Advanced Concrete Technology
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Lecture – 35
Introduction to Durability

So with that we come to the end of this chapter on creep and shrinkage. So this chapter on durability, although it is completely covered in chapter 5 in the text book, what I have done is, I have broken it up into several parts. The first part where I will talk about the introduction to durability and how we measure durability in concrete, that will be the first part. The second part will deal with chemical attack of concrete.

And then the third part will be dealing with corrosion and other mechanisms of deteriorations within concrete, okay. So corrosion, we will take it separately apart from chemical attack and then the first part will primarily what we talk about in this chapter will be primarily dealing with the mechanisms of transport of aggressive fluids into the concrete, okay.

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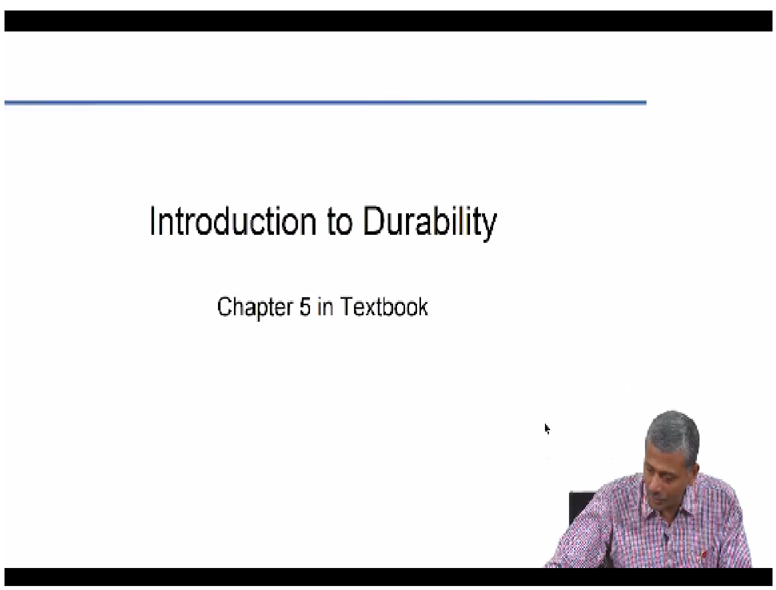

So of course you have heard the term durability.

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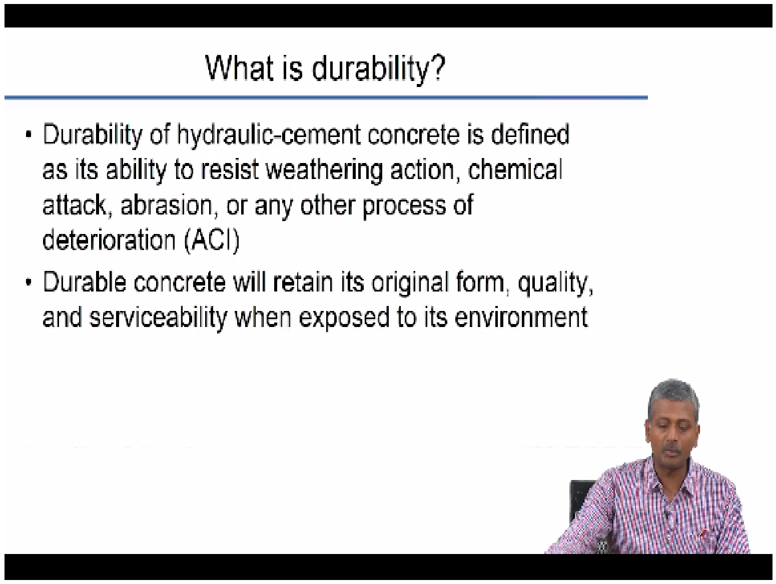

You probably also understand the significance of this term, essentially durability of cement concrete is defined as its ability to resist weathering action, chemical attack, abrasion, or any other process of deterioration, okay. This is the ACI or American Concrete Institute definition. Please note that we are already talking about deterioration that happens because of non-load related effects, non-structural effects, okay.

So this is basically expressed as a response of the concrete to the external environment in which the concrete is servicing, right. So durability can mean different things for concrete in different environments. For example, a concrete in the interior of the building, for example this beam or column that you have in this room may not be required to be as durable as a beam or column which is serving in a port structure which is right next to the sea where it is exposed to a completely aggressive environment, right.

So the design of concrete, although it may be done for the same level of strength, has to take into account the fact that the concrete is in a very different service environment and depending upon the life that you want from your concrete, you have different requirements for the durability of the concrete. Now talking about life that you want for the concrete, what is an expected life of a structure?

What do you consider would be an expected life first of a residential building? 50 years, yes, 50-

75. Now if you build an individual house, 50-75 years means your great grandchildren or may your grandchildren will be there. No by the time your grandchildren come along, their requirements will be so different that they will be cursing you for building that type of house, right.

So in reality when you build a residential home, the lifetime of the residential home is probably more closure to 25-30 years because within that time you would like to at least remodel or reconstruct or change the entire design of the house, okay. But when we come to something like a bridge, what would be the expected design length? At least 100 years because the bridge is doing a very important function of connecting points across an inaccessible location.

So the bridge has to be there for a long time and hopefully in that time, it is maintenance free, right. So the British built a lot of railway bridges, right which you travel on almost every other week, right and these railway bridges, some of them are nearly 150-170 years old. Of course, they are getting worn out now and need a lot of repair but then they have serviced for such long time and we would expect them to continue service for a very long time to come, right.

If you build a monument like what did Shah Jahan have in mind when he built the Taj Mahal in terms of the service life? 1000s of years, yes. When you build a monument, you expect it to last several life times, right. So in a monument, the design service life is completely different, right. The idea of a design service life is completely different when you are building a monumental structure.

