Retrofitting and Rehabilitation of Civil Infrastructure
Professor Swati Maitra
Ranbir and Chitra Gupta School of Infrastructure Design and Management
Indian Institute of Technology, Kharagpur
Lecture 04
Materials Related Distresses (Contd.)

Hello friends, welcome to the NPTEL Online Certification Course on Retrofitting and Rehabilitation of Civil Infrastructure. Today we will discuss Module-A, the topic for Module-A is Deterioration of Concrete Structures.

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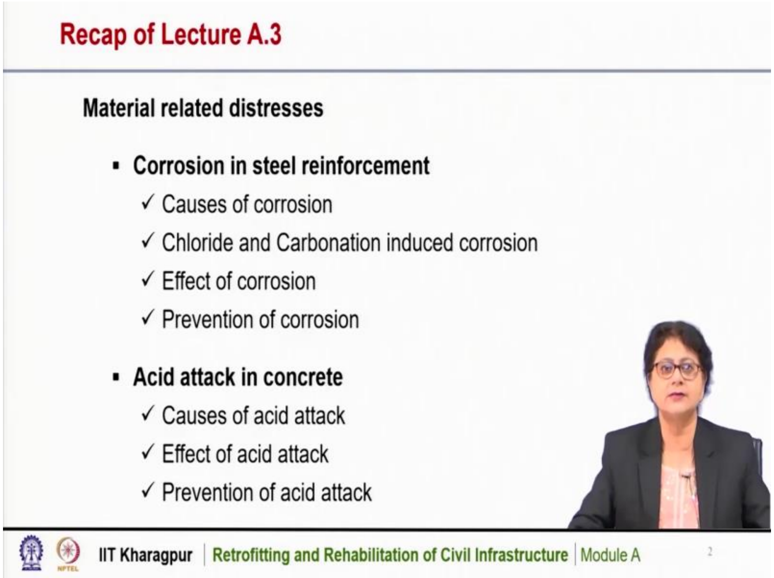

In the previous lecture, we have discussed two material-related distresses, one is corrosion in steel reinforcement and another is acid attack in concrete. We have discussed that what are the causes of corrosion, we have discussed the chloride-induced and carbonation-induced corrosion, the effects of corrosion, and how we can prevent corrosion in steel reinforcement.

In acid attack in concrete, we have discussed the causes of acid attack, the effects of acid attack, and how we can prevent the acid attack in concrete.

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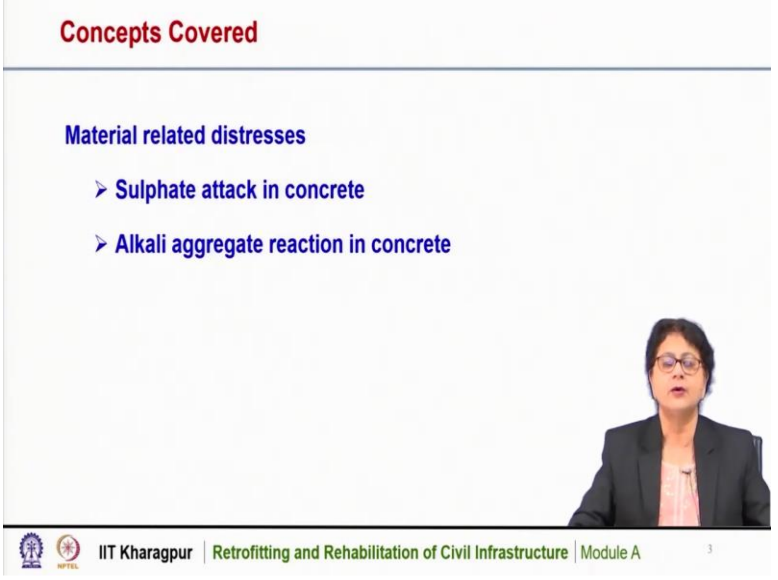

Today, we will discuss another two material related distresses, one is sulphate attack, and the other is alkali-aggregate reaction in concrete.

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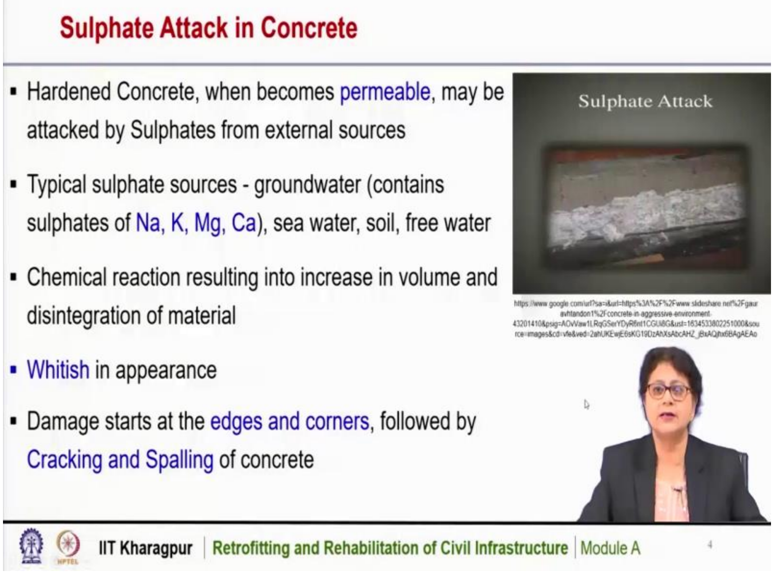

Sulphate attack has been found in concrete structures which are existing structures. In hardened concrete, when the concrete becomes permeable in nature due to the presence of cracks, it may get attacked by several sulphates from external sources. The external source of sulphate may be different like groundwater that may contain several sulphates of sodium, potassium, magnesium, calcium, etcetera.

