Retrofitting and Rehabilitation of Civil Infrastructure
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Lecture 11
Other Tests

Hello friends, welcome to the NPTEL online certification course on Retrofitting and Rehabilitation of Civil Infrastructure. Today we will discuss Module B, the topic for Module B is condition evaluation and testing.

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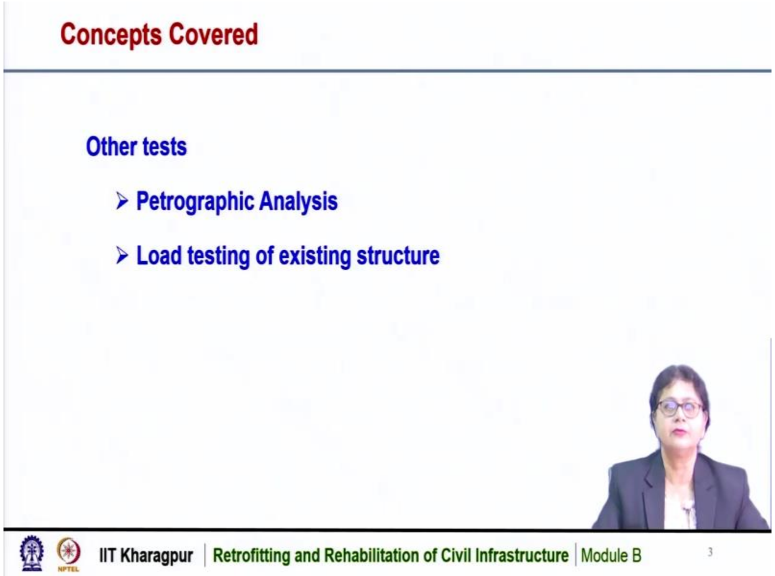

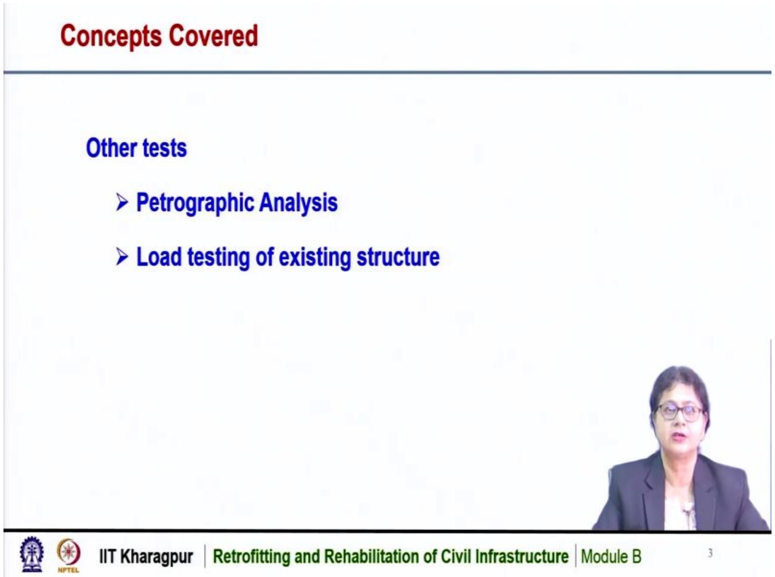

In the previous lecture, we have discussed several non-destructive testings and those are related to the corrosion activity of steel reinforcement of concrete structures. We have discussed electromagnetic cover measurement test, half-cell potential measurement test, resistivity measurement test and carbonation depth measurement test.

Today, we will discuss two other types of investigations that are carried out on existing structures. One is petrographic analysis and the other is load testing of existing structure.

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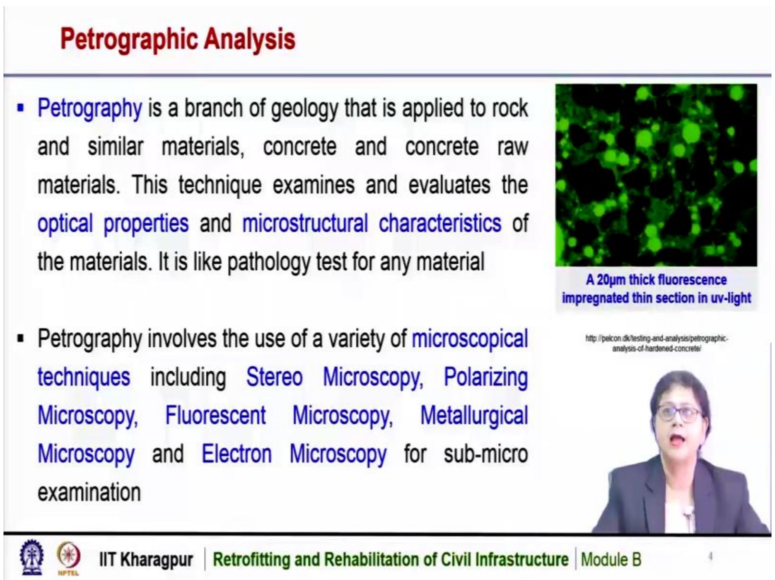

Petrographic investigation is an advanced investigation using high end equipment. Petrography is a branch of geology that is applied to rock and similar materials, concrete and concrete raw materials. In this analysis or investigation, the examination and evaluation of the optical properties of the material and the micro structural characteristics of the materials are investigated.

So, we are investigating the properties of the material at the micro level. It is like pathologic tests of any material. Petrography involves the use of a variety of microscopic techniques and the common microscopes that are used for the petrographic analysis are stereo microscopy, polarizing microscopy, fluorescent microscopy, metallurgical microscopy and scanning electron microscopy for sub micro examination.

So, we are investigating at the microscopic level of the structural characteristics of the material. So, here also we can see a picture, 20 micron thick of the material, which is being tested on a fluorescent microscopy and this is a typical picture of that.

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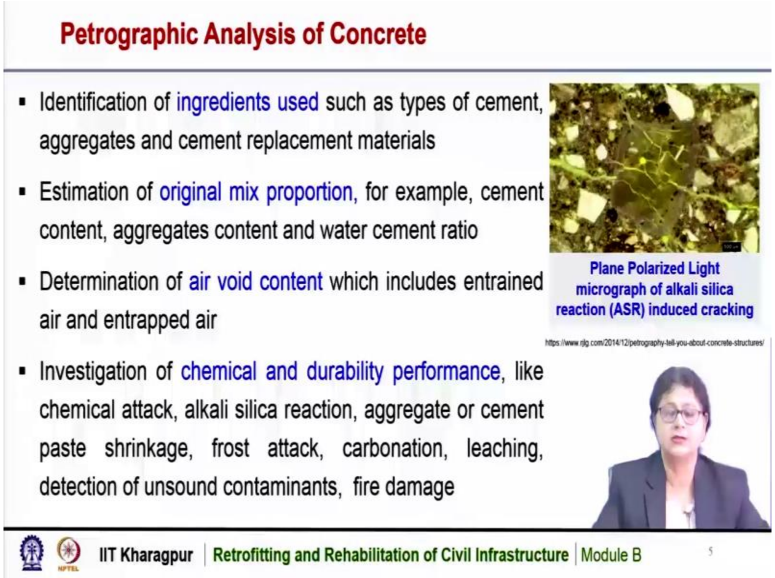

In petrographic analysis, several investigations can be carried out. We can identify the ingredients used in a material; for example, in case of concrete what type of cement or aggregate or supplementary cementitious materials, whether it is used or not that can be identified from this type of analysis.

We can estimate the mix proportion of the concrete. The cement content, the aggregate content and the water cement ratio can be found out from this analysis. The determination of air void content can be found out which includes the entrained air and also the entrapped air. And particularly for existing infrastructure we can investigate several durability characteristics, when the concrete is attacked by several chemicals.

