Advanced Concrete Technology
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Lecture - 37
Durability Issues in Concrete – Part 1

Good morning everyone. Yesterday, we were talking about different kinds of transport mechanisms that led to concrete durability problems. Let us continue our discussion in that. We first saw that there many different transport mechanisms that either happen individually or in combination depending upon the kind of service environment.

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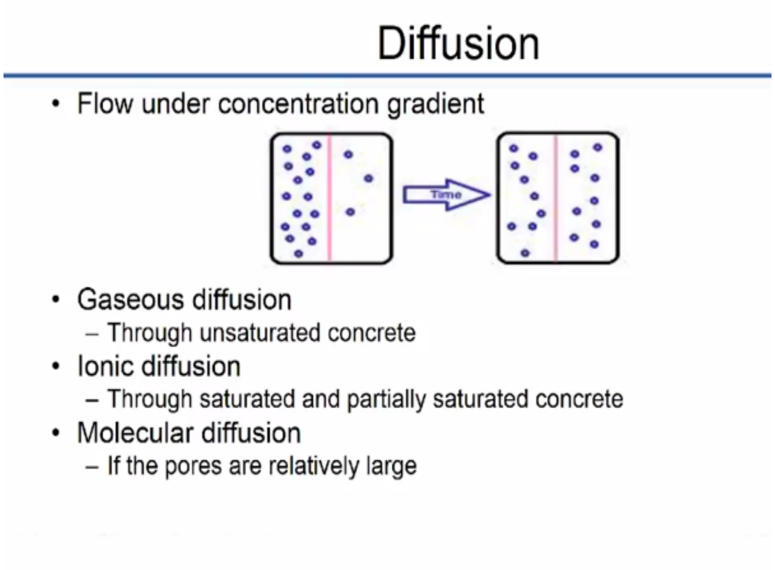

Diffusion

- Flow under concentration gradient

- Gaseous diffusion
  - – Through unsaturated concrete
- Ionic diffusion
  - – Through saturated and partially saturated concrete
- Molecular diffusion
  - – If the pores are relatively large

We started talking about diffusion which is basically the flow under concentration gradients. Ionic species will tend to diffuse through semipermeable barriers from locations of high concentration to locations of low concentration and this will happen until there is some sort of an equilibrium reached in this process. When gas is diffused through concrete they primarily need an unsaturated medium that means they need very little moisture in the system preferably no moisture for the gas to diffuse easily.

Whereas when you have ionic species they generally diffuse through saturated or partially saturated concrete. So we are talking about chloride-induce corrosion where chloride ions are diffusing from the external environment into the concrete and this happens primarily in locations like underwater or where you have lot of moisture available in the atmosphere to carry these chlorides inside.

Whereas when we talk about carbonation, we essentially look at conditions for the concrete that are mostly dry in which case the carbon dioxide penetration can happen over a long distance into the concrete. And when we talk about molecular diffusion like water, pores have to be relatively large to accommodate these molecules to penetrate.

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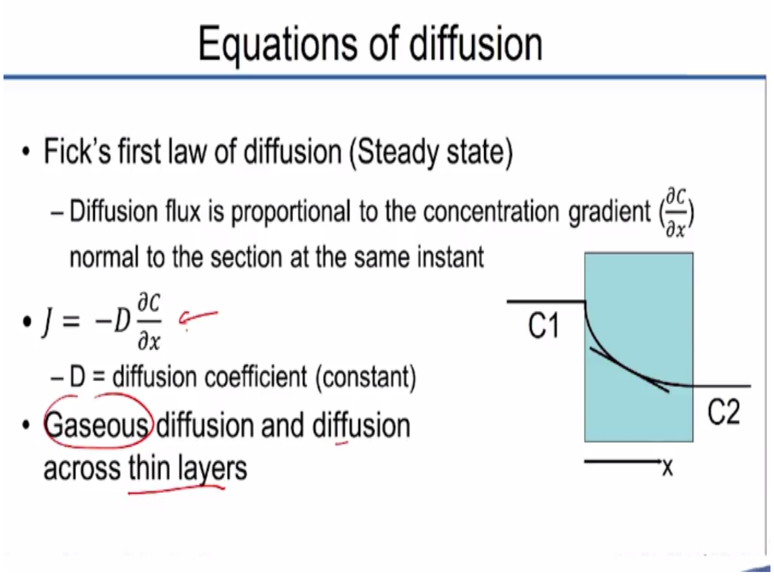

Equations of diffusion

- Fick's first law of diffusion (Steady state)
  - Diffusion flux is proportional to the concentration gradient ($\frac{\partial C}{\partial x}$) normal to the section at the same instant
- $J = -D\frac{\partial C}{\partial x}$
  - D = diffusion coefficient (constant)
- Gaseous diffusion and diffusion across thin layers

Now we talked also about 2 different cases, 1 is steady state diffusion where the properties of the material do not change with respect to time that means when the concentration gradient is the same, its variation across depth of the material will still be the same and this is applicable to the very thin layers and especially when you have gaseous diffusion happening through the system.

And this is defined by first law of diffusion where the diffusion flux J is related to the concentration gradient through a proportionality constant that is your diffusion coefficient. So the material characteristic that you need to evaluate to understand the resistance of the material diffusion is the diffusion coefficient D.

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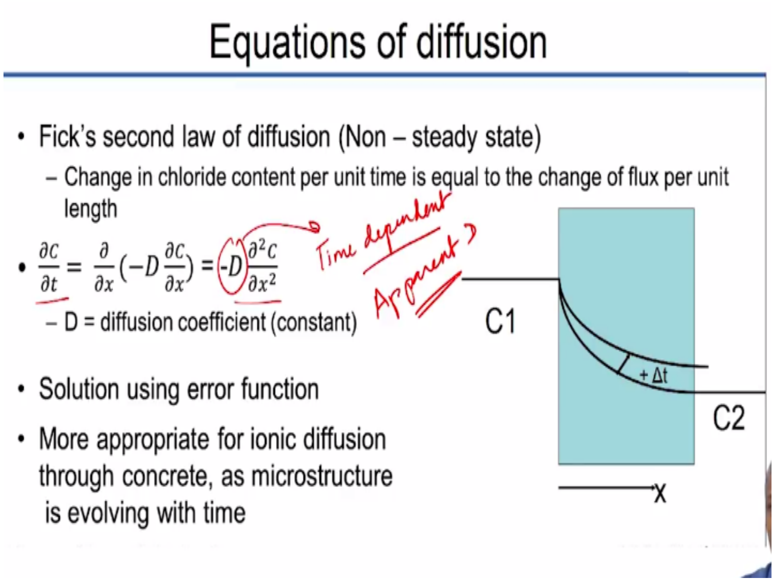

Equations of diffusion

- Fick's second law of diffusion (Non – steady state)
  - Change in chloride content per unit time is equal to the change of flux per unit length
- $\frac{\partial C}{\partial t} = \frac{\partial}{\partial x}\left(-D\frac{\partial C}{\partial x}\right) = -D\frac{\partial^2 C}{\partial x^2}$
  - D = diffusion coefficient (constant)
- Solution using error function
- More appropriate for ionic diffusion through concrete, as microstructure is evolving with time

Time dependent

Apparent ?

Now when you come to concrete we know very well that with time the properties of concrete undergo changes, with additional hydration the structure of concrete develops even more and because of that you have a change in the rate at which the diffusion can happen as time progresses forward. Because of this, we cannot apply a steady state condition to concrete and we go with non-steady state condition.

And in this fix second law of diffusion is used and you have the time variability of the concentration related to this spatial variability of the concentration related by a diffusion coefficient. Now as we discussed yesterday this solution of this PDE requires the use of an error function, but 1 important aspect to understand is the factor D, which we otherwise call as diffusion coefficient, that itself is something which is not going to be constant throughout the service life of the concrete.

Because what you measure at 28 days may be quite different from what you measure at 56 days or 90 days or 1 year. So this value of D also is evolving with time in other words D is basically a time dependent diffusion coefficient that is why we call it an apparent diffusion coefficient. It is not really the true diffusion coefficient.

Because a true diffusion coefficient will be independent of the time at which you are evaluating it. So this is an apparent diffusion coefficient because this is time dependent. So you need to be careful about your measurement of this diffusion coefficient based on experiments done on concrete you need to exactly specify the age at which you determined this value.

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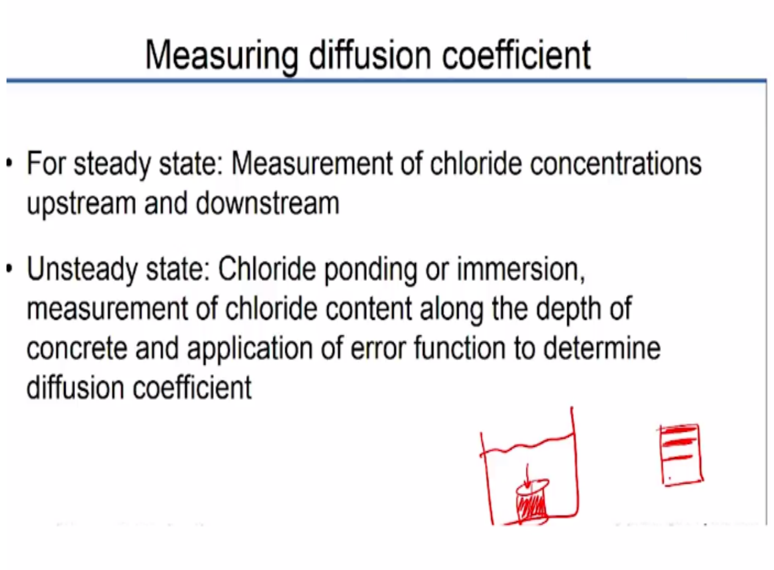

Measuring diffusion coefficient

- For steady state: Measurement of chloride concentrations upstream and downstream
- Unsteady state: Chloride ponding or immersion, measurement of chloride content along the depth of concrete and application of error function to determine diffusion coefficient

Now how do we measure this diffusion coefficient? As far as the steady state equations are concerned or steady state condition is concerned all you have to do is measure the chloride concentration upstream and downstream. You know the thickness of your material you apply the direct first law of Fick's first law and you can directly get a diffusion coefficient, but that does not work in the case of materials like concrete with the changing their characteristics with respect to time.

For second law what we have to for unsteady state diffusion we need to do chloride ponding experiments. So here you have a tub filled with chloride and you put your cylindrical concrete specimen within this tub and what happens is the chlorides will tend to diffuse unidirectionally from the top of the concrete specimen so I need to cover the perimeter using something impervious like an epoxy coating so that the chlorides do not penetrate through the coating.

