Hydration, Porosity and Strength of Cementitious Materials

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Lecture - 38
Durability of Concrete- 1

[FL] and welcome to this lecture 38 on our course on Hydration, Porosity and Strength of Cementitious Materials. And this is the first lecture in a two lecture module on Durability of Concrete.

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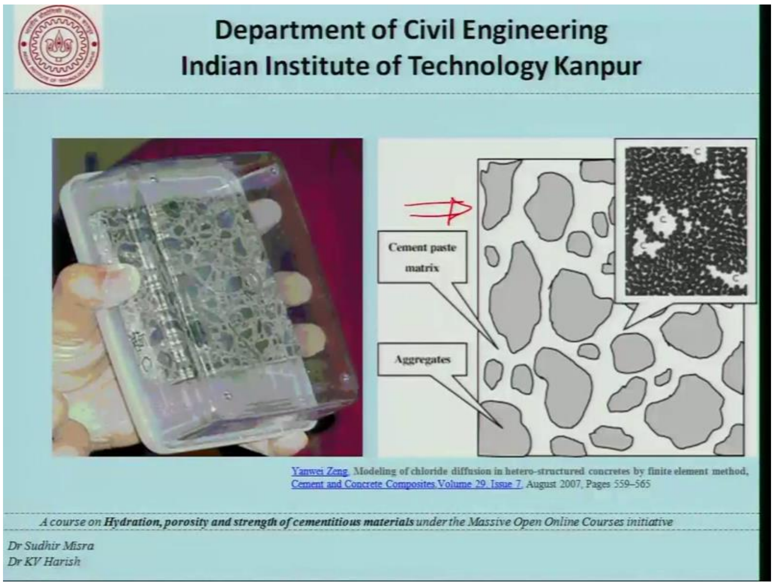

We go back to the slide a model of what concrete is, and today we will discuss how we will use this particular model of concrete having aggregate and the cement waste matrix; in the context of discussing the durability of this material when it is exposed to environmental action.

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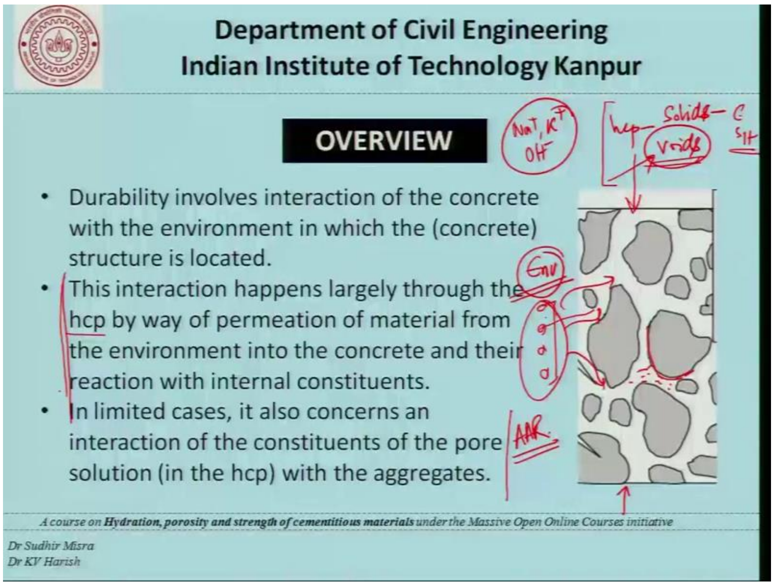

So, now durability involves interaction of the concrete with the environment in which the concrete structure is located. Basically we have this concrete which is interacting with the environment outside. And we must understand that the durability of this material is very close to be related to the environment in which it is located. So, that is what is the first of our discussion today.

This interaction happens largely through the hcp; that is the hardened cement paste by way of permeation of material from the environment into the concrete and their reaction with the internal constituents. What this means is that there are constituents from the environment which move into the concrete through the hcp, and of course the hcp itself is made up of solids which are the csa gel and products like that and there are voids. So, when we talk of permeation of these materials into the hcp we are talking of the movement of these materials through the voids in the hcp.

Now, as these materials move through the voids they interact with the other constituents of the hcp namely the C-H-S gel and so on and so forth, and also at times with the aggregate. So, that is what is the route analysis of our understanding of durability. In limited cases it also concerns an interaction of the constituents of the pore solution in the hcp with the aggregates. Now this is particularly true with the mechanism of alkali-aggregate reaction, where the hydration products itself they contain sodium and potassium ions apart from hydroxyl ions and these are very much part of the hcp and they interact with these aggregates which in that case is reactive.

So, apart from that consideration we had largely concerned with this issue that is the permeation of deleterious material from the environment into the concrete through the voids in hcp.

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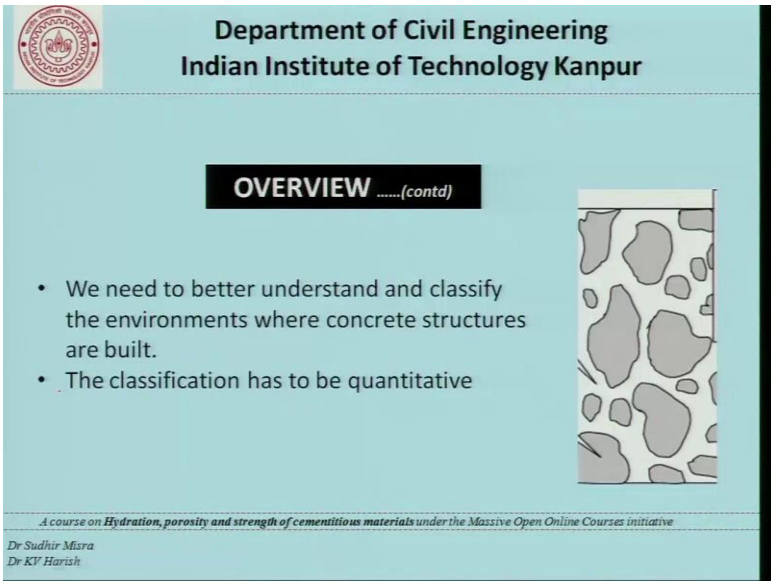

Continuing with our discussion, we need to better understand and classify the environment where these concrete structures are built and this classification had to be quantitative to the extent possible.

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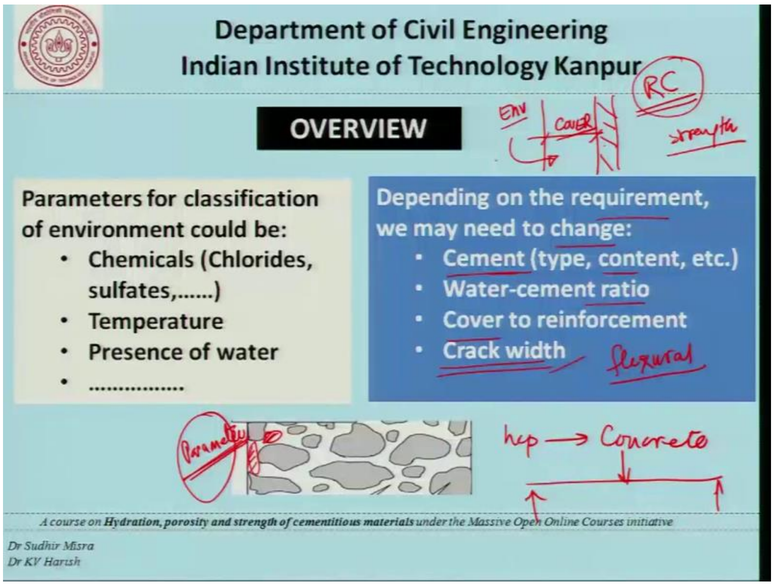

Now, this quantification could be in terms of certain parameters, such as chemicals that is chlorides or sulfates or any other chemicals that we may identify in the environment of the structure, or it could be the temperature in which the concrete structure is built, or it could be the presence of water and the characteristics of the water the frequency with which the concrete structure is exposed to water. For example, if it is rain or it is rivers or it is the sea and so on and a host of other such parameters.

