Maintenance and Repair of Concrete Structures

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Lecture - 06
Corrosion of Embedded Metal (Coated Steel Rebars and Non-Metallic Rebars)

Hi, welcome to this NPTEL MOOC course on Maintenance and Repair of Concrete Structures. Today is the fourth lecture and we will be focusing on corrosion of embedded metals.

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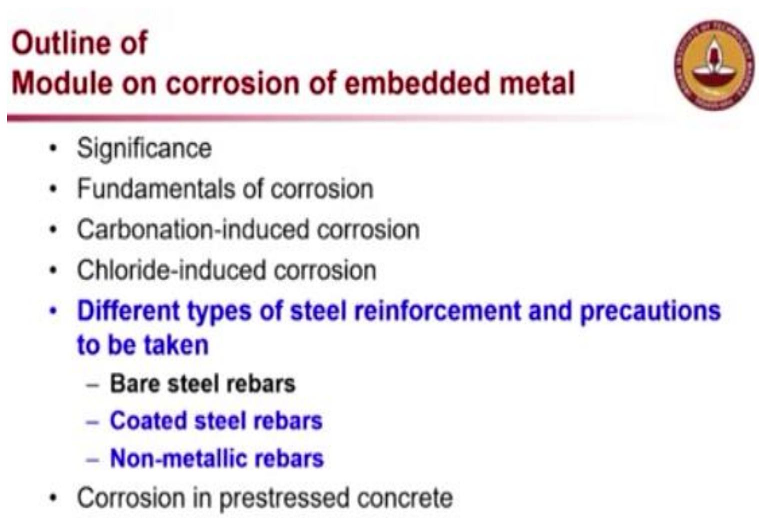

And this is the outline of this module on corrosion of embedded metal. In the previous lectures, we already covered the significance of corrosion, fundamentals of corrosion, carbonation-induced corrosion mechanisms, chloride-induced corrosion mechanisms and in last lecture, we talked about how bare steel rebars, what are the challenges associated with the quality of the bare steel rebars and what to be ensured.

And then today, we will talk about the coated steel rebars, mainly the metallic coating and the non-metallic coating and also the non metallic rebars, that also we will have a very brief session on that today.

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So this is a recap and you have seen this slide already. So essentially, what we will cover today is this type 7, 8, 9 and 10, on galvanized steel rebar, fusion bonded epoxy-coated rebar, cement polymer composite coated rebar and fiber reinforced polymer rebars.

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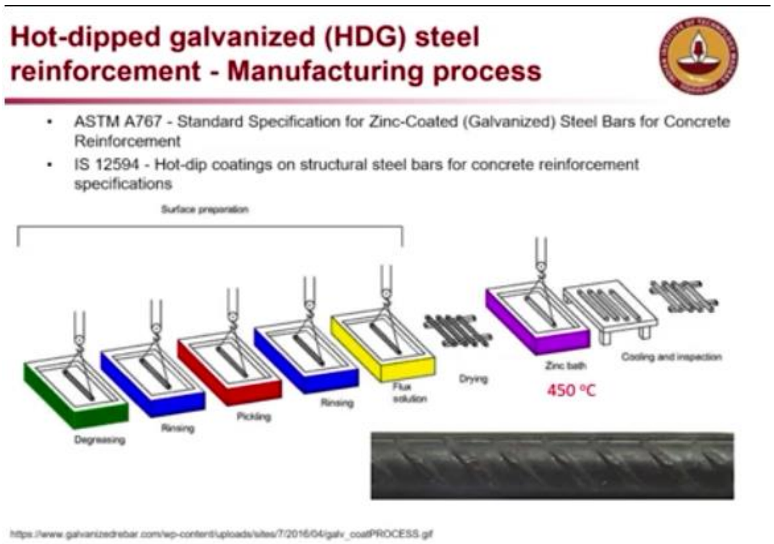

So first, let us talk about the galvanized steel rebars or hot dipped galvanized steel reinforcement. These are the two specifications which are available for selecting or qualifying the type of this type of rebars. ASTM A767 and IS standard 12594. How is this galvanization being done? So first process is to clean the rebars, because from the steel mill when it reaches this galvanization unit, they might have some dirt soil or oil or anything. Whatever being on the steel rebar, it has to be cleaned.

For that any coating, which when we do it first thing to do is to make sure that surface of the metal surfaces very well prepared or cleaned. So that is done in this process here up to here and then it is dried and after which the steel bar is immersed into a zinc bath, which is at 450 degree celsius approximately and then that the zinc is added to the steel surface and then you are allowing it for cooling and further inspection before the steel is sent out of the factory.

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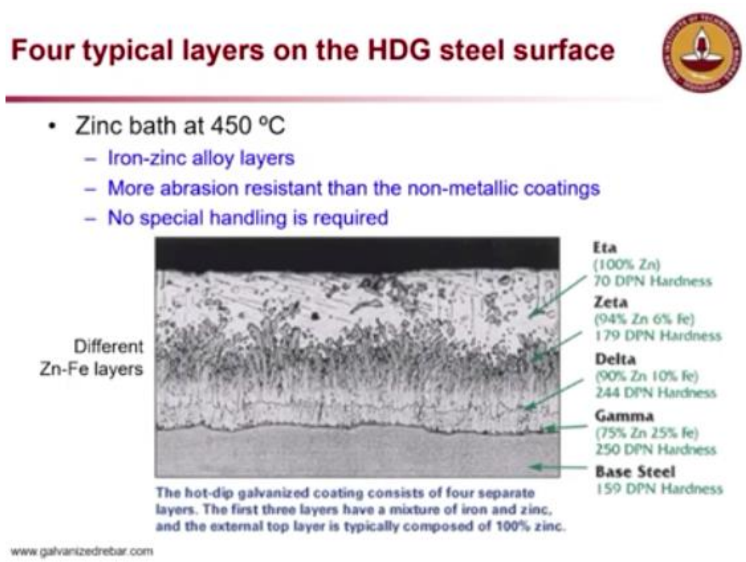

Now what is there in this zinc coating? Typically there will be four layers of the zinc, which is formed you can see here, this is the bare steel and then you have this very thin layer of gamma phase here and then another layer here and then you can see another border somewhere about here and then this is the pure zinc region.

So essentially, there are about four regions, which you can see in this. Because of this and the steel gets protected and main thing to note here is, even the outer layer you have about 70 DPN hardness, which is much better than typical non-metallic coatings and because of this high hardness, you needs no to be handled in a very delicate manner. You can handle as we do in a normal construction site. Rough handling does not really create much problem for this type of steel.

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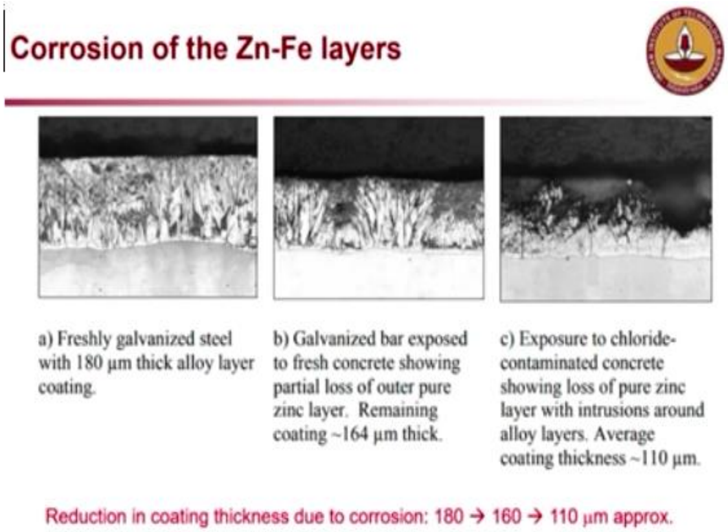

And this is one example, just to show you how that the zinc will corrode and you can really have significant thickness loss. This particular corrosion of zinc helps the steel from further corrosion or in other words galvanic protection is enabled because of this zinc coating. And you can see here the steel surface here, this is not at all getting corroded, but the thickness loss is happening only for the zinc coating.

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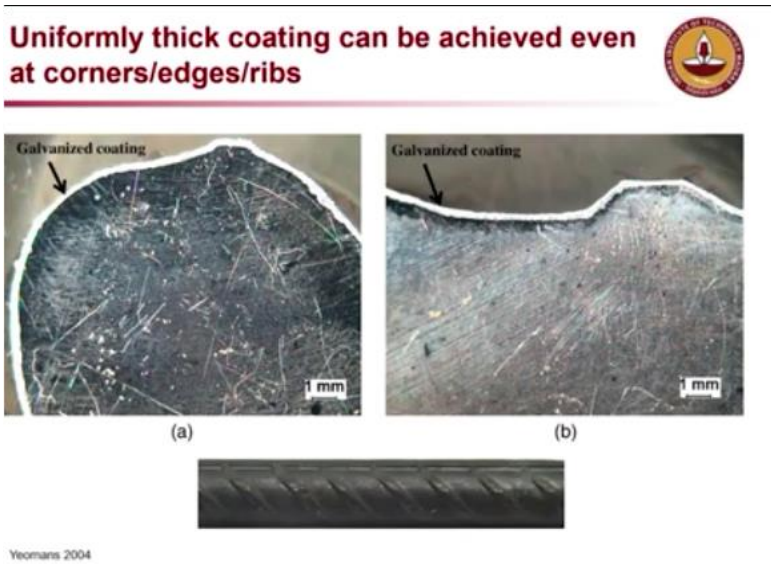

And one major advantage of this type of steel or coated rebar is that the coating itself is very uniform at all the surfaces on the steel; because steel rebars usually will have a lot of ridges, it will have the ribs, as you can see here on this bar, there are a lot of uneven surfaces on the steel's surface and this zinc coating is actually providing a uniformly thick coating. As you see here, it is very uniform over here even and on this also you can see it is very uniform throughout this region. So you get a really nice uniformly thick coating on the steel surface, which is a very good advantage.

