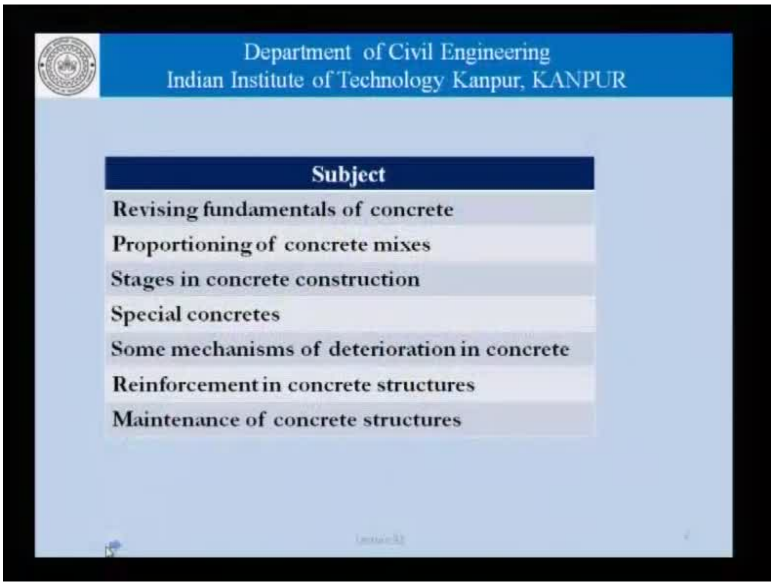
Concrete Engineering and Technology
Prof. Sudhir Misra
Department of Civil Engineering
Indian Institute of Technology, Kanpur

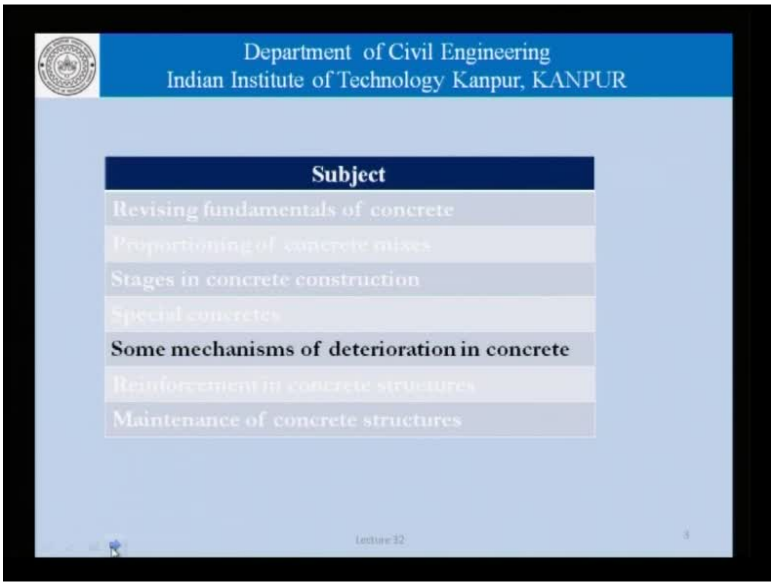
Lecture - 32
Carbonation and freezing and thawing in concrete structures

(Refer Slide Time: 00:23)

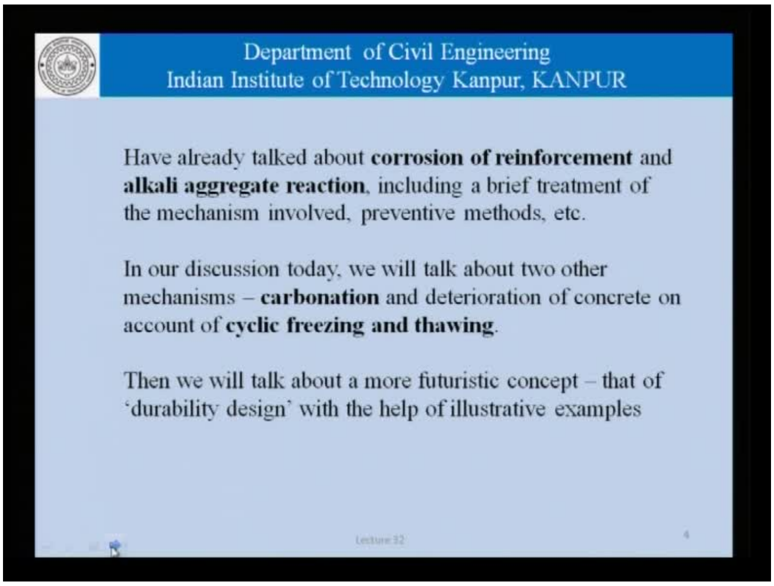


[FL] and welcome to another lecture in our module of concrete engineering and technology where we are talking about different aspects of concrete; beginning with the fundamentals, proportioning of mixes, stages in construction, special concretes deterioration, reinforcement and maintenance.

(Refer Slide Time: 00:36)



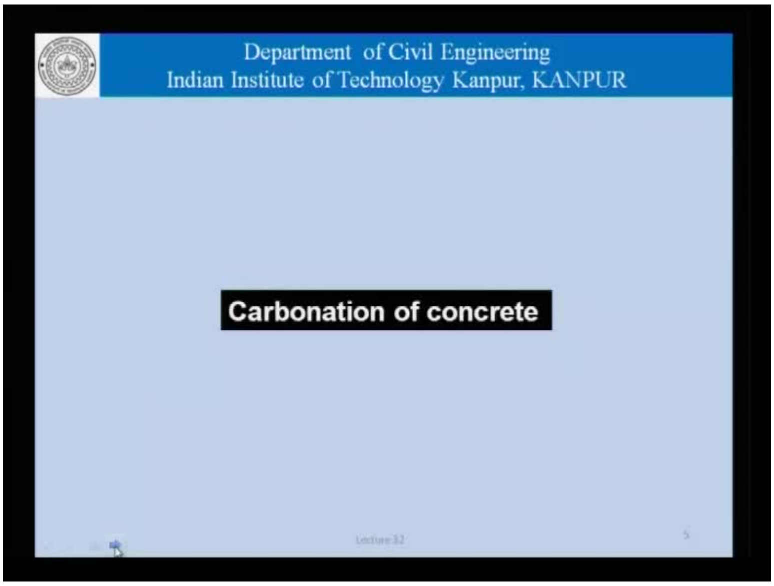
(Refer Slide Time: 00:43)



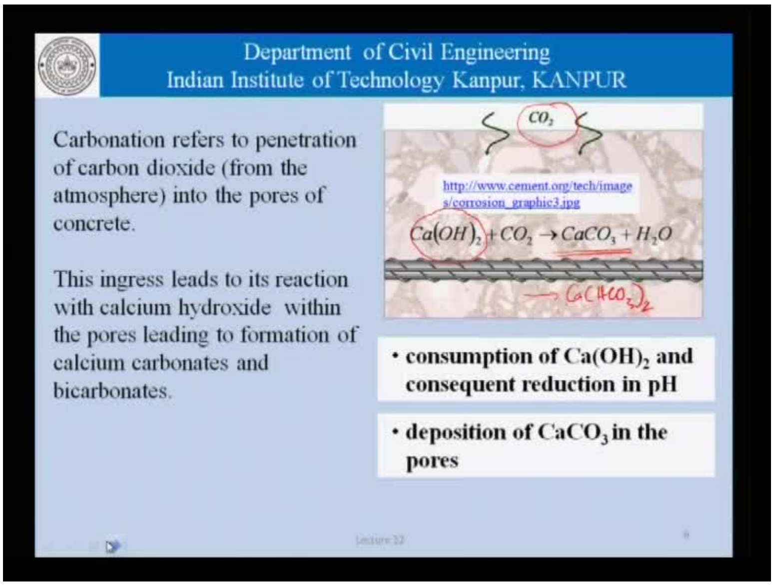
And, when we talked about some of the mechanisms of deterioration in concrete, we have talked about corrosion of reinforcement and alkali aggregate reaction; including a brief treatment of the mechanisms involved, preventive methods, implications and so on and so forth. In our discussion today, we will be talking about two other mechanisms; carbonation and the deterioration of concrete on account of cyclic freezing and thawing. We had mentioned carbonation and passing, when we were talking about reinforcement corrosion in reinforced concrete structures.