Seawater is another source of sulphate salts. Soil also may get contaminated with several sulphates and free water also may get contaminated with sulphates and concrete structures if they are exposed to such type of soils or groundwater, they may get affected due to this.

Because of the sulphate attack, there is a chemical reaction that is taking place that results into increase in the volume and disintegration of the material afterwards. Due to sulphate attack, the surface is affected first and a whitish appearance is there on the concrete surface. We can see here one picture of a sulphate attack in concrete.

You can see here, the whitish appearance is there on the surface of the concrete member. Due to the sulphate attack, the damage starts at the edges and corners of the members followed by cracking and spalling of the concrete. Due to the sulphate attack, thus the concrete gets affected, gets distressed and its performance and durability is also affected.

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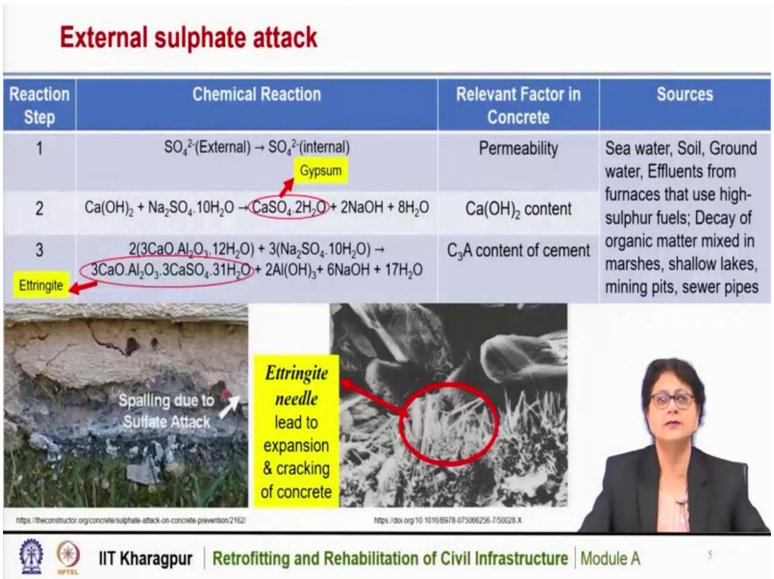

Sulphate attack in concrete may be external or internal. In external Sulphate attack, the sources of sulphate are from the external sources. For example, seawater or soil which is contaminated with several sulphate salts or groundwater may also contain sulphates and that may cause the external sulphate attack in concrete. The effluence from furnaces that use high sulphur fuels, if they are mixed with groundwater or soil that may affect the concrete.

And because of that, sulphate also may get attacked. Decay of organic material, when mixed in marshes or shallow lakes mining pits or sewer pipes or soil that may also affect the concrete surface due to which the concrete may get affected and sulphate attack may take place. In Sulphate attack, because of these external sources, there are chemical reactions that is taking place.

In this chemical reaction, the sulphate salts like for example, sodium sulphate reacts with calcium hydroxide present in the concrete to form gypsum, gypsum is calcium sulphate, this is the hydrated calcium sulphate and that is formed due to the reaction of sulphate salts with calcium hydroxide. In another reaction of sulphate salts, the sulphate salt is reacting with the tricalcium aluminate which is present in the concrete.

This tricalcium aluminate or C_3A is an ingredient of cement and that is present in concrete. The sulphide salt when it reacts with tricalcium aluminate or C_3A, the reaction product is the ettringite or calcium sulphoaluminate. We can see here that the reactive product is the ettringite which is formed due to this reaction. So, the factors which are responsible for sulphate attack or external sulphate attack are the sulphate salts and they react with calcium hydroxide and tricalcium aluminate to form gypsum and ettringite.

So, because of these reactions, there is the formation of the reactive products. So, here you can see that this is the product which is formed due to the reaction of sulphate salts with C_3A. Ettringite needles are formed, you can see here the ettringite needles are formed due to the sulphate attack and this leads to the expansion and cracking of concrete. Here in this picture, it is shown that because of the sulphate attack, the concrete surface gets cracked and it spalled out as well. So, this is the effect of a sulphate attack.

It is to be noted that gypsum is also added during the formation of cement in the clinker. Because of that, the reason for adding Gypsum is to prevent the flash sighting of cement. Gypsum reacts with the C_3A to form this ettringite and this formation of ettringite is occur due to the early stage of hydration. This is not that beneficial at that stage of hydration because in that stage concrete still is in its plastic or semi-plastic stage.

So, the expansion of volume due to the formation of ettringite is accommodated by the plastic state of concrete. However, when concrete becomes hardened and it is getting attacked by sulphates in this type of reaction taking place then there is no chance of accommodating the excess volume or expansion of volume. As a result, there is cracking of concrete surface and the distresses are observed as you can see here in this picture, it is the surface gets cracked and spalled due to sulphate attack.