They only penetrate unidirectionally and from time to time all you have do is section of the concrete with respect to depth and powder it and measure the extent of chloride which is varying with the function of the depth of the concrete. So that is what you do, you basically do chloride ponding and measurement of chloride content along the depth of the concrete which can then be fitted using the error function to determine the diffusion coefficient.

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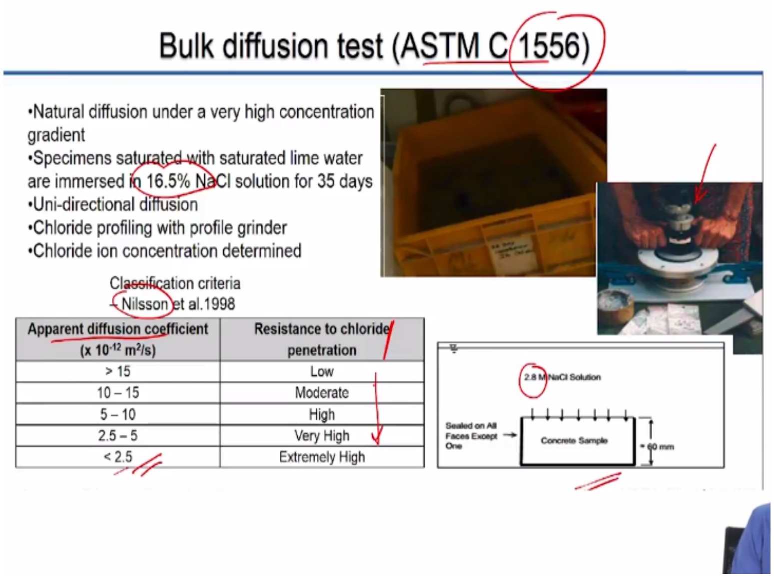

Bulk diffusion test (ASTM C 1556)

- Natural diffusion under a very high concentration gradient
- Specimens saturated with saturated lime water are immersed in 16.5% NaCl solution for 35 days
- Uni-directional diffusion
- Chloride profiling with profile grinder
- Chloride ion concentration determined

Classification criteria
– Nilsson et al.1998

Apparent diffusion coefficient ($\times 10^{-12}$ m^2/s)	Resistance to chloride penetration
> 15	Low
10 – 15	Moderate
5 – 10	High
2.5 – 5	Very High
< 2.5	Extremely High

Again this what is depicted here. This is covered in a standard ASTM C1556. It is also known as a bulk diffusion test. The older version of the bulk diffusion test was a ponding test, in which you had to actually create a slab of concrete and put sodium chloride solution at the top that means you pond the sodium chloride solution on top of the concrete, but then the process is similar. You need to take cores through the concrete from time to time.

And determine the chloride profile that means the extent of chloride concentration along the depth of the concrete. So here you have 16.5% sodium chloride solution is what is used and chloride profiling is done with the profile grinder. What is shown in this side here or you can even have a more workshop oriented process like a lathe. You can use a lathe to section of the concrete layer by layer and then determine the extent of chlorides inside.

So based on this so again this is again a schematic which is showing the cylindrical concrete samples sitting inside a tub of sodium chloride solution of course here is present in terms of molarity 2.8 molar that corresponds to about 16.5% sodium chloride. So that is very aggressive, very concentrated solution of sodium chloride. So of course we want to accelerate the tests, so we use a very high concentration of sodium chloride in this case.

And based on the diffusion coefficient value D that you get the apparent diffusion coefficient values, there is a qualitative classification given for the resistance to chloride penetration. This is not standardized. I mean these values are not standardized. The test is standardized, but these values are not standardized. They are based on an assimilation of different literature which is looked at data collected from various different sources.

You will hear this term this person's name quite often Nilsson, he is one of the premier researchers who has worked on chloride diffusion through concrete so this data was published by Nilsson’s group that a concrete which had < 2.5 * 10 power - 12-meter square per second of apparent diffusion coefficient which showed an extremely high resistance to corrosion and on the other hand > 15 * 10 power - 12 would be the concretes.

Which will be very poor in terms of the resistance to chloride induced corrosion, or chloride penetration. So please remember this is only chloride diffusion. We are not talking about how that leads to corrosion of the steel. We are still only talking about how much chloride can actually get into the system. So this is the resistance to chloride penetration that the bulk diffusion test is telling you. So we need to use the right terminology always.

We need to ensure that we are addressing what is being measured correctly. So you come to the next few test when we talk about migration for instance you will see that the chloride is driven into the concrete under a potential gradient and not really a concentration gradient. So that is something that we need to address properly by using the right terms.

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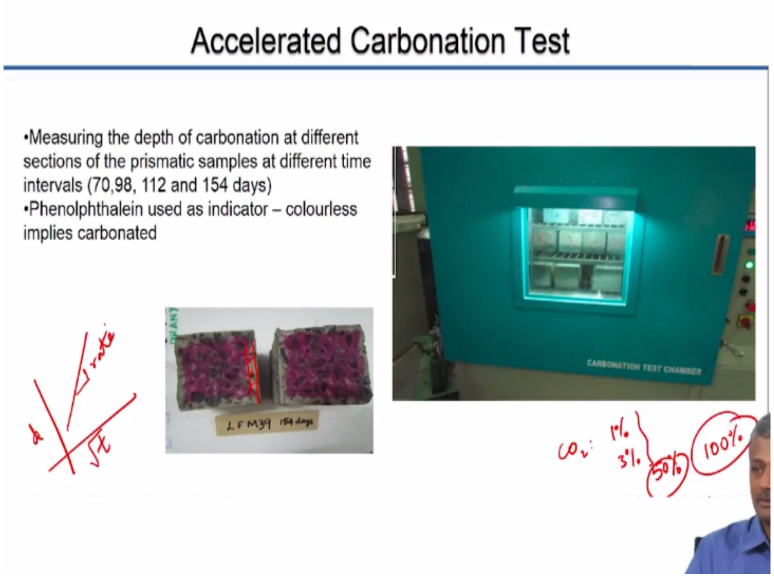

Accelerated Carbonation Test

- Measuring the depth of carbonation at different sections of the prismatic samples at different time intervals (70,98, 112 and 154 days)
- Phenolphthalein used as indicator – colourless implies carbonated

Now the other diffusion test is the carbonation test. So here you subject a concrete to accelerated carbon dioxide environments because what is the carbon dioxide content of atmosphere? 0.03 or 04, 0.04% is the extent of CO2 in the atmosphere. So if you leave your specimens out for natural carbonation it will take a long time for you to get the result which indicates the potential for the material to resist CO2 propagation into the concrete.

Now for that what we do is we create these chambers where we can control the temperature and the humidity to an extent which maximizes the rate of carbonation, we also choose a high level of CO2. So CO2 level could be 1%, 3%, or sometimes people have used even 50% inside these chambers. So we are stimulating an accelerated CO2 environment of course this 50% or 100% CO2 is something totally unrealistic.

So, most people tend to prefer between 1 and 4% as valid concentrations of CO2 inside the chamber. So you need to control temperature, humidity and CO2 concentrations and from time to time we need to split your specimen and spray phenolphthalein in it. Now phenolphthalein you used earlier in chemistry. It is a good acid base indicator. So beyond a certain pH, you will start seeing a colourless band on the surface of the concrete.

So when carbonation happens CO2 penetrates the concrete. The CO2 interacts with calcium baring species in the concrete and leads the concrete to become more and more acidic. So the pH keeps reducing. So when the pH crosses about 11.5 or 11 or sometimes even < about 10.5 the phenolphthalein would indicate a colourless concrete for all pH levels above that it will indicate the pink concrete. So concrete inside is obviously not carbonated.

Concrete at the surface is carbonated in this case. You can measure the depth of carbonation and then with respect to time when you plot this depth, what you generally obtain I will show you some data later, when you plot this against square of time you get a linear relationship. The depth of penetration of CO2 plotted against the square root of time gives you linear relationship. What is that mean? If you plot against time what will happen? You will get a quadratic relationship.

It is sort of starts tapering of towards the end. That is why when you plotted against square root of time, we get a linear relationship. Why does it taper off? Why does the rate of penetration of CO2 drop with respect to time? Saturation, probably not saturation. What is actually happening is your surface ones are getting converted to calcium carbonate. There is densification happening. So the penetration of CO2 is going to get reduced with respect to time.

So with normal ordinary Portland cement concrete you will see that the densification caused by the surface conversion of line to CaCO3 calcium carbonate tends to densify the concrete and that slows down the rate at which your CO2 further propagates. So you start seeing a limiting sort of relationship. So that is why when people plotted you plotted against square root of time you get a; that is not very linear.

You get a linear relationship and the advantage here is you can actually then take the slope of this and call it the carbonation rate and that carbonation rate can further be used for modeling the concrete or understanding the service life of concrete exposed to a carbonation environment. Now that would obviously mean that you consider that once the carbonation depth reaches the level of the reinforcing steel.

Because of the acidic conditions prevailing, the steel will start corroding at that point of time. It does not address the fact that when carbonation happens, the moisture content is rather low in the system and the steel would need moisture to actually corrode. So there is a dichotomy here. On one stage you need less moisture or partially saturated or unsaturated concrete for the CO2 to propagate into the concrete. On the other hand, you need moisture to ensure that the corrosion propagates in a regular fashion.

So there is lack of moisture for CO2 penetration, but you need moisture for corrosion. Although carbonation depth may be high in certain instances you may not get the associated corrosion that takes place for reinforcing steel even though the pH conditions are ideally suited for the corrosion to happen because of the moisture availability being a criterion that determines where the corrosion happens or not. Anyway we will talk about that again later when we discuss corrosion in more detail.

