Building Materials and Construction
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Module - 7
Lecture - 2
Durability of Concrete: Chloride Ingress, Corrosion, AAR

Continuing with durability of concrete, we will look into some more processes that is chloride ingress corrosion and alkali aggregate reaction.

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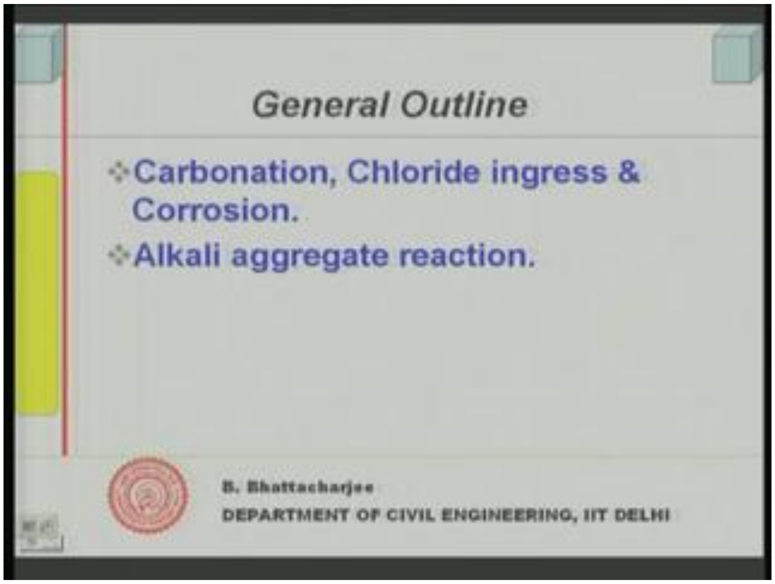

General Outline

- Carbonation, Chloride ingress & Corrosion.
- Alkali aggregate reaction.

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But however, we stopped yesterday with carbonation. So, we will have some discussion on carbonation as well. So, anyway general outline of this lecture therefore follow, we will discuss some issues of carbonation which we actually left inconclusive, in the last lecture. Look into chloride ingress and resulting corrosion from both carbonation and chloride ingress causes. Then, we will look into another degradation process called alkali aggregate reaction into this lecture.

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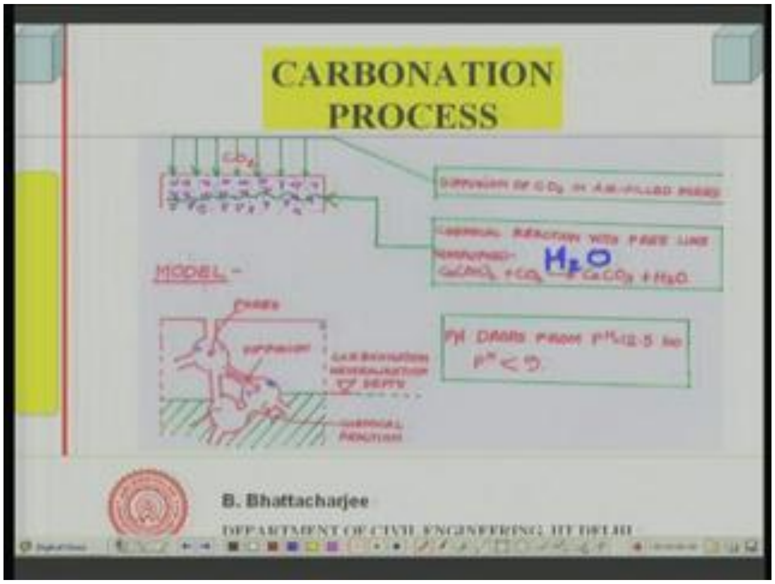

CARBONATION PROCESS

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So, let us continue, with the carbonation process which, we have seen yesterday; if you recall that we actually where discussing about the carbonation process, where we said carbon dioxide from atmosphere can penetrate into the concrete right. Because, carbon dioxide is just present in the atmosphere and it can enter into the, it can enter into the concrete right and through that is there through the surface, it will enter and in presence of moisture.

This carbon dioxide which will defuse into the airfield the chemical reaction of calcium, it will react with calcium hydroxide that is present as a hydration process of cement and form calcium carbonate and water. Now, this process all takes place in presence of H2O; you know it takes place all in presence of H2O, in if there is no moisture the reaction does not go on. And if you recall again, then we said that this process, since it consumes all the calcium hydroxide and alkaline material in concrete the pH gets reduced below 9.

This 1 important point is that carbonation process do not continue in completely dry concrete not does it continue, in fully saturated concrete, because in it requires presence of moisture and also in completely saturated condition; when it is you know all pores are filled, with water the carbon dioxide will not be available. So, this point is important and we should recall this. Now, carbonation front as we call it; it progresses from surface to inside you know surface to inside. For example, here is a carbonation front and this is our pores and this is moist here moist here faintly and they are there then carbonation process. So, this is just recalling from whatever, we have discussed yesterday.

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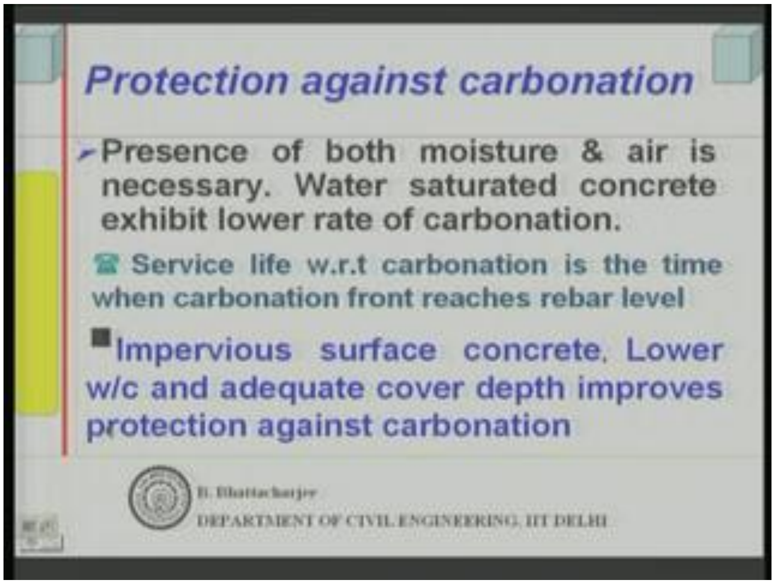

Protection against carbonation

- Presence of both moisture & air is necessary. Water saturated concrete exhibit lower rate of carbonation.
- ☎ Service life w.r.t carbonation is the time when carbonation front reaches rebar level
- ■ Impervious surface concrete, Lower w/c and adequate cover depth improves protection against carbonation

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Now, following from there if you look at it how do you protect protection against car against carbonation. You see, first thing is presence of moisture and air both are necessary, for carbonation to progress for carbonation to you know progress water saturated concrete exhibit lower rate of carbonation, anyway. So, condition should be such that we should actually see that, there is no moisture penetration into the concrete and then service life, with respect to carbonation is the time when carbonation front reaches the rebar level.

Because, we said we have if you recall we when we defined the service line, with respect to corrosion we said that first there is a period, which you call period and during this period the carbonation carbon dioxide from atmosphere. We enter into the concrete and you know pH at the reinforcement bar level will get reduced, when carbonation front reaches to the carbonation front reaches to the reinforcement bar level that is the time, when we call it the service life or is been has taken place and that is what is the service life with respect to carbonation.

If you recall back again, we said that some of the oxides form during process they are not very dangerous, because they you know their density is relatively high nearly, as high as that of the steel. And therefore they do not cause volume expansion and all this oxides, which are not, so dangerous they form passive films and this passive film formation takes place only at high pH’s, pH you know sufficiently high and carbonation actually reduce down this pH’s. And therefore, the passive layer formation which has taken place that gets broken and depassivation takes place.

So, therefore service life with respect to carbonation we define as if you remember from this diagram. Let me just redraw it, it was something like this you know this is this 1 and this is, so we call this as t p and t p when this time is t p, you know this time is a de-passivation time and this is the time when the carbonation front has just reached, the reinforcement bar level. So, it starts from the surface and gradually re reaches up to the river level and that is what we call as service life, with respect to carbonation right ok.

Best way to protect concrete or reinforcement bar against de passivation due to carbonation is to have a impervious surface concrete, you know surface concrete should be impervious or in general total concrete is made actually, at the mom at the moment; we make the complete concrete impervious and how do we make it by lower water cement ratio and also, we provide adequate cover depth such that cover will take large time to reach to the river level ok. This is what is with respect to carbonation coarse concrete at the at the point of crack, if the crack as gone up to reinforcement it will carbonated.

There are other detailed issues related to carbonation wetting and drying actually, influences the carbonation time or service life, with respect to carbonation such issues; we will not discuss here. But, these are the issues relevant issues also one can look into. So, for our purpose we understand that carbonation is a phenomena which actually, does not create any problem to the concrete, but it can lower the pH at the reinforcement bar level by even, when the carbonation front progresses from surface to the surface to inside through the depth of the concrete and when it reaches to the river level de-passivation can occur.

So, we have to prevent the de-passivation, and therefore impervious low water cement ratio concrete is a useful solution to make that of course, you can put many other covers but it as to be cost effective also.

