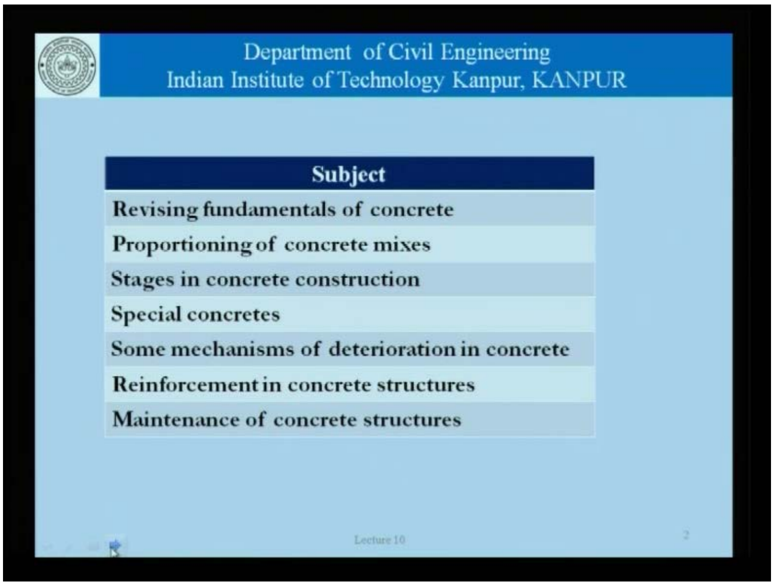
Concrete Engineering and Technology
Prof. Sudhir Misra
Department of Civil Engineering
Indian Institute of Technology, Kanpur

Lecture - 10
Pores and porosity in concrete

(Refer Slide Time: 00:23)



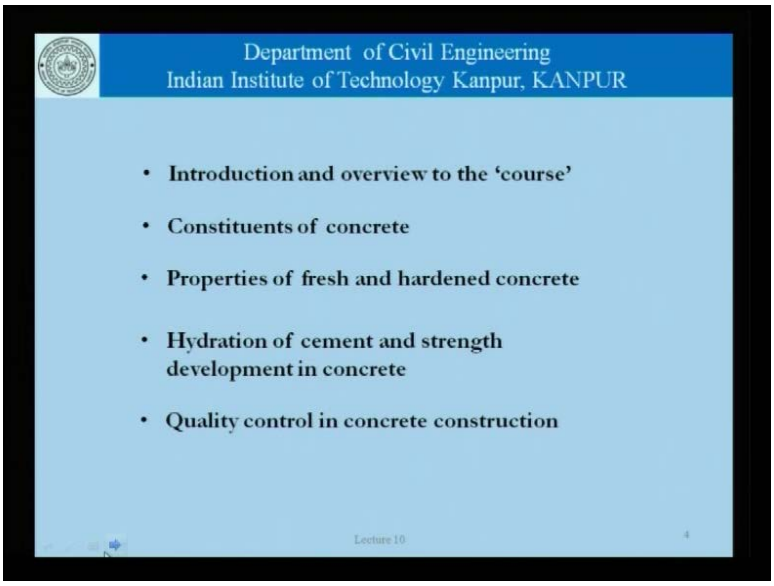
Department of Civil Engineering
Indian Institute of Technology Kanpur, KANPUR

Subject
Revising fundamentals of concrete
Proportioning of concrete mixes
Stages in concrete construction
Special concretes
Some mechanisms of deterioration in concrete
Reinforcement in concrete structures
Maintenance of concrete structures

Welcome to this lecture on concrete engineering and technology. In this course, we are trying to study fundamentals of concrete, proportioning of concrete mixes, stages in concrete construction, special concretes, mechanisms of deterioration in concrete, reinforcement of concrete structures, maintenance of these structures, and so on, in light of the developments that have taken place in the field of science, cement chemistry, admixtures, and so on.

As for as our discussion on revising the fundamentals of concrete is concerned we are trying to do and over view of this course, constituents of concrete, cement, sand, coarse aggregate and water in addition to chemical and mineral add mixtures, properties of fresh and hardened concrete, hydration of cement and strength development, and quality control in concrete construction.

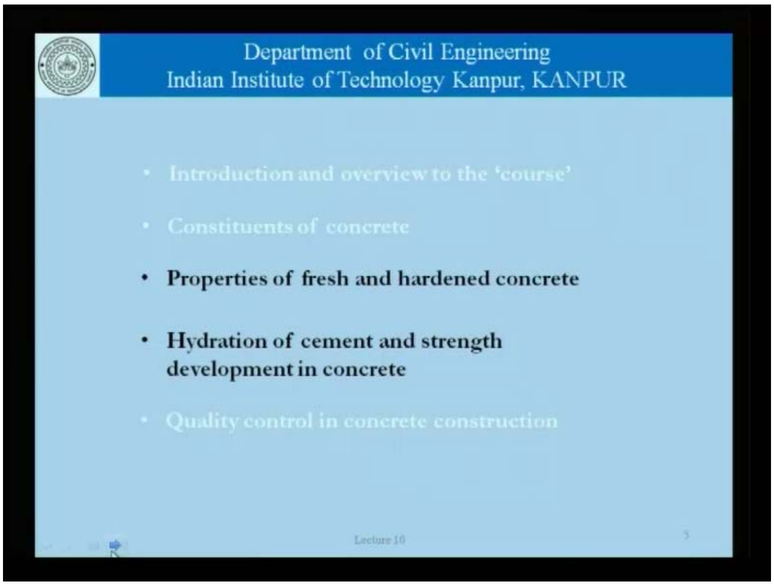
(Refer Slide Time: 00:56)



Department of Civil Engineering
Indian Institute of Technology Kanpur, KANPUR

- Introduction and overview to the 'course'
- Constituents of concrete
- Properties of fresh and hardened concrete
- Hydration of cement and strength development in concrete
- Quality control in concrete construction

(Refer Slide Time: 01:20)

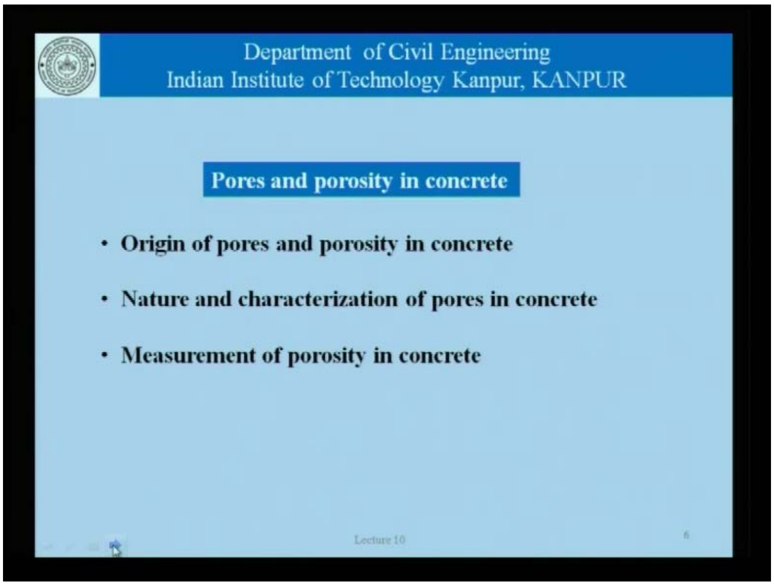


Department of Civil Engineering
Indian Institute of Technology Kanpur, KANPUR

- Introduction and overview to the 'course'
- Constituents of concrete
- Properties of fresh and hardened concrete
- Hydration of cement and strength development in concrete
- Quality control in concrete construction

Out of that our discussion today would focus on a topic which spends between properties of fresh and hardened concrete, and hydration of cement and strength development. One must remember there in a complex material like concrete is very difficult to classify and stick to that classification in a water type manner. There are subjects which spend one or more compartments. For example, hydration of cement is the basis on which strength development takes place on the basis of which special concretes can be designed, and so on. Quality control of concrete, spans, constituents, methods, properties of concrete, and so on.