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And let us say during the rough handling or even bending of the steel rebars, the coating gets damaged or gets peeled off at some locations like this one, here the steel gets exposed. So here you have a little damage and the steel gets exposed in that region. However, because this coating is directly in contact with the steel, it helps in protecting it in using galvanic action. In other words, you have galvanic protection is very well provided even if there is a little damage on the steel surface, which is a huge advantage, especially when we talk about the rough handling in our construction sites, and even for bending, it is very good.

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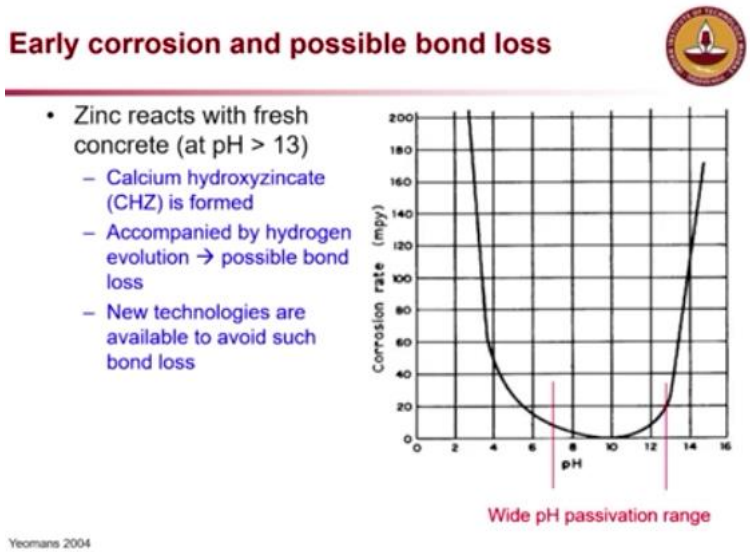

Now it is has been reported that when the galvanized coated steel is immersed in concrete or is embedded in concrete, because of the very high pH of the fresh concrete, this calcium hydroxyzincate is formed in the very beginning. In other words, when the pH of the concrete is greater than 13, some people say 13.1, 13.3, anyway, let us take for this class, we will say when the pH is greater than 13, there is a possibility of this calcium hydroxyzincate, which is formed on the zinc surface and following which there will be a reaction of hydrogen evolution. And in this hydrogen evolution, the hydrogen which is released where from the reaction will kind of lead to a debonding of this concrete from the zinc surface. So the bond loss is possible and however, this used to be like a concern in the past and people have actually tried different technology and today we have technology available, which will prevent this bond loss.

Before we go to that bond loss thing, one more thing I wanted to mention and there is a wide pH passivation range you can see here the corrosion rate is very low when the pH is in this rang. When the concrete gets hardened in the long run, even if the pH is about 8, you still have very low corrosion rate. That is a very good advantage, when you talk about carbonation-induced corrosion and things like that.

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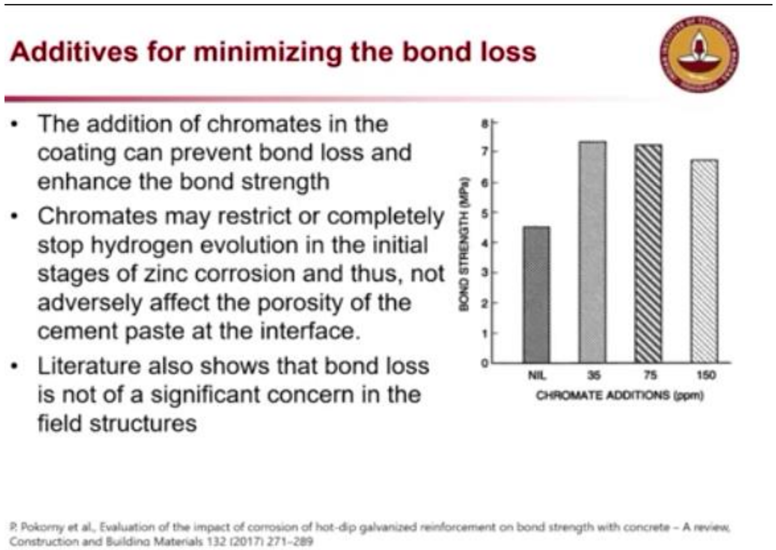

So we are coming back to how people overcome this issue associated with the hydrogen evolution and bond loss. The addition of chromates was tried and then it has been found that when you add chromates to this zinc coating, the bond loss is actually not really there. You can see here, when there is no chromate you see the bond strength is about 4-5 and when you add chromate at different concentrations, you get bond strength is about 7. So we can say that if you have the zinc coating with chromate, you don't really need to worry about the bond strength loss.

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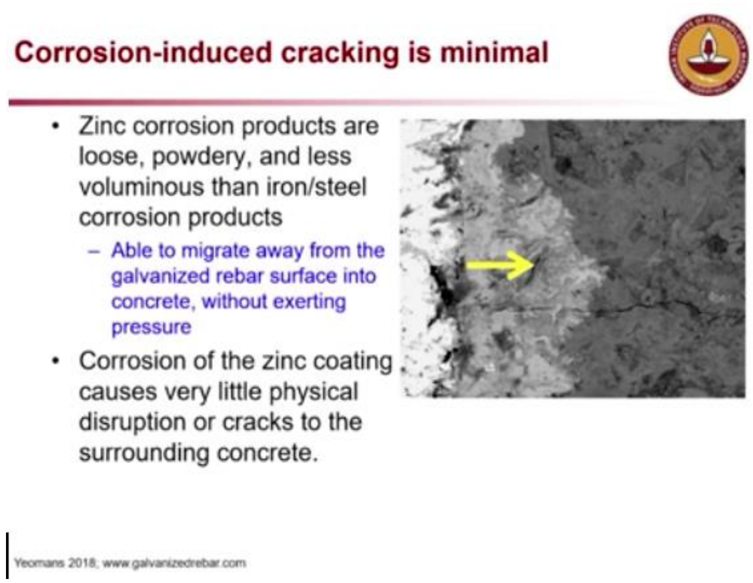

Also another advantage is this zinc corrosion does not lead to cracking of the concrete. For example, if you are talking about an uncoated steel rebar, when there is a slight corrosion that can lead to cracking of the concrete cover. On that slide I mentioned, it can be even less than 1 mil and that can even lead to cracking of the concrete cover. Of course, it depends on the tensile strength of the concrete cover, but still in most cases it can lead to significant cracking. This is not happening in case of zinc corrosion products, because zinc corrosion products are loose and powdery in nature and then less voluminous. It does not accept any expansive stresses on to the concrete. And if depending on the porosity of the concrete, it can actually ooze into the pores of the concrete near the steel surface or near the zinc surface.

So that is a very good feature or advantage of this zinc coated or galvanized steel rebar, because the cracking of concrete cover can be also delay or minimized.

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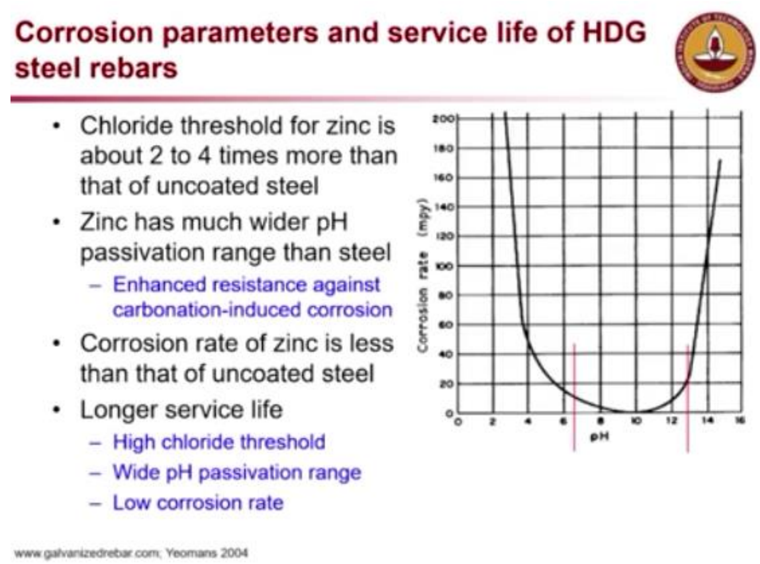

Other thing which is very important about this type of rebars is the corrosion parameters or parameters which are very crucial for determining the service life of the systems with HDG steel rebar. So first parameter we will talk about is chloride threshold which is about 2 to 4 times more than that of the uncoated steel. Chloride threshold is the amount of chloride which is required to initiate corrosion and that amount is about 2-4 times more than that is required for uncoated steel that means you need more time to initiate corrosion or service life can be enhanced.