Now once we have classified the parameters that we have here which largely help us understand the environment in which we have the concrete structure depending on that we may need to change our cement type. That is now we are coming to the options that we have to react, that is for this kind of an environment what is the kind of things that we want to do to ensure durability of our hcp which in turn will ensure the durability of the concrete?

One thing that we can do is to change the type and content of the cement, that is we could use higher least strength cement, low heat of hydration cement, we could use sulfate resisting cement and so one could change the content of the cement in the concrete. Or we could change the water cement ratio that is we could also change the strength. We can have a requirement that for a certain type of environment we must have at least a certain strength in the concrete or we must have at most a certain amount of water cement ratio.

Similarly, we can have a requirement on the cover to the reinforcement. Please remember that if we have the environment here there is a reinforcing bar here when we come to reinforced concrete structures and this distance that we have is called the cover. So, this cover has the structural uses also, but from a durability point of view it serves as the shield to protect the reinforcement from deleterious material that may go into the concrete from the environment.

So, depending on the environment we may try to change the cover that we provide to the reinforcing bars. Also, again in the context of reinforce concrete structures there is this issue of flexural cracks, which are formed when a beam is subjected to bending stresses. So now, the width of those cracks is also another parameter which we need to address or keep in control if we want to ensure the durability of the concrete structure. And there are other things that we can do which we will talk about as we go along in our discussion.

Now, before we get into our discussion on the details for the parameters for classification of environment and the kind of action that we need to take as designers to ensure durability, let me give you some examples which will tell us the diverse nature of the environments in which concrete structures are built.

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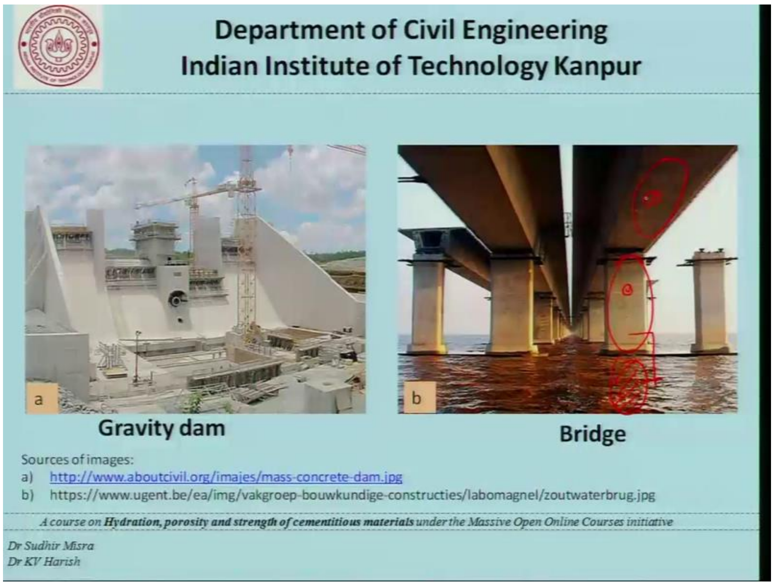

The first example that we can take of is a concrete dam. This is a massive concrete structure which could be a part of a hydroelectric or a navigation scheme. We can have concrete bridges which could be reinforced or pre stressed. Now if you look at a structure of this nature, the concrete in this region of the bridge versus in this region of the bridge versus of course there is concrete below here which is submerged in the water and there is foundation which is also made of concrete.

The kind of environment of those concretes is quite different. What is embedded in the soil has a certain environment, what is continuously submerged in water is a different environment. There could be a region here which is subjected to cyclic wetting and drying and the region here or here for that matter is more or less always dry except for rain water which may hit or may not hit or there could be splashes or tides which cause some amount of wetness.

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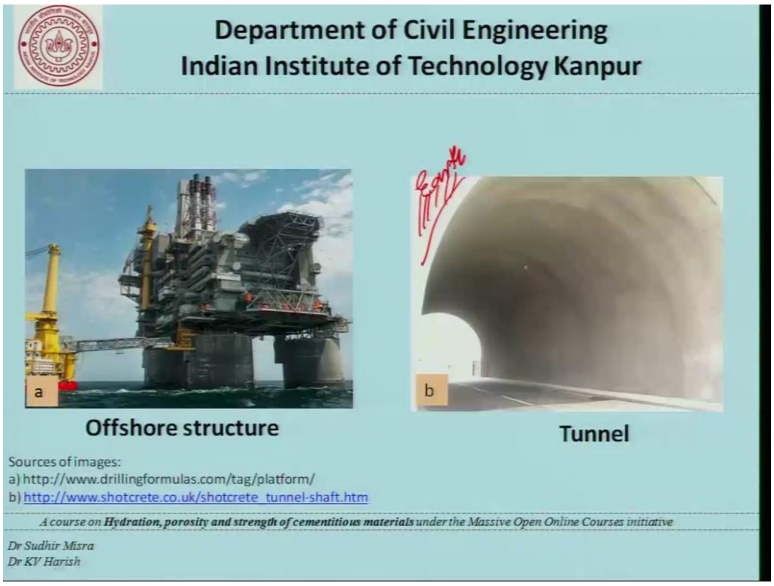

Going further this is an offshore structure, which again has the more or less. Going further this is an offshore structure which could have the same kind of a description as we have just discussed in the case of the bridge or we could make concrete tunnels. Now these tunnels have quite a different environment. On the outside of the tunnel we usually have earth or soil, and on the inside we have air. And this is largely protected from rain and so on.

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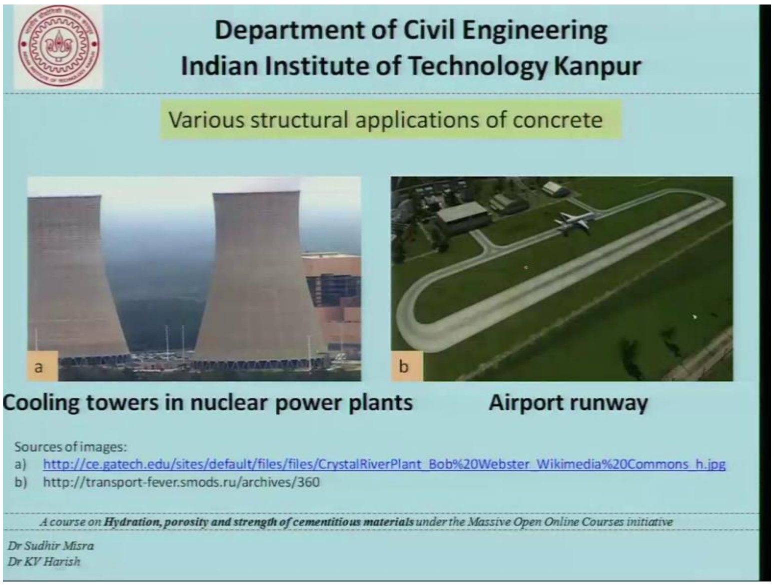

There could be cooling towers in nuclear power plants or there could be concrete airport runways. These are all subject to different kinds of loads, they are constructed using different technologies, most of the time they use quite different curing methods and the kind of strength requirements. So, we have to keep all these things in mind when we are trying to talk about the durability of these structures. So, it is not the concrete durability itself it is the structural durability of the structure.