You do not want your monument to be rebuilt after 50 years, right. So now they are building 2 large monuments in India, Statue of Sardar Patel and Statue of Chatarpati Shivaji, right. Very soon aircraft that are landing in the Mumbai area and Gujrat area will have lot of trouble because they have to content with heads of 2 very prominent personalities, right. So now the thing is, of course that is basically just a race between the States to see who has got the highest statue.

But both these projects are incidentally executed by the company that most of your are going to work for that is L&T. There are very interesting concretes that are used in those projects which makes it very nice to follow the progress of but nevertheless, what I wanted to say is when these monuments are building, being built, we intent them to last for a very very long time, okay. So the design for durability also should take into account the type of structure for which you are defining the durability.

So the requirements for service life are different for different type of structures. So based on that kind of design methods that you adopt, the kind of materials that you select will also be quite different, okay. So durable concrete is expected to retain its original form, quality and serviceability when exposed to its environment, right. So again, concrete which is durable in a particle environment will ensure that it is always in the right shape, size and does not have any retrogression in its quality during the service life, okay.

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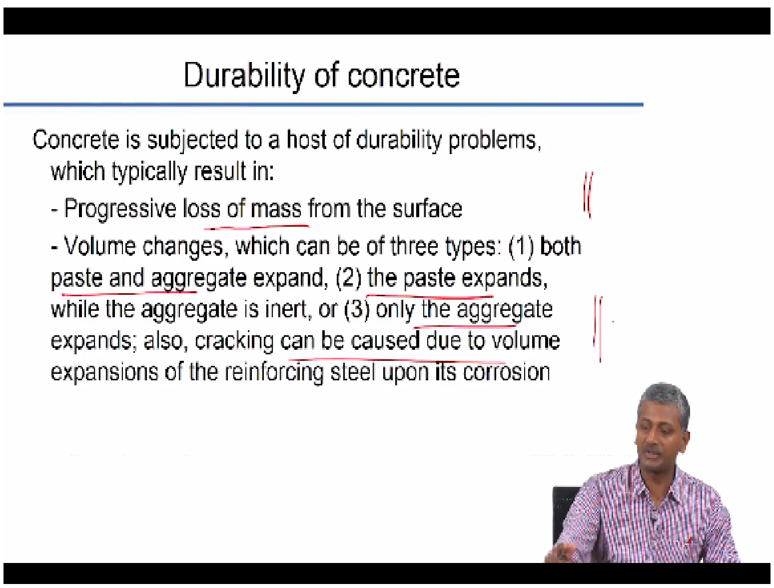

Well let us talk about the structures that are having major damages within 10-15-20 years of service. But the monumental structures do not have damage in 500-1000 years sometimes. Why? They are over designed, okay, that is one thing. The structures that were built in the past obviously are overdesigned, okay. So what is not there in the old structures that? Yes, there is no steel.

There is no steel in the old structures, that is why many of them are lasting generations. Whenever you design a structure with steel, you need to content with the fact that steel will corrode and that basically will start marking the end of your service life. So steel corrosion is probably the most important factor that we have to deal with as far as concrete in the modern era is concerned.

When you do reinforce concrete design? the service life of the concrete structure is primarily controlled by the time it takes for the steel to start corroding. In monumental structures, you do not really find steel. When you go to temples and other monuments, probably there is no steel inside at all because again it is against the Shastras to put steel inside the temple. The anything magnetic is not permitted inside the temple premises, right.

Many of you probably are aware of that fact. Now again without steel there is no cause for worry because stone has a natural tendency to last for 1000's of years. It does not degrade as rapidly as some of the other materials. Having said that there are locations where even stone can be subjected to very harsh environments. For example, when you are on the sea coast, there is salt in the air and this salt can crystallize within the pores of the stone.

And this crystallization can generate pressures that are large enough to degrade the stone. In some locations, there are very high winds because of which there will be wind driven weathering of the stone. So there are lot of cases where stone can also get weathered, right and because of that you may get reduction in the service life but still we are talking about 100s of years. We are not talking about anything < 100s of years.

But with concrete or with reinforced concrete, we just talked about the fact that we have generally varying requirements between 20 years to 100 years. We do not really talk about more than 100 years easily. Although in design we may say that we are considering a design life of 100-200 years. How do we actually put into practice? Because concrete is something that is not just on paper and not just in the factory, it actually happens on the site.

There is too much involvement of people who are not associated with the design in the process of actually producing the concrete, right. You may design for a cover of 75 mm but what cover actually gets put into place is determined by the worker on site, right. So somebody can simply spoil all your plans of a long-term design life by simply reducing 75-50, there goes your cover by 25 mm, you can expect that that can causes significant reduction in your design life.

So again those are aspects that are sometimes beyond the control but we need to bring them within our control by adopting measures that can help us address those issues and that is what also we will discuss about in the end of this chapter. So concrete is subjected to several types of durability problems but one common threat between these durability problems is that the kind of deterioration that you see is quite similar in most durability problems.

Either you have a progressive loss of mass form the surface that means you have erosion of material happening from the surface or you may observe different types of volume changes and volume changes can be when paste and aggregate are both expanding. When can that happen? Sorry. No in ASR alkali and silica reaction, it is the aggregate that expands and that needs to cracking of the paste.

The paste is not really subjected to any reactions there, okay. The aggregate only expands in the third case that is basically case number 3 where only aggregate expands because of ASR. Both paste and aggregate can expand when there is freezing. Water inside the pores of the aggregate and the pores of the paste will freeze to convert into ice and that will lead to expansive pressures, right.