(Refer Slide Time: 02:18)



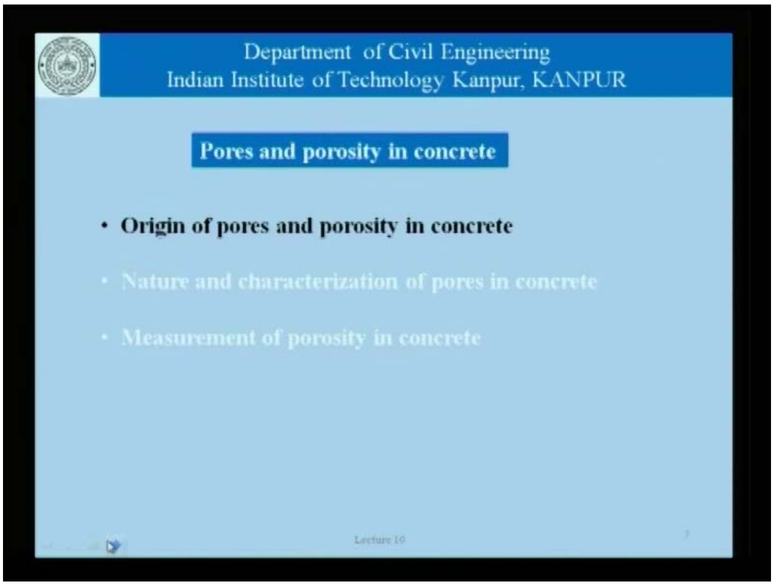
Department of Civil Engineering
Indian Institute of Technology Kanpur, KANPUR

Pores and porosity in concrete

- Origin of pores and porosity in concrete
- Nature and characterization of pores in concrete
- Measurement of porosity in concrete

So, the discussion today would be on the pores and porosity in concrete. What we will talk about is the origin of pores and porosity in the material, and we will talk about the nature and characterization of these pores, and finally, the measurement of porosity in concrete. So, this is an outline of what we would be talking about in this discussion.

(Refer Slide Time: 02:46)

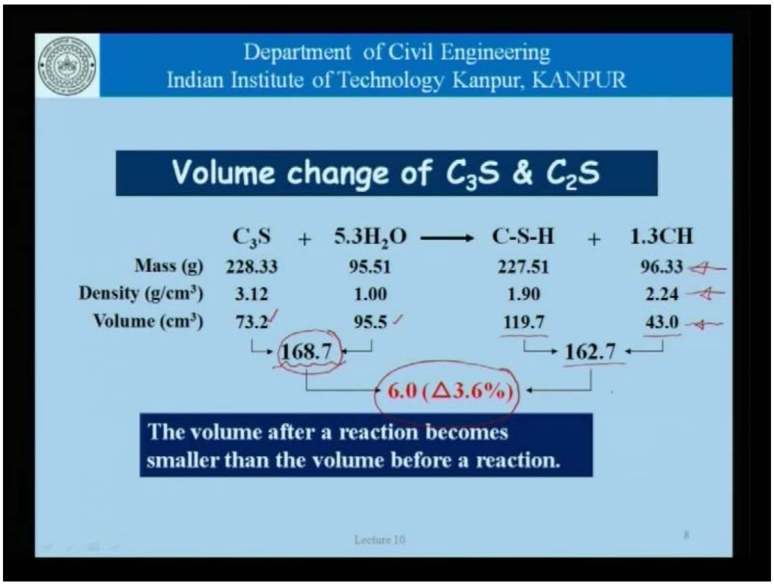


Department of Civil Engineering
Indian Institute of Technology Kanpur, KANPUR

Pores and porosity in concrete

- Origin of pores and porosity in concrete
- Nature and characterization of pores in concrete
- Measurement of porosity in concrete

(Refer Slide Time: 02:51)



Department of Civil Engineering
Indian Institute of Technology Kanpur, KANPUR

Volume change of C_3S & C_2S

	C_3S	+	$5.3H_2O$	$\longrightarrow$	C-S-H	+	1.3CH
Mass (g)	228.33		95.51		227.51		96.33
Density (g/cm^3)	3.12		1.00		1.90		2.24
Volume (cm^3)	73.2 ✓		95.5 ✓		119.7		43.0

$73.2 + 95.5 \rightarrow 168.7$

$119.7 + 43.0 \rightarrow 162.7$

$168.7 \rightarrow 6.0\,(\Delta 3.6\%) \leftarrow 162.7$

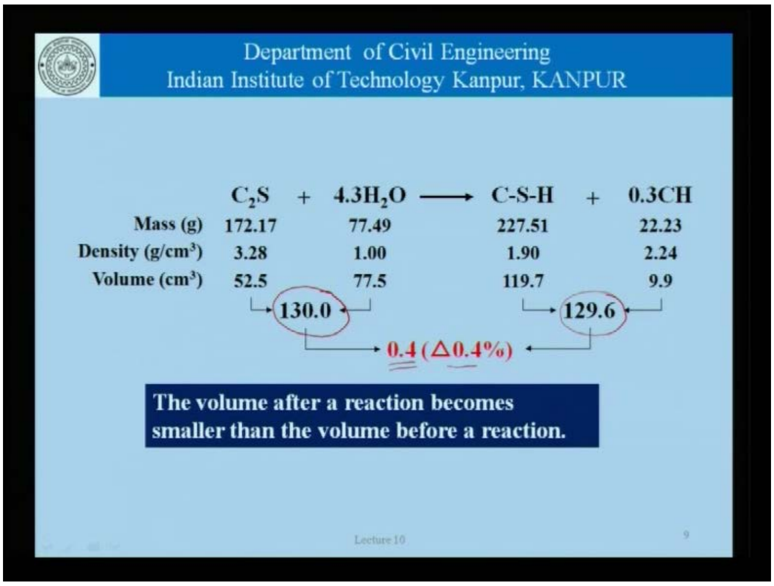
The volume after a reaction becomes smaller than the volume before a reaction.

Now, beginning our discussion with the origin of pores and porosity in concrete, let us look at the volume changes that take place when C 3 S and C 2 S which is the tri-calcium silicate and the di-calcium silicate, they hydrate. Now, these equations here give us the chemistry of hydration of these products. As for as C 3 S is concerned, C 3 S plus 5.3 H 2 O gives us C S H which is the calcium silicate hydrate gel, and 1.3 times CH which is calcium hydroxide.