For example, alkali silica reaction or acid attack or sulfate attack or shrinkage, frost action, all these things can be found out from petrographic analysis at the microscopic level. So, here is one typical picture when the concrete is affected due to alkali silica reaction and we can use the polarizing microscope to find out the cracks present in the material due to this alkali silica reaction.

So, several of the investigations can be carried out in much detail at the microscopic level using this petrographic analysis and we have to use on high end equipment, different types of microscope for determining this type of characteristics in an existing material.

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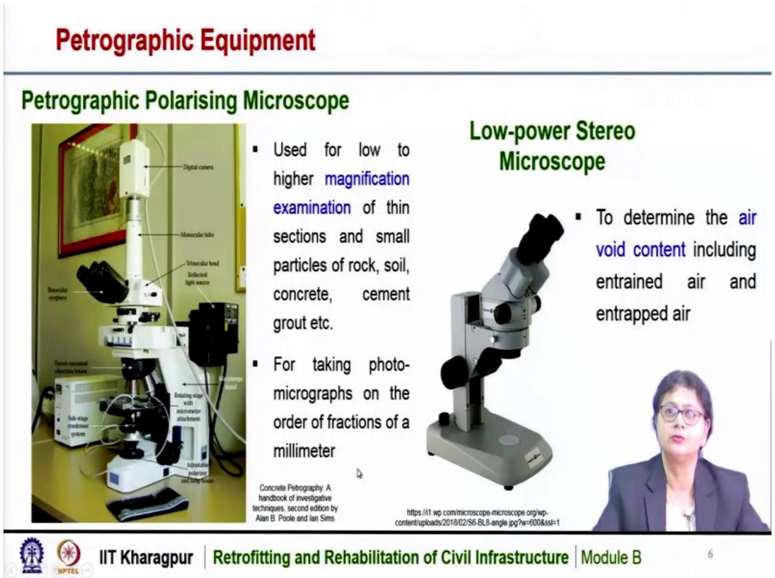

Here are some pictures of the petrographic equipment. This is a petrographic polarizing microscope. We can see here; this is the polarizing microscope used for this investigation. This is used for low to higher magnification examination of thin sections and small particles of rock soil or concrete materials. In this testing, we can take the photo micrographs on the order of fractions of a millimeter.

So, we can see that very small or very thin thickness of the material can be investigated through this microscope and we can get the detailed characteristics with this. This is a picture of low power stereo microscope to determine the air void content including the entrapped air and the entrained air present in the material. So, these microscopes are used for examining the material characteristics.

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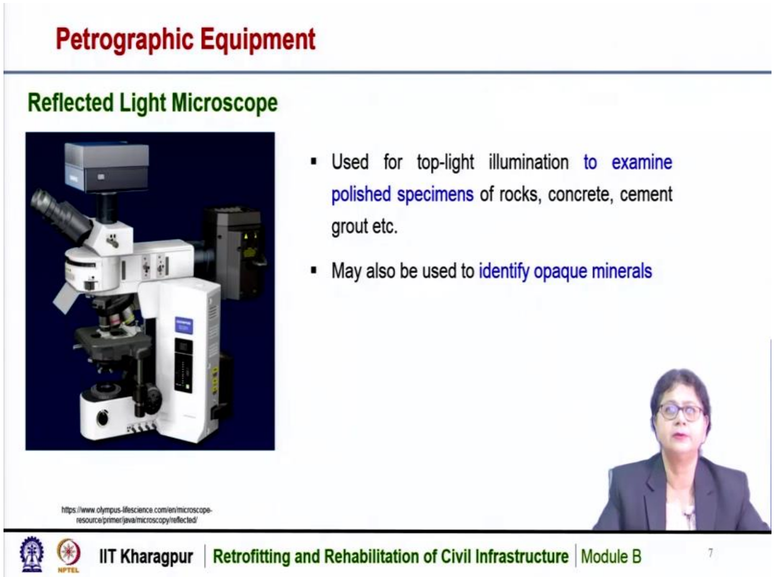

This is a picture of reflected light microscope. This is used for top light illumination to examine the polished specimens of rocks, concrete or cement grout etcetera. And this can also be used to identify different opaque materials. So, reflected light microscope is also another type of petrographic equipment, particularly used to examine the polished specimen.

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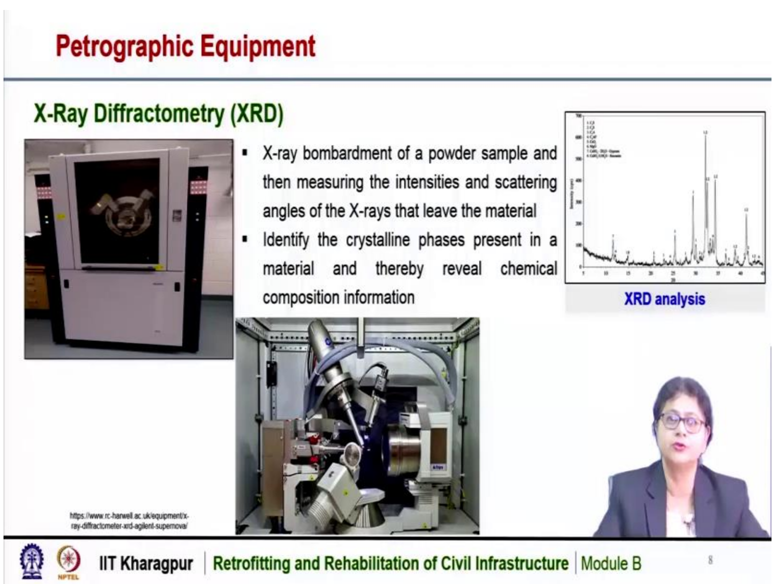

This is X-ray diffractometer or XRD. XRD, we can see here this is the XRD equipment and this is the inside of that equipment. And in this testing, it is X-ray bombardment of a powdered sample is done and then we can measure the intensities and scattering angles of the X-rays, that leave the material. So, here X-ray bombardment is done on the sample which is a powder sample and then we can measure the intensity and scattering of the X-rays.

And then by analyzing the results we can identify the crystalline phases present in the material and thereby reveal the chemical composition information. So, what are the crystal present in a material that can be identified from this test. So, here is a typical XRD analysis plot. From this test, we can see here that there are sharp peaks and these sharp peaks generally represent the crystal structures.

And not so sharp peaks, the blunt ones, they are generally represent the amorphous materials present in it. So, we with this test we can identify the crystal structures present in the material and what is its composition also can be found out from this test.

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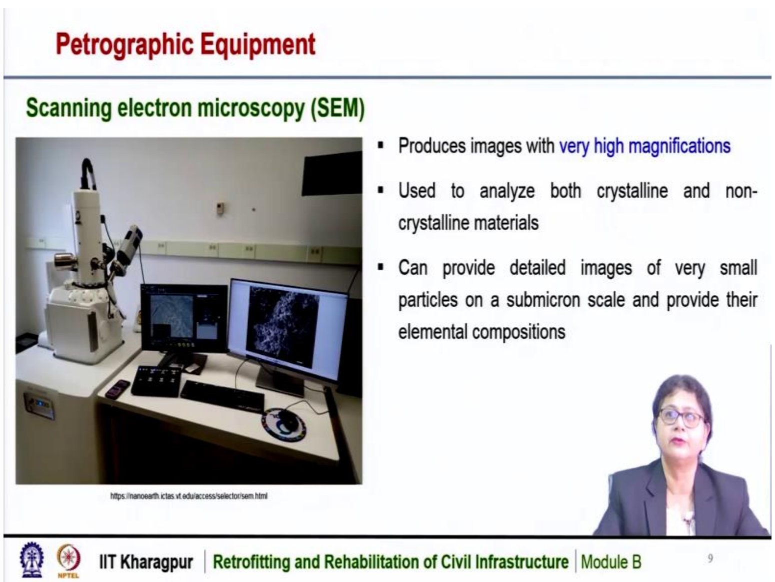

Scanning electron microscope is largely used for various investigations. It produces images with very high magnification and that magnification we can also alter and with that, we can identify the detail characteristics at a much higher level. So, it is used to analyze both crystalline and non-crystalline materials. It can provide the detailed images of very small particles on a sub-micron scale and provide their elemental composition.