Well, yes, mean expansion is happening for the whole concrete but the paste itself can expand locally, the aggregate can expand locally depending upon the extent of porosity that is available in the aggregate. The second case is only the paste expands while the aggregate is inert. When does this happen? Any chemical attack basically will alter the paste, whereas the aggregate is usually inert in those processes, like sulphate attack for instance.

So again cracking caused due to volume change when reinforcing steel corrodes, can also lead to a change in volume with the concrete, right, that can also lead to expansive pressures. So you have 2 different types of manifestations, one is loss of mass from the surface. The other is expansion of the concrete which is caused by several different scenarios, right. So this is a common threat between these issues.

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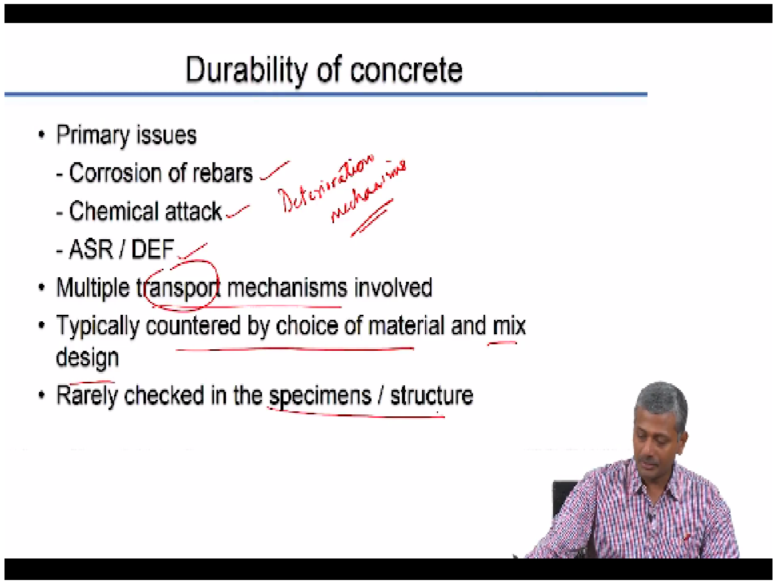

And one more common threat that exists between durability problems. Of course, these are the different durability problems that we are talking about. If corrosion of rebars, chemical attack, alkali and silica reaction, delayed ettringite formation, these are the most primary issues that we deal with as far as durability is concerned. There are other smaller problems also which are more typical of the kind of situation that the concrete is serviced in.

Now what you need to understand is during the process in which this problem actually manifests inside the concrete, there are several different transport mechanisms involved. See these are deterioration mechanisms and there are several transport mechanisms. What you think is understand by transport mechanism, understood by transport mechanisms? Okay, you are talking about diffusion, you are talking about permeability, you are talking about absorption, these are all different transport mechanisms.

The mechanisms by which the fluids or aggressive agents are transported to the inside of the concrete, okay. So very often while we study in the lab the durability primarily measuring only one transport parameter. In reality whenever a durability problem manifests itself in concrete, it is because of the combination of different transport mechanisms. So there are multiple transport mechanisms that are involved.

And typically we design for durability by choosing the material appropriately and the amount of the material in terms of the mix design. But the problem is once the concrete structure is in place, we do not really check the durability in the specimen or the structure. We check the strength and we assume that everything else depends on the strength, okay. So that is how we look at this.

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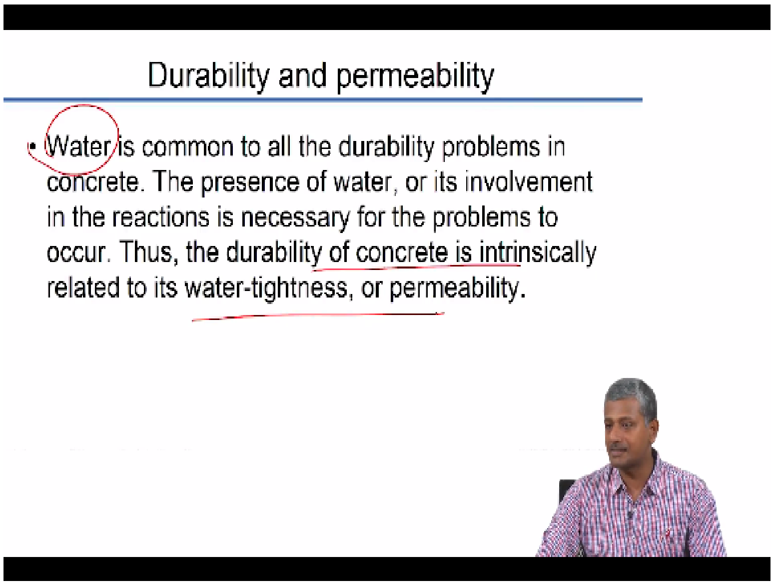

Now when we talked about the fact that most durability problems lead to a common manifestation in terms of even loss of mass or expansion of the concrete. There is also one more common threat is that most durability problems or all durability problems are connected to the permeability of the concrete because of the presence of water that is absolutely essential in the durability problems of concrete.

So water is common to all durability problems. Either it should be present for the reactions to occur or after the reactions for the manifestation of the damage to occur, water is needed. Especially whenever there is expansion, most of the expansions are because of imbibing additional quantities of water.

So if you can cut off the water supply to concrete when it is hard and subjected to durability problems, many of these problems will cease to exist. So completely dry concrete will have hardly any durability problems as opposed to a concrete that is subjected to periodic wetting. So if there is water available, there is definitely chance of durability problems. So durability of concrete is intrinsically related to the water-tightness or permeability of the concrete.