Following the discussion on carbonation and freezing and thawing, we will also talk about a little bit about the concept of durability design. And, that is something which is listed here as futuristic. Basically, it means that we do not do that kind of durability design in our structural design or durability design in that sense is not a part of the normal design process; that we go through when we design structures today. So, this something which we would possibly lift to see in the future and that is something which we will talk about at the end with the help of illustrative examples.

(Refer Slide Time: 02:09)



(Refer Slide Time: 02:11)



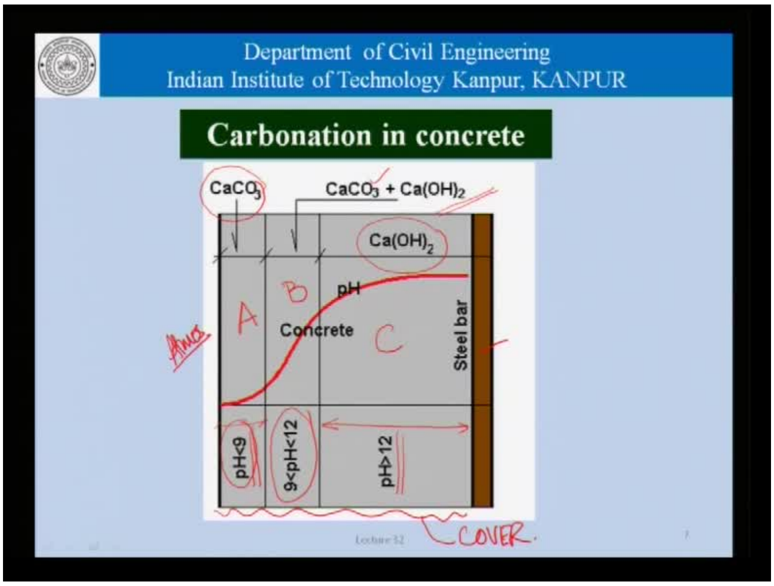
Now, beginning our discussion today with the carbonation of concrete. Basically, concrete structure exposed to the atmosphere or exposed to a certain amount of carbon dioxide. And, this carbon dioxide can penetrate into concrete through the pores which are there in concrete. And, these pores and pores spaces, the kind of volume of pores; all those ideas have been talked about earlier. And, we know that on account of hydration, a lot of calcium hydroxide is available in the pores spaces. Now, as far as carbonation is concerned, most concrete structures or in fact all concrete structures in atmosphere are exposed to a certain amount of carbon dioxide which is present in the atmosphere.

Now, this carbon dioxide can obviously permeate into the concrete through the pores spaces which are there on account of the normal porosity; the genesis of which is arising out of movement of water which is left behind after hydration and so on. So, carbonation basically refers to the penetration of carbon dioxide from the atmosphere into the pores of concrete. And, this ingress needs to its reaction; that is the reaction of carbon dioxide with calcium hydroxide, within the pores leading to formation of calcium carbonates and bicarbonates. So, we know that there is a lot of calcium hydroxide sitting in the pores spaces as a result of the hydration reactions.

We know that all the solid complexes in cement when they hydrate; they give rise to calcium hydroxide. And, this calcium hydroxide is the reason for having a very high p H of pores solution and is available within concrete. Now, the penetration of carbon dioxide from the atmosphere into the concrete leads to this reaction here; which shows calcium carbonates are formed and if this continues we also get calcium bicarbonates being formed. So, basically carbonation is the process by which calcium hydroxide within the pore solution is converted to calcium carbonates and bicarbonates; as a result of the reaction of calcium hydroxide with the carbon dioxide.

So, in principle what happens as a result of the carbon dioxide ingress, is the consumption of calcium hydroxide and the consequent reduction in p H of the pore solution. So, this calcium hydroxide is responsible for the very high p H; which is in excess of about say 12 or 13 in the pore solution. Now, naturally if calcium hydroxide gets consumed and converted into calcium carbonates or bicarbonates, the p H of the pore solution will go down. So, this reduction in the p H has its own implications as far as the durability is concerned; as we shall see shortly. And, we have the second part of it which is deposition of calcium carbonate in the pores. So, this deposition of calcium carbonate in the pores has its own implications in terms of the properties of the concrete.

(Refer Slide Time: 05:40)

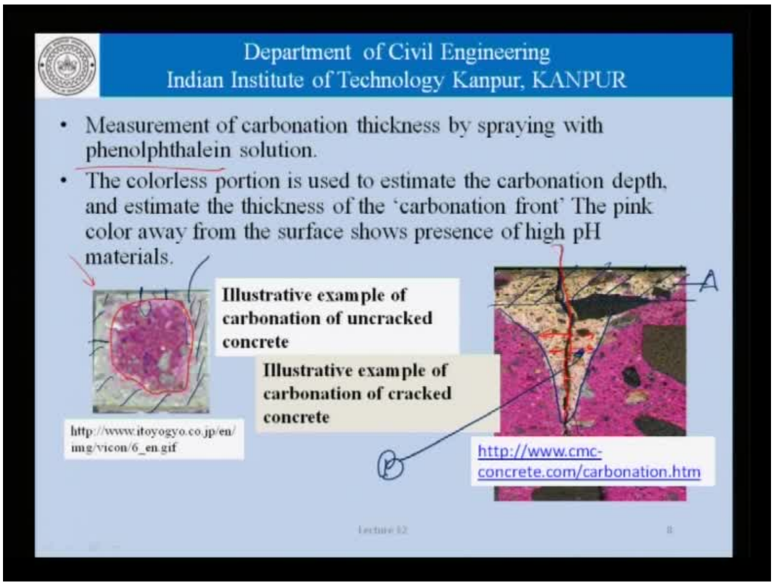


Now, once we have that; now, here is a representation of what really goes on as a result of the carbonation and concrete. So, we have a zone here, which is the closest to the atmosphere. So, here is the atmosphere, we have this region here; which is the cover concrete and we have this steel bar here. Now, as carbon dioxide penetrates into the concrete and reacts with calcium hydroxide within, we can imagine or think that there is this region here; where let us say a large amount of calcium hydroxide has been converted to calcium carbonates.

So, in this portion here we can say that we have very little calcium hydroxide left. And, we have a reasonably large reduction in the p H. In contrast we have a region here, which is a still largely unaffected by the penetration of carbon dioxide from the atmosphere. And, we have a lot of calcium hydroxide still sitting here and the p H is still in excess of let say 12 or 13 or whatever it is. Between these two zones, we have a transition zone here where the p H is let us say between 9 and 12 and here we have both. Some amount of calcium carbonate which has been found and not all calcium hydroxide has been consumed and therefore, we have some calcium hydroxide there as well.

Please, remember that this is only a schematic representation to help us understand the carbonation process. Basically, what we are trying to do is to say that; well, one of the functions of cover concrete is to protect the reinforcement against the corrosion. And, since carbonation is one of the reasons for corrosion, we are trying to understand how we can module the changes in the different zones of cover concrete to better understand a model the process of carbonation. So, we are trying to divide the cover concrete into a zone A B and C. Where zone A is a zone where most of the calcium hydroxide has been consumed and a lot of calcium carbonate has been deposited. Zone C is largely unaffected and therefore, there is practically no calcium carbonate there; its all calcium hydroxide. And, zone B is still in the transition where some calcium carbonate is there and there is still some calcium hydroxide.

(Refer Slide Time: 08:42)

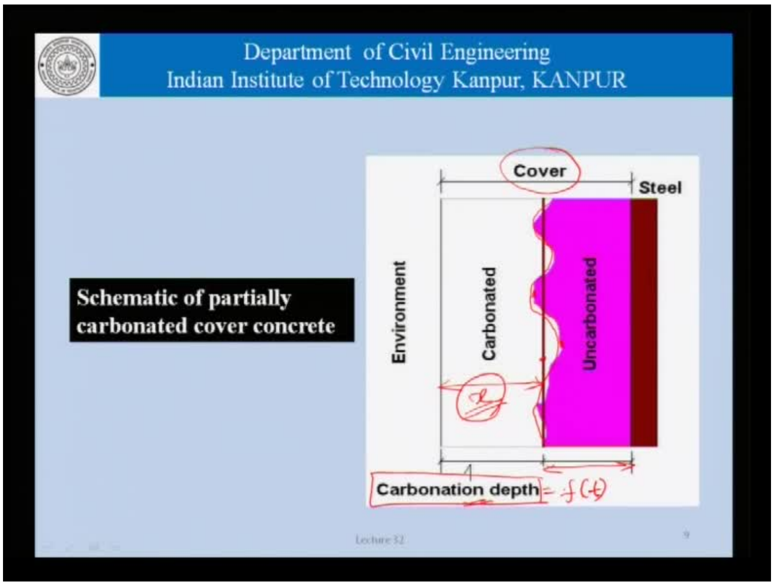


So, with this model understanding let us try to see how the carbonation is measured in concrete. Now, as far as the measurement of p H is concerned, one of the most simple things we know from high school is the phenolphthalein test. We know that phenolphthalein turns pink in high p H. So, now we have a concrete surface such as the one that shown here and we spray phenolphthalein on it. We can identify more or less zone here, which is pink that is this is the zone which has high p H and there is this shown here which is colourless. And, this is the zone where the calcium hydroxide has been converted to calcium carbonates.

