Corrosion, Environmental Degradation and Surface Engineering

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Lecture – 21
Non- destructive testing – Part 2

Hello and welcome to the 18th lecture of the course on corrosion, environmental degradation, and surface engineering. This is a second lecture on NDT, which is non-destructive testing. And then we started this topic of testing, realising the importance of testing because, finally, our aim is to minimise the failures and minimise the even initiation and progress of the failures by taking the necessary actions well in advance. Therefore, testing plays a crucial role. The first slide highlights the importance of non-destructive testing (NDT) in maintaining the efficient operation of industries. NDT is essential for inspecting complex structures or assemblies without the need for disassembly. This approach offers a significant advantage: it eliminates the need to dismantle the systems.

The primary importance of NDT lies in its ability to test equipment without dismantling or causing harm, allowing continuous testing without halting operations. NDT can uncover weaknesses and faults in materials or structures, unlike destructive testing. Initially, industries rely on destructive testing to understand materials when insufficient data and knowledge are available. Once adequate knowledge and understanding of potential failures are gained, they then adopt non-destructive testing (NDT) methods.

There was also importance given to the two industries; we say the aircraft industry really needs to have NDT. Even the pipelines, so these are the running kilometres or kilometres, are closed, and if there is a failure, certain there will be a lot of leakage of gases, water, or maybe oil. So, we want to avoid all those kinds of failures. So, that is why NDT is required, similarly for pressure vessels. So, these are very important for those industries.

That's why we focus heavily on Non-Destructive Testing (NDT). Of course, I am writing here because we have been placing most of the emphasis on surface failure; we are not going to give much importance to the complete fracture. In this case, even if something is wrong inside a pipeline, I will not be able to understand it from the outside. So, those failures are also required to detect whether the thickness of the system is or maybe the component is continuously releasing because of the corrosion when the failure occurs. This is why we emphasize the importance of detecting issues, even those on or near the internal surface. If a crack is close to the surface, it may become visible after a few hundred or thousand cycles. Detecting such issues well in advance is crucial, which underscores the importance of this feature.

Another important thing about NDT is that if we are using established techniques, those techniques are based mostly on standards that have been given by the various societies. So, if we are following some standard practice or standard test, then it will be applicable to everybody, and then we can document, publish, and really share with the industries those documents. And another thing is that we are trying to detect the failure well in advance. So, in fact, it is an economic way to realise that if we have done something wrong, or maybe some cracks have been left, or maybe some manufacturing process is not efficient to build a vacuum and a system, those can be detected by NDT, and then we can improve the quality. So, that is why using NDT to find issues leading to major failures is an economic way to improve quality control.

So, that is very important for us compared to destructive testing; NDT processes are more sustainable, and in my earlier lecture, we mentioned very clearly that sustainable development is required, and to develop sustainable manufacturing sustainability, we require a minimum to minimum rejection, and that is why we should be able to utilise our existing resources in a much better manner and produce minimum waste. That is where the entity really helps us: it uses fewer resources and produces less waste. So, it is really helpful to us. These are the merits of the NDT, which is why we are continuing. However, we also give a lot of importance to corrosion, and when we discuss NDT, even with destructive testing, corrosion will play a very important role. So, we will be covering a few slides on corrosion or corrosion testing, maybe destructive testing or non-destructive testing.

So, when we think about the corrosion itself, corrosion testing can also be divided into two groups: destructive testing and non-destructive techniques. So, same division as the way we have used for the normal case, the corrosion testing is also a part of that only. In this case, with the destructive testing, we basically try to measure the weight loss: is the weight loss positive or negative? Positive weight loss indicates that material has been removed from a surface, while negative weight loss means that material has been added. Material addition occurs in chemical environments where reactions cause environmental material to be absorbed onto the surface. This absorption leads to an increase in weight as material from the environment accumulates on the surface.

So, that is why we need to count it. Now, we have learnt that there will always be a wear loss that will always have a positive side. However, in corrosion, there is a possibility of a negative side as well, where the top surface is swelling and accumulating the material from outside. That is why the weight loss can also be negative. However, this weight loss itself is an indicator of corrosion severity. If the weight loss is significant, we know that the severity will be on the higher side, or maybe the corrosion process is causing severe damage to the surface.

Another important aspect we've learned is that metallographic investigation provides valuable data, which can be used to predict the residual life of a system. This data includes the depth of chemical penetration, the extent of the attack, pit diameter, and the presence of intergranular corrosion, indicating severe damage due to high stress levels. Such information is crucial and is obtained through metallographic testing.

Additionally, we have studied corrosion coupons, which were discussed in previous lectures. In this method, numerous coupons (e.g., 100, 200, 500) are used to test how corrosion progresses, whether it's linear or non-linear. By varying the concentration of chemicals, we can determine the actual corrosion rate. For example, if sulfuric acid (H_2SO_4) is used on a component, increasing its concentration allows us to observe the effects on the material, identifying any minimum or maximum limits. This method helps us understand corrosion behavior under similar conditions.

So, that is why the coupons, which we use particularly for this kind of distinctive testing, need to be made from materials that have the same material as the system. Another thing that came to mind is something like mechanical testing. What will happen if the corrosion is happening, and I give an example of something like inter-granular corrosion or maybe pitting something like that? So, if there are cracks or may be deep cracks possible, will there be any damage to the material's strength? Will the tensile strength come down, the compressive strength will be less, and the and the bending strength will be less? Those things can be figured out using mechanical testing, particularly when the material is subjected to corrosion. So, material testing after corrosion. Keeping to non-destructive testing is the same; we go with visual inspection and ultrasonic testing. These two topics have already been covered in our previous lecture, and then we will be taking a few examples, particularly pertaining to corrosion.

So what will happen in the corrosion case of visual inspection, what kind of UT can be done in the corrosion testing. We will be also covering the radiographic testing in the present lecture; remaining methods will be covered in the next topic that is a NDT-3. Now if I want to express in other words, we can really express weight loss testing, weight is measured before and after the test, the same thing what we do in a wear testing and the difference in the weight value such as the severity of corrosion. If weight loss is very high then initially severity will be very high, if weight loss is negligible 0, then we will say there is no severity of corrosion. If it is a test turning out to be negative, then we say the material is accumulated from outside. Now here there is a one problem also, if volume is continuously increasing or mass is continuously increasing, but there is a possibility of the thermal crack or maybe say the additional cracking happening in the material. We will cover an example where the overall weight increases, leading to negative weight loss. In this scenario, the dimensions of the material will increase, causing damage to concrete, particularly the reinforcement within the material. This reinforcement gets corroded internally, resulting in continuous accumulation without any material removal.