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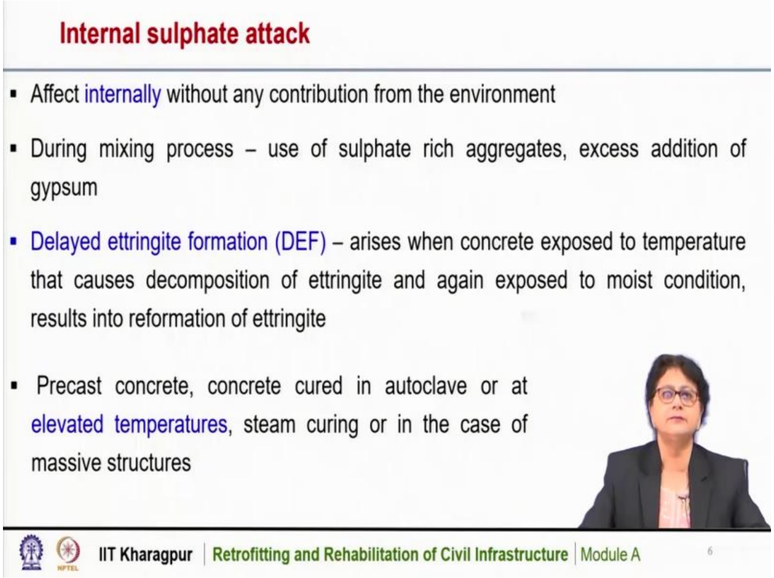

Concrete may also get affected due to sulphate internally without any contribution from the environment. During the mixing process, if sulphate rich aggregates are used or the gypsum which is added is excess in quantity, then, in that case, that may lead to internal sulphate attack in concrete in letter stage. Because of this internal sulphate attack, there is ettringite formation and it is termed as delayed ettringite formation or DEF.

This delayed ettringite formation arises when concrete exposed to temperature that causes decomposition of ettringite and again exposed to moisture condition. That moisture condition may be due to high relative humidity or presence of water which results into reformation of the ettringite.

Precast concrete or concrete when it is cured in autoclave or at elevated temperature or in steam curing. In those cases, there may be a chance of delayed ettringite formation. This may be also in case of mass concrete where there is high temperature due to the massive structures and that may also cause delayed ettringite formation in later stages. And because of that, the concrete may get affected.

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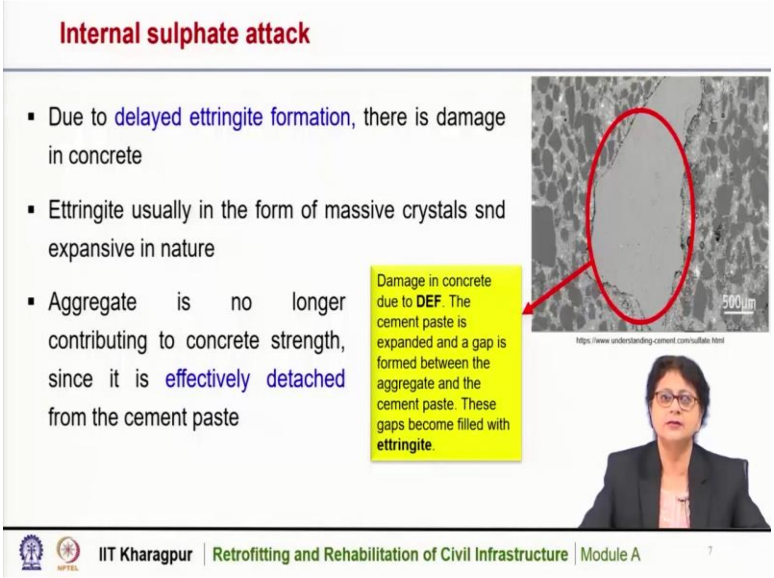

Due to the delayed ettringite formation, there is damage in concrete. Ettringite usually are in the form of massive crystals and expansive in nature. So, in this case, it is not in the form of the needle, ettringite needles, but in the form of a massive crystals. Here you can see that in this picture damage in concrete is there due to the delayed ettringite formation.

The cement paste is expanded and a gap is formed between the aggregate and the cement paste. We can see here that a gap is formed between the aggregate particles and the cement paste. These gaps are now filled up with the ettringite and these ettringites are in the form of crystals and they are expansive in nature.

And because of that, aggregate is no longer contributing to the concrete strength as it is effectively detached from the cement paste. Ettringites are formed in this gap and aggregates are practically detached from the cement paste, thus it is not effective in contributing the strength and there is loss of strength as well in the member.

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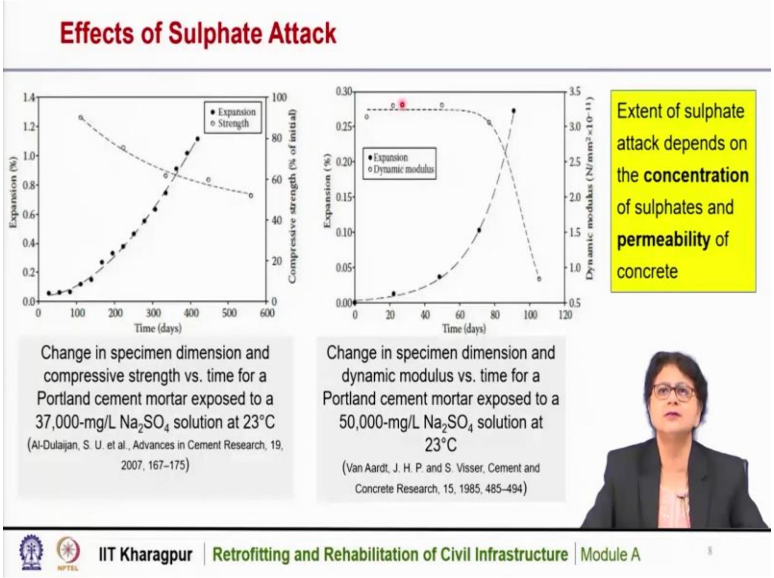

The effects of sulphate attack may be quite significant. The extent of sulphate attack depends on the concentration of sulphates and also the permeability of concrete member. Here in this diagram, we can see the effect of sulphate attack because of the difference in the concentration, the variation of the expansion due to time has been plotted here.