And also zinc has much wider passivation range when you are talking about carbonation induced corrosion, this plays a major role. Let us say you have very severe carbonation environment or the environmental conditions are very severe or in other words humidity range is very ideal for carbonation to occur and then in such case, you will see that the pH of the concrete reduces. pH of the concrete reduces from around 12.5 or something, if it is less than 9, then you will have carbonation issue, but in case of zinc coating, it can even go further down or even at a lower pH than 9, the rate is not that significantly high, unlike what is the case with the uncoated steel.

And moreover one more thing is the corrosion rate, in our service slab discussion, we discussed that there is an initiation phase and then there is a propagation phase. Even for the propagation phase, that means even if the zinc has started corroding, the rate of corrosion is going to be much less as compared to the uncoated steel. So, all these will lead to a longer service life. So there is definitely an advantage of going for zinc coated or galvanized steel rebars.

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And people have used it in many structures. This is a temple in South Chennai and this is a bridge abroad where, but only thing is the cost. The cost is much more, 2-3 times more than that of the uncoated steel. But I think depending on the type of structure you are building, the importance of that structure and if you want to really look for the lifecycle cost not the immediate or the capital investment, if you are really looking at lifecycle cost, you might find that use of this kind of coated steel is really beneficial.

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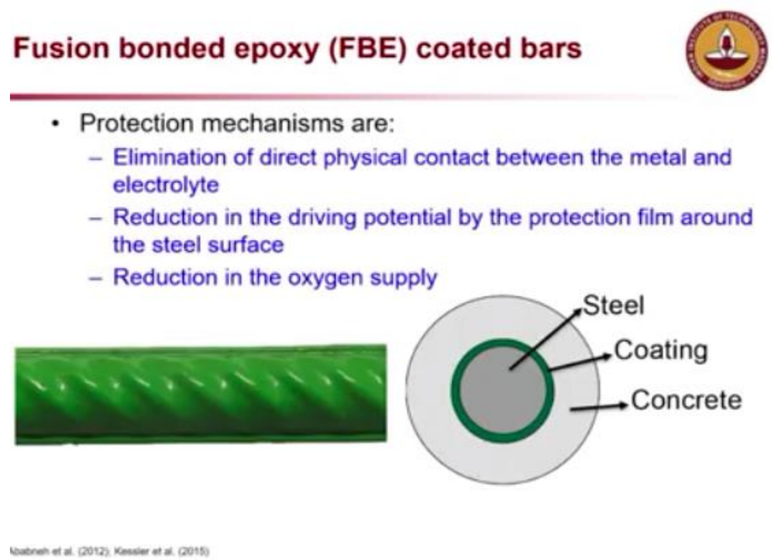

Now let us look at fusion bonded epoxy coated steel rebars. This is also widely used. See as a technology, what is a protection mechanism? This fusion bonded or this epoxy coating, it eliminates the direct physical contact between the steel and concrete and because of that barrier, there is a reduction in the potential or the drive for the corrosion. This is essentially a physical barrier, which is present between the steel and the concrete and that also reduces the availability of oxygen, which is necessary for corrosion reaction to happen. You can see here this scheme and the picture. This is the gray part is the steel, darker gray and then you have this green coating and then you have concrete as the outer surface.

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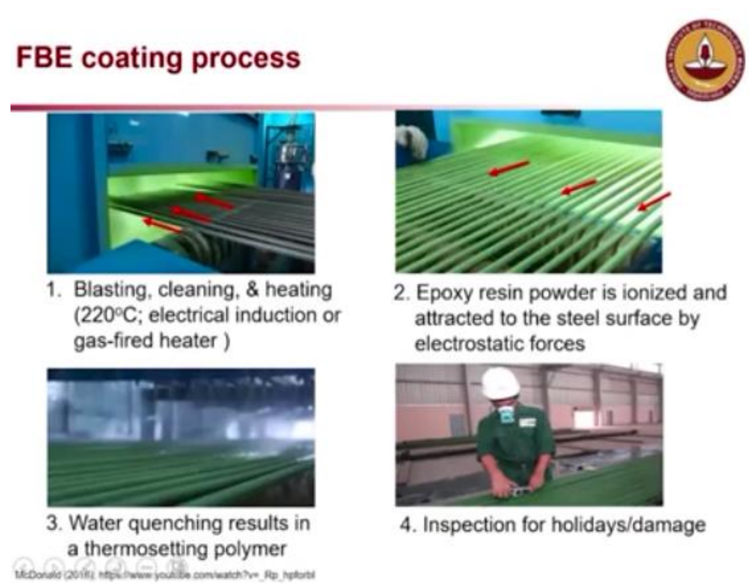

Now how is this manufactured? First you take the steel rebar and then clean it, as you have seen in the top left picture one. First you take the steel and then it is sandblasted or grid blasted and then cleaned and then it is heated to about 200 plus degree Celsius and then it is passed through a chamber which is having a mist of this epoxy resin powder and it is attracted to the steel surface by electrostatic forces and then you have quenching.

Why quenching is required? Because you do not want this epoxy to be on the steel surface for long period, which will probably lead to flowing of this epoxy downward, which might lead to non-uniformly thick coating also. So to ensure that it is uniformly thick, the water quenching is the best way to do.

And then of course before sending it out you have to inspect for holidays or any damage is present. But what we are seeing most time is, when it comes out of the factory, it is probably very good, but as because of the poor handling at site, it sometimes not really wise to use this.

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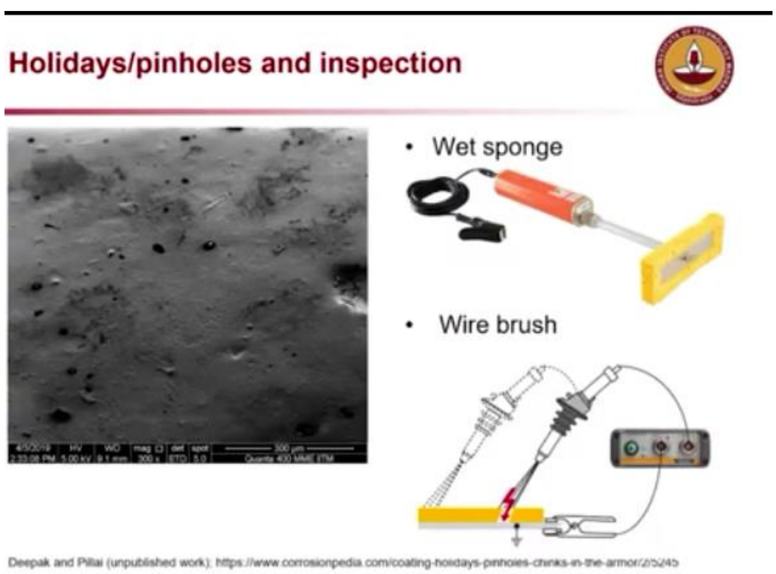

This is a micrograph collected from one of the steel rebar, which was collected from the site. You can see that all these black spots; they are all holidays or pinholes. So these pinholes all will lead to early corrosion and there are ways to check whether how many of these pinholes are present on the steel surface. I mean the lot of pinholes you can see on this steel. This is a rebar surface which you are looking at. So there are two major types of equipment, one is using a wet sponge and other one is using a wire brush. Basically you keep this wet sponge or the wire brush on the steel surface and make an electrical circuit and if there is a holiday, then electrons will pass through that and then circuit gets completed. And if the coating is very good insulator then you will not have the closed electrical circuit and then with that way we can actually determine whether the quality of the coating is good or bad.

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Chronology of changes in ASTM A775 (2017)

Year	Changes made
1981	First version approved
1989	Permissible damage level was reduced to 1 % of the steel surface area
1989	Introduction of anchor profile of 1.5 – 4 mil (38 – 100 μm)
1990	All the damages should be repaired
1993	Limit on coating thickness was introduced (177 - 300 μm)
1994	Flexibility test - bend angle was increased to 180° from 120°
1995	Limit on number of holidays - one holiday per foot length is allowed
1995	Coating should be done within 3 hours after cleaning of steel surface
1997	Coating disbondment test was introduced to check the adhesion between concrete and steel
2004	Coating thickness limit was increased (177 - 400 μm) for larger diameter rebars
2004	Limits on individual measurements were introduced (should not be less than 80 % and should not ne more than 120 % of the allowable limits)
2007	Requirements for patching materials is added to the standard

http://www.epoxyinterestgroup.org/index.cfm/_api/render/file/?method=inline&fileID=9CF988F2-A756-4516-5FA16A419128D013

This is ASTM A775 very latest code and this table shows how this code was modified over a period of time, what are the major changes which were made in this coating specifications. You can see that there are a lot of changes, as time passes people learned that something which is already in the specification is not good, so they modified it. So this is a nice summary of these changes made in this code.

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ASTM 775 (2017) & IS 13620 (2004)

	ASTM 775 (2017)	IS 13620 (2004)
Time to coating application after cleaning	3 hours	8 hours
Coating thickness	177 - 400 μm for larger diameter rebars (No. 19 - 57); 177 - 300 μm (for others)	100 to 300 μm; this does not apply to patch area
	Individual measurements should be within 80 to 120 % of allowable limits	90% of measurements should be within limits
Coating continuity	< 3 holidays per meter length	< 6 holidays per meter length
Adhesion	No visible cracks or debonding after 180° bending	No visible cracks or debonding after 120° bending
Permissible coating damage	All damage should be repaired; Allowed damage level **< 1 %**	Coating damage **< 40 mm²** need not be repaired; Allowed damage level **< 2 %**
Coating (patch) material	Guidelines for coating material	No guideline

IS 13620:1993 – reaffirmed in 2004

Need to be relooked for the long-term corrosion resistance

Now let us compare this ASTM A775, latest version which was published in 2017 and the other IS 13620 2004 specifications. So you can see here the time to coating application after the cleaning, in ASTM, it allows only 3 hours whereas in the IS it allows 8 hours. So this might also be a problem, because if you have 5 additional hours between this coating and the cleaning process, then the possibility of other materials getting deposited on the steel surface is high. So this is something which we need to think about we may have to really reduce this also.

