cannot do this on all the structures which we have, depending on the shape and size of this structure.

And some experiments have already proven that some chlorides are still left behind on the steel surface, so in such cases a prolonged application of voltage is required and also high current densities when apply, it may reduce some of the ferric compounds in the corrosion products to magnetite, which increases the porosity which means the volume of this corrosion products reduced, when it reduces and it means increasing the porosity and very probably weakening the steel binder bond also. So, these things might happen. So, you had to be cautioned about all this but these are very good techniques to adopt.

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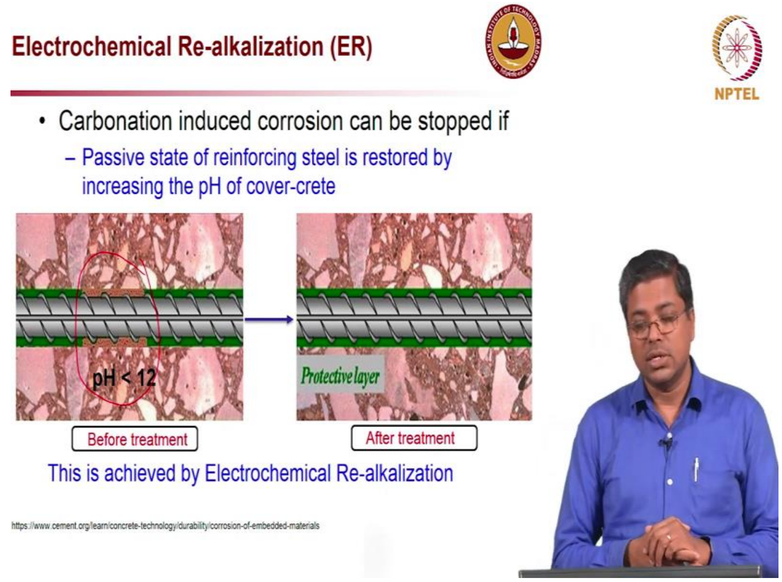

The third technique which we are going to talk today is electrochemical re-alkalization. This is a technique which can be applied when the concrete structure is exposed to carbonation in a region with high concentration of carbon dioxide. So, on the picture on the left side we are showing it as the center portion, you don't see that green patch, it's basically the region with a low pH and as it is on the right side, the picture shows after the treatment that portion which was having a low pH is also now having a high pH. So, when you have a high pH the steel is protected, when you have a low pH that steel is not protected. So, you have to re-alkalize that portion, which is having a low pH so, that the steel can be protected. So, how can do we do this?

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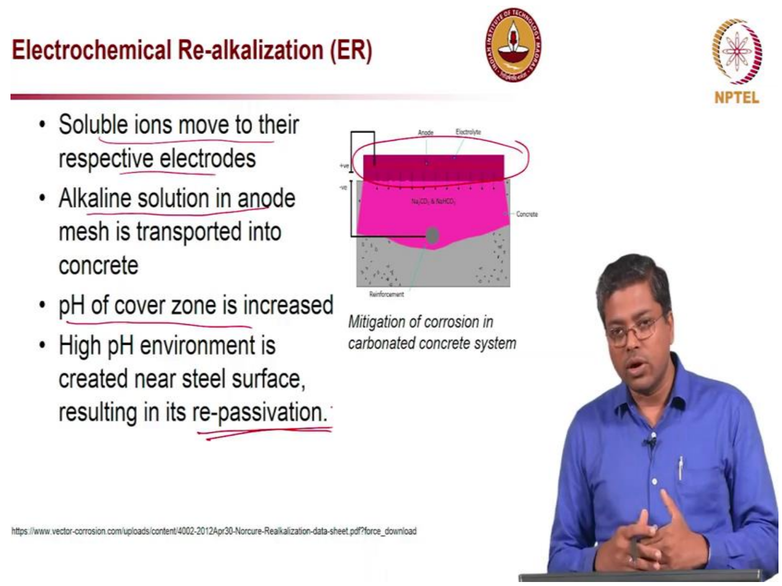

