Retrofitting and Rehabilitation of Civil Infrastructure
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Lecture 15
Repair Techniques (Continued)

Hello friends, welcome to the NPTEL online certification course on Retrofitting and Rehabilitation of civil Infrastructure. Today we will discuss module C, the topic for module C is general repair and retrofitting of concrete structures.

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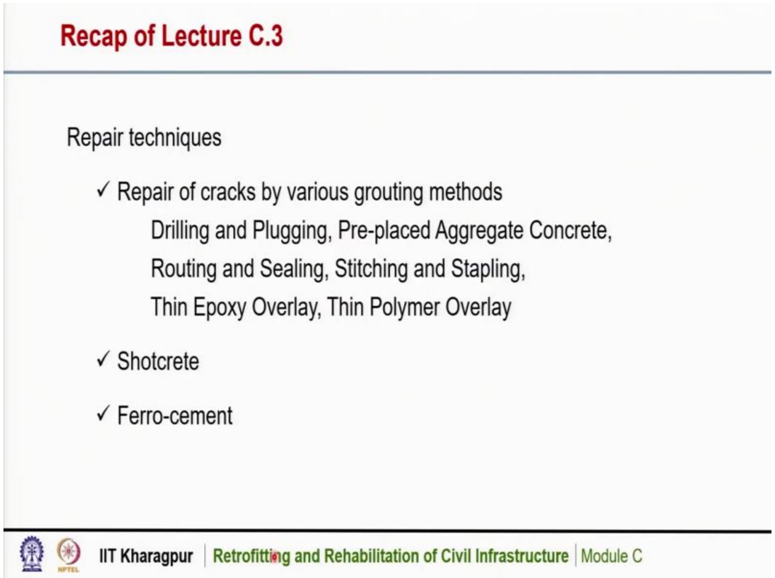

In the previous lecture, we have discussed several repair techniques. We have discussed the repair of cracks by various grouting methods like drilling and plugging, pre-placed aggregate concrete, routing and ceiling, stitching and stapling, and thin epoxy and polymer overlay. We have also discussed shotcrete and ferro-cement, which are effective repair technique for existing structures.

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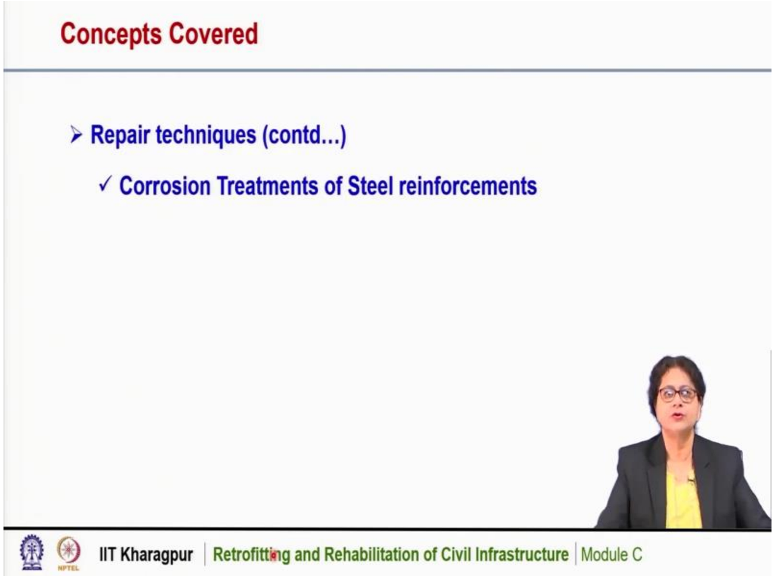

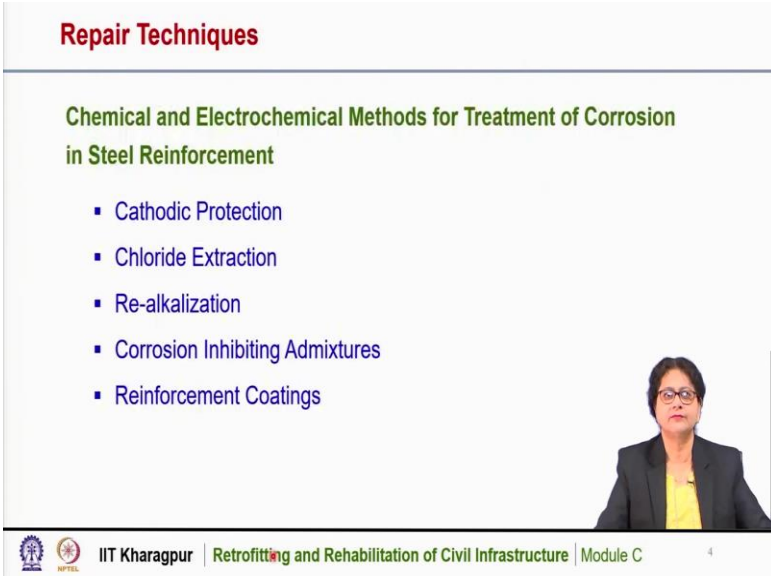

Today, we will continue the repair techniques; we will discuss several corrosion treatments of steel reinforcement in existing structures. There are several chemical and electrochemical methods for treatment of corrosion of steel reinforcement. We will discuss the cathodic protection, chloride extraction technique, realkalization and also we will discuss the corrosion inhibiting admixtures and reinforcement coatings which are used to treat the corrosion in reinforcement.

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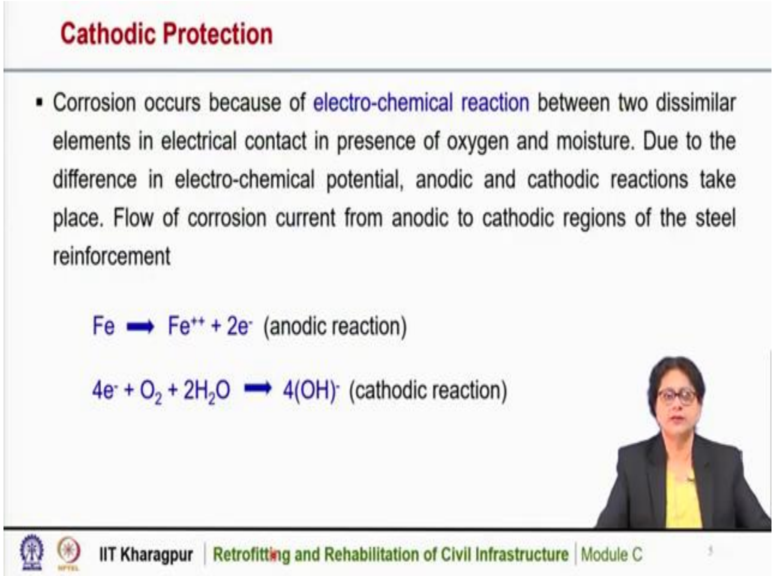

Before discussing the corrosion protection technique by cathodic protection, let us just recap the corrosion method. Corrosion occurs because of the electro-chemical reaction between 2 dissimilar elements, when they are in electrical contact in presence of oxygen and moisture. Due to the difference in the electrochemical potential, anodic and cathodic reactions are taking place.