Then coating thickness, the uniformity is one thing and the thickness, how much is the thickness average allowable, in case of ASTM, you see 177 to about 300 microns whereas in the case of IS you see about 100-300. Even the thinner coating is allowed in IS 13620, which is probably again not a good idea. Because we have experimental evidence that when the coating is less, the tendency for the coating to be cracked is high, which will lead to early corrosion. So we may have to make it more and more stringent.

Even continuity, number of holidays allowed in ASTM is less than 3 in IS we allow up to 6. And adhesion, no visible cracks or debonding after 180 degrees in ASTM whereas IS say only up to 120.

In case of our earthquake resistant structures, where if we are using these type of rebars, the stirrups are bent to about 135 degrees, this is the angle by which we bend the stirrups, so at 135 definitely this angle should be more than 135 to be able to consider as a test for steel rebars which are going to be used for earthquake resistant designs. And allowable damage level on the coating in ASTM it says less than 1%. We say up to 2% is okay or 40 millimeter square is okay.

I believe that these specification should be much more stringent and that will probably help us in ensuring that the structures are going to be durable. So these need to be relooked. It is very important.

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And let us see what really happens in the practice, so this is also if you see a coating damaged at the site, especially at the ends we generally apply additional coating. So this when you do this process in the red box, when you apply additional coating, it is actually done at the site, it is not really done by fusion bonding, because at site there is no elevated temperature, ambient temperature you are doing it, so definitely fusion bonding will not happen.

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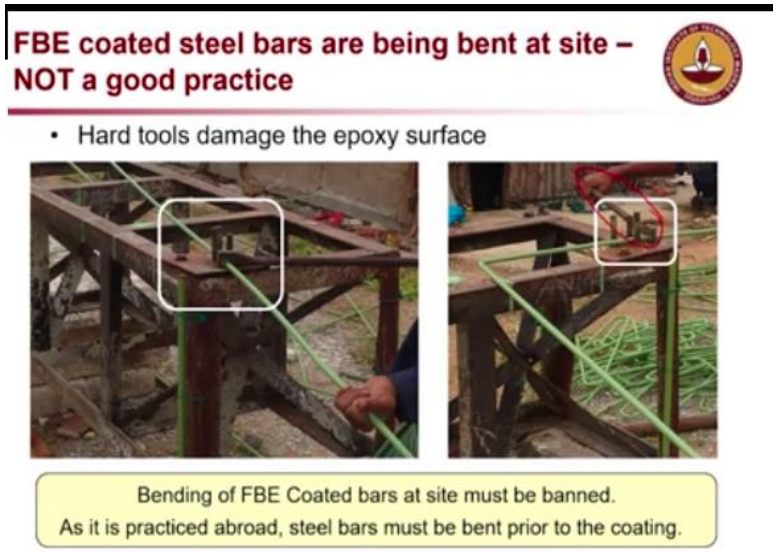

And when you bend these rebars after the epoxy coating, the type of tool which are used is like this. The lever arm which you use is made out of steel, you are definitely going to pinch the softer epoxy coating which will lead to damage especially near the bend region.

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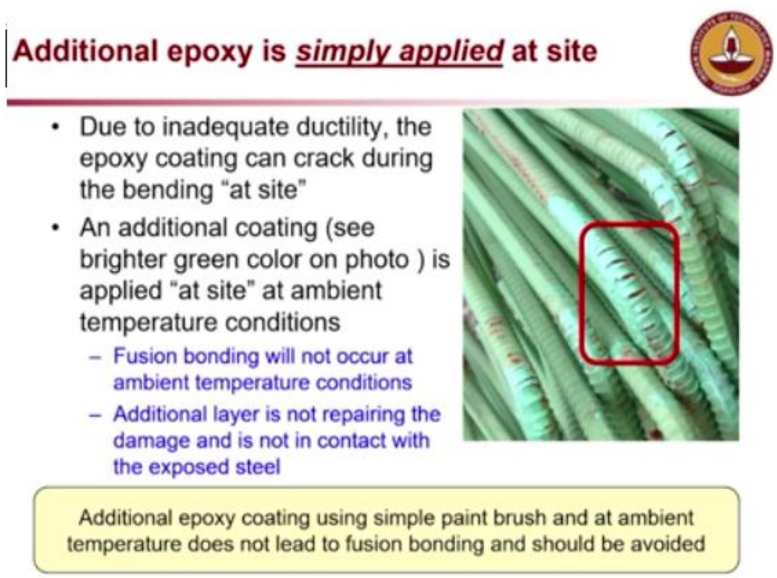

So this is how it is you can see here and these are the damages which are caused due to the pinching of the lever arm and also if the epoxy does not have good elastic property at the time of this bending, it will lead to cracks like this at the bend region. And these are bars which are just 90 degree bend and imagine if they are actually used for stirrups for earthquake resistant designs which would have to be bent to 135 degrees. So that is another problem. We should not bend these bars after epoxy coating. The best practice to bend it before epoxy and then take it to the site.

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Now what will happen if there are damages like this on the rebar? What will happen is, some of the scratches will tend to corrode or will become anode like this here. The scratche at the center is an anode and then the remaining scratches help or functions like a cathode and they do not corrode. So you can see very clearly here, some can become anode and the other help in corroding by becoming cathode and this is dangerous, because then you will have localized corrosion happening, which will not be the case if it is an uncoated rebar.

The corrosion will happen more uniformly. Here the chances of localized corrosion is very high and that is something which we need to be worried about.

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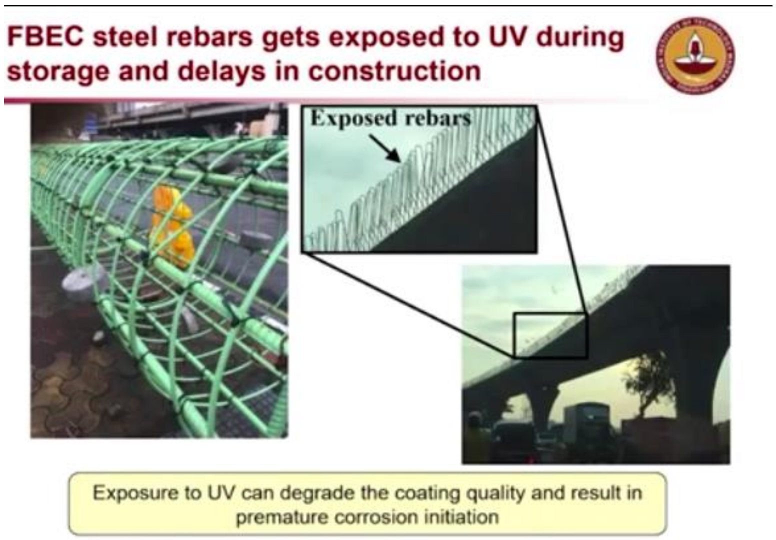

These are some pictures collected from construction sites in a major city in India and you can see that these bars are exposed to sunlight. This means there might be construction delays or there might be different stages of construction. So during this whole process, these bars gets exposed to sunlight for weeks or months or even sometimes years, depending on various construction delays.

So there is a possibility that rebars gets exposed to sunlight and what is the exposure to sunlight means is it is exposed to UV radiation. Here is another example you can see this again, a lot of scratches are there on this bar, damages and it is exposed to sunlight. I have seen this structure it is there like this for several months, there was some significant delays. So significant exposure to UV radiation is happening, which leads to cracking.

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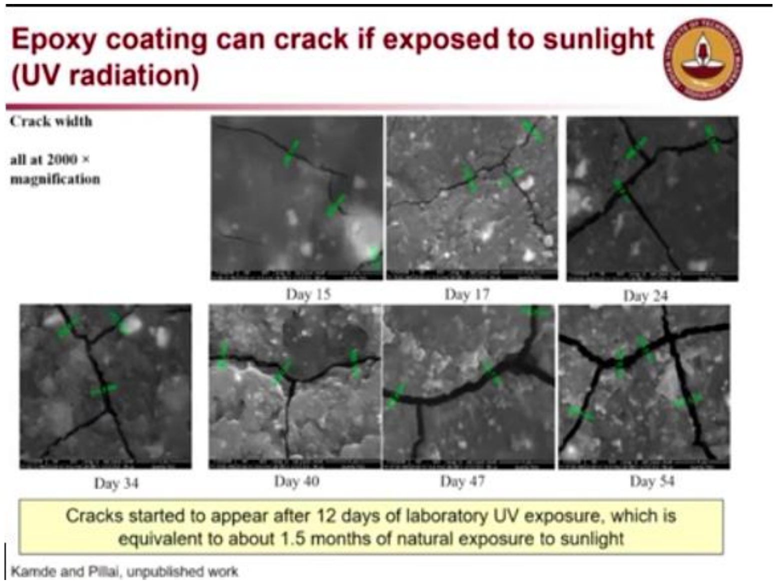

So we looked at some of this, we did as experiment and then we found that when these are exposed to UV radiation, cracks tend to form. In about 15 days, you can actually see that the cracks are forming in this. So this is about 0.3 micrometer in crack width size and as time passes you can see that crack width is slowly, slowly increasing. From here, you can see the crack width is increasing and then day 34 and then 40, 47, 54 all this. As you go towards the right the crack width is increasing means more and more volatile materials is being lost from the epoxy coating and once there are cracks, it is very easy for moisture, oxygen, chlorides, etc., to penetrate and lead to under-film corrosion or crevice corrosion. That is a major problem.

