Concrete Engineering and Technology
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Department of Civil Engineering
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Lecture - 24
Alkali – aggregate reaction (Part 1 of 2)

And welcome to another lecture on concrete engineering and technology.

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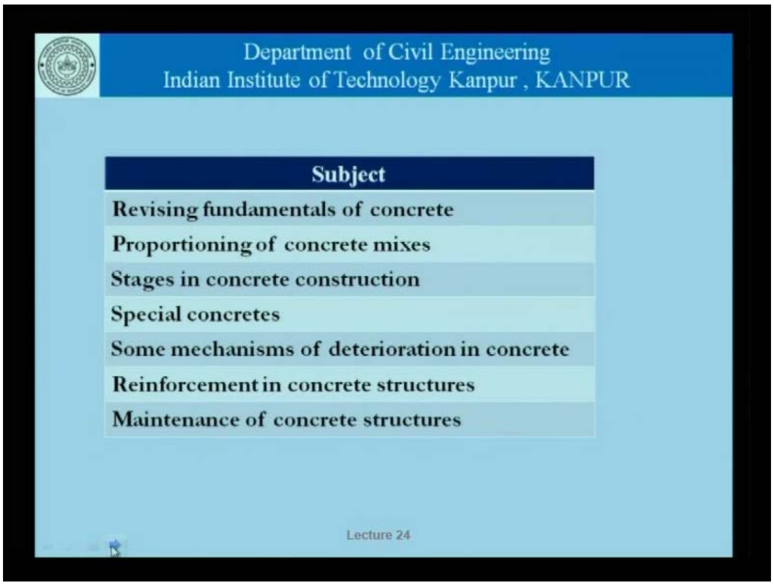

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Subject
Revising fundamentals of concrete
Proportioning of concrete mixes
Stages in concrete construction
Special concretes
Some mechanisms of deterioration in concrete
Reinforcement in concrete structures
Maintenance of concrete structures

Lecture 24

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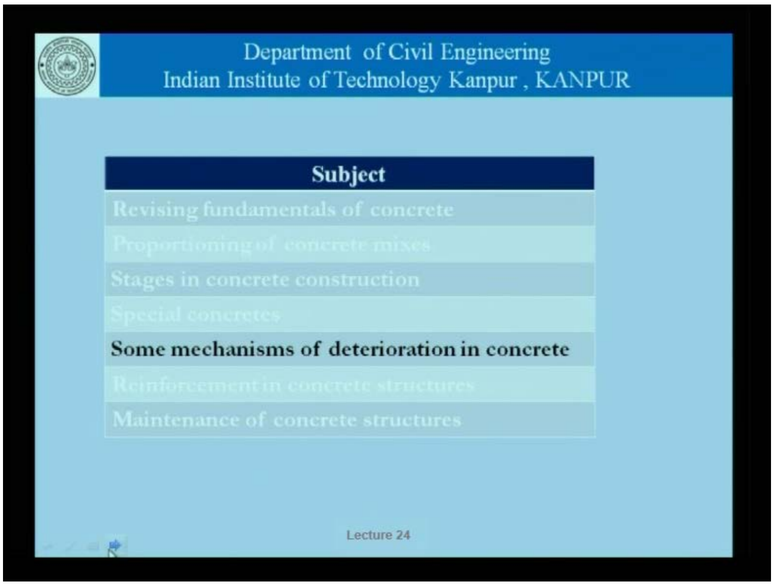

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This slide outlines basically the content that we are trying to go through. The discussion today would start on some of the aspects of mechanisms related to deterioration of concrete.

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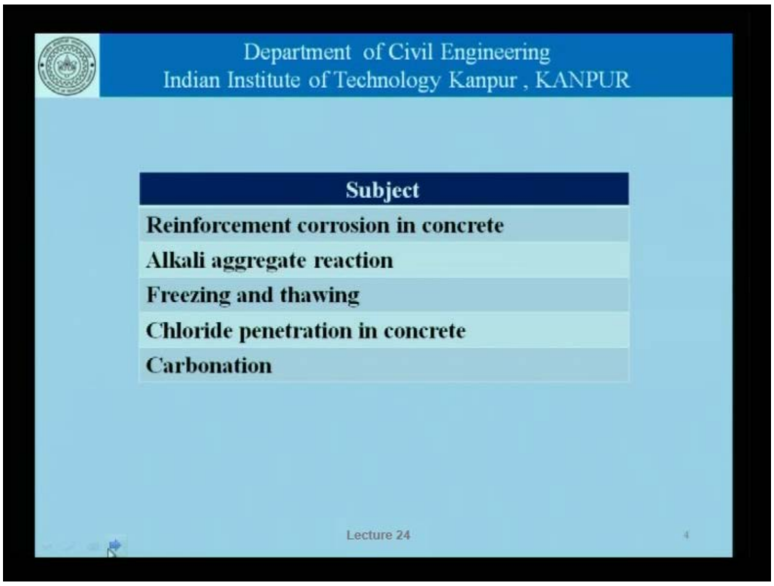

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Subject
Reinforcement corrosion in concrete
Alkali aggregate reaction
Freezing and thawing
Chloride penetration in concrete
Carbonation

Lecture 24

And the subjects that we have been talking about or we plan to talk about in this course include reinforcement corrosion, alkali aggregate reaction, freezing and thawing, chloride penetration and concrete and carbonation.

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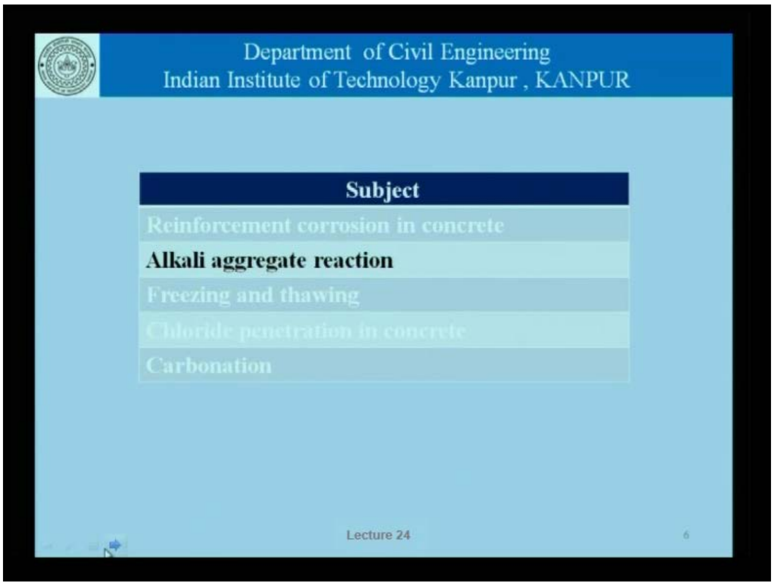

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Reinforcement corrosion in concrete
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So, today’s discussion largely focuses on alkali aggregate reaction.

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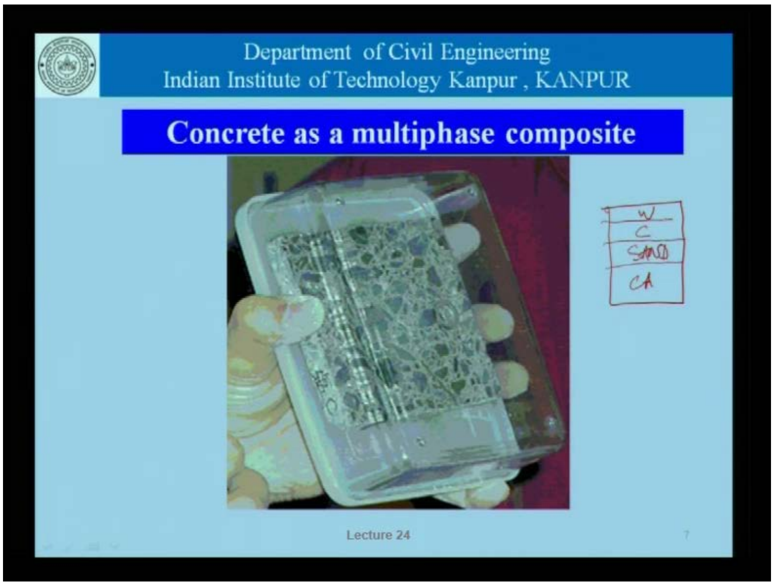

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Concrete as a multiphase composite

Lecture 24

Now, let us look at this picture which shows concrete as a multiphase composite. We have looked at this picture before, but that was from the point of view of proportioning your concrete mix. At that time, the focus was to say that well there is a certain amount of concrete, of certain volume of material which has to be filled and their we would place certain amount of coarse aggregate, a certain amount of sand and cement and water to make concrete.

Today, the focus is not on the volumetric’s, but on what really happens at the interfaces of aggregates and the mortar face in which they are embedded. So, this is a problem where we are looking at the interaction, the chemical interaction that occurs between the aggregates which we can see here and the surrounding mortar face. The mortar face has a chemical nature; the pores there are filled with pore solution which has a lot of ions in it. Those ions are coming from the hydration products of cement.

So, the ionic composition of the pore solution is related to the chemical composition of cement. So, what happens around these rims or the interfaces really is that the aggregate surface reacts with the compounds or the chemical complexes which are present in pour solution and that is the beginning or that is the whole essence of alkali aggregate reaction.

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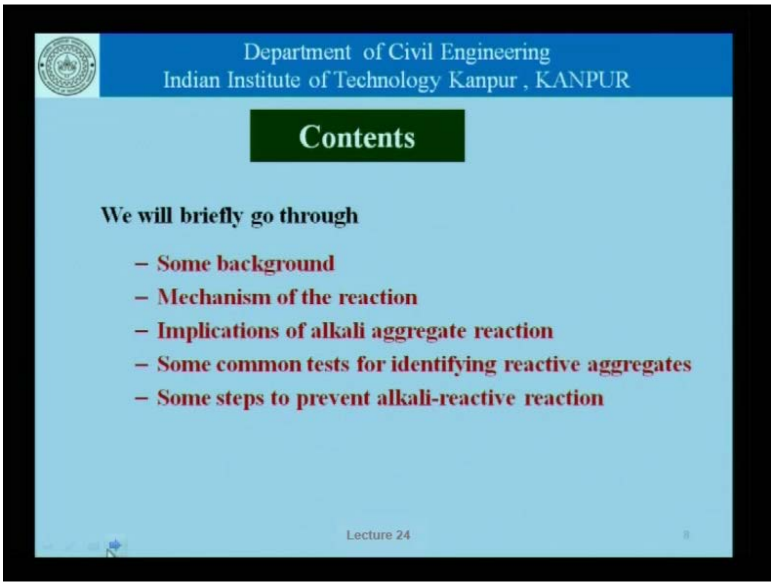

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Contents

We will briefly go through

- **Some background**
- **Mechanism of the reaction**
- **Implications of alkali aggregate reaction**
- **Some common tests for identifying reactive aggregates**
- **Some steps to prevent alkali-reactive reaction**

So, what we will do today is to go through very briefly some background material on alkali aggregate reaction, have a bird's eye view of the mechanisms involved. We will try to understand a little bit about what happens to concrete and concrete structures when alkali aggregate reaction takes place. We will try to understand or go through the principals involved in testing aggregates for potential alkali aggregate reactivity and we will try to go through some steps that may be taken to prevent alkali aggregate reaction or at least the steps that can be taken to mitigate the harmful effects that may come as a result of that reaction.