And in this figure also it has been plotted with variation in the concentration of sulphate solution. So, we can see here that as the time increases, the expansion also is increasing. The variation in compressive strength of the concrete member is also plotted with respect to time and we can see that there is a significant decrease in the compressive strength in percentage from around 80 to 90 percent to around 50 percent reduction in the compressive strength.

The expansion, if we can see that in two figures it is quite different. Here we have seen that it is due to the effect of sodium sulphate solution at 23 degrees centigrade when the concentration is 37,000 mg per litre. Here, in this case, the similar plots have been prepared and we have seen that it is the effect of sodium sulphate solution at 23 degrees centigrade when the concentration is 50,000 mg per litre.

So, we can see here that the expansion is quite significant here. In about 92 to 100 days, the expansion is about say 0.27 percent whereas, when the concentration is less in similar 90 to 100 days, the expansion is less than half. So, there is a significant difference when the concentration is more.

The effect of a sulphate attack is significantly different, when the concentration of sulphide solution is different, higher is the concentration higher is its effect, higher is the expansion and so more cracking and spalling of concrete. The dynamic modulus is also shown here and we can see that significant loss of the dynamic modulus with time due to the effect of sulphate solution in concrete.

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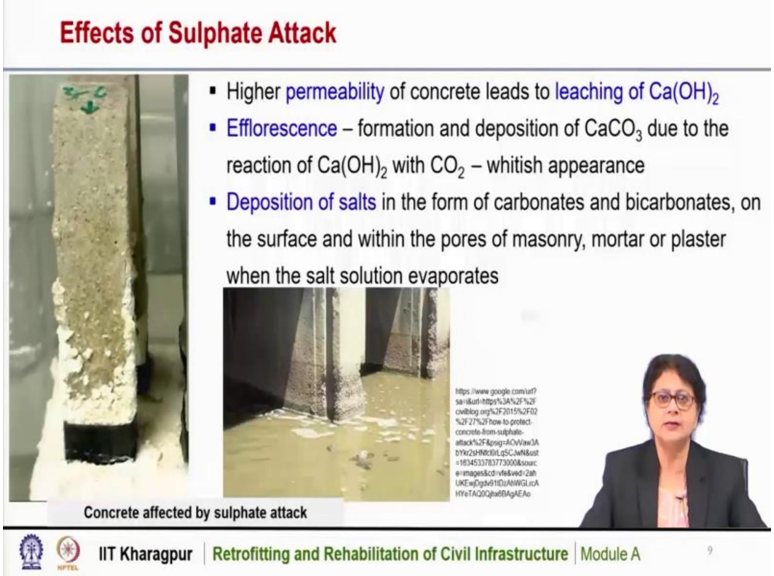

Effect of permeability is also significant in sulphate attack. Higher the permeability of concrete leads to leaching of calcium hydroxide. Calcium hydroxide is the product of hydration and which is present in concrete. And because of the sulphate attack, there may be leaching of calcium hydroxide that leads to formation and deposition of calcium carbonate due to the reaction of calcium hydroxide with carbon dioxide, this is called efflorescence.

Due to this efflorescence, there is a deposition of calcium carbonate on the surface that results into the whitish appearance. So, here we can see in this picture, that the whitish appearance on the surface of concrete because of the sulphate attack, the deposition of salts in the form of carbonates and bicarbonates on the surface and within the pores of masonry, mortar, and plaster is taking place when the salt solution evaporates. Here also in this picture, we can see that the surface is degraded due to the sulphate attack.

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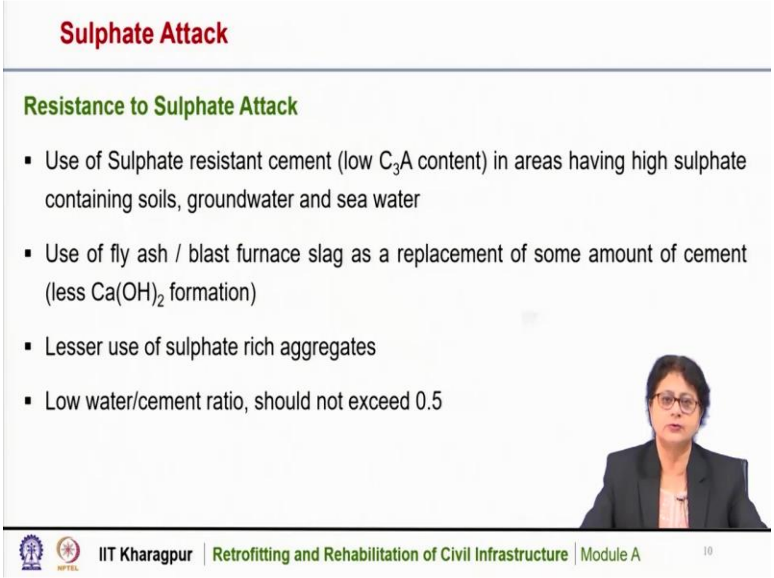

Resistance of sulphate attack can be done with several measures. We can take several measures to resist sulphate attack. Use of sulphide resistant cement in areas particularly where the groundwater contaminates sulphate salts or soil or near the sea water, we can use sulphate resistant cement. In sulphate resistant cement the C_3A content is generally low and that is beneficial because the external sulphate attack may not take place in that case or if it is taking place then also the amount is low.