This is the way how which it can be done, this is schematic showing, which is very similar to the schematic in the previous technique which was on electro chemical chloride extraction. You can see an anode here which is the red line through the electrolyte, this line here, and you can see electrolyte and as the current is supplied or voltage potential difference is applied, the concrete cover region gets re-alkalized or gained sufficiently high pH, so the entire steel now is very well protected, in other words, the region around the steel reinforcement is pink in color that indicates the pH of that concrete around the steel reinforcement is sufficiently high to protect the steel from corroding. Now, so, how it works, soluble ions move to their respective electrodes. In other words, in this case, all the hydroxide ions will move towards the, reinforcement or go into the concrete and thereby the pH of the concrete is increased. So, alkaline solution is provided here, this is the alkaline solution in the anode mesh is transported into the concrete. Now because of this application, the pH of the cover zone is enhanced or increased until the steel is protected from corrosion. So, high pH environment near the steel reinforcement results in re-passivation. In other words, the passive layer which was originally there got broken because of a lowering of the pH. Now, with this treatment, the pH is increased and the passive layer is rebuilt or re-passivation happens.

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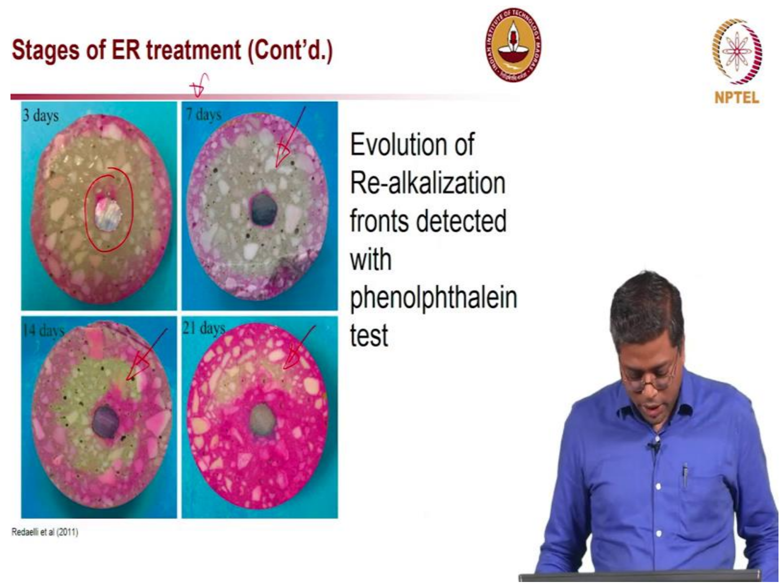

So, this is the step so, in the beginning the system will look something like this. So, here you have highly carbonated concrete and in the step two when you apply voltage, the similar way as we saw in the chloride extraction technique because of the cathodic reactions, some alkaline environment is formed around the steel also, but mainly this progression of this alkaline front is moving towards the reinforcement is also important. And then eventually the entire cover region is completely re-alkalized or in other words, the pH of the entire cover region is now very good, especially the region around the reinforcement. These are some examples showing how a laboratory experiment, it is done in Italy polytechnic of the Milano, you can see here, evolution of re-alkalization front. In the very beginning because of the cathodic reaction at the steel surface, you can see some amount of re-alkalization happening and it is progressing in 7 days, so you can see the pink front moving towards the center of the cylinder, and here you can see further moving down here is almost it is re-alkalize. So, about 21 days you can get a cylinder like this re-alkalize. So, if you have a similar cover concrete in a real structure, you can decide how long you have to apply the current and at what voltage you have to apply.