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Here is a shell structure where the concrete could be very thin and made in a very difficult shape which makes the strength development, the placing of concrete, the placing of reinforcement within the concrete very difficult and that has implications on quality and therefore durability. So, we have to be extra careful when casting these kind of a special structures.

Now come to sleepers, the railway sleepers below the railway track and these are largely factory made products. And the durability of these is an independent discussion itself. Most of the times these sleepers are made with (Refer Time: 10:05) concrete with reasonably high strength and made using steam curing and that has its own implications in terms of strength development and the final probability and so on.

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We have concrete used in multi-storeyed buildings, where the outside columns, and the inside columns, the part of the concrete which is shielded from rain, and not shielded from rain and all that introduces very different and very difficult kind of modeling problems for an engineer.

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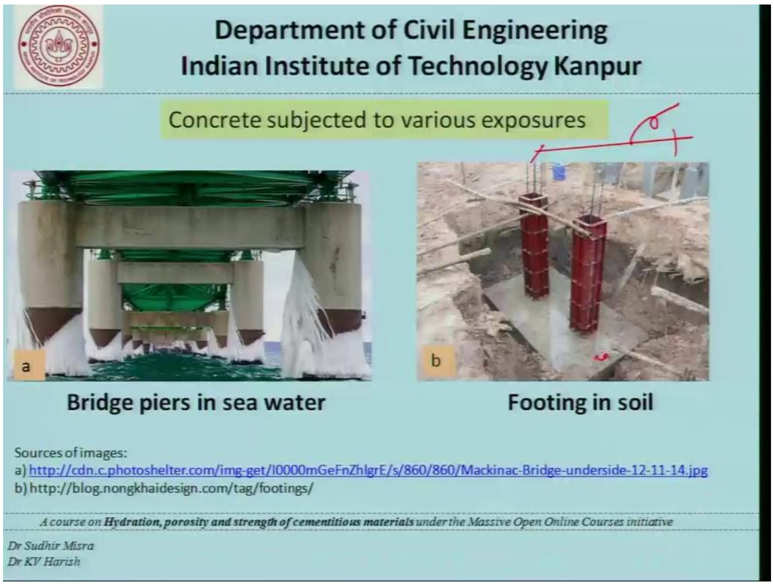

This is the concrete in an arch dam. We could go to concrete bridge piers in sea water where we can see that it is a combined effect of temperature and marine environment. So, there is cold weather and there is marine environment. As for as the cold weather is concerned we must remember also that the temperature does not remain the same, and we could have an environment where the concrete is exposed to cyclic freezing and thawing; that is the temperature outside goes below 0 and goes above 0 a certain number of time.

So, the temperature in the environment crosses this 0 degree line which is the freezing point of water in a certain cyclic manner. So, there could be a certain number of cycles in a year. And we could talk in terms of the severity of freezing and thawing in terms of the number of such cycles that can be expected in a certain structure. Now, how this affects the durability is something which we have already covered briefly when we were talking about how the pore water in the hardened cement paste would be subjected to freezing and then later on thawing. And once the water freezes it exerts an expansive pressure on the pore walls.

Continuing further, we have concrete used in footings and soils and that is where we have ground water kind of a attack as far as the concrete is concerned. And these footings are also carry a certain amount of reinforcement and we need to ensure that the reinforcement is appropriately protected, it is not only the sulfates but a times with ground water could also contain chlorides. So, we need to model the kind of environment that we are working in.

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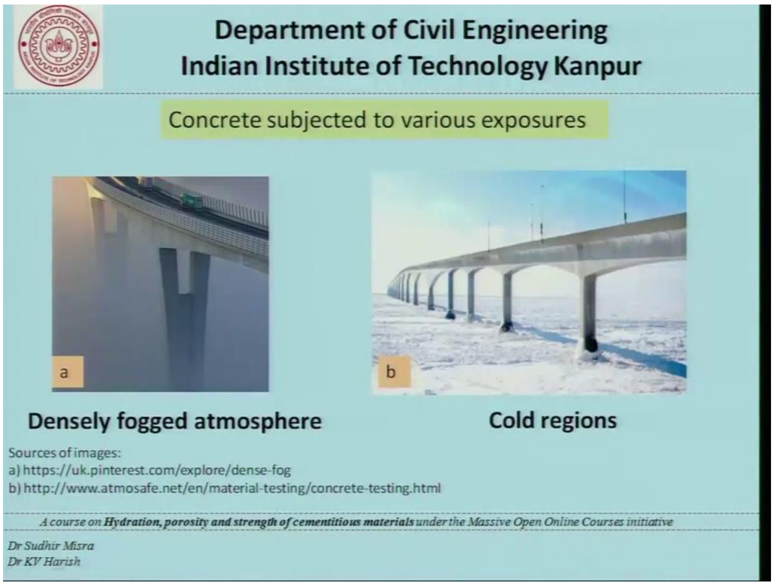

Going on there could be a concrete in dense fog, there could be a concrete bridge in very cold regions; where the discussion that I just had with you on cyclic freezing and thawing is very appropriately applicable and we need to talk of durability of such concretes as well.

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There is a coastal environment, where the structures are slightly away from the seashore, but the sea breeze would carry the chlorides to the buildings. And we have the problem of chloride induced reinforcement corrosion in structures which are not only very close to the sea, but also reasonably in land. So, how do we model all these structures? That is a challenge that designers must face.

This is another picture of a concrete structure subjected to sea water splashing. And this introduces penetration of chlorides in the one side, cyclic wetting and drying on the other besides the structural loads that we talk about.

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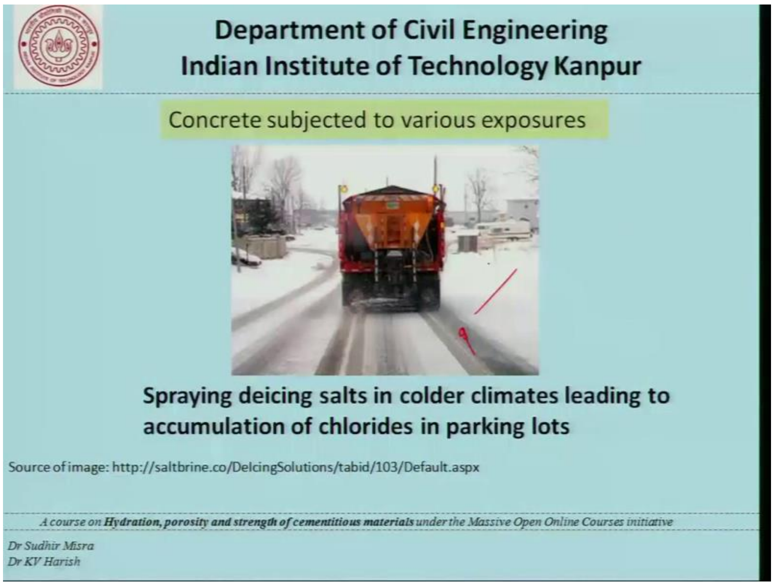

Here is an application of deicing salts in colder climates. What really happens is that you can see that the highway here or the road is covered with snow. Now in order to make sure that the road is available for traffic, what is usually done is to spray salt on the snow to melt it away. This has two implications: number one, the salt that we spray permeates into the concrete of the pavement and the other one is that the vehicles moving on these pavements which is wet and it has salt water.