So, scanning electron microscope, we can see here, a picture of scanning electron microscope and from that we can find out the much detailed structure at the microscopic level. So, it is widely used to carry out the petrographic investigations. Scanning electron microscope is used widely for petrographic examination.

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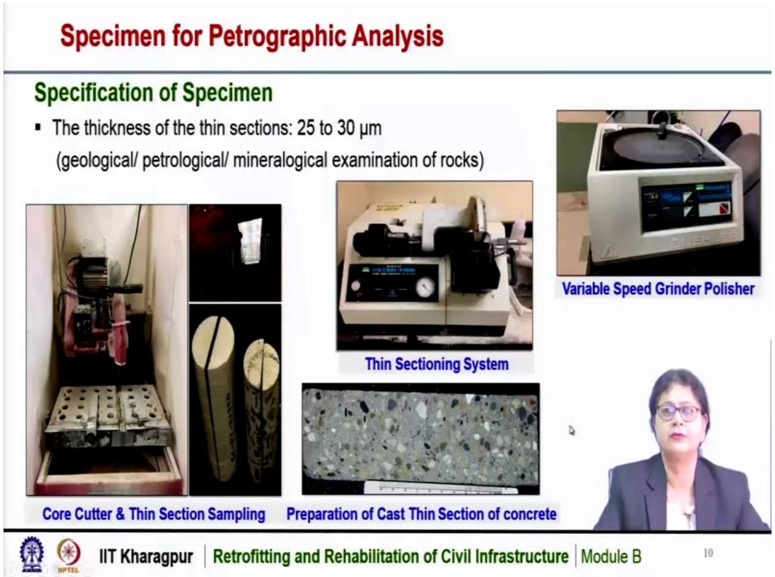

Specimens required for petrographic analysis are generally very small. It is sometimes made of thin sections and the thickness of the thin sections is very small in the level of microns. You can see that; 25 to 30 micron is the general thickness of the material for testing. And here are some of the pictures, we can take some cores and from the cores the thin sections can be made and then we can polish it and grind it with this and this is a cast thin section of concrete and from that we can take some material for testing.

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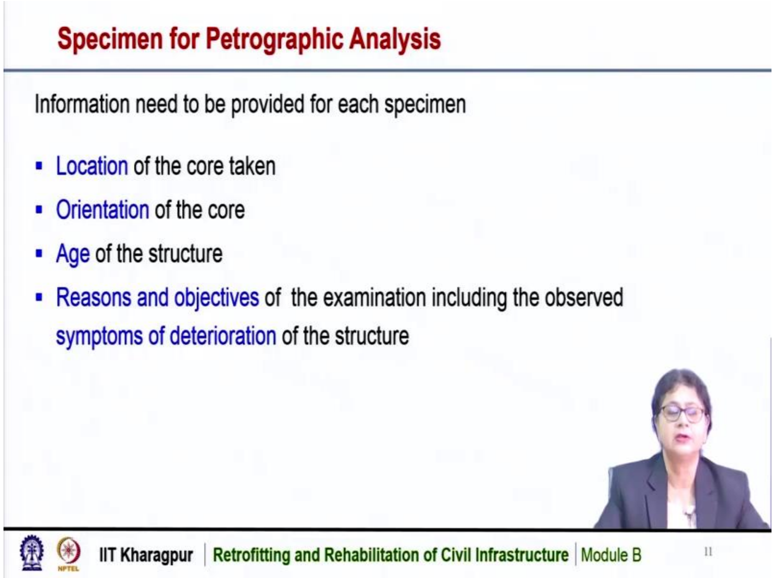

Specimens for petrographic analysis, generally we require very thin specimen, very small specimen because we need to test it under the microscope. So, specimen size is very small, but we also need some more information about the specimen. When the core is taken from an existing structure, we need to know the location of the core from where the core has been taken from the structure.

What is the orientation of the core extraction, what is the age of the structure. So, this information will help us in analyzing the petrographic data. And then the reasons and objective of the examination including the observed symptoms of deterioration of the structure. So, particularly if some distresses are observed then only for further investigation, we carry out petrographic analysis.

So, those informations also need to be reported while analyzing the data and that will give us a complete understanding of the condition of the structure.

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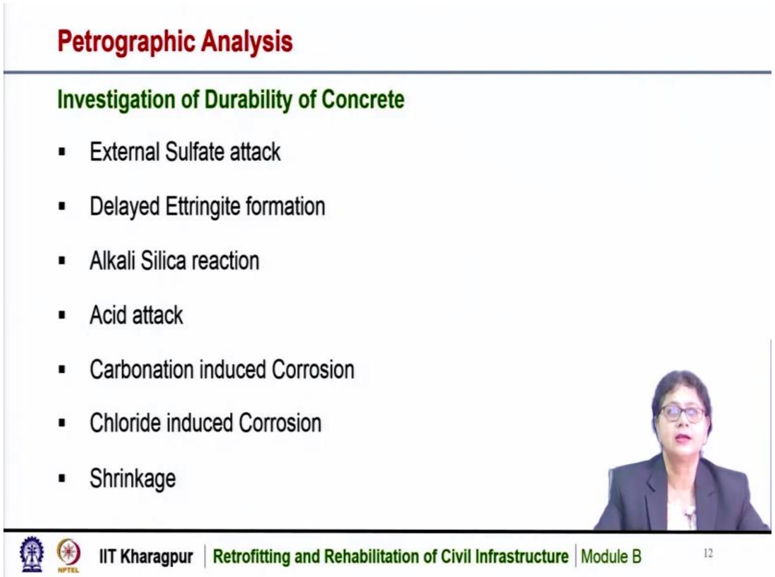

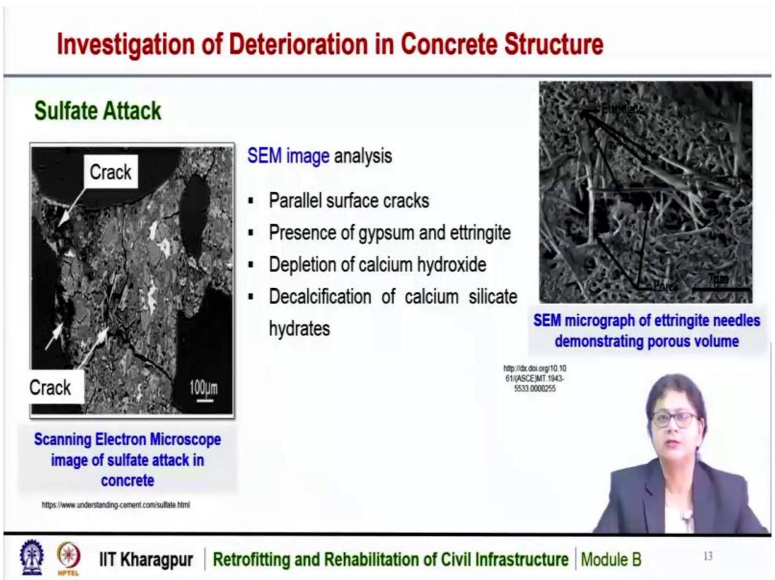

Petrographic analysis is quite effective for the existing structure's evaluation. We can investigate the durability of the structure. Various deterioration can be identified from the petrographic analysis. The external sulfate attack, the formation of delayed ettringite, the alkali silica reaction, the acid attack, carbonation etcetera can be found out from petrographic analysis.

So, by observing the material under the microscope and we can find out these type of distresses has been occurred in the material or not. And that we can see in the next few minutes. So, investigation of deterioration in concrete structures; for example, sulfate attack, in sulfate attack there are cracks developed on the material and this is a typical picture of scanning electron microscope and from that, we can see that there are lots of cracks developed on the surface due to the sulfate attack.