The diameter may be 13 mm initially becomes a 15 mm, 16 mm or 30 mm naturally the material is getting added, and then there is a overall structure and there is a unbalance in this situation. Naturally, there will be more and more generation; more and more expansion of the cracks will happen; and finally, the whole system will break. So even though material loss is a negative side, it is still concerning what will happen to the dimension, so that is very important for us to understand. So from that point of view, weight loss testing is very important, and again, in metallography, we need to really look at the cross section of corroded material. We need to prepare it, as I mentioned earlier. In destructive testing, we mostly make the samples.

So samples are prepared; in this case, we need to etch and then examine under the microscope. It can be any microscope; it can be optical; it can be SEM; it can be TEM; it depends on what the real requirement is. So this kind of technique will reveal the corrosion damage, and the corrosion damage may be something like the extent of attack pitting and intergranular corrosion, which I also expressed earlier. As I mentioned in the testing corrosion coupon, we make many coupons so that we can evaluate or follow some sort of trend analysis. Therefore, we can conclude that corrosion testing is a standard technique for evaluating and monitoring corrosion rates in industrial systems. Coupons are typically rectangular shapes; as I showed in one of the earlier lectures, mostly they are rectangular in shape, but sometimes it can also be a circular cross section, or we say that the other shapes are also possible; most typically, a rectangular may be done in a circular.

So the coupons are typically rectangular in shape and made of the same material, which I already expressed as the system component, and exposed to a similar environment. The main thing is that we need to simulate a similar kind of environment that can be scaled down. This can be scaled up depending on whether we are going from micro to micro or nano to micro to understand the complete system. So this is what we really require, and then what we do is periodically remove and analyse the coupons. There are 100 coupons, and we want to see what happens over the 100 days. So we remove one coupon every day. So the first coupon may have been exposed for only one day, the second coupon for two days, and the third coupon for the third day, or something like that.

So we can say that by biopinetically removing and analysing these coupons, we can access the corrosion rate and determine the type of corrosion, which is quite possible, and the corrosion modes may change as wInitially, the corrosion occurs in a single mode, but after a period of 5 days, 10 days, or 15 days, additional corrosion accumulates and intensifies significantly. tly. So we can really figure out what the root cause of failure is and what the really important factor is. What is the main factor that is enhancing the corrosion drastically? So those things are possible when we go ahead with this testing corrosion coupon, and this is very important for us and the future. We can also think and keep good control. We say that we have learnt everything, and now we want to test and make a system under control.

Therefore, we have the ability to manipulate the control system effectively. We can determine the impact of corrosion-induced degradation through processes such as tensile, bending, and impact testing. So what is really helping is really giving a lot of data to us, so that more and more understanding may occur, like when I can test some acidic environment or some sort of NaCl sodium chloride environment. I can figure out what is happening out there with sodium chloride over the period, or it may be what is happening when the exposure is towards the kind of HCL, or it may be nitric acid, or it may be sulphuric acid, or something like that. Now while we say non-destructive visual testing, which I have already covered in an earlier lecture, and corrosion will cause some sort of discoloration, Particularly when we are talking about the corrosion, it can really discolour the system, or the component can really leave a number of bits on the surface.

Ultrasonic testing is crucial for detecting subsurface issues that aren't visible on the surface, such as crevice corrosion, which can cause more damage internally. In such cases, visual inspection is insufficient, and methods like ultrasonic testing (UT) or radiography are needed. Today's lecture will cover these techniques. In UT, we use transmission and reflection to determine the appropriate method, allowing us to gather signals and make predictions.

I'll now discuss a research paper published in 2018. This study examined the corrosion behavior of aluminum alloys 7072 and 7075 under different conditions. The researchers mixed silicon carbide in concentrations of 1%, 2%, 3%, and 4%, and exposed the samples to various environments, including HCl, sulfuric acid (H_2SO_4), and NaCl (salt solution). The samples were exposed to these solutions for 96 hours, after which weight loss was measured to determine the corrosion rate in mm per year. The data showed that sulfuric acid (H_2SO_4), indicated in red, had a significant impact in all four figures.

So in all four figures 1, 2, 3, and 4, the sulphuric acid is causing more and more damage compared to the HCL. HCL comes at number 2, and the NaCl salt solution is not really affecting it at all in this case. So what has been happening? This is for the pure aluminium alloy. This is an aluminium alloy with 2% nano silicon carbide. This is an aluminium alloy with 4% nano silicon carbide, and they are mixing, making a hybrid composition that is 4% silicon carbide and then 4% aluminium oxide as well.

The researchers used a hybrid combination of materials to determine the corrosion rate and evaluate the effectiveness of new materials, which is a current top research area. They found that incorporating more materials can control the corrosion rate. For instance, in pure alloy, the corrosion rate is higher, but with the addition of 2% nano silicon carbide, the rate is reduced to a maximum of 0.08 compared to 0.14 in the pure alloy. However, when the concentration is increased to 4%, the corrosion rate rises to 0.12 due to increased cracks and discontinuities, which decrease homogeneity.

To address these issues, the researchers added aluminum oxide to the 4% silicon carbide mixture. This adjustment improved overall performance by reducing the corrosion rate and minimizing mass loss. This research indicates that developing better materials requires validating innovative techniques to ensure they lead to improved products. They found that while 2% silicon carbide yielded better results than 4%, the best outcomes were achieved with a hybrid combination of 4% silicon carbide and aluminum oxide.

This is the best. So, this is giving us the best results, and it has been concluded based on what we have tested. If we do not test, we will not be able to compute. This is a reference, and it was published in 2018. Now, coming to the metallography, and again, I am trying to cover the literature for 2019. There is a paper on the metallography and corrosion of ancient Chinese biometallic bronze swords. Historically, swords were made of bronze, and excavations have revealed that such swords date back to 476-221 BC in China. The lower part of these swords, used as a handle, and the extended blade have been found in a degraded state, showing significant material removal and damage.

A case study suggested that these swords typically contained 23% tin, but recent findings show only 16% tin. This discrepancy indicates either material removal due to corrosion or variability in tin content across different sections of the sword, possibly due to limitations in the casting and manufacturing methods of the time. The ancient manufacturers lacked the knowledge to create a homogeneous mixture, resulting in inconsistent composition.