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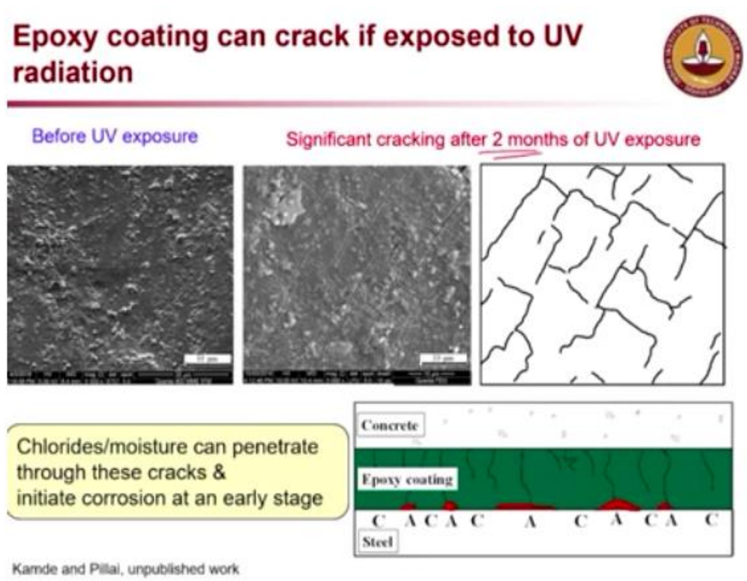

So this is another picture, just to show you after exposure for about two months, how the crack will be, there are very severe cracks. So the first picture shows without any cracking, second picture it shows the cracks and if it is not really visible, look at the third picture, which really shows all the cracks which are on the second micrograph. So this is a serious concern, because most of our construction sites, there will be delays and you really want to have a steel system which will not have any cracks on the coating until the steel is covered with the concrete. Otherwise, it is very vulnerable to corrosion even without the presence of chlorides. That is the most important point to take here is that the cracks can lead to corrosion even when there is no chlorides at the steel surface. That means very short span of service life or the corrosion free service life is going to be very, very small.

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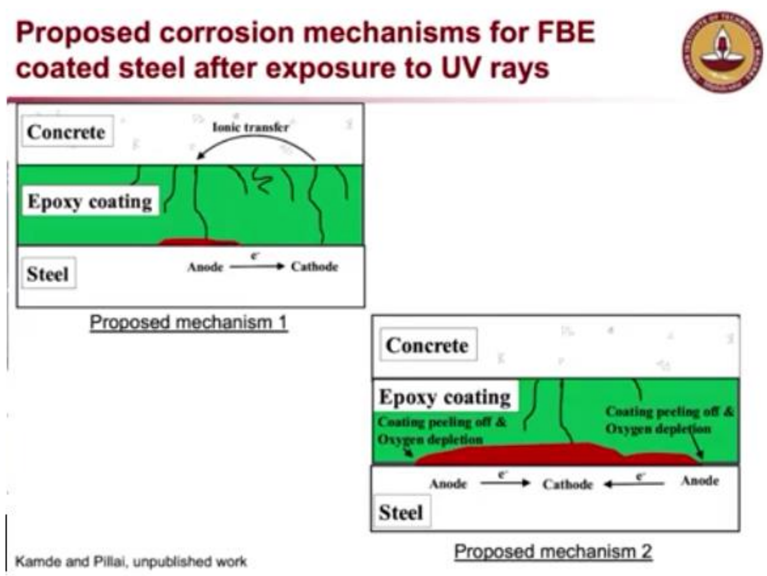

This picture on the bottom right basically to show the mechanism, you can see here one crack right here, one crack is there and then oxygen, chlorides, moisture all that can penetrate through this crack in the epoxy coating.

This is the concrete region. This is the green portion, is the epoxy coating and this is the steel region okay. Now once it reaches, once the moisture and oxygen goes through the crack and reaches the steel surface, it will then move to the right and left and then you will have an anode formation and a cathode formation right in that region. Wherever there is an oxygen depleted region that region will become an anode and if it is relatively rich in oxygen, that region will become a cathode. So this will definitely lead to significant under-film corrosion in short period of time.

And another laboratory study says if the coating is very good, the corrosion was observed only after about 100 days. When the coating was exposed to UV radiation, the corrosion was observed in about just just 50 plus days. So there is a significant reduction in the time taken to corrode the steel rebar.

So multiple evidences say that the UV exposure or exposure to sunlight can really leads to significant corrosion or early corrosion of the epoxy-coated rebar, even when there is no chlorides presence.

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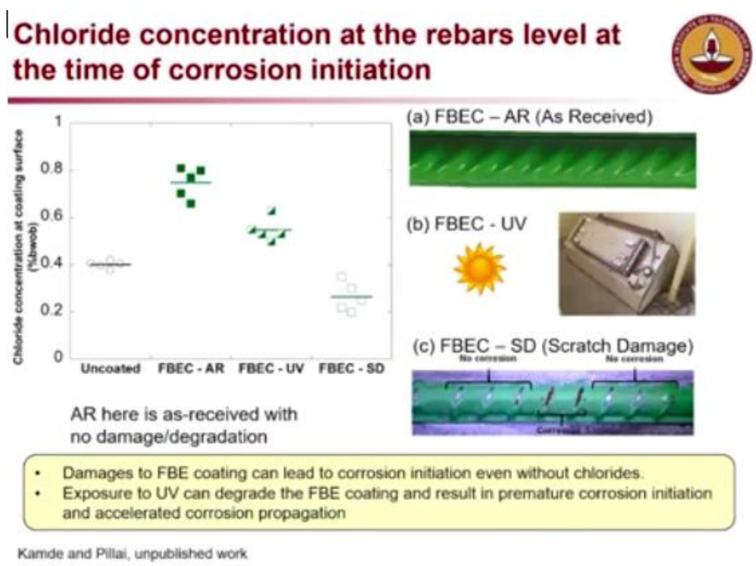

And so I said even when there is no chloride present, it can actually initiate and you can see here, this particular rebar corroded, when there is only 0.2% of chloride. This SD stands for scratched rebar. So this is experimental results from tests on as received and no damage, if there is damage then it is a different story. So then as received, but with UV, case 2 or case B and at last we have as received SD which is scratch damage, which is very prevalent in this type of rebars because of the dragging etcetera on the site.

Now what we observed is, there is a significant difference in the chloride concentration or the amount of chloride required to initiate the corrosion. We can say it is chloride threshold for this type steel system, coated steel system. If there is no coating, it is about 0.4 and if the coating is very good and no damage, then definitely there is an increase in the chloride threshold.

So this coating as a technology is very good, but because of the poor handling at site, it gets reduced and with the two months of exposure, we were able to see significant reduction in the chloride threshold and if the rebars were damaged, further reduction was observed. So definitely, there is a reduction in the when the rebars are damaged. So we cannot really use the bars with scratches or damages on these coatings, we should not.

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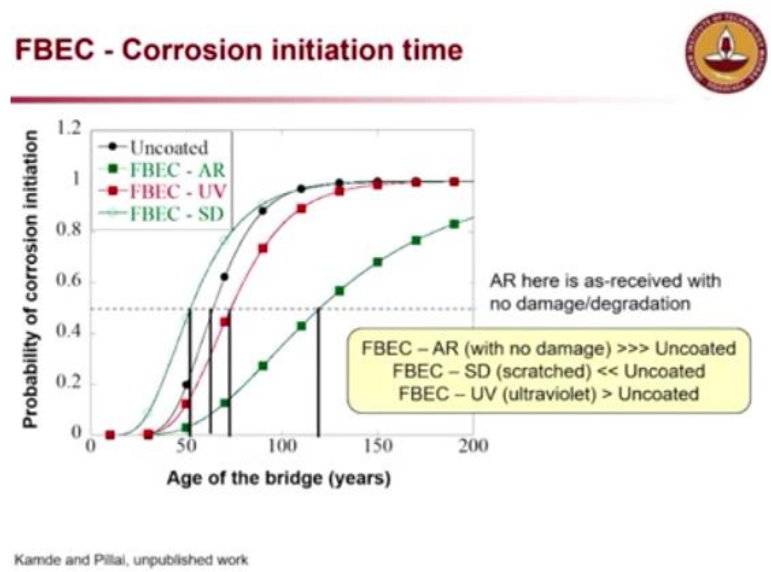

So what is the effect of all these on the service life or which we can say here as a corrosion initiation time or time taken for the chlorides to reach the steel surface and initiate corrosion. And here this AR means no damage or no degradation, as received good quality epoxy-coated rebars. So very clearly here, the uncoated bar which are the solid filled circular markers, we can say an average time taken for initiation.