In SEM image, we can see several surface cracks which are occurred from the sulfate attack. The presence of gypsum and ettringite, if it is there that also can be identified from SEM image. The depletion of calcium hydroxide can also can also be found out from the SEM image and decalcification of calcium silicate hydrate also can be identified from the SEM image analysis.

So, this is the typical scanning electron microscope image of sulfate attack in concrete. We can see here, there are lots of cracks on the surface due to sulfate attack. And this is a typical picture of the SEM micrograph of ettringite needles that has been formed due to the sulfate data and these ettringite needles are formed and these can be clearly seen in this picture, that demonstrate the porous volume of the material and this is due to the effect of sulfate attack. So, we can find out from this image, the characteristics of the material when it is attacked by sulfates.

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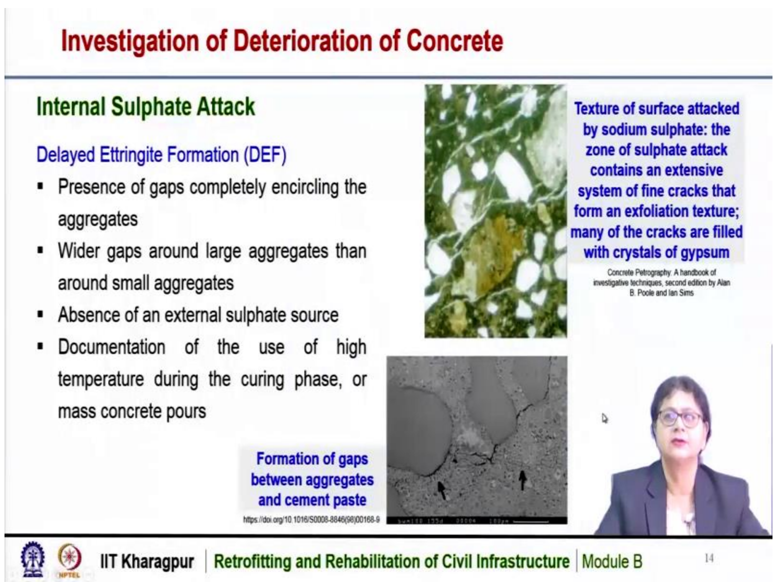

Internal sulfate attack can also be identified with a petrographic analysis. The delayed ettringite formation can be found out when we can examine the material. We can also find out the presence of gaps completely encircling the aggregates which is due to the delayed ettringite formation. There are gaps around large aggregates as compared to smaller aggregates.

The absence of an external sulphate source and documentation of the use of high temperature during the curing phases or mass concrete pours, because a delayed ettringite formation is associated with high temperature. So, the presence of gaps or cracks can be identified from the petrographic analysis like scanning electron microscope image. So, here you can see a typical picture of the delayed ettringite formation. We can see here, lots of cracks on the surface the texture of surface is attacked by sodium sulfate.

The zone of sulfate attack contains an extensive system of fine cracks that form and exfoliation texture and many of the cracks are filled with crystals of gypsum. So, this can be seen from the petrographic analysis. When there is delayed ettringite formation, there are gaps created around the large aggregates and that separates almost the aggregate from the cement paste. So, here also in this picture, we can see the formation of gaps between the aggregate and cement paste.

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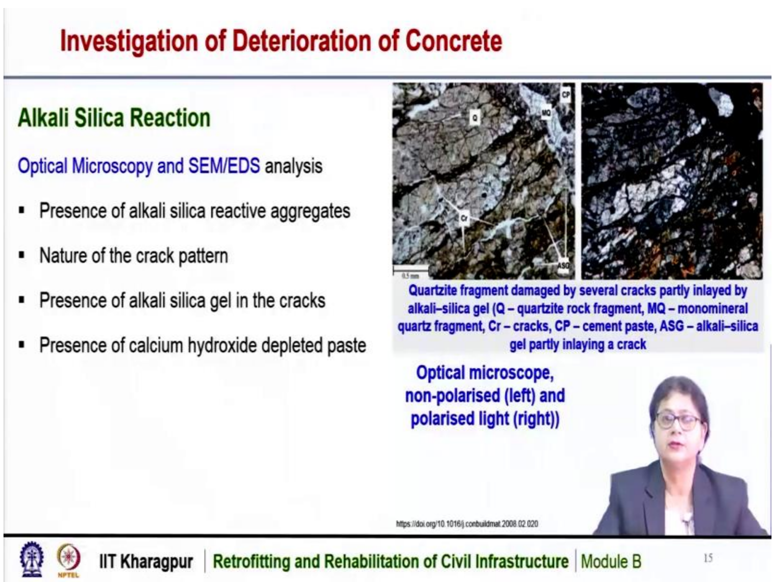

Alkali silica reaction can also be identified from petrographic examination, using optical microscopy and scanning electron microscope analysis. The presence of alkali silica reactive aggregates or the nature of crack pattern can be identified from these pictures and the presence of alkali silica gel in the cracks or presence of calcium hydroxide also can be found out from these microscopic studies.

So, here are some pictures of the optical microscope one is non polarized and the other is polarized light. So, we can see here that the presence of alkali silica gel or cracks or cement paste all can be identified here. We can see here this is the quarzite fragment damaged by several cracks partly inlayed by alkali silica gel and the rock fragments and the cracks, cement paste alkali silica gel are clearly visible here.

So, this is non polarized picture whereas, this is the polarized picture of the optical microscope. So, the alkali silica reaction effect can be found out from this type of microscopic images.

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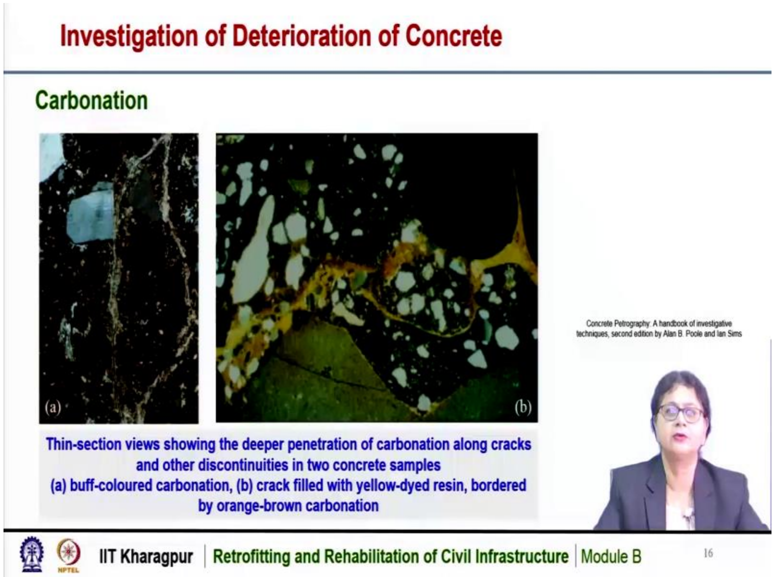

Carbonation type of distresses can also be identified from petrographic analysis. Here are some pictures. The thin section views showing the deeper penetration of carbonation along the cracks and other discontinuities in two concrete samples. We can see here there are two concrete samples and due to the effect of carbonation there are cracks developed along the material and the left side identifies the buff-coloured carbonation area.

And this right side picture shows that crack filled with yellow dyed resin bordered by orange brown carbonation. So, the test is done with yellow dyed resin and the cracks are filled with those resins. So, they can be identified much clearly. So, carbonation type of distresses can also be identified quite clearly with this type of microscopic images.