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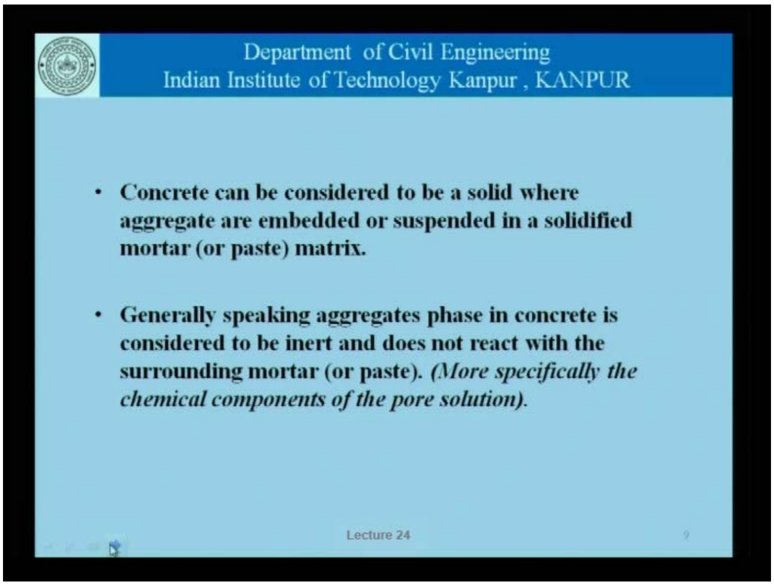

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- **Concrete can be considered to be a solid where aggregate are embedded or suspended in a solidified mortar (or paste) matrix.**
- **Generally speaking aggregates phase in concrete is considered to be inert and does not react with the surrounding mortar (or paste).** ***(More specifically the chemical components of the pore solution).***

So, getting started our initial premise or the assumption in the concrete engineering was that concrete can be considered to be a solid where the aggregate are embedded or suspended in a solidified mortar or paste matrix.

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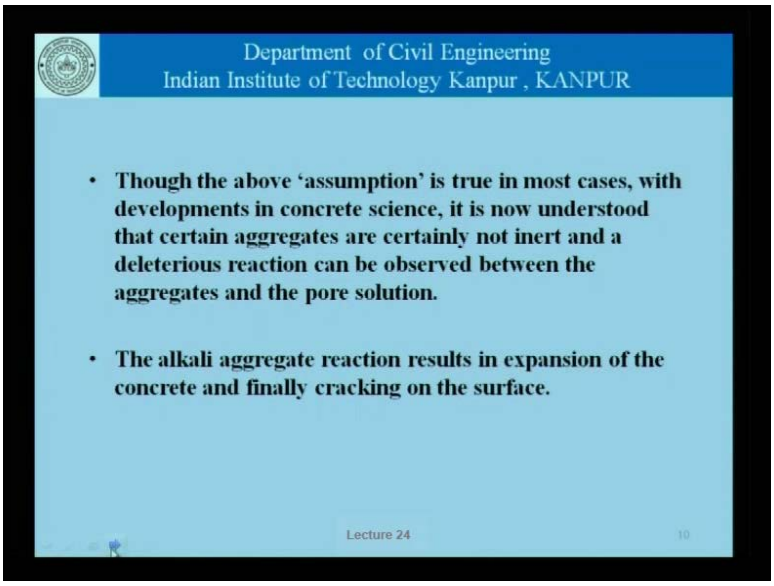

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- **Though the above 'assumption' is true in most cases, with developments in concrete science, it is now understood that certain aggregates are certainly not inert and a deleterious reaction can be observed between the aggregates and the pore solution.**
- **The alkali aggregate reaction results in expansion of the concrete and finally cracking on the surface.**

Lecture 24

So, that is they do not chemically react. Then generally speaking the aggregate phase in concrete is considered to be inert and does not react with the surrounding mortar or paste. More specifically the chemical components of the pore solution and that is what we were talking about when we were looking at a close up of a core or surface of concrete drawn from within. This assumption of the aggregates being largely inert is true in most cases, but with the developments in concrete science it is now understood that certain aggregates are certainly not inert and at an iterious reaction a harmful reaction can be observed between the aggregates and the surrounding pore solution.

The alkali aggregate reaction results in the expansion of concrete and finally, cracking on the surface. So, without going through the entire mechanism this is what really happens. Once, alkali will get reaction occurs the changes that happen in the concrete cause the concrete to expand and this expansion results in cracking which appears at the surface. This picture here shows representation of what really happens. There is alkali in the concrete and if it reacts or if it is occurring in combination with reactive aggregates then we have some reaction products which are formed and these reaction products if you read the literature are sometimes called gels.

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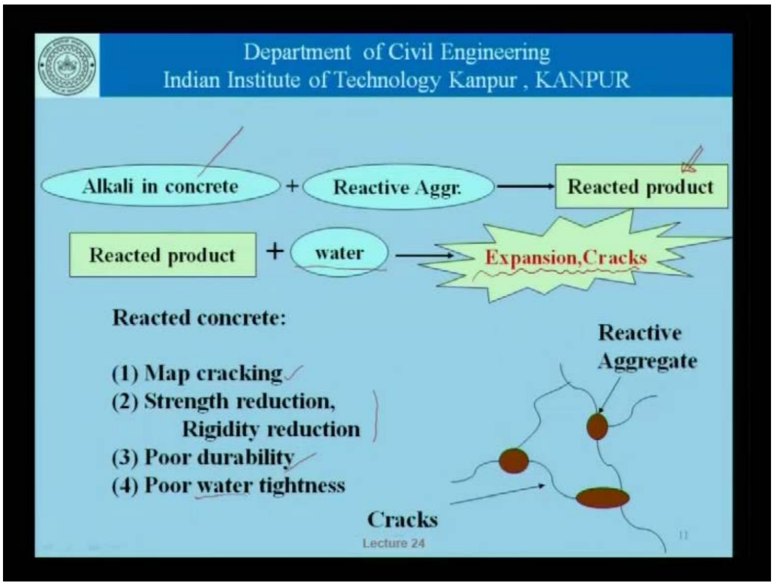

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Alkali in concrete + Reactive Aggr. → Reacted product

Reacted product + water → Expansion,Cracks

Reacted concrete:

(1) Map cracking
(2) Strength reduction,
Rigidity reduction
(3) Poor durability
(4) Poor water tightness

So, this reactive gel absorbs water and water is present in concrete in abundance. Either it is present from the initial time or in certain cases it absorbs water from the atmosphere, there is rainfall and so on which contributes to making the concrete wet and all that water is available for the gel to absorb and that absorption leads to expansion and cracking. So, if we look at it schematically in a very interesting kind of a diagram which is shown here, if we have reactive aggregates as shown then we can have cracks between these aggregates as can be seen here.

And these aggregate cracks or these cracks appear on the surface causing wide spread cracking. The cracking is wide spread because aggregates obviously in concrete are completely distributed all over the place. There are aggregates close to the surface, there are aggregates within the concrete and all of them are reacting except that when those closer to the surface have a greater meaning for us because the cracks are formed on the surface, the water absorption is easier for aggregates and the reaction products formed closer to the surface and so on.

Now, in the case of reacted concrete or the concrete that has undergone damage or deterioration on account of alkali aggregate reaction. We can have map cracking that is the kind of cracks that we see in a concrete structure damaged on account of alkali aggregate reaction. We see strength reduction and the reduction in the models of elasticity of concrete as a result of the formation of these cracks. There is this issue of poor durability. Once, these cracks of formed it can be argued that the structure is no longer serviceable. Aesthetically, these cracks are very unappealing, there is poor water tightness obviously in a structure once cracks are formed and if aggregates are used in the structure which is supposed to be water tight and that concrete undergoes alkali aggregate reaction, the water tightness is definitely compromised.

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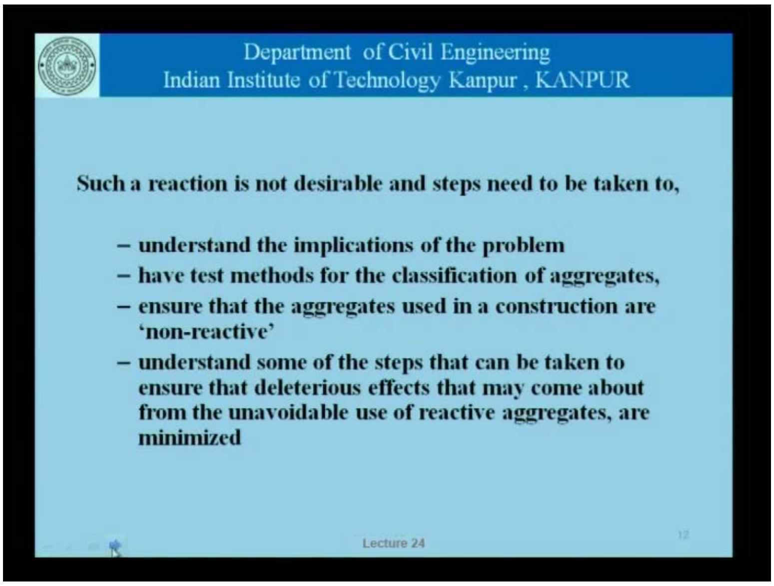

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Such a reaction is not desirable and steps need to be taken to,

- **understand the implications of the problem**
- **have test methods for the classification of aggregates,**
- **ensure that the aggregates used in a construction are 'non-reactive'**
- **understand some of the steps that can be taken to ensure that deleterious effects that may come about from the unavoidable use of reactive aggregates, are minimized**

So, indeed a reaction such as the alkali aggregate reaction is not desirable and as engineers we need to take steps to understand the implications of the problem, have test methods for the classification of aggregates, ensure that the aggregates used in the construction are non reactive and understand some of the steps that may be taken to ensure that the deleterious effects that may come about from the unavoidable use of reactive aggregates are minimized. If you follow cement and concrete to a certain extent it is easy to understand that aggregates in a particular construction site are usually drawn from quarries in the nearby areas. And the mineralogy or the reactivity of aggregates can be studied once and if we know that certain quarries are reactive or the aggregates from certain quarries are reactive, engineers using aggregates from those quarries need to become careful.