And there is a flow of corrosion current from the anodic region to the cathodic region of the steel reinforcement. In the anodic reaction, we can see here that Fe ions are form and in the cathodic reaction the OH ions are formed. So, there is a flow of current from the anodic region to the cathodic region. Thus, the Fe ions are flowing to the cathodic region. Thus, there is a loss of material under steel reinforcement.

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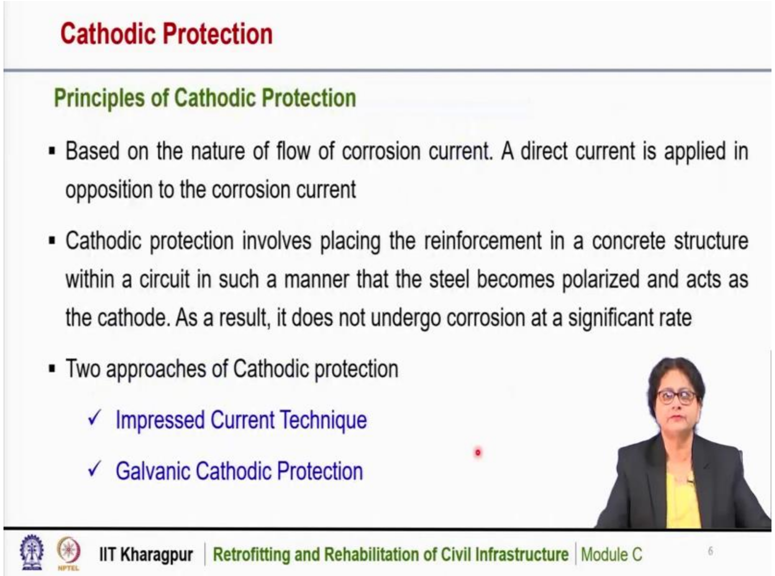

The cathodic protection principle is based on the nature of flow of corrosion current. Here in this technique a direct current is applied in opposition to the corrosion current. Corrosion treatment is done in this cathodic protection that involves placing the reinforcement in a concrete structure within a circuit in such a manner that the steel becomes polarized and acts as a cathode. As a result, it does not undergo corrosion at a significant rate.

So, here we are making the steel reinforcement behaving as cathode instead of anode as is done normally in case of corrosion reaction. Here the steel behaves as a cathode. So, it does not undergo corrosion at a significant rate. Cathodic protection may be of 2 types or we can use 2 approaches for cathodic treatment. One is impressed current technique and the other is galvanic cathodic protection.

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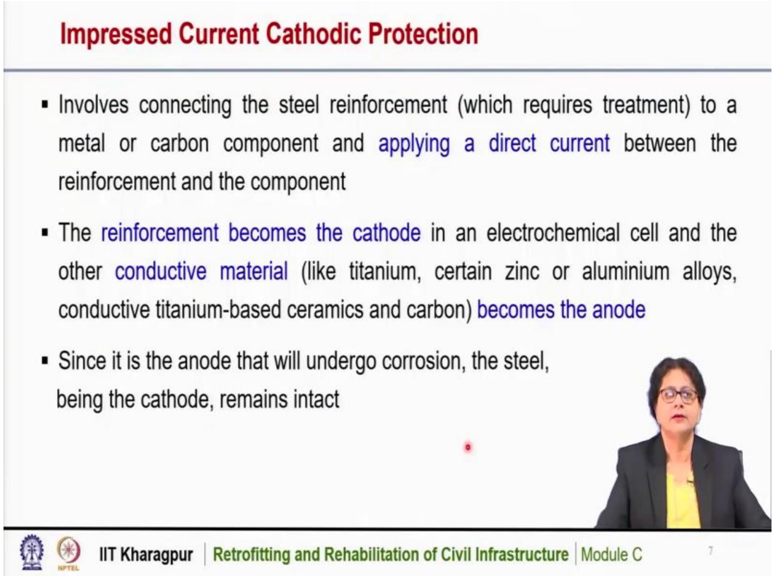

In impressed current cathodic protection, the method involves connecting the steel reinforcement to a metal or carbon component and we apply the direct current between the reinforcement and the component. So, the reinforcement becomes the cathode in the electrochemical cell and the other conductive material behaves as an anode.

The conductive material that is used in cathodic protection are titanium or certain zinc or aluminum alloy or conductive titanium-based ceramic or carbon, etcetera. So, these conductive materials are behaving as anode and the steel behaving as a cathode. So, the anode is undergoing the corrosion and the steel since it is behaving as a cathode, remains intact and does not corrode.

So, in impressed current cathodic protection technique, we are introducing a direct current between the reinforcement and the component. Thus, the reinforcement behaves as a cathode. So, it does not undergo corrosion and this is an effective method and we will see the working principle here.

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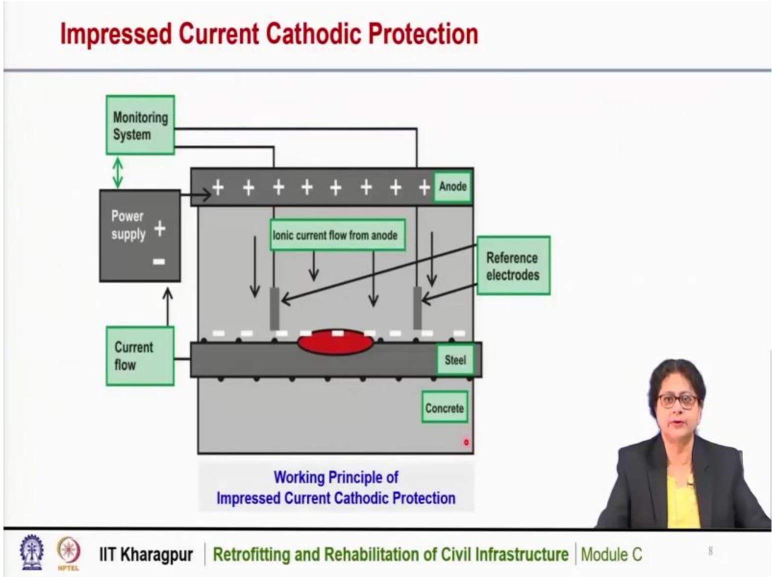

This is the working principle of impressed current cathodic protection. You can see here this is the existing concrete structure and this is the steel reinforcement, this part is the portion which is affected due to corrosion. Now, power supply is attached to the external anode and that is connected to this external anode and the reinforcement. There are 2 reference electrodes.

And since, the reinforcement is now behaving as a cathode, so, there is a movement of ions from the anode to the cathode. So, the steel is protected, there is no flow of current or flow of ions from the reinforcement to the cathodic region, because this behaves as a cathode. So, the flow of ions is from the anode to the cathode. So, it is opposite to the conventional corrosion current.