And that is why whenever we want to measure durability of concrete, we always talk about some methodologies of measuring the permeability, right. Whenever we design test methods, most of them are based on permeability but as we will discuss later in this chapter, permeability is just one expression of the transport mechanisms. There are several other ways in which fluids and gasses can actually get into the concrete.

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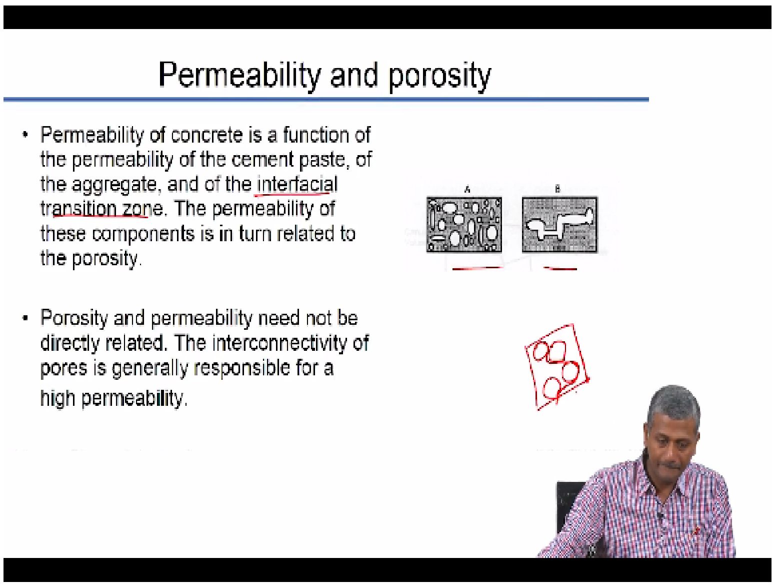

Now permeability of course is related to how interconnected the pores are, okay and porosity is determined by what? What determines the porosity of a concrete? The water to cement ratio determines the porosity of the concrete, okay but then the water to cement ratio also affects the permeability of the concrete. The higher the water to cement ratio, the greater the amount of pores, the larger the amount of pores, the greater is the chance that these pores are interconnected.

But then it does not necessarily mean that if you have an air entrain system which has more porosity, that the air entrain system will also result in greater permeability. It is not necessary. You can design air entrain concrete with low permeability also because these voids that area created because of air entrainment, are mostly discrete. So this picture on the right shows you typical understanding of what is meant by porosity and permeability.

So the system on the left that is A will have several pores. The porosity is high but these pores are not really connected. System B, you only have a single pore which is completely connected throughout the structure of the system. So you can expect that there will be greater permeability in the case of B, okay. So porosity and permeability of course not just depend on water-cement ratio of the paste, they also depend on the ITZ.

And this we have discussed before that when you have percolation of the ITZ, when you have ITZ that is close by, you can create a channel of flow through the concrete quite easily. So that is why when we design high strength concretes, we choose higher paste contents so that we can separate the aggregates further and that leads to the interfacial transition zones that become discrete. They are not connected to each other, that reduce the permeability significantly.

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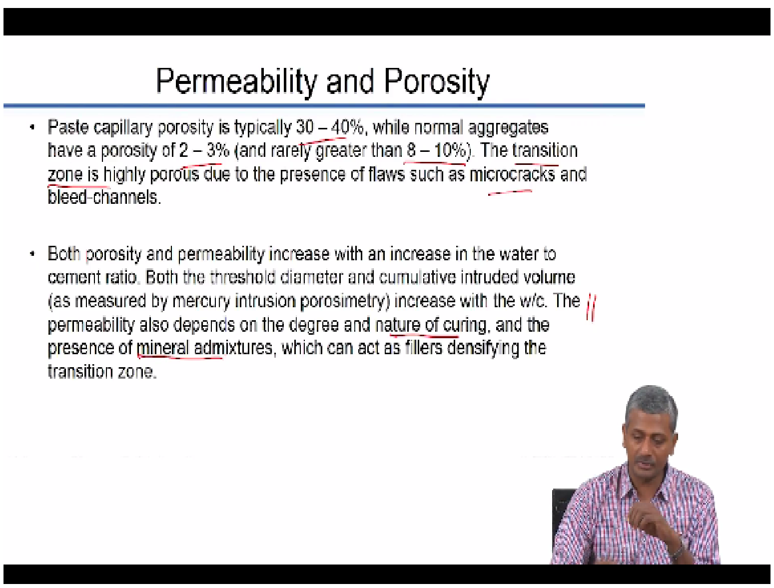

Now in general, the capillary porosity of paste when we talk about paste, we are looking at about 30-40% porosity. Aggregates only have a porosity of 2-3% when you talk about granite and other aggregate. Of course, there are aggregates which may have higher porosity also but rarely it is > 8-10%. So we expect that when we study the permeability of concrete, the primary deciding factor for the permeability will be the ITZ because it has got lot of pores and cracks and bleed channels inside the ITZ.

Because of that you can expect that the permeability of the concrete is going to be much affected even though the aggregate itself is not very porous, okay. So capillary porosity in a paste may or may not lead to a high permeability but the ITZ porosity will definitely lead to high permeability especially when the ITZ is percolated.

And again water to cement ratio is the primary factor, although we can also have an influence of the nature of curing, the presence of metal admixtures especially because they are very fine grained materials that can act as densifiers for the interfacial transition zone. So whenever you use metal admixtures, you expect that there is going to be reduction in your permeability primarily because of additional CSH that you form as well as you have additional pore filling because of the fineness of the mineral admixtures.