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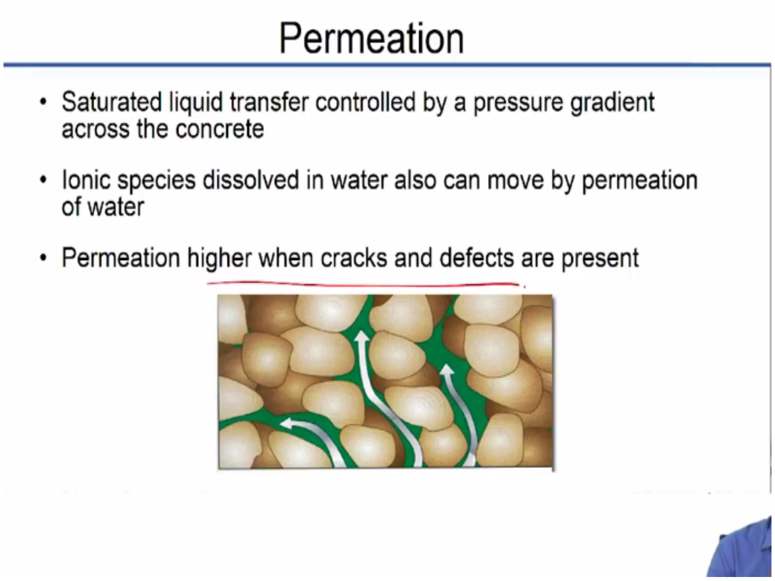

Permeation

- Saturated liquid transfer controlled by a pressure gradient across the concrete
- Ionic species dissolved in water also can move by permeation of water
- Permeation higher when cracks and defects are present

The other major transport mechanism that occurs in concrete is permeation. Now permeation or permeability is associated with the flow under a hydraulic gradient, pressure gradient. So saturated liquid transfer happens which is controlled by a pressure gradient across the concrete so we have high pressure of water on the outside, low pressure on the inside obviously it will drive the water into the concrete. Now the ionic species that are dissolved in water can also move because of permeation.

Ionic species do not always have to move because of diffusion. They can also be carried by the water into the concrete. For example, sulphates which are dissolved in water inside the ground water can get carried by water into the concrete because of permeability. So, permeation obviously is higher when there are cracks and defects present in the concrete. So obviously water does not have to diffuse or permeate through regions of porosity. It can permeate directly through the cracks and defects in the concrete.

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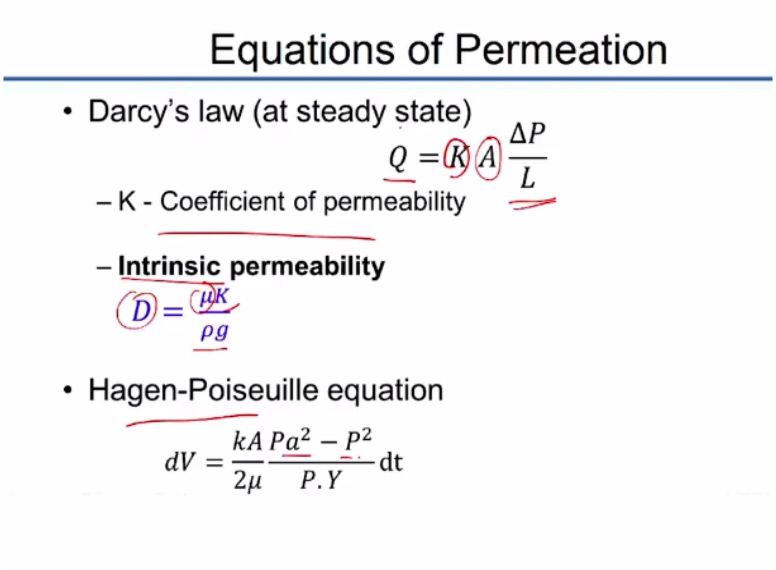

Equations of Permeation

- Darcy's law (at steady state)

$$Q = K A \frac{\Delta P}{L}$$

  - K - Coefficient of permeability
  - **Intrinsic permeability**

$$D = \frac{\mu K}{\rho g}$$

- Hagen-Poiseuille equation

$$dV = \frac{kA}{2\mu} \frac{Pa^2 - P^2}{P.Y} \mathrm{dt}$$

And you know this equation quite well. Darcy's law which is under steady state conditions again. What does it mean? What is steady state condition mean for permeation? You have a saturated condition and secondly you have a similar pressure gradient at all points of time. So time invariance of the pressure gradient exits. So here so the flow is given in terms of the permeability coefficient K * the area of cross section across which the permeation is happening * the pressure gradient, the difference in pressure/the length over which the difference exists.

So this K here is called the coefficient of permeability and often times we convert this into what is known as intrinsic permeability which is actually a material property. This coefficient of permeability si determined experimentally but it is also related to a more fundamental material property called intrinsic permeability, D = viscosity of the fluid * the permeability coefficient measured by permeability experiments/the density of the fluid * the acceleration * gravity g.

So that is the more important parameter for us to get from this equation. The only difficulty is setting up this kind of an investigation for concrete can be quite difficult. Because now you are talking about subjecting a concrete to water pressure on 1 side and then making this water come out on the other side. Water has to actually flow out of the concrete and you need to wait until the rate of flow at the downstream end is constant to get the steady state condition.

The rate of flow which is coming at the downstream end should become constant. So imagine it will take you a long time for that to be achieved. First of all, for water to come out through the pores of the concrete itself will take a very long time and after the water comes out and establishes the steady state your concrete would have already matured by 10 to 12 days beyond the point where you have started the test.

So what I am saying is to get that steady state you need to wait at least 10 to 14 days and in that time concrete has matured already significantly. So because of that you are not really capturing the true properties of concrete at that point of time. So it is a difficult aspect to establish. Now when you are talking about gaseous diffusion under pressure you use the Hagen-Poiseuille equation which is also quite similar. You have the different squares of difference in pressures and then you are related to the amount of flow that is happening for the gas through the concrete.

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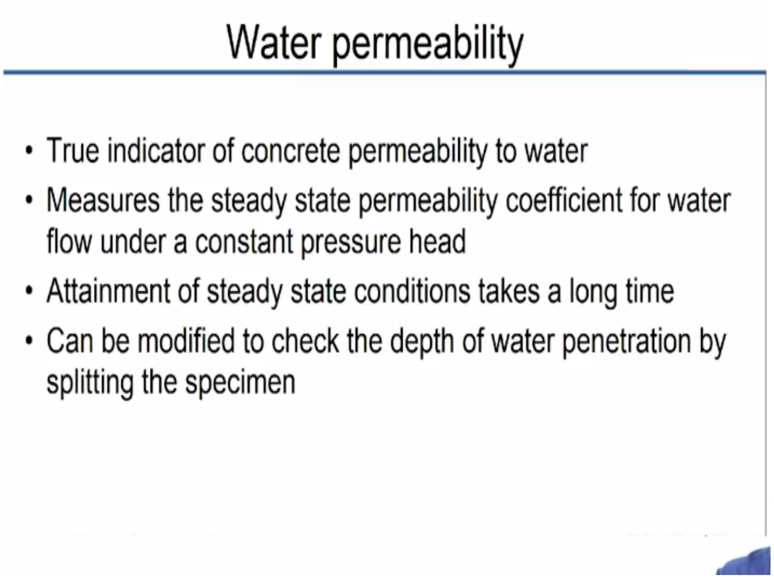

Water permeability

- True indicator of concrete permeability to water
- Measures the steady state permeability coefficient for water flow under a constant pressure head
- Attainment of steady state conditions takes a long time
- Can be modified to check the depth of water penetration by splitting the specimen

So water permeability is the common experiment which is done and has been standardized in most cores unfortunately it is not something that is easy to conduct basically it measures the steady state permeability coefficient for water under a constant pressure head. Now you know very well we just discussed now attainment of steady state takes a long time. So because of that, this test has been suitably modified by different standards to not just look at the flow at the other end, but stop the test when the water has penetrated the concrete by a certain distance.

For example, you apply the same pressure, but instead of making the water penetrate the entire distance and flow out of the concrete you stop the test after 2 or 3 days split the concrete open and measure the depth of water penetration and use that as an indicator of the durability. Now only difficulty is there is you cannot apply any law to determine the permeability coefficient. You only have an arbitrary parameter that is equal to the depth of water penetration and use that as a durability characteristic to classify the concrete characteristics.

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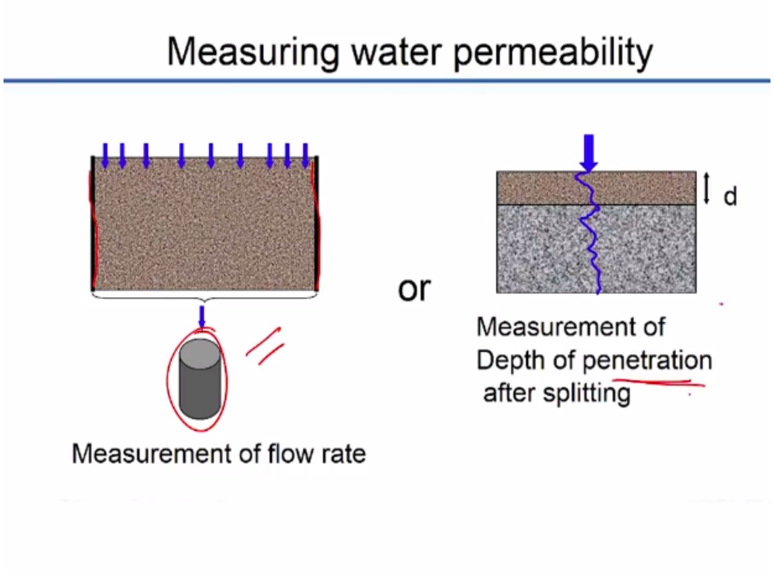

Measuring water permeability

So these are 2 different methodologies. One is obviously looking at the flow rate of water flowing out through the concrete. The other is the depth of penetration of water after the certain amount of time. Now the other disadvantage with the water permeability test is that sealing the sides of the concrete can be a really difficult task because you want the water to actually flow through the concrete and not from the sides.

So sealing the sides and ascertaining that water does not flow on the sides; that takes a very long time also to set up. So this test is not easy and nobody seems to be using these tests nowadays.

What people prefers the water penetration test so we can’t call it a water permeability test anymore, we call it water penetration test under pressure.

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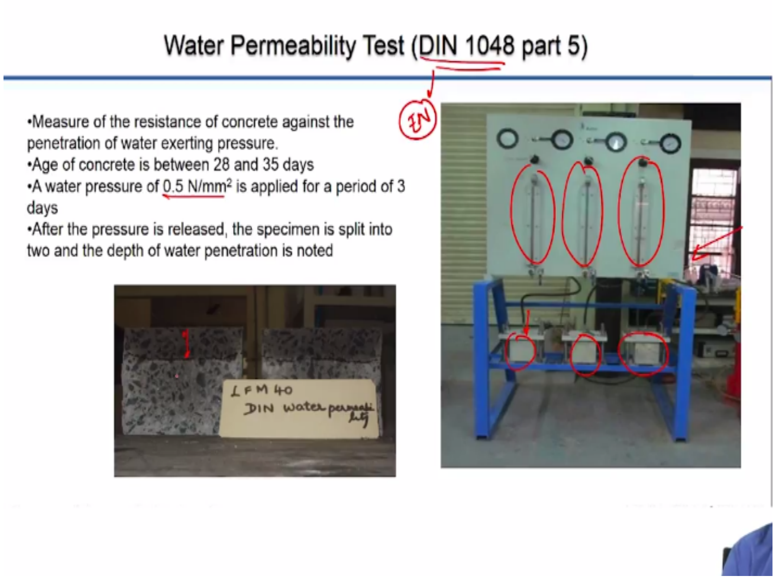

Water Permeability Test (DIN 1048 part 5)

EN

- Measure of the resistance of concrete against the penetration of water exerting pressure.
- Age of concrete is between 28 and 35 days
- A water pressure of 0.5 N/mm^2 is applied for a period of 3 days
- After the pressure is released, the specimen is split into two and the depth of water penetration is noted

And this has been standardized by German standards DIN 1048. Now of course this is also now an EN standard. I am sorry I do not have the EN number for this. It was originally a German standard, but it is an EN standard. So this is the water permeability apparatus that is there in our laboratory. So here this graduated tube here tells you the amount of pressure that you have set up for the water in the system.