So, that salt water sticks to the tyres of these vehicles which then if they go to parking lots made with concrete then we park the car there and that salt water dries out or drops on to the slabs of parking lots. And those slabs are also now getting subjected to salt water attack. Even though there is no direct salt water being applied to them, but the salt water being carried out to them from such applications of deicing salt on roads is the source of chlorides. Apart from the fact that this salt also damages the vehicles itself.

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Now, here is an example of deterioration in concrete structures and we can see reinforcement corrosion. So, I do not want to get into the discussion of reinforcement corrosion itself in this discussion here in this class, but we must see that here the concrete has more or less all been washed away or eaten away or has falled off and we can see only reinforcement. In this column here all the cover concrete has been lost, it is for such deterioration does not happen very quickly fortunately for us, but it does happen over a long period of time. So, when we design a concrete structure we have to be careful about ensuring that during the service life of the structure the required amount of functionality or the required amount of structural integrity is not compromised.

These are all examples of reinforcement corrosion. Here also we can see this falling from the columns and here we see is falling of the concrete from the bottom of the beams. So, all these problems or all these illustrations of reinforcement corrosion make us aware of the fact that reinforcement corrosion and the need to protect the reinforcement from corrosion is an important aspect of designing concrete structures. And what we can do is to actually use our knowledge of the hardened cement paste and the mechanism of densifying the hardened cement paste to our advantage to ensure such design.

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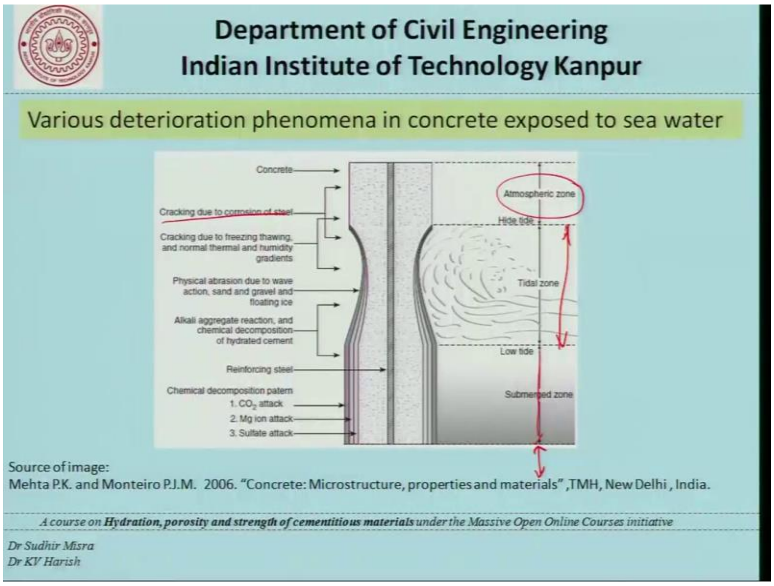

This is a model showing a concrete being exposed to sea water. We can divide the concrete into a zone where the concrete is largely exposed only to the atmospheric environment and occasional rain and so on. Then there is a tidal zone where the concrete is subjected to wetting and drying. Then there is a submerged zone and beyond that there would be a zone where the concrete is actually not submerged in water, but it is actually submerged in soil and that would be the foundations.

So, depending on what zone we are in we could experience cracking due to corrosion of steel cracking due to freezing and thawing, alkali-aggregate reaction and so on depending on whatever kind of constitutions we have chosen to have.

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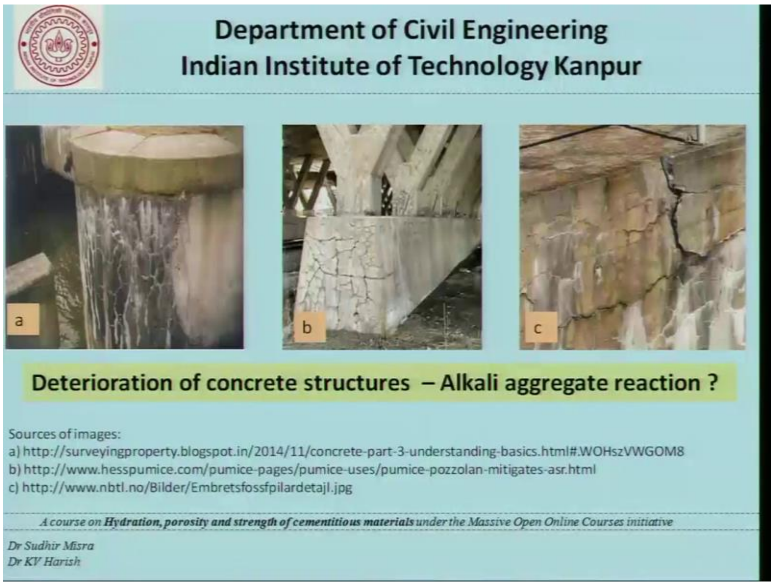

Now, here are examples of concrete structures where we could say that suspected alkali-aggregate reaction. And that is in this case the aggregates which we thought are largely inert are not really inert. And we have a reaction of aggregates with the sodium potassium and the hydroxyl ions in the cement paste and that is what is causing a deleterious action, including formation of cracks, appearance of the white gel, and so on.

We must remember that once these cracks are formed, these are not the structural cracks that these are not cracks brought about on the structure due to the action of structural loading. These are the cracks which have a reason in their structure because of problems in the concrete itself. But once these cracks are formed they accelerate, the permeation of any kind of deleterious material from the environment into the concrete.

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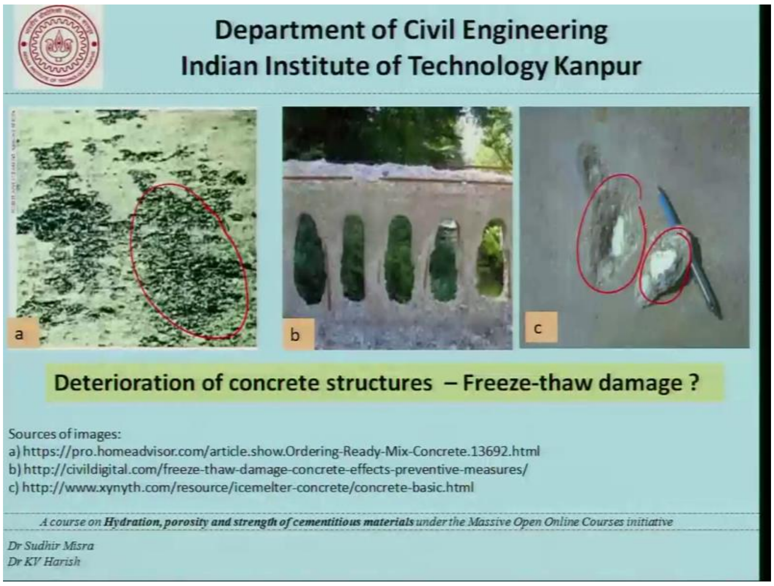

Here are examples of structures which have been subjected to freezing and thawing. So, we can see that the action has largely affected the cement paste phase of the concrete and that had indeed better been the case because that is the phase in concrete which is more susceptible to reaction of freezing and thawing. Of course, beyond a certain point we will have a situation like this which is called the aggregate pop out. So, these are examples of action or the final results in terms of freezing and thawing.