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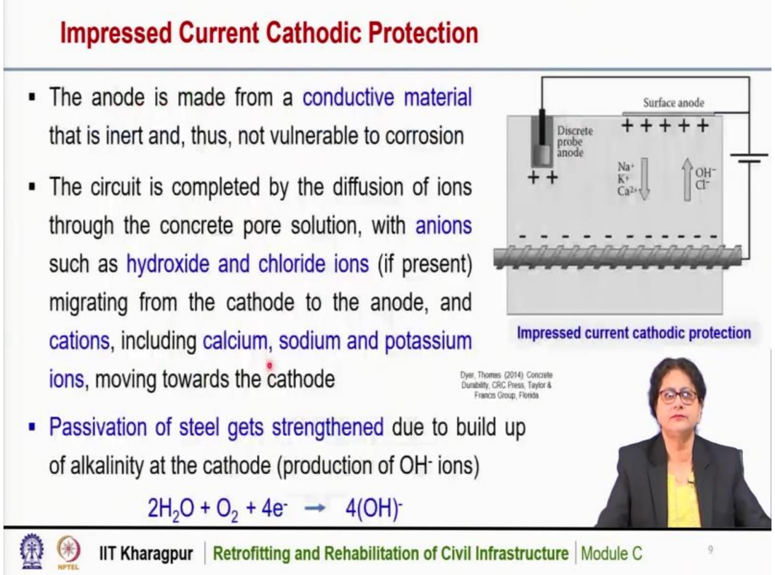

The anode is made from a conductive material in case of impressed current cathodic protection and the conductive material is inert and thus is not vulnerable to corrosion. The circuit is completed by the diffusion of ions through the concrete pore solution with anions such as hydroxide or chloride ions migrating from the cathode to the anode and cations including the calcium sodium or potassium ions moving towards the cathode.

So, we can see here that this is the existing concrete and this is the steel reinforcement which is now behaving as a cathode and this is the anode which is attached at the surface of the concrete. So, this is the surface anode and this is the power supply which is connecting the anode and the cathode and there is a movement of ions from the reinforcement to the anode.

This is the reaction that is taking place at the catalytic region, the OH ions are formed and that OH ions is moving from the reinforcement to the anode and the flow of ions, the metal ions from the surface anode to the reinforcement. So, the circuit is completed and by the diffusion of ions with anions such as OH and chloride, if chloride is present, due to chloride induced corrosion they are migrating from the reinforcement to the surface anode.

And the cations that is the Na or K or Ca ions, they are moving towards the cathode that is the reinforcement. So, the passivation of steel gets strengthened due to the buildup of the alkalinity at the cathode, because the OH ions are formed here. So, the alkalinity is also increased with the increase of the pH level. So, this is the schematic diagram of the impressed current cathodic protection technique.

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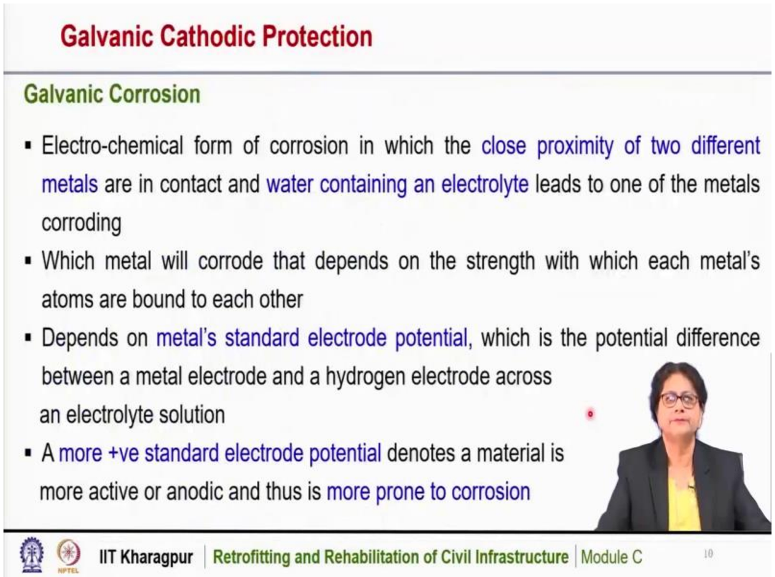

In case of galvanic cathodic protection, we will discuss first the galvanic corrosion. The galvanic corrosion is the electrochemical form of corrosion in which the close proximity of 2 different metals are in contact and water containing an electrolyte leads to one of the metals corroding. So, which metal will corrode that will depend on the strength with which each metals atoms are bound to each other.

It depends on the metal standard electrode potential, which is the potential difference between a metal electrode and a hydrogen electrode across an electrolytic solution. So, here in the galvanic corrosion takes place when there is close proximity of 2 different metals, they are very close contact to each other and water containing an electrolyte and that leads to the corrosion of one metal. The metal which is more positive standard electrode potential denotes the metal is more active or more anodic.

So, that metal will corrode. So, it will depend on the strength of each atom. Each metal atoms are bound to each other and also on the metal standard electrode potential. So, of the 2 metals which is more positive standard electrode potential that indicates the material is more active or more anodic and so, that metal will corrode, the other metal will not. So, this is the principle of galvanic corrosion.

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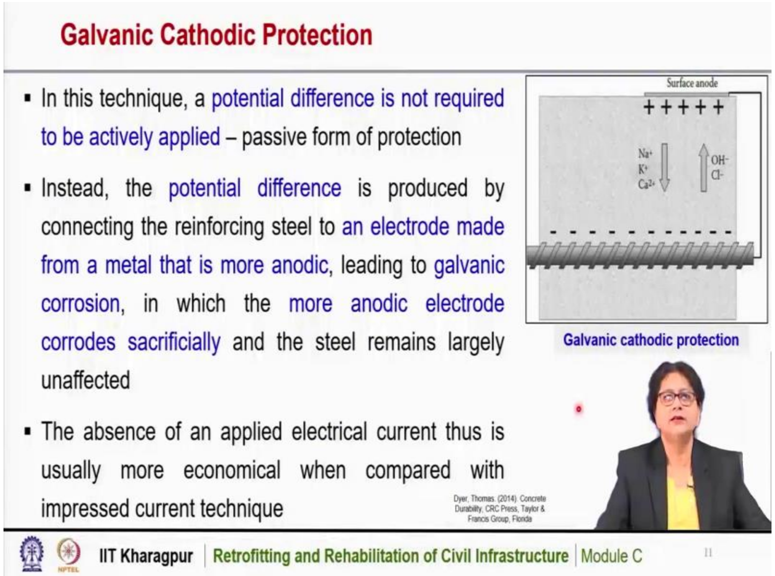

And in galvanic cathodic protection we consider this principle. So, in this technique a potential difference is not required to be actively applied like it is done in the impressed current technique an external power supply is needed, but here it is not required. So, it is a passive form of protection we can call it. Here the potential difference is made by placing another metal which is more anodic. So, instead the potential difference is produced by connecting the reinforcing steel to an electrode made from a metal that is more anodic.

So, that is the surface anode and that is to be placed and that leads to the galvanic corrosion. So, the metal which is placed as a surface anode, that will undergo corrosion and more anodic electrode corrodes sacrificially under steel remains largely unaffected. So, here in galvanic cathodic protection, we are using another metal which is more anodic, so it behaves as an anode and steel behaves as a cathode.