So, there is depleted amount of or there is a depletion in the levels of calcium hydroxide. And, therefore, the p H in this portion here where we can say that carbon dioxide has penetrated completely. Of course, once we look at actual situation here we can see there are pockets, where it is difficult to identify whether the region should be classified has pink or white. And, also this depth which we would like to measure unlike what we saw in the previous slide, is not straight. So, these are things which an engineer has to bother about as far as the principle is concerned it is establish that as carbon dioxide moves in calcium hydroxide is consumed and the depth up to which this consumption has taken place can be measured through a simple phenolphthalein spray.

This here is the example of carbonation as will occur in crack concrete. What is being seen here, is that in addition to the carbonation which has taken place in this part which is let us say A which is similar to this kind of an area; where carbon dioxide has generally penetrated into the cover concrete. In addition to this carbonation has also spread in this portion; let us say call it B. Because carbon dioxide has gone through this crack and spread into concrete through the crack causing the calcium hydroxide in the neighborhood of cracks also to be consumed. And, in such cases of course, a definition of carbonation depth becomes a lot more complicated. But to deal with these complications is part of our engineering exercise. And, once we understand the processes then it is only a matter of making the right kind of approximations, the right kind of models and making engineering decisions.

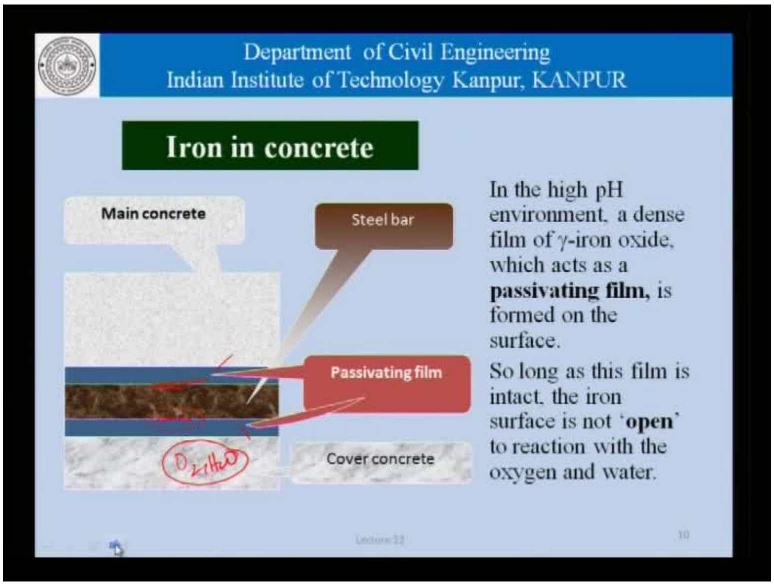
(Refer Slide Time: 11:53)



Now, let us get back to a schematic representation once again of cover concrete as shown here. Where we are now saying that instead of including the transition depth; we say that well, we will simplify the matter and say that there is a carbonated depth and an uncarbonated depth. So, we are saying that the cover concrete in the previous slide was shown to be divided into 3 parts; the totally carbonated, partially carbonated and the uncarbonated. In this case, now we are only saying that well let us not talk about the partially carbonated depth; let us talk in terms of a carbonated zone and an uncarbonated zone. The carbonated zone would appear to be white, if we attesting it with a phenolphthalein kind of a spray and the uncarbonated zone will be pink. Now, this front here has been purposely shown to be not necessarily straight and that is what we will see in actual practice most of the time; if we actually carry out any phenolphthalein spray from core or any structure that we visit.

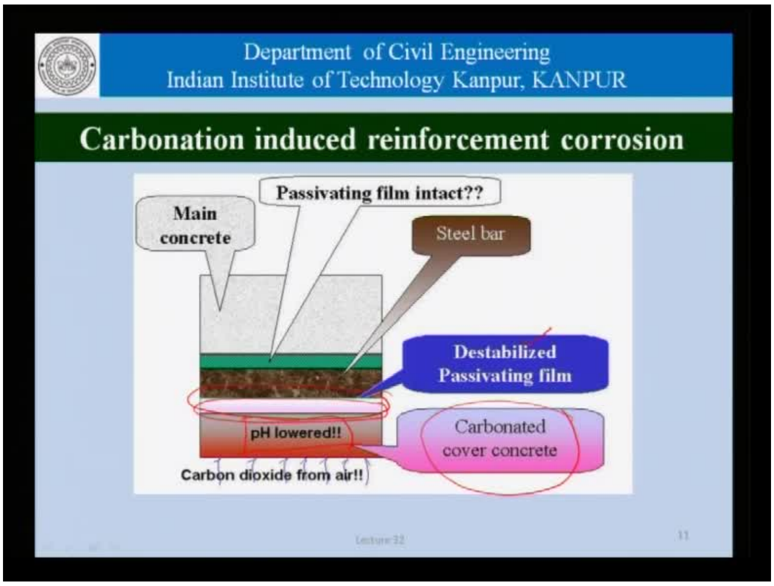
This depth here, now how we define this depth is a different matter whether we take it to be the maximum here, we take it to be the minimum here, we take it to be some kind of an average; whatever it is, now this irregular nature of the carbonation front notwithstanding. If we were to decide or draw a straight line as I shown here, then this depth if it has a value of x; notwithstanding how we measure the x, whether we take it to be the maximum value here or the minimum value here or the average value whatever we do, this x is sometimes call the carbonation depth. And, naturally this carbonation depth is a function of time as more and more time goes by the carbonation depth increases. And, that is something which we need to keep at the back of our mind, when we are talking about carbonation in concrete.

(Refer Slide Time: 14:13)



We have seen this picture before and it basically talks in terms of how iron and concrete is protected against corrosion, it is the high p H environment. And, therefore, a dense film of gamma iron oxide which acts as a passivating film is formed on the surface as shown here. And, so long as this film is intact the surface of the iron which is this place here, is not open to the reaction with oxygen or water which may be present in the cover concrete. But if this surface becomes available for attack, then the reinforcement is susceptible to corrosion.

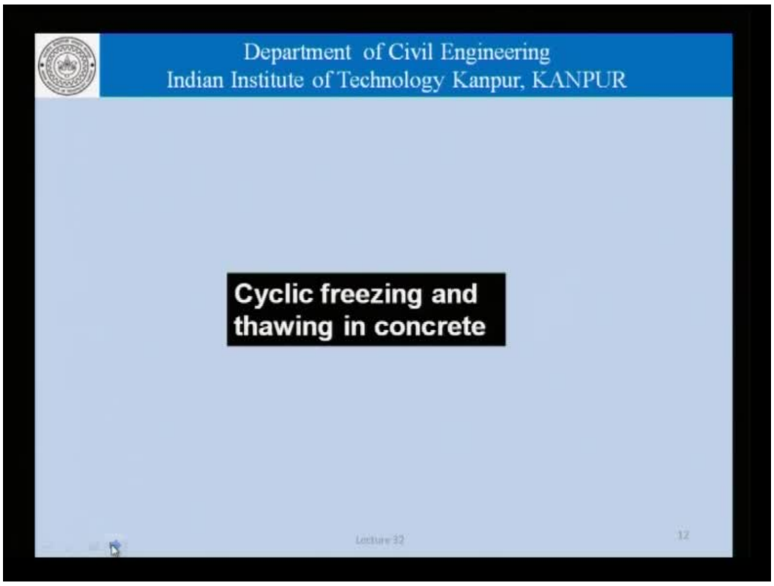
(Refer Slide Time: 14:58)