Use of fly ash, blast furnace slag as a replacement of some amount of cement also is beneficial. So, the reaction also will be taking place in a lesser content, lesser use of sulphate which aggregates will also prevent the sulphate attack in concrete and low water-cement ratio is beneficial as a low water-cement ratio will resist the concrete to become less permeable and that is a desirable condition for resisting sulphate attack. So, when the water-cement ratio is less than 0.5 that is effective in resisting sulphate attack in concrete.

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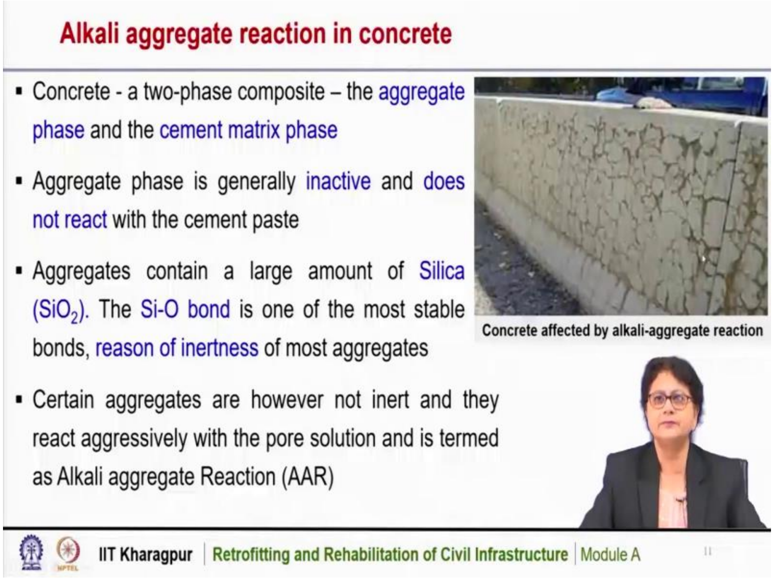

Now, we will discuss another material-related distresses in concrete, this is alkali-aggregate reaction. Concrete is a two-phase composite; one is the aggregate phase and the other is the cement matrix phase. Aggregate phase is generally inactive and does not react with the cement paste. It is always the cement paste that is more reactive or more susceptible to all these types of attacks.

Generally, aggregates contain a large amount of silica and this Si-O bond is one of the most stable bonds and that is the reason for the inertness of most of the aggregates. So, the silica which is present in aggregate is responsible for the innovativeness of the aggregates. However, certain aggregates are not so inert and they react aggressively with the pore solution and that is termed as alkali-aggregate reaction.

So, in alkali-aggregate reaction, it is the aggregate which is present in the concrete and these aggregates are not inert. They are reactive and these reactive aggregates react with the pore solution and that causes the damage in concrete and this damage is called alkali-aggregate reaction or AAR. Here we can see a typical picture of a concrete surface affected by alkali-aggregate reaction, the entire surface is getting affected due to this type of distress. And we can see here in this picture, the surface is damaged due to this type of distress.

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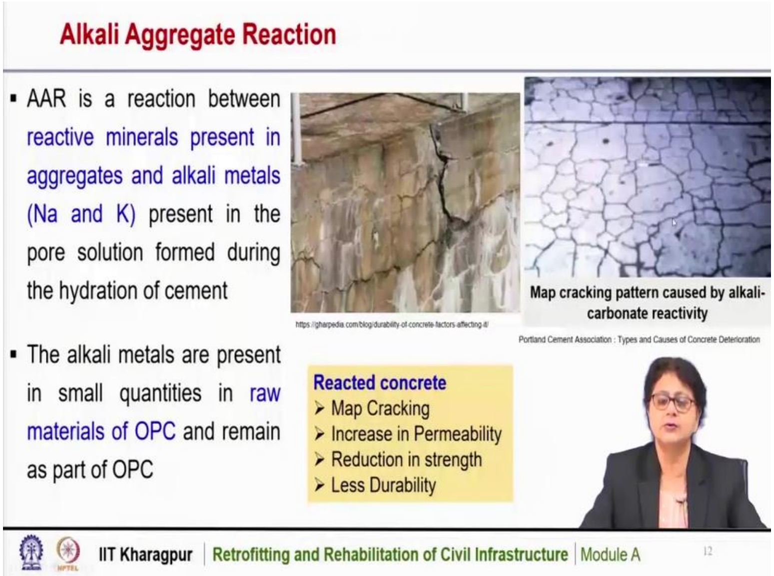

Alkali aggregate reaction is a reaction between the reactive minerals present in aggregates and alkali metals present in the pore solution formed during the hydration of cement. These alkali metals are generally sodium or potassium and these alkali metals are present in small quantities in the raw material of OPC or Ordinary Portland Cement and they remain as part of the cement. So, these alkali metals are present in the small quantities and that may cause this type of reaction also with the reactive aggregates.