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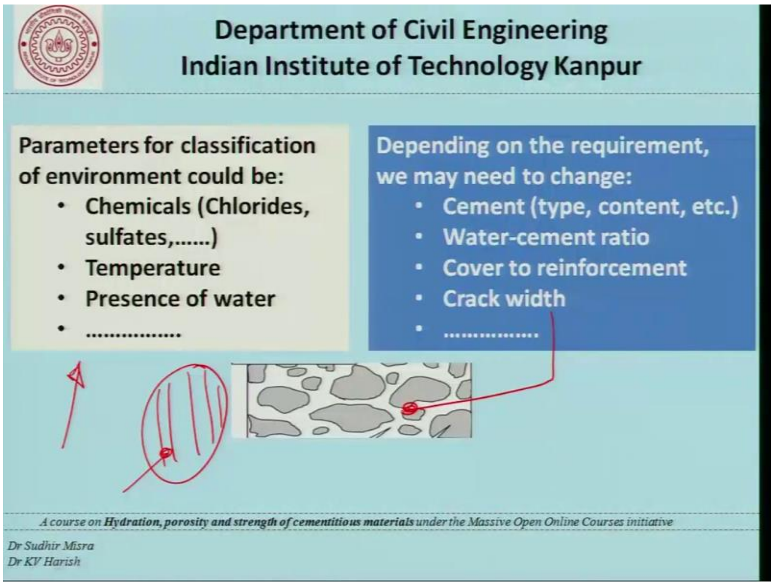

Now, we had seen this slide before. What we want it to do was to classify the environment that is the part here outside the concrete structure and depending on this classification on the kind of parameters that we used to classify this environment this picture here tells us what to do with this concrete here to ensure durability.

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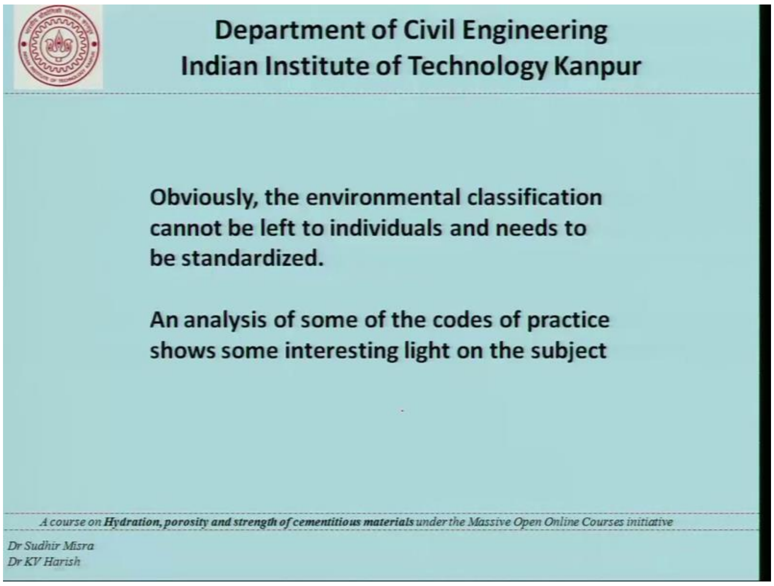

This classification of environment cannot however be left to individuals and needs to be standardized. An analysis of some of the codes of practice show some very interesting light on the subject. And from this point onwards we will be talking about that.

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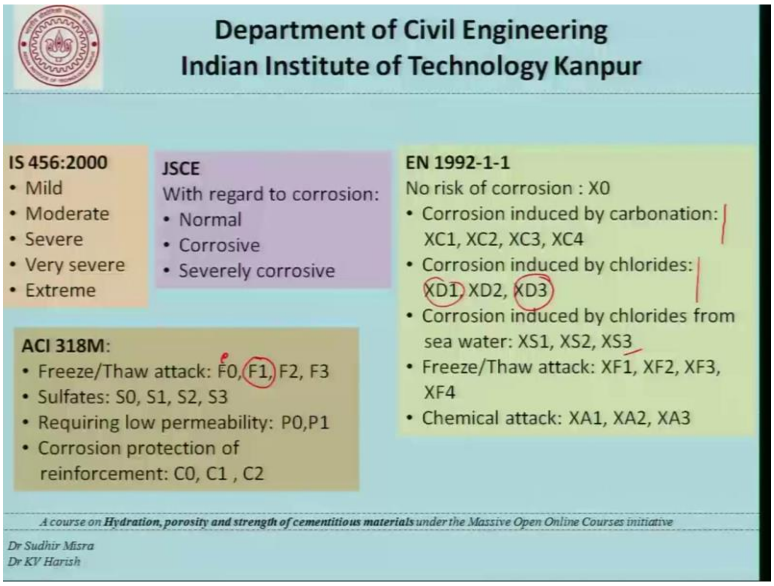

As a first example let us take IS-456 the version of 2000 which we follow in India. And this code classifies the environment into mild, moderate, severe, very severe, and extreme. This code tells the designers that for a particular concrete structure try to understand if the environment is mild, moderate, sever, very severe, or extreme and take appropriate measures which are also defined. There are also guidelines available as we will see on how to classify a structure into a mild or a moderate or a severe classification.

Coming to another code let us talk of JSCE which is the Japan Society for Civil Engineers. And from the point of view of corrosion it has classified the environment into normal, corrosive, and severely corrosive.

Similarly if we look at EN-1992 it talks of environments where there is no risk of corrosion and that is called X0. There is another environment where we could talk of structures which are susceptible to corrosion induced by carbonation. Carbonation we have talked earlier is penetration of carbon dioxide into the concrete. And here the classification is XC1, XC2, XC3, and XC4. Moving forward there are structures which could be susceptible to corrosion induced by chlorides. And those are classified as XD1, XD2, and XD3. Corrosion induced by chlorides from sea water are classified as XS1, XS2 and XS3. In the case of freeze thaw attack the classification is XF1, XF2, and XF3, XF4. And then there is a chemical attack which is XA1 XA2 and XA3.

The American code that is the ACI that is the American Concrete Institute 318M talks off- a likely freeze thaw attack and classifies their structures as F0, F1, F2, and F3, where F denotes the freezing and thawing. It talks of structures which could be susceptible to sulfates and classifies them as S0, S1, S2, and S3. There could be structures which require low permeability for whatever reason and talks of P0 and P1; and corrosion protection of reinforcement which is classified as C0, C1, and C2.

So, now, if we look at all these codes in a certain comprehensive manner; if we see the provisions of these codes in totality, we see that indeed there is a difference of detail which is available in all these codes. But the effort is to classify the environment and try to understand what kind of measures we need to take. We have to first of all from our previous experience assume, that yes in this structure on this environment there is likely to be corrosion.

For example, if we believe that the structure is likely to be corroded on a count of carbonation or the reinforcement in the structure is likely to be susceptible to chloride induced corrosion which is not sea water or whether there is sea water. So, we must choose a particular classification, no matter what code we use. Of course, we need to know the description of mild moderate and severe; we need to choose this description before we can move to design.