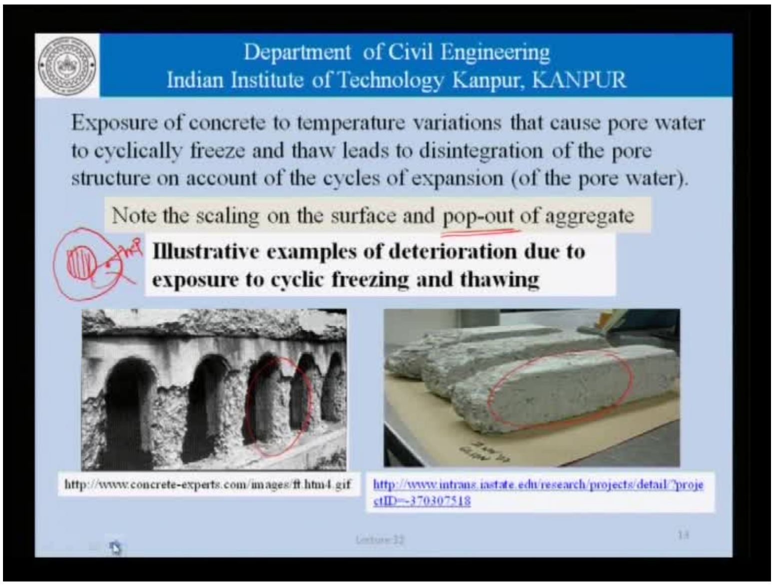
So, as far as the carbonated concrete is concerned; what really happens is that once the concrete becomes carbonated as shown here, this p H in the cover concrete is lowered and therefore, the passivating film in this part is destabilized. And, therefore, it is as good as not existing. And, that renders this surface of the reinforcement susceptible to corrosion. So, as far as addressing the problem of carbonation in reinforced concrete structures from the point of view of durability and reinforcement corrosion, it can be said that carbonation leads to corrosion by the form that on account of the penetration of carbon dioxide into the concrete, the calcium hydroxide is consumed. This lowers the p H and if the p H falls below; let us say 9 or 10; the passivating film that is stable otherwise becomes thermodynamically unstable. And, that means that the surface of reinforcement becomes vulnerable to corrosion on account of the presence of oxygen and water in the cover concrete.

So, the presence of oxygen and water in cover concrete is never in question. It is only that the presence of the passivating film that prevents of physical contact between the reinforcing surface and the oxygen and water; that prevents corrosion in normal concrete. But once that film is destabilized the surface is vulnerable to attack.

(Refer Slide Time: 16:40)



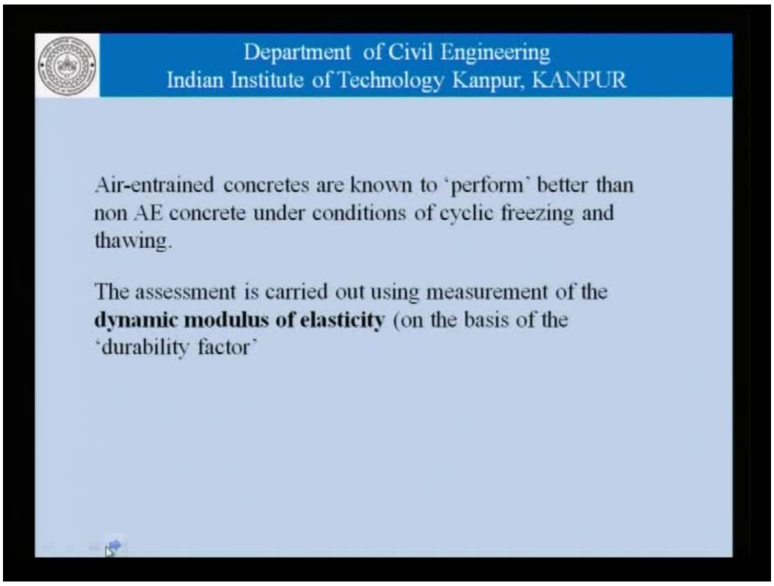
(Refer Slide Time: 17:00)



So, with this overview of the carbonation process and its ensuing implication in terms of reinforcement corrosion; let us briefly talk about cyclic freezing and thawing in concrete. Now, explosion of concrete to temperature variations that cause pore water to cyclically freeze and thaw, leads to disintegration of the pore structure on account of the cycles of expansion of pore water. We know that when the water freezes at 0 degree centigrade, it expands. And, therefore, if the concrete is saturated with water and the temperature of the atmosphere becomes such that the pore water freezes. It will obviously cause some kind of expansive stresses in the surrounding pore structure. And, if this happens cyclically, that is the water freezes and then that is the temperature in the atmosphere rises over period of time; it thaws and freezes once again and that is what is cyclic freezing and thawing. If that happens repeatedly over period of time, then the pore structure actually disintegrates and this disintegration of the pore structure is what we are talking about; when we are talking about the problem of freezing and thawing in concrete.

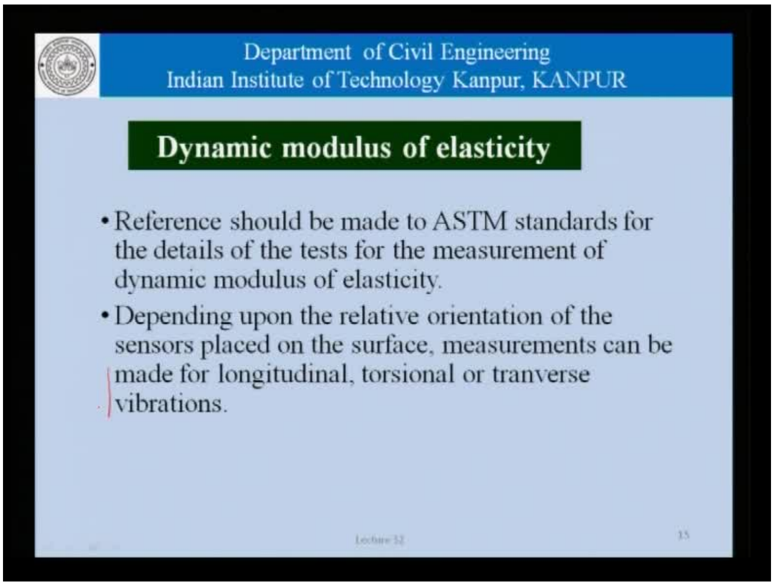
These here our illustrative examples of deterioration on account of exposure to cyclic freezing and thawing. So, we can see here whether it is this structure here or these beams which are specimen tested in laboratory. We can see that there is a lot of disintegration in pore structure and also pop out of aggregate. See, what really happens is, that if we have an aggregate sitting inside hardened cement paste; on account of cyclic freezing and thawing. This pore structure of HCP is the one that will disintegrate. The aggregate itself is not so vulnerable, even though it has its own porosity and so on; but it is the HCP of the cement paste which is vulnerable or H it is more vulnerable. Now, on account of repeated cycles or freezing and thawing, the HCP disintegrates. Now, if the HCP around the aggregate disintegrates and gets removed, then the aggregates become unlocked from their matrix and we have a pop out of aggregates.

(Refer Slide Time: 19:43)



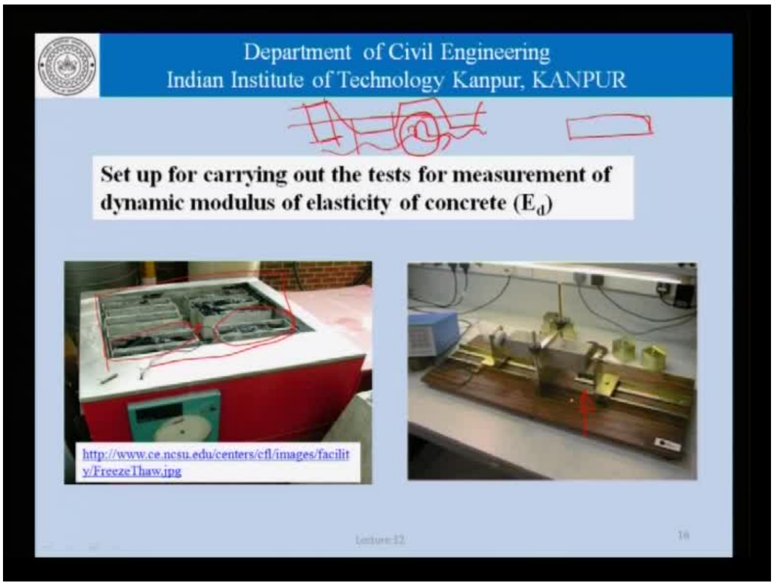
So, one of the things that happens as far as freezing and thawing of concrete is concerned is scaling, pop out and a general disintegration of the surface layers. Now, air entrained concretes are known to perform better than non-air entrained concretes under conditions of cyclic freezing and thawing. And, this is something which we have talked about before, when we are talking in terms of proportioning of concrete mixes and even earlier discussion on durability. The assessment in terms of whether a concrete is durable or not, is carried out based on the measurements of the dynamic modulus of elasticity; on the basis of a durability factor. Now, what these terms are we will probably see.