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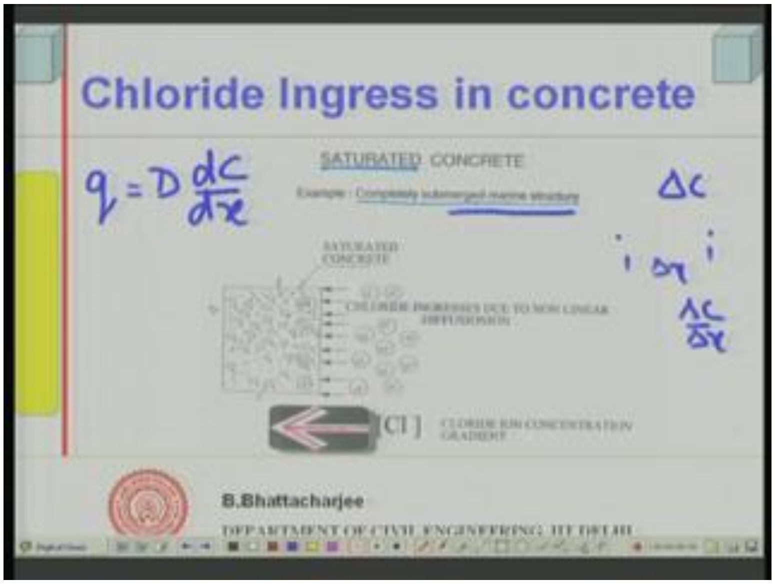

Chloride Ingress in concrete

$q = D \frac{dc}{dx}$

SATURATED CONCRETE

Example : Completely submerged marine structure

Δc

Δx

$\frac{\Delta c}{\Delta x}$

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Now, next way how de-passivation takes place is the chloride ingress into concrete. Now, as I mentioned earlier that chloride and carbonation, they are not really much of a problem as far as concrete is concerned, it does not change the property of the concrete nor its strength gets reduced or anything of that kind but they affect the g bar reinforcement bar the steel, you know which you put as reinforcement in concrete, because their corrosion can be initiated if sufficient chloride as gone in. So, this is also related to t p this is also related to t p.

Now, they are less distinguished two situation 1 is what is you know saturated concrete. Now, we are looking at external ingress, so we are looking into chloride ingress external chloride. There can be chloride coming from the ingredients themselves, which of course you should not allow, but that is you call as internal concrete but that is you know why through if a good quality control is there normally, such chloride should not be present. But, we will discuss about that somewhat a little bit about that also sometime later but let us look into let us look into a situation you have concrete as in chloride environment.

Let us say somewhere, in the marine environment in the in contact, with the chloride water and the concrete is likely to be saturated in such situation and there this saturated concrete in com completely, submerged marine structure. Let us say the chloride can enter into the concrete, because this is fully saturated. So, there is all water inside now concentration of chloride here, will be low compared to concentration of chloride outside where you have got you know lot of chloride solution is there. So, chloride iron can penetrate into the concrete chloride iron can penetrate into the concrete due to concentration gradient.

We, know that when a concentration gradient exist between 2 location you know that is if there is a delta c is a concentration difference between, 2 points and the distance between them is delta x, then you know delta c delta x is nothing but concentration gradient and the flow is proportional to some diffusion coefficient into d c by d x, where q is the rate of flow of this iron per unit area per unit time into some diffusion coefficient multiplied by concentration gradient. So, when it is saturated this can, because there is a concentration gradient existing there is high concentration of chloride here, low concentration of chloride here and it is all saturated water is there.

So, chloride iron will defuse from this side to this side you know this is the phenomena molecular diffusion this iron diffusion, of course this phenomena is still more complex then what we are simply defining through this fixed diffusion equation. But, we let us understand physically, since there are high concentration of chloride here low concentration of chloride here. So, chloride can defuse from higher concentration to low lower concentration and the process of chloride ingress into the concrete, will be through the process of process of diffusion in saturated concrete right.

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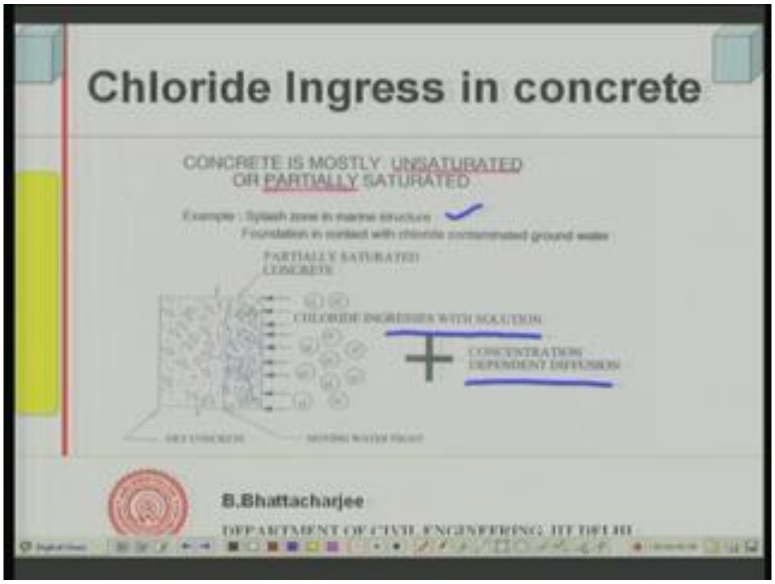

Chloride Ingress in concrete

CONCRETE IS MOSTLY UNSATURATED
OR PARTIALLY SATURATED

Example : Splash zone in marine structure
Foundation in contact with chloride contaminated ground water

PARTIALLY SATURATED CONCRETE

CHLORIDE INGRESSES WITH SOLUTION

+

CONCENTRATION DEPENDENT DIFFUSION

DRY CONCRETE

MOVING WATER FRONT

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Let us see, what happens if you are looking at the situation of unsaturated concrete unsaturated concrete, in case of unsaturated concrete the phenomena would be slightly more different, because here. You see, in unsaturated concrete partially saturated concrete something like zone in marine structure you know where, wave hits and there is alternate waiting and drying or foundation, in contact with chloride contaminated ground water you know above the lowest ground level, ground water level and below the highest ground water level and so on.

So, many places this situation 1 can come across where the concrete becomes, remains partially saturated not fully saturated all the time, you know submerged situation it is fully saturated all the time. But, in places where waiting and drying goes on, it is partially saturated, because sometime in sometimes the liquid or the solution will enter into the concrete and then sometime later it will dry. So, in such a situation the flow through partial or you know partially, saturated concrete takes place and in partially saturated concrete both the phenomenas, will actually you know contribute to the chloride ingress.

First of all chloride ingress, with the solution would take place that means; some solution goes inside since, the solution contain chloride some amount of chloride will enter the concrete with the solution. Because, there is solution so solution goes and it is it contains chloride. So, some solution huh you know solution itself, will be in the chloride and that is quite significant amount possibly much more than the diffusion component. Now, solution itself will carry some amount of chloride right. As the saturation increases chloride concentration, inside the concrete will also increase.

Now, when it dries off let us say, situation of waiting and drying when it dries off the moisture or water will get vaporized and moisture vapor, will get out what about the source will remain deposited there. So, again this again the solution ingresses, ingress takes place some more chloride will go in. So, in partially saturated situation waiting and drying can result, in very high level of chloride concentration. Now, since there is even in even in when it is partially, saturated state some pores and some portion of the pores are filled with, solution which will have a lower concentration then outside.

So, diffusion process can also takes place, so in partially saturated concrete both diffusion and solution ingress, both contribute to the chloride ingress or whatever chloride ingress and the chloride front may enter, you know depending upon the situation right.

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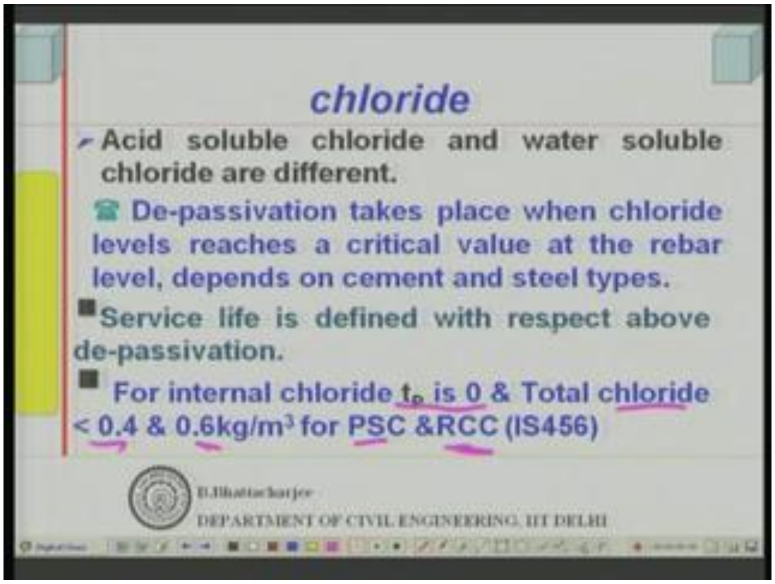

chloride

- Acid soluble chloride and water soluble chloride are different.
  - ☎ De-passivation takes place when chloride levels reaches a critical value at the rebar level, depends on cement and steel types.
- Service life is defined with respect above de-passivation.
- For internal chloride t_0 is 0 & Total chloride < 0.4 & 0.6kg/m^3 for PSC &RCC (IS456)

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Now, when the chloride in the concrete reaches a particular value a threshold value or some critical value, then we say that de-passivation can take place. You know just some amount of chloride entering into the concrete very little amount of chloride entering into the concrete may not initiate d, but at some level at some level of the chloride concentration de-passivation can start ok. You know some critical level sometimes, it is referred to as threshold chloride level, but let us understand something more about this chloride you see the chloride that is present in concrete.