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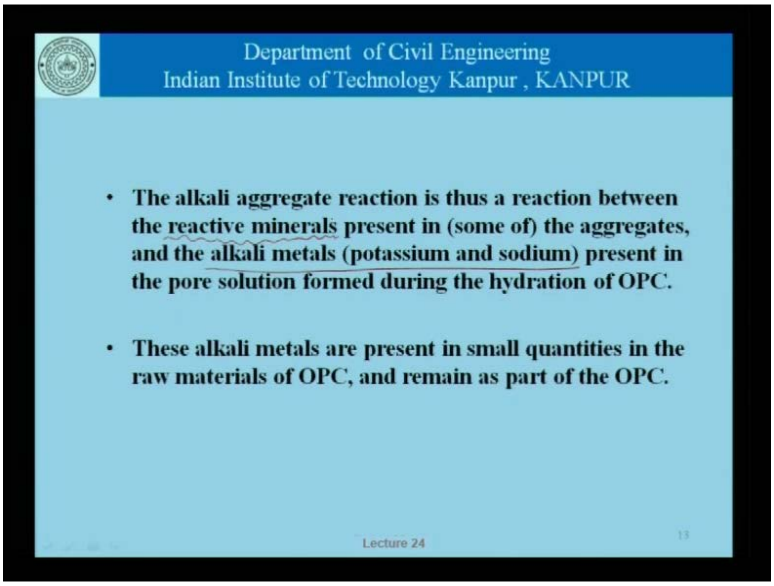

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- **The alkali aggregate reaction is thus a reaction between the reactive minerals present in (some of) the aggregates, and the alkali metals (potassium and sodium) present in the pore solution formed during the hydration of OPC.**
- **These alkali metals are present in small quantities in the raw materials of OPC, and remain as part of the OPC.**

Lecture 24

Summarizing, the alkali aggregate reaction is reaction between the reactive minerals present in some of the aggregates and the alkali metals, sodium and potassium present in the pore solution formed during the hydration of ordinary portland cement. And these alkali metals are presents small quantities in the raw materials of the OPC and remain as a part of the OPC.

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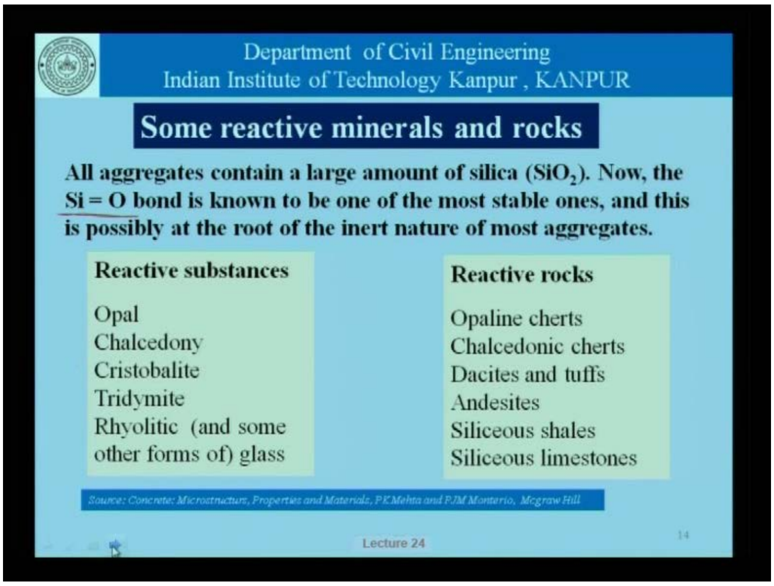

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Some reactive minerals and rocks

All aggregates contain a large amount of silica (SiO_2). Now, the $Si = O$ bond is known to be one of the most stable ones, and this is possibly at the root of the inert nature of most aggregates.

Reactive substances

Opal
Chalcedony
Cristobalite
Tridymite
Rhyolitic (and some other forms of) glass

Reactive rocks

Opaline cherts
Chalcedonic cherts
Dacites and tuffs
Andesites
Siliceous shales
Siliceous limestones

Source: Concrete: Microstructure, Properties and Materials, P.K.Mehta and P.J.M Monterio, Mcgraw Hill

Lecture 24

So, when we talk of the alkali aggregate reaction, the alkali refers to the presence of alkali metals, that is sodium and potassium in the ordinary portland’s cement. When we say aggregate, the aggregate at the end is made up of minerals and those minerals which are reactive, reactive in the sense that they react with the alkali metals. Then we have alkali aggregate reaction.

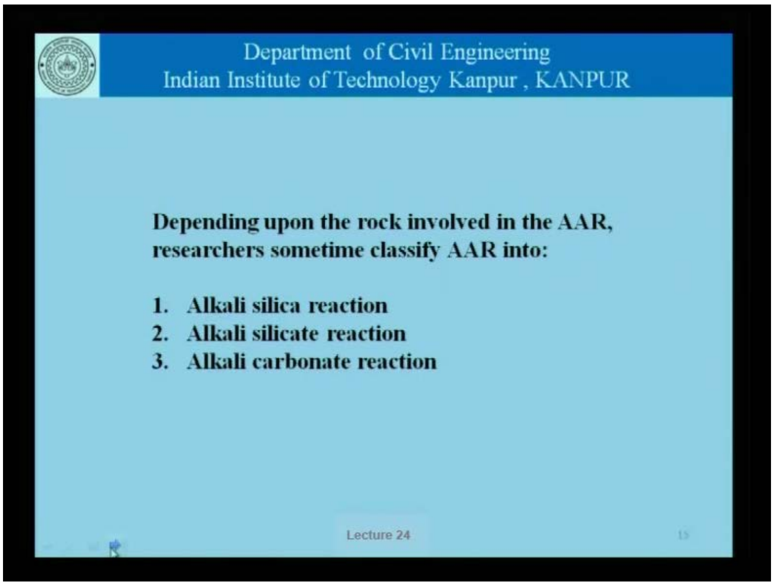
So, it is not really the aggregate that reacts. Obviously, the aggregate is made up of minerals and the minerals they react and if an aggregate is made up of reactive minerals we have alkali aggregate reaction and if the aggregate has non reactive minerals there is no alkali aggregate reaction. As far as listing down some of the reactive minerals and rocks is concerned, we should remember that all aggregates contain a large amount of silica and now the S i O bond is known to be one of the most stable ones and this is possibly at the root of the inert nature of most aggregates.

However, certain forms of silica is reactive and it is not really only silica, there are some other minerals also which have been identified to be reactive of late and the reactive substances could be opal, chalcedony, cristobalite, tridymite, rhyolitic and some other forms of glass like (( )) glass and the rocks which contains these minerals. And the rocks containing these reactive minerals could be opaline cherts, chalcedonic cherts, dacites and tuffs, andesites, siliceous shales, siliceous limestones and so on.

So, it is really a matter of identifying what is the principle mineral in the rock which an engineer wants to use as an aggregate at a given site. Once, that analysis has been done it is easy to identify or understand, plan whether or not the concrete that is going to be used at a particular site is likely to suffer alkali aggregate reaction or not. Of course, the presence of reactive minerals is only one part of the story. We have also to understand that at the end of it there is the alkali and that is something which we will address later on when we are talking of controlling ways and means of alkali aggregate reaction.

Now, depending upon the rocks involved in the alkali aggregate reaction researchers sometimes classify this problem into that of alkali silica reaction. The alkali silicate reaction and at times alkali carbonate reaction. So, we are not going to the chemistry involved in the reactions as to how the alkali metals attack the different minerals and how the alkali ions penetrate into the structure of the silica bond and cause deteriorative or disruptive reactions.

(Refer Slide Time: 13:32)



Depending upon the rock involved in the AAR, researchers sometime classify AAR into:

1. **Alkali silica reaction**
2. **Alkali silicate reaction**
3. **Alkali carbonate reaction**

But we must remember that these are some of the different classifications that have been developed as more and more information about alkali aggregate reactions has been published and has become available.

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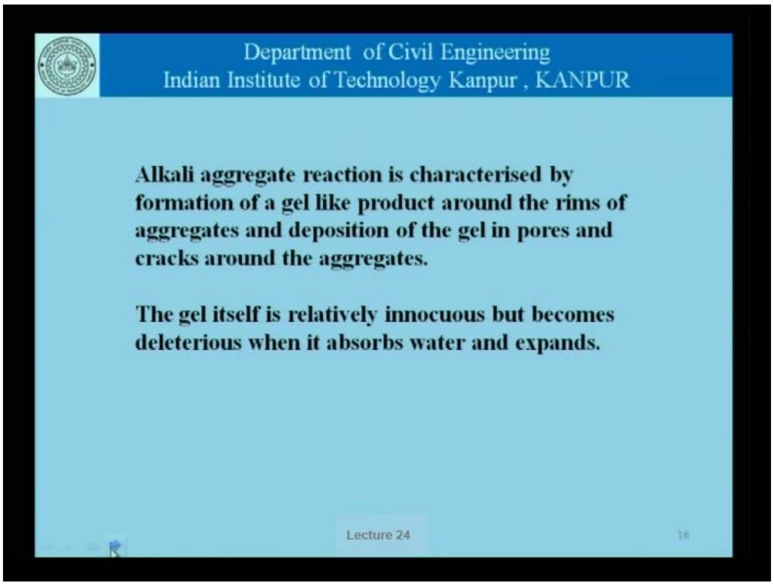
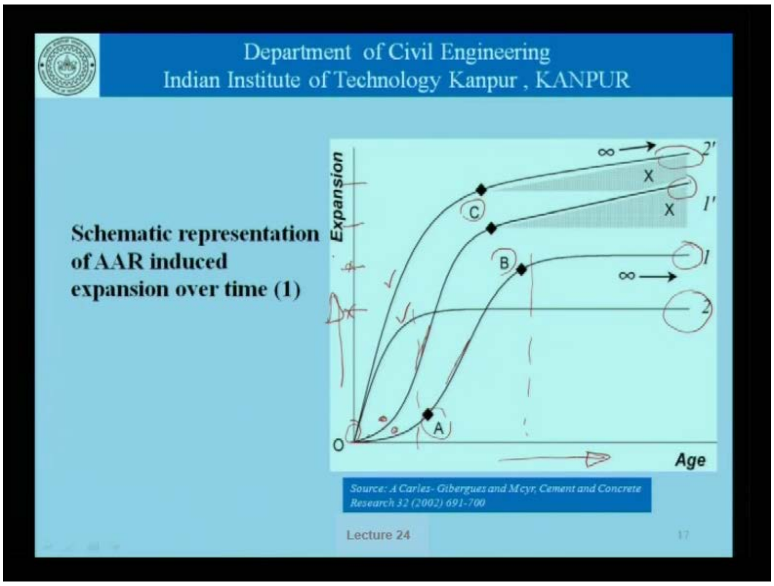


Alkali aggregate reaction is characterised by formation of a gel like product around the rims of aggregates and deposition of the gel in pores and cracks around the aggregates.