And if the coating is very good, you can say you can easily get 100 plus years of life, but again when you look at this, they are just basically very close to each other. You cannot really say a lot of differences. So the message to be taken here is that epoxy-coated rebar or to be precisely fusion bonded epoxy-coated rebars are very good to use provided we develop the quest for quality at our construction sites. And we handle these rebars with quality in mind, delicate handling is necessary, we should not allow any scratching of the rebar, any peeling off should not be allowed and also it should not be exposed to sunlight.

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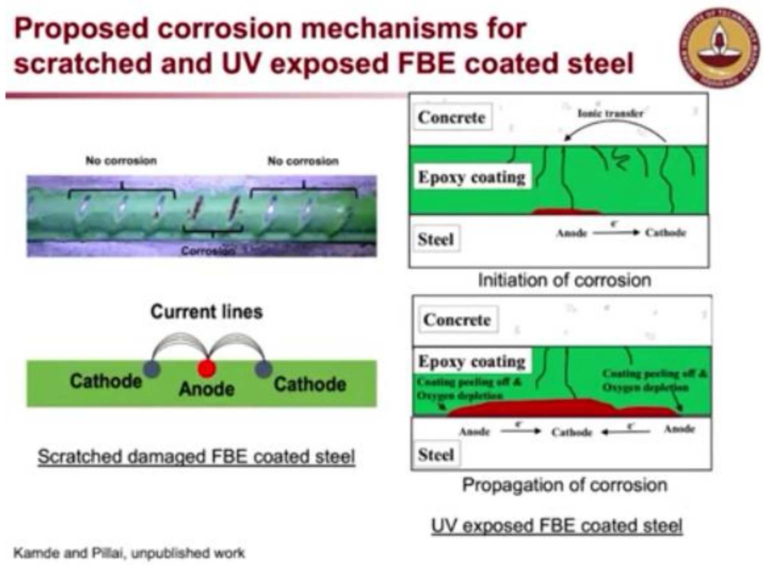

These are the conditions, which we must follow if we are going for epoxy-coated rebars, otherwise it is better not to use the epoxy-coated rebars rather go for uncoated rebars, which will give you almost similar performance with a very similar service life. So this is just a summary of these two. If there is scratching, this is the proposed mechanism. If there is a UV exposure, this is the mechanism. Scratch damage this is what is going to happen and UV damage this is what is going to happen (Refer slide).

We already looked at it the formation of anode and cathode cells, anodic and cathodic sites and under the film corrosion or crevice corrosion, this is going to really lead to localized corrosion which is hard to identify or detect and at the same time it can lead to significant section loss locally.

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These are some pictures showing on a five years old bridge, even without any chloride, these rebars were corroding. So I am reinstating that it is more dangerous to use damaged epoxy-coated steel rebars than conventional uncoated steel rebars.

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And this is some picture showing how ideally this should be done. These rebar should not be bent at site at all and even the ends should be epoxy coated. This is what the practice is abroad, even if they are going for epoxy coating, the bending and all those mechanical processes are done before the epoxy coating is done. Bending and cutting everything is done before epoxy coating. That is how we should also practice if we are actually going for it.

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And for the tie wires also we should not use uncoated of metallic tie wires. We should go for plastic coated tie wires, or in other words a material which is of similar hardness or softness as the epoxy coating should be used.

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And if we are using needle vibrators, we should use not the metallic needle vibrators, but the vibrator should have a sleeve, which is made of a soft material like rubber as you see in the picture here. These are rubber coated needle vibrators. So that these type of scratches are not induced on the rebars, because of the vibration process. In normal construction, we do not see this, because this process is happening after the concrete is placed. And also the couplers which we use metallic couples, as you tighten these couplers or fasted them onto the rebars what you are actually doing is you are pinching on to the epoxy coating or really damaging the epoxy coating.

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Another type of non-metallically coated rebar which is widely used in the construction is this cement polymer composite or CPC coated rebars. Let us look at what is this rebar. You have three major processes. First you have to clean the rebar surface. The recommendation is clean it by a sandblasting which is sometimes very difficult to practice at most of the construction sites. So you have to really get a very clean steel surface and then you apply a primer coat on that steel surface which is item number 2 here and then on top you apply a seal coat which is item number 3 here.

So this is how this is made and what is primer coat? It is essentially cement with an acrylic polymers as additive. I am sorry, it is the reverse. It is acrylic polymer with cement as additive. So you should read this acrylic polymer with cement as additive and seal coat also acrylic polymer with cement as additive. The cement is the additive here, not the polymers. So just please correct that and they are available in different color.

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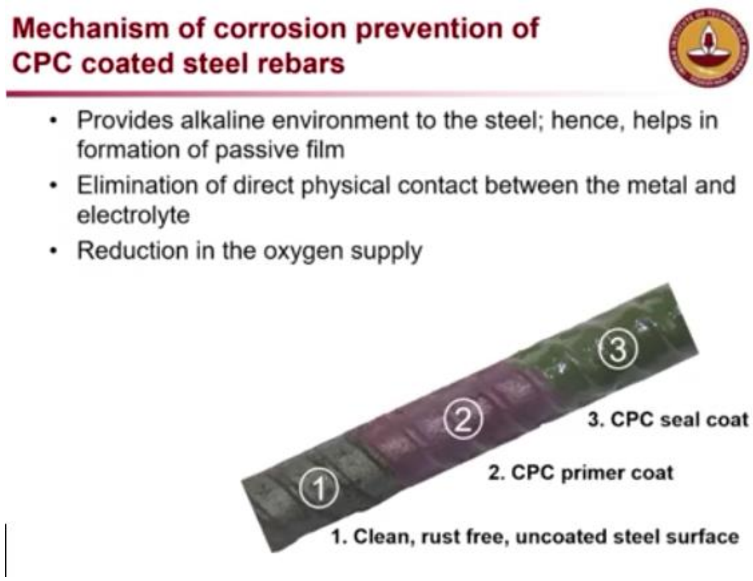

The protection mechanism is this type of coating provides an alkaline environment. Because of the presence of the steel in this coating it provides an alkaline environment to the steel, which helps in providing a or forming a good passive film. Which is not the case in the fusion bonded epoxy coated rebar, where there is no alkalinity provided on the steel surface. It is just a physical barrier it is dependent on, but in this case of CPC coated rebar, physical barrier plus this alkaline environment helps in corrosion protection. And also this coating eliminates direct physical contact between the metal and the concrete or the steel and the concrete and also you get reduction in the oxygen supply. So these are similar mechanisms but one added feature is that this alkaline environment is available in case of CPC coated regions.

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Now that is what I just discussed is the best practice and if you have a good coating, it will have long life, but if you have considering the way it is being done at the many construction sites, we are seeing a lot of challenges or trouble or concerns with the use of this type of coating. This picture was taken from a coastal bridge construction. You can see the piers and the cage for the pier of this particular bridge and what you see here is the top portion of this it is not at all coated. And only the bottom portion is coated here and that too was coated after the cage is made. When you are making something which is after the cage is made, getting the entire steel surface coated is very difficult. So ideally we should coat the steel surface and then make the cage, but in this particular case, it is done the other way. So what is the end effect is something like this as you see on the closer picture on the right you can see that some region is white in colour and some region is rust colour, the brown color. So definitely, there is a non-uniform or uneven or discontinuous coating. That is a challenge.

When you have this discontinuous unevenness or non uniform thickness, etc., you are actually inviting trouble by creating corrosion cells or you are inducing corrosion or you are increasing the chance of corrosion in such cases. Either you apply a good coating or do not apply coating. That is the message to be taken.

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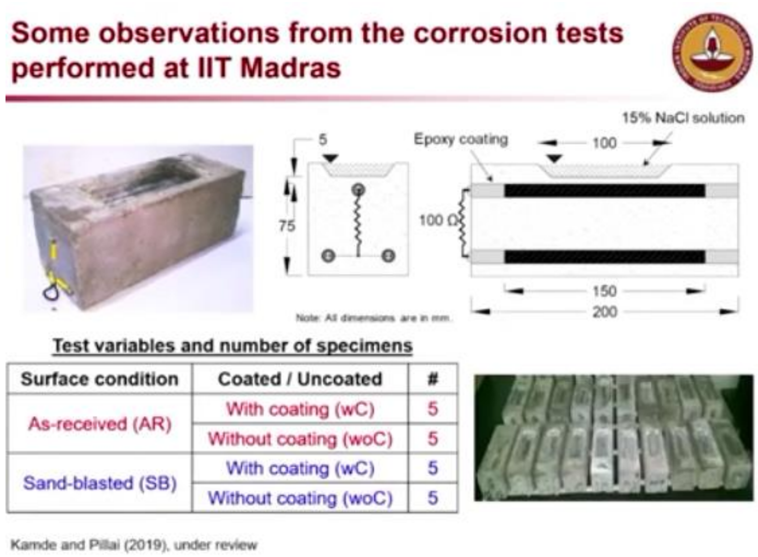

Now to study this or quantify the effect of this improper coating, we did some study. We prepared specimens like this, small prism specimens with three rebars, 1, 2, and 3. You can see the cross section here, how the specimen looks like and then we pondered the specimen with chloride solution for long period.