If, I want to find it out I will actually take out some portion of the concrete grind it and dissolve it, in either water or in acid concentrated nitric acid right. So, there are 2 types of chloride 1 can distinguish water soluble chloride and acid soluble chloride. So, when I dissolve it in concentrated nitric acid, you see when I dissolve it in concentrated nitric acid this is acid soluble chloride which actually, I dissolve it in concentrated HNO3 and this is simply, in water. So, I dissolve it in concentrated HNO3 that we call as acid soluble chloride and it has been observed that acid soluble chloride is more than; this you know this is greater this is this is greater than this.

This is more this is more compared to water soluble chloride what does it mean; some of the chlorides present, in the concrete do not go into water solution they do not get dissolved into water and some chlorides get dissolved into water right. And therefore, we distinguish 2 types of chlorides total chloride and free chloride; free chloride are the 1's which are water soluble and actually, they can contribute to the corrosion reaction process whereas, the total chloride you know in totality they do not contribute. But, they can think 1 can think them as the potentiality of you knows contributing to the free chloride.

So, there are two types of chloride total chloride and free chloride and difference between, them is what is bound chloride. So, you can have some amount of bound chloride present, in concrete and this bound chloride; bound chloride is bound both physically as well as chemically. We shall see this a little bit later on. So, de-passivation actually takes place, when chloride levels reaches a critical value at the rebar level quite often it depends on cement and steel type as well different types of steel might have de-passivation levels of chloride 1 idea was that chloride to ratio should be greater than, 0.6 well.

There are, but it would also depend upon type of cement, because there are several varieties of cement blended cements; which have come and chloride binding reaction to chloride situation is different than, the earlier ordinary cement, it may be effect it may you know, this critical chloride level may also depend upon types of steel. Because, you have now varieties of steel actually available, we shall discuss those about steel sometime later on, but therefore it depends upon all that right. So, de-passivation takes place at some threshold level and service life therefore, we define with respect to above de-passivation.

So, when the chloride level as reached to such a level you know such concentration that de-passivation of the steel occurs that time, we call as a service life. So, de-passivation as to occur you know it is usually as been defined in terms of chloride concentration, but if it if you know, so far it has usually been defined in terms of some chloride concentration but 1 thing the intensity which, with which chloride actually causes de-passivation or the level or the critical level, you know as far as the codes are concerned allowable chloride level in concrete.

This has been reducing from time to time you know earlier whatever, 1950's whatever, the chloride allowable chloride level in concrete and today is allowable chloride level, in concrete in most of the codes of practice, you will find that there is a reduction, in this value. So, because this is a complex phenomena its understanding is still developing. So, but we have certain values which we will into later on. Now, service life therefore we define with respect to de-passivation when de-passivation chloride level as reached to such a level that de-passivation occurs, with respect to chloride.

Now let us, come to internal chloride, you know when you have internal chloride that is it has come from ingredients chloride can come from ingredients it can come from outside also outside, I mentioned was in marine environment or ground water contaminated, with chloride of course in western world they use salt. Because, you know this freezing did in the winter and they use what is called salts and they, this salts used to contain lot of chloride and this chloride would penetrate into the concrete and cause corrosion of.

So, salts problem has actually created chloride I mean; chloride induced corrosion in western world in North America and Europe, but internal chloride comes from the ingredients and that you have not tested, if you have not tested the ingredients properly. For example: if the water that you are using especially, the ground water from deep ground water source that may contain a lot of chloride in you know or composite monsoon type of climate of northern India, because you if you are using ground water that may contain a lot of lot of chloride then marine environment, I have talked about.

But, chloride might also come into the internal like marine close to the marine environment, if you use the water sea water that can also bring in chloride. So, internal chloride can come from water is 1 of the biggest source the second source could be the sand particularly, if you are using land sand. Now, this land sand is not thoroughly washed and it will contain lot of soluble salts. If it is thoroughly washed then of course, soluble salts go away and therefore chloride also goes away river sand would usually contain much less chloride, because soluble chlorides would have been washed away by the river itself.

So, internal chloride can also be present if the quality control or was not proper 1 did not check the water quality before, putting it into the concrete and this can lead to severe problem, because you can have if you have sufficient quantity your t p that is your t p can simply 0 t p that is de-passivation time can be 0. So, from the first day onwards you can have in of corrosion right; from the beginning only problem is you have to have an only one additional thing you need is the presence of water. So, if your quality of concrete is not good and you have lot of you have used ground water, which contains lot of chloride in very short time you can see corrosion distress may be you know maybe visible right.

Now, that that is why IS codes Indian standard codes are actually restricted the total chloride in concrete 0.4 and 0.6 kg per meter cube for concrete this is for concrete and this is for reinforced concrete. So, reinforced concrete you should not have more than 6 kg per meter cube of chloride in total chloride. So, this is chloride you should not have more than, that in internal chloride. This can be avoided easily avoided internal chloride can be easily avoided by testing the water the aggregates etcetera, usually chloride bearing admixtures are not used much today. Because, of the reinforcement corrosion problem.

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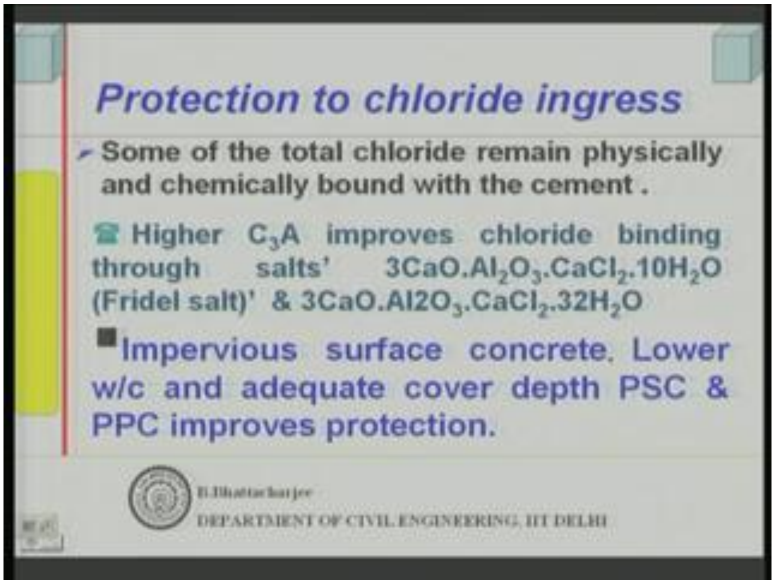

Protection to chloride ingress

- Some of the total chloride remain physically and chemically bound with the cement .

☎ Higher C_3A improves chloride binding through salts' $3CaO.Al_2O_3.CaCl_2.10H_2O$ (Fridel salt)' & $3CaO.Al2O_3.CaCl_2.32H_2O$

■ Impervious surface concrete. Lower w/c and adequate cover depth PSC & PPC improves protection.

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So, this is what is internal chloride and external chloride we have just discussed right. Now, how do I protect protection against chloride in I mean; chloride ingress some of the total chloride remain physically bound and chemically bound, with the cement that is what I mentioned. So, this is important and how does it get chemically bound you see C3A in cement reacts, with the chloride. Now, chloride may be in form of sodium chloride but it will react, with calcium hydroxide forming calcium chloride.

Now, this calcium chloride reacts with C3A and then forms what is known as Fridel salts complex you know 3CaO Al2O3.These are called Fridel salts or other kind of calcium eliminate calcium eliminate chloro eliminate salts calcium chloro eliminate salts, you see C3A is the most reactive component, in the ordinary cement. So, it reacts with so many things like it reacts with sulphate it reacts with also chloride usually, you will have sodium chloride present usually, you will have sodium chloride present sodium say sodium chloride this will react with calcium hydroxide. This will react with calcium hydroxide giving rise to calcium chloride plus sodium hydroxide you know so or any other form of any other form of any other form of chloride, they will react with calcium hydroxide.

So, you will have calcium chloride and this forms this reacts with C3A forming what is called Fridel salts. This you know this forms calcium chloro eliminate and hydrate and this is what happens right. So, therefore when this forms this is not this is not water soluble this is not soluble this cements chemically combine does not come into the solution. This cement is chemically combined, this cannot does not come into the solution. So, this is chemically binding chemically combined right. Now, use here you see if you have higher C3A more bound chloride, you will have some chlorides also get physically bound to the surface of the gel structure you know physically bounds absorbed in the surface.