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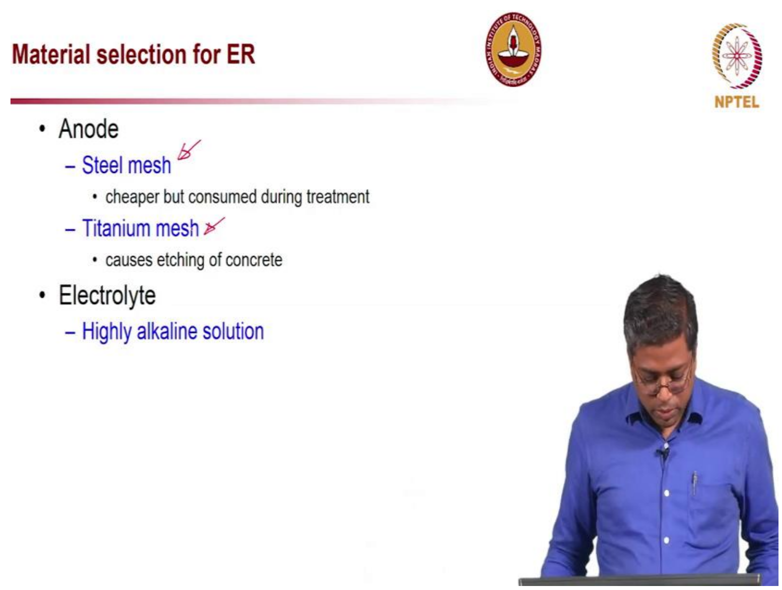

Now, what are the materials required, again like chloride extraction, steel mesh is good and titanium mesh is also used, but the same thing what I discussed in chloride extraction, those kind of concerns should be looked at, whether money and other technical issues and then you can decide and a electrolyte is required, for that highly alkaline solution is required.

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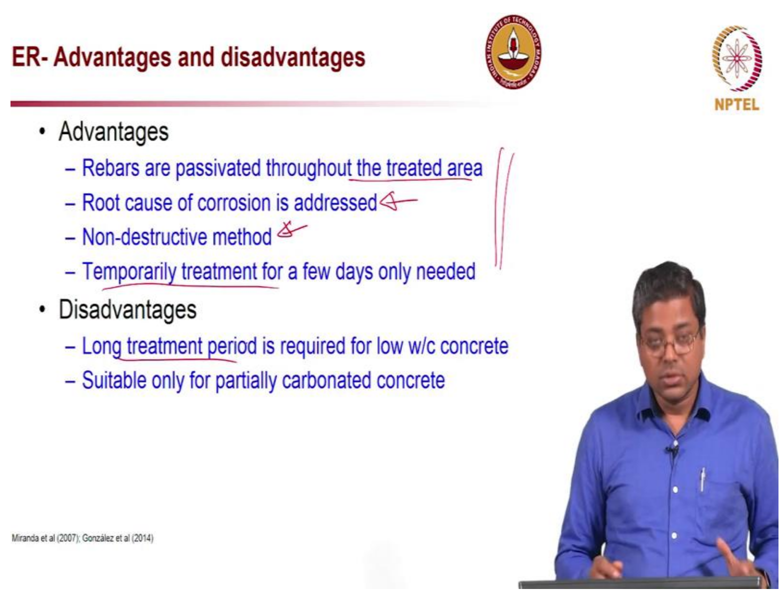

Now, what are the advantages of electrochemical re-alkalization technique? Now, advantages are very similar to that what is we saw in the case of chloride extraction. You can see rebars are passivated throughout the treated area, because you were using a mesh so every region is getting passivated. Root cause is addressed, that is the main thing in the entire course, we have been talking about address the root cause first for any damage or any deterioration you are talking.

Here the root cause for the corrosion of the steel is carbonation in other words the reduction of pH. Now by this application, we are increasing the pH level at the steel surface, by which the passive layer is reformed and protects the steel, definitely a non-destructive method and temporary treatment, temporary treatment for a few days is only required. Now, disadvantages are long treatment period is required for highly resistive low water cement ratio concrete and suitable only for partially carbonated concrete.

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Now, I am going to show you some examples.