So, if we look at the mass, this equation, this numbers here tell us what is the mass balance involved. From the density considerations of these individual constituents we get the volume changes that are involved, well, C 3 S hydrates. If we look at this total here, we have 73.2 cc of C 3 S reacting with 95.5 cc of water which means that the volume of the reactants is 168.7, and the volume of the products which is given here is only 162.7 which means that there is a net change for about 6 cc as for as the hydration of C 3 S is concerned, and that is the change of about 3.6 percent. The volume after the reaction becomes slightly smaller than the volume before the reaction.

Similarly, in the case of C 2 S we have 130 cc of reactants reacting and finally, giving as 129.6 cc of the products. Here the volume changes much smaller; it is about 4 cc and which is about 0.4 percent or whatever; and here too the volume after the reaction becomes smaller than that of the reactants.

(Refer Slide Time: 04:28)



Department of Civil Engineering
Indian Institute of Technology Kanpur, KANPUR

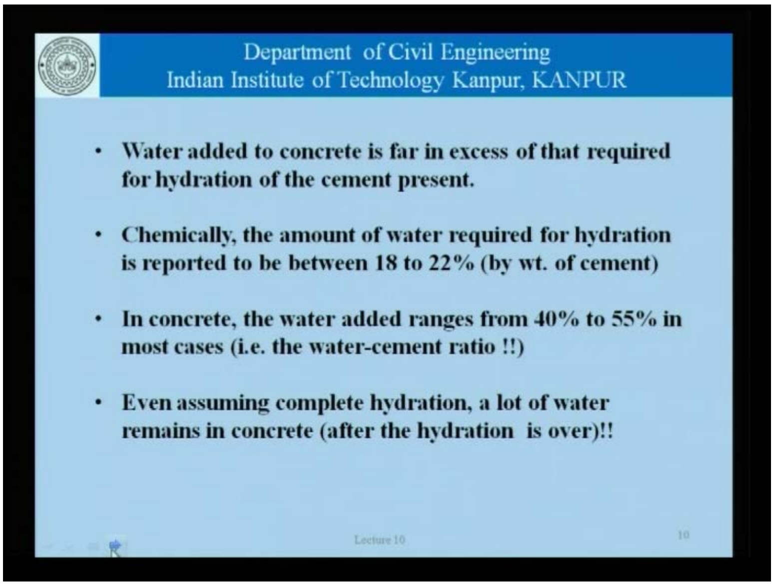
	C_2S	+	$4.3H_2O$	$\longrightarrow$	C-S-H	+	0.3CH
Mass (g)	172.17		77.49		227.51		22.23
Density (g/cm^3)	3.28		1.00		1.90		2.24
Volume (cm^3)	52.5		77.5		119.7		9.9

130.0 → 0.4 (Δ0.4%) ← 129.6

The volume after a reaction becomes smaller than the volume before a reaction.

Lecture 10

(Refer Slide Time: 05:02)



Department of Civil Engineering
Indian Institute of Technology Kanpur, KANPUR

- **Water added to concrete is far in excess of that required for hydration of the cement present.**
- **Chemically, the amount of water required for hydration is reported to be between 18 to 22% (by wt. of cement)**
- **In concrete, the water added ranges from 40% to 55% in most cases (i.e. the water-cement ratio !!)**
- **Even assuming complete hydration, a lot of water remains in concrete (after the hydration is over)!!**

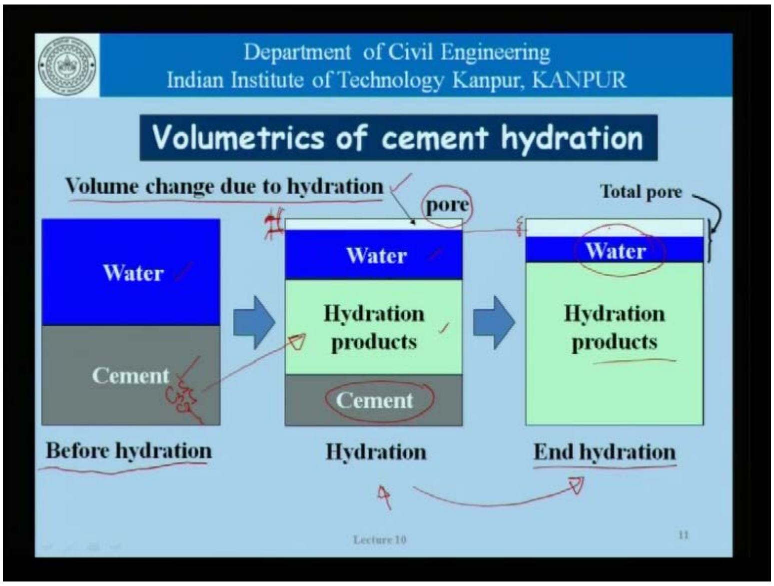
Lecture 10

Now, what are the implications of this change in volume as for as concrete is concerned. In addition to the volume changes that take place on account of the hydration of the different phases of cement or different solid complexes of cement. See, C 3 S and C 2 S which we solved just now, are two of the important solid complexes making of the cement. They are the, to be C 3 A and C 4 F, the tri-calcium aluminate and tetra-calcium aluminoferrites.

In addition to these volume changes, one must remember that the water added to concrete is far in excess of that required for the hydration of cement; hydration of cement from a chemical point of view, or the point of view of chemistry, stochiometry. If we read different reference papers, books, we would find that the amount of water which has been sited to be required for the complete hydration of cement varies form say, 18 percent to 22 percent by weight of cement; which basically means that in order to hydrate 100 grams of cement different people have different values to quote, but the value of the amount of water required for the hydration of that cement varies from about 18 to 22 grams.

In contrast to that, in concrete, the water added ranges from 40 to 55 percent in most cases that indeed is the water cement ratio. When we talk of water cement ratio in concrete what we are talking about is how much water and how much cement is present in the concrete by weight. Now, therefore, even if we assume complete hydration of the cement a lot of water remains in concrete after the hydration is over.

(Refer Slide Time: 07:09)



Department of Civil Engineering
Indian Institute of Technology Kanpur, KANPUR

Volumetrics of cement hydration

Volume change due to hydration

This picture here or this set of pictures here shows us the volumetrics of cement hydration. It is a schematic representation, and should not be taken too literally. If we have a certain amount of cement, we add a certain amount of water to it; this is the picture before hydration. Once the hydration starts the cement comprising of C 3 S, C 2 S, and whatever it is, that starts getting converted to hydration products. And, since in this picture we are talking of an intermediate stage where all the hydration has not yet taken place there is some unhydrated cement, some amount of hydration products which are been formed, and some amount of water which is still left. So, some amount of water has been consumed, and some amount of cement has reacted with the water, and the hydration is taken place.