So, this is also called a sacrificial anode, because from that anode the ions are migrating. So, they are sacrificial anode and the steel behaves as a cathode. In this galvanic cathodic protection, the absence of an applied electric current leads to the more economical as compared to the impressed current technique.

So, here we can see that this is the schematic diagram of the galvanic cathodic protection. This is the steel reinforcement, which is to be treated that is present within an existing concrete and a surface anode is placed and this is the sacrificial anode and since, steel behaves as the cathode, so there is a production of OH ions and if chloride is also there, that will move to the anode. So, from the steel they will move to the surface anode and the metal ions are moving from that to the reinforcement. So, the steel is unaffected and this surface anode actually corrodes.

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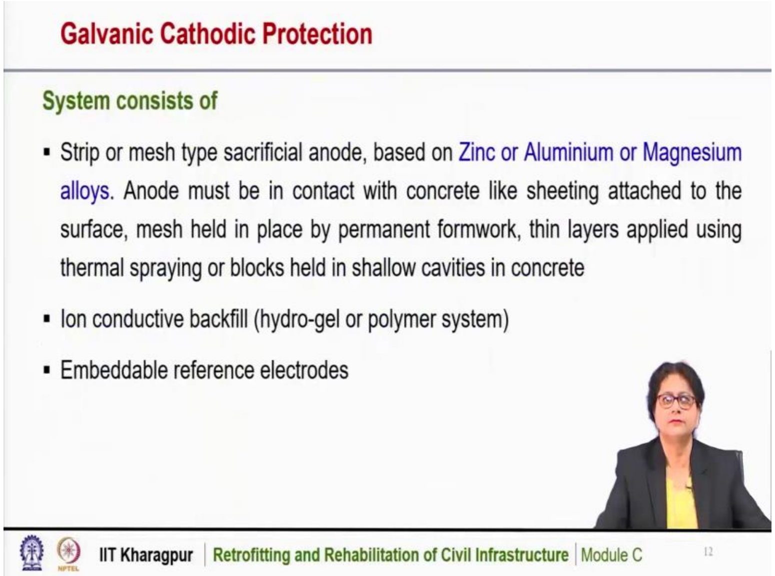

In galvanic cathodic protection the system consists of a strip or mesh type of sacrificial anode based on zinc or aluminum or magnesium alloys. So, the sacrificial anode is generally of zinc or aluminum or magnesium alloy and the anode must be in contact with concrete like sheeting attached to the surface or a mesh held in place by permanent formwork or thin layers applied using thermal spraying or blocks held in shallow cavities, in concrete etc. The system also consists of an ion conductive backfill and embeddable reference electrodes.

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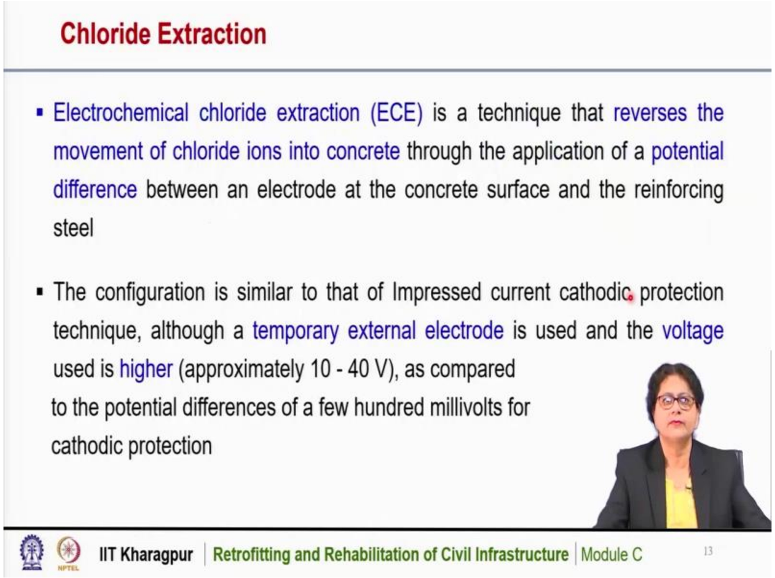

So, cathodic protection is an effective treatment for corrosion of steel reinforcement. Another treatment is chloride extraction. Electrochemical chloride extraction or ECE is a technique that reverses the movement of chloride ions into concrete through the application of a potential difference between the electrode at the concrete surface and the reinforcing steel.

In most of the cases when it is the corrosion taking place due to the action of chlorides, so chloride ions are formed or chloride ions are there on the reinforcement and in chloride extraction technique, it reverses the movement of chloride ions into concrete and this is done by the application of a potential difference between the electrode at the concrete surface and the reinforcing steel.

The configuration is similar to the impressed current cathodic protection technique, although a temporary external electrode is used, and the voltage used is much higher here, approximately 10 to 14 volts as compared to the potential difference in case of cathodic protection, which is of a few 100 millivolts.

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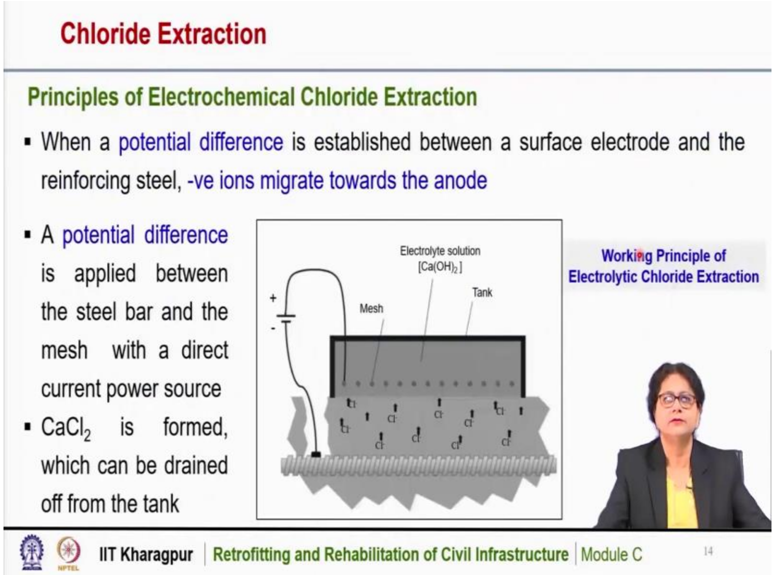

The principle of electrochemical chloride extraction is shown here in this diagram, then there is a potential difference is established between the surface electrode and the reinforcing steel, negative ions migrate towards the anode. So, here we can see that since the reinforcement is corroded due to chloride, so there are chloride ions and because of this potential difference there is a migration of the negative ions which is the chloride ions from the reinforcement to this anode.

Now, a potential difference is applied between the steel bar and the mesh with a direct current power source, we can see here that power source is there and there is a flow of current and a potential difference is applied between the reinforcement and the anode. So, on the concrete surface a tank is placed which is filled up with electrolyte solution and in case of chloride extraction, calcium hydroxide electrolytic solution is used and with that reaction there are formation of calcium chloride and which can be drained off from the tank.

So, when it is attached with an electrolyte solution and there is an electric power supply, the potential difference is established between the steel bar and the mesh and then there will be a migration of the negative ions, negative chloride ions. We can see here from the steel bar to the anode and then the steel is protected from a chloride.