Here you can also see other pictures, map cracking pattern caused by the alkali-aggregate reaction and because of this reaction, there is cracks appear on the surface. So, it is like a map cracking on the entire surface that results into increase in the permeability of the member which also causes reduction in strength and the durability of the member.

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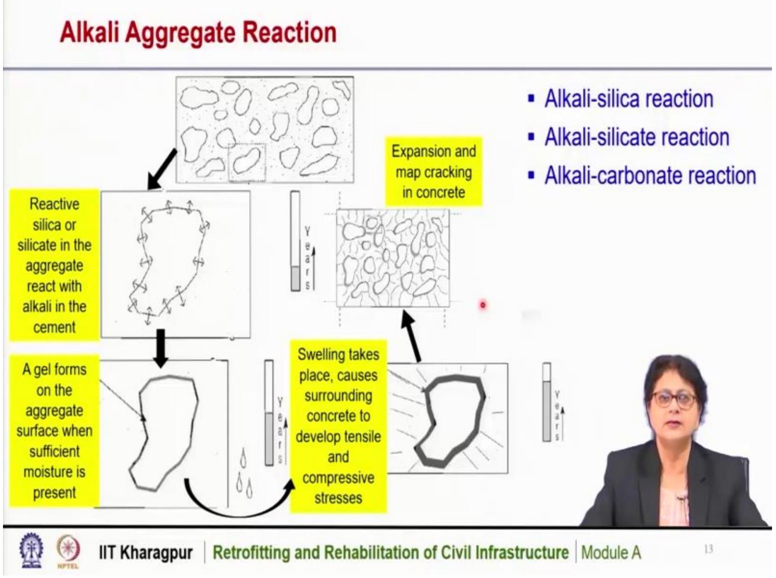

Alkali aggregate reaction may be alkali-silica reaction or alkali silicate reaction or alkali carbonate reaction. Here we can see that it is schematically shown that how the reaction is taking place in case of alkali-aggregate reaction. Look at this schematic diagram, this is a concrete member where these are the aggregates which is present in the mix and this portion is the cement paste.

Now, generally, the aggregates are inert and they do not react with the pore solution or the cement paste, but some aggregates if it is reactive in nature, then the reactive silica which is present in that aggregate react with the alkali present in this cement. So, this is the reaction that is taking place around the reactive aggregates.

Because of this reaction, a gel like substance is formed on the aggregate surface when there is sufficient moisture present in the mix. And generally, water is present in the mix, it may come from outside or from inside as well. So, the reaction is taking place, and a gel like formation taking place around the aggregate.

This causes swelling around the surface, swelling takes place that causes the surrounding concrete to experience tensile and compressive stresses. So, here we can see that surrounding concrete is experiencing stresses and that leads to cracking of the surface, this leads to expansion and map cracking in the concrete. So, schematically it is shown that how the reactive aggregates react with the alkalis is present in the cement and the gel like formation is there which causes expansion and map cracking in concrete.

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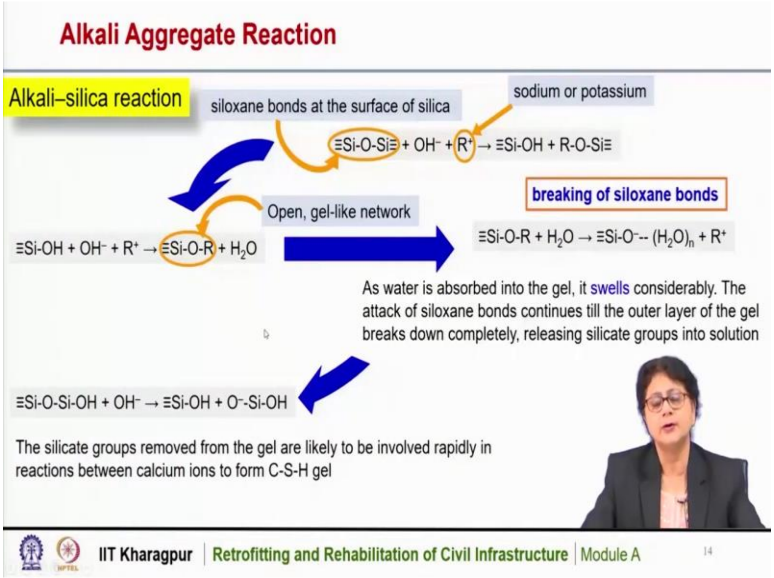

Now, we will discuss the alkali-silica reaction, alkali silicate reaction, and alkali carbonate reaction. In alkali-silica reaction, it is the siloxane bonds at the surface of the silica which is present in aggregate and that is reacting with the alkalis present in the cement paste. So, this is the sodium or potassium denoted by R and this siloxane bond is reacting with the hydroxide ions and alkalis present in the mix to form this Si-OH, this is actually in these reactions.

It is actually the breaking of the siloxane bonds in aggregate. So, for the reaction taking place you can see here that Si-OH again reacts with hydroxide ions and alkalis present to form this Si-O-R and water, as water is absorbed into the gel it swells considerably. So, this is the gel like structure and when water is absorbed into this gel it swells further.

The attack of siloxane bonds continues till the outer layer of the gel breaks down completely releasing the silicate groups into the solution. So, you can see here that these are the products that are formed due to this reaction. Then again further reaction taking place with this product and this Si-O-H is formed.