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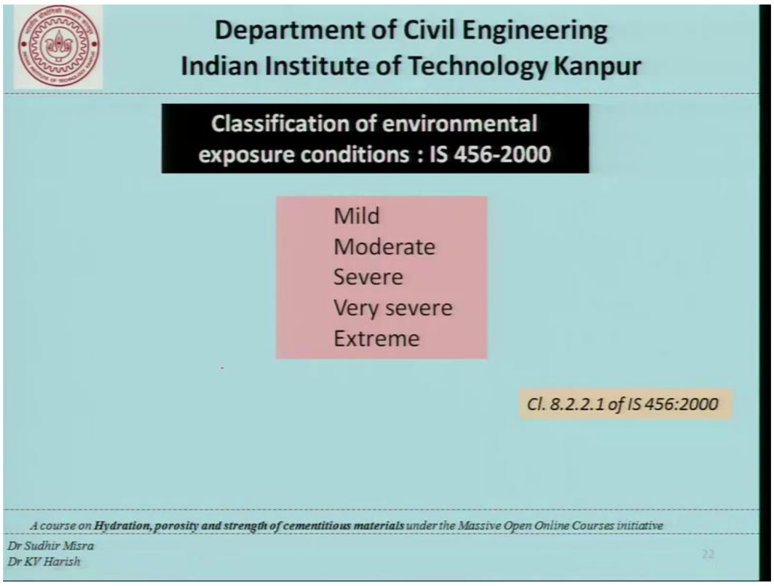

Now, let us try to look at more details of some of these classifications. So, IS 456 talks in terms of these five classifications: mild, moderate, severe, very severe, and extreme.

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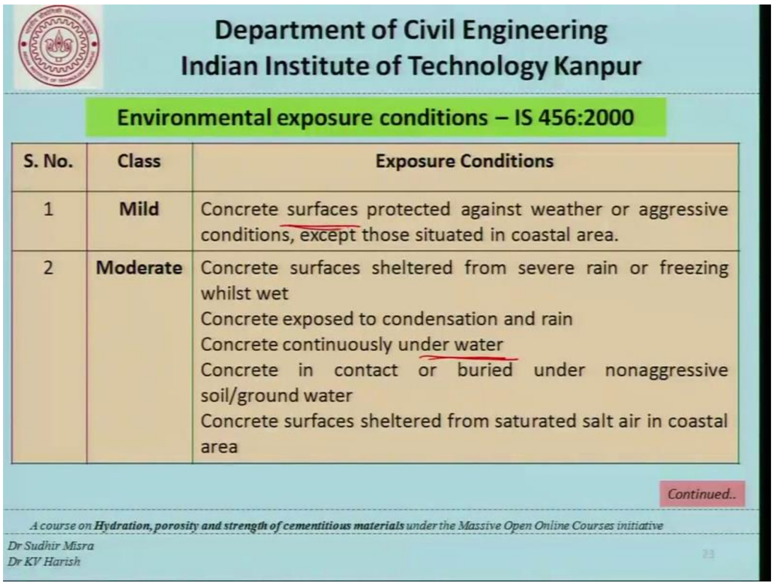

And if we look at the details mild is classification which says that concrete surface is protected against whether or aggressive conditions except those located in coastal areas. Moderate or concrete surfaces sheltered from severe rain or freezing whilst wet. Concrete exposed to condensation and rain continuously under water. Please remember that this is under water not under sea water. And concrete in contact are buried under non-aggressive soil or ground water. Concrete surfaces sheltered from saturated salt air in coastal areas. So, we are talking in terms of concrete surfaces all the time.

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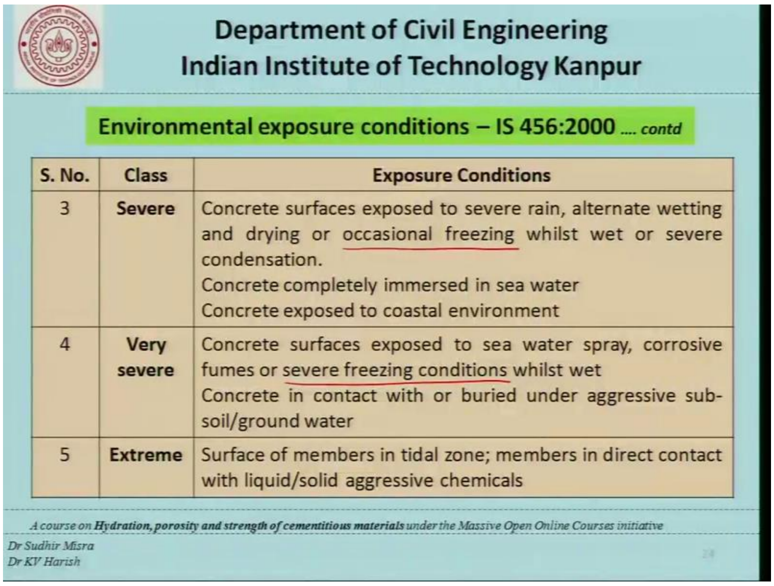

Carrying forward there is severe which means concrete surfaces exposed to severe rain alternative wetting and drying or occasional freezing, whereas when it comes to very severe we are talking of severe freezing conditions.

Now, this does not give you quantitative information on; this does not talk of a quantitative discussion on what is occasional freezing and what is severe freezing. In certain codes we will that number that if its more than 25 cycles per year that we expect freezing and thawing to occur and that kind of data is now available from metallurgical offices, we need to treat the concrete in one classification or another.

Similarly, the extreme conditions are members in tidal zones or members in direct contact with liquids or solids aggressive chemicals.

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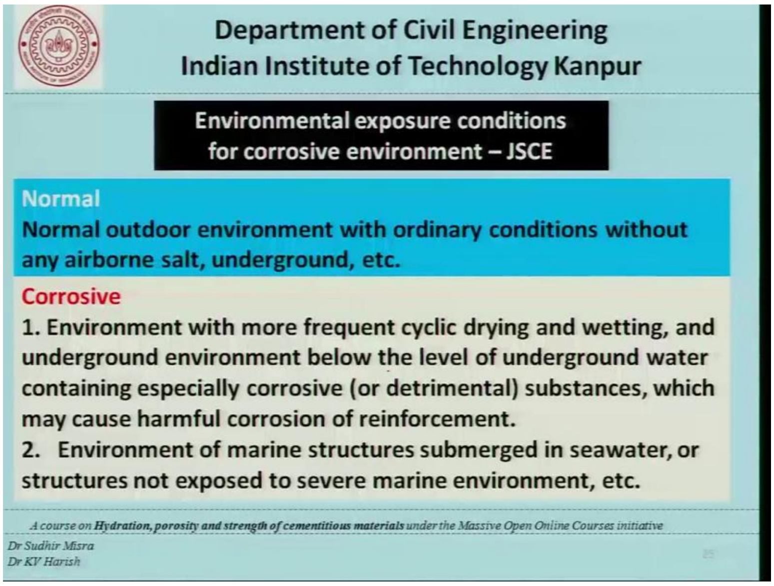

Now moving to the Japanese classification: normal refers to normal outdoor environment with ordinary conditions without any airborne salt underground and so on. Whereas, corrosive conditions are environment with more frequent cyclic wetting and drying, and underground environment below the level of underground water containing especially corrosive or determental substances which may cause harmful corrosion to the reinforcement. Or we have environment where marine structures submerged in seawater, or structures not exposed to severe marine environment. This is the classification of JSCE for corrosive conditions.