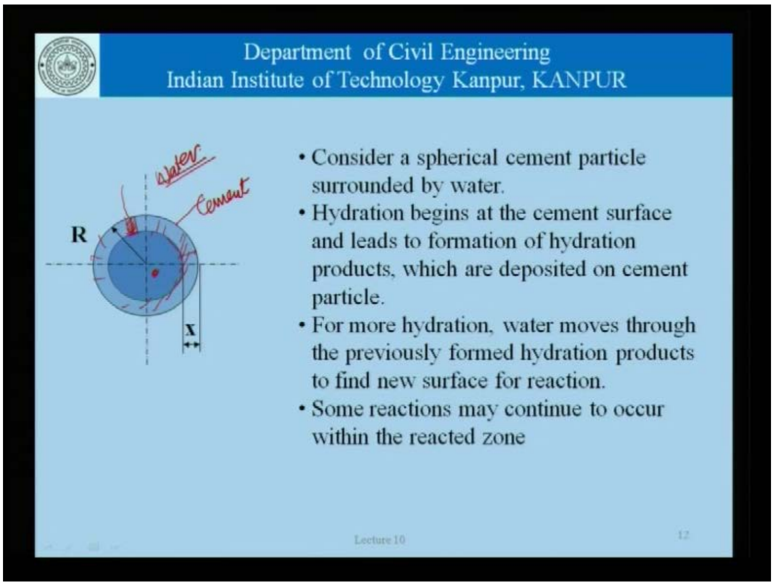
Now, given the fact that hydration that is the reaction of C 3 S, C 2 S, and so on, involves a reduction in the volume. We get this amount of volume here which is basically pores space. So, the amount of unhydrated cement plus hydration products plus remaining water which is upto this point here, is slightly smaller than the original volume which stood at this level. So, this is the pores which have got generated as a result of changes in volume of the hydration products, or the hydration products occupying just that shade smaller volume compared to the reactants.

If this hydration continues, or other, as this hydration continues, we finally have a situation where the hydration ends. And, we do not have any unhydrated cement. At that point in time, the hydration products have all formed. This amount of pore space which is arising out of the changes in the volume of the reactants and the products has slightly increased from this level here to this level, as shown. And, this amount of water is the unreacted water which is still remaining in the cement paste. Cement paste is the material that we are talking in the about in this picture.

We are talking about water and cement, what happens to them as the hydration goes on from the initial point to an intermediate point, to a point where complete hydration is taken place. In that cases, well, there is certain amount of water which is still remaining, and this is the amount of water which was added in excess of that required for complete hydration. Now, why was that water added in first place? That water was added to provide workability to the concrete.

Those are few of carried out experiments, and I will encourage you to do that; if you mix ordinary portland cement we say about 30 percent water or 27 percent water, you will find that the dough or the paste that you get is highly highly unworkable. We cannot really use it the way we would like to use concrete. And, concrete is just nothing but sand and coarse aggregate added to that paste. Only when more water is added the paste becomes a little more flowing; and at 40 percent, 45 percent it becomes such that, even if we add sand and coarse aggregate to it the concrete still remains workable.

(Refer Slide Time: 11:29)



Department of Civil Engineering
Indian Institute of Technology Kanpur, KANPUR

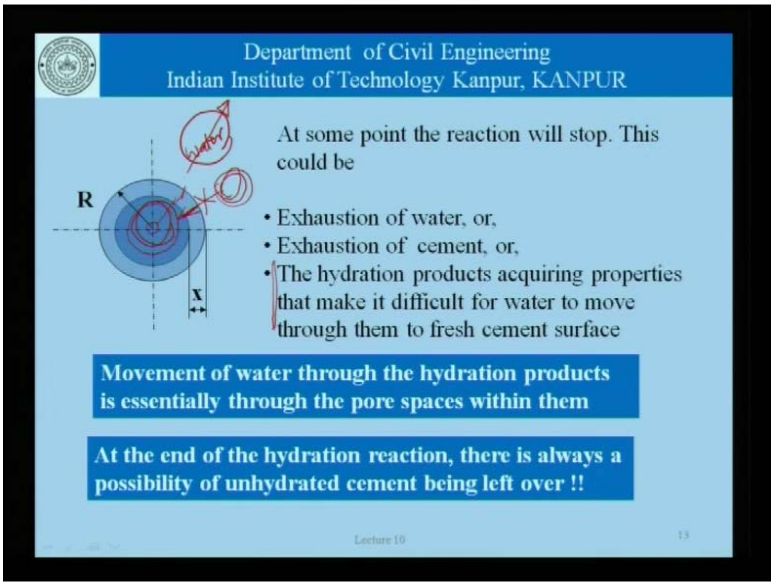
- Consider a spherical cement particle surrounded by water.
- Hydration begins at the cement surface and leads to formation of hydration products, which are deposited on cement particle.
- For more hydration, water moves through the previously formed hydration products to find new surface for reaction.
- Some reactions may continue to occur within the reacted zone

So, having said all that let us take a look at what happens in cement hydration, very quickly. This is a cement particle surrounded by water, and as for as concrete is concerned we can consider millions of cement particles really suspended as for as concrete is concerned in a, in water.

If the cement particle is now considered spherical and surrounded by water, hydration begins at the surface of the cement, and leads to formation of hydration products which are deposited on the cement particle. This portion here is the portion where you may say reaction has taken place or the hydration has taken place, and the cement particles has now shrunk to the size which is shown here, and this is the volume of hydration products which is just shaped smaller than the cement particle and the water volume together.

For more hydration, that is once these hydration products have been deposited on the cement particle, water from outside needs to move through the previously formed hydration products to find new surface for the reaction. So, basically water moves from outside and finds new surface here. And then at another point in time we may have situation where more cement has been hydrated. Of course, the model can also include the idea that some reactions continue to occur within the reacted zone. So, as the water moves through this layer of hydration products it is possible that some of the water is also used up in supplementary reactions or secondary reactions within the reaction products or the hydration products. And, only part of it reaches the fresh surface of cement and continues the hydration there.

(Refer Slide Time: 13:54)



Department of Civil Engineering
Indian Institute of Technology Kanpur, KANPUR

At some point the reaction will stop. This could be

- Exhaustion of water, or,
- Exhaustion of cement, or,
- The hydration products acquiring properties that make it difficult for water to move through them to fresh cement surface

Movement of water through the hydration products is essentially through the pore spaces within them

At the end of the hydration reaction, there is always a possibility of unhydrated cement being left over !!

Lecture 10

13

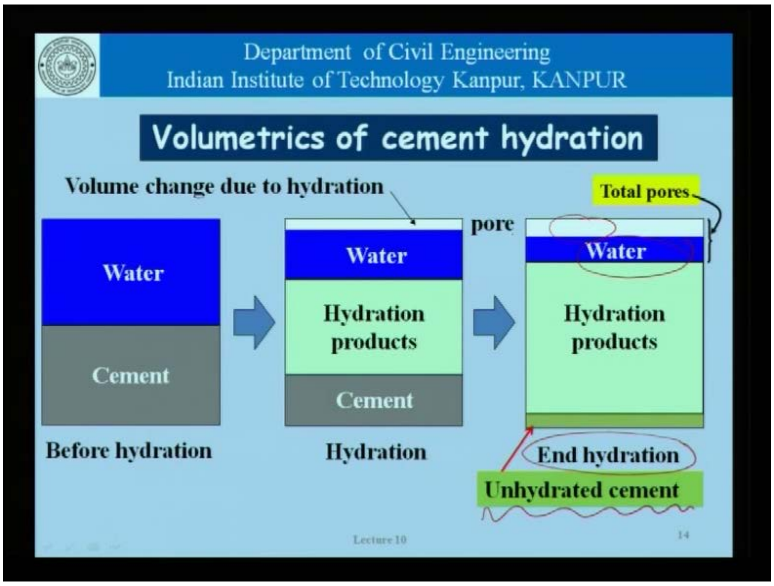
So, this discussion which is a schematic representation, or a very highly simplified understanding or an explanation for the hydration of cement is relevant because at some point the reaction will stop; that is, hydration stops. Now, this could be on account of exhaustion of water. That is, the water depth was available here is finished. We do not have any water left in the paste or the concrete. Or, the exhaustion of cement; that is the reacted layer over a period of time will become larger. The unhydrated cement particle would continue to shrink. And, there would be time when there is no more cement available for hydration. At that time also hydration basically stops.