The gel itself is relatively innocuous but becomes deleterious when it absorbs water and expands.

So, now alkali aggregate reaction is characterized by the formation of a gel like product around the rims of the aggregates and deposition of the gels in pores and cracks surrounding the aggregates. So, let us look at this piece of concrete which is part of a once again and what is being said is that alkali aggregate reaction involves the formation of gels around these aggregates and that is what is a reaction rim. So, if we look at pictures of concrete affected by alkali aggregate reaction, we will be able to identify a reaction rim in the neighborhood of the cracks or in the neighborhood of the aggregates. Now, this gel itself is relatively innocuous and becomes deleterious only when it absorbs water and this absorption of water leads to an expansion of the gel and thus finally, the cracking.

(Refer Slide Time: 14:45)



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Schematic representation of AAR induced expansion over time (1)

Source: A Carles- Gibergues and Mcyr, Cement and Concrete Research 32 (2002) 691-700

Lecture 24

This here is a representation of the expansion that is been observed in concrete over time with different kinds of alkali aggregate reaction. So, if we look at age which is time in this direction and the amount of expansion which is observed in this direction, then depending on different factors, we have different kinds of expansion that is observed. Different kinds of expansion means the characteristics of expansion are different for example, in this graph here and this one here the expansion starts more or less immediately whereas, in these two cases the expansion is very slow to begin with and then gradually becomes more rapid when we have a much faster increase in the expansion with time. So, that is the rate is much faster at that point in time, but one thing which is very interesting to observe in all cases is the fact that in all the cases there seems to be a limiting value at which the expansion ceases.

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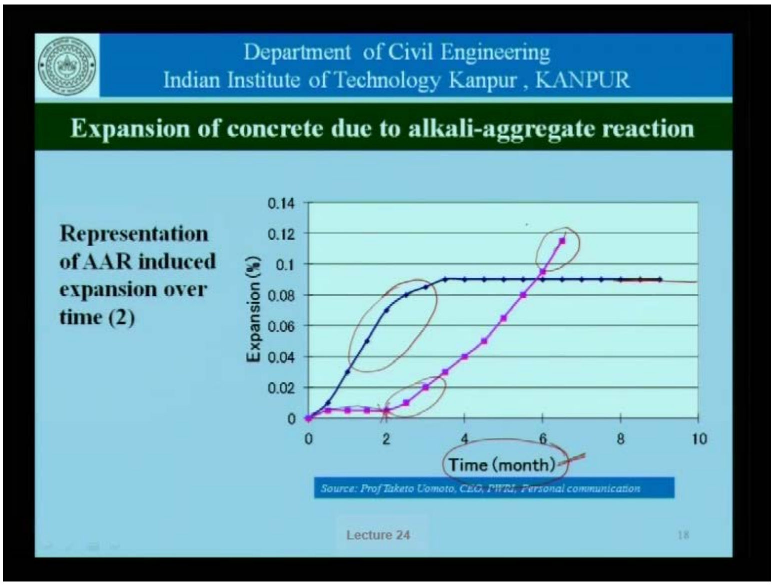

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Expansion of concrete due to alkali-aggregate reaction

Representation of AAR induced expansion over time (2)

Source: Prof Taketo Uomoto, CEO, PWRI, Personal communication

Lecture 24

18

So, now this limiting value at which the expansion ceases that is the expansion does not occur anymore and that may happen at different points in time, it may happen at different levels of expansion and so on, but apparently it does happen. As engineers we therefore, know that alkali aggregate reaction does not continue ad infinitum, it does not continue all the time. Why it stops is a different problem, it is something which we can ponder about, create a model which replicates that phenomenon based on science and that is something which we will try to do.

This here is another illustration of expansion in concrete due to alkali aggregate reaction and we see exactly the same kind of behavior. This aggregate expands much faster initially, but then it tapers off, it does not expand beyond this point. This aggregate does not expand initially, but picks up after a certain point in time and then it goes on to increase. We must remember that these times are in months. When studying alkali aggregate reaction we should also keep in mind that concrete structures are built and remain in service for several tens of years.

And therefore, the reaction is very, very slow. It is slow for various reasons. Silica is not a easy bond to break or penetrate. Number one, the surface area available for the aggregates is large and the amount of alkali fortunately as far as cement is concerned is relatively low and so on. So, all this contributes to the reaction being very slow and therefore, when we talk in terms of months or weeks, what really is done is accelerated tests in the lab and these accelerated tests have their own limitations in terms of translating the time axis and also the fact that reading such as this which still does not show the tapering phase or the asymptotic final expansion. They are to be borne in mind from that point of view.

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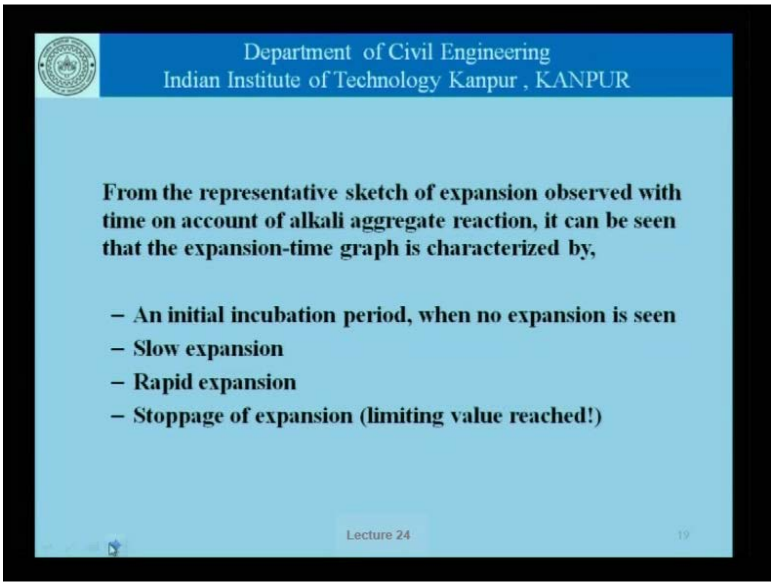

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From the representative sketch of expansion observed with time on account of alkali aggregate reaction, it can be seen that the expansion-time graph is characterized by,

- **An initial incubation period, when no expansion is seen**
- **Slow expansion**
- **Rapid expansion**
- **Stoppage of expansion (limiting value reached!)**

Lecture 24

Now, from the representative sketches of the expansion observed with time on account of alkali aggregate reaction, it can be seen that the expansion time graph is characterized by an initial incubation period when no expansion or very little expansion is seen. The expansion begins to pickup, there is slow expansion to begin with, the reaction enters into a rapid expansion phase and finally, the expansion stops, some kind of a limiting value being reached.

And looking at it physically this process follows the following phases. There is the permeation of alkali metal ions that is sodium and potassium through the aggregates. There is the breakup of the silica bond and the lodging of alkali metals within the normally stable and inert silica tetrahedron along with the formation of complexes. There is absorption of water from pore solution by the complexes leading to expansion of those complexes and finally, cracking of the concrete due to expansive pressures from this complexes.

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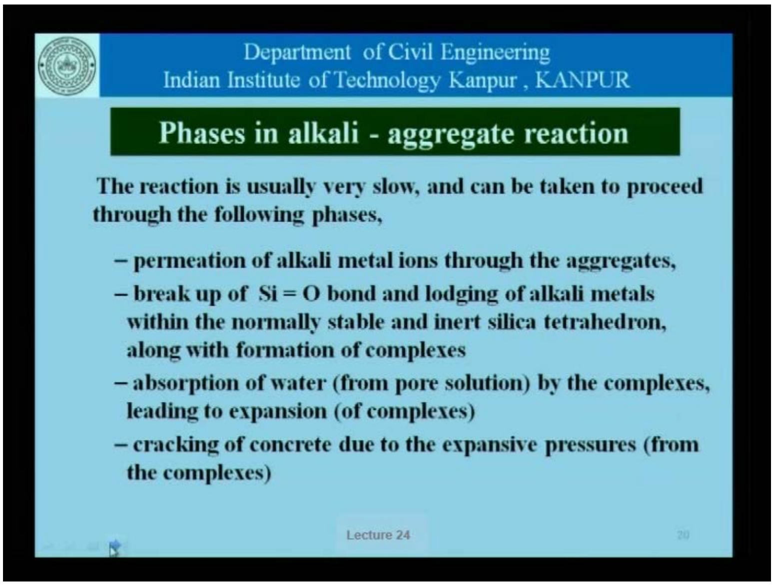

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Phases in alkali - aggregate reaction

The reaction is usually very slow, and can be taken to proceed through the following phases,

- **permeation of alkali metal ions through the aggregates,**
- **break up of Si = O bond and lodging of alkali metals within the normally stable and inert silica tetrahedron, along with formation of complexes**
- **absorption of water (from pore solution) by the complexes, leading to expansion (of complexes)**
- **cracking of concrete due to the expansive pressures (from the complexes)**

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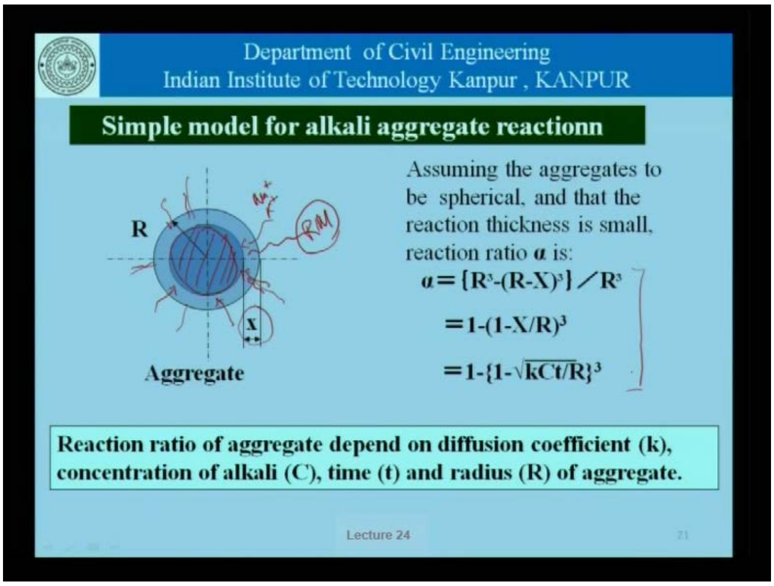

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Simple model for alkali aggregate reactionn

Assuming the aggregates to be spherical, and that the reaction thickness is small, reaction ratio α is:

$$\alpha = \{R^3-(R-X)^3\} / R^3$$

$$= 1-(1-X/R)^3$$

$$= 1-\{1-\sqrt{kCt}/R\}^3$$

Reaction ratio of aggregate depend on diffusion coefficient (k), concentration of alkali (C), time (t) and radius (R) of aggregate.