So, in totality the bound chloride consist of both physically as well as chemically bound chloride. Now, here you see slightly different in case of sulphate high C3A would cause sulphate attack formation, in case of chloride of course high C3A would mean; that you will have lot more binding capacity and that is why sulphate resisting cement is not good in marine environment, because you have both chloride as well as sulphate. So, where you have both chloride as well as sulphate the if you use high c high c I mean; low C3A. Then, chloride binding will get reduced if you use high C3A sulphate attack would be more.

So, therefore that is why sulphate resisting cement is not good in marine environment ok. So, that is what is chloride binding? Now, what should I do, then I should have impervious surface concrete that is the first fundamental you see always carbonation or chloride ingress. All cases moisture comes in some cases also carbon dioxide comes in. So, in all situations actually I need an in impervious surface concrete, because the surface through which it is the surface through which all this fluid you know attacking fluid or this chemically aggressive fluid comes in therefore, I must make the surface impervious you can put a coating alright, but that will be costly.

So, by and large the concrete itself would be m such that it surface is impervious lower water cement ratio, therefore is the solution always a solution and adequate cover depth. Now, here as far as chloride is concerned PSC that is p slag cement and pp cement also improves the protection. So, they improve the protection by both means you know this can improve the protection to all concrete by improving the permeability or improve the imperviousness which we have seen earlier.

Because, we said when we were talking about the hydration of p we you know hydration of cement and p etcetera. We have seen that additional CHS structures CHS are formed in the cost of calcium hydroxide calcium hydroxide reduces a lot more form and the pores would be segmented more or they will be less even totality p will reduce when you use slag or you know fly ash or similar other p fuel ash in cement or use blended cement. So, therefore imperviousness of 1 thing which improves the improved, that would actually protect carbonation also, but here it does additionally because the chloride binding of PPC is more PSC is more.

They will be they you know they can they can bind also chloride more and they provide impervious services surfaces. So, therefore putting altogether this type of cement also shows better performance against chloride. Now, chloride and carbonation is not a problem as I said they only initiate corrosion process.

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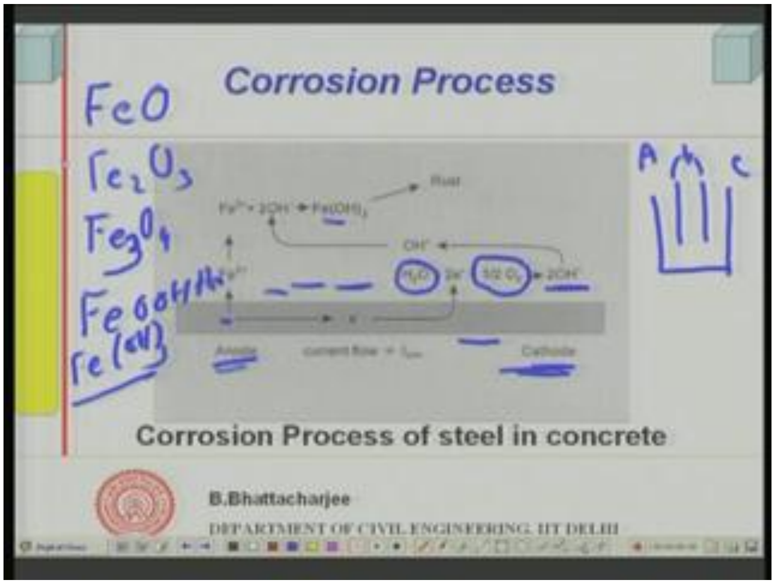

Corrosion Process

Corrosion Process of steel in concrete

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So let us look into the corrosion process you see corrosion process in of river in concrete as in corrosion and it can be well described by this diagram. This is by a river this is the river and some you know it is an electrochemical process, it has been understood that corrosion of is an electrochemical process. So, river corrosion is an electrochemical process after all metal. So, it can give away some electron you know it, it forms generally electrovalent bond and therefore where it loses metal loses electron and also this you know, its metallic bond structure is responsible for its good being good conductor of electricity etcetera.

So, metal can lose electron very easily. So, therefore reactions of metal usually takes place with charged transfer can take place with charged transfer. Now, where electrical charged transfers are involved such reaction, we call as electrochemical reaction. Now corrosion of river in concrete is also an electro chemical reaction and in such electro chemical reaction you must have an a note and also some portion you know somewhere, you should have a cathode. So, remember your electrolysis then you remember there used to be an anode cathode and electrolyte and the anode and cathode are externally connected.

Anode and cathode are externally connected example anode if this is my anode and this is my cathode, they will be externally connected you know they will be externally connected by some connected, you know they will be externally connected. So, that current can pass through that is the circuit of a battery right. So, here also I have anode and cathode but anode and cathode are there in the same bar some portion of the bar will act as anode some portion will act as cathode, because there are non-uniformities.

So, the potential or in other words the capability of losing electron is more somewhere or losing iron positive iron is more somewhere, right in compared to somewhere more compared to some other places where it may not lose or allow metal dissolution here. Anode and cathode are there in this bar, because there are in non-uniformity physical as well as chemical non-uniformity in the bar itself, some portion will form as anode some of the portion will form as cathode. So, in the same bar you have anode and cathode where is the electrolyte the electrolyte is the pore solution outside.

So, the pore solution outside concrete pore solution outside form as a neutrolite and then you have external connection for carrying the current in case of an electrolysis electrolytic cell here this itself, carries the from anode and cathode are internally connected to the river itself. So, in other words you have a circuit completed like this as shown. So, what happens at the anode metal get dissolved metal get dissolved into Fe you know iron. Since, we are dealing with iron Fe plus plus 2 electron. So, it loses 2 electron metal and goes into solution this electron moves towards the cathode and at cathode it actually moves into the solution reacts, with water important and also oxygen forming hydroxyl iron typical cathode reaction and anodic and in anode metal dissolves.

This hydroxyl iron then moves this side right to some side and then reacts, with the Fe 2 plus plus forming this product. Now, this product is not stable depending upon the complete environment you might have formations of FeO, Fe2O3, Fe3O4, or FeOOHH2O, which I mentioned yesterday you know something like this or FeOH3 whatever, it is there are several possible reactions are possible and this I said was this I always I said was, so you know I said this you know this I just gave example of black rust and red rust. And black rust are not problematic rust red rust is problematic, because it expands in volume and causes pressure into the concrete which eventually cracks.

So, now the corrosion process therefore is an electro chemical process, but 2.0, I would like to highlight here that is I require H2O and I require oxygen. So, presence of electrolyte anode cathode the connecting river this is automatically provided by the river itself river itself, act as this you know connector anode and cathodes are there in the river themselves only thing that should come from outside is water and oxygen. So, in presence of water and oxygen this process corrosion process can start and go on.

Now, if you have high pH if the pH is high then red black rust formation takes place and it remains d only when pH is low this d you know it remain it high pH, it is passivated it high pH it is passivated you know it remains passive you know it remains passive at high pH it remains passive at high pH.

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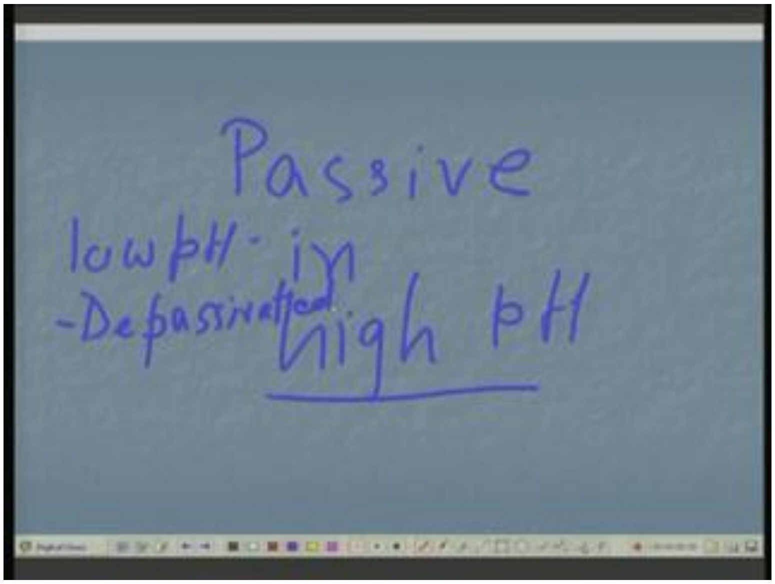

Passive

low pH - in

-Depassivated high pH

So, passive it remains passive in high pH at pH s it gets de-passivated this is 1 form and then corrosion can proceed the other s situation is when chloride other situation is chloride you know. So, this is 1 high pH, so low pH and or low pH it gets de-passivated right passivated de-passivated. So, that is important at low pH it gets de-passivated ok. So, low pH it gets de-passivated right the second way that this reaction you know this de-passive layer over the bar can get de-passivated is due to chloride. Now, what does chloride dochloride when it is sufficient in quantity when chloride quantity is sufficient it can you know chloride c quantity is sufficient actually it will react, with this Fe.

So, chloride reacts with this chloride reacts with this chloride reacts, with this forming ferric chloride ferrous you know chloride compound chlorides of iron and this chlorides are not stable. So, they get broken down and chloride cement free, but Fe goes and forms red rust. So, when you have sufficient chloride 1 of the theories is that sufficient chloride it can break the passive layer, it can destroy the passive layer attack the Fe and reacts with Fe attack and reacts, with Fe forming chlorides iron chlorides Fe chlorides, but which are not stable.