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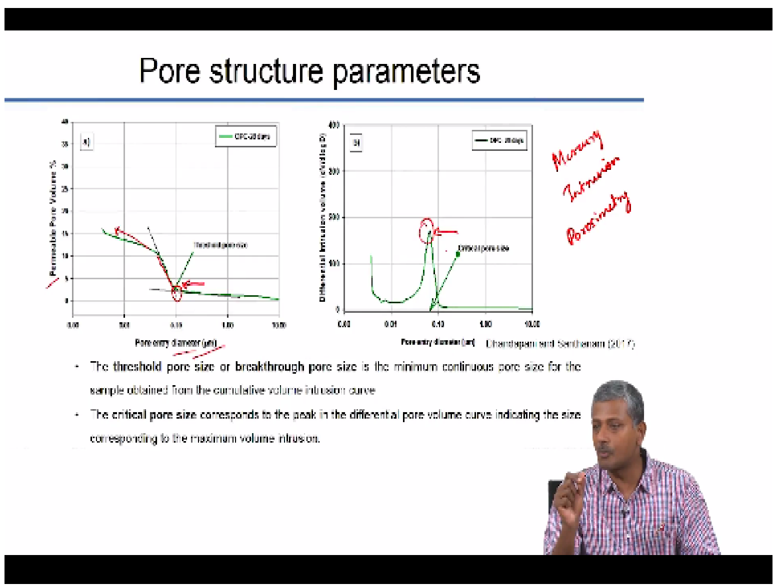

So if you look at data from mercury intrusion porosimetry, this experiment is called MIP or Mercury Intrusion Porosimetry. So here what is being done is you take mercury and you cause this mercury to percolate or penetrate the pore system of the concrete under increasing pressures. So when you increase the pressure, the mercury is able to penetrate smaller and smaller diameters because pressure is inversely related to the diameter.

So here the permeable pore volume is plotted against the pore entry diameter on the x axis. So here you can see that the permeable pore volume is quite low until here but all of a sudden there is an increase in the permeable porosity in the system at a particular pore diameter that is close to about 0.1 micron. We are talking about 100 Angstroms, right. No, no, sorry 100 nanometer, 0.1 micron is 100 nanometer.

So that 100 nanometers you see a sudden intrusion which increases. That means that signs of porosity is somewhat of a threshold diameter which needs to be overcome for the mercury to penetrate a larger pore system that exists beyond that pore, okay and then you again have a gradual change in the volume of penetrable porosity. Now if you look at the differential plot, you take the same plot and differentiate it with respect to the diameter, you get this kind of a plot.

And from here what you can actually get is the critical pore size that you have in your system. That means what sized pores are present in the maximum quantity in your system. So that is your critical pore size. So when you reduce your water to cement ratio in the system, both the threshold pore size and the critical pore size will tend to reduce. When you substitute cement with silica fume or slag or other mineral additives, you can again expect the same effects that the threshold pore size decreases and the critical pore size also moves to the left.

So MIP is a very useful experiment from that regard that it can actually help you determine the pore structure parameters that are existing inside your concrete. Only problem here is you are not going to be able to measure this for the ITZ because for the experiment, you will have to take very small samples from your concrete and these samples will be essentially the mortar within the concrete.

You will not be able to take the mortar and aggregate interface because the size of the sample is restricted. So studying ITZ with MIP may not be possible at all unless you are talking about the ITZ that exists between cement paste and fine aggregate. The coarse aggregate ITZ is simply not going to be determined by MIP, okay. There are tonnes of sophisticated analytical techniques that can be used to concrete studies but the problem always is the sampling.

Whenever you deal with more and more sophisticated methods, the sample size becomes smaller and smaller, right and because of that concrete which is a really macro material, imagine taking a small, few grams of sample from the concrete. We are talking about concrete which weighs tonnes, like a beam weighs several tonnes and we want to take a few grams for microanalysis and we want to interpret the results of this microanalysis and apply it to the entire beam.

How do you do that? So sampling is always a big problem with concrete. How do you get the sample? How do you make your decisions? Very difficult. That is why most of these studies that are done on the analytical procedures is applied primarily to paste and not to concrete because the concrete, you have lot more complications but then again modeling the paste and translating the results into concrete where the influence of the ITZ can be tremendously high.

Again that requires a lot of understanding of the system. That is where the complications are. That is why lot of research is also being done. How do we relate the paste and mortar characteristics to concrete so that we can actually scale down the test and do a much better understanding in the laboratory before we actually do it on the field.

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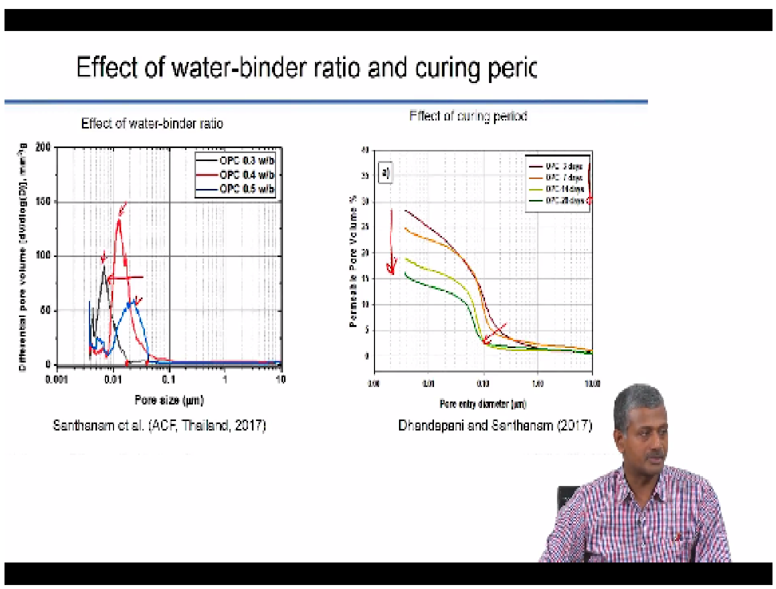

So if you look at the effect of the water-binder ratio, you see that the critical pore size is, this is 0.5 water-binder ratio. This is 0.4 and that is 0.3. So as you are reducing the water-binder ratio, your critical pore diameter is shifting to the left that means it is reducing, okay. What you also see is the threshold diameter, right. You see the threshold diameter is here for the 0.5 system and here for the 0.3 system.