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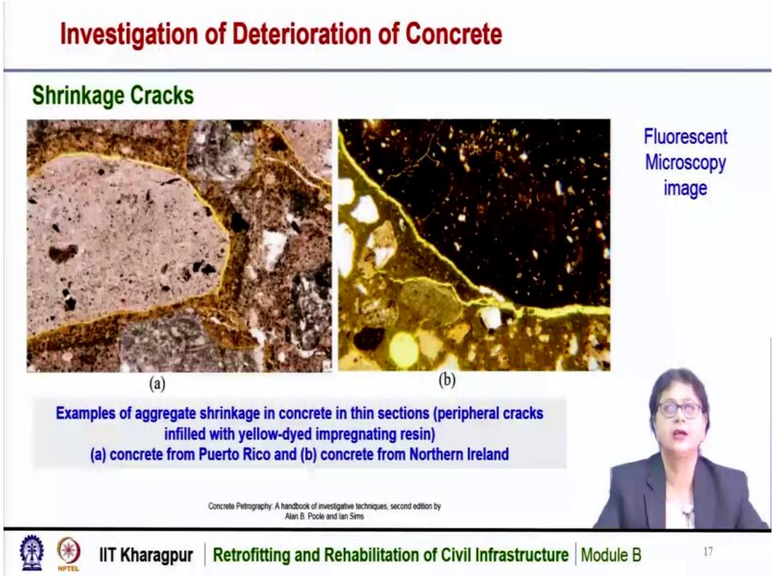

Shrinkage cracks can also be identified much clearly using several of the microscopes. Here are some pictures of fluorescent microscopic image and we can see here that the examples of aggregate shrinkage in concrete in thin sections, the peripheral cracks infilled with yellow dyed impregnating resin. So, here also while doing the test, the yellow-colored resin is impregnated, so, that the cracks are filled up with that and it can be identified easily.

So, here are two samples of concrete. We can see here, that the cracks around that aggregate and it is filled up with yellow diet resin. So, the cracks are clearly visible in these pictures. So, here also it is clearly visible that this is the crack on the surface of the concrete and it is clearly identified from this fluorescent microscopic image.

So, these type of distresses are very clearly found out from the petrographic analysis from the microscopic images and with that, we can identify that what type of distress is the structure is undergoing, whether the distress is further progressing or not. And, if there are some chemical reactions, so, what are the reactants. So, those informations can be found out from the petrographic analysis.

So, petrographic analysis gives us a much-detailed information about the current condition of the structure, in terms of the material degradation. So, it is widely used also for identifying the deterioration of concrete structures. However, it requires several high-end equipment and those equipments are quite expensive.

And that is the limitation for carrying out petrographic analysis in large scale. However, it gives a much-detailed information about the characteristics of the structure or material and with that, we can get much detailed information of the material.

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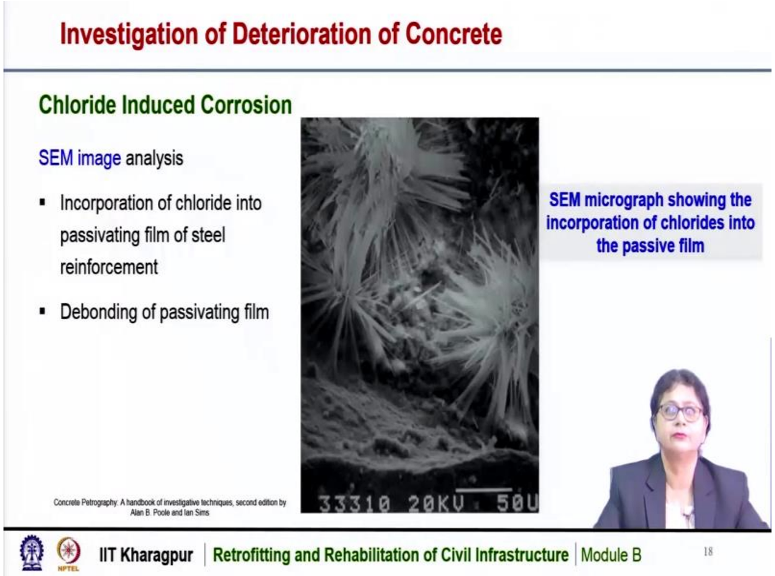

Chloride induced corrosion can also be identified. We can see here a picture of scanning electron microscope showing the incorporation of chlorides into the passive film. So, incorporation of chloride into the passivating film of steel reinforcement can be identified from the SEM pictures and when the passivating film is debonded, that also can be found out. So, here also we can see that this is a scanning electron microscopic picture and that shows that there is an incorporation of chloride into the passivating film. So, the chloride induced corrosion type of distress can be also found out from the petrographic analysis.

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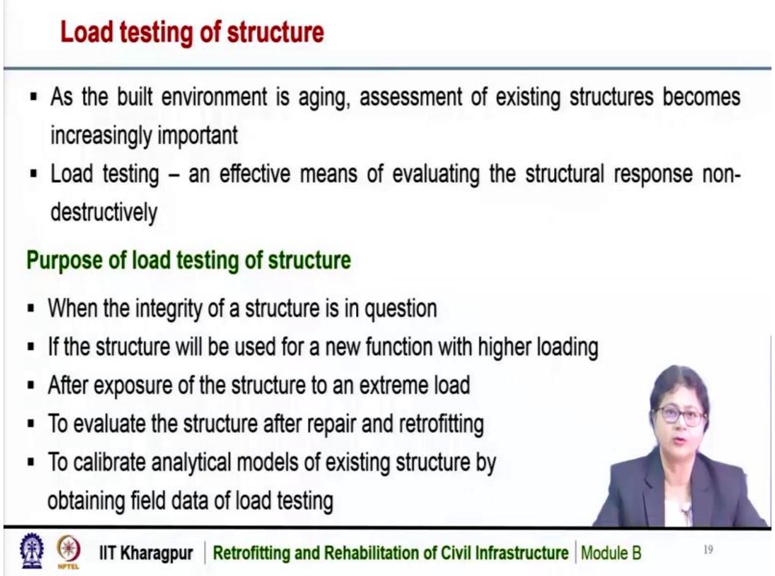

So, we have discussed petrographic analysis, that gives us a much detailed information about the condition of the structure or condition of the material, whether any deterioration has been occurred or not and what type of deterioration, what is the extent of it that we can understood from the petrographic analysis.

Now, we will discuss load testing of structure. As the built infrastructure is aging, so it is important to assess the existing structure to find out its present strength and other properties. So, load testing is an effective means of evaluating the structural response non-destructively. So, we can perform load testing to find out the present strength of the overall structure and it is done non-destructively.

The purpose of load testing of structure is required, when the integrity of our structure is in question. If the structure will be used for a new function with higher loading condition that means, changing the functionality. So, for that case, whether the structure is capable of carrying that high load or not for that purpose also we can carry out load testing after exposure of the structure to an extreme load.

Sometimes there may be a huge load coming on the structure maybe due to natural calamity like earthquake or storm. So, if the structure is exposed to that type of extreme condition or extreme loading, then whether the structure is still able to carry that type of loading or not, we can carry out load testing. To evaluate the structure after repair and retrofitting it is standard practice for the repair and retrofitting. When it is over, we can carry out the load testing of the structure to see that whether the sufficient strength has been achieved or not.

To calibrate analytical models of existing structure by obtaining field data of load testing, sometimes for existing structure, the detailed drawing and design are not available. So, we can develop an analytical models and to calibrate the analytical models, we can do load testing. So, load testing is done for existing structures and also maybe for new structures, but it is important that we should carry out load testing when the integrity of the structure is in question.

If the structure is used for a new function and it is subjected to higher loading, we can carry out load testing after the exposure of the structure to an extreme load. We can carry out load testing to evaluate the structure after repair and retrofitting. And also to calibrate the analytical models we can do the load testing of structure.