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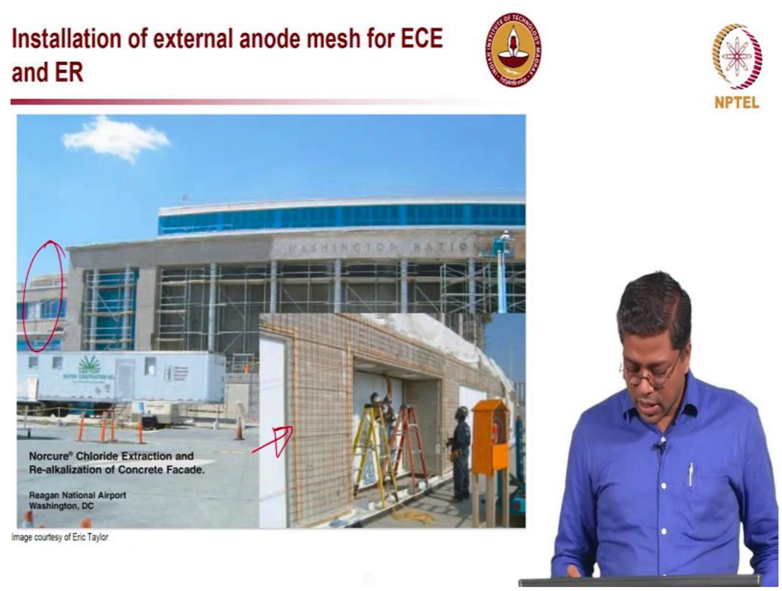

This is an airport in US where you can see, this portion on the bottom right as the close up region, you can see a lot of steel mesh is provided and then chloride is extracted. And see in this case, both chloride extraction and re-alkalization happen, two things are done at the same time.

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And then this is a close up image. So one point here is, if the steel rebars have very limited cover, then when you go for re-alkalization you don't want to apply more current to that particular steel, which might create additional problems. So, sometimes we need to insulate the regions with which are having very small covers.

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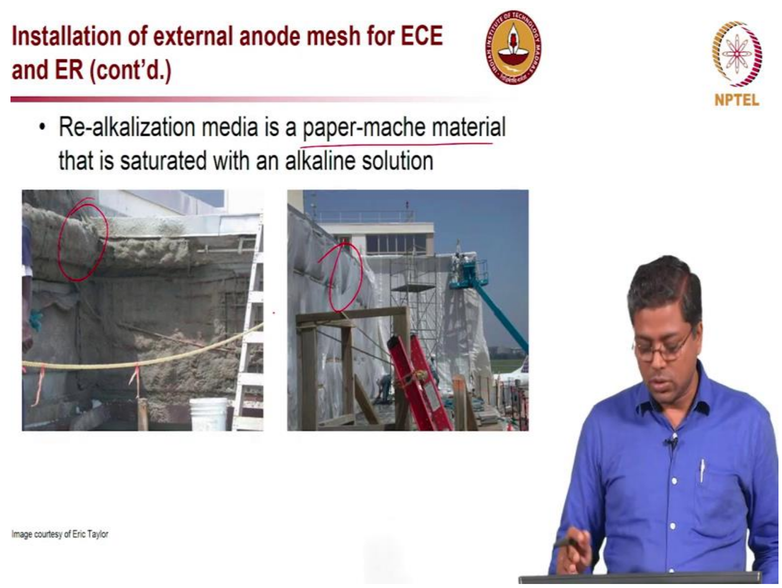

Now, this is the type of material you can see, it is a paper-mache material which can hold a lot of this alkaline solution and as you apply the current and it is very easy and also removal also is easy. It is just something which can be removed and come as waste. So, in other words, very easy technique to apply depends again on the type of locations and when I say very easy, it does not mean very easy, but compared to other techniques. And if you have a relatively easy to work with surfaces, then these kinds of techniques are very useful.

You can see here this is the paper-mache which is applied, then saturated, then covered and then the current is applied. Why it covered is that you want to keep it wet, sometimes it takes weeks, so, you don't want the material to dry. So, you have to keep it covered.