There is a third possibility, and that is the reaction products which are formed here, they acquire properties that make it difficult for water to move through them to the fresh cement surface. That is, even though there is unhydrated cement here, there is water available here, but this water cannot move through the hydration products. The hydration products have a quite such properties; that is they become so dense. And, even then hydration would basically stop.

Now, what this model brings out is the fact that movement of water through the hydration products is essentially through the pores spaces within them. How else would water move through hydration products? We have to have spaces between them, and these spaces are precisely what are the pores spaces within hydration products. The hydration products are not solid in that sense. Even at the end of the hydration process or the hydration reaction there is always possibility of unhydrated cement being left over.

So, especially in the situation like this it is likely that there will be an unhydrated core of cement left behind which means that the cement is still there, water is still there, but still there is no more hydration taking place.

(Refer Slide Time: 16:19)



Department of Civil Engineering
Indian Institute of Technology Kanpur, KANPUR

Volumetrics of cement hydration

Volume change due to hydration

Total pores

pore

Water

Cement

Before hydration

Water

Hydration products

Cement

Hydration

Water

Hydration products

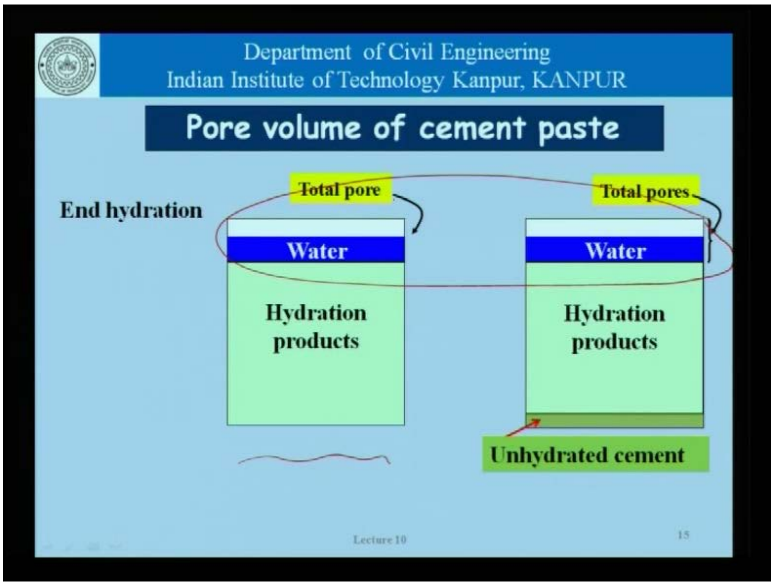
End hydration

Unhydrated cement

And that, in the diagram that we used previously is the situation that is shown here. That the hydration has ended, but that does not mean that the cement has exhausted; there is some unhydrated cement still left here. But, even in that case, some amount of excess water will be there, some amount of pores which have been formed on account of shrinkage of the products or the hydration products with respect to the volume of those reactants will still be there. So, nothing really changes as for as our understanding of the genesis or the origin of pores in cement paste is concerned.

It still remains that, it still remains true that the water that is added is an excess of that required for the hydration. And, at the end of the hydration process on any account complete hydration of cement, or even if there is some reacted cement left behind, some amount of water remains behind the concrete or the paste which is unreacted. That water we having been added to provide the required workability to the material.

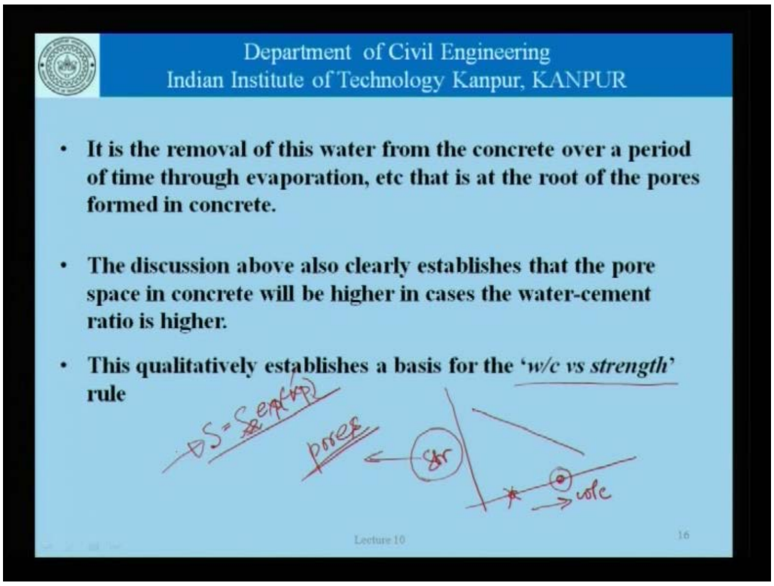
(Refer Slide Time: 17:38)


Department of Civil Engineering
Indian Institute of Technology Kanpur, KANPUR

Pore volume of cement paste

And this is what is the picture; that even at the end of the hydration product, even at the end of the hydration reactions whether it is complete hydration here of the cement or it is unhydrated cement left behind, this part is still true. We still have this space which is available to us, or which becomes available.

(Refer Slide Time: 17:58)

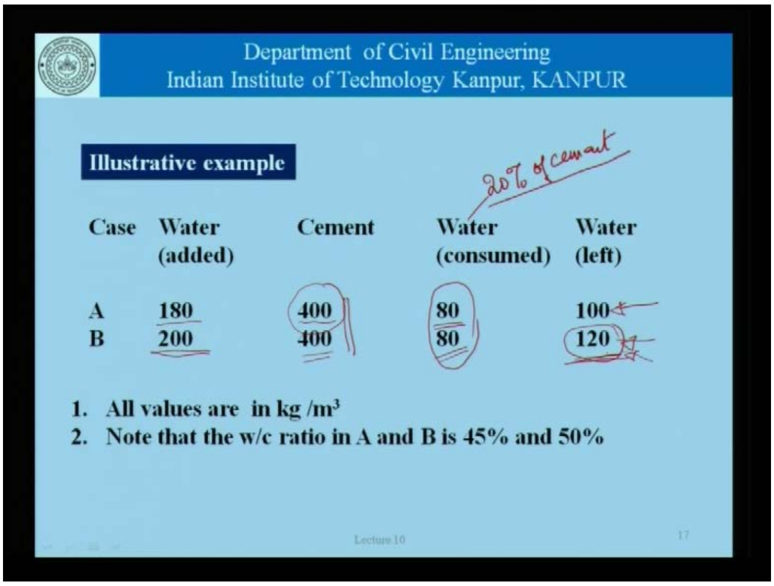

Department of Civil Engineering
Indian Institute of Technology Kanpur, KANPUR

- **It is the removal of this water from the concrete over a period of time through evaporation, etc that is at the root of the pores formed in concrete.**
- **The discussion above also clearly establishes that the pore space in concrete will be higher in cases the water-cement ratio is higher.**
- **This qualitatively establishes a basis for the '*w/c vs strength*' rule**