(Refer Slide Time: 20:19)



As far as the dynamic modulus of elasticity is concerned I would say that you should read appropriate ASTM standards for the details of the test. And, depending on the relative orientation of senses placed on the surface, measurements can be made for longitudinal, torsional or transverse vibrations; this will become clear once we see how the measurements are done.

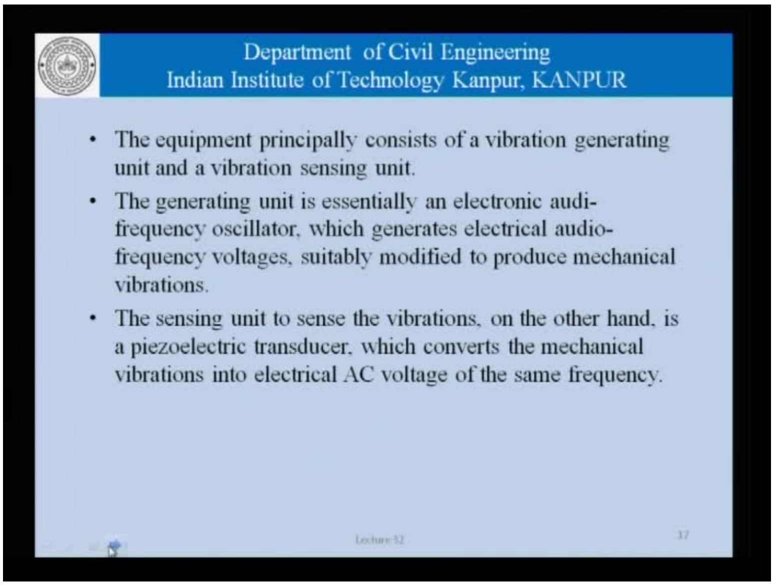
(Refer Slide Time: 20:46)



But, before that let us see how the test is actually carried out. This picture here shows how the specimens are tested in terms of exposure. So, these are some kind of boxes here and in these boxes we keep concrete prisms measuring a standard size; usually 10 centimeter by 10 centimeter by 40 centimeter. And, this chamber here, the entire chamber; all this specimens in this, they are subjected to cyclic freezing and thawing by having a fluid here and the temperature of that fluid is varied between two extremes. So, once we have the temperature cycle which is also frozen as far as the standard is concerned; we know that this is the maximum temperature, this is the minimum temperature, we know the durations of the cycles. And, therefore, we can define how many number of cycles of temperature variation we are carrying out.

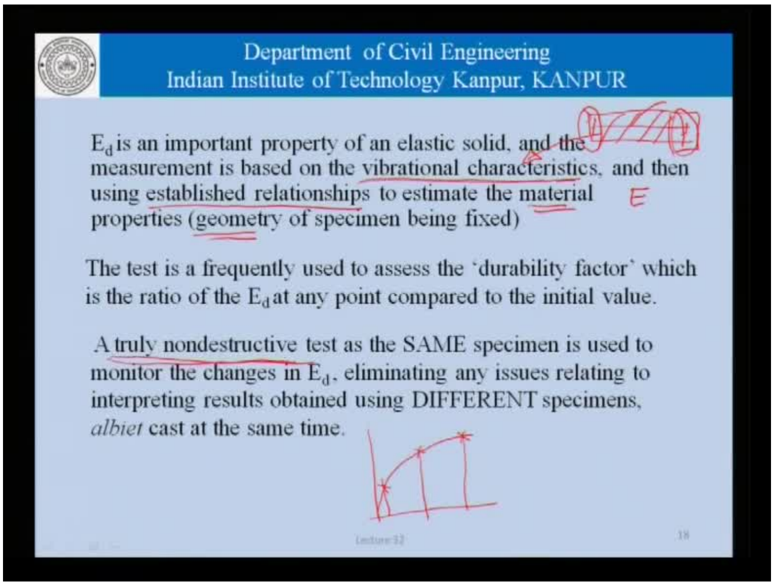
So, exposing these concrete specimens to this regime of varying temperatures, we try to subject them to deterioration. And, while the test is being done at different points and time, we try to estimate the modest of elasticity using a setup which is something like this.

(Refer Slide Time: 22:17)



Now, this setup basically consists of a vibration generating unit and the vibrations sensing unit. The generating unit is essentially an electronic audio frequency oscillator which generates electrical audio frequency voltages, suitably modified to produce mechanical vibrations in the concrete specimen. On the sensing side, to sense these vibrations on the other hand, is a piezoelectric transducer which converts the mechanical vibrations into electrical AC voltage of the same frequency.

(Refer Slide Time: 22:53)

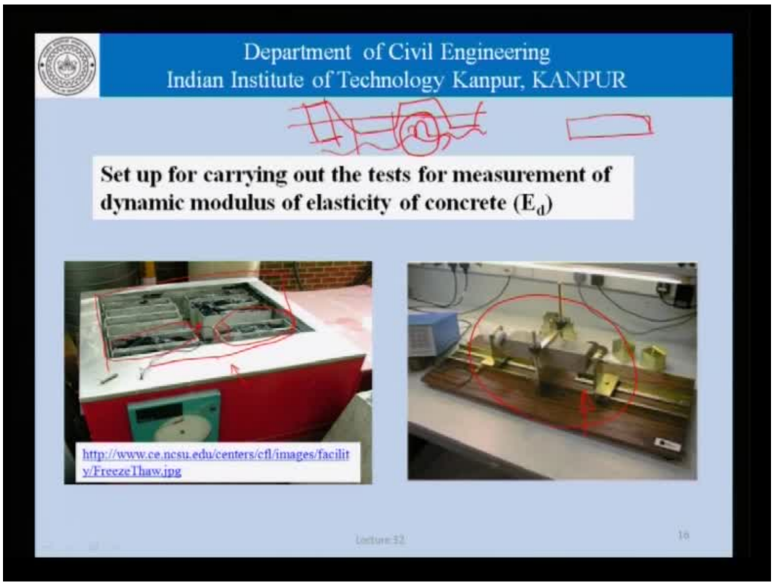


So having carried out this exercise, we try to estimate E d which is the dynamic modulus of elasticity, on the basis of the vibrational characteristics. So, what we do is we have a specimen here, we have a generating unit here and we have a sensing unit here and based on whatever we measure in the sensing unit, we get an idea of the vibrational characteristics of this specimen here. And, based on these vibrational characteristics, the natural frequency and so on; we can use the established relationships to estimate the material property which is E in our case, knowing the geometric properties of the specimen. Usually, the vibrational properties or a function of the geometry and the material properties. So, here we are trying to estimate the material properties by measuring the vibrational properties and having a prior knowledge on the geometry on this specimen. And, from those material properties, we are able to assess the health or the performance or the characteristics of the concrete.

The test is frequently used to assess the durability factor which is the ratio of the E d that is the dynamic modulus elasticity; at any point compared to the initial value. So, it is not really only the absolute value of E d that we are talking about. But we are talking about the change in the dynamic modulus of elasticity of that particular specimen as it occurs over period of time. And, to that extent the method is a truly not destructive test, as the same specimen is used to monitor the changes in the modulus of elasticity; the dynamic modulus elasticity E d, eliminating any issues relating to the interpretation of results obtained using different specimens, all though they may be cast at the same point and time.