And this is your concrete specimen which is tightly sealed on the top and bottom to ensure that there is no leakage of the water from the sides. So this water basically comes through that tube there, penetrates the concrete and after 3 days of application of 0.5 megapascal pressure or 5 bar pressure for 3 days after that you split the concrete open and measure the depth of penetration. So this is showing you the depth of penetration of water into the concrete.

Now one thing you need to understand is this test method does not call for a particular conditioning of the concrete sample to be done. That means the concrete should be directly taken from the moist curing and subjected to this water penetration. Sometimes what may happen if the concrete is of a poor quality that after moist curing your entire concrete has totally saturated?

Now when you do the permeability experiment it is very difficult to actually get a clear idea about the depth of penetration when you split open the concrete.

For concretes that are having lesser water cement ratios it is quite easy to get this result because you will see a clear band of water moving through the concrete, but for concrete with high water cement ratio has been actually get quite difficulty. So in those cases you might want the subject your concrete specimens to some preconditioning that means you dry it for certain period of time and then do the test, but for the most part this test method is prescribed for concretes without any preconditioning that means you directly take it from the moist condition.

And test it only then we can apply a direct permeation law otherwise what is going to happen. If the concrete is dry what it will also do? It will absorb because it is drier than the water it is going to absorb water and then you will have other mechanisms apart from permeation also which are acting in the same experiment. That is the reason why the code specifies that you need to use this concrete in a saturated state directly taken from moist curing.

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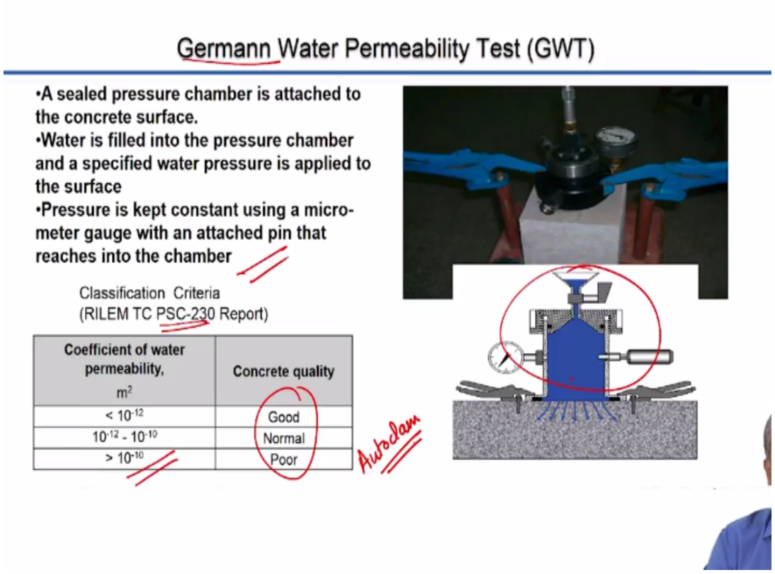

Germann Water Permeability Test (GWT)

- A sealed pressure chamber is attached to the concrete surface.
- Water is filled into the pressure chamber and a specified water pressure is applied to the surface
- Pressure is kept constant using a micro-meter gauge with an attached pin that reaches into the chamber

Classification Criteria
(RILEM TC PSC-230 Report)

Coefficient of water permeability, m^2	Concrete quality
$< 10^{-12}$	Good
$10^{-12} - 10^{-10}$	Normal
$> 10^{-10}$	Poor

Autoclam

Now there is also a nondestructive instrument from Germann instrument, this is not German. The previous test was German and this test is Germann. Germann is a company based in Norway which meaks nondestructive test instrumentation for concrete and here what they have done is they have made this special apparatus which has a water filled chamber which can be fixed to the surface of the concrete.

So you can actually take this to any concrete surface horizontal or vertical and get the system clamped on to the concrete and then measure the actual water penetration happening when you apply pressure in the water filled chamber on the top. So the principal is the same. You are still applying pressure to the water to get it into the concrete, but the advantage here is that you can carry this to any real structure and do the test.

So pressure is kept constant using a micrometer gauge with an attached pin that reaches into the chamber. The amount of adjustment that you need to give for the pressure to remain constant is then converted to the amount of water that is penetrating into the system and ultimately you get again a water permeability coefficient from this test and then based on the conditions that are prescribed of course this is again not a standardized test it is again covered in a report of RILEM committee.

And it tells you that for different values of permeability the concrete quality can be assessed qualitatively. There is again no quantification here. Concrete has good, normal, or poor when your permeability coefficient is so much. There are also other devices available like this. There is another device called Autoclam which is also available in the market which can be used to directly fix on top of your concrete structure and determine the permeability coefficient.

Now, the advantage of these nondestructive measures is that now you have a chance to apply these directly on the structural concrete. Because the durability test on structural concrete is not really going to damage it unless you remove a specimen to do the test. If you are simply going to be doing it nondestructively there is no problem at all. So these kinds of test can actually be applied for onsite measurement of the quality of concrete apart from cover depth you can also actually directly measure the permeability coefficient.

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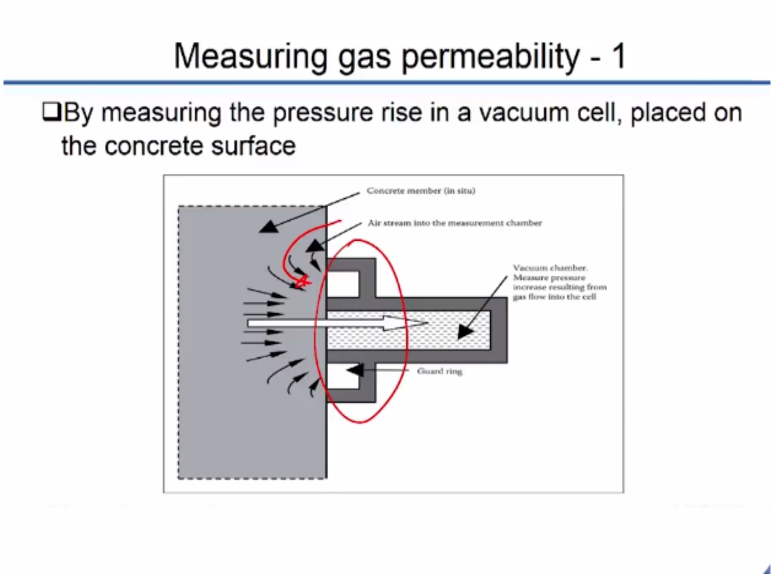

Measuring gas permeability - 1

- By measuring the pressure rise in a vacuum cell, placed on the concrete surface

Now gas permeability can be measured in several ways. Water permeability I talked about 2 different techniques. So gas permeability can be done in several ways. One is by measuring the pressure rise in a vacuum cell which is placed on the concrete surface. So you again have a cell with which you create vacuum and affix it to the concrete surface so the air which is flowing from the sides will tend to go through the porosity of concrete and disturb the vacuum inside the cell and that can be gauged as the permeability coefficient of the concrete. So that is what is happening in this case.

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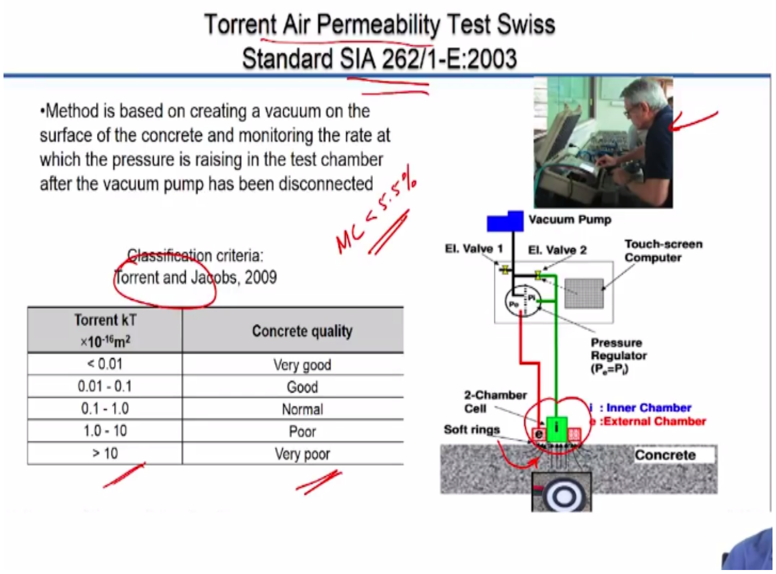

Torrent Air Permeability Test Swiss Standard SIA 262/1-E:2003

- Method is based on creating a vacuum on the surface of the concrete and monitoring the rate at which the pressure is raising in the test chamber after the vacuum pump has been disconnected

MC < 5.5%

Classification criteria:
Torrent and Jacobs, 2009

Torrent kT $\times 10^{-16} m^2$	Concrete quality
< 0.01	Very good
0.01 - 0.1	Good
0.1 - 1.0	Normal
1.0 - 10	Poor
> 10	Very poor

This test has been standardized in Switzerland. So Swiss standard test and it is also available with an instrument called Torrent Air permeability tester and we have this instrument in our lab.

Again this has this vacuum chamber which is connected to the concrete specimen and then it is operated using this valve to ensure that the vacuum is maintained and then the air flow happens from the concrete into this chamber which creates a pressure difference between the 2 chambers.

And that is recorded as a coefficient of permeability which is called torrent air permeability coefficient based on the name of the person who has done the development that is Mr. Torrent himself he came to our lab to we bought that equipment luckily at that time he was also visiting India so visited our lab and then he demonstrated. This was the first time that he actually had the inventor of equipment demonstrate the equipment in the lab.