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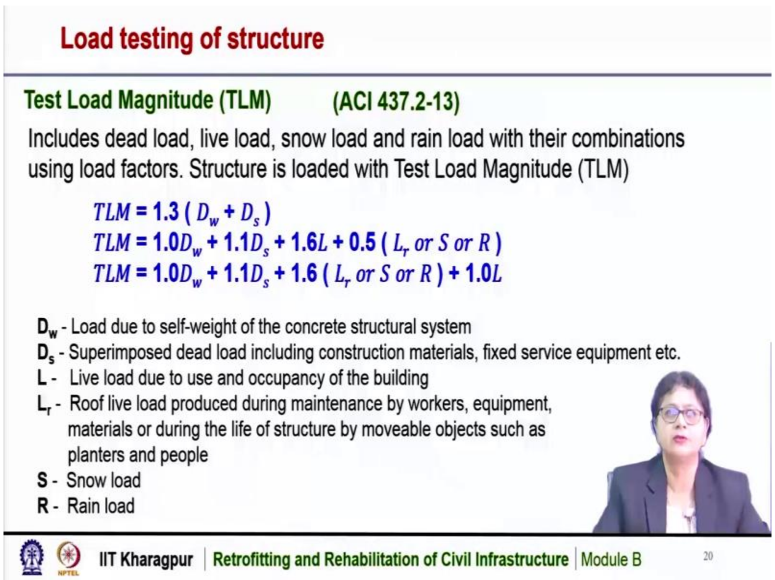

Now, we will discuss test load magnitude or TLM. Test load magnitude includes dead load, live load, snow load, and rain load with their combinations using load factors. Structure is loaded with test load magnitude when the load testing is carried out on an existing structure. This is as per the ACI code ACI 437.2-13. So, as per this code, the test load magnitude has been defined and $TLM = 1.3 (D_w + D_s)$, where D_w is the load due to the cell fit of the structure and D_s is the superimposed dead load including the construction materials, fixed service equipment et cetera.

TLM include includes dead load, live load, snow load, and rain load with their combinations using different load factors. The structure is loaded with test load magnitude or TLM. And they are tested. There are several combinations of TLM. $TLM = 1.3\ (D_w + D_s)$, D_w is the load due to self-weight of the structure and D_S is the superimposed dead load including the load for the construction materials fixed service equipment etcetera.

L is the live load due to the use and occupancy of the building an L_r is the roof live load produced during maintenance by workers equipment materials or during the life of the structure by movable objects. S is the snow load and R is the rain load. So, TLM there are several combinations.

$TLM = 1.3\ (D_w + D_s)$

$TLM = 1.0D_w + 1.1D_s + 1.6L + 0.5\ (L_r\ or\ S\ or\ R)$

$TLM = 1.0D_w + 1.1D_s + 1.6\ (L_r\ or\ S\ or\ R) + 1.0L$

So, these are the different combinations of TLM considering dead load, superimposed load, live load roof load snow load or rain load. And this we have to consider while carrying out the load testing of structures.

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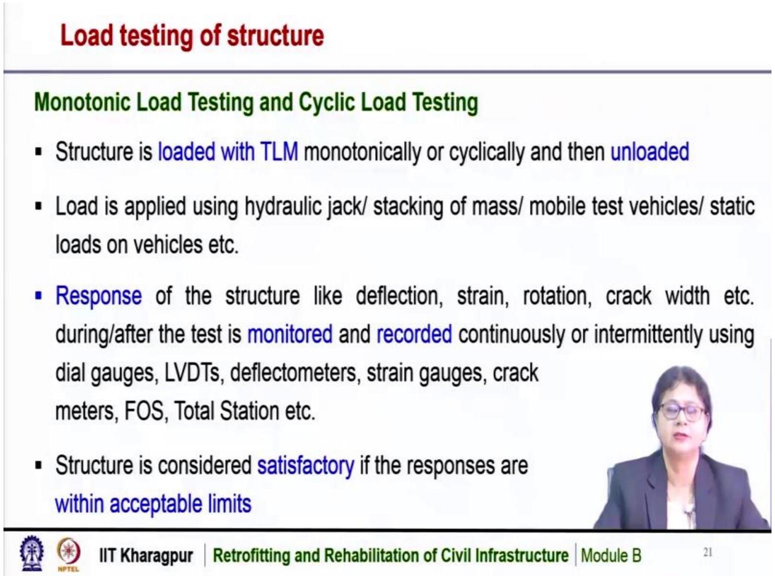

The load testing of structures can be done in two ways one is monotonic load testing and another is cyclic load testing. The structure is loaded with TLM either monotonically or cyclically when they are tested and then it is unloaded. So, in both the cases, load can be applied using hydraulic jack or stacking of mass or mobile test vehicles or static loads on vehicles et cetera. And when the load is applied, the response of the structure is measured. The response may be in terms of deflections, strain, rotation, crack width, etcetera.

And that response is measured and monitored also recorded during or after the test and the recording should be done continuously or intermittently using dial gauges or LVDTs, deflector meters, or strain gauges, crack meters, fiber optic sensors, or total stations etcetera. So, these are the equipments, which are normally used to measure the responses of the structure when it is loaded. The structure is considered satisfactory if the responses are within acceptable limits.

So, in both cases either monotonically loading or cyclic loading cases, the structure is loaded and that load is applied using hydraulic jack or some stalking mass or some vehicles and the responses are collected. The responses may be in terms of deflection, rotation, strain, etcetera, and dial gauges, or LVDTs, or deflectometers, or strain gauges are generally used for the measuring the responses of the structure.

And when the responses are within the acceptable limits, we can consider that the structure is satisfactory and is capable of taking the desired load.

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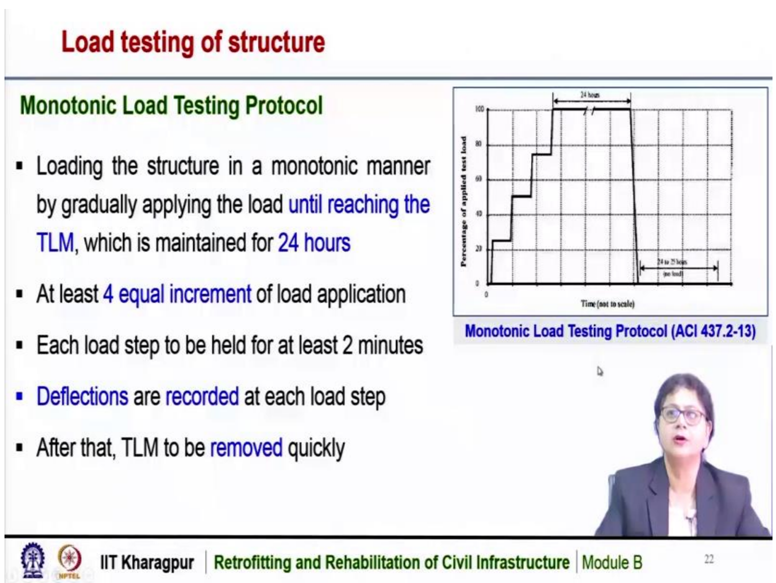

The monotonic load testing protocol is that the loading of the structure is to be done in a monotonic manner, by gradually applying the load until reaching the TLM, which is maintained for 24 hours. So, here you can see that, the load is applied monotonically at least 4 equal increments of load application until it reaches to the TLM. And when it reaches to the TLM, you have to keep the load constant for at least 24 hours.

And then it is to be unloaded. At each load step the load must be held for at least 2 minutes and then you can go for the next higher loading. The deflections are recorded at each load step and also at the top level. After that the TLM needs to be removed quickly. So, these are the steps by which the load is applied till it reaches to the TLM and then you have to keep it for 24 hours and then unloading. So, this is the load testing protocol as per ACI 437.