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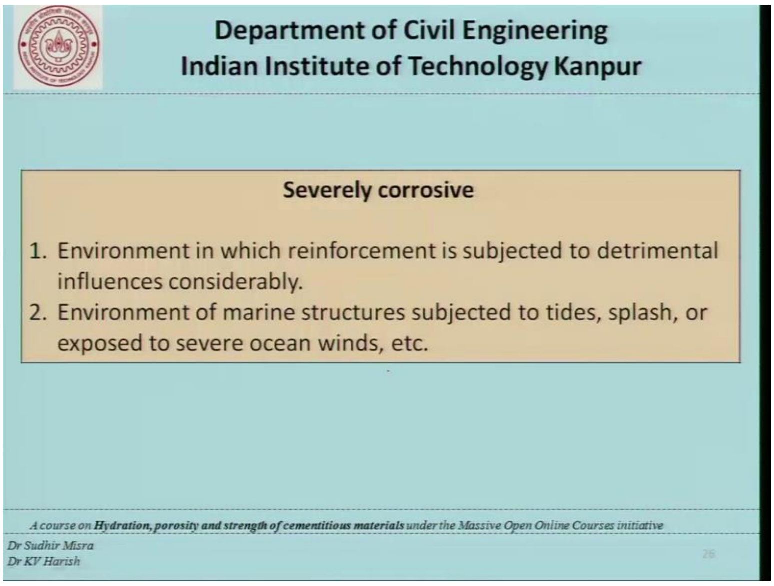

Continuing with that the third class is severely corrosive where we talk of environment in which reinforcement is subjected to detrimental influences considerably, and environment of marine structures subjected to tides splash or exposed to severe ocean winds.

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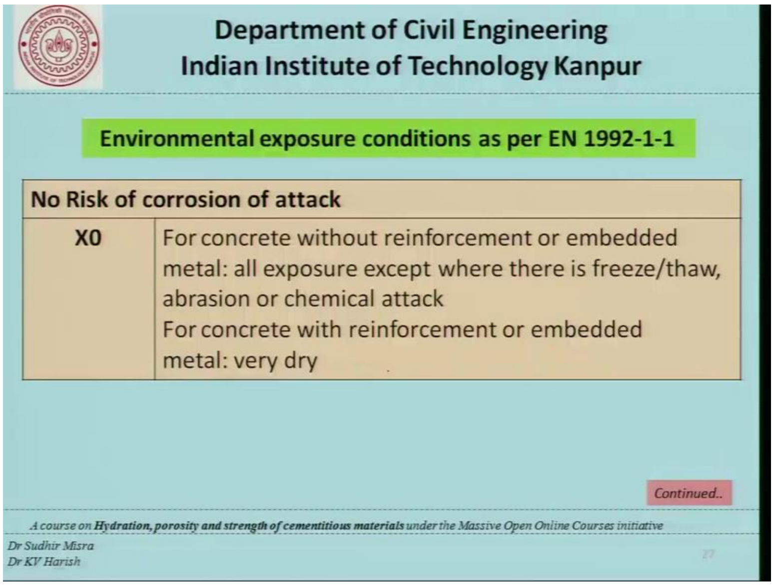

Moving on to the EN-1992 classifications: I will not read out all this slide, but there is the description for XC0, XC1, XC2, XC3, and XC4 where XC is the corrosion induced by carbonation.

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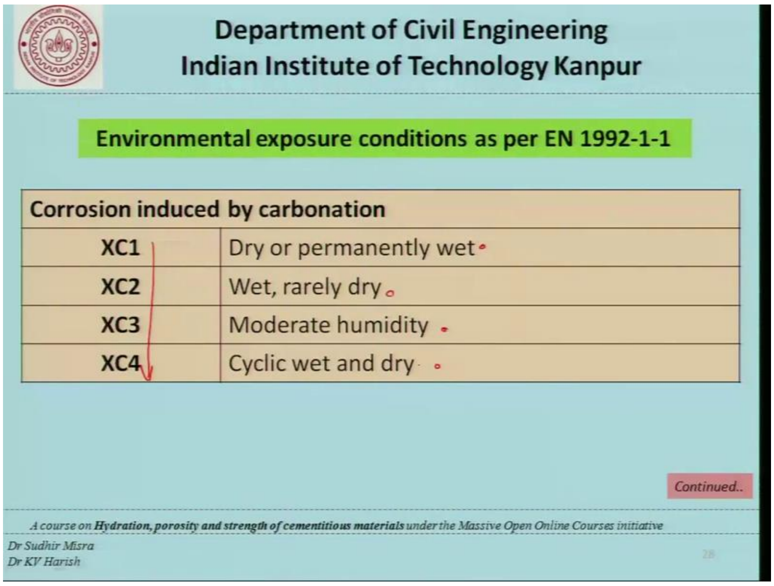

So, we can see that as XC1, XC2, and XC3, XC4 goes like this we are really talking in terms of how the wetness of the surface changes from permanently wet to rarely dry and so on.

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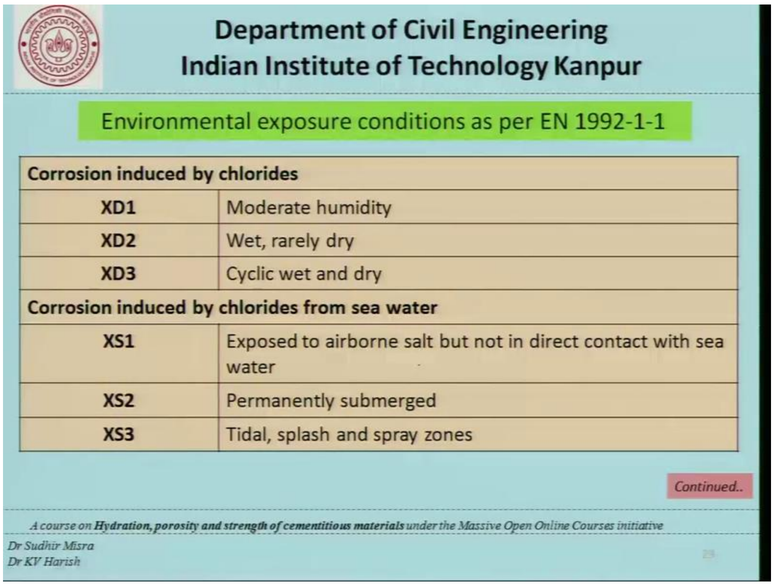

When it comes to corrosion induced by chlorides, similarly we have a classification and a description of XD1, XD2, and XD3. And from sea water we have XS1, S2, 3.

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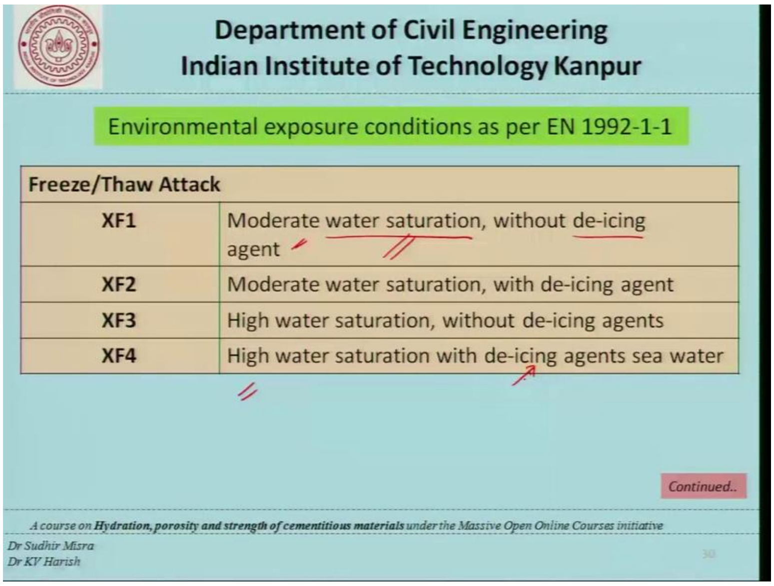

And we continue to have freeze thaw attack in terms of XF1, XF2, XF3 and XF4. And we see that it depends largely on water saturation and a combination with de icing agent application. So, depending on whether the water saturation levels are moderate or high and whether or not the de icing agents are used with the sea water the classification changes.