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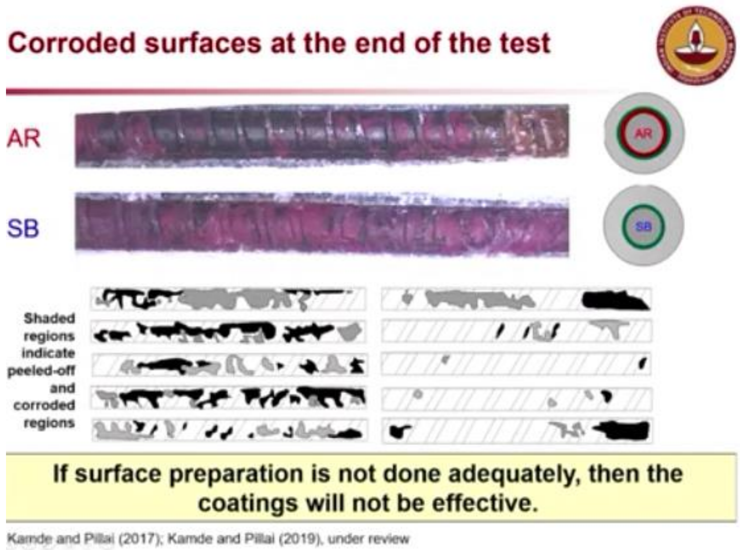

And we found that, as you see on the first photograph AR, which is actually a well coated but with some rust on the steel surface that is what as received means as received with some rust on the steel surface, we applied the coating which is the practice being done or adopted at the construction sites. But the right practice is to do sandblasting and then apply the coating. So we tried these two cases. How they are performing or how the corrosion resistance is getting affected.

You see on the left picture, this sketch on the left side you can see that lot of region is either corroded or peeled off. This light gray is like peeled of region and the black is the corroded region. Significant corrosion has been observed in the case of as received rebars. So this is AR case and this is SB case on the right side. On the right side SB case, the amount of corrosion is much less.

So definitely steel surface preparation is very, very important and we if we are adopting CPC coated technology, we must ensure that the coating is applied on a clean sandblasted surface. Otherwise, it is going to be harmful to the structure.

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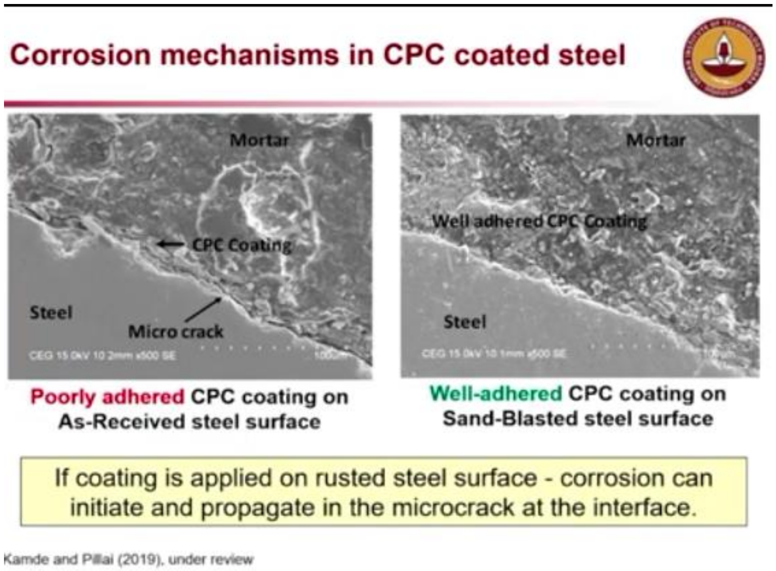

These are two micrographs, the one on the left side shows how the coating is adhered to the steel surface. You can see steel here and this is the coating and then there is a nice crack which is all along the interface between the coating as you can see there is a micro crack, which is absent in the case on the right side. So you can see steel here steel and then well adhered CPC coating and there is no crack between the or there is no crack at the interface between the steel and the mortar. So definitely, the surface preparation plays a significant role.

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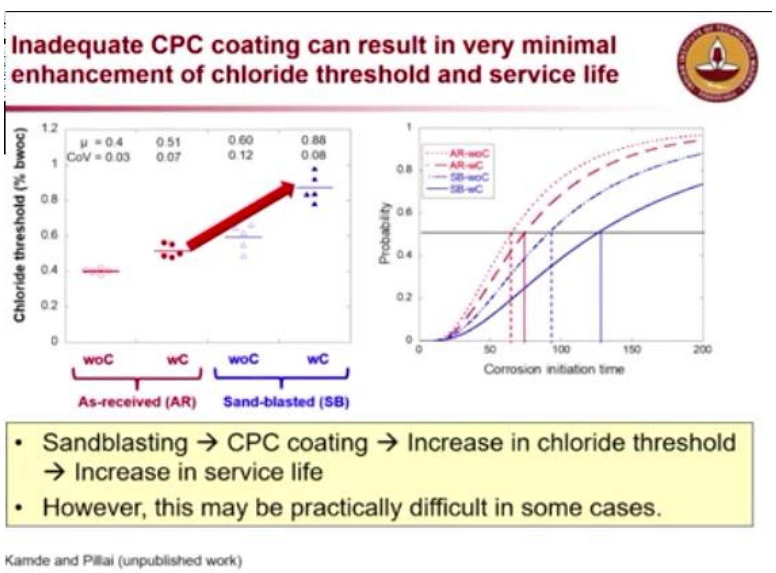

How it affects the service life? If the coating application is not really good, how the service life gets affected. So again, as I discussed earlier the chloride threshold for uncoated steel, we can assume it to be about 0.4 or this is what we determined. Here woC is without coatingand wC is with coating. Again here the without coating and with coating and the left two is as received case and this is sandblasted case.

Definitely there is an advantage of sandblasting in increasing the chloride threshold. If you compare the first two like these two in the case of as received case, you can see that the as received case, there is no significant increase in the chloride threshold; it is only from 0.4 to 0.5. But if you actually sandblast and provide this coating, you get the chloride threshold increases from 0.4 to about 0.8 plus almost double.

So that really tells you that the life can be enhanced if the coating is applied with proper sandblasting. So the message is the coating technology is good, provided the steel surface is very well cleaned at the time of application of coating and what is the impact in terms of service life is that if the coating is applied on a sandblasted surface, you might get an average service life of 100 plus years, 120, 125 years, just for the specific case. But if you actually have applied coating without sandblasting, it is almost about 70 years. So it very clearly says that this application of this coating if it is done without proper cleaning, it does not really do any good job. It is just mere waste of money.

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Another type of rebar, which is used in the construction market today, it is slowly getting into the market. It is fiber reinforced polymer rebar or non-metallic rebars. Typically glass fibers are all used and basalt fibers are also used. These are the two major types of fibers, which are used for this type of bars and why it is being used? It is very light compared to steel rebars and it can be manufactured in whichever shape and length that is also possible.

So what is this FRP rebar is? You have fibers like this and this is the polymer matrix or epoxy and then at the end you get a product like this. So all these fibers are held together or glued together with an epoxy resin. These are just pictures on the right side shows some of these fibers, which are available in the markets. That bottom picture clearly shows you can also get these type of rebars, which are already bent. Definitely you cannot bend this. These are very brittle materials. So you cannot bend these at the construction site. You have to do it early enough.

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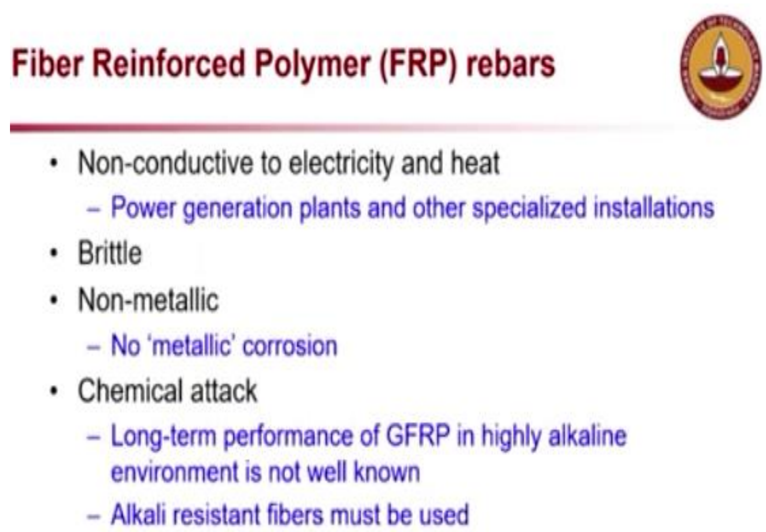

Advantages are these are non-conductive. So it can be very good for applications where power generation plants and other specialized installations where electric short circuit is a significant concern due to the use of the facility. And they are very brittle. This is a disadvantage of this thing and this is a good thing and then non-metallic, non-corroding material.

But again you have to see, what is the definition of corrosion? If you are talking or if you are defining corrosion as a metal loss, of course that is not there, but if you are defining corrosion as the material loss, then you have to think about the chemical attack also. So no metallic corrosion but this chemical attack and how it influences the performance of the bar in long run to be analyzed. The attack is mainly due to the highly alkaline environment in concrete and probably the moisture which is present in the concrete.

How these GFRP or this FRP rebars, (GFRP is glass fiber reinforced polymer) or even basalt, anything perform in the long run in presence of highly alkaline concrete and in presence of moisture must be studied before we can widely use these type of rebars. There are some technologies already available like alkali resistant fibers are used.