So threshold diameter is also getting shifted to the left in the case of reducing the water-binder ratio. What you see on the right is the effect of the age of curing. So curing 3 days, 7 days and 14 days and 28 days. You see that the curve is gradually shifting to the left. You also see a reduction in the permeable pore volume as more and more curing is being done.

That is only expected because there is more hydration happening. As more hydration happens, there will be lesser porosity and permeability in the system, okay. So what you are measuring here is the accessible porosity. Apart from that there may be also porosity that is discrete from each other, not connected. So that is inaccessible porosity but that you are not seeing in your MIP results.

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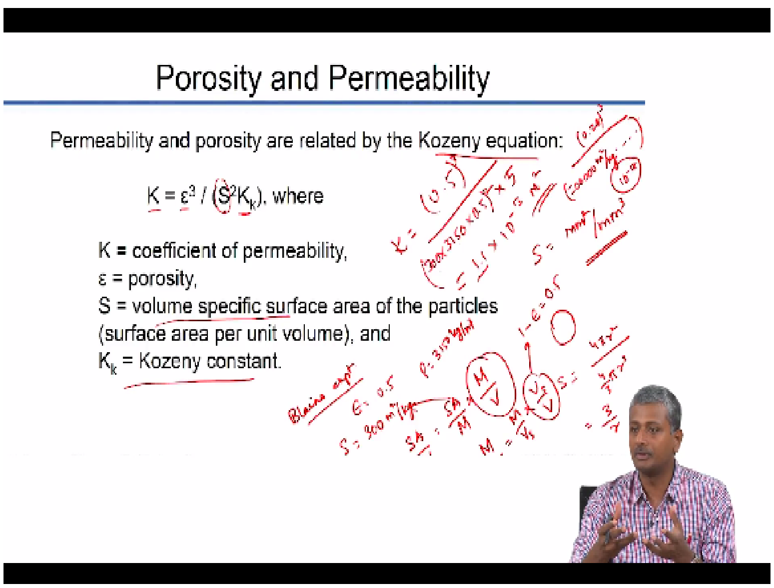

Now people have always tried to explore this relationship between porosity and permeability. For general porous materials, the porosity and permeability can be connected with what is known as a Kozeny equation. According to this equation, the coefficient of permeability K=cube of porosity/square of surface area x constant called the Kozeny constant. Now let us look at what this Kozeny constant is made up of.

But meanwhile I should tell you that S, surface area, is the volume specific surface area of the particle. That means the units of surface area per unit volume would be square millimeter per cubic millimeter. So if you take a sphere for example. For a sphere, what is this S equal to? What is the surface area of a sphere, 4 pi r square. Volume is 4/3pi r cube. So that is equal to 3/r. Surface area per unit volume for a sphere is 3/r, okay.

So like this you can work out the surface area of different geometries, okay. So here again surface area of the particles we are considering. The particles that are making up the solid phase around the porosity, okay. Because that is going to now define the kind of interconnectivity between the pores.

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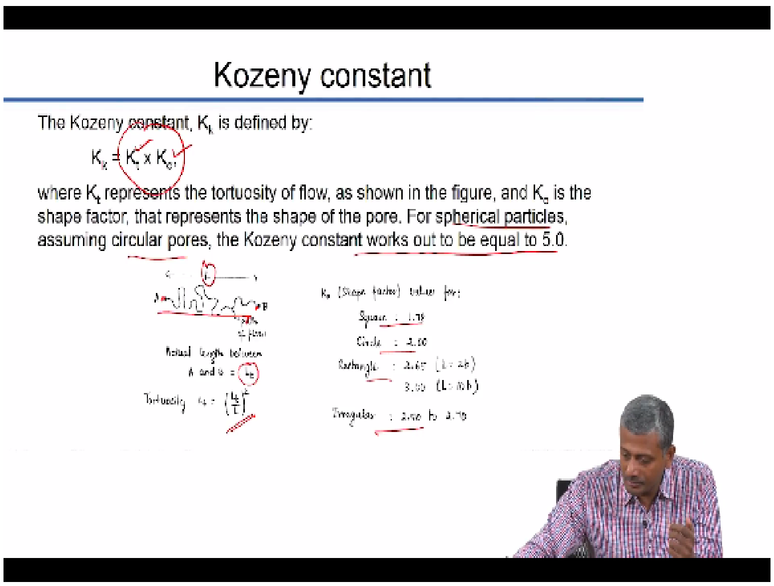

And this Kozeny constant itself is composed of 2 different factors. One is the tortuosity coefficient. The other is the shape factor. The tortuosity coefficient means that if a fluid has to get transported from a point A to a point B, it can either take a straight path, okay. If there is no hindrances to the flow, it can take a straight path, that is the most direct path and the length is L in that case.

But the actual length traversed by fluid may depend on what hindrances are in the path because of which it actually takes a zig-zag sort of a path and that is what has been marked in that figure. So the actual length traversed, let that be Lt, then the tortuosity coefficient is given by Lt/L the whole square, okay. The shape factor depends on the shape of the porosity. If you have a square shape or circular shape or rectangular shape or irregular shape, you get different types of shape factors.