So based on this again, you can have of course from a publication from the manufacturer himself there is actually a classification for concrete quality that can be done based on the permeability coefficient in the Torrent air permeability test. Now in this case, what you need to ensure is the concrete is dry. We are talking about gas permeability. So concrete has to be sufficiently dry. So although this instrument can be used to calculate the earth permeability coefficient of any real structural concrete you have to ascertain that the concrete in the structure is in a dry condition.

So, before you do this test, you need to determine the moisture content of the concrete of the surface, and that should be < 5.5$. Before you apply this to real structural concrete you need to ensure that the moisture content of the surface of the concrete is < 5.5%. How did you determine moisture content in concrete? There are moisture meters available which can work based on capacitance measurements.

And that can be used to determine the extent of moisture in the surface. Those you have done the nondestructive testing course have already used this moisture meter. So moisture meters can be used to detect extent of moisture in the concrete. It is < 5.5 you can then go ahead with the testing of the air permeability.

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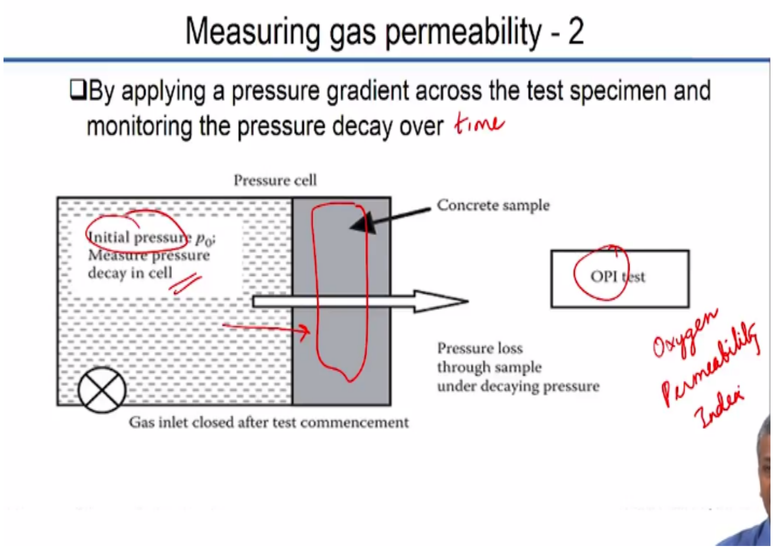

Measuring gas permeability - 2

- By applying a pressure gradient across the test specimen and monitoring the pressure decay over time

The other way is to apply a pressure gradient across the test specimen and monitoring the pressure decay over time. I am sorry the word time is missing or may be the image is somehow covered that for some reason. Pressure decay over time is measured okay and so this is basically the pressure cell where you have some initial pressure maintained. You have the concrete sample sitting here and which time what is going to happen?

The pressurized gas is going to flow through the concrete and then this pressure that is registered in the cell is going to keep on decreasing. If you have a pressure transducer measuring the pressure, then the difference in pressures can tell you the extent of permeability of the concrete. This is captured in the oxygen permeability index test and this test is standardized in South Africa. It is now being adapted in several other countries also. I will show you what this test is all about.

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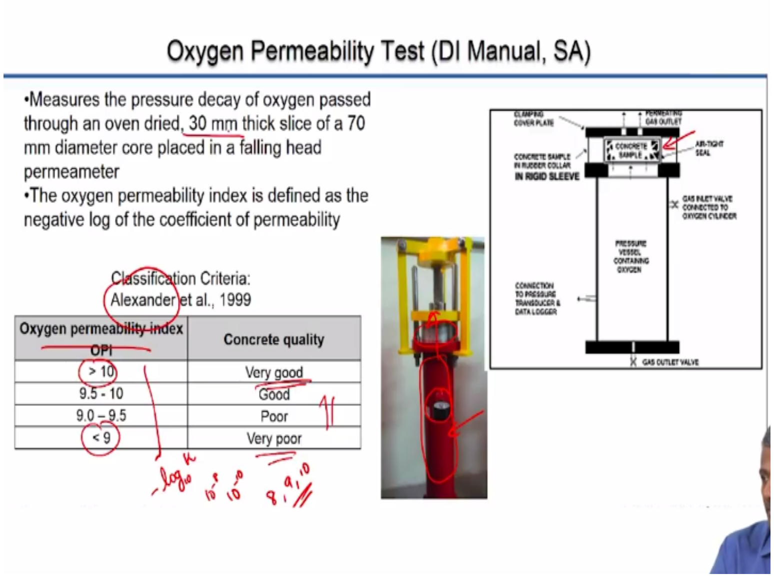

Oxygen Permeability Test (DI Manual, SA)

- Measures the pressure decay of oxygen passed through an oven dried, 30 mm thick slice of a 70 mm diameter core placed in a falling head permeameter
- The oxygen permeability index is defined as the negative log of the coefficient of permeability

Classification Criteria:
Alexander et al., 1999

Oxygen permeability index OPI	Concrete quality
> 10	Very good
9.5 - 10	Good
9.0 – 9.5	Poor
< 9	Very poor

$-\log_{10} K$ 10^{-8} 10^{-10} 8, 9, 10

So this is your pressure here and that is the pressure transducer that is actually measuring the pressure inside. Now oxygen is used because you are able to describe clearly what the molecular size of oxygen is going to be because you know the molecular mass. You know the average atomic size and so on because of which you are able to fix very clearly how the pressure drop will be related to the permeability coefficient.

If you use air, then you have mixture of gases and converting that to a suitable equation is going to be quite difficult. So here what we do is we have the pressure cell filled with oxygen. The concrete sample is held very tightly in a rubber collar so that when we ensure that the concrete sample gets sealed, the concrete expands against a rubber collar and ensures that there is no gap let behind between the concrete and the collar.

So we want the oxygen to penetrate only through the concrete and not on the sides. So sealing the concrete in this case is very important and then with time the oxygen gas tends to go out of the concrete and pressure decay is monitored and converted to an oxygen permeability index which is a negative log of the permeability coefficient K. Now permeability coefficient you know will be in the order of 10 power - 8, 10 power - 10 like that.

So when you convert that to a negative log, you actually get a whole number like 8, 9, 10 like that or 8.5, 9.5, 10.4 values like that are obtained. So now what does this tell you. If the permeability coefficient is low the permeability index is going to be high. So permeability coefficient of 10 power - 10 means your index is going to be + 10. So the higher the index the better the classification of the concrete.

And this has been again prescribed by the people who actually set forth this standard in the first place, the South African researchers and accorded them for an OPI value of > 10, your concrete quality is very good, < 9 is very poor and of course there are intermediate values given. What you can do now is use this sort of a qualitative classification to adjudge the kind of concrete that has been supplied for a construction project.

Or you can even take concrete course from the structure, subject that to oxygen permeability test and determine whether the concrete quality is good or not. Again in this case, a 30 mm thick slice is taken. Why 30 mm thick? because in most cases your cover concrete is about 25 to 40 mm. So 30 mm thick slice means it is actually representing your cover concrete. The only difficulty here is if your concrete is very large aggregate.

Let us say 25 mm aggregate and you take a 30 mm cover then you may get a lot of variability in your system. The other side of looking at that is, in reality also when use 25 mm aggregate you do not have much more than 30 mm cover. So that is actually reflecting a real life situation, variability can be expected and that needs to be built into the kind of assessment that you are doing for the system.

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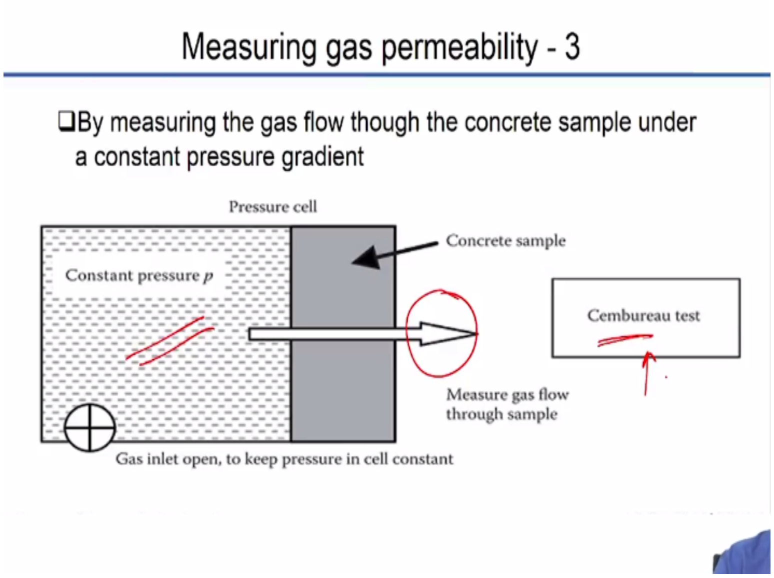

Measuring gas permeability - 3

- By measuring the gas flow though the concrete sample under a constant pressure gradient

Third way to measure gas permeability is keeping a constant pressure inside the chamber and simply measuring the gas flow which is coming on the outside and that is the European test called Cembureau test. Principal is similar. Just like you had for sand you must have done 2 different experiments the constant head permeameter and the falling head permeameter. So the constant head permeameter is more like the Cembureau test.

The falling head permeameter test is similar to the oxygen permeability test developed by the South Africans. So again the prescription or rather than the performance requirements which are stipulated by these different test methods could be quite different and you need to ensure that you are addressing the right kind of test method.

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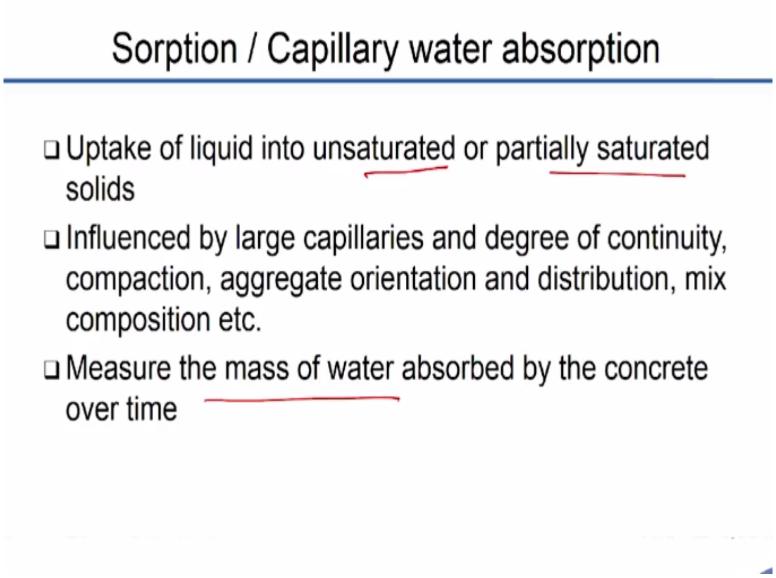

Sorption / Capillary water absorption

- Uptake of liquid into unsaturated or partially saturated solids
- Influenced by large capillaries and degree of continuity, compaction, aggregate orientation and distribution, mix composition etc.
- Measure the mass of water absorbed by the concrete over time

The other mechanism that commonly occurs in durability or in service of the concrete is sorption or capillary water absorption. So this refers to water uptake by capillary absorption into the concrete. So this already assumes that a concrete is going to be dry or partially saturated so that it is able to suck up or absorb the water which is in the surrounding soil or the environment. So uptake of liquid into unsaturated or partially saturated solids is covered in sorption.