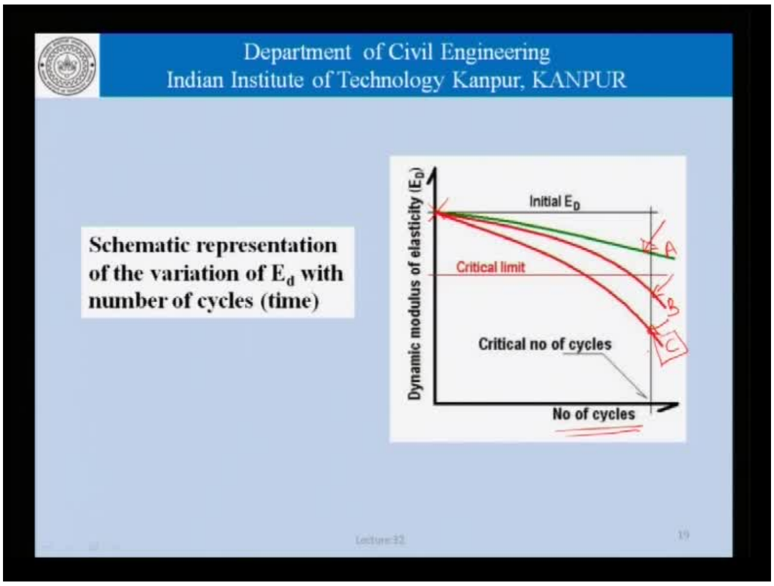
If I have to explain that once again, we know that concrete develops strength over period of time. We know that the strength of concrete is so much here, so much here and so much here. How do we get this information? We get this information by testing cubes or cylinders which are cast at the same time but tested here, some other cylinders are tested here some other cylinders are tested here; we assume that the concrete is the same. And, therefore, whether we are using different specimens or the same specimen it really does not matter. In fact, as far as strength testing is concerned we cannot really use the same specimen because the test is destructive in nature. In this case, here the test is truly nondestructive; that is the same specimen.

(Refer Slide Time: 26:12)



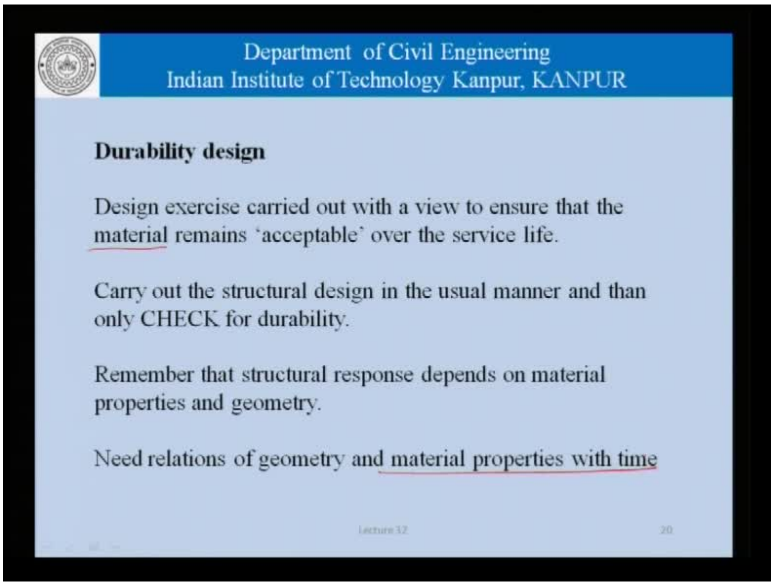
If we go back to this setup here, the underlying assumption is the testing the concrete using this kind of a vibrational method does not alter this specimen at all. And, therefore, the same specimen continues to be exposed for further cycles in this chamber. And, the same specimen can be used at different points in time to see or monitor the changes that occurring the dynamic modulus of elasticity. And, that is a very big advantage when using this method, because we are really using the same specimen. It is one of the reasons, because of which we also work with the relative values rather than the absolute values.

(Refer Slide Time: 27:01)



Now, this picture here shows a schematic representation of the variation of the modulus of elasticity with a number of cycles which is actually related to time. So, we have an initial value of the dynamic modulus of elasticity and as the number of cycles of exposure increases, that is with the passage of time; different concretes could show different patterns of change in the E d value. So, if you have these 3 concretes; let us say A B and C, we can see that the concrete A shows the minimum change in the dynamic modulus of elasticity and this concrete C is not performing well. Now, this is the first pass or basic discussion on freezing and thawing and how the performance of concrete under cyclic freezing and thawing can be assessed or monitored. Now, let us come to the second part of our discussion today, which is durability design.

(Refer Slide Time: 28:12)

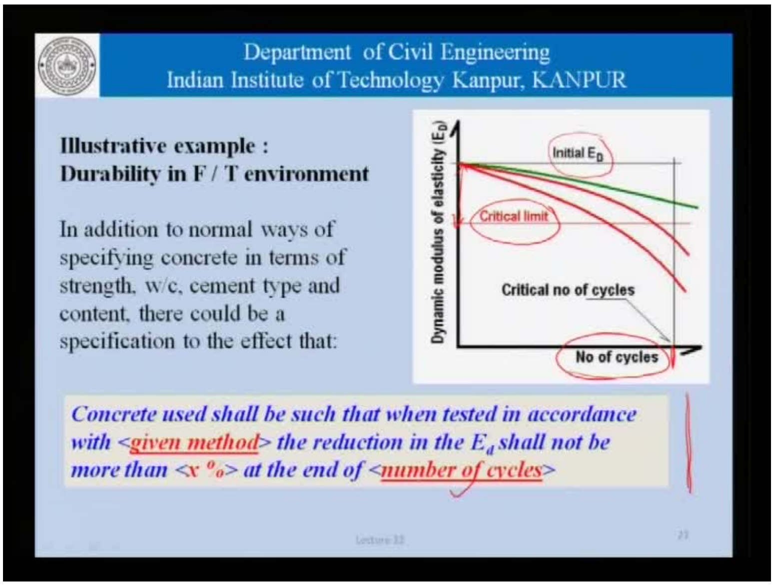


Now, design exercise carried out with a view to ensure that the material remains acceptable over the service life; that is the essence of durability design. So, deliberately I have use the word material and not structure. Because what we are talking about here is that the material properties should still be acceptable. There are situations where we need to talk about the structure itself and that also we will see in a subsequent example. It involves carrying out the structural design in the usual manner and then check for durability. It is not necessarily full-fledged design carried out based on durability considerations but at least a check on whether a design carried out in a established manner using principles which are known, from the structural point of view; how does it perform in terms of the durability of the material?

Usually, in our structural design procedures, we do not consider the changes in the material properties over time; in terms of strength, in terms of modulus of elasticity and so on, it is only very rarely that we account for the changes in the properties over a period of time. But with the present level of understanding, it is only natural that concept will come in; that we should check whether or not the material will survive to a level which is still acceptable at the end of the service life.

We should remember that the structural response depends on the material properties in the geometry, whether we are talking in terms of deflections or strains or deformations or cracking. All this is related to not only the lower that is applied but also the material properties of the material that we are using and the geometry of the member; whether it is a beam or a column or slab or whatever. As far as most concrete structures are concerned, the geometry does not change with time. It is difficult to when we saw the situation where the beam or the column will grow or shrink insides. It is mostly the material properties that will change in any case as far as durability design is concerned or being able to check durability, we need to have relations in terms of geometry and material properties with time. And, this is the essence of durability design. That is, what kind of models that we use to relate the properties of the material with time.

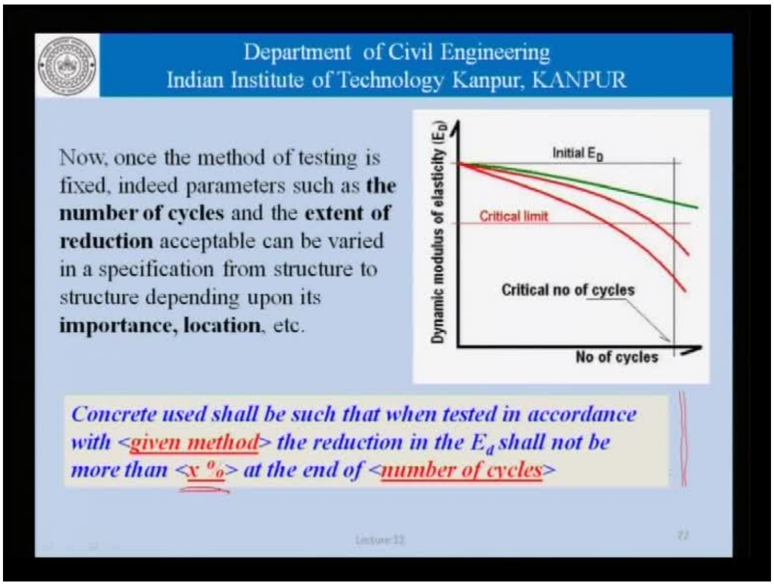
(Refer Slide Time: 31:15)



Let us talk in terms of an example, which is easier to understand. Let us consider the example of durability in freezing and thawing environment. Let us talk in terms of durability in cyclic freezing and thawing environment that we just did a few minutes ago. We have talked of this kind of a variation in the dynamic modulus of elasticity of concrete. We said that the concrete has an initial value of E d and if that concrete is tested using a certain standard, then the dynamic modulus of elasticity will reduce and the performance of that concrete would depend on the properties of the material and so on. So, as far as durability design is concerned, in addition to the normal ways of specifying concrete in terms of strength, water cement ratio, cement type and content. There could be a specifications to the effect that concrete used shall be such that when tested in accordance with any given method, the reduction in E d shall not be more than a certain percentage at the end of a certain number of cycles.