Now generally for spherical particles, assuming circular pores, the Kozeny constant works out to be 5, that means the multiplication of Kt and Ko works out to be 5.0 for spherical particles. If you make an assumption of spherical particles, your system gets much more simplified and then you can relate directly the permeability to the porosity. Let us just do this for the Blaine permeability experiment, the Blaine air permeability experiment where you are measuring the fineness of your cement, right, okay.

So let us, let us do it there. So in the Blaine experiment, what is the porosity? What is porosity in a Blaine experiment? You prepare your bed to a certain porosity (()) (24:16) porosity. You have done the Blaine experiment class in your lab. Nobody is sure. You did not do? Blaine air permeability experiment? You did not do it in the lab? Okay. The porosity that you pack the bed to is 0.5, okay.

The porosity is 0.5. Your surface area, for cement, what is the surface area typically? 200 square meters per kilogram but that is the mass specific surface area, right. You need to convert that to the volume specific surface area. How will you do that? So surface area per unit volume=surface area per unit mass x mass/volume, right but then you have porosity in the system, right. So your volume is different, your mass, this is not exactly your density because density is mass of solids/volume of solids but here you have porosity in the system.

So you need to convert that to an equivalent mass/volume, okay. So what is that equal to? So surface area/unit mass is this obviously. What is mass/volume=? So again you can define mass by volume=M/Vs x Vs/V, right. M/Vs is your density, right. So that is rho, density is 3150 kg per cubic meter, right and this Vs/V is what? Not void ratio. Solids by total volume is 1-porosity, 1-porosity, okay.

So 1-porosity is again 0.5. So now can you work out? Anybody has a calculator? Can you work out what the coefficient of permeability of this cement in a regularly packed Blaine experiment is? So that what you will get? K, sorry, K=0.5 cube/S squared. So S is 300x3150x0.5 squared x Kozeny constant, let us assume spherical particles in circular pores. Let say it is 5. So what do you get. So something x 10 to the power -13.

“Professor - student conversation starts” 1.11 **“Professor - student conversation ends”** 1.11, 1.1 x 10 to the power -13, okay. So what are the units. So this is meter square per kilogram. This kilogram per cubic meter. So this is 1/meter, so 1/meter, so that becomes meter square where. So this is meter square. Units are in square meter, okay. Coefficient of permeability units are in square meter in this case, okay. Now what is it telling you? That the permeability of this packed bed of cement particles is of the order of 10 power -13-meter square.

But of course, you remember that generally we express permeability in terms of, in Darcian expressions, we express permeability in terms of square meters, sorry, meter per second, meter per second but here it is expressed in meter square. So to convert this to meter per second, you need an expression which is relating the intrinsic permeability to the measured permeability but that is different.

Let us not worry about that. Now just in the same expression, if you were to work out the permeability of CSH using the same expression, what values would you use for the porosity? What is the porosity of CSH? We assume something when we calculated the hydrated cement paste structure. 28%, right, 0.28/ what is the density of, what is the surface area of CSH? We talked about different measurements which lead to surface area of 200,000-300,000 square meters per kilogram, right.

So we are talking about surface area which is 3 orders of magnitude higher than that of cement. So you can imagine that when you do the same calculation, you may actually get some expression which is probably more going to be 10 power -18 or 10 power -20 of that order. So CSH itself has a much lower permeability as opposed to this bed of cement particles.

So again we are talking about systems where you have gradual reduction in permeability as hydration happens because you can imagine when cement and water are just mixed together first, the water forms your capillary porosity and the entire water system is essentially your permeable system. But as more and more hydration happens, as CSH gets formed more and more, more of that volume surrounding the cement is getting transformed into CSH.

But of course, we have to think about the fact that it is not just CSH, it is calcium silicate hydrate + other cement paste compounds like calcium hydroxide and so on. So there will be capillary porosity but then overall porosity may lead to a permeability of several orders of magnitude lower than what your initial permeability is going to be in the system. So your permeability evolves when hydration happens and you can actually see that from this expression itself, okay.

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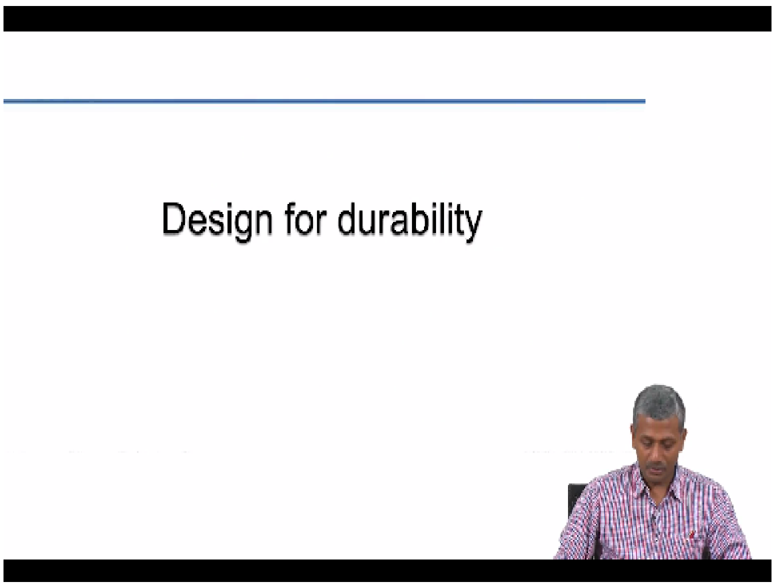

So I will give a few pointers about design for durability and then we will break for today and then resume next week.