Now, as for as this excess water is concerned which is available in the matrix, what happens to that? It is the removal of this water from the concrete over a period of time through evaporation, and so on, that is at the root of the pores that are formed in concrete. So, this water which is left behind gradually evaporates. And, this evaporation of water leaves us with the concrete, and leaves us with the concrete which has pore spaces, which were otherwise occupied by the excess water. This discussion that we had about more water being added to provide workability, some of it remaining behind at the end of the hydration process, clearly establishes that the pore space in concrete will be higher in cases, though water cement ratio is higher. If we add more water, that is we increase the water cement ratio, the amount of water that is left behind at the end of the hydration process will also be more.

And, that qualitatively establishes a basis for the water cement ratio verses strength relationship. What is a water cement ratio verse strength relationship? It says that if we increase the water cement ratio the strength reduces. I mean, whether it is linear or not, is a different matter. But, the strength goes down. And this strength is related to the pores. And, now we have seen that if the water cement ratio is higher here compared to this point, the excess water available over in above that required for the hydration of cement is higher.

(Refer Slide Time: 20:42)



Department of Civil Engineering
Indian Institute of Technology Kanpur, KANPUR

Illustrative example

20% of cement

Case	Water (added)	Cement	Water (consumed)	Water (left)
A	180	400	80	100
B	200	400	80	120

1. All values are in kg /m^3
2. Note that the w/c ratio in A and B is 45% and 50%

Lecture 10

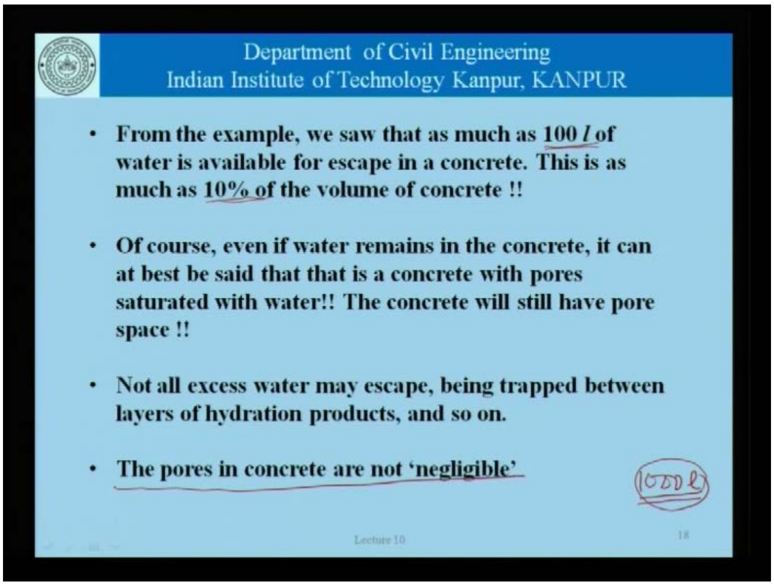
17

And therefore, the pores will be more, and therefore the strength will be less. Because intrinsically, because strength is related to porosity through an expression which is something like this, which says strength S is equal to S naught times the exponential of minus k times p, where p is the porosity, k is a constant, and S naught is the intrinsic strength of the material. Now, this is something which we will deal with more when we talk about the strength of concrete, not so much when we are talking really about the porosity today or the pores and the genesis. But, yes, through this discussion we have established a qualitative reason for the decrease in strength as the water cement ratio is increased.

Let us take an illustrative example. If we add 180 kgs of water per cubic meter, and that is a normal water content as for as concrete is concerned; if we use 400 kgs of cement with that, and if we assume that 20 percent by weight of cement is the amount of water that is required for complete hydration; this value becomes 80 kgs because we are using 400 kgs of cement, 20 percent of that is 80 kgs. So, 80 kilograms of water will be consumed, and the 100 kilograms, the 100 liters of water will be left behind.

In another situation, if for the same cement content we have added 200 kgs of water which means that the water cement ratio has increased; there is more water, the mix is more workable. The amount of water that is required for the hydration is still the same because we have not changed the cement content. We still need only 80 kgs for hydration. The amount of water which is left behind is 120, instead of 100. So, this will finally have more pore spaces because in this case 100 liters of water will escape, in this case 120 liters of water is available for escape.

(Refer Slide Time: 22:09)



Department of Civil Engineering
Indian Institute of Technology Kanpur, KANPUR

- From the example, we saw that as much as 100 *l* of water is available for escape in a concrete. This is as much as 10% of the volume of concrete !!
- Of course, even if water remains in the concrete, it can at best be said that that is a concrete with pores saturated with water!! The concrete will still have pore space !!
- Not all excess water may escape, being trapped between layers of hydration products, and so on.
- The pores in concrete are not 'negligible'

1000 l

Lecture 10

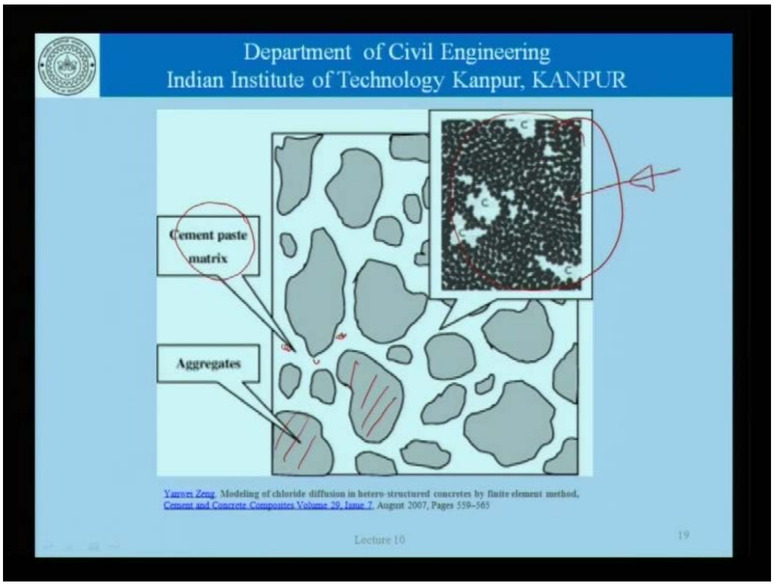
18

Now, what this example tells us is that as much as the 100 liters of water is available for escape in a concrete containing 180 kgs of water and 400 kgs of cement per cubic meter. And, that is as much as 10 percent of the volume of concrete. We proportion the concrete for a 1000 liters that is 1 cubic meter. And, if in this 1 cubic meter or 1000 liters, there is a 100 liters of water which is available to escape; that is the huge amount of water which is available to escape. Well, whether all of it escapes, whether all of it can escape, and so on, is a different story.