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Now this is a picture showing a poor quality FRP rebar this is because poor inadequate manufacturing process or the quenching process or in other words the epoxy was allowed to flow in the vertical direction like this and leading to small, you see bubbles forming like this not bubbles of epoxy is formed. This is also not good. It is an indicator that there is lot more epoxy in the rebar than what is actually required. In other words, it is not really well compacted, the structure. You do not need epoxy as filler. You need epoxy as a binder only or glue not necessarily as a filler. So adding too much epoxy and inadequate quenching or setting process is not really is something which needs to be looked at. It should be uniform. These kind of bubbles should not be there. These are all indicators of poor quality.

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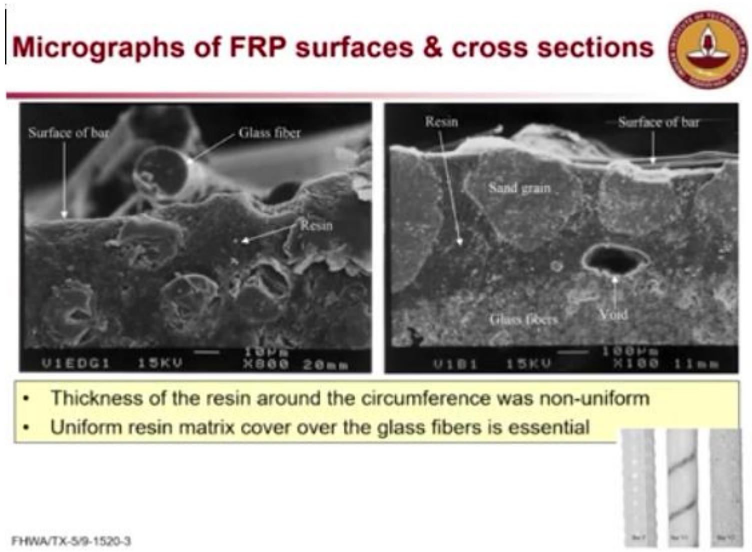

And again here, you can see there is a lot of air void present in this. That is also something not a good thing to have on this kind of rebars.

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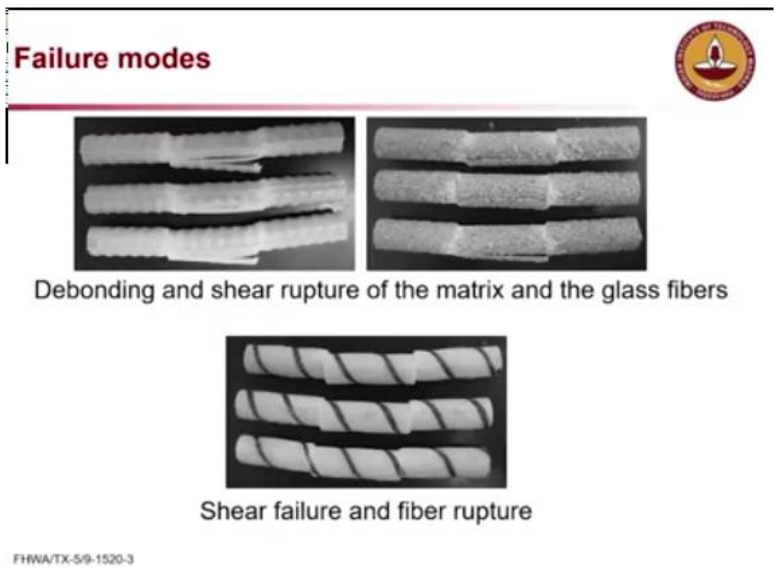

And let us see how, what is a failure mode of this type of rebar. These are definitely very brittle and you can see here on the picture, first picture, this one debonding and shear rupture in this one also. You can see the fibers are getting debonded like this here and also there is a shear, also there is a shear rupture like this you can see here, these are the two types of failure observed on the first two pictures or the first two type of FRP bars.

And here on the third picture here, you can see there is a shear failure and slight debonding happened on the first specimen, but it may not be a major concern, the major governing failure. So all these have to be considered and before we start using these rebars in a larger scale.

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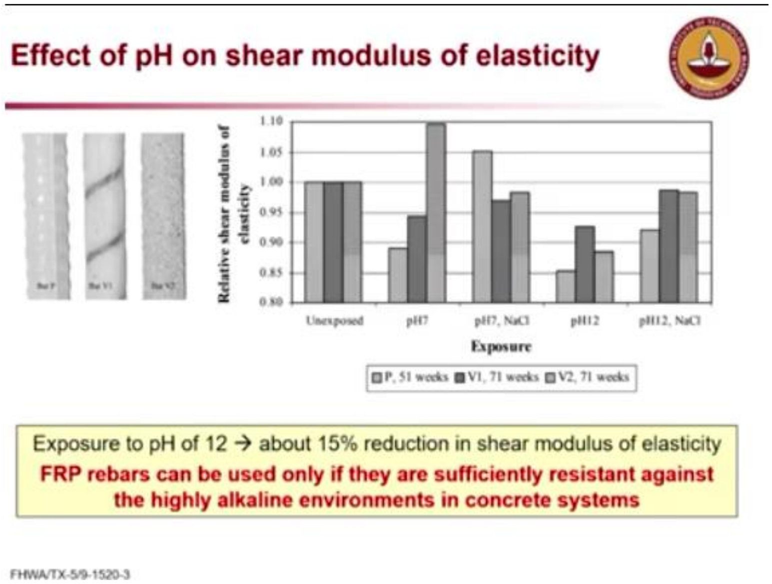

And how the pH affects the shear modulus? Definitely you can see in about, in this picture under in the graph on the right side bar chart. So this is related to the unexposed bars most of the other bar charts are below this, relative shear modulus of elasticity is less than 1 indicating that there is a possibility of reduction in the mechanical properties of this type of bars, when they get exposed to exposed to chemicals, in other words concrete. Even though, there is no metallic corrosion but the other forms of degradation must be tested or investigated before we go ahead and use this type of rebars.

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Cost comparison (approx.) of various rebars

Steel Rebar Type	Cost Ratio
Conventional uncoated TMT/QST steel	1
Corrosion Resistant Steel (CRS)	1.06
Cement Polymer Composite Coated steel	1.2
Fusion-Bonded Epoxy-coated steel	1.4
Galvanized steel	2
Fiber Reinforced Polymer bars	3
Solid Stainless steel	6 to 7

In addition to the capital cost, the durability and life cycle cost must also be considered while making material choices

https://www.engineeringcivil.com/comparison-of-epoxy-coated-rebar-vs-cpcc-rebar-vs-crs-rebar.html; Burgoyne and Balafas 2007; http://www-civ.eng.cam.ac.uk/cjb/papers/cp74.pdf

And this is just a cost comparison on how different type of steel rebars which are coated, what is the cost between the two. The galvanized steel, you can see is about twice the cost. FRP rebars it is about thrice the cost and the CPC coated and fusion bonded epoxy coated is about 1.2 to 1.4.

So this is probably the reason why these two types of non-metallic coated rebars are used, but we should be very careful about going for lifecycle. I mean, do not look at only the capital cost, but also look at the lifecycle cost and the durability. These two are very, very important to look at before selecting steel reinforcement, because the structures life will depend not only on the concrete, but also on the performance of the steel that balance which we were talking earlier. That is very, very important.

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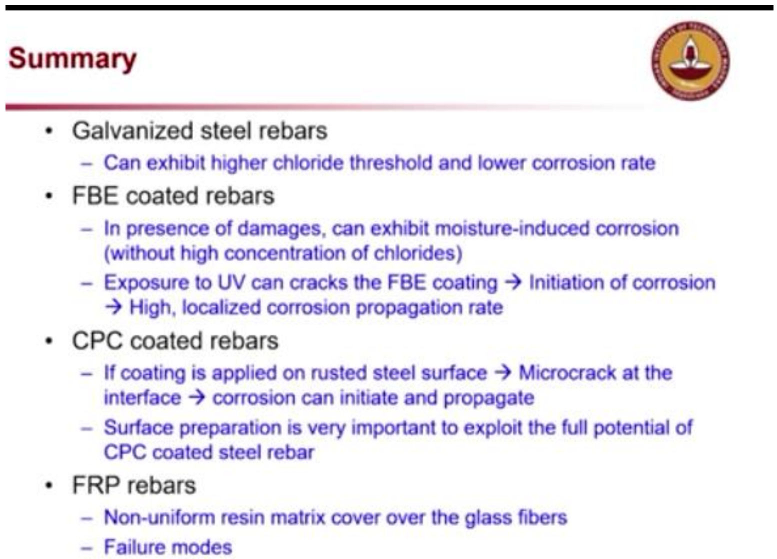

And so we covered, how this galvanized steel rebars can exhibit higher chloride threshold and low corrosion rate and also a wider pH passivation range. So those are the advantages of galvanized steel rebars, fusion bonded epoxy-coated rebar and CPC coated rebars both are good, if they are manufactured in a proper way and implemented in a proper way, they can give you long life.

But considering the site practices and rough handling, etcetera or even inadequate preparation of the steel surface, these rebars are not performing. We have enough evidence showing that they will not really last very long as compared to an uncoated rebar. Then also we discussed about the fiber reinforced polymer rebar. Definitely, we should look at the longevity of those rebars in highly alkaline environment, like we see in concrete. They may not corrode. There is no metallic corrosion, but other form of chemical attack is possible, so that should be taken into consideration.

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These are the references for further reading in this material.