Now, these chlorides then break down and Fe reacts with oxygen water hydroxyl iron etcetera forming red rust whereas chloride is again free to go back and attack some more Fe. So, in this process chloride does not get consumed chloride is not consumed, but Fe is consumed to form red rust. So, chloride attacks iron from some compounds which are not stable.

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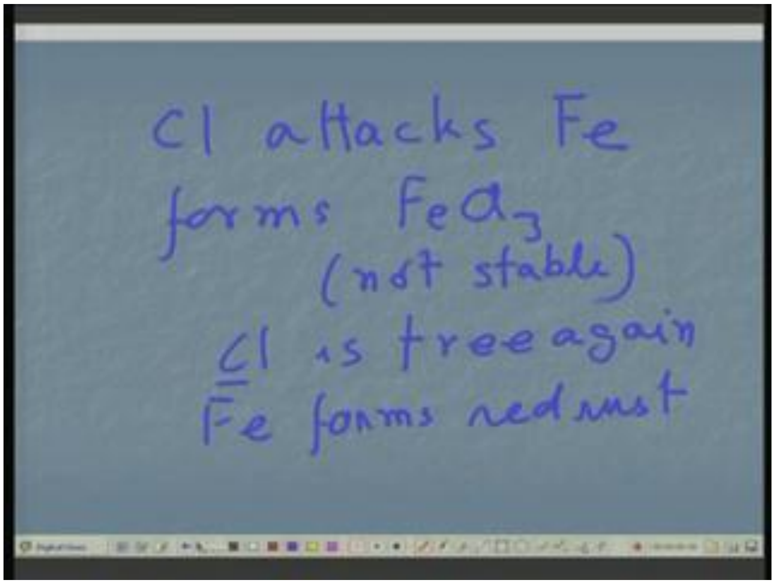

Cl attacks Fe
forms $FeCl_3$
(not stable)
Cl is free again
Fe forms red rust

So, chloride actually attacks chloride attack Fe forms this sort of compounds not stable and then chloride is free again Fe forms red rust Fe forms red rust. So, you can see chloride in sufficient quantity chloride in sufficient quantity can really cause problem you know if it is in sufficient quantity because it does not get consumed itself, but continuously go on processing I mean; producing red rust. So, this is the phenomena of reinforcement corrosion right, so this is what the basics of reinforcement corrosion in.

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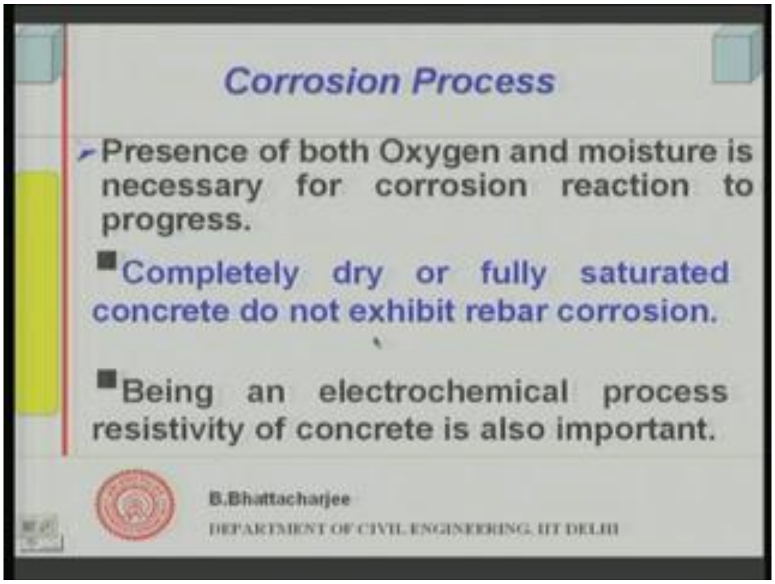

Corrosion Process

- Presence of both Oxygen and moisture is necessary for corrosion reaction to progress.
  - Completely dry or fully saturated concrete do not exhibit rebar corrosion.
  - Being an electrochemical process resistivity of concrete is also important.

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Let see what happens next what is this effect now, when this is happening corrosion process is happening both oxygen and moisture is necessary. This is the first thing we have stated that this is necessary and therefore completely dry or fully saturated concrete do not exhibit rebar corrosion. So, first thing is it must be moistoxygen must be available and if both of them are not available then of course, corrosion cannot proceed. So, if you can protect the concrete reinforce concrete structure against water ingress corrosion, will not progress oxygen of course you cannot stop.

If the pores are there oxygen will always be present, but water moisture ingress can be stopped right also since, the current flow as to take place through the concrete resistivity of the concrete plays a strong role high resistivity concrete obviously, will show lower corrosion rate tendency of corrosion is always there, because iron Fe is not stable Fe is stable only in combined form you know in FeFeO etcetera, oxide sulphide etcetera, Fe is always stable in combined form, but it is not stable just as Fe, because in nature it is not available we produce it at the expense of energy.

Therefore tendency of corrosion will always be there, but we can control the rate and re resistivity of concrete plays a role there or you keep it dry no moisture comes in. So, there will be corrosion although I am given an option given a chance.

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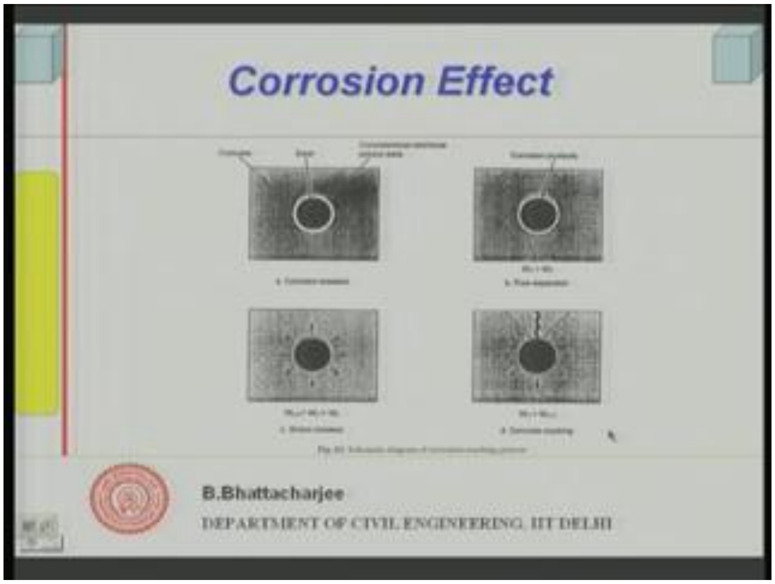

Corrosion Effect

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Now, what are the effects of corrosion effects of corrosion are something like this you see the first step when corrosion process progresses what will happen is this is the steel bar. And this is the layer around this is the wall concrete and this is the layer around a steel bar and this is somewhat, because of the wall effect etcetera this bond area no interface again interfacial zone between the steel bar. And the concrete that will be somewhat zone concrete, because of wall effect shrinkage and similar things which we have discussed several times.

This will be somewhat poor like aggregate surface, now when corrosion products starts accumulating here if the product occupies more volume than the original material, then it will try to expand it will try to expand and therefore it causes expensive forces you know forces outward forces, because this trying to expand trying to occupy more volume that is why black rust is not so dangerous red rust is, because red rust occupy three to 4 times more volume then the original steel. So, it dissolves some amount of the metal amount is now converted into 4 times volume.

So, when there are four time volume it will exert readily outward pressure and eventually if this is your cover depth I, this is your cover depth it will crack there will be cracks on this direction. So, this is called general corrosion usually throughout the structure, if this is occurring then this sort of cracks are usually observed but something more dangerous is known as pitting well locally they are reinforcing reinforcing bar may be consumed with a large cathode area a node area being very small in such situation loss of the metal could be also important together with such cracks, because such cracks may not be visible being in just 1 isolated place or 2 isolated places, but the loss of metal can result in serious problem huh particularly in precious concrete answer structures.

So, if the loss of metal becomes so much that it fails then if it is in a critical location or critical component it can even initiate collapse of this structure, but they do give you signal much earlier particularly this 1 of general corrosion definitely give you lot of signal before failure and therefore 1 as to maintain it repair it even if it as occurred first of all 1 as to prevent that it does not occur, but even if it has occurred 1 can repair it easily right.