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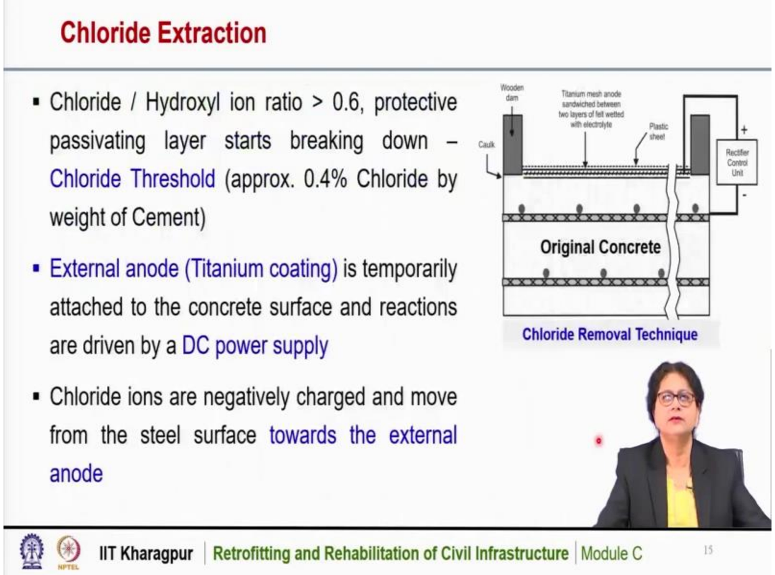

Chloride or hydroxide ion ratio when it is more than 0.6, the productive passivating layer starts breaking down. So, there is a chloride threshold which is approximately 0.4 percent of chloride by weight of cement and due to the chloride induced corrosion when the chloride by hydroxide ion ratio exceeds 0.6, then the passivating layer starts breaking.

So, here in this case in case of chloride extraction, the external anode is temporarily attached to the concrete surface and reactions are driven by a DC power supply. So, here we can see that this is the existing concrete and these are the reinforcement and there is a power supply. This is the external anode and titanium coating is a commonly used external anode in case of chloride extraction that is placed on the surface of the concrete and there is a potential difference.

So, when there is a potential difference between the 2, then chloride ions are moving from the reinforcement to the anode. So, chloride ions are negatively charged and moved from the steel surface towards the external anode. So, thus chloride is extracted from the existing corroded steel reinforcement.

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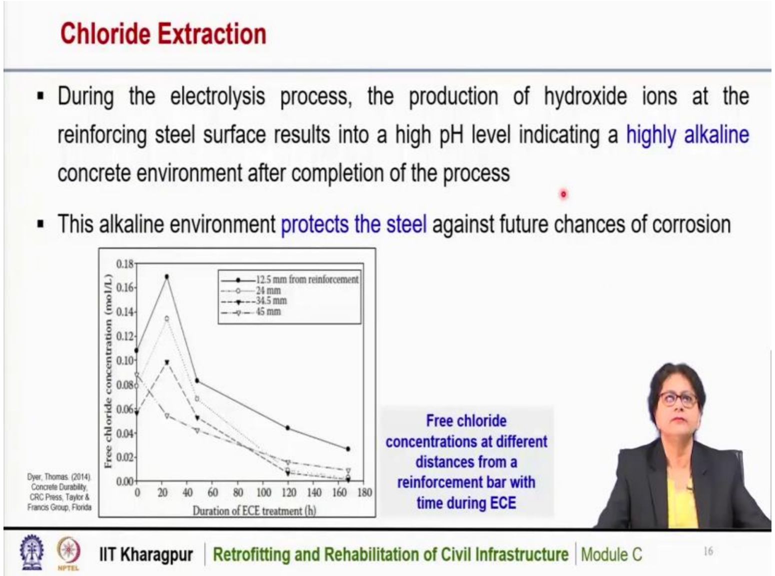

During the electrolysis process, the production of hydroxide ions at the reinforcing steel surface result into a high pH level, indicating a highly alkaline concrete behavior after completion of the process. So, OH ions are formed because that is the cathodic region, OH ions are formed and that results into the high pH level or the high alkalinity in that region. This alkaline environment protects the steel against further chances of corrosion.

So, here in this diagram, we can see that the variation of the duration of ECE treatment with the free chloride concentration at different distances from the reinforcement bar with time during the extraction process. So, we can see here that as the duration increases, the chloride concentration is reduced. So, at different depths from the surface also the chloride concentration is reducing over time. So, this is due to the chloride extraction. So, it can effectively reduce the chloride concentration near the reinforcement.

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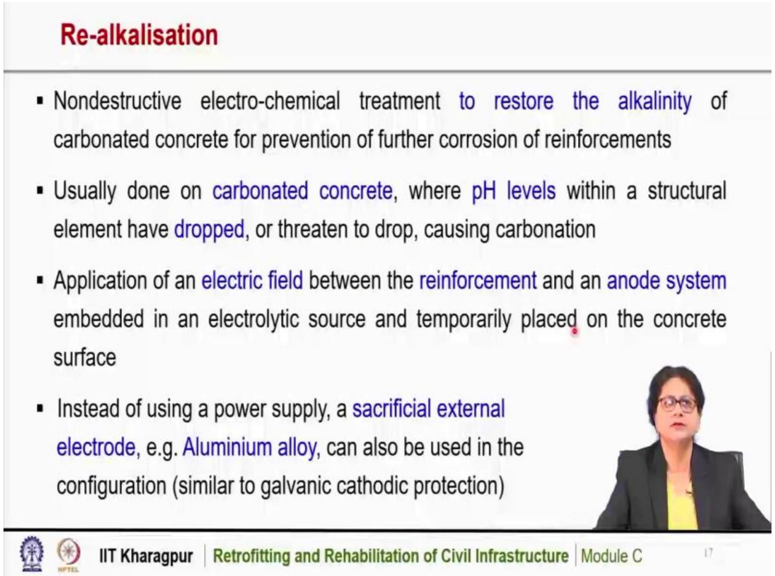

Another technique of corrosion treatment is re-alkalization. Re-alkalization is a non-destructive electro chemical treatment to restore the alkalinity of carbonated concrete for prevention of further corrosion of reinforcement. It is usually done on carbonated concrete, when the pH level within the structural elements have dropped or threatened to drop causing carbonation.

In carbonation type of corrosion, the pH level reduces and the concrete is affected due to carbonation. So, here in the re-alkalization, the alkalinity of the concrete is restored what is done here the application of an electric field between the reinforcement and an anode system embedded in an electromagnetic source and temporarily placed on the concrete surface.

Now, instead of using a power supply, a sacrificial external electrode like aluminum alloy can also be used in the configuration similar to galvanic cathodic protection. So, here also in re-alkalization, we can also use a power supply or we can also use a sacrificial external electrode.