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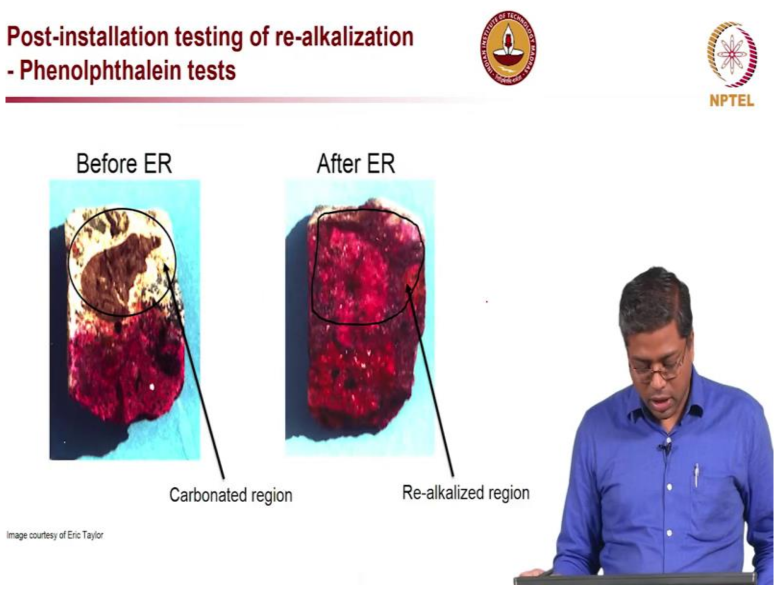
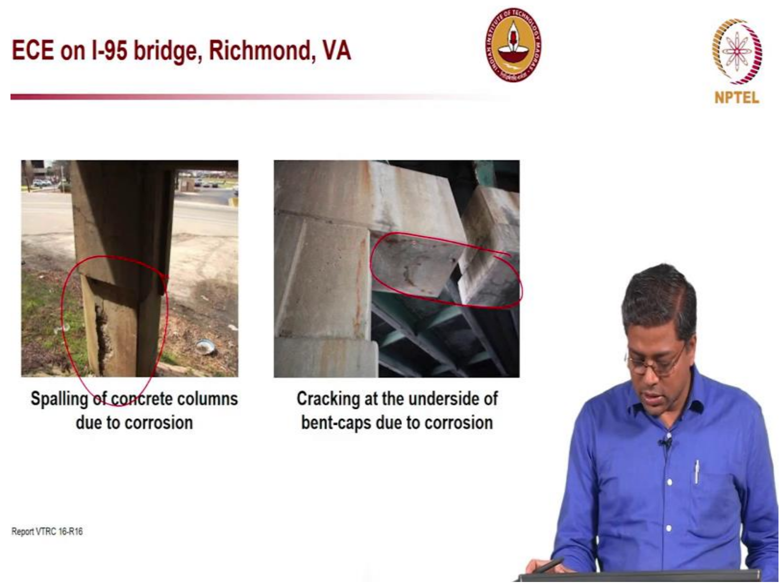


So, this is an example or a proof showing that these kinds of techniques really work. On the left side you can see before the electrochemical re-alkalization. So, the phenolphthalein test indicating this much region is actually fully carbonated. And here you can say after the treatment, that region is now fully re-alkalized or the pH is above 9, 10 that range so that steel is protected. **(Refer Slide Time: 37:56)**



This is an example where electro chemical chloride extraction was applied and you can see here the picture with heavily spalled concrete column on a bridge and in the same bridge, concrete bent caps are also corroding. And this was very clearly the based on the preliminary test, it was found that chlorides are the root cause for this corrosion. So, hence it was decided to remove the chlorides or address the root cause first. Removed the chloride using this electrochemical chloride extraction technique

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And as you see on this picture here, bottom right you can see a lot of this electrical units and the entire bent cap is also, the paper-mache is kept and are applied and then it is covered with plastic sheet to prevent evaporation or maintain the moist environment and then the current is applied. And you can see that this kinds of techniques are applied on large scale structures. Of course, you have to really think about different techniques and which is the best techniques that can be used for case to case basis.