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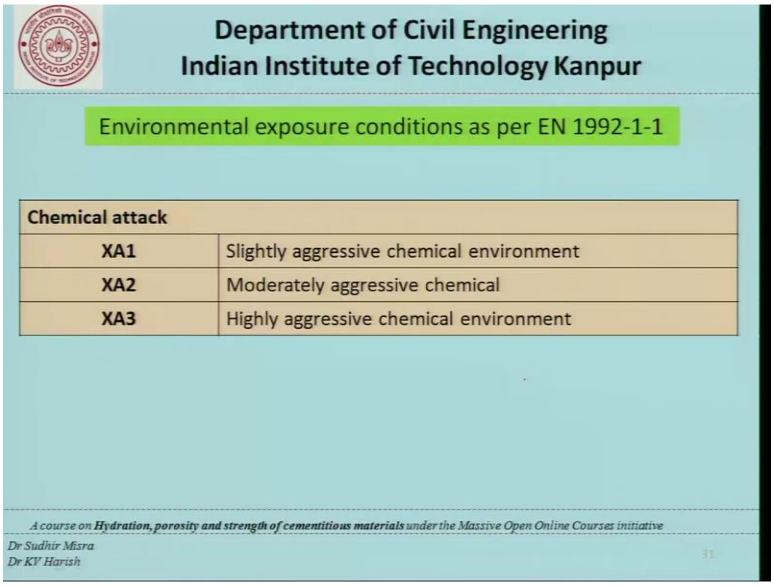

Continuing on we have XA1, XA2, and XA3 which is a chemical environment where we talk in terms of the aggressiveness of the chemical environment around concrete. And before we go to the American classification I would only like to draw your attention to the fact that if you see the discussion in here the water saturation levels and exposure to seawater are two very important determinants as for as the environment classification is concerned.

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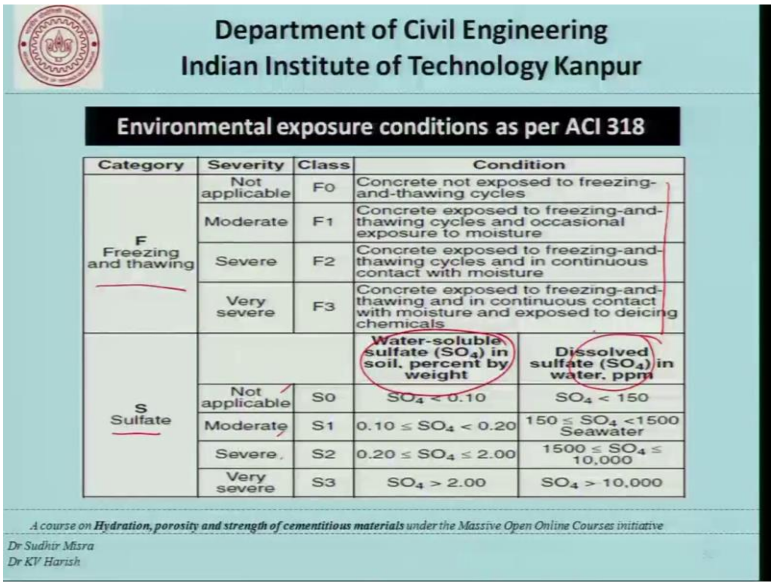

Category	Severity	Class	Condition	
F Freezing and thawing	Not applicable	F0	Concrete not exposed to freezing-and-thawing cycles	
	Moderate	F1	Concrete exposed to freezing-and-thawing cycles and occasional exposure to moisture	
	Severe	F2	Concrete exposed to freezing-and-thawing cycles and in continuous contact with moisture	
	Very severe	F3	Concrete exposed to freezing-and-thawing and in continuous contact with moisture and exposed to deicing chemicals	
S Sulfate			Water-soluble sulfate (SO_4) in soil, percent by weight	Dissolved sulfate (SO_4) in water, ppm
	Not applicable	S0	$SO_4 < 0.10$	$SO_4 < 150$
	Moderate	S1	$0.10 \le SO_4 < 0.20$	$150 \le SO_4 < 1500$ Seawater
	Severe	S2	$0.20 \le SO_4 \le 2.00$	$1500 \le SO_4 \le 10,000$
	Very severe	S3	$SO_4 > 2.00$	$SO_4 > 10,000$

Now going to the ACI 318 specifications; they have freezing and thawing which is given with f, not applicable, moderate, severe, and very severe which is described here. Similarly for sulphate attack or the vulnerable or the likelihood of a sulfate attack from not applicable to moderate, sever, and very severe classified in terms of what is the water soluble sulfate content in the soil or the dissolved sulfate in water, where the concrete is likely to be exposed to the environmental condition is different.

So, what this kind of a table tells us is that as we plan to build a structure in an environment we need to carry out the solid analysis and find out whether or not there are any sulfates in the ground water whether the soil has sulfates and so on. So, that we have an understanding of what is the kind of concrete that would be required, because the kind of concrete is also related to the cost. So, if we are doing a meticulous planning at that stage we will not have too many surprises when it comes to this stage of actual execution of any project.

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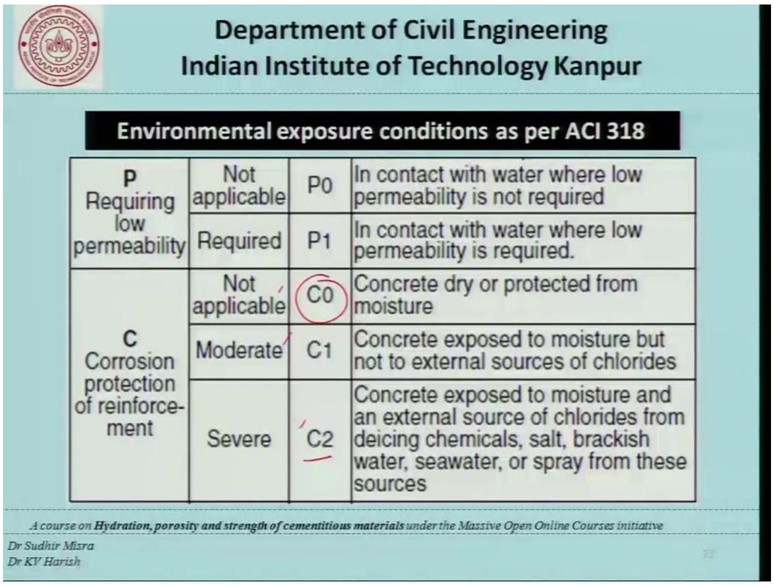

Continuing we have a situation where the designer feels that the concrete will require low permeability or there will be corrosion protection of reinforcement which is required which could be C0, C1, or C2. In the case of C0 concrete is dry and protected from the atmosphere and therefore there is no reason for any special thing to be done to protect the reinforcement from corrosion. Going on to severe corrosion likelihood we have a situation where concrete is exposed to moisture, and an external source of chloride from de icing chemical salt, brackish water, seawater, or spray from these sources.

So now, this more or less completes one pass or one round of the discussion on how the environment can be classified as for as severity is concerned. The next discussion would be on given this classification; what is the kind of action that we need to take or we are required to take to ensure durability. And that is something which we will take up in the next discussion. Here are some of the references and I will try to make it available to you the links for the codes that we have used in our discussion today. And we look forward to seeing you next time.

Thank you.