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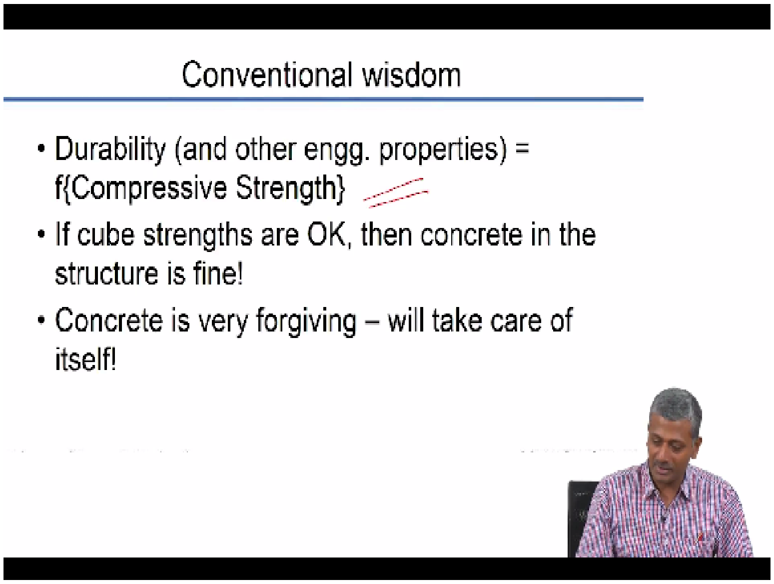

The conventional wisdom, we all know very well what is done in the field that whenever we design concrete, we design it primarily for the compressive strength. We assume that the durability and all other engineering properties including modulus of elasticity are all dependent on the compressive strength. Already we talked about the fact that your expression involving modulus and strength may not be valid for several of the new types of concrete that we are looking at today.

And you may need to actually test these concretes to really establish what the modulus of elasticity should be, right. Especially when you are dealing with special concretes like heavy weight or light weight concrete or dealing with self compacting concrete, high strength high performance concrete, your relationship could start differing from what has been prescribed in the coral relationships.

But for now what people are doing in design process is that simply assuming that whatever properties are there, are a function of the compressive strength. So in general we assume that if the cube strength, from cubes that have been prepared when the concrete is delivered to the site, these cubes that are prepared and stored in ideal laboratory conditions are tested after 28 days. If those cube strengths are fine, we never question the quality of the concrete in the structure, right.

Only when there is a non-conformance in the strength of the cubes, do people start worrying about, okay, what may be there in the structure. So as long as that is fine, we assume everything is okay and we always think that concrete is extremely forgiving. If we create damage, it will soon heal itself and take care of itself but all this obviously is not correct.

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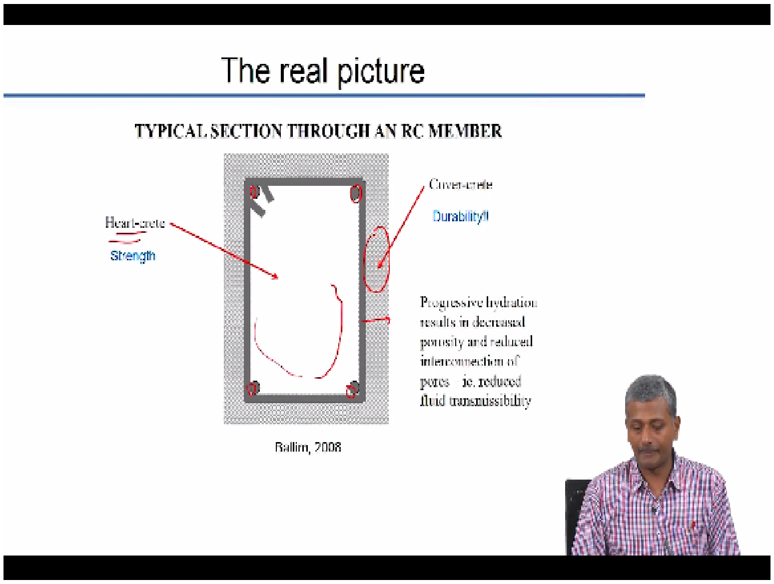

There are lot of problems that you can expect with concrete. For example, if you do not do curing, so let us take an example of a typical reinforced concrete member like a concrete column, right. You know that you have steel which is the primary longitudinal steel and you have the tie bars around the steel, okay. The concrete that sits outside the steel is called the cover concrete whereas the concrete which is sitting inside can be called the heart concrete or heart-crete, okay.

That is the common terminology that people who deal with durability talk about. Now if you really imagine, if you do not do any curing for this column, it is very difficult to imagine that water which is sitting inside will ever be able to dry out of the concrete because it has got to travel a large distance to come out of the concrete. So if you do not do curing of the system, your concrete which is sitting inside the steel is not going to be effected much by that.

That means your strength development will be gradually happening at the right level that you wanted to happen. In other words, lack of curing in a column may not compromise the strength of the column but if you do not cure properly, this cover concrete where we expect increasing hydration to reduce the extent of permeability in the system, the quality of the cover concrete will keep on reducing if you do not do a good job of curing.

So curing has to be done from the point of view of durability but then here the curing is not effecting the strength of the column much. It is actually affecting only the durability very much. So the assumption that as long as strength of concrete is okay, the durability should also be fine is not a correct one. We need to ensure that the concrete durability is also maintained by its own set of parameters rather than just worrying only about the strength.

So strength-based design needs to be augmented by durability-based design to ensure that we get a structure that is long-lasting, has a long-term performance that we want.