Now, if we look at a simple model what we look at is something like this. We take a spherical aggregate and this aggregate is surrounded by some amount of sodium and potassium ions and the amount being governed by the kind of sodium and potassium that is present originally in the cement as impurities and so on. And these sodium and potassium ions they gradually permeate through the aggregates and the extent of diffusion after all the aggregates are not very porous.

So, this diffusion of sodium and potassium ions into the aggregates is a painfully slow processes, very fortunately so for civil engineers. Now, this X here represents the thickness of the aggregate which has been reacted or which has been affected by the infiltration or penetration of the alkali ions. Inside this aggregate, this part here is still unreacted. So, if we go back to the discussion that we had a couple of minutes earlier this part here is really the rim.

So, in this part the original silica or the reactive silica has now been transformed into a gel or the gel products have been formed and if there are some pores and fishers or cracks around in this area then this reaction products would be able to travel a little bit and we can see those reaction products or the gel in the cracks and fishers around the aggregate as well. So, this reaction ratio of aggregate depends upon the diffusion coefficient k, the concentration of alkali C, the time t and the radius of the aggregate.

So, if we keep this mathematical formulation in mind which defines the reaction ratio which is essentially how much of aggregate has reacted with respect to the original aggregate size, we can understand that the size of the aggregate is a very important determinant as far as the amount of reaction or the extent of the reaction is concerned. So, really speaking there are several factors at play. One is the size of the aggregate which governs the surface area and the other is the absolute quantity of alkali metals sodium and potassium in the pore solution.

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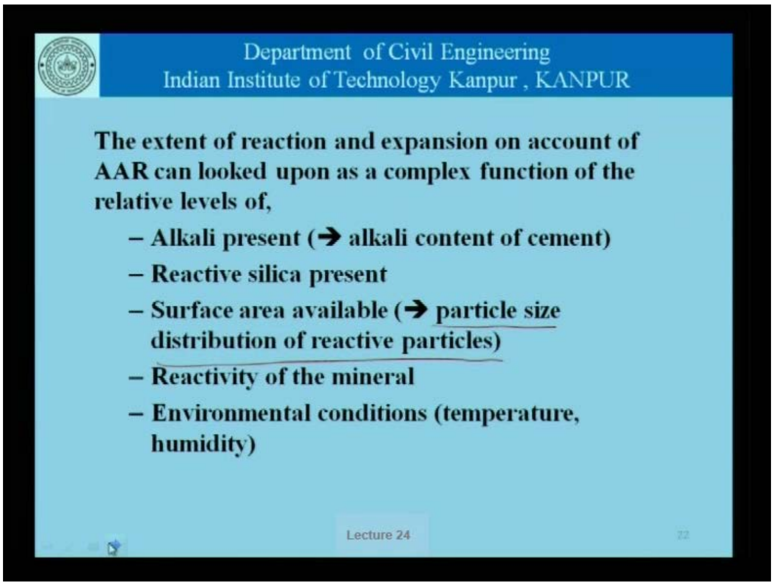

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The extent of reaction and expansion on account of AAR can looked upon as a complex function of the relative levels of,

- **Alkali present (➔ alkali content of cement)**
- **Reactive silica present**
- **Surface area available (➔ particle size distribution of reactive particles)**
- **Reactivity of the mineral**
- **Environmental conditions (temperature, humidity)**

Lecture 24

22

Now, since the alkali metal quantity is really a constant, once we know how much cement has been used, once we know what was the chemical composition of the cement that was used we know the type of or the extent or the quantity of the alkali metals present in the pore solution. Now, these amount of alkali metals are available for the reaction of a certain surface area of the aggregates. Now, if the particles are smaller the surface area becomes larger and the concentration of alkali metals per surface area or per unit area goes down.

So, if on the other hand the particles are larger the concentration available of alkali metals is larger and so on. So, this has to be kept in mind when we try to develop tests for identifying potentially reactive aggregates. In other words the extent of the reaction and the expansion on account of the alkali aggregate reaction can be looked upon as a complex function of the relative levels of alkali present which is the alkali content of cement and the cement content in the concrete.

The extent of reactive silica present and that varies from one type of rock to the other. The entire rock need not have only reactive silica, it can have a certain percentage of the minerals which are reactive, the other minerals being non reactive and geologists would advice us on this aspect. The surface area available, the particle size distribution of reactive particles, we would remember or we know, we must keep in mind that as far as aggregates are concerned we have fine aggregates and we have coarse aggregates.

Even though when I was showing the core of the concrete and the kind of discussion so far I have tried to focus on course aggregates being reactive. But it must remembered that at the end of it fine aggregates are equally susceptible to alkali aggregate reaction. They are also supposed to be inert materials. Sand is not supposed to be a part of the reactive phase of concrete, the reactive phase of concrete comprising only of cement and water which take part in the hydration reaction.

So, the sand is also coming from rocks and could be reactive. The sand also has a mineralogical composition and depending on the minerals present in the sand, the sand could be reactive and therefore, we are talking of a particle size distribution of reactive particles. Now, this discussion includes sand and coarse aggregate. We should also remember that in several of the test methods that we will talk about later on, the test involve the use of sand or use of particles from even coarse aggregate which are ground to a very fine value, so that we accelerate the reaction.

And in order to accelerate the reaction we add more and more alkali in the system to get our results in a hurry, to carry our accelerated tests. All minerals are not necessarily equally reactive. We listed some of the minerals in the previous slide opal, chalcedony, some kind of class and (( )) class, (( )) class and so on. All these minerals are not equally reactive. The reactivity of the minerals is also important aspect when we try to understand the extent and expansion on account of alkali aggregate reaction. Environmental conditions, temperature and humidity; this is a very important player as far as the progress of alkali aggregate reaction is concerned.

Now, one must remember that even though we must understand and include in our model the importance of environmental condition such as temperature and humidity, but in civil engineering applications we cannot really control the atmosphere. The atmosphere is given, if we want to build a bridge at a certain place we are given the fact that the temperature and the relative humidity at that point in, at that point place varies in certain manner over the years or over the year and over the years. We cannot really change that, but we must keep that in our design calculations or in we must reflect those in over design thought or when we try to design this structure there.

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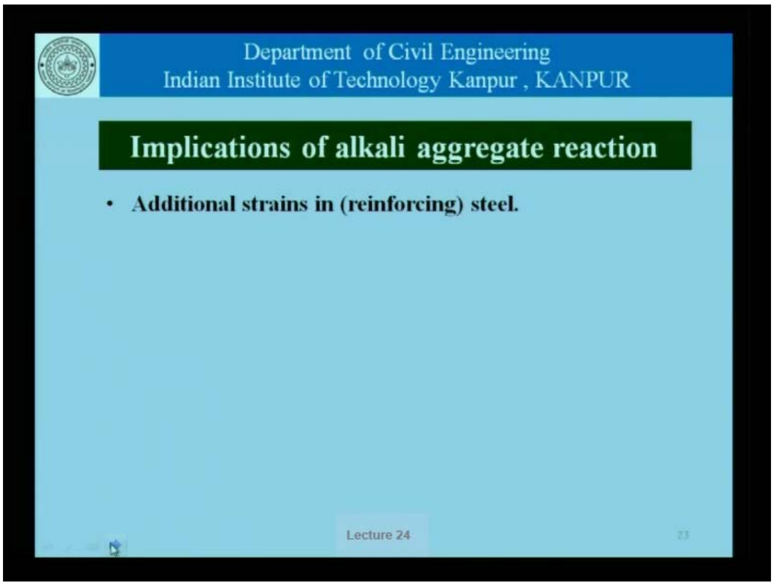

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Implications of alkali aggregate reaction

- **Additional strains in (reinforcing) steel.**

Now, what are the implications of alkali aggregate reaction? It leads to additional strains in reinforcing steel. Now, we know that concrete is not very often used without reinforcement. Reinforcing steel is in integral part of a lot of concrete construction.

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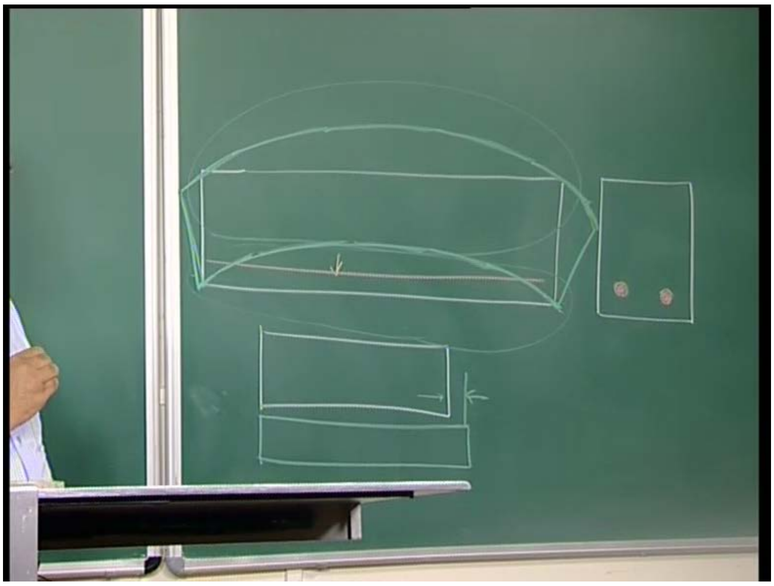

Now, if the concrete has alkali aggregate reaction what happens to the reinforced concrete which is a composite made out of steel and concrete. Now, this here is a simple reinforced concrete beam having this cross section and this length with this amount of reinforcement at the bottom. Now, if the concrete that is made undergoes alkali aggregate reaction and subsequent expansion, what do we expect? If the concrete is unreinforced then it will simply expand from one position to another that is something like this.

So, this amount of expansion in the concrete has been induced on account of alkali aggregate reaction neglecting of course, the end effects whereas, in reinforced concrete this is not likely to happen. This portion of concrete is not reinforced and is relatively free to expand whereas; this portion at the bottom the expansion is constrained. So, what is likely to happen is that these fibers here will become longer, the expansion will be larger and the expansion here will be smaller and the only way that this can be satisfied is by having the reinforced concrete beam deform the way that is shown here. And this expansion, which has which occurs here in the concrete, this expansion has to be reflected also in the expansion of the bar. So, without doing anything the reinforcing bar has now undergone some amount of tensile strains.