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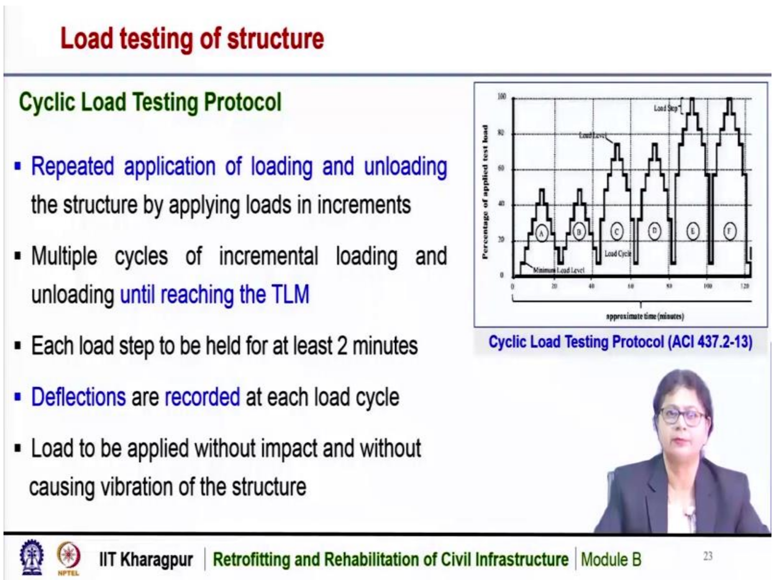

In case of cyclic load testing protocol, the load is applied repeatedly. It is the repeated application of loading and unloading of the structure by applying loads in increment. So, here also the load is applied repeatedly, but for each cycle the load is applied incrementally. So, here we can see that, at each cycle, the load is applied incrementally and multiple cycles of incremental loading and unloading is there until it reaches the TLM.

So, this is the TLM and at the intermediate cycles, the loads are applied and that intermediate cycles also the loads should be applied incrementally. So, with few cycles, we can reach to the TLM we have to keep it for some time and then unloading. So, each load step to be held for at least two minutes as before and the deflections are recorded at each load cycle. Load to be applied without impact and without causing vibration to the structure.

So, this is important the load should be applied gradually and incrementally. And there should not be any vibration or shock to the structure and then again it needs to be unloaded. So, this is the cyclic test protocol as per ACI 437. And in this way, the cyclic load or the repeated load can be applied to an existing structure.

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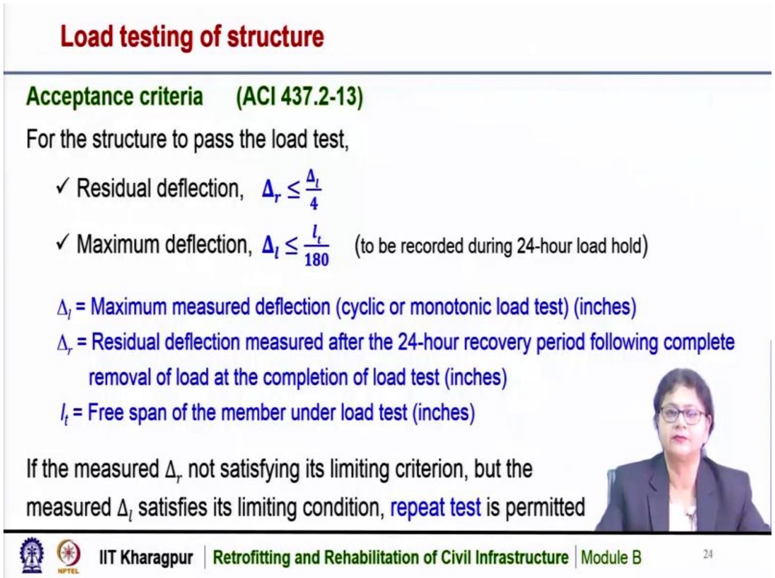

The acceptance criteria are mainly based on the deflection. So, for the structure to pass the load test, the residual deflection that is $\Delta_r \le (\Delta_l)/4$, Δ_l is the maximum measure deflection both for cyclic or for monotonic load test cases. And Δ_r is the residual deflection measured after the 24 hour recovery period, following complete removal of the load at the completion of load test.

So, when we keep the TLM for 24 hours and then it is unloaded. So, this is the residual deflection measured after the 24 hours recovery period, following complete removal of the load. And l_t is the free span of the member under load test. So, the residual deflection is Δ_r. It should be less than equal to $(\Delta_l)/4$ and maximum deflection is $l_t/180$. So, if the measure Δ_r not satisfying its limiting criteria, but the measure Δ_l satisfies its limiting condition a repeat test is permitted.

So, for that structure to pass the load test, both the conditions need to be satisfied. The residual deflection as well as the maximum deflection should be within the limiting criteria. However, if the residual deflection is not satisfying, but the maximum deflection is satisfied, then a repeat test can be done.

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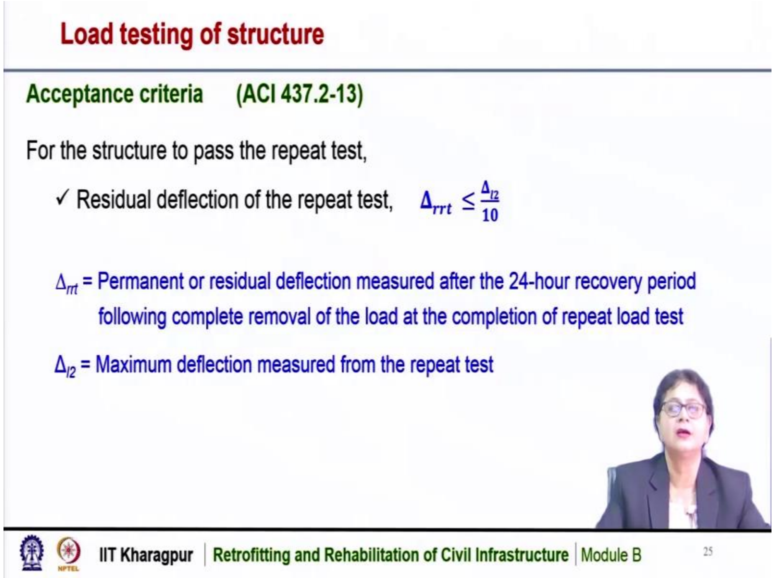

Now, for the repeat test, the structure need to pass the repeat test as well. So, in that case the residual deflection of the repeat test that is $\Delta_{rrt} \leq \Delta_{l2} / 10$. Δ_{rrt} is the permanent or residual deflection measured after the 24 hour recovery period, following complete removal of the load and the completion of repeat load test. And Δ_{l2} is the maximum deflection measured from the repeat test.

So, the residual deflection in the repeat test should be less than equal to the maximum deflection measured from the repeat test by 10. So, this condition need to be satisfied, if a repeat test is to be carried out. So, when it satisfies both the conditions, then that the structure passes the repeat test. So, it is okay for load testing.

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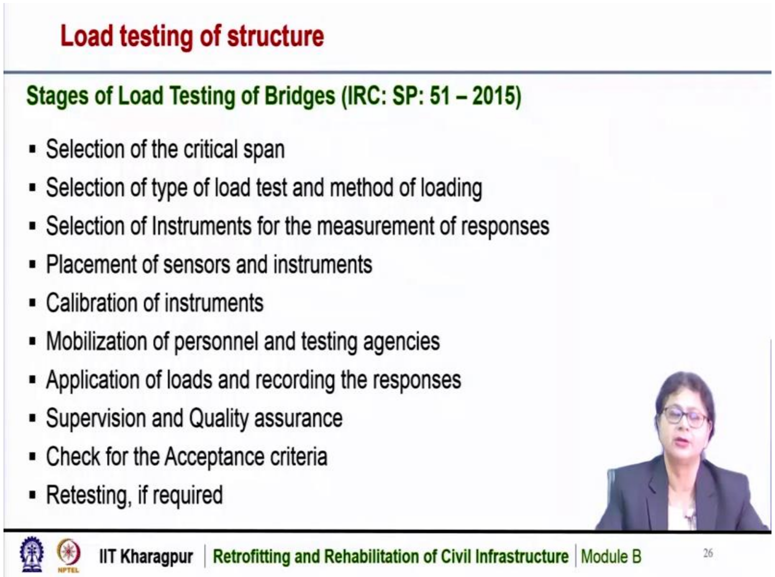

In India we have IRC SP 51, which gives us the load testing for bridges only. So, in the IRC code, there are several steps which have been mentioned for load testing of bridges. After selecting the critical span, it is to be selected the type of load test and the method of loading. The steps are the selection of the critical span for any bridge, there may be several spans.