Now, this is the kind of specification which is performance based, performance taking into account the environment in which the concrete has been exposed. So, it is not only specification of the concrete in terms of the strength, that well if a concrete is subjected cyclic freezing and thawing, use air entrained concrete of 5 percent, using air entraining agent which has a certain property, use a certain type of cement and so on. But we basically say that well no matter what you do, at the end of it when tested in certain manner the extent of reduction in the dynamic modulus of elasticity should not exceed the certain number.

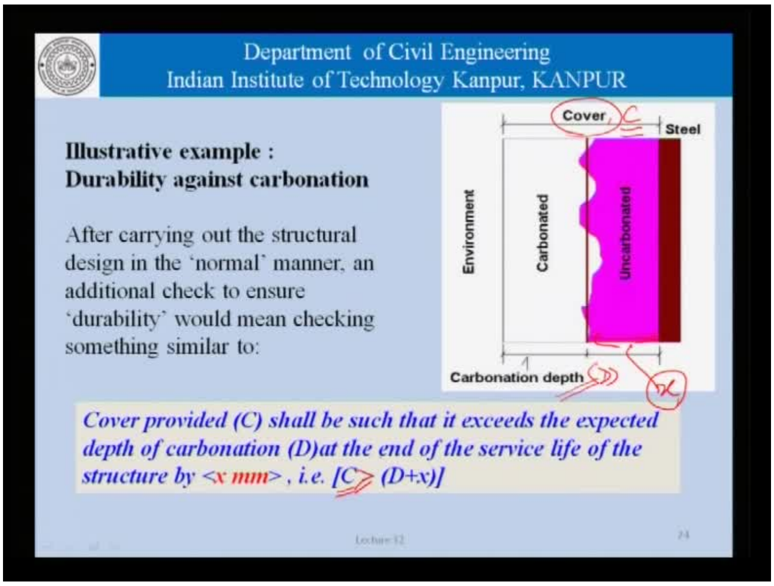
(Refer Slide Time: 33:30)



So, basically we lay down this critical limit and this number of cycles. Now, this part, this part. Now, once the method of testing is fixed, the parameters such as the number of cycles and the extent of reduction acceptable can be varied in specification from structure to structure depending upon its importance and location and so on and so forth. So, it is not necessary to have the same level of performance or to ask for the same level of performance in all concrete structures. The expected level of performance could be different depending in terms of the importance, the impact of that structure and so on and so forth. And, therefore, in certain cases we may accept, let us say 20 percent reduction in E d and 100 cycles; but in certain cases we may just expect 10 percent. In certain cases may be we will expect up to 30 percent.

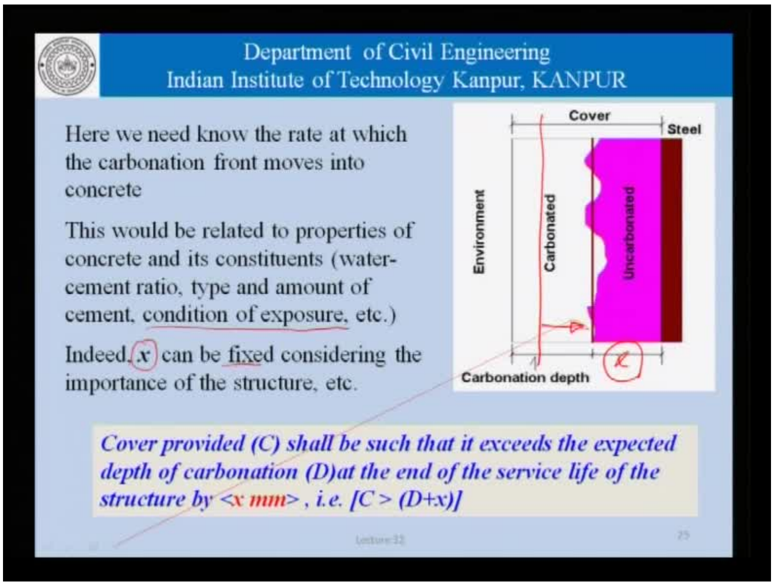
So, depending on what kind of a structural design we do, what is the importance of the structure that we are trying to design; this is the kind of performance requirement that we can lay down when specifying a concrete. So, we carry out the design of the structure in a usual manner and then see that the concrete that we are going to use also needs these performance criteria.

(Refer Slide Time: 34:51)



Now, let us take another illustrative example that of durability against carbonation. Again carbonation something which we just completed and we have seen, how we are going to handle the situation in terms of defining a carbonation depth and relating it to the cover concrete. In this case, after carrying out the structural design in the normal or the usual manner, an additional check to ensure durability would mean checking something similar to cover provided C, which is this value here, shall be such that it exceed the expected depth of carbonation, which is D here, at the end of the service life of the structure by x millimeters and this is the value x.

(Refer Slide Time: 36:30)

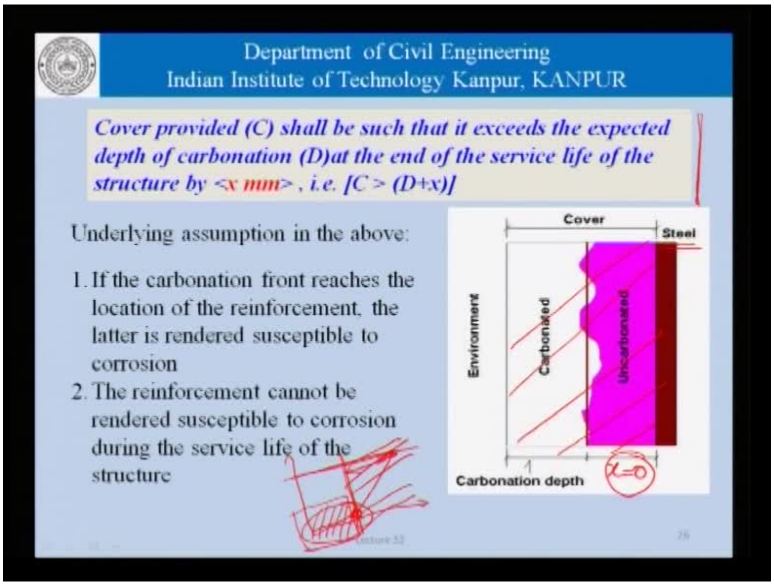


So, we are saying that C should be greater than or equal to D plus x. In this case, I am sure you can notice that we are not talking in terms of only the material; we are talking of a composite action of this structure. That is, for the concrete we are trying to say, how much is the design carbonation depth over the service life of the structure. And, saying that the cover provided should be such that it is greater than the likely depth of carbonation by a certain amount. Of course, in this case we need to know the rate at which the carbonation front moves into the concrete, we need to know how this depth changes with the period of time. So that at the end of service life where it would be and that is an estimate that we are making even at the outside.

And, indeed the rate of movement of carbonation in front into concrete would be related to properties of the concrete and its constituent. For example, the water cement ratio, the conditions of exposure are important in terms of examples whether the concrete is indoor or outdoor. Because if it is indoor it is not subjected to rain, if it is outdoor it is subjected to rain; rain tends to make the concrete wet. And, in wet concrete carbonation progresses at different rate then it progresses in the dry concrete. So, all these factors have to be born in mind when we are talk in terms of how quickly or how slowly will the carbonation front move into the concrete through the cover concrete. And, as far as the x is concerned that is this additional depth, that is the additional uncarbonated concrete; this can be fixed considering the importance of the structure and other considerations.