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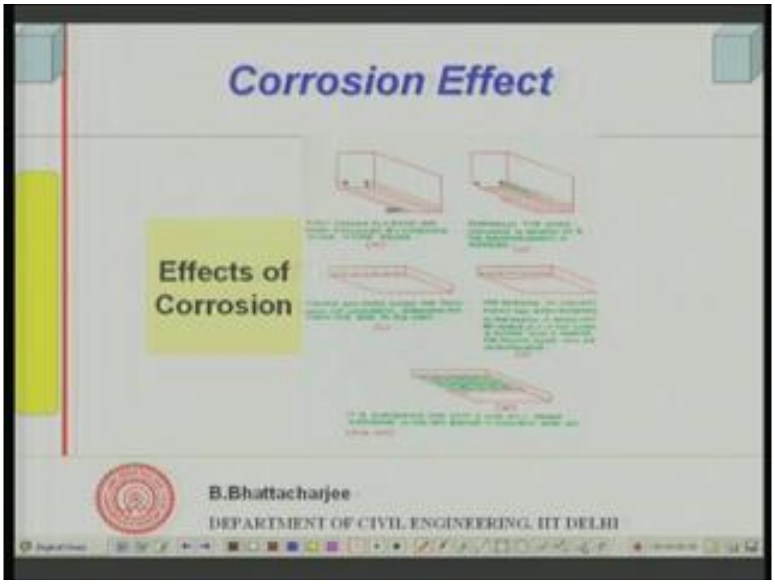

Corrosion Effect

Effects of Corrosion

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So, now if you see the effect of corrosion further we will see that this is what will happen in case of general corrosion in most of the places. For example: if you look at beams the first stage you will see some crack parallel to the reinforcement bar this is your reinforcement bar, you will see cracks parallel to the reinforcement bar on both direction an eventually concrete follow in slag of course, the cracks developed in this manner then there will be sagging of the bottom portion and eventually the concrete follow leaving the reinforcement bar exposed the green 1's are the reinforcement bar.

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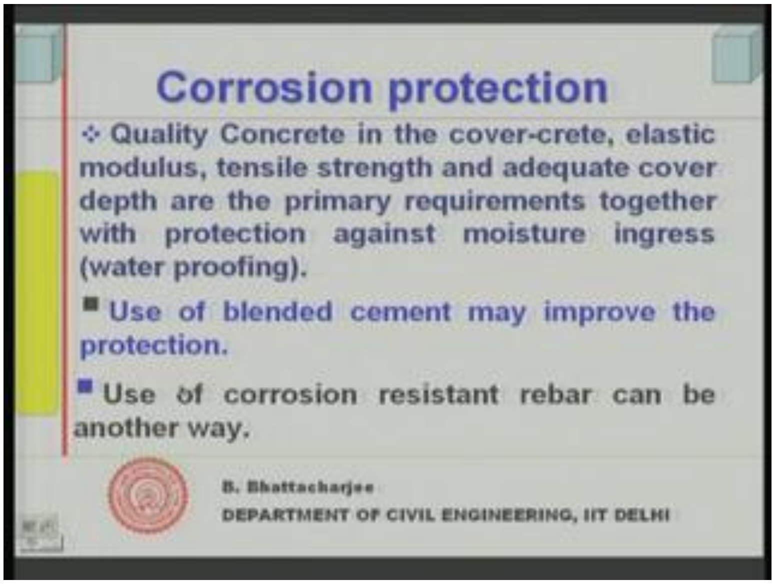

Corrosion protection

- Quality Concrete in the cover-crete, elastic modulus, tensile strength and adequate cover depth are the primary requirements together with protection against moisture ingress (water proofing).
- Use of blended cement may improve the protection.
- Use of corrosion resistant rebar can be another way.

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So, this is the effect of corrosion and you want to see a real life picture we can just show it. So, usually quality of concrete in the cover that is the cover concrete modulus of elasticity that is important, because you see what is happening is there are 2 fold effect first of all throat clearing concrete cover should be good and sufficient there should be it should be good and it should be sufficiently thick also, if it is sufficiently thick first of all de-passivation time itself, will be longer if it is coming from outside like carbonation or chloride secondly the cover also will protect provide protection against cracking.

Because, if it has to crack when the crack as to appear it will take longer time, because you have more material there. So, cover plays both role it should be good as well as thickness should be adequate, now why higher elastic modulus you know tensile stresses are generated because of the pipe busting situation you know we have seen the river pressure is exerted all in the all in readily outward direction. So, if readily outward readily outward pressure is generated then the stress that is developed in concrete will be a function of elastic modulus and it will crack only when the stress generated by such expansion is more than that in such strength of concrete.

So, modulus of elasticity of concrete tensile strength of concrete plays a role higher tensile strength will obviously delay the cracking higher modulus of elasticity, will make you know stresses transferred will be relatively less. So, good quality concrete cover is very important and adequate cover is also very important you know it is the primary requirement together, with protection against moisture ingress this is most important the moisture should not come into the concrete, because if moisture comes in corrosion process can set in if you have no moisture, no water, no oxygen, no corrosion.

So, that is very fundamental to protection of corrosion use of blended cement improves this protection although you know it may it may be said that it; it consumes lot of calcium hydroxides. So, there may be something happening to its pH maybe although clear cut evidences are along that line is but anyway what this blended cement does is they make it impervious they make concrete impervious. And therefore water penetration is much less chloride would be less besides that they, increase the resistivity of the concrete and thereby they provide good protection against corrosion.

But, only when your concrete quality is good, if you make a bad concrete non-engineered concrete you use any cement is not going to serve your purpose, first thing is this issues I should have good quality concrete, with good elastic modulus tensile strength etcetera and protection against moisture ingress then all other thing would be good there can be corrosion resistant rebar is another way of another way by which you can protect.

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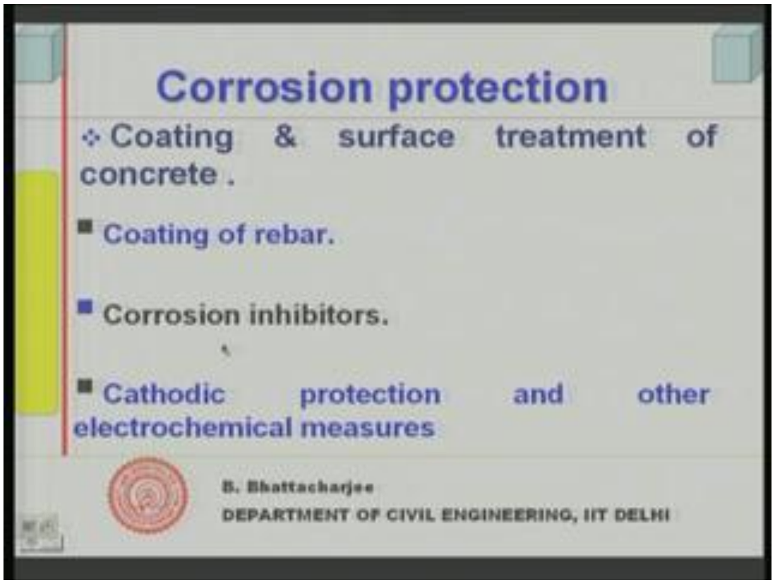

Corrosion protection

- ❖ Coating & surface treatment of concrete .
- ■ Coating of rebar.
- ■ Corrosion inhibitors.
- ■ Cathodic protection and other electrochemical measures

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Coating and surface treatment of concrete is one way of protection against corrosion coating of rebar but cost as to be seen. There are fusion bonded there are other kind of rebar coating. So, you are actually creating a barrier between the rebar and the creating a barrier between the rebar and the electrolyte that is what you are doing huh inorganic coating of the kind of could be also. So, there are varieties of coating of reinforcement bar is possible, so you create a barrier between them of course some of them can reduce down the b strength between the concrete and the steel.

But, if you know how much the loss you can design is accordingly. So, that is not a problem surface treatment of concrete or the other solutions. Now, surface treatments may be costly it would have depend up on the situation environment what environment you are working on there are some something called corrosion inhibitors, which you can put into the concrete and they will stop either the anodic reaction or the cathodic reactions sodium nitrate. They are some of those are other kind of inhibitors also available huh both anodic and cathodic inhibitors are available.

But, their use is not very you know till date they are not you know they are not very not very extensive use have been made of them, because they have all side effects and everything is not 1 is not sure about. But these are also some other solutions cathodic protection where electrochemically you protect the reinforcement bar by applying either an external current such that it will oppose the corrosion current a second way is to have what is called as sacrificial anode.

Now, such anode is connected to the reinforcement bar and it is you know it is the metal is chosen in such a manner that it will always be anodic compared to iron. So, it will get dissolved iron will be protected well details we will not discuss about but cathodic protection and other measures then there are some other electrochemical measures like huh you know, you can actually remove chloride from the concrete by a process called dechlorination or you can increase the you know alkalinity of concrete by alkaline alkalination and things like that. So, these are also electrochemical processes some of them are costly not yet tried there are problems involved with maintenance, because cathodic protection you have to monitor it continuously. But, those are definitely some of those means of protecting.