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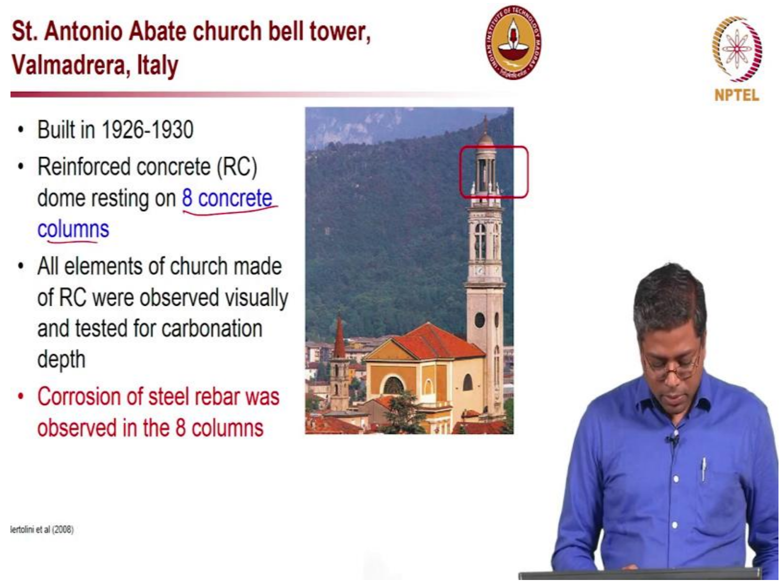

Now this is an old church, as you see on the bottom top right, the red box, there were 8 concrete columns, which were supporting the dome of this church. And it was found that this was completely carbonated. So, the, electro chemical re- alkalization technique was adopted in this, I am going to show you some picture on the next slide, close ups.

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But, so here you can see how it is corroded and then you can see here corrosion. So, there were lot of places where corrosion was observed and being a heritage structure, they really wanted to remove all this chloride or address the root cause first before any repair is done.

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So, in that approach, initially the patchwork was done and then re-alkalization technique was adopted and made sure that the concrete cover is completely free from low pH environment or it is having high pH to protect the reinforcement inside, you can see here a mesh is used to apply this electrochemical re-alkalization technique.

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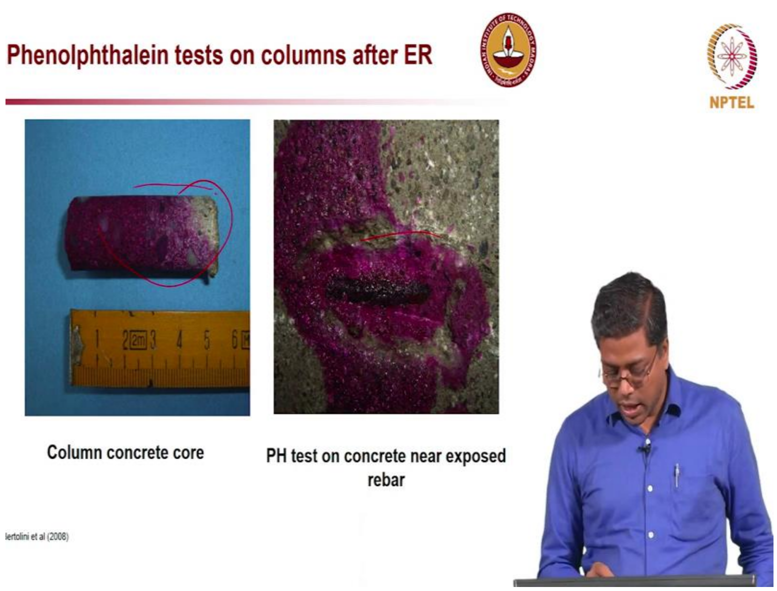

This is again for the same concrete column initially, concrete cores were taken out and it was found that carbonation was the reason and also after the treatment, you can see some of this region just near the reinforcement now well protected or the pH is very high near the reinforcement.