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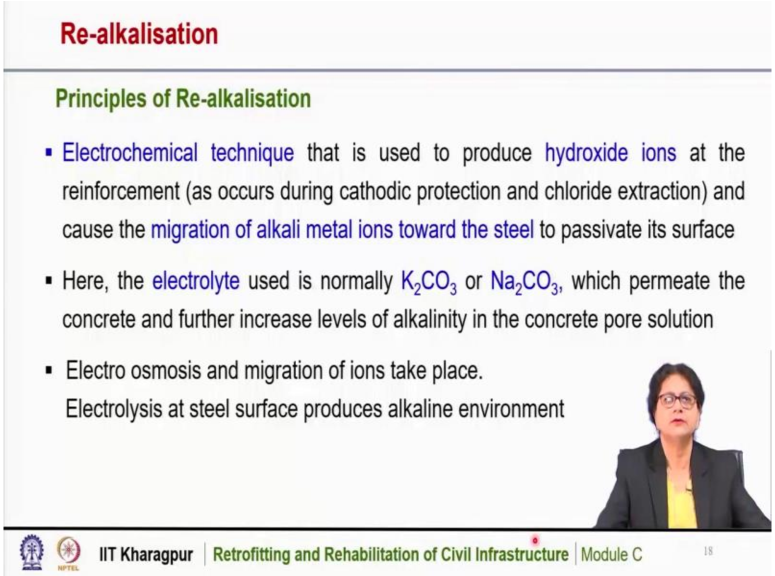

The principle of re-alkalization is that it is a electro chemical technique that is used to produce hydroxide ions at the reinforcement as occurs during cathodic protection and chloride extraction. So, here also we are using the similar type of thing and which causes the migration of alkali metal ions towards the steel to passivate its surface.

Here the electrolyte used is generally sodium carbonate or potassium carbonate, which permeate the concrete and further increase the levels of alkalinity in the concrete pore solution. The electro osmosis and migration of ions takes place, the electrolysis at steel surface produces the alkaline environment.

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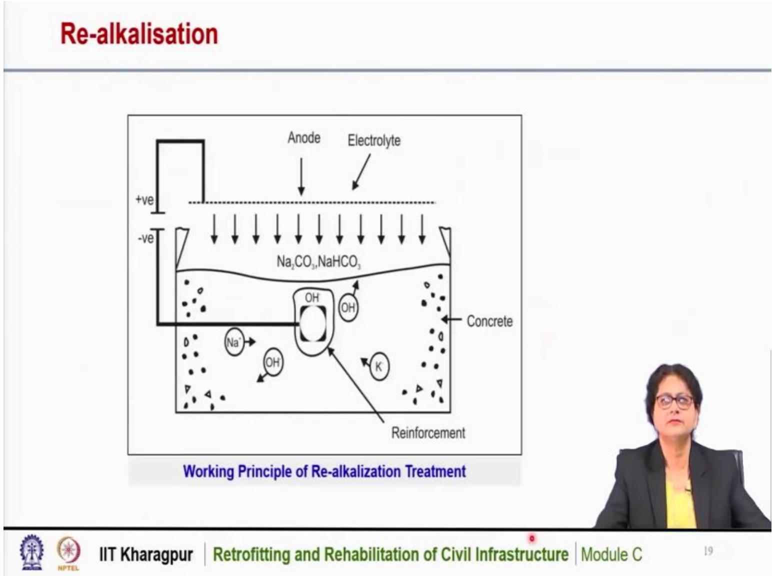

So, this is the schematic diagram of the working principle of re-alkalization treatment. We can see that this is the concrete and this is the reinforcement and this is the external anode which is placed on the surface. Two are connected with the power supply, the electrolyte used maybe sodium carbonate or sodium bicarbonate.

Electrodes are there and we can see this is the reinforcement and since it is behaving as a cathode, so, OH ions are formed and this electrolyte solution because of that solution, there is the sodium ions are released and they are coming to the reinforcement. So, there is a migration of the sodium ions near the reinforcement and also the migration of OH ions from the reinforcement to the anode.

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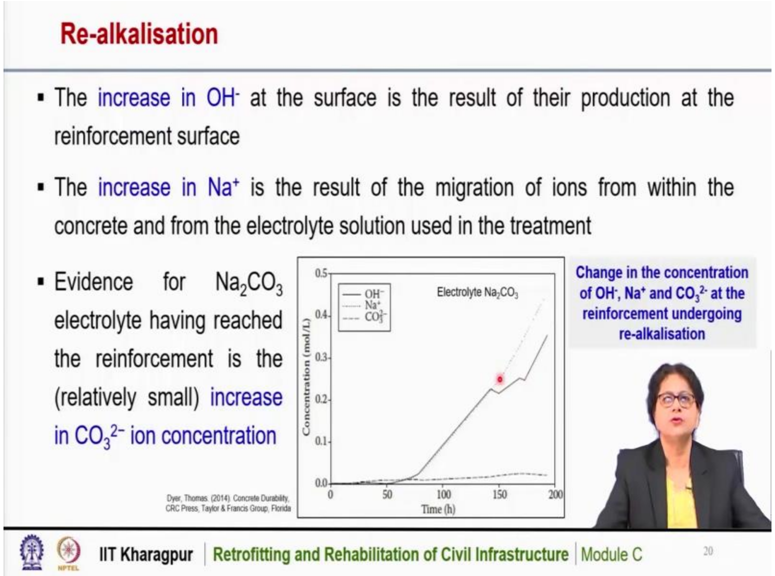

So, the increase in the OH ions at the surface is the result of their production at the reinforcement surface. The reinforcement now behaves as a cathode and so, there is the OH ion formation and that is produced and it is migrating to the surface. The increase in the OH at the surface is due to the production of the OH ions and the reinforcement.

The increase in the Na ions is the result of the migration of ions from within the concrete and from the electrolytic solution used in the treatment. The evidence of sodium carbonate electrolyte having reached the reinforcement is the increase in the carbonate ion concentration. So, here in this diagram, we can see the variation in the change in the concentration of OH ions, sodium ions and carbonate ions and the reinforcement undergoing re-alkalization.

The time versus concentration of ions are plotted. And we can see that, as the time increases the OH ions at the reinforcement increases, the sodium ions also increases because of the migration and also the carbonate ions increases, concentration increases because of the sodium carbonate electrolyte have reached the reinforcement. So, this is due to the re-alkalization and this increases the alkalinity of the concrete.

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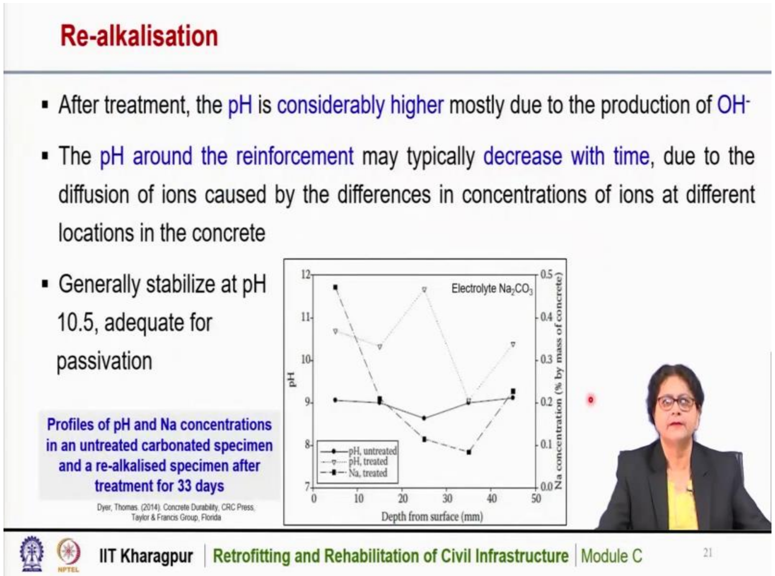

After the treatment the pH is considerably higher mostly due to the production of OH- ions at the reinforcement region or at the catalytic region, the pH around the reinforcement may typically decrease with time due to the diffusion of ions caused by the differences in concentration of ions at different locations in the concrete.