Or capillary water absorption and it is obviously going to be influenced by how much capillary porosity you have, what is the degree of connectivity of these pores aggregates because aggregates will determine how much ITZ is available and because of that your mix characteristics can be quite nicely captured with the help of a sorption based experiment. So what you simply do is measure the mass of water absorbed by the concrete over time.

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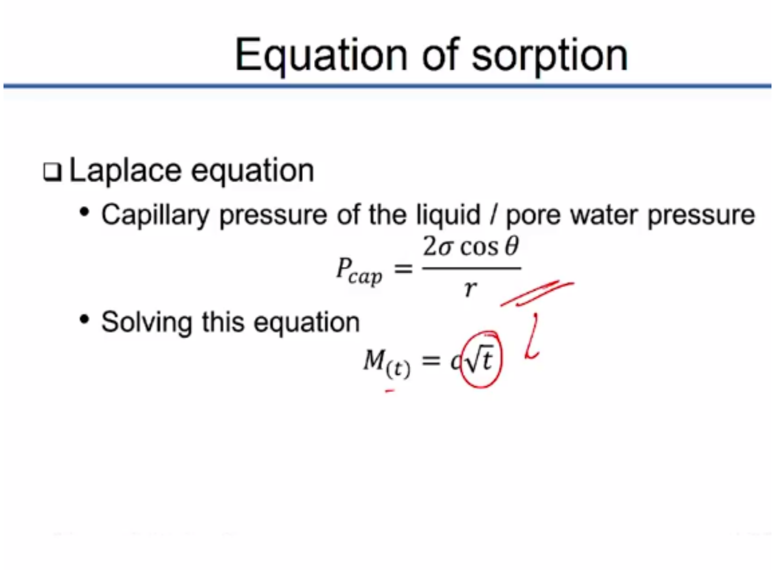

Equation of sorption

- Laplace equation
  - Capillary pressure of the liquid / pore water pressure

$$P_{cap} = \frac{2\sigma\cos\theta}{r}$$

  - Solving this equation

$$M_{(t)} = c\sqrt{t}$$

It is a quite simple way to do it and equations that deal with sorption include capillary pressure equation which you know very well and when you solve this capillary pressure equation you get the mass of water absorbed varying as a function of the square root time. Just like your diffusion of CO2 you have the same sort of a square root of time relationship between the mass of water absorbed by the system and the time taken for this to happen.

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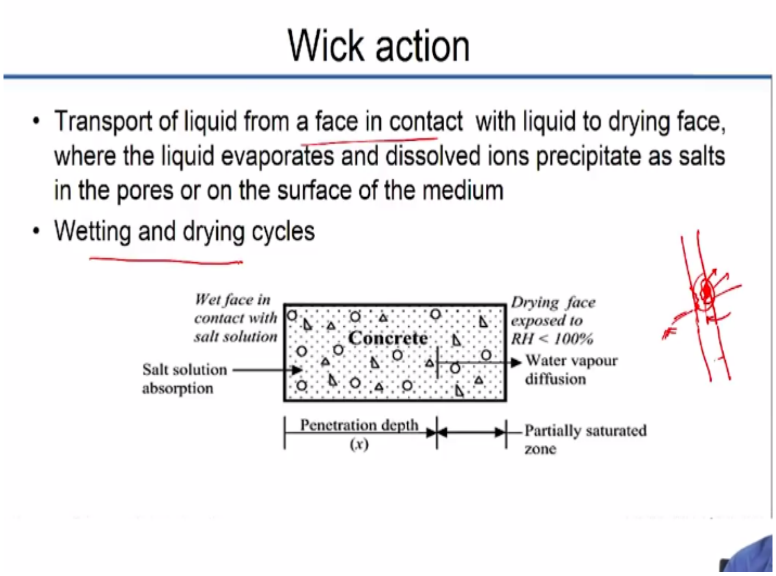

Wick action

- Transport of liquid from a face in contact with liquid to drying face, where the liquid evaporates and dissolved ions precipitate as salts in the pores or on the surface of the medium
- Wetting and drying cycles

The other way that this aspect can actually lead to a greater rate of durability problems in your concrete is wick action. You know very well that when you have a dry surface in 1 end and another surface that is in contact with a liquid which has ionic species or dissolved ionic species because of the wick action of the porosity that is on this side because of drying front on this side you will actually suck up more of the liquid into the system.

And locally your concentrations of the ionic species may actually get exceeded even beyond what is actually there in your external system. So transport of the liquid from a face in contact with liquid to drying face happens and the liquid evaporates leaving behind a concentrated amount of the dissolved material. So dissolved ions can precipitate as salts in a more concentrated fashion.

So think of it in a situation for example, if you have a column standing in a ground that is sulphate soils. The soil in rich in sulphate. The water is transporting the sulphates into the concrete. There is external atmosphere that is causing drying of this water. So it is causing this water to rise up to this place here deposit your salt solution at this interface the water dries out leaving the salt behind.

So you can imagine that in a condition like this the amount of damage that you will see will be much greater at the interface of the soil and air rather than deep inside the soil. So, because of the action of which we call as wick action. So that is what is exactly happening in this case and of course what we have to realize is this can happen in any condition because you are going to get drying and wetting cycles.

So in the case of drying cycles the moisture from inside is trying to get pulled out to the external environment, when the moisture dries out it leaves the salt in a higher concentration of the surface and during wetting again these salts can be pushed further into the concrete. So you have a constant change in the concentration of the specimen.

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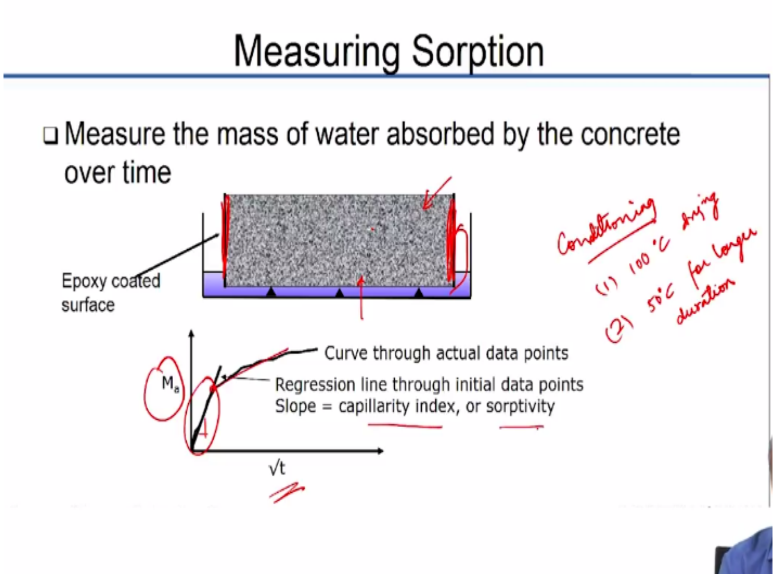

Measuring Sorption

- ❑ Measure the mass of water absorbed by the concrete over time

Conditioning
(1) 100°C drying
(2) 50°C for longer duration

So how do you measure sorption? The simplest way is to simply take a slice of concrete and put it in a water bath where water is able to get in only from 1 surface of the concrete. So what we do is we cover the perimeter of the concrete specimen to ensure that the water does not enter through the sides. It has only 1 way of entering through the bottom surface of the concrete, but before we subject this to sorption the entire concrete has to be first conditioned to obtain a completely dry environment.

So conditioning methods could be quite different. So conditioning usually involves Owen drying the sample. So one way is actually drying it 100 degrees, but more commonly what people do is dry at lower temperatures typically 50 degree for longer duration. Why do you think people try to do this? why not dry it for 100 because you know that at 100 degrees all the water will simply go off.

But what also can happen at 100 degrees is you may actually lead to more defects forming in this structure because of the extremely high level of drying. At 50 degrees the drying is much more gradual so you dry it for a longer duration to ensure that the water actually has a way to get out of the system, but does not really affect the kind of structure that you have inside. It does not induce additional damage or cracking inside.

So that basically is how you do this test. You then plot your mass of water absorbed against square root of time what you see is the first few hours of collection of data that you have has a nice linear correlation with the square root of time. Later the slope of this graph may change to a much more gradual increase of water absorption in the system. So, the slope of this line or linear portion drawn through the initial points in the curve is otherwise called capillarity index or sorptivity index and that can be used a durability parameter to assess the quality of concrete.

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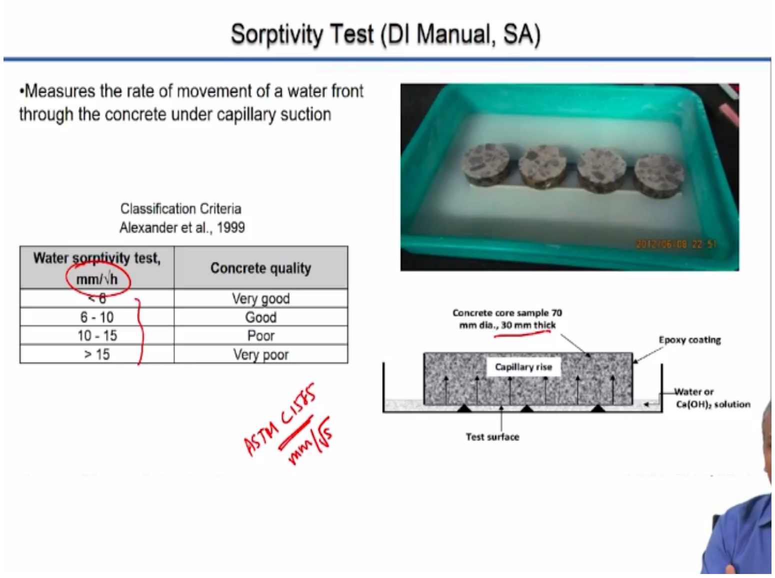

Sorptivity Test (DI Manual, SA)

- Measures the rate of movement of a water front through the concrete under capillary suction

Classification Criteria
Alexander et al., 1999

Water sorptivity test, mm/√h	Concrete quality
< 6	Very good
6 - 10	Good
10 - 15	Poor
> 15	Very poor

ASTM C1585
mm/√s

So this again a sorptivity test which is described by the South African durability index manual. There is also an ASTM test which I have not given here. ASTMC 1585. There is an ASTM test that also measures the same sorptivity. Only thing is there is a difference in the way that the results are interpreted. In the ASTM test the sorptivity is given in terms of millimeter per square root of second. In the South African test, it is converted to millimeter per square root of hour.