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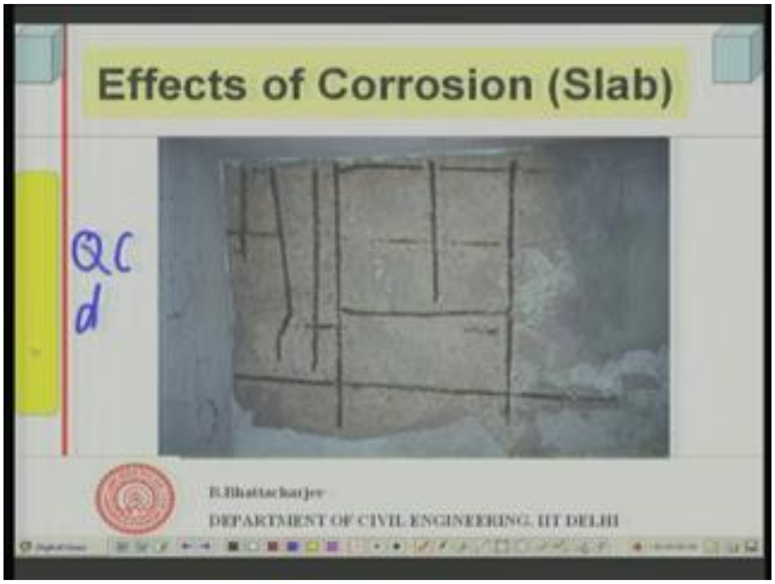

Effects of Corrosion (Slab)

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Now, this is the example of real life example of corrosion in a slab huh you know real life example of corrosion in a slab. So, we have seen corrosion protection and let us see what is what happens if you have not really taken care of it in the right time and this is real not coming from anywhere, in the sea coast but coming from composite monsoon of Delhi mainly, because ingredients were not properly tested. So, all protection measure stated I would like to emphasize on the fact that corrosion essentially many places; we can avoid corrosion.

If you have good quality control of concrete adequate cover you know cover depth cover depth of the cover, I should have adequate depth of the cover most of the cases in real structures depth will be very small quality of concrete is a causality especially in non-engineered concrete where you know it is all mixed manually and things like that. So, concretes which are concrete structure many buildings structures particularly constructed in 1980s and even 19’s which are manually constructed the quality control is bad if you do not test the ingredients for chloride in this particular case chloride came from the ingredients.

So, if you do not test the ingredients this can lead to corrosion, so effect of corrosion real life situation could be something like this, but first fundamental is the quality of concrete quality of cover concrete and stopping the ingress of moisture right. So, this is what is all about corrosion.

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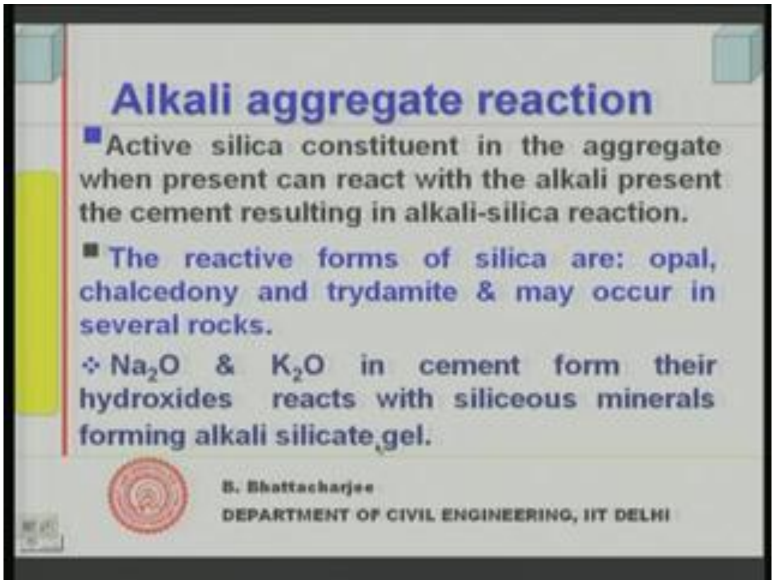

Alkali aggregate reaction

- Active silica constituent in the aggregate when present can react with the alkali present the cement resulting in alkali-silica reaction.
- The reactive forms of silica are: opal, chalcedony and trydamite & may occur in several rocks.
- Na_2O & K_2O in cement form their hydroxides reacts with siliceous minerals forming alkali silicate gel.

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Let us see, now into the another degradation process called alkali aggregate reaction now, this occurs in with certain types of aggregates you know active silica constituents in aggregate, they are certain active silica and when they are present in aggregate can react with alkali present in cement. So, active silica and alkali present in cement you know the always sodium hydroxide and potassium sodium oxide and potassium oxides these alkalis are present in cement; they are present as flexes in the cement.

So, because they bring down the burning temperature of the cement you know, so therefore they are present in cement always now, this alkali can react with some active silica some of them. If they are present and they can result in what is known as alkali silica reaction. Now, this reactive forms of silica are some of them are opal you know this is the mineral mineralogical name minerals opal chalcedony and trydamite, these are some of them, if they are present they are active silica they may you know they- occur in several rocks.

So, they can cause this alkali aggregate reaction right this 1s readily forms their hydroxides, because they are present in cement, so they readily forms their hydroxides and reacts with siliceous material forming alkali silicate gel. Now, this alkali silicate gel actually is voluminous in nature they occupy more volume then the original reactants and therefore they exert pressure around aggregate and it will result in cracking, it will result in right, this gel that forms.

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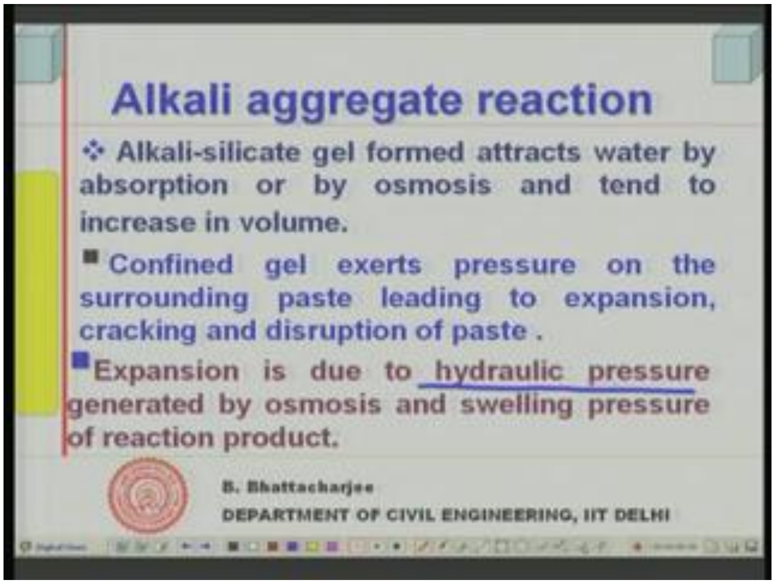

Alkali aggregate reaction

- Alkali-silicate gel formed attracts water by absorption or by osmosis and tend to increase in volume.
- Confined gel exerts pressure on the surrounding paste leading to expansion, cracking and disruption of paste .
- Expansion is due to hydraulic pressure generated by osmosis and swelling pressure of reaction product.

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How do how do they do it the mechanism actually, alkali silicate gels which the you know active silica and the alkali in cement they form they attract water and they absorb them also by osmosis and tend to increase the volume. So, this gel because it is a gelatinous structure by osmosis, it can bring in water and you know it can it the water can come in and it can absorb the water as well and thereby when it absorbs water it swells actually. So, increases the volume this gel exerts pressure onto the surrounding paste leading to expansion cracking and disruption of paste that is what we said.

The expansion is actually expansion is actually attributed to hydraulic pressure generated by the osmosis, and swelling pressure of the reaction product both hydraulic pressure of the process of osmosis takes place through membranes from you know side of higher concentration to the lower concentration like you find, if you have 1 side concentrations higher another side concentrations less; there will be a pressure existing between the 2 sides. So, this is also related to you know like diffusion process, we talked about molecular diffusion in solution they are similar. So, osmotic pressure is related to that also, so osmosis can take place in through this gel and this can exert hydraulic pressure together, with the swelling pressure of the reaction all this actually causes expansion and therefore the cracks.

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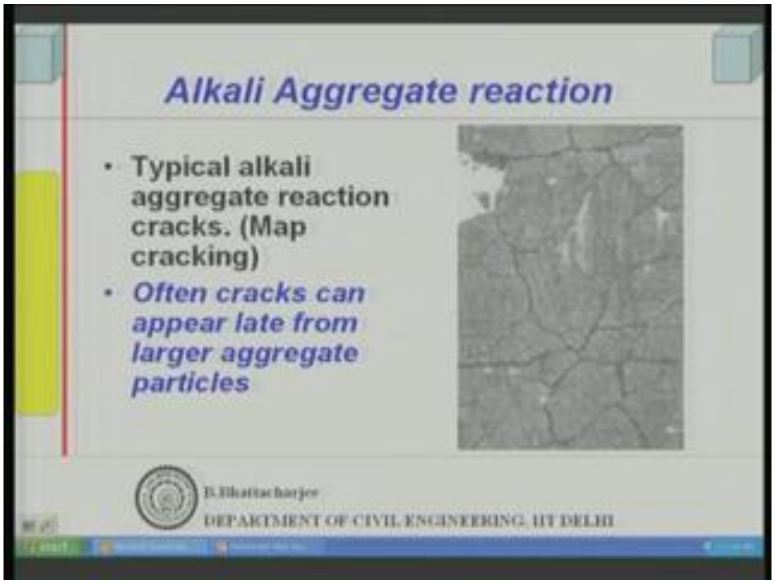

Alkali Aggregate reaction

- **Typical alkali aggregate reaction cracks. (Map cracking)**
- ***Often cracks can appear late from larger aggregate particles***

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The result is something like this you know typical this results in what is called map cracking map cracking you can see this is from a real life scenario usually, it will take place around a aggregate so just below side of the aggregates and then crack proceeds. So, it starts from if there is an aggregate from the aggregate all around you know at other places from the aggregate all around because expansive pressure will go from the aggregate surface to the outward into the paste and it generates and finally, this sort of map cracking results from and this concrete as fallen of finally.