Even if the water remains in the concrete, it can at best be said that that concrete is one which has pores saturated with water. The concrete still has pore space. So, the fact that water is present in those pore spaces does not take away from the fact that pore spaces have been formed; that space is not solid hydration products. Of course, as I said just now, not all excess water may escape, being trapped between layers of hydration products, and so on.

The bottom line is, the pores in concrete are not negligible. The extent of porosity in concrete is not something which can be ignored. It has to be something, or it is something which needs to be studied. It is something which needs to be better understood, and that is what our focus is today.

(Refer Slide Time: 23:53)



Department of Civil Engineering
Indian Institute of Technology Kanpur, KANPUR

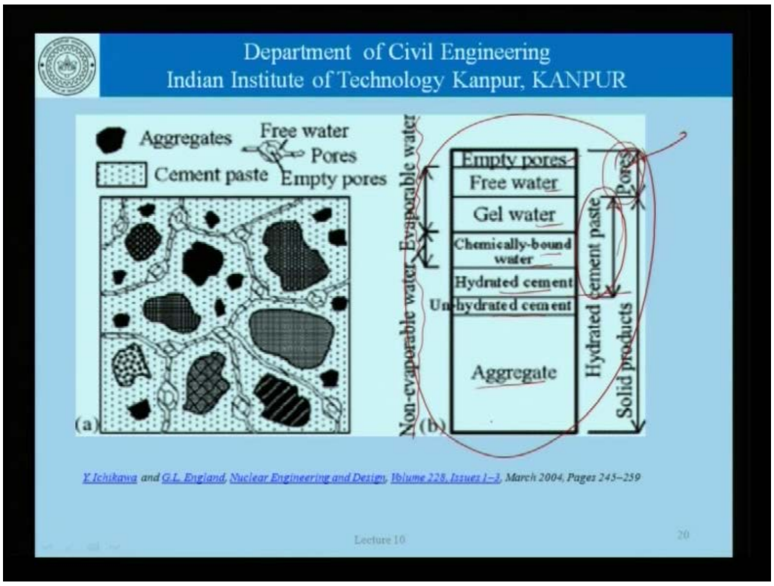
Yanwei Zeng, Modeling of chloride diffusion in hetero-structured concretes by finite element method, Cement and Concrete Composites Volume 29, Issue 7, August 2007, Pages 559–565

Lecture 10

19

Now, this is a picture of how people try to model these pores and pore structures. These here are large aggregates; they could be sand particles for all you know; it really does not matter. As for as cement matrix or cement paste matrix is concerned the white portion here is all cement paste, and this is what becomes what is shown here in this detail. There are hydration products, and there are pore spaces within the cement matrix.

(Refer Slide Time: 24:34)



Department of Civil Engineering
Indian Institute of Technology Kanpur, KANPUR

Y. Ichikawa and G.L. England, Nuclear Engineering and Design, Volume 228, Issues 1–3, March 2004, Pages 245–259

Lecture 10

20

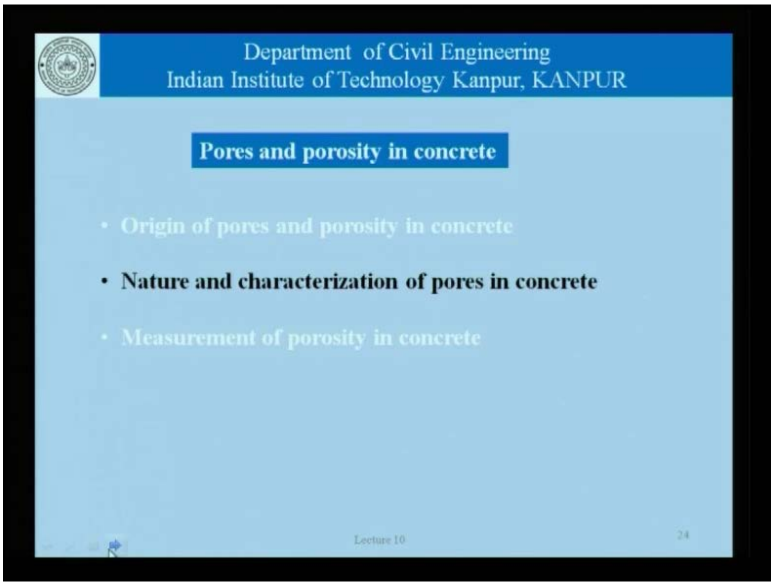
Another model by another researcher is shown here where there are aggregates, there is cement paste, there is free water, there are empty pores, there are saturated pores, and so on. And, this here is some kind of a representation of the different phases- there is aggregate, there is unhydrated cement, there are hydrated cement, there is chemically bound water, there is gel water, free water, empty pores, and so on.

So, beginning from this point onwards, this is cement paste; unhydrated cement does not count in cement paste; and it depends on the definitions that we take. Free water and empty pores have been called pores in this reference. As for as this side is concerned it says evaporable water and non-evaporable water; some non-evaporable water is that which is chemically bound. There are hydration products which holds certain amount of water within them which is chemically bound. And, that chemically bound water cannot easily escape, but the other can escape.

So, once we understand this kind of a model, or this kind of a schematic representation of what we are talking about, we are prepared to embark on a more detail discussion of pores and porosity. Let me also show you this piece of concrete once again. And, what we have been showing through this pictures just now is the blow up or a very highly magnified view of portions such as this, where there is aggregate, there is a matrix. And, the pores that we are talking about is the pores in this matrix, because it is in this matrix that we originally had water and cement.

And, this is where the hydration is taken place; this is where the hydration products have been formed; some of which were slightly slightly smaller when compared to the reactants. This is where there is excess water which is trapped. Some of it is trapped within the reactions products and has not escaped. Some of it has already escaped, and so on and so forth. So, keep it in mind that this is the small area that we are talking about, when we are talking about pores and porosity in concrete.

(Refer Slide Time: 27:24)

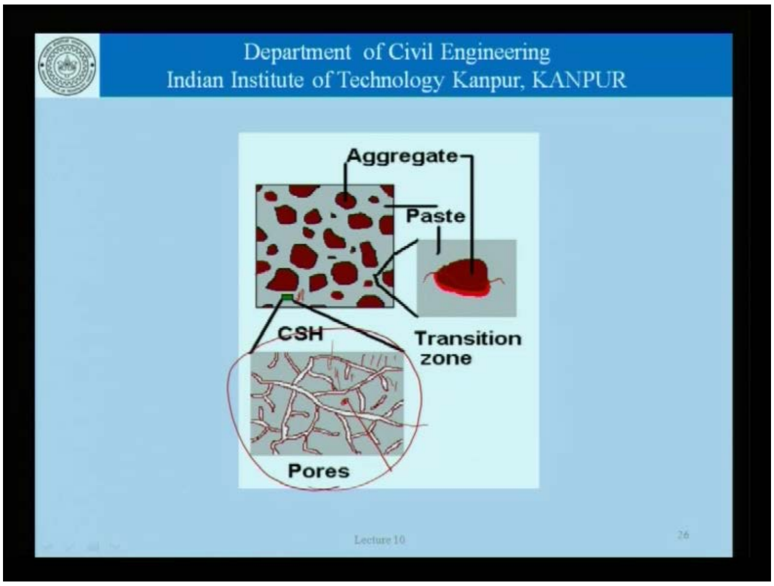


Department of Civil Engineering
Indian Institute of Technology Kanpur, KANPUR

Pores and porosity in concrete

- Origin of pores and porosity in concrete
- **Nature and characterization of pores in concrete**
- Measurement of porosity in concrete