So here what we are simply doing is measuring the slope that is given by this. So this obviously going to be grams' square root of r, but this gram is going to get converted to millimeter based upon the amount of water rising, the column of water, equivalent column of water. So based on this test, again qualitative criteria can be used to adjudge the quality of your concrete. Again the sample is 30 mm thick.

And the advantage that the South Africans have done is you can extract the core sample and slice it to 30 mm first use it for the oxygen permeability test because again you are drying it for the test anyway conduct the test and then use if for sorptivity test. That way you can do 2 tests for the same specimen.

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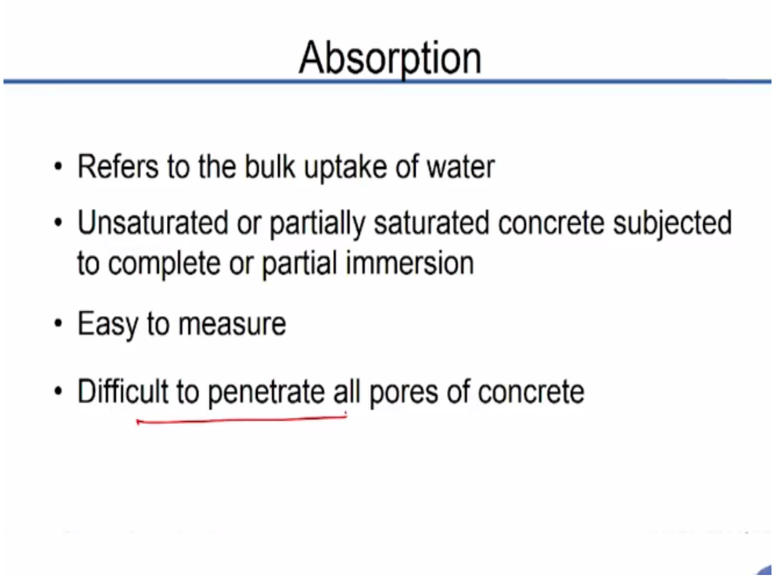

Absorption

- Refers to the bulk uptake of water
- Unsaturated or partially saturated concrete subjected to complete or partial immersion
- Easy to measure
- Difficult to penetrate all pores of concrete

The most common test that everybody does is an absorption test. So this refers to the bulk uptake of water. So take your concrete specimen, dry it until it achieves a constant weight then put it inside water under water for a certain period of time so there will be a lot of absorption and you wet it until it achieves a constant weight and measure the mass difference that gives you the extent of absorption.

The only thing is of course is difficult to penetrate all the pores of concrete because you are relying on the water outside trying to get inside it or so on. So you can actually improve this process by boiling the water. When you boil the water what happens surface tension decreases. It is able to penetrate more and more into the system. Another alternative is to vacuum saturate the concrete.

You put the dry concrete inside water and put it inside vacuum. So you are then forcing the water to enter the porosity which is otherwise not easily accessible, but end point is the same. You are making water penetrate the pores of the concrete and measuring the extent of absorption that may happen. This is similar to the absorption test that is done for aggregate. Only thing in aggregate cases we do not use boiling water or vacuum saturation. We use normal water absorption.

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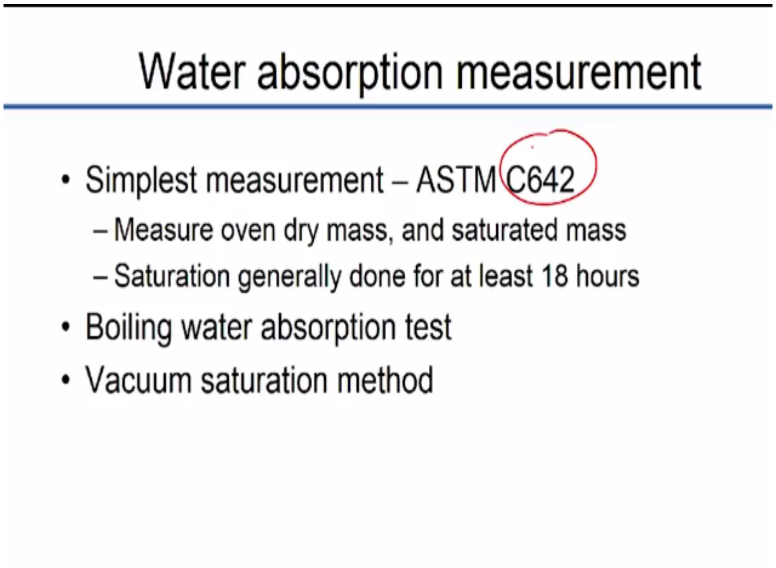

Water absorption measurement

- Simplest measurement – ASTM C642
  - Measure oven dry mass, and saturated mass
  - Saturation generally done for at least 18 hours
- Boiling water absorption test
- Vacuum saturation method

This is the easiest measure. It is covered in ASTM regulation C642 and in this case you can also measure the porosity of the system because again the water is accessing all the pores that are available from the surface. So you get it measure of your porosity of the system also.

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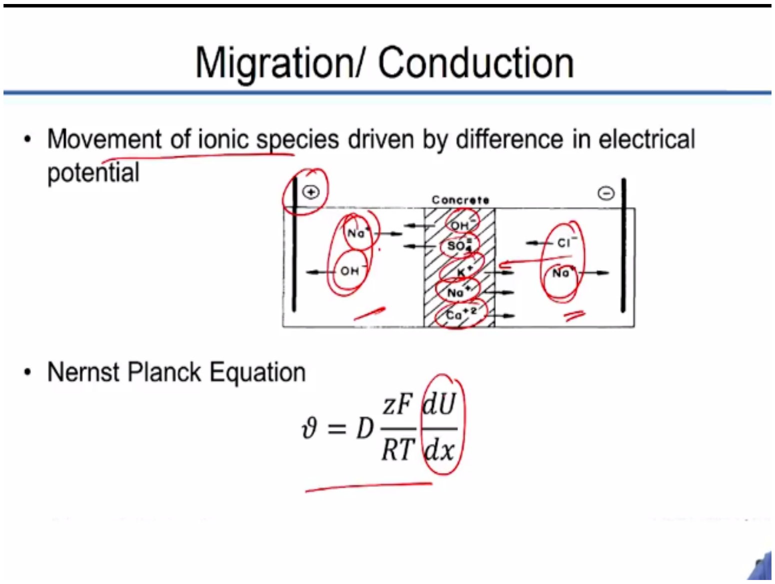

Migration/ Conduction

- Movement of ionic species driven by difference in electrical potential

- Nernst Planck Equation

$$\vartheta = D\frac{zF}{RT}\frac{dU}{dx}$$

Now the bulk of the tests that we look at as far as concrete is concerned either deal with water absorption or water penetration or the use of chloride related test methods that are based on migrations. The migration is movement of ionic species driven by difference in electrical potential. So in other words you have some liquids on either side of you concrete you apply a potential difference.

What you will end up doing is make the ionic species in the liquid move through the concrete to a location of lower concentration. So for example, if you have sodium chloride on 1 side and sodium hydroxide on the other side what you will end up doing is when you have this potential difference created between the electrodes the chlorides will be driven through the concrete to the positively charged electrode.

So you are trying to create the potential difference in dried ionic species through the concrete. The complicated scenario here is when you apply this potential gradient there is OH -, sodium hydroxide is there, sodium is there in the solution. Sodium is there inside the concrete, potassium is there inside in the concrete, calcium is there, hydroxyl, sulfphate, all these ionic species are present inside your concrete and in the external solution.

So when you apply the potential difference all these ionic species start moving. So the resultant charge that you are passing through the concrete is not truly a true indicator of what is happening in the concrete. It is a collection of all these ionic movements that are actually happening. Because of this migration base test cannot be taken as a direct representation of penetration of these chlorides in the concrete.

You have to take it in terms of just the value that you are getting. You cannot really apply it to determine the chloride diffusion coefficient. You can apply the Nernst Planck equation which looks at the potential gradient and relates that to the diffusion or permeability of the ionic species happening inside this media.

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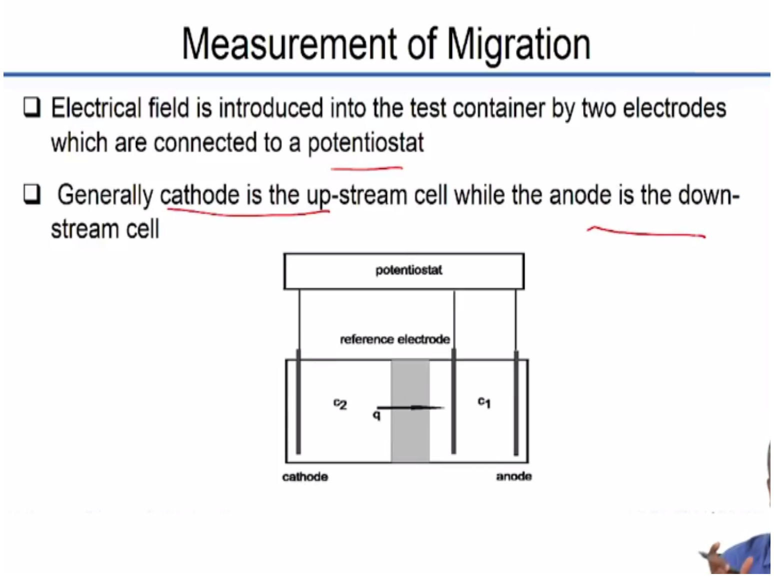

Measurement of Migration

- ☐ Electrical field is introduced into the test container by two electrodes which are connected to a potentiostat
- ☐ Generally cathode is the up-stream cell while the anode is the down-stream cell

So measurement of migration is typically done by inducing an electric field by 2 electrodes which are connected to a potentiostat and then the cathode is in the up-stream cell and the anode is in the downstream cell and then what you do is you dry the potential difference and you look at the amount of charge that is then passing through your concrete.