The silicate groups removed from the gel are likely to be involved rapidly in reactions between calcium ions to form C-S-H gels like disposal ionic reaction. So, in this alkali-silica reaction, it is actually the breaking of the siloxane bonds that taking place. A series of reaction goes on and the siloxane bonds are broken.

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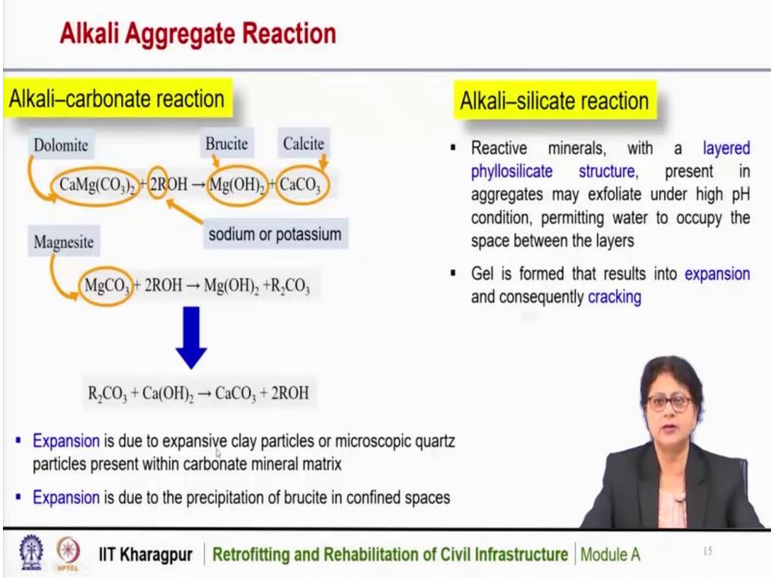

In alkali carbonate reaction, the dolomite which is this one, this is the dolomite reacts with the alkalis present in the mix. That alkali maybe has sodium or potassium and the reactive products are brucite and calcite. These are precipitated and that causes expansion due to this precipitation. Magnesite also reacts with the alkalis and magnesium hydroxide is formed. This again reacts with calcium hydroxide to form calcium carbonate and this hydroxide.

So, this type of reaction is taking place and expansion is due to the expansive clay particles or microscopic quartz particles present within the carbonate mineral metrics. So, because of these reactions, expansion is taking place, and as we have mentioned that expansion is due to the presence of expansive clay particles or microscopic quartz particles or due to the precipitation of brucite in confined spaces.

In alkali silicate reaction, the reactive minerals with a layered phyllosillicate structure present in the aggregates may exfoliate under high alkaline condition permitting the water to occupy the space between the layers. A gel like structure is formed that results into expansion and consequently cracking of the member.

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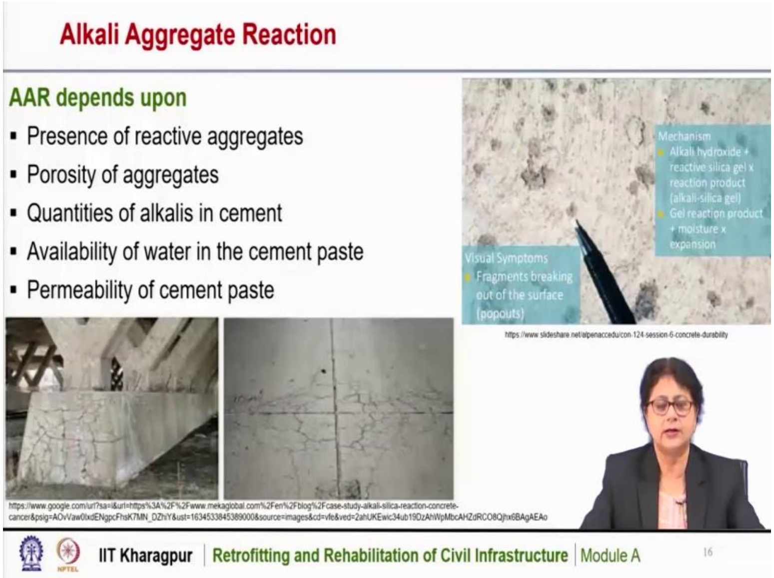

AAR depends on several factors, one, of course, is the presence of the reactive aggregates. Reactive aggregate is the main factor that is responsible for alkali-aggregate reaction. Porosity of aggregate is also another factor that may affect this type of distress, the quantities of alkalis is present in cement because the reactive aggregates react with the alkalis present.

So, the amount of alkali is also responsible for this type of alkali-aggregate reaction and its extent. Availability of water in cement paste and permeability of cement paste are other factors for alkali-aggregate reaction. So, these are other typical pictures of concrete structures which are affected due to alkali-aggregate reaction.

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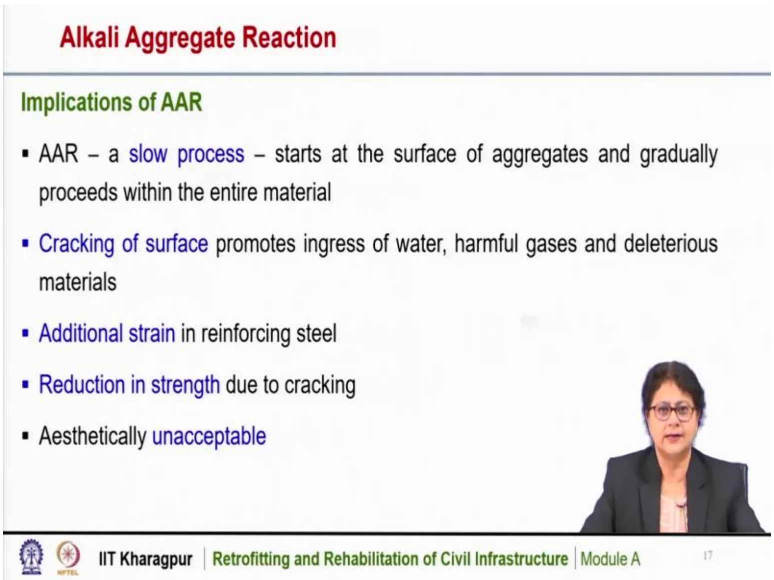