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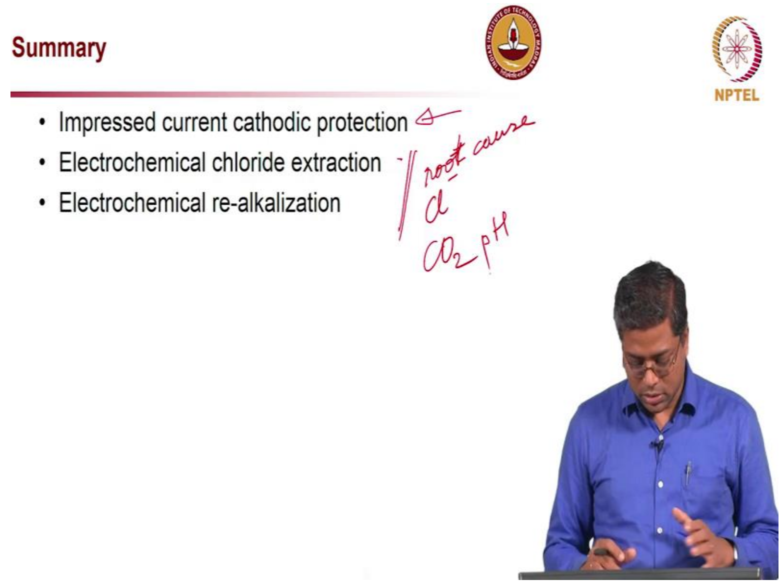

So, to summarize, we looked at mainly these three techniques, impressed current cathodic protection, then electro chemical chloride extraction and also looked at electrochemical re-alkalization. So, impressed current cathodic protection can be adopted when you have a very good system to monitor the performance of the system over a long period of time. In other words, if the because of these electrical units which are installed at site and we need to ensure that those electrical units don't get degraded or damaged or you know, stolen by somebody. So, if such things can be ensured that they don't get stolen and they are really working well and if the corrosion rate is very high this system works better than the sacrificial anode cathodic protection. But because when you talk about these types of repair, we are talking 20 to 25 years of life and in such a long period of life if the system has to work, you have to ensure that the system and the components are also protected very well.

Then we were looking at electro chemical chloride extraction, which is mainly addressing the root cause. So, in the last two techniques we are mainly addressing the root cause, that is in one case it is chloride in in the other case it is CO_2 or the pH. So, electro chemical chloride extraction is very good when you want to protect the structure from further corrosion for a long period of time and works very well if it is done before the corrosion starts. So, again as a preventive maintenance technique, this can be very good, both these can be very good and electrochemical re-alkalization also can be looked at as a preventive technique. And it is very good when you want to protect the steel for very long period of time by re-alkalizing the steel and protecting the steel from corrosion.

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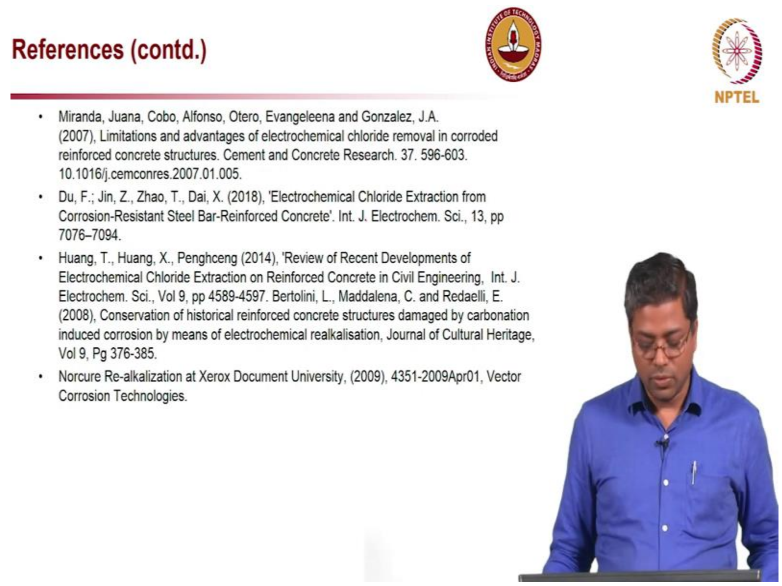

And these are the references which we used two slides on that and with that we end today's lecture. Thank you.