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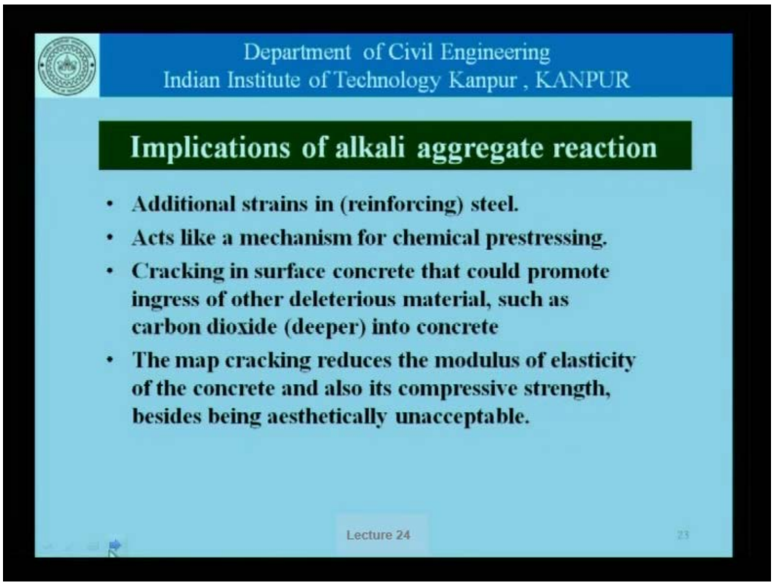

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Implications of alkali aggregate reaction

- Additional strains in (reinforcing) steel.
- Acts like a mechanism for chemical prestressing.
- Cracking in surface concrete that could promote ingress of other deleterious material, such as carbon dioxide (deeper) into concrete
- The map cracking reduces the modulus of elasticity of the concrete and also its compressive strength, besides being aesthetically unacceptable.

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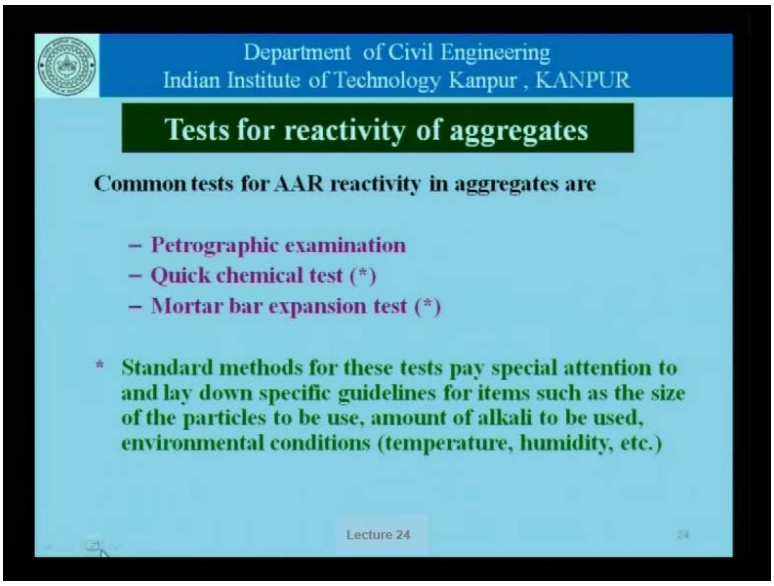

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Tests for reactivity of aggregates

Common tests for AAR reactivity in aggregates are

- Petrographic examination
- Quick chemical test (*)
- Mortar bar expansion test (*)

* Standard methods for these tests pay special attention to and lay down specific guidelines for items such as the size of the particles to be use, amount of alkali to be used, environmental conditions (temperature, humidity, etc.)

So, apart from additional strains in the reinforcing steel the situation acts like a mechanism for chemical prestressing. There is cracking at the surface of the concrete that could promote ingress of other deleterious materials, such as carbon dioxide deeper into the concrete and there is map cracking that is cracking on the surface of the concrete that reduces the modulus of elasticity of the concrete and also its compressive strength, besides being aesthetically unacceptable.

Now, we come to the tests for reactivity of aggregates. These tests are important because we need to identify if the aggregate that we are going to use in a particular construction they are reactive or not. We want to make sure that they are not reactive and if we know that they are reactive then we need to take appropriate corrective action. Some of the tests that are carried out in this regard are spectrographic examination, the quick chemical test and the mortar bar expansion test and these are standard methods.

The standard methods pay special attention and lay down specific guidelines for items such as the size of the particle to be used, amount of alkali to be used, environmental conditions, temperature, humidity and so on because these are accelerated test in the laboratory. They have to carry out under standard conditions and those standard conditions need to be defined in terms of the particle size distribution of the aggregate sample.

The amount of alkali that is used in the, in preparing the sample, the environment in which the aggregate and the alkali or whatever we use as a simulating environment is stored in terms of the temperature, humidity and so on and also the parameters that we will use to monitor the reactivity, And finally, there have to be specifications which tell us that if the test is carried out in accordance with such and such a procedure and such and such a parameter has been used to monitor the extent of reactivity, what is the maximum or minimum acceptable level of that parameter and beyond which or below which the aggregate will be deemed to be reactive.

We must remember that these tests need to be carried out quickly, so that a decision can be made as to whether the aggregate from a particular quarry should be used or not. They should be reliable because it should not happen that aggregate has been discarded simply because it was deemed to be reactive and finally, turns out it is not reactive. The reason for the reliability is also the fact that there is economics involved. If we reject the aggregate from a particular quarry then the aggregate has to be brought from another place which could be further away.

That has implications in terms of the cost of the project, the duration of the project. It has environmental issue for example; the transportation of aggregates over a longer distance increases the carbon foot print emissions and so on. So, there are all kinds of reasons why this exercise has to be carried out with at most care.

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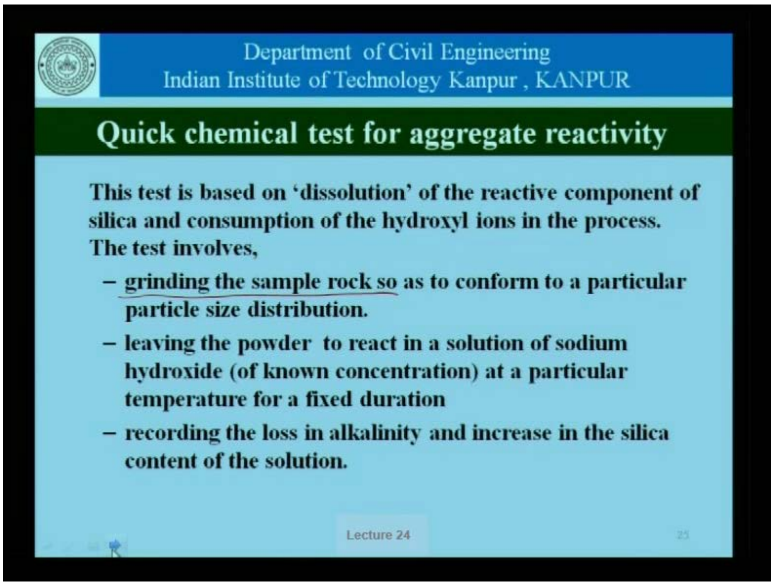

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Quick chemical test for aggregate reactivity

This test is based on 'dissolution' of the reactive component of silica and consumption of the hydroxyl ions in the process. The test involves,

- **grinding the sample rock so as to conform to a particular particle size distribution.**
- **leaving the powder to react in a solution of sodium hydroxide (of known concentration) at a particular temperature for a fixed duration**
- **recording the loss in alkalinity and increase in the silica content of the solution.**

Lecture 24

Let us look at the quick chemical test for a reactivity of the aggregates. The test is based on the dissolution of the reactive component in of silica and consumption of the hydroxyl ions in the process. The test involves grinding the sample rock so as to conform to a particular particle size distribution. Now, once we grind it we are reducing the rock to a very small particle size. So, the distinction between coarse aggregate and fine aggregate is lost.

We are trying to evaluate the suitability of that rock for use in concrete either as a coarse aggregate or as a fine aggregate and that decision the engineer takes separately. What is going on here is only identification as to whether the rock from a particular quarry or a particular rock basically has reactive components of silica or not. So, the first step is grinding that rock sample, leaving the powder to react in a solution of sodium hydroxide of known concentration at a particular temperature for a fixed duration and recording the loss of alkalinity and the increase in the silica content of the solution.

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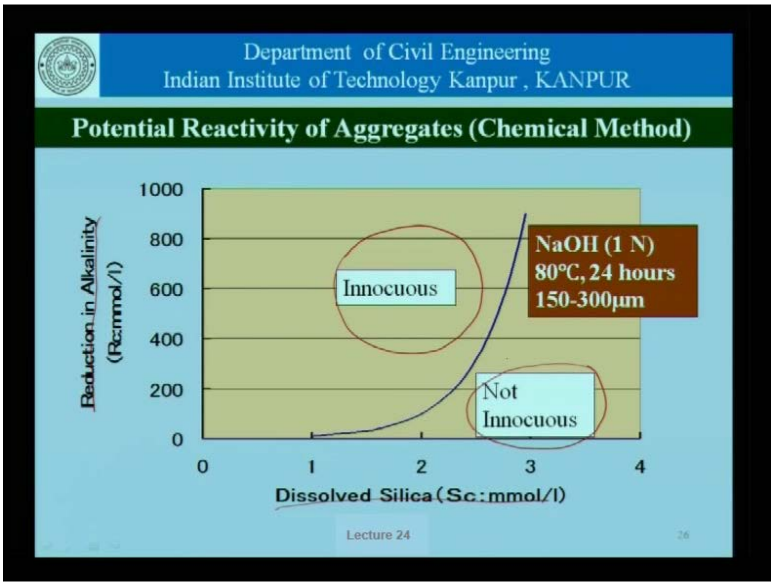

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Potential Reactivity of Aggregates (Chemical Method)

Now, based on lots of test that have been carried out if the reduction in alkalinity and the silica content, the dissolve silica is plotted in a graph, this test is based on a, this test is based on S T M standards, that is a standard method in ASTM to carry out the test. There is a line that is defined or that has been drawn which defines that if the value comes in this region the aggregate can be deemed to be innocuous whereas if it comes in this region, it is not innocuous.

And the test being carried out at 1 N N a O H at 80 degree centigrade for 24 hours and so on using rock samples which have been ground to 150 to 300 micrometer size. Now, this is based primarily on experience of reactive aggregates and non reactive aggregates. It is not really based on a scientific measurement of the amount of reaction that has taken place or the extent of the reaction rim that has been formed and so on. It is a purely engineering, empirical approach which says that well from all the experience that has gathered over the tens of years that civil engineers have used coarse aggregates and fine aggregates from different quarries and different locations, has there been a known case of alkali aggregate reaction, a known case of large scale cracking in structures made from the coarse aggregate or the fine aggregate drawn from that place.