Implications of alkali-aggregate reaction – Alkali aggregate reaction is a slow process, it starts at the surface of the aggregates and gradually proceeds within the entire material. Due to the alkali-aggregate reaction, the cracking of the surface occurs, which promotes further increase of water, harmful gases, and deleterious material and that accelerates further damage. Because of this cracking, the entire surface gets affected and a map cracking type of appearance is formed.

Because of this expansion, the reinforcing steel also experiences an additional strain and that may cause further expansion and distress. Reduction in strength is also another important issue because of large area of cracking and aesthetically it is unacceptable. The alkali-aggregate reaction results into map cracking on the entire surface and that is as aesthetically not very acceptable.

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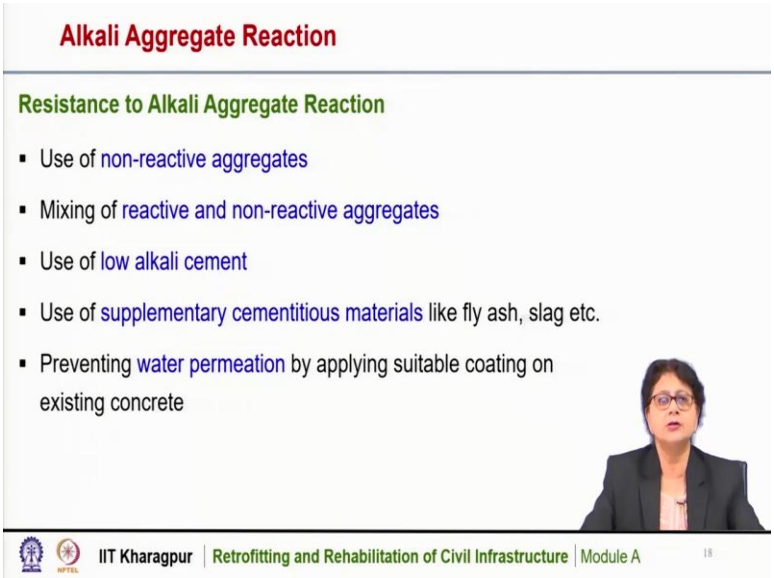

The alkali-aggregate reaction can be resisted with the use of non-reactive aggregates. If in some cases it is unavoidable to use non-reactive aggregates then a mixing of reactive and non-reactive aggregates may reduce the alkali-aggregate reaction in concrete. Use of low alkali cement is also beneficial because the alkali content if it is low, then the reaction also will be less, so the distress also will be less.

Use of supplementary cementitious materials like fly ash or slag is beneficial as these may contain less amount of calcium hydroxide or alkalis. Preventing water permeation by applying suitable coating on existing concrete is also beneficial in resisting alkali-aggregate reaction in concrete.

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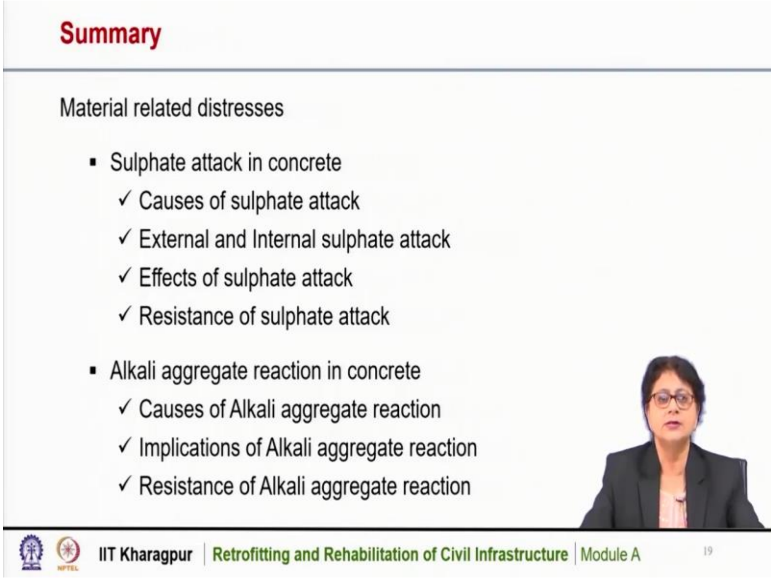

So, to summarize, we have discussed today, two material-related distresses in concrete one is sulphate attack and the other is alkali-aggregate reaction. In sulphate attack, we have discussed the causes of sulphate attack. There are two types of sulphate attack one is due to external sources and the another from internal sulphate attack and that we have discussed.

The effects of sulphate attack and how we can resist sulphate attack in concrete that will also been discussed. In alkali-aggregate reaction we have discussed the causes of alkali-aggregate reaction in concrete, what are the implications, and how we can resist alkali-aggregate reaction in concrete that we have discussed. Thank you.