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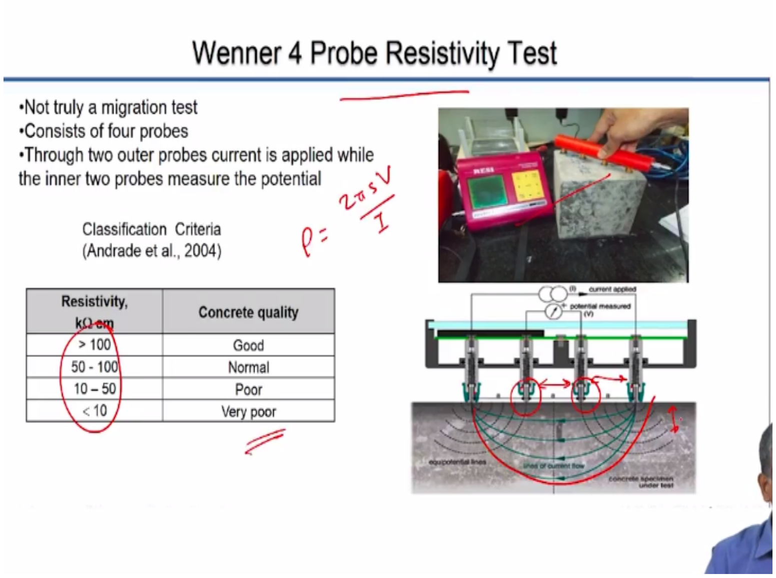

Wenner 4 Probe Resistivity Test

- Not truly a migration test
- Consists of four probes
- Through two outer probes current is applied while the inner two probes measure the potential

$\rho = \frac{2\pi s V}{I}$

Classification Criteria
(Andrade et al., 2004)

Resistivity, kΩ cm	Concrete quality
> 100	Good
50 - 100	Normal
10 – 50	Poor
< 10	Very poor

So this is done using several different ways of measuring it, one common method which is quite easy to use even on site is the Wenner 4 Probe resistivity test. So here you have 4 probes that are equally spaced that are placed on the concrete surface. You apply a current through the external probes. So the external probes there is current applied and then you determine the voltage or potential drop across the inner probes.

You determine the potential drop across the inner probes and convert that potential drop to the resistivity rho = 2 * pi * spacing * the potential that is measured between the probes/the current that is passed in the system. 2 * pi * s * V/I. Now resistivity you know very well that concrete is going to be conducting through its inner connected porosity. When there is interconnected porosity only conduction will happen.

So resistivity is the opposite of conductivity. So if the concrete has a very less amount of interconnectivity of pores the resistivity is expected to be high. That means the durable concrete will have a higher resistivity. So you can use the same test to then classify a concrete in terms of resistivity with respect to how easy it will be for ionic species to flow in the concrete and lead to conditions of corrosion.

So again resistivity gives you a direct measure of your permeability or interconnectivity of the pores in the system, but what is 1 major drawback in this case in this experiment? Concrete has to be completely saturated. If it is unsaturated what happens? Obviously resistivity is going to very high because of the lack of moisture in the porosity. The porosity has to be filled with water for conductivity to happen otherwise this experiment will not make any sense.

So there is a difference of nearly 6 to 7 orders of magnitude of the resistivity between dry concrete and moist concrete. You can get that level of difference. So again here just like your torrent air permeability test what you need to do is go with the moisture meter first, determine whether your concrete has properly saturated and then conduct the test to get suitable readings, but the fact that this test is so easy to use all it needs is this probe of course this is the older version of the instrument.

What we have currently you can put batteries in this probe is simply a stick like thing. You stick in the top of the surface you actually get the measurement of the resistivity directly. Now the advantage here is obviously you can use this to control or to detect the quality of concrete that is being placed in the structure directly keeping in mind that in a real structure there is going to be reinforcement and that reinforcement may also effect the resistivity value because you are getting more conduction paths through the concrete of the reinforcement is present.

So for that what you will have to ensure is the spacing between the electrodes is small enough so that your current lines are flowing only through the cover zone of the concrete. If you use a small spacing, you ensure that the current lines are only flowing through the cover zone of the concrete in that case you are actually measuring the property of the cover zone itself. Otherwise you will have the steel also coming into the system.

So there is a new Panama Canal that is being constructed and the researches from Spain who are involved in this construction of the Panama Canal and actually employed the use of resistivity in best measurements to determine the quality of concrete that is resupplied to the canal. So this durability test is actually being used as a performance requirement for the concrete supplied for the Panama Canal.

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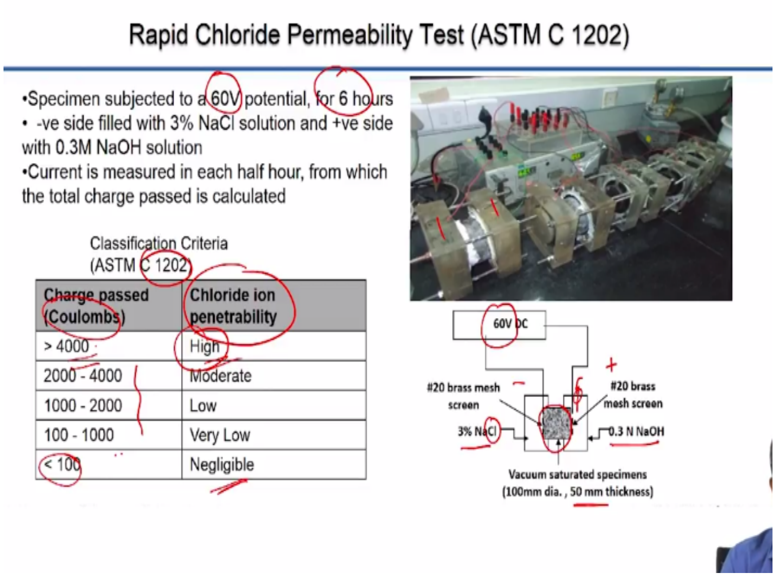

Rapid Chloride Permeability Test (ASTM C 1202)

- Specimen subjected to a 60V potential, for 6 hours
- -ve side filled with 3% NaCl solution and +ve side with 0.3M NaOH solution
- Current is measured in each half hour, from which the total charge passed is calculated

Classification Criteria
(ASTM C 1202)

Charge passed (Coulombs)	Chloride ion penetrability
> 4000	High
2000 - 4000	Moderate
1000 - 2000	Low
100 - 1000	Very Low
< 100	Negligible

Now the test which is most commonly used all around the world is the rapid chloride permeability test again. The name itself has the term permeability in it, but truly speaking it is not a permeability test, it is a migration test. So here you have 2 cells. One is filled with the sodium chloride solution, 3% sodium chloride the other is filled with a 0.3 normal sodium hydroxide solution.

And then you connect this to a power source where 60 volts potential difference is created between these cells. the concrete which is about 50 mm thick and has 10 mm diameter is kept between the cells and so this is your positive site and that is the negative side so when you apply this potential difference you tend to drive as I showed you earlier the main purpose is to drive the chlorides from the negative cathodic end towards the anodic end and this happens through the concrete.

But reality is that there are other ionic species also that are within the system that are going to be moving around. So because of that the result that you actually measure may not be truly indicative of the resistance to chloride ion penetration. Nevertheless, people seem to be using this in that sense and even the ASTM test method that standardizes this test calls the measure property as chloride iron penetrability and if you get more than 4000 coulombs charge passing through the system in a total of 6 hours.

So this current is, this potential is applied for 6 hours through your specimen and then you determine the extent of current passing through from time to time and convert that to the charge. Because you know that charge = current * time. Coulombs = ampere * second. So you convert that to a charge passed in terms of coulombs. If it is more than 4000 your chloride ion penetrability is deemed to be high < 100 it is negligible.

Then you have these intermediate ranges in between 2000 to 4000 is moderate, 100 to 1000 is very low and 1000 to 2000 is low. So again although something quantitative like the Coulomb charge passed is calculated through the concrete, the interpretation of the result is still based on the quality of the concrete. That is a very important thing for you to remember. When you measure the strength you report the strength.

You don’t say the concrete is nice or good if the concrete strength is 40. My concrete is excellent if the strength is 47.5 no, we just say 47.5 means 47.5 strength, but here when we get a permeability or charge passed of 3000 coulombs we do not say that my concrete permeability =

3000 coulombs. We say that the concrete quality is moderate with respect to chloride ion penetration. So durability test has to be interpreted in the correct fashion.

So you cannot use this in a quantitative sense. Let me tell you why. If you have a poor quality concrete, you expect that it is going to be having a high penetrability. When you have a poor quality concrete, because again the conduction through a poor quality concrete implies that a conduction is happening through several interconnected pores. So the poorer the quality the more the interconnected pores so more charge will pass through the concrete system.

But then when you are driving a potential it is in the 60 volts and this concrete is carrying charge that charge will tend to heat up the concrete even more. The concrete gets hotter it will carry even more charge, then it gets hotter it carries even more charge and this process leads to a continuous heating of your concrete. The temperature differences of the order of 50 to 60 degree Celsius can actually get created in this test.

And then you can actually see the boiling of these solutions actually inside the cell also when certain types of concretes are used. So in that case when you actually calculate the permeability in terms of charge passed you may get values of 10,000 coulombs or 12,000 coulombs. I have seen people even reporting those things once in a while, but that is not correct. Moment it crosses 4000 your already entering the high permeability range and you need to just stop the test.

There is no point in continuing beyond that because the heat generation will push up the permeability value tremendously. The other problem is when you use materials like geopolymer. We know that geopolymer is rich in alkaline. We put a lot of alkaline solutions inside. We discussed this earlier. We use alkaline activators to activate the polymerization of this aluminous silicates.

When you have the excess of alkali loading in your concrete what you expect will happen to its conductivity, conductivity will be higher. So when you do the RCPT test on a geopolymer concrete you will obviously get a very high permeability with respect to the values that are suggested here. The concrete quality may be otherwise good. If you do a water absorption test for instance you may actually get a good quality of concrete.

But when you do RCPT you will end up having a very poor performance because of the conductive ionic species that are present in the system. So you need to ensure that you are adjudging the quality of the concrete based on the correct test if you want to discuss the difference between different types of concrete. For example, if you use steel fiber reinforce concrete same experiment.

If you use long enough steel
fibers, there may be sufficient connectivity between steel fibers to actually provide conduction paths through the concrete. So you need to be very careful about using this test for all types of concrete. The other aspect is you need to saturate the specimen before it is used in this test so that you do not have other mechanisms also. Already it is a complicated process, this migration.

There is diffusion all kinds of things are happening if you have a dry specimen, there will be absorption also. So you need to ensure that the specimen is saturation and so this procedure with which this test is used also incorporates saturation of the specimen before the test is actually conducted.