So, the critical span should be selected for load testing, there may be one or two spans may be considered for load testing of bridges. After selecting the critical span, it is to be selected the type of load test and the method of loading. So, what type of load test whether cyclic loading or monotonic loading to be applied and how we can apply the load by stacking mass or by vehicles that we have to decide.

Next is the selection of the instruments for measurement of the responses. What are the measurements to be taken generally it is the deflection or strains that are to be measured. And so, what are the equipments required? So, what are the strain gauges, what are the dial gauges or LVDT is to be needed that we have to select. Then placement of the sensors and instrument if we select the critical span. So at what location we want to measure the deflections.

Based on that we have to place the sensors and the strain gauges on that location to get the structural response, then we need to calibrate the sensors, that is a requirement for all instrumentation. We need to calibrate the sensors and then we can start the test, then mobilization of personnel and testing agency because we require a lot of skilled personnel for carrying out the test and collection of the responses.

Application of load and recording the responses, once all that elements are done, then the load test can start and we can record the responses. Supervision and quality assurance is important for this type of work because it requires a lot of precision. So, supervision is important. Check for the acceptance criteria. So, we have to check that whether the acceptance criteria, the limiting criteria is satisfying for the test or not. And if required, retesting can be done. So, these are the general stages of load testing of bridges and that is mentioned in IRC SP 51.

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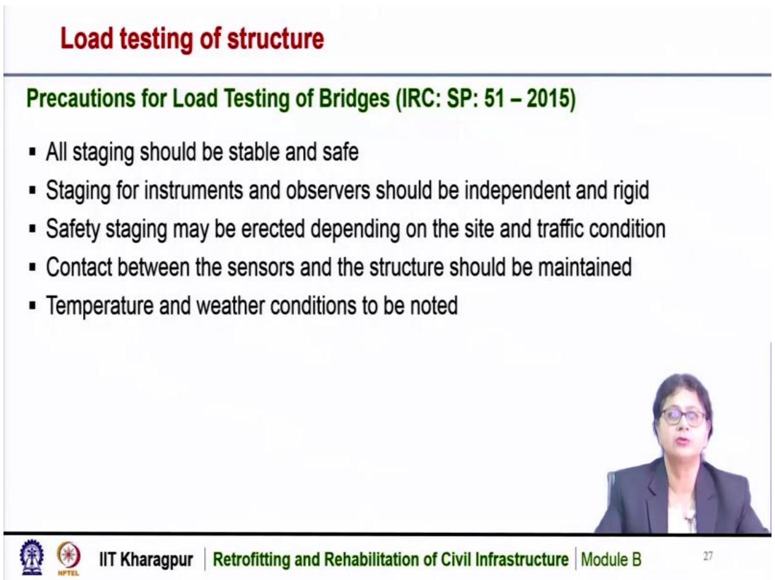

For load testing of bridges, we have to take care of several considerations, several precautions need to be taken. The precautions are all staging should be stable and safe. The staging because on the staging, people need to stand and carry out the test or are carrying out the measurements. So, the staging should be stable and safe. Staging for instruments and observers should be independent and rigid.

The staging for the personnel should be different from the staging for the instruments, because the movement of the personnel may affect the responses. So, it should be different and it should be sufficiently rigid. The safety staging may be erected depending on the site and traffic condition, because sometimes the bridges are in use. So, a safety staging also may be required depending on the traffic condition and also on the condition of the site.

The contact between the sensor and the structure should be maintained and that should be checked while carrying out the test. So that the LVDT is touching to the member or not. So that needs to be checked properly, and temperature and weather conditions are to be noted because sometimes there may be some influence of temperature or humidity etcetera. So, that also needs to be noted while carrying out a load test.

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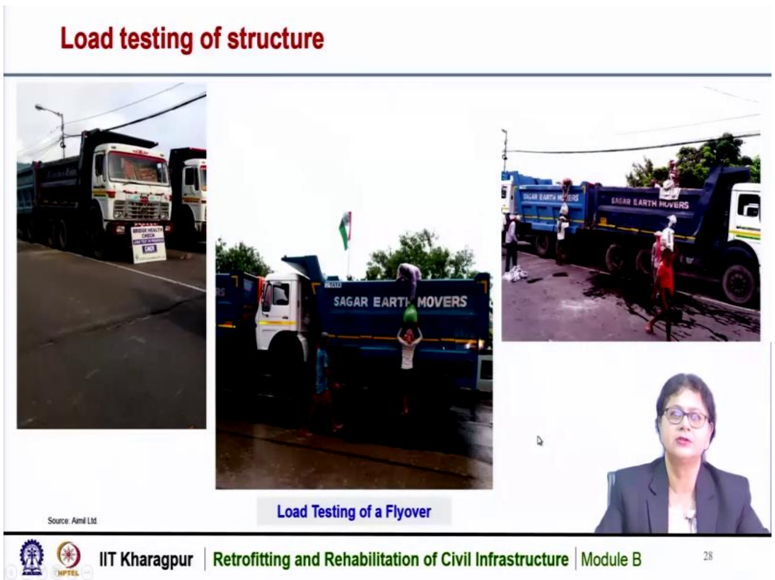

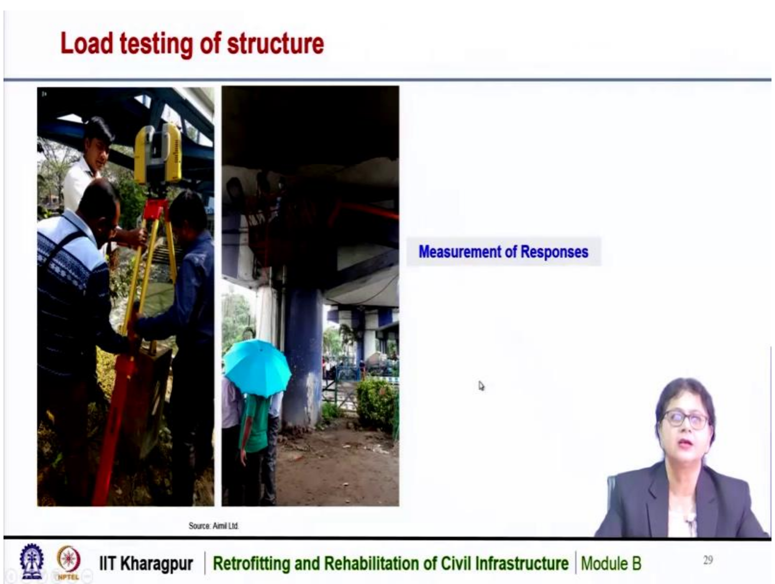

These are some of the pictures of load testing of a flyover in Kolkata. You can see here that the load testing is being done by loaded trucks. The trucks are placed on the deck slab of the bridge, you can see here and it is loaded with stacking mass. See here the it is loaded and the load testing is being carried out. And these are the pictures of the measurement of responses. We can see here that the responses of the deck slab or the girder is being measured.

And here is the total station, to measure the responses sometimes. It is difficult to get access to the bridge when there is a water body or it is very high. So in that case, sometimes total station is very effective for measuring the responses. So, here in this case, it is used for measuring the responses of the flyover. So, load testing is done for existing structures to check whether it is sufficiently strong to carry out the load coming on it and that is an effective means of non-destructive testing on the structure.

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So, these are the references for the Module B and with this, we close the Module B of this lecture. Thank you.