Researchers used optical micrographs, microscopes, and X-ray diffraction (XRD) to analyze the microstructure and corrosion phases of the bi-metallic sword. They observed that the sword was broken and corroded, likely due to the burial environment. The presence of decomposing bones nearby created a corrosive environment, producing insoluble pyromorphite. This chemical acted as an electrolyte, forming a chemical cell around the sword and leading to its degradation.

So, this kind of study really helps to understand now, if anything ancient that we have we want to preserve it for years and years, what kind of environment is really required. So, this test really helps, and then another thing they mentioned was that there were some sort of void on the cracks, which are really providing the active environment in the presence of the solution, which is corrosive in a corrosive environment. In addition, there are voids and cracks, which are helping to make a kind of electrochemical cell.
As corrosion progresses, metals migrate and redeposit, leading to different chemical compositions in various sections. This explains why tin might have moved from one section and redeposited in another, resulting in inconsistent tin content.

To preserve such antiques, it is crucial to create a stable environment by removing all active corrosive agents. This will help maintain the integrity of the sword and prevent further degradation.
To achieve good results in preserving antique artifacts like swords, it is necessary to remove corrosion media and fill any cracks or voids. Filling cracks with appropriate materials can stop or at least delay the corrosion process. In today's lecture, we will cover a case study demonstrating how filling cracks can delay corrosion. By removing active corrosion agents, the sword can remain stable. Storing bi-metallic swords and similar artifacts in a dry, clean environment is essential for preservation.

The case study provides detailed findings, including a table showing different phases present in the sword. Typically, we observe alpha, beta, and delta phases in steel or bronze, with epsilon phase being rare. However, a small section of epsilon phase, around 0.5%, was observed in this sword. Additionally, two types of alpha phases were identified: one containing 14% tin and the other 10.2% tin. This indicates the presence of different alpha phases in the sword.

Of course, they did XRD, and then they figured it out, and then they tried to spot some sort of green patch and some yellow patch, which means there were different kinds of phases of the corrosion. In this case, they also find the green colour, red colour, and yellow colour already there. In addition, there are some other corrosive products available on the surface. So, these are important, and then they could conclude that there is a non-uniform distribution of elements within alloys that may be some sort of chemical action happening, and then there is more and more non-uniformity coming into the picture. If that is not happening at the current time, that means when they were really manufactured, there was some sort of non-uniformity, which has come from a cooling and solidification process. That means whatever manufacturing process was chosen at that time, even there was a non-uniformity. There was no uniform cooling, and there was no uniform solidification. That is why there is a migration of the material, and somewhere we are getting one kind of chemical composition, and in another portion we are getting another chemical composition. So, it may happen over the period because of the burial environment, because of a chemical reaction, or because of the manufacturing time itself; those things were not uniform, and they were not able to keep uniform. So, both options are possible in this situation. Now that is another term for what we call corrosion coupon testing, and we generally go with many coupons, not one or two coupons.

In this case, we are examining the effects of elemental sulphur on mild steel. So, we say the impact of elemental sulphur on the corrosion of mild steel, and this is the mild steel in this case; this is the elemental where the first sulphur has been kept. Now if you keep this unit for almost 4 days, even at room temperature, I found that a lot of iron oxide sulphide gets on the surface, and instead of this kind of surface and this kind of colour, everything becomes black on the top, and that is because of the iron sulphide. So, that means if an elemental sulphur is exposed to mild steel naturally, it will corrode the mild steel , and it will make iron sulphide, which is a black colour. If you leave for a longer period of time, the layer will be thicker. That is why we say that elemental sulphur can cause a localised corrosion process.

I use the term "localized" because, in the absence of water, the corrosion is limited to specific areas, unlike generalized or aqueous corrosion, which occurs when water is present. When elemental sulfur comes into contact with metal or steel, it can cause localized corrosion. However, if water is present, hydrolysis of the elemental sulfur will produce sulfuric acid (H_2SO_4), leading to severe generalized corrosion, especially at temperatures above 80°C.

When testing, the temperature plays a critical role. At 25°C, localized corrosion occurs, while at higher temperatures like 80°C, the formation of acidic solutions causes more extensive corrosion. It is essential to monitor the effects of temperature and time on corrosion, observing changes daily or even every few hours to understand the process better. A series of experiments are needed to study the effect of temperature on the acidification of water, particularly when elemental sulfur is exposed.

Corrosion coupon testing is highly effective for such studies. By using multiple coupons made from the same material and exposing them to different conditions, we can gather comprehensive data. Fang et al.'s study, published in 2008, tested temperatures ranging from 25°C to 150°C and reported their findings. Corrosion coupons provide valuable data and images, which are essential for understanding corrosion over time.

In their study, a 2 mm sample showed corrosion, with a denser film forming on the surface after 4 days at 25°C. This film, likely a sulfide, displayed curved edges and exfoliation. Upon magnification to 10 microns, surface lines were visible, indicating the film's characteristics and the corrosion process. This exfoliation and the film's properties were further detailed through magnification, demonstrating the changes over time.

And then this coupon has more severe cracking than exposed to one day, which means they compare if this is after 4 days, but they compare with the one day and then exposure after one day. What will happen, or maybe the material coupon or maybe the surface that has been shown after one day? Naturally, compared to one day, this is much more severe damage. So that there is no passivation within a fun day itself, many times we say the passive corrosion after one day stops with no further change. So then, what would have been the results after one day? After four days, there is no significant change, which means the same changes are not happening. While they indicated this coupon has more severe film cracking than when it was exposed for one day, that means there is a progression in the corrosion, and another thing we are able to observe in this case is This kind of line, you say, is the polishing traces on the original steel substrate because the coating is happening, this layer is getting deposited, or iron sulphide is formed on the surface. So we need to look at what the initial original surface steel substrate was, and if there were any sort of marks or maybe polishing traces, those have also transferred to the sulphide film.

So that is what you mean by polishing traces on the original steel substrate laptop imprint on the sulphide film formed by the solid-state chemical reaction. So there was a solid-state chemical reaction of iron sulphide on the iron, and the sulphur formed the iron sulphide, and if you allow more and more days, it will become thicker and thicker. Because of the solid-state reaction, whatever the surface roughness of the mild steel, it is also coming directly from iron sulphide. So this is water, then the solid-solid because of the very intimacy between the two surfaces, this is getting transferred, and the surface texture is getting transferred on the other film. Now that is what we have been shown over here again, the same paper has been referred to in this case. Now there is another point on which we discussed something: there is a possibility of damage to the material property, or maybe a lesser transylate strength or a lesser bending strength.