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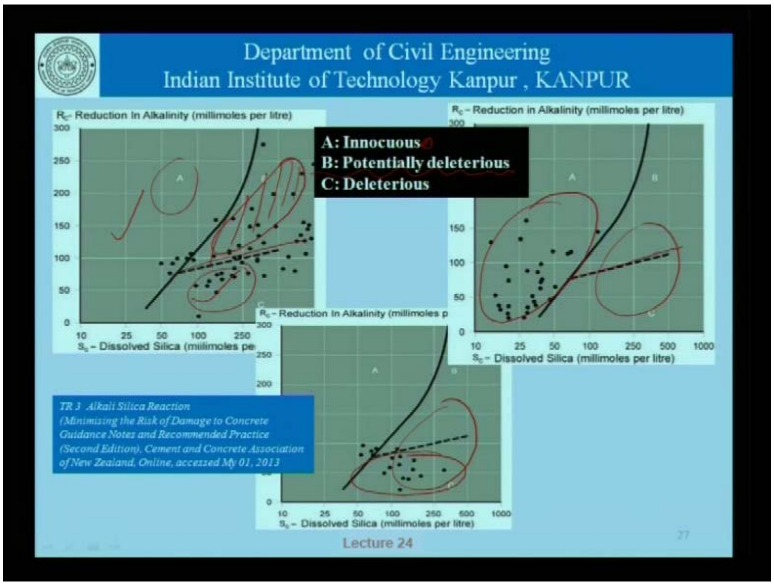

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A: Innocuous
B: Potentially deleterious
C: Deleterious

TR 3 Alkali Silica Reaction
(Minimising the Risk of Damage to Concrete
Guidance Notes and Recommended Practice
(Second Edition), Cement and Concrete Association
of New Zealand, Online, accessed My 01, 2013

Now, this here is another picture of test carried out using that ASTM method that we have talked about and this is the innocuous zone and this zone which in the previous picture was given as deleterious or not innocuous has been further divided with the dotted line here which says that aggregates in this portion are potentially deleterious whereas, the aggregates in this portion are deleterious. So, these are the aggregate which are actually deleterious, these are the aggregates which are innocuous and these aggregates here are potentially deleterious.

Now, this potentially deleterious means that it is not really very clear as to whether in the long run we will have a harmful effect on account of alkali aggregate reaction if we use aggregates from that region. This has implication, several implications. This throws the quick chemical test into a bind. We do not know sometimes how to use the results from this test. The test results are inconclusive. So, as far as the region A and the region C is concerned that is innocuous and deleterious. This decision is relatively clear, but a reaction, but a decision on this portion here is not possible only on account of or only from the results of the quick chemical test.

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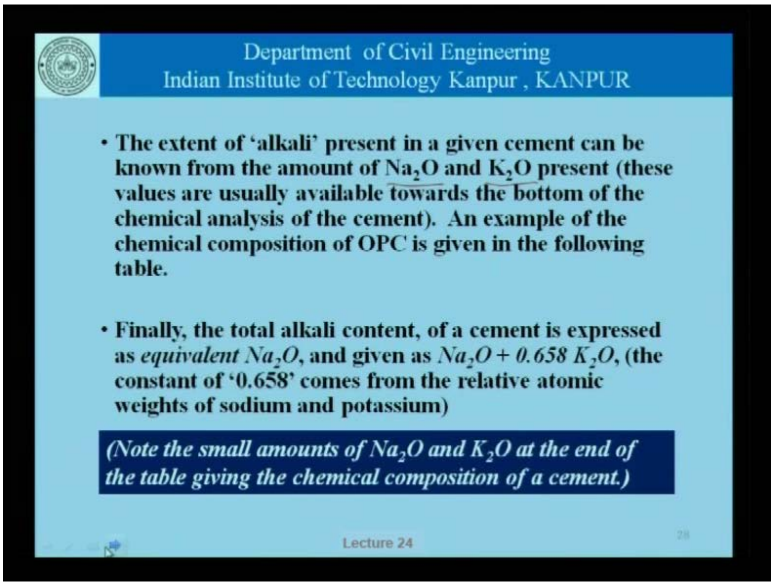

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- The extent of 'alkali' present in a given cement can be known from the amount of Na_2O and K_2O present (these values are usually available towards the bottom of the chemical analysis of the cement). An example of the chemical composition of OPC is given in the following table.
- Finally, the total alkali content, of a cement is expressed as *equivalent* Na_2O, and given as $Na_2O + 0.658\ K_2O$, (the constant of '0.658' comes from the relative atomic weights of sodium and potassium)

(Note the small amounts of Na_2O and K_2O at the end of the table giving the chemical composition of a cement.)

For that we should understand something else, we talk of the extent of alkali present in a given cement and that is known from the amounts of sodium oxide and the potassium oxide present in the cement and theses values are usually available towards the bottom of the chemical analysis of the cement.

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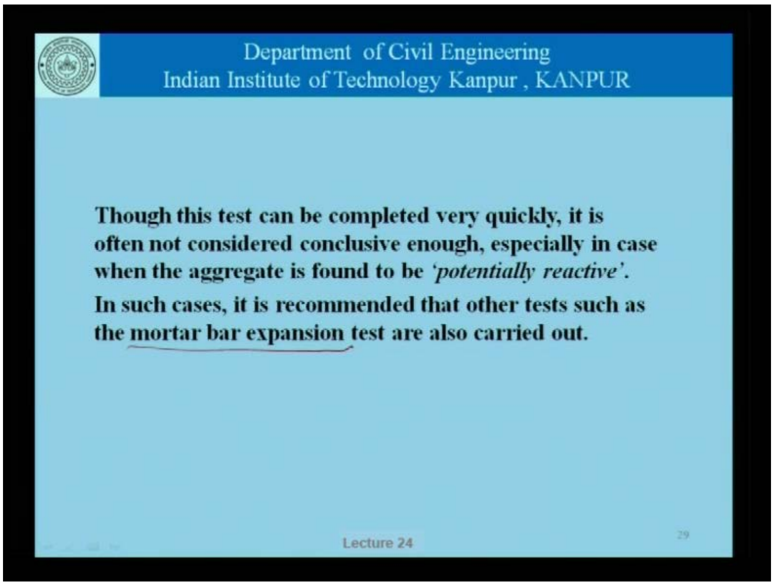

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Though this test can be completed very quickly, it is often not considered conclusive enough, especially in case when the aggregate is found to be *'potentially reactive'*.

In such cases, it is recommended that other tests such as the mortar bar expansion test are also carried out.

And the total alkali content of the cement is expressed as equivalent sodium oxide and given as N a 2 O plus 0.658 times K 2 O and the constant 0.658 coming from the relative atomic weights of sodium and potassium. So, this helps us understand the total amount of alkali present in the cement as we mentioned before the quick chemical test can be completed very quickly, it just takes about 24 hours to carry out the test and another couple of hours to carry out analysis.

It is often not considered conclusive enough especially in the cases when the aggregate is found to be potentially reactive or potentially deleterious. And in such cases it is recommended that other tests such as the mortar bar expansion test is carried out. The quick chemical test really is just a test of suspending ground aggregate particles in solution of alkali, a strong solution of alkali and accelerating the process by increasing the temperature. This is not a test representative of the conditions that a concrete is likely to face. So, the mortar bar expansion test which is mentioned here which is sometimes carried out after the quick chemical test or as a measure to validate the findings of the quick chemical test that is slightly closer to the real situation.

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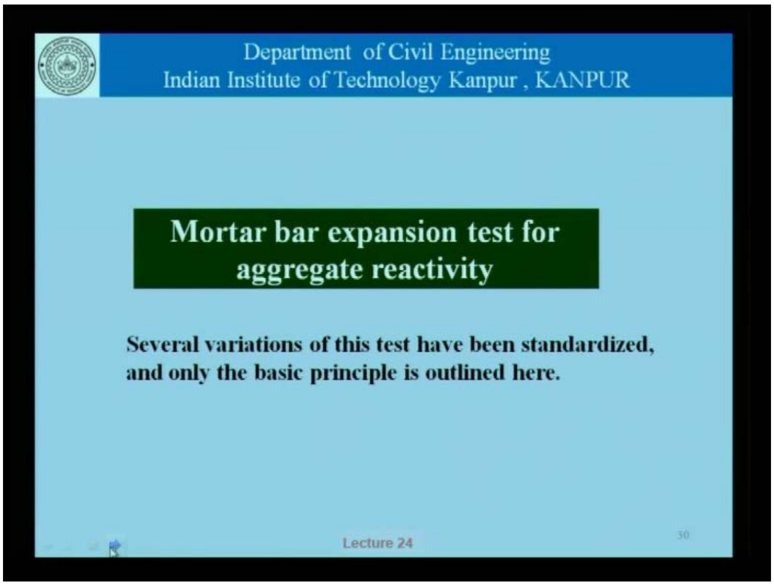

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Mortar bar expansion test for aggregate reactivity

Several variations of this test have been standardized, and only the basic principle is outlined here.

Lecture 24

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Several variations of this test have been standardized and only the basic principle is outlined here.

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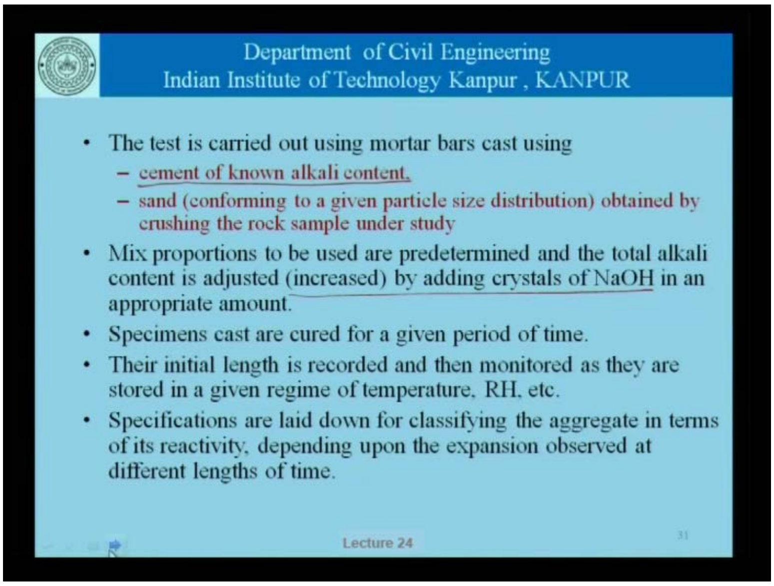

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- The test is carried out using mortar bars cast using
  - cement of known alkali content.
  - sand (conforming to a given particle size distribution) obtained by crushing the rock sample under study
- Mix proportions to be used are predetermined and the total alkali content is adjusted (increased) by adding crystals of NaOH in an appropriate amount.
- Specimens cast are cured for a given period of time.
- Their initial length is recorded and then monitored as they are stored in a given regime of temperature, RH, etc.
- Specifications are laid down for classifying the aggregate in terms of its reactivity, depending upon the expansion observed at different lengths of time.