The pH may stabilize around 10.5. Initially it may increase, but after some time, there may be diffusion of ions caused by the difference in concentration of ions at different locations of the material. And after some time, it may stabilize.

So, here we can see that in this plot, these are the variation of pH with depth of surface for untreated, treated material. we can see when there is no treatment, there is no change in the pH level with depth from the surface of concrete and the range of pH also is around 9 which is more acidic and when it is treated, then the pH level increases as you can see that it increases and then it is further increasing.

After some time, it may decrease due to the diffusion of ions, and then it may stabilize at around 10.5 pH level which is adequate for passivation. The concentration of Na is also plotted here and we can see that as the depth increases from surface, the concentration of Na ions also reduced and that Na ions actually migrating to the reinforcement. So, it reduces with depth from surface.

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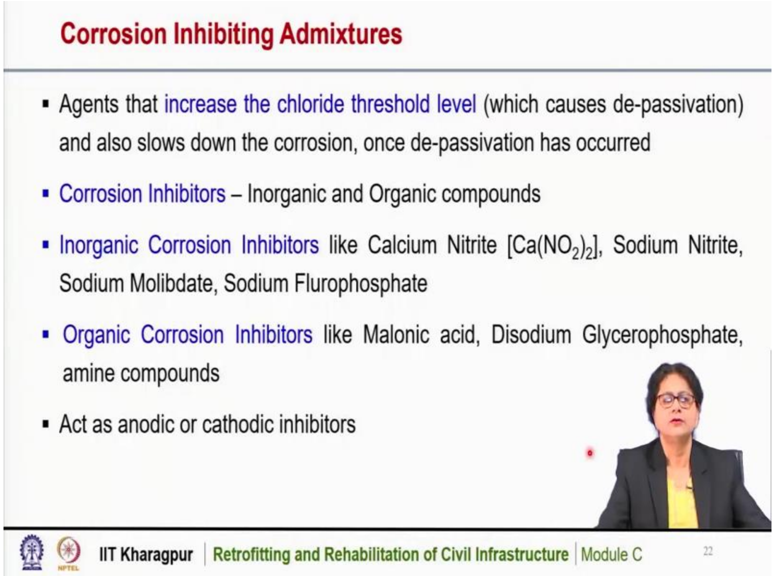

So, re-alkalization is also another treatment for corrosion of reinforcement and it is quite effective also to restore the alkalinity of a concrete. Now, we will discuss corrosion inhibiting admixtures, corrosion inhibiting admixtures are agents that increase the chloride threshold level which causes de-passivation actually, and also slows down the corrosion once de-passivation has occurred. So, corrosion inhibiting admixtures are used to increase the chloride threshold level and which slows down the corrosion rate.

The corrosion inhibitors may be organic or inorganic compounds. Inorganic corrosion inhibitors are like calcium nitrite, sodium nitrite, sodium molybdate, etc. Organic corrosion inhibitors, maybe malonic acid, disodium, glycerophosphate, amine compounds etc. The corrosion inhibiting admixtures may act as anodic or cathodic inhibitors.

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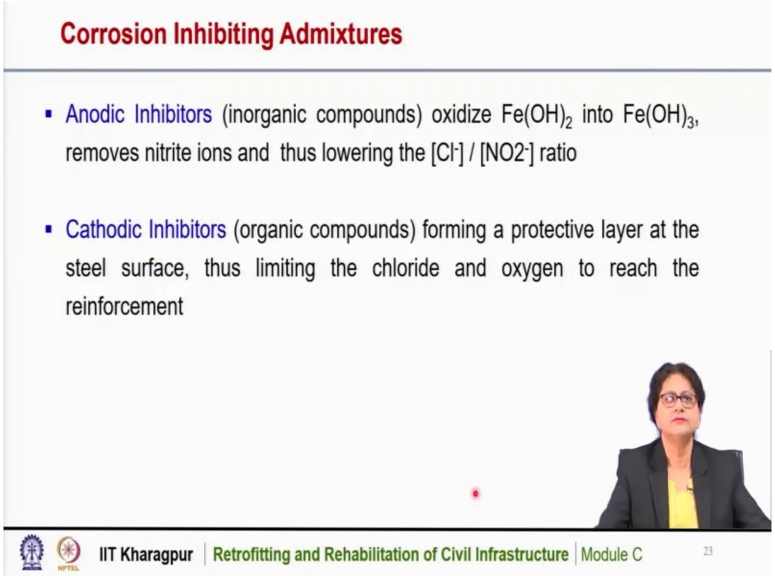

Anodic inhibitors are generally inorganic compounds, they oxidize a $Fe(OH)_2$, or ferrous hydroxide into ferric hydroxide and removes the nitrite ions. Thus, the there is a lowering of the chloride to nitrite ratio. So, this is advantageous because it increases the chloride threshold level.

In case of cathodic inhibitors, which are generally organic compounds, they form a protective layer at the steel surface, thus limiting the chloride and oxygen to reach the reinforcement. So, cathodic inhibitors actually form a protective layer to the steel surface, so that the chloride or oxygen is restricted to reach the reinforcement. Whereas, in case of anodic inhibitors, they remove the nitrite ions thus lower the chloride and nitrite ratio.

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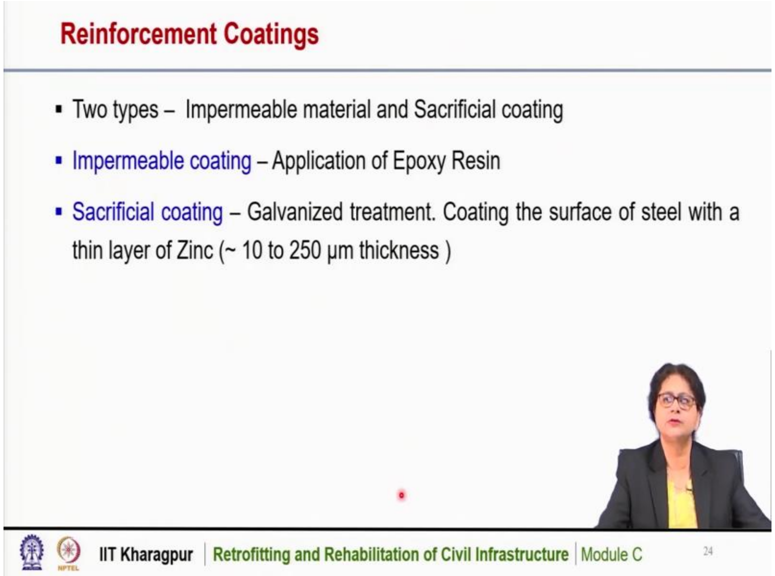

In case of reinforcement coating, there are two types of reinforcement coating that are used. One is by impermeable material and one is by the sacrificial coating. Impermeable coating is by the application of epoxy resin and in sacrificial coating it is the galvanized treatment. The coating of the surface of steel with a thin layer of zinc and the thickness is in the range of 10 to 250 micron.