So to understand that, we then required mechanical testing, and that is why this had to say corrosion testing and mechanical testing as such. To understand that kind of effect, we required samples the way we mentioned in the earlier corrosion coupon testing. So we really required that kind of thing, and then there is one case study available in the literature that was published in 2019. We have picked up on the fact on the fact that we say that there is a there is a corrosion effect on sintered 316L stainless steel. Now here, the suffix L indicates a low carbon content, and the carbon content is kind of a 0.02, and most of the stainless steel material's carbon content is on the higher side, maybe something like a 0.06, 0.08, or something like that.

In this case, the chromium content is purposefully kept low. However, the stainless steel used contains 17% chromium, 12.5% nickel, 7.5% nickel, 12.75% nickel, and 2.15% molybdenum. Given these compositions, a question arises about how to proceed with material or corrosion testing.

To test corrosion, they used a salt fog or salt spray test. They created a chamber for cyclic exposure of corrosion media on steel samples made from sintered 316L stainless steel, which has the chemical composition mentioned above. The SLMS equipment was utilized for this purpose.

SLM stands for Selective Laser Melting, a process where 100-micron-sized spherical powder particles are melted to prepare the sample. This technique is part of additive manufacturing. They controlled the layer thickness (LTE) to around 30 microns per layer, forming a thick layer as the layers were melted and fused. The number of passes affects the layer's thickness. The samples were prepared and tested in different environments, particularly a nitrogen environment.

So the other activities can be stopped completely; only the melting of the material happens, and then we are able to get a good sample without any exposure to an oxidising environment. This is what they have done, and then finally they presented results on this. They also said that for the material testing, they made this dog bone specimen shape as per the standard ASTM E8M standard that has been given. This is a standard that has been demonstrated over here. Of course, they use three processes, or three different kinds of manufacturing processes. One manufacturing process sample 1, a second manufacturing sample 2, and a third manufacturing sample 3 have been used.

Now what is the difference in a manufacturing process when we are using the additive manufacturing process, or, as we say, we are using only the SLM manufacturing process? But now they have a change in power rating and power setting. The first case is the power rating, and the setting is minimum; the third case is the is the power setting, which is maximum.

In the first case, the velocity was kept at 200 mm/s. In the second case (S2), the velocity increased to 300 mm/s, while in the third case, it dropped back to 200 mm/s. Despite these changes, the energy level imparted to the material was highest in the third case. For S2, the energy level was approximately 188.9, very close to the 188.3 energy level used in the S1 manufacturing process.

The microstructures of the samples were examined and labeled as follows: A represents S1, B represents S2, and C represents S3. In sample S1, some corrosion marks or irregular shapes are visible. However, samples

S2 and S3 show fewer corrosion marks and appear more similar to each other. All three samples exhibit milling or polishing marks.

In S1, S2, and S3, the polishing marks are evident. Additionally, a bar chart illustrating mass loss (MOSLOS) is shown to compare the results across the different samples.

So the mass loss of a specimen is a function of exposure time. So exposure is 0 over 24 hours, and the last one is 240 hours. So what is it really, and this is basically simple salt? It is not a very chemically reactive surface, but it is still corroding in this case. So in the first hour, we do not have to think much about. Coming to the second one, we find a significant loss of material in sample 2.

In sample 2, there is a significant loss of this sample, even though surface texture is good, surface roughness is good, and appearance is good, but it is causing a huge mass loss. If you look at the red colour, this patch is very small, significant, and very much less than the S2. In S1, we can observe some corrosion and an uneven surface, but the mass loss remains significantly lower. Therefore, we need to understand why. After 96 hours, we find a very little accumulation of material loss in samples S3 and S4, while the reduction has gone from around 50 milligrammes per centimetre square to roughly 10 milligrammes.

There has been a significant reduction in reactivity. After 24 hours, the reactivity level we observed was significantly higher than after 96 hours, where it dropped to only 20%. This indicates some form of passivation is occurring, making the material less reactive over time. For sample S1, material accumulation on the surface resulted in negative weight loss.

So in fact, this material and this sample S1 are really accumulating. Now, after 186 hours, the accumulation in the case of the S2 has gone very high. So in this case, material loss is not happening; in fact, material gain is happening. So these are the steps, and after 240 hours, we find the S2 is very sensitive compared to the S1, but the S3 remains very good, not losing material or gaining material, which means it is turning out to be more chemically inactive again. There is a material that is the same after 316 hours of testing specimen geometry; everything is the same; only what has changed has changed: the energy level that is exposed to the surface.

So the manufacturing process is only fine-tuned. Now the material is the same, but the manufacturing process is fine-tuned, and we find a significant difference in the results. So this is where we say that when we go for the testing and we figure it out and we can really tune it, we can really make the manufacturing process perfect for the particular situation or particular condition. If I want to express it in words, we can call it the S1 sample. If we look at the saw in a few years, the S1 sample exhibits irregular and non-uniform surfaces, whereas the S2 and S3 samples exhibit uniform surfaces without much visible cracking. While in S1, we could see the samples were kind of having some sort of crack or defect or some sort of corrosion as well. So another thing is that we are able to see some sort of mark; it can be milling marks, it can be surface grinding marks, depending on what we have seen on a magnified view, and then when experiments were done, those were done in a salt spray experiment in the kind of fog environment or vapour environment, and then to evaluate what will be the corrosion behaviour of this material, and we could figure out there is a weight variation.

So the variation in weight of the three sample groups throughout the acceleration test and corrosion test was particularly shown in the figure. This variation in weight represents both, as I say, mass gain and mass loss. Generally, in a wear test, we look at only the wear loss, while in this case, we are looking at the corrosion. That is why the corrosion test is slightly different from the wear test. We found that the S1 group of the sample exhibited a low mass loss during the first 24 hours, followed by a variable weight gain, as we have seen in the negative law, and the weight loss was negative.

There was a variable weight gain as the exposure duration increased. In contrast, the S2 sample group experienced significant mass loss during the initial 96 hours. After this initial period, the samples began to gain material. Despite a slight variation in energy levels (188.3 for one and 188.9 for the other), this minor difference caused a substantial variation in properties.

The S3 sample group exhibited less corrosion than the S1 and S2 groups. This behavior can be attributed to the better surface quality and higher chemical inactivity of the S3 samples compared to the other two materials.