This test is carried out using mortar bars, cast using cement of known alkali content. So, we use a cement, we carry out the chemical analysis, we know how much of alkali is there in that cement, we use sand conforming to a given particles as distribution obtained from crushing the rock sample which is being studied. The proportions ought to be used are predetermined and the total alkali content is adjusted. Because the cement alone will not be able to contribute enough alkali to cause the kind of expansion that we would like to see happen in a reasonable period of time, so that a decision can be made as to whether the aggregate is suitable or not.

And therefore, we want to increase the amount of alkali in this accelerated test and that increment is carried out by using crystals of sodium hydroxide in an appropriate amount. The specimens are cast and cured given period of time and their initial length is recorded and then monitored as they are stored in a given regime of temperature and humidity and specifications laid down the acceptable or unacceptable levels of expansion at different points in time.

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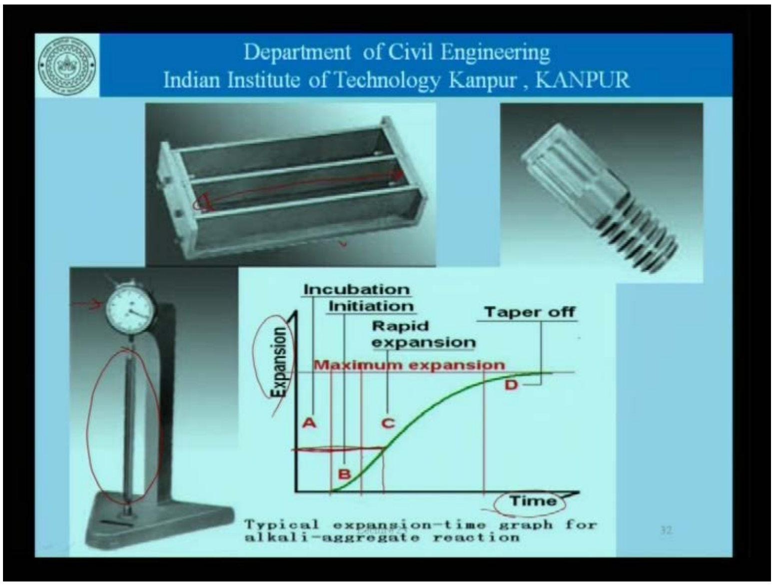

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Typical expansion-time graph for alkali-aggregate reaction

Now, how this test is carried out is shown here. This is a special mold for casting the specimens for the mortar bar expansion test and here we also see the simple device which is used to measure the change in length of these specimens. These specimens which are caused in this mold, they are placed here and the changes are monitored or the changes in length is monitored using the dial gauge here, there are different ways of doing it, but in principle that is what it is and what we try to study is the time versus expansion graph.

And once we have specifications they have to tell us that either the maximum expansion at a particular point in time should be so much. Anything below that is acceptable, beyond that is not acceptable or they should lay down a time at which a certain expansion is reached. If the expansion does not reach or if the expansion reaches that level beyond a certain point in time the aggregate is acceptable.

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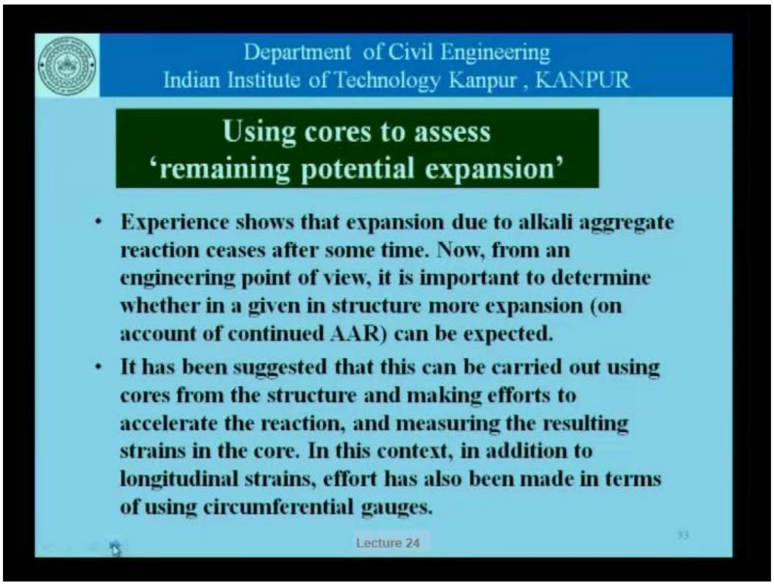

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Using cores to assess ‘remaining potential expansion’

- Experience shows that expansion due to alkali aggregate reaction ceases after some time. Now, from an engineering point of view, it is important to determine whether in a given in structure more expansion (on account of continued AAR) can be expected.
- It has been suggested that this can be carried out using cores from the structure and making efforts to accelerate the reaction, and measuring the resulting strains in the core. In this context, in addition to longitudinal strains, effort has also been made in terms of using circumferential gauges.

Lecture 24

If it reaches that point before that it is unacceptable. It might happen that the aggregate from a particular quarry has been used without testing it for reactivity and it turns out that it was reactive. Now, at some point in time the engineers have to make a decision as to what kind of measures need to be taken to prevent further expansion. See alkali aggregate reaction is a problem that cannot be reversed. If we have the reactive silica and the alkali, the reaction is bound to happen.

What can be done in an existing structure which has been suspected to be afflicted with alkali aggregate reaction is only to find out whether the limiting expansion or the limiting amount of damage has already being done or the structure is still in the reaction phase. So, for that what we need to do is to take cores from the structure and as it is discussed here experience has shown that expansion due to alkali aggregate reaction ceases after sometime and from an engineering point of view it is important to determine in a given structure, more expansion can be expected or not and it has been suggested that this can be carried out by using cores from the structure and making efforts to accelerate the reaction and measuring the resulting strains in the core.

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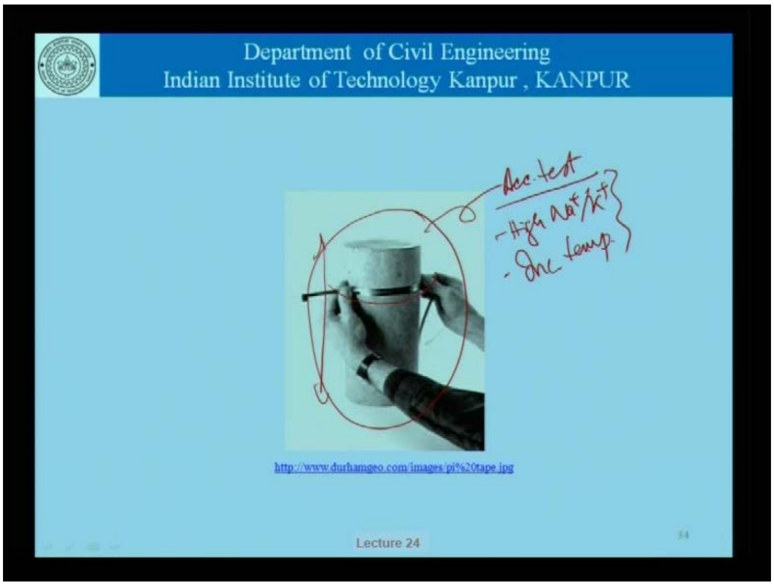
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Acc. test
- High Na^+/K^+
- Inc. temp.

http://www.durhamgeo.com/images/pi%20tape.jpg

In this context in additional to the longitudinal strains effort is also made to use circumferential gauges as it is shown here. So, in addition to the longitudinal expansion in this core in this direction, effort is also made to measure the changes in the circumferential strain and this core that is taken from the structure is tested using accelerated tests with high sodium potassium environment, increased temperature and so on.

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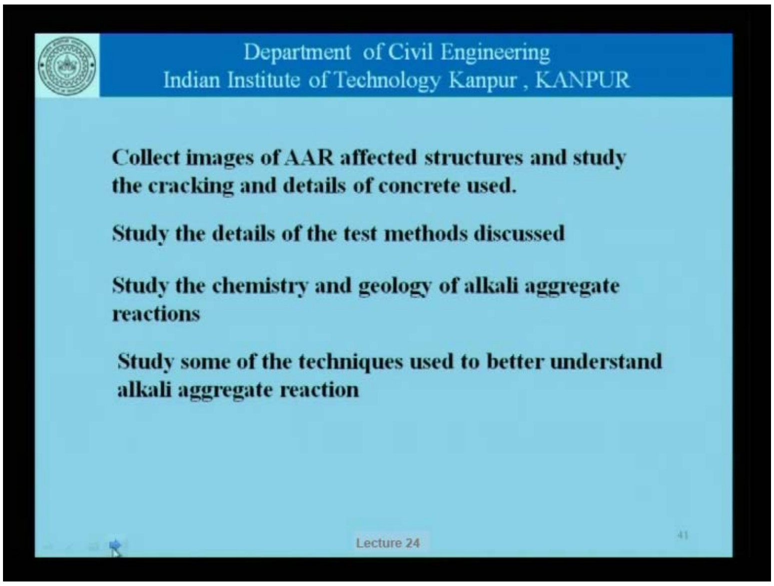
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Collect images of AAR affected structures and study the cracking and details of concrete used.

Study the details of the test methods discussed

Study the chemistry and geology of alkali aggregate reactions

Study some of the techniques used to better understand alkali aggregate reaction

So, this is a semi destructive procedure for assessment of the extent of damage on account of alkali aggregate reactions in a existing structure. Now, having gone through some of these aspects of alkali aggregate reaction let us close the discussion for the day with some questions which need to be thought about and some work that needs to be carried out. We can collect images or photographs of alkali aggregate reaction effected structures and study the cracking and the details of the concrete used in terms of the characteristics of the aggregate that are used from a geological point of view, the kind of cement that was used, how much of alkali was there, the proportion that was used and so on.

You study the details of the test methods that we discussed. We discussed the quick chemical test and the mortar bar expansion test. We did not discuss the details of those tests in terms of their specimen size, in terms of the actual storage conditions and so on. So, that is something which we need to go into a little bit more, we also need to extend the kind of tests that are used. We had done only the mortar bar expansion test. Now, sometimes it can be argued that the mortar bar expansion test itself is not really representative of the actual situation in concrete.

And therefore, we should use concrete specimens. Except that in concrete specimens the aggregate size is being very large, the reactions being very slow, it takes a much longer time for the expansions to be such that we can make a final decision. So, these are some of the aspects which one can go into and study in greater length. We have not done the chemistry and geology of the alkali aggregate reaction and that is something which will be very interesting as to how the alkali metals really react with the silica and what is the geology, what is the mineralogy of different aggregates and very interesting field in terms of the techniques that are used to better understand alkali aggregate reaction.

What we did today was just a very, very cursory or a very simplistic view of the test methods to evaluate aggregates, but in order to study alkali aggregate reaction some very sophisticated techniques are used and that would be an eye opener if you really want to get into what techniques have been used, what are the available methods to identify the gel, how it has moved into different cracks and so on. And with this we come to a close of the discussion today.

Thank you.