So, in very important structure we may say that well x should be at least 15 millimeters, in other structures we may say 5 millimeters is acceptable and so on. The principle thing is that if we keep on increasing x, what we are really doing is prescribing higher and higher cover values. And, that has its own implication in terms of the self-weight of the structure the economic and so on.

(Refer Slide Time: 38:36)

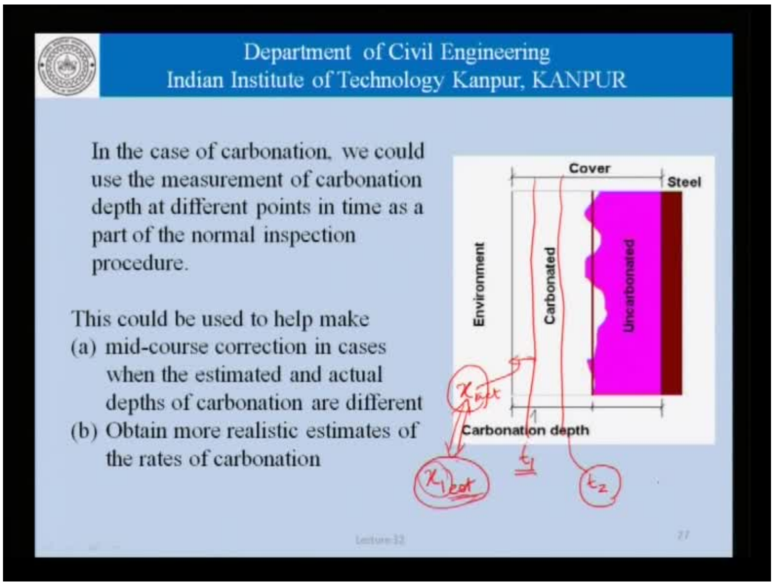


Now, let us examine this provision that we wrote, provide a cover depth C such that it exceeds the expected depth of carbonation D at the end of service life, the structure by x millimeters; a little more. The underlying assumption in this statement is; 1, if the carbonation front reaches the location of the reinforcement, the latter is rendered susceptible to corrosion. That is if this x becomes 0; that is the entire concrete up to the reinforcement location is carbonated, then this steel is rendered vulnerable to corrosion. Now, this is the first thing that we have assumed when we are making a statement of this nature.

In addition to that what we are saying is that the reinforcement cannot be rendered susceptible to corrosion during the service life of the structure. So, the service life of the structure is supposed to be only till such point as the reinforcement is rendered susceptible to corrosion. Now, whether or not corrosion actually occurs; is not something which we are talking about. There can be obviously situations where; even if carbonation occurs, the rates of corrosion may be such that they may be too low. They may be acceptable; but that part of service life is not being considered here. So, to that extent this thought processes fairly conservative.

In fact, if you look at models, which talk in terms of service life of reinforce concrete structures and reinforcement corrosion, very often we see a model which is something like this which says that this is the life during which no corrosion takes place. And, beyond this point the corrosion is initiated here. And reaches a point here which leads to formation of cracks. We have talked about this when we are talking in terms of the corrosion process within concrete and the deposition of corrosion products and the reinforcing bars and so on. In this discussion here, we are simply ignoring this part. We are saying that well our service life is confined to only the portion where the reinforcement is rendered susceptible to corrosion. Whether or not corrosion occurs, what is the rate at which the corrosion will occur, those are something which we are not talking about.

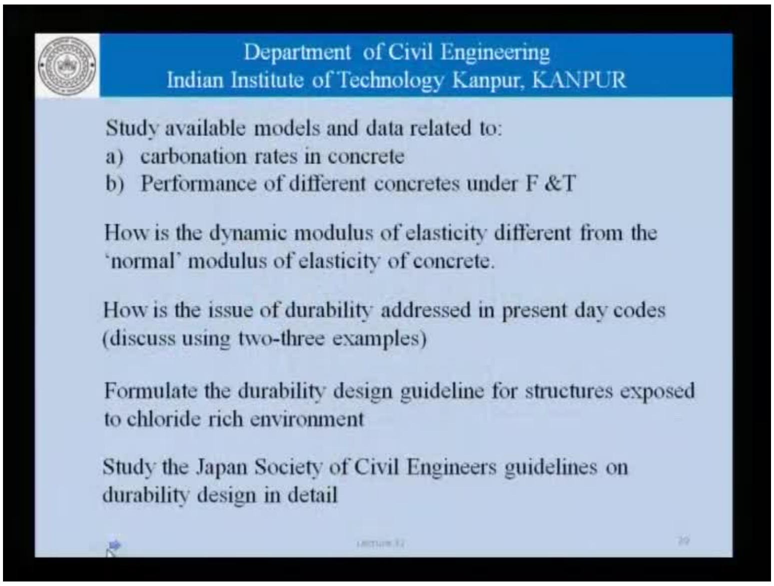
(Refer Slide Time: 41:31)



Now, continuing our discussion with carbonation, in this case we could in fact use the measurement of the carbonation depth at different points and time, as the part of the normal inspection procedure. If we are inspecting a structure and we normally do that at least in the case of more importance structures; there is a regime or there is a protocol where the structure is normally inspected periodically. Then, as part of the inspection protocol, we could measure the depth of carbonation that has occurred at that point in time. What that will do is to help us make a mid-course correction in cases when the estimated and the actual depth of carbonation are different. And also obtain more realistic estimates of the rates of carbonation.

So, what we are saying is that if we measure the rate of carbonation at some point here, at time t is equal to t 1. And find that this is the depth of carbonation that we actually find. This should be compared with the x 1 estimated; that is at this point t 1, what was the estimated value of x 1? And if we compared this x 1 estimate versus x 1, actual if you want to call that; then, we will know whether we made a conservative or a non-conservative estimate in terms of the propagation of carbonation.

(Refer Slide Time: 43:34)



Similarly, we can make a correction and then measure this carbonation depth at t 2. And, see we can measure the carbonation depth t 2 and so on and so forth. So, with this we come to a close of the discussion on carbonation and durability related issues from point of your durability design. And, before we close let us go through a few questions; what you could do is to study available models and data which relates to carbonation rates in concretes. In particular, I would like to draw your attention to the famous kishtani equation, which I am sure you can find a literature. Performance of different concrete under freezing and thawing; we made a statement that air entrained concrete perform better. That is something which you can always verify from the observations made in different researchers, as to how much is the air content which is required; because air content also has the implication in terms of strength.

I would like you to answer the question, how is the dynamic modulus of elasticity different from the normal modulus of elasticity of concrete? W e have so many equations which relate; for example, the characteristic strength of concrete or the strength of concrete, we have the stress strain, curve of concrete and from that we can estimate different modulus of elasticity of concrete. And, what is this dynamic modulus of elasticity and how is it different from these different modulus of elasticity of concrete that can be defined? I would also like you to take a look as to how the durability related issues are addressed in present day codes. You can discuss two or three examples in terms of the different exposure conditions, whether it is chloride penetration or chloride induced corrosion or carbonation, freezing and thawing.

You could use different code of provisions, may be the American ACI may be the ACI provisions or the New Zealand provisions, the Indian provisions, the European provisions; I am trying to compare how concretes have been specified. Because at the end of it, durability has been of concerned to engineers for a long period of time. And, certain specifications in codes do address the problem, except that the prescription is simply a number. That is in this case do this, in this case use at least M 30 concrete, in this case do not have a water cement ratio more than 35 percent or 40 percent, use a minimum cement content of 350 kilograms per cubic meter. They are not related to the performance of the concrete; if we use that then what really happens or what will actually happen in a given situation. So, that is what is slightly different in the concept of durability design that we talked about just now.

And, carrying on from there we did the formulation let us say in a very simple manner. What we did it none the less for freezing and thawing and carbonation related deterioration. I would like you to formulate the durability design guideline for structures exposed to chloride rich environment; that is structure, which are susceptible or vulnerable to chloride induced reinforcement corrosion. What would be the paralyze you could draw from our discussion on carbonation and its related carbonation front considerations? How would you modify those, if you were dealing with chloride induced corrosion?

And, finally, I would like you to study the Japan Society of Civil Engineering guidelines on durability design in a little bit more detail. And, see how the provisions given there in are related to the kind of discussion that we had in this lecture. And also try to relate the concepts of porosity diffusion, the coefficient of diffusion and so on. And, with this we come to an end of our discussion today.

Thank you.