So chemical inactivity has been formed or made because of the manufacturing process. Now they also have given microstructure, as I say, their metallography. So they have a given microstructure; as you can see here, there are many cracks and irregularities, and in the case of the S1, Similarly, we are able to find some sort of irregularity in S2, while S3 is more or less good. However, we were able to find some sort of irregularity after 96 hours. That is why, looking at the bars of the different samples, we found there was some sort of weight loss after 96 hours, and that is indicative over here. While in this case, after 96 hours, we are able to find out the deep crack in this, or may be the pit formation, and this is continuously increasing. Then, this pit is continuously increasing, and up to 240 hours, this has also gone very high, and in that way, after 240 hours, it has come to the visible sign or something like that.

So, this analysis shows the surface at 20 microns, while here we are looking at 1 mm, not 200 microns. This is visible on the edge of the surface. Overall, even though the weight loss and gain are not very significant in the case of S1, the microstructure reveals severe surface problems. For S2, significant defects were visible after 24 hours, and while these defects decreased, crevices and micro-pit formations are still present in S2. In S3, significant variations were seen after only 24 hours of exposure, with more variations observed after 96 hours, but not much change at 168 and 240 hours.

The surface morphology of the specimens from each group, exposed to salt, has been shown for 24, 36, 168, and 240 hours. We can see pits, crevices, and cracks on these surfaces.

The cracks have also been visible. These are the two common forms of corrosion on stainless steel surfaces. So this kind of corrosion will occur. If I want to express it in my own words, I will say that when conducting a corrosion test, it is essential to evaluate the surface profile better, or, perhaps, instead of the surface profile, we say metallography. So that will lead to a better understanding. We could see that the surface of a S1 group develops a round kind of pit; the pit dimensions are also different, and the depth, which we could not measure in this case, is also different. As the duration of exposure increases, the fissure may become more pronounced and grow in size. Eventually, after 240 hours of concentrated corrosion, particularly at 1 mm in length, it becomes visible.

Initially, we were looking at the SEM images, but finally, after 240 hours, they became visible on each of the samples as such, and then it was shown to you that the 1 mm was visible as such. Now coming to the SEM micrograph on the surface of S3, it is substantially less severe. Of course, there is still severe wear, but substantially less wear compared to S2 and S1. In addition, the S3 exhibited some sort of localised corrosion or some sort of pit after 96 hours. The reason being that there may be some sort of defect in the matrix, and if we further improve the manufacturing process, that can also be minimized. So if I want to say that the S1 group, even though mass loss and all that has not been substantial, and S2 has much moresensitivity for that, but while coming to the metrography, We say now that S2 compared to S2 S1 is on the worse side and S3 is the best among 3. However, even in S3, we found after 96 hours that there was some sort of weakness in the matrix that required more refinement in the manufacturing process.

Finally, the main aim of the test was to figure out what has happened or what is happening to the material property. So that is why they have given this kind of diagram, say a tensile test, on a specimen, and they have given a result of elongation, yield strength, and UTS, or ultimate tensile strength. So this case, for example 1, we are able to see there is a significant difference between S1 and S2. So yield strength is substantially lower for S1 compared to S2, and then there is no significant change in S1 and S2, S2 and S3 yield strength, but the elongation is still there, which means this kind will cause a ductile failure while this will cause a completely brittle ductile failure, and the last ultimate tensile strength is the highest for S3.

Now, if we compare S1 and S2, we see that the energy levels were nearly the same: 188.3 and 188.9, respectively. However, the scanning velocity and laser power were increased when moving from S1 to S2. This resulted in the ultimate tensile strength increasing by 297 MPa and the yield strength by 268 MPa. This substantial change indicates that even with the same chemical composition, variations in the manufacturing process can lead to significant differences—297 and 269 MPa increases in ultimate tensile and yield strengths, respectively.

Comparing S2 and S3, there is a notable change in the energy level used for S3, with a reduced scanning velocity. This led to a substantial increase in ultimate tensile strength and elongation, although there was no significant change in yield strength.

This data suggests that manufacturing process adjustments can lead to significant improvements. While the ultimate tensile strength increased, the yield strength did not show a substantial increase, indicating a need for further matrix improvements.

In conclusion, samples deposited with maximum energy exhibited less corrosion due to lower defect distribution. High energy input reduces the chances of localized deformation, leading to more uniform distribution. Consequently, as the corrosion process progresses, material properties remain relatively stable even after prolonged exposure.

It does not mean that will always be for everything; this was only exposure to the NaCl, which is a weak salt; it is not a very strong chemical or acid formation. However, if anything goes wrong in this case, they try to demonstrate the process, and after that, they conclude that even exposure, say over the 200 hours plus, causes no substantial change in a material property. However, during the manufacturing process itself, there is a substantial change, but exposure to the corrosive media is not causing a substantial change. So these points need to be considered appropriately, and we need to account for them. Again, we are not concluding that every corrosion reaction will have a similar kind of effect, and NaCl may not give a substantial change, but it is quite possible that sulphuric acid, HCl, and nitric acid will give a significant change. So every new chemical, new composition, and new material needs to be tested to figure out what kind of mechanism will be there.

There is no uniform rule, policy, or mechanism that can explain everything. This is why testing is essential for each individual case. Now, focusing on NDT, particularly for corrosion, the first method we address is visual testing, which we covered earlier. In a study from 2015, an improvement to this method was introduced. Instead of traditional visual testing, they implemented a technique called textured digital analysis.

Textured digital analysis represents an advancement in visual testing by aiming for automation. Instead of relying on the naked eye or even magnified devices, this approach seeks to automate the process to determine what is happening. The study presented in the paper provided results showing zero corrosion initially. By day two, they observed some corrosion, and as time progressed, more corrosion occurred, eventually leading to severe corrosion.

This method is essentially automated visual examination, utilizing textured analysis based on the top surface texture. By analyzing the surface texture, we can predict the extent and type of corrosion—whether it's mild, medium, severe, or no corrosion at all. For instance, they observed zero corrosion initially, but after 44 days, severe corrosion was noted. This kind of data helps determine the residual life of the material and predict overall system longevity, including crack initiation and progression.

Such experiments and testing are crucial. Automated visual examination, based on textured analysis and documented images over 45 days, can provide valuable insights. Although they showed only ten images, they collected over 44, documenting corrosion on ASTM A36 steel. By capturing, diagnosing, and predicting changes through these images, this process serves as an initial tool for machine learning. It helps develop algorithms that could automate future testing procedures, making it a low-cost, low-tech alternative to expensive methods like radiography.