So, we can use two types of reinforcement coating, that can prevent the corrosion type of distress one is impermeable coating by epoxy resin type of material and another is by the use of sacrificial coating, which is a galvanized treatment and that is done by the layer of zinc.

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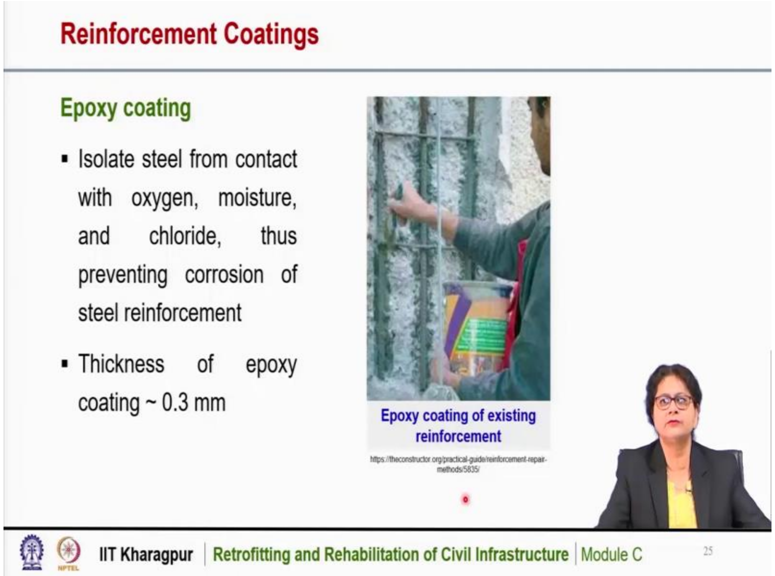

Epoxy coating actually isolate the steel from the contact of oxygen, moisture or chloride, thus preventing the corrosion of steel reinforcement the thickness is also much less in the order of 0.3 millimeter, here is one picture of epoxy coating of existing reinforcement, we can see that the reinforcements are exposed and the epoxy coating is applied on the exposed reinforcement to prevent corrosion.

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In case of sacrificial coating, it is the galvanized treatment that is being done and zinc is used for that purpose. Zinc being more anodic than steel, so it undergoes corrosion and steel remains and corroded. Under the conditions of relatively low chloride concentration and pH level, typical of concrete, zinc is passivated. So, the passivated zinc actually protects the steel reinforcement and behaves as a physical barrier to the reinforcement against chlorides.

The chloride concentration that is required to de-passivate the zinc is much higher. The corrosion products of zinc being non expansive. So, cracking is reduced thus further protection of steel. So, in case of sacrificial coating zinc is used, which becomes more anodic, so it undergoes corrosion and steel behaves as cathode. So, it remains unaffected.

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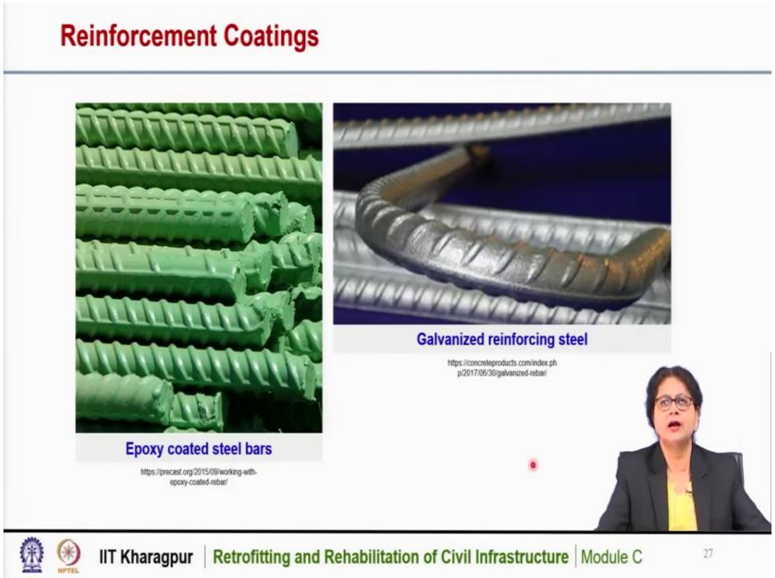

These are the pictures of reinforcement coating, one is with epoxy coating, these are the pictures of epoxy coated steel bar and this is a picture of galvanized reinforcing steel. So, these are effective measures and that can be taken for the protection of steel reinforcement against corrosion.

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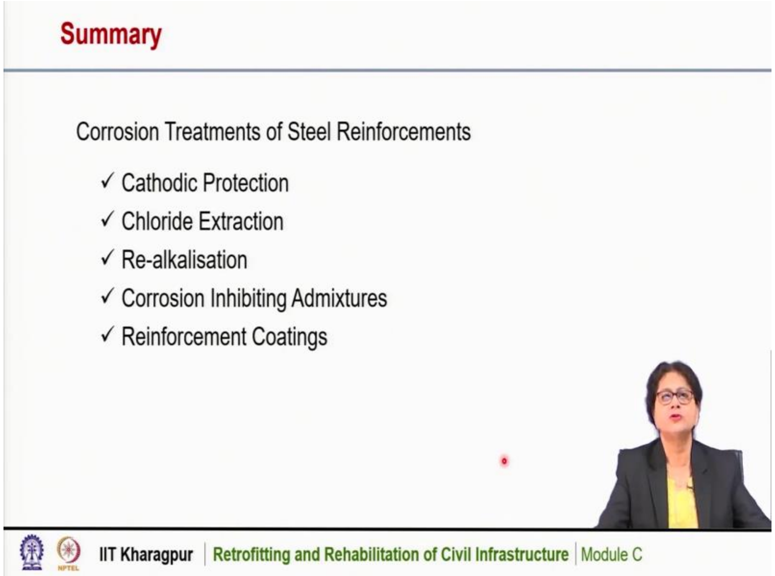

So, to summarize, we have discussed several corrosion treatments of steel reinforcement, we have discussed cathodic protection, chloride extraction and re-alkalisation. These are very effective methods of corrosion treatment. However, these treatments are complex and take a lot of care and expense. So, it has to be carried out on very specialized structures, not for any general structures, we can do all these type of treatments.

So, for very specialized structures and important structures, critical structures, we can carry out this type of corrosion treatment, like cathodic protection, chloride extraction and re-alkalisation. For other structures, we can also use corrosion inhibiting admixtures or reinforcement coatings to protect the steel reinforcement against corrosion. So, corrosion, application of corrosion inhibiting admixtures or reinforcement coating are also quite effective in preventing corrosion in steel reinforcement.

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Thank you.