So, alkali aggregate reaction can result in this map cracking now, the fineness of the aggregate has got an got a got a role to play if the aggregate, if very fine this cracks can be seen real relatively early, but in large- aggregate for example in aggregate when this alkali potential aggregate, alkali aggregate reactive you know potentially alkali reactive aggregates are there if it is there, in the coarse aggregate it can take years not even 5 10 years dam is 1 such example where actually cracks can because of alkali aggregate reaction. So, these cracks can come in the long run and you know this is of course put you in a difficult situation.

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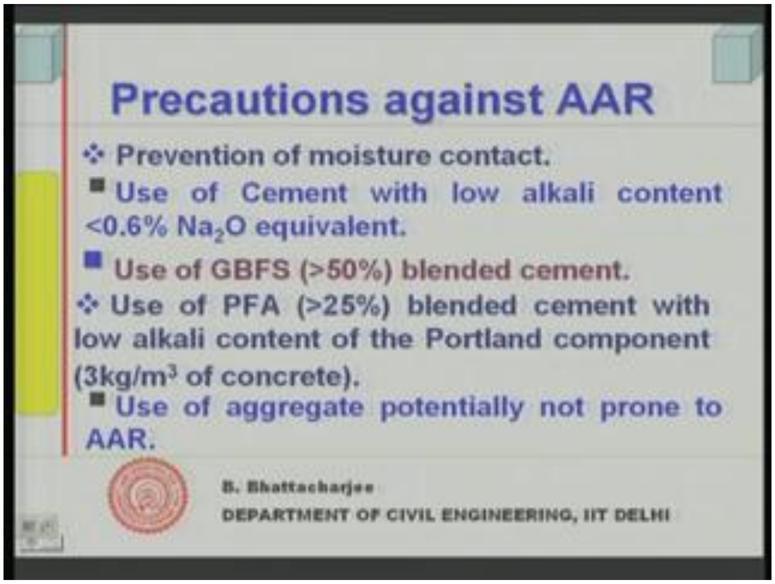

Precautions against AAR

- ❖ Prevention of moisture contact.
- ■ Use of Cement with low alkali content <0.6% Na_2O equivalent.
- ■ Use of GBFS (>50%) blended cement.
- ❖ Use of PFA (>25%) blended cement with low alkali content of the Portland component (3kg/m^3 of concrete).
- ■ Use of aggregate potentially not prone to AAR.

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So, alkali aggregate reaction takes place and it gives you gives rise to map cracking first thing this 1 occurs in presence of moisture, because gel has to absorb the moisture as to come inside. So, if you can prevent moisture contact no problem the alkali aggregate reaction. There use of cement with low alkali content less than 0.6 percent sodium oxide equivalent, you know we talk in terms of alkali content of the cement in sodium oxide equivalent, because this is actually actual sodium oxide content plus potassium oxide content multiplied by constant of 1.685 or something like that.

So, this because you know there its related to their own molecular weight and things like that, so we talk in terms of sodium oxide equivalent 0.6 percent sodium oxide equivalent. So, that is what it should be now and also they reduce down this in fact they do contain alkalis but fortunately those alkalis are in some glassy faces together in some sort of form which do not contribute to alkali aggregate reaction both GBFS and PFA that is fly ash or similar other material pulverized fly ash they do have alkalis present in them.

But, those alkalis are in such form that they a do not contribute to the alkali aggregate reaction, so what you are doing whenever you add this materials there is a dilution of the alkalis present in the cement. So, total alkalis present in the cement is now, relatively less if you are using 50 percent GBFS you are actually reducing the alkali content the OPC component by 50 percent and that is what has been suggested, you use more than 50 percent in blended cement use PP PFA more than 25 percent in blended cement, with alkali content of the portl and cement should be more than 0.3 kg, I mean; 3 kg per meter cube of concrete use of aggregate most important use of aggregate potentially not prone to alkali aggregate reaction.

This is traditionally, if certain aggregate as been used for many years and it did not show alkali aggregate reaction, then that can be used safely but if somebody is using a new aggregate then it as to be tested it is not very easy there are several tests including test to test the alkali aggregate reaction potentiality of an aggregate. They are spectrographic tests you know you look under microscope the presence of opal etcetera, but they are not 100 percent full proof right. So, this is 1 in 1 would like to make them 100 percent p full proof as much as possible by all test and see that that particular no traces of such material is there and is potentially the aggregate is not potentially alkali aggregate reactive before using it new aggregates in dams. Since, aggregates are used locally or large industrial sites even local aggregates you are using, because you cannot carry the aggregate from far of places in such places testing the aggregate for potential alkali aggregate react is very important.

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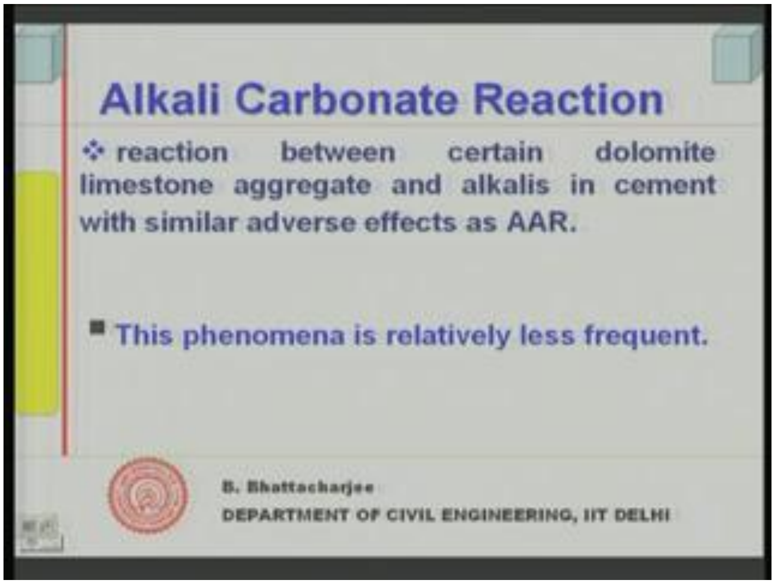

Alkali Carbonate Reaction

- reaction between certain dolomite limestone aggregate and alkalis in cement with similar adverse effects as AAR.

- This phenomena is relatively less frequent.

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There is a second variety called alkali carbonate reaction not very not very often, it is observed. This reaction takes place between certain dolomitic limestone and alkalis in cement and this has got also similar adverse effect as alkali aggregate reaction right quite often it has been attributed to the clay minerals present, in the dolomite it is not very clear not much research and it is not very it is a rare thing it does not occur very often. This phenomena is relatively less frequent and therefore not much has been done, in fact this is this quite often you know not well understood as well. So, these are this is all about the degradation processes that, we would want to look into this component of our lecture

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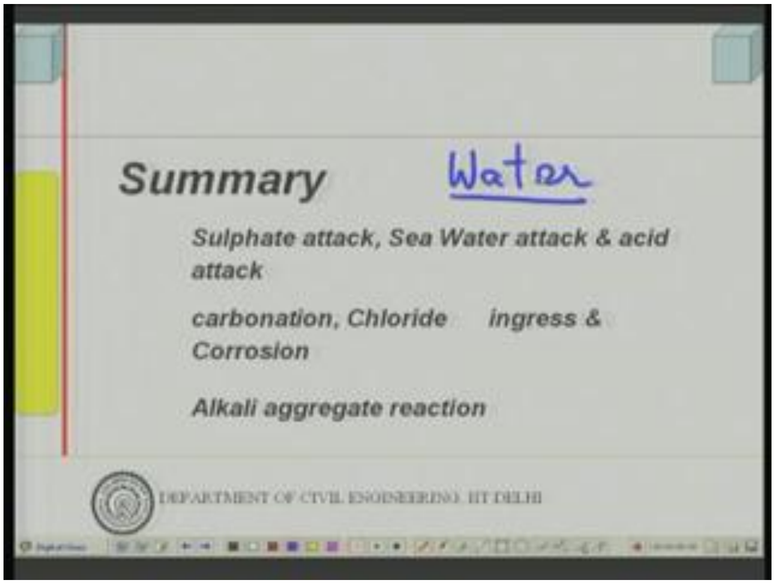

Summary

Water

Sulphate attack, Sea Water attack & acid attack

carbonation, Chloride ingress & Corrosion

Alkali aggregate reaction

So far therefore combining with the last lecture the summary of the 2 lectures on durability Sulphate attack we have seen. We have seen sea water attack and we have seen acid attack carbonation and chloride ingress carbonation and chloride ingress leading to river corrosion that is what we have looked we have discussed; what is the corrosion process and we have also looked into alkali aggregate reaction. Now, all degradation process are chemical degradation process are by and large over there is 1 physical degradation, we would like to look into if the first attack in our discussion.

Then, look into general strategy of you know general strategy towards protection against or durability enhancement of concrete important issue that, I would like to highlight in the summary is that you see all places we have found that water is 1 of the major agent ingress of water is one of the major agent for all chemical degradation process to take place and concrete must be sufficiently impervious to avoid such chemical degradation, I think with that we conclude our this discussion, in the next one we will look into frost.