Instead of using costly equipment, we can use a camera and an understanding of failure mechanics to develop comprehensive algorithms for early detection. This approach benefits material scientists, metallurgists, and mechanical engineers by providing a cost-effective and simpler testing method. By analyzing surface texture, visual testing becomes a valuable, economical tool that requires less technical training compared to more complex methods like radiography.

Another test we previously covered is ultrasonic testing. In this case, we focused on reinforced concrete, which contains steel bars that can be exposed to corrosive media like chloride solutions. When chlorides reach the steel surface, corrosion can occur, causing the steel dimensions to expand. For example, a diameter of 13 mm can increase to 15 mm or 20 mm. This expansion generates tensile stress in the concrete, which is strong in compression but weak in tension, leading to cracks. These cracks further expose the steel to corrosion, creating a cycle that accelerates the degradation.

Ultrasonic testing involves using two sensors to send and receive ultrasonic waves, detecting subsurface cracks. Surface cracks can be identified without sophisticated equipment, but subsurface cracks require more advanced tools because they might lead to surface failures after hundreds or thousands of cycles. Predicting these failures in advance can prevent catastrophic damage.

In the context of steel-reinforced concrete, also known as rebar, the corrosion of these steel bars shortens the useful life of concrete structures. By detecting subsurface cracks early with ultrasonic testing, we can mitigate the risks and extend the lifespan of these structures.

Typically, concrete buildings are expected to last up to 50 years. However, if there is corrosion or chemical exposure from drainage water, the lifespan can be significantly shortened. This shortening occurs due to corrosion of the rebar and the development of corrosion-induced cracks. These effects can be evaluated through normal and accelerated tests.

To conduct these tests, we can artificially create cracks in the concrete and develop algorithms to predict the behavior of unknown concrete structures based on this data. When corrosion is present, the amplitude of recorded ultrasonic waves will be reduced compared to non-corroded concrete. Corrosion causes more scattering and less collection of the waves, reducing directionality and increasing diffraction, which in turn lowers the energy or amplitude received.

By understanding and testing these phenomena, we can write algorithms to detect ultrasonic wave attenuation caused by corrosion-induced cracking. This is achieved by analyzing the energy spectrum of the recorded waves.

So, if we collect and analyse the energy spectrum, or maybe the only amplitude itself, we find there is a change. This case study has been picked up from a 2014 research paper, and then the chemical composition of concrete has been shown over here. Now, this ratio has been shown to be 50 percent (50%), that is, the water-to-cement ratio is 50 percent (50%), and of course, every concrete needs to be kept for some time. So that it gets cured. So, they cured it for the 28 hour days the 28 damped curing period was used. So, now they have sufficient strength, and after curing, they subjected it to the electrolytic corrosion test by submerging it in water containing 5 percent (50%) NaCl. It is basically a kind of marine water or a synthetic chemical that they have used, and they also use an electric current density that is 50 milliamperes per square meter (50 mA/m^2).

So, it is a very small current density they have used, and then they try to figure out whether there is already corrosion media density, and maybe there are some cracks. Then, a kind of electrochemical reaction will start, and finally, it will reach the rebar, and the rebar is a steel-reinforced bar, and then they use two sensors on the surface. Another point was that in this kind of concrete block, they use five-side epoxy. So, if there is no conductivity, there is no ingress of water. So, they can really figure out what is really happening.

So, only the bottom part, which did not have epoxy, allowed water ingress. This is illustrated by the positioning of two sensors on the specimen's contact media. The specimen was coated with epoxy, preventing water ingress from the top, while the receiver detected reflected waves from the bottom or the sides. Water ingress was possible only from the bottom, not from the other five sides.

After 90 days of exposure to the electrochemical corrosion test, they observed a significant surface crack. This deep crack was noticed after approximately three months, and by day 98, the crack had spread to a width of 141.4 mm. This crack was visible on the surface, eliminating the need for ultrasonic testing in this case. However, if we predict and simulate crack development by writing an algorithm based on observations from day 19, and see that this type of crack can develop by day 98, it would be very valuable.

Detecting the initiation of subsurface cracks and predicting their progression to the surface after 90 to 98 days provides valuable insights. The study showed that before the electrochemical test, a black color was observed, and after 90 days, a minimum energy green color line was detected. This indicates the progression and detection of corrosion over time.

The amplitude is lowest in the green color range. They aimed to predict the presence of a continuous drop in energy level over time, which indicates the development of cracks and ongoing damage. By writing an algorithm based on this data, they could predict the remaining useful life of the concrete.

Referring to earlier observations, after 24 days of corrosion testing, the amplitude of the waveform was reduced, a trend that continued through to 90 days. On day 24, a lower amplitude was observed in many areas, though some spots showed higher amplitude. This variability is expected due to different environmental factors affecting the sensors, such as vibrations.

The finding remained consistent from 24 to 90 days, indicating that corrosion-induced cracking leads to increased reflection scattering over time. More cracks result in more wave scattering and reduced reflection energy.

They used P-waves, which I discussed in a previous lecture, with a velocity of approximately 4022 m/s. They initially estimated the reflection time to be around 20 microseconds (20 μs).

However, they found the reflection time to be around 75 microseconds (75 μs), indicating the presence of cracks and scattering. This delay, compared to the expected 20 microseconds (20 μs), suggests that the return of complete energy is not as prompt due to these imperfections. Continuous monitoring at the microsecond level is crucial to observe how quickly the waves return to the surface.

In today's lecture, we will cover another technique: radiography. Radiographic testing, or radiography, uses X-rays for thinner sections or materials with lower density. For thicker sections or high-density materials, gamma rays can be used. However, gamma rays are rarely employed due to their high energy requirements and associated hazards. Despite these issues, gamma rays are still a part of radiographic testing, which is why we include them in our discussion.

So, it uses x-rays or gamma rays to penetrate an object or material to examine its internal structure. So, we do not go with a surface examination of internal structure, and then we want to really reproduce what happens inside the body or inside the body of a structure. Now, it requires sources for x-rays or gamma rays to emit the radiation towards the object being examined. So, there needs to be a kind of source of these rays, and then there should be direction at whichever point we want to really impinge or ascend, and then examine the surface or maybe the object in its complete volume, not just the surface. Then this is what will be output; as such, it produces images, which will be known as a radiograph on a film or digital detector. So, in a film, it is basically classical radiography, and then on a digital detector, it is something like a new digital radiography based on two categories: classical radiography and digital radiography, to disclose any defect or anomalies within the surface or within the material as such.

Now, what are the advantages? Radiographic testing can be used for both ferrous and non-ferrous materials, unlike some techniques, such as magnetic particle testing, which are only useful for ferrous materials. This method can be applied to both thin and thick structures; X-rays are suitable for thin structures, while gamma rays are effective for thick structures. Another advantage is that the images captured can be stored either on film or in digital form, providing valuable data for future comparison and trend analysis.

However, there are significant issues. Radiographic testing requires stringent safety protocols and regulations due to the potential health hazards to personnel and environmental damage from radiation exposure. There are two categories of radiographic testing: digital radiography and conventional radiography. Digital radiography is preferred over conventional methods as the latter is now considered outdated.

It increases productivity, enhances sensitivity, and increases environmental. Basically, it causes less damage to the environment because less radiation is required, and now, with machine learning, we also know that image processing tools are continuously enhanced. So, we can use image processing tools with that, and based on that, it causes fewer losses and fewer resources. So, it is cost-effective or cost-saving. So, digital radiography will be preferable compared to conventional radiography.

If there are failures on the surface, radiography should not be our first option; we can use other examination methods. However, if we need to investigate internal details and determine the sensitivity of various cracks or the potential for increasing corrosion—such as in concrete with embedded iron materials that may corrode and fail—radiography becomes a valuable technique. Radiography can be a good option or compete with other techniques for internal examinations. If faults can be detected using other methods, radiography may not be necessary. However, for more reliable readings and predictions, radiography is recommended.

Now, let’s look at a case study from a 2010 reference paper. In this study, radiography was used specifically for examining pipes.

We know the pipe has internal cracks, some sort of failure, or maybe surface damage, which we need to detect. So, that is why they wanted to go ahead with the radiography of the test sample they got from the pipes and then use this technique for the two different thicknesses: 12.7 mm, 25.4 mm is something like a half inch, and one inch, and then the material has already been defined; the base material has been shown in this kind of table 2. So, this is like a low carbon percentage that has been utilised in this case, and this is a grade that is something like API material, and then it is a 5LX70, and the whole thing has been described in this reference.

Now, they made a total of 6 samples, which is why we are seeing that there are total sink samples, and then they wanted to really do some testing for the welding.

There are big pipes, so when they get welded to the surface, what kind of process will happen? So, that is why they made the six samples, and they wanted to simulate the condition of the welded junctions to investigate, and of course, they used a sample measuring 250 mm by 250 mm, and that sample has been shown over here at 250 by 250 mm, and there is a centre portion that has been shown for the welded portion, as you are able to see over here. And then, after obtaining the samples, they created some cracks on the surface—intentional cracks on the surface. So, so that we can do a testing comparison, something like a steel-grade pipe. So, in this situation, they wanted to go ahead with a magnetic particle, they wanted to go ahead with conventional radiography, and they wanted to go ahead with digital radiography.

So, an overall comparison can be made. So, in this case, the first case and then the examined is the magnetic particle investigation to see the surface crack on this portion. This is what was demonstrated in the first case. Now, when coming in the conventional radiography, they also found that the cracks are visible with the conventional radiography, and then they found that this technique can also be utilized. So, I find more cracks on the magnetic particle side compared to this. Now, you are able to see some sort of crack over here, but if we go ahead with the digital radiography, we are able to see many, many cracks with many branches.

Now, medical and magnetic particles are basically for ferrous material, as we say, and radiography is for ferrous and non-ferrous material. So, even if I use polymers or some other material, this kind of process can be utilized. Now, we are comparing conventional versus digital, and we are able to see that there are many cracks. There are many branches of the cracks, and many portions of the cracks are visible. So, we say that with a rectangular mark on the digital image, a collection of fractures, or maybe cracks with multiple branches, can be seen. This image should clearly depict these branch fractures, demonstrating that the digital technique is superior and has the ability to detect and visualise discontinuities.

As a result, the digital radiography method is more sensitive than the conventional radiography method. So, we just say that the radiography is better compared to conventional radiography. Of course, if it is a magnetic material or ferrous material and if there are surface cracks, I will not go with the radiography, but if it is a very minor crack that is invisible, then we want to go with the radiography. If there are pipes and cracks on the cracks on the inside surface, then we should go ahead with the radiography. So, in my words, I will say that in conventional radiography, images are captured using x-rays to expose film, which is then developed and processed with chemicals to produce the final images. You know, when we took a photograph earlier, we used to have something like an image printed on paper as such. So, those who are final now, in these days, the environment is changed. Everything is digital; we capture the image and it will be live; we keep it; otherwise, we delete it.

So, the same kind of process is happening with the radiography. Earlier, there was classical or conventional radiography we used to find out the final images. Of course, the final image that comes out depends on the quality, or, say, the skill, of the person who is taking this kind of image. So, image quality was dependent on things like exposure setting, kind of film processing, and then basically the skill of the person who was operating the camera. So, I can say conventional radiography requires manual manipulation of the exposure; everybody has a different skill to capture the images. So, really, the manipulation of exposure and chemical processing, in my view, are not straight-forward. Everybody can learn that it will take a lot of practice and then require a lot of adjustments from the from the initial exposure processing firms.

So, it will becomes like you know individual afford of the person who is very good only he or she can do. While coming to digital radiography, it can capture the camera using the digital X-ray detector and then transfer to the electrical or electronic signal. Consequently, the signal will be processed and displayed on the computer screen. This process can produce very high quality images and provide instantaneous feedback. See earlier cameras and all we used to get an image after 2 days, 3 days, or something. So, there was no immediate exposure or any immediate feedback coming to the digital radiography; we have immediate feedback available.

If something has gone wrong, we can do a greater number of iterations immediately, and in less time, we can get faster and better results. So, digital adjustment can also be done, and now that we have a variety of software that can be readily used, all the digital images can be manipulated and enhanced. So, those are important. Digital radiography overall is causing fewer radiation doses compared to conventional radiography. So, it is good from an environmental point of view also, and overall, it gives a benefit in terms of the workload, efficiency, image manipulation, or capturing immediate image availability, and then overall good results and then good feedback given that the how to go gets better and better results. Even after a few iterations, a person learns and then can find the solution. Now, I will just cover a similar thing, corrosion testing, particularly for the steel reinforcement, and using this kind of radiography, we can say the already I mentioned the reinforcement, which is important.

So, again, I am trying to repeat that corrosion can occur in the construction industry when a steel reinforcement is exposed to moisture and oxygen, which happens mostly, and the presence of cracks will accelerate the corrosion process significantly. Now, from where the cracks will come, we say there are numerous factors; we know that there will be some sort of shrinkage after curing. There will be some variation in dimensions. So, those kinds of shrinkage, even the thermal expansion joints, are also there. So, thermal expansion and contraction will occur, and then there will be different kinds of loading, sometimes more loading, sometimes less loading, and maybe cyclic loading. There is also the possibility of environmental factors, which we have already covered in an earlier lecture.

These all factor will give formation or will form the cracks. Now, once the cracks are formed, the cracks will enable corrosion to reach steel reinforced by penetrating deeper into the concrete and making direct contact with a steel surface. Once the corrosion reaches the reinforced steel, they initiate and foster the corrosion process. So, this is the well within a surface on the very inside, but concrete has a number of possibilities of cracks, and even with the naked eyes we have seen on the surface of concrete, there are cracks while we are talking about the very inside cracks, and they reach directly to the reinforced steel. And then once it reaches naturally after the dielectric electrochemical process has started, it will increase the corrosion rate. That is why in the earlier test, we wanted to know how the corrosion rate increased.

So, in this case, it can be shown that way. Now, corrosion causes the formation of corrosion on a steel surface, which has a greater volume than the steel itself. So, this is what I was mentioning: corrosion. Because of corrosion, there will be more and more deposition on the surface itself. If there is a wear process available, then the material will be removed; if there is no wear process available, then only accumulation will happen, and more and more volume will increase. So, in this case, particularly rusting, the expansion of rust within a concrete generates internal pressure, which exhausts tensile forces on the surrounding concrete, and we know very well that concrete is not very good at tensile force, which is why we go hard with the reinforcement.

If the reinforcing steel induces tensile stress in the concrete, it can lead to significant problems. This stress can cause internal fractures and deterioration of the concrete. Once cracks form and allow corrosive solutions to penetrate, the damage accelerates, leading to rapid wear, corrosion, and further fracturing. The combined effects of corrosion and fracture can severely compromise the structural integrity and durability of the reinforced concrete, even if there is no significant wear involved. Additionally, corrosion can weaken the bond between the steel reinforcement and the surrounding concrete, resulting in debonding. This reduces the load-bearing capacity of the concrete and increases the risk of structural failure over time.

So, it is not instantaneous, but over time, failure will occur, and that is why we are going to cover one case study that will highlight those points. So, this is corrosion testing, the radiographic testing that has been done here. This is what we previously demonstrated on the surface. Now, we are showing and using the radiography that there may be a possibility of subsurface, and then what we are saying in this case is that UN is basically an uncracked sample. I will see if we have something like a longitudinal crack, and I will see if we try to bridge the crack. As I mentioned, if we use some sort of bridging medium, like epoxy, inside the concrete itself and then there is a crack and epoxy is added to that surface, it will cause a binding again.

There are two methods for addressing cracks: an automated process and a manual process. In the automated method, we use capsules or similar mechanisms to bridge the gap, while in the manual method, we physically seal the crack ourselves. We refer to these as manually healed or automated healed methods, respectively.

In our analysis, we examined both longitudinal and orthogonal cracks. After starting the process, we observed the results at intervals of 2 hours and 30 hours of exposure. Chloride ingress was evident in all cases, and we noted varying levels of corrosion depending on the method used.

So, orthogonal without manual has been shown in this case; automated healing has also been shown, and then there is a longitudinal we are able to see. So, everywhere we find that whenever this crack has been healed with a manual process, it has been showing better results in this case. While in the case of orthogonal, a substantially better result has also been obtained in this case. This paper, published in 2018, employs X-ray radiography to visualize the interface between the rebar and the matrix, as well as the corrosion delay caused by self-healing polyurethane encapsulating the fracture. That means they are using polyurethane to self-heal the crack, and then they start bonding to the crack and do not allow chemicals or solutions to ingress into the reinforced material. So, we can delay the corrosion based on what we have shown now coming to the radiography completely. You can see here that the white circle has been shown on the surface, and we say that this is the testing of the of the corrosion impact on the reinforced sample. Over here, we are trying to find out the radiography.

Now, this white circle has been shown as rebar. What is the reason? In this all-white circle, you are able to see that these are the reinforced or rebar as such. And then, what is the reason why we are getting these white circles? You mentioned that this type of material exhibits high X-ray attenuation properties, both towards and against X-rays. In this case, near this steel reinforcement, you will be able to see the mortar. A mortar is a mixture of the bigger particles compared to the sand, and they will be laser particles compared to the stones that we use for concrete. So, this mortar is of the kind that has been shown as a red colour zone. You are able to see the red colour in this. However, in the red colour also, we are able to see there are some sort of yellow dots, and the yellow indicates there is a less dense region within the mortar, and then there is a possibility of air bubbles, cracks, and corrosion.

Using radiography, we can accurately identify issues within the concrete. The white circles on the radiographic images represent the steel bars, which we should disregard. Instead, focus on the yellow areas: an increase in yellow indicates a higher likelihood of failure.

In this case, the radiographic images show extensive yellowing on the surface, which contrasts with what might be visible to the naked eye. This discrepancy highlights the importance of relying on radiographic results for a comprehensive assessment. After 70 hours, the radiography revealed more cracks on the surface, signaling potential failure.

Additionally, the gray areas in the images represent corrosion byproducts, indicating regions affected by corrosion.

As corrosion byproducts accumulate, the volume increases, leading to more cracks. Radiography helps us identify these issues by highlighting the yellow areas, which indicate voids and potential cracks that can cause further damage. Based on this, we can either remove the corrosive media, eliminate the conductive path, or enhance the material properties.

The experiments demonstrate that healing longitudinal and orthogonal cracks can delay the onset of corrosion. For example, in the case of longitudinal cracks (LC) without any healing, we observe more yellowing. However, with manual or automated healing, the yellow areas are significantly reduced. Similarly, for orthogonal cracks, manual healing shows less yellowing compared to automated healing.

This indicates that radiography effectively reveals the extent of corrosion and crack development. The use of sulfuric agents in the concrete delays the process, allowing us to develop algorithms to predict overall failure rates.

Thank you for attending this lecture.