(Refer Slide Time: 27:35)

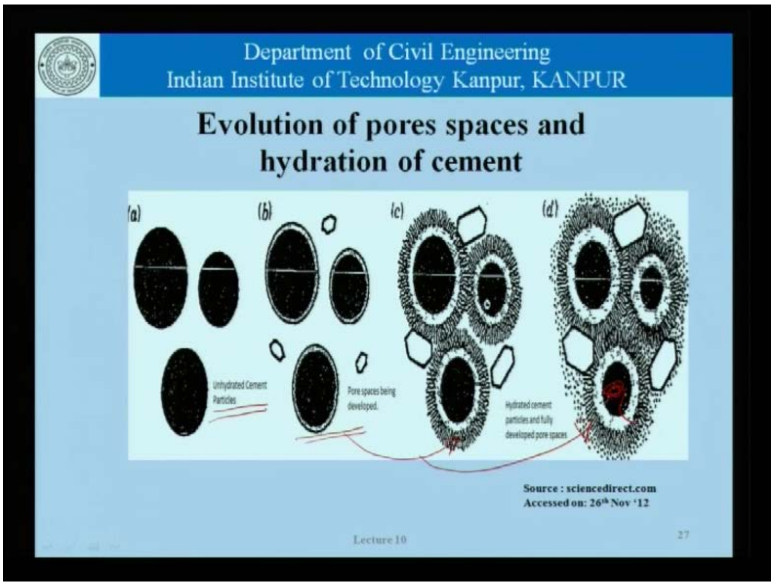


Department of Civil Engineering
Indian Institute of Technology Kanpur, KANPUR

Now having done this discussion on the origin of pores and porosity in concrete, let us try to understand a little bit about the nature and characterization of pores in this material. This is a picture that we have seen in the fog, and is nothing but an idealization or a schematic representation of the piece of concrete that I actually showed you. We have aggregates here, we have cement paste here, and the cement paste is shown here which shows CSH and all kinds of hydration product sitting here, and there are pores within the HCP which may or may not be filled with water.

And, of course, there is some water which could be sitting within the hydration products such as here, which has been called chemically bound water. In addition to these pores in the hardened cement paste, there is also a transition zone which is around these coarse aggregates which has properties which are different from the main HCP, and that has another kind of pores space, and that pores space varies only from the point of view of size.

(Refer Slide Time: 28:50)



Department of Civil Engineering
Indian Institute of Technology Kanpur, KANPUR

Evolution of pores spaces and hydration of cement

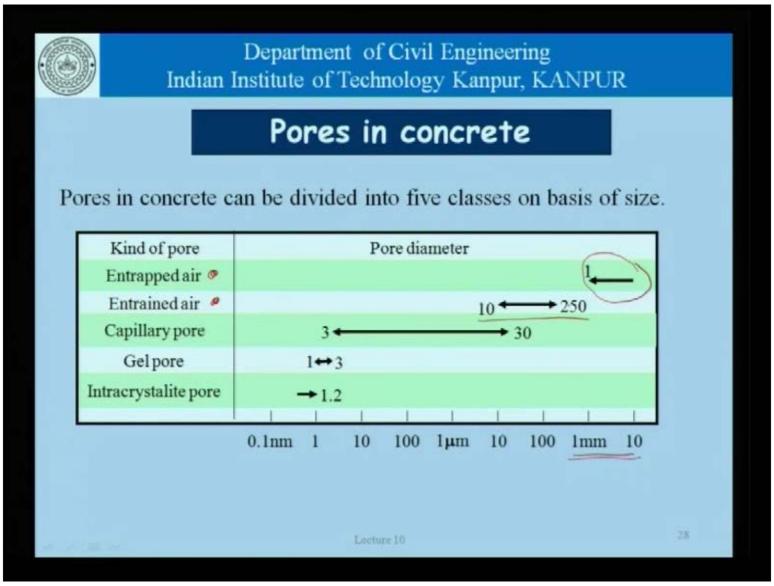
Source : sciencedirect.com
Accessed on: 26th Nov '12

Lecture 10

27

Now, this is another picture of the evolution of pore spaces and hydration of cement. We have unhydrated cement particles suspended in water. Gradually the water in the cement begins to react; hydration products begin to form; we reach a stage like this; and then finally, we reach a stage like this. There is some unhydrated cement which is shown here. And, there are pores spaces within the hydration products, and so on and so forth.

(Refer Slide Time: 29:20)



Department of Civil Engineering
Indian Institute of Technology Kanpur, KANPUR

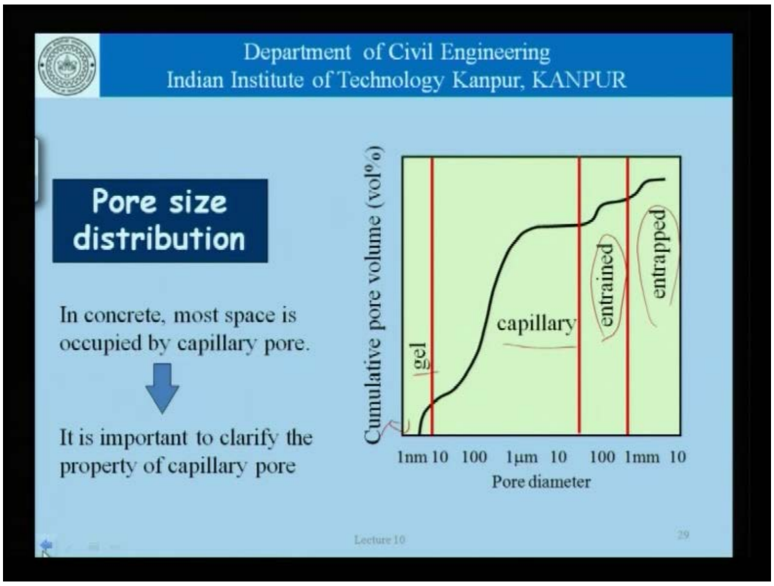
Pores in concrete

Pores in concrete can be divided into five classes on basis of size.

Kind of pore	Pore diameter
Entrapped air	1 ←
Entrained air	10 ↔ 250
Capillary pore	3 ↔ 30
Gel pore	1 ↔ 3
Intracrystalite pore	→ 1.2

If we look at the pores in concrete, we look at literature, we find that the pores in concrete can be divided into 5 clauses on the basis of size- there is entrapped air, there is entrained air, capillary pores, gel pores, and intracrystalite pores. And, these pores or these pores spaces are vary in size. As for as entrapped air is concerned it could be as much, or it could be as large as a millimeter or more. An entrapped air is precisely what is very dangerous because the pore size is very large. It is air which is not intentionally entrained.

(Refer slide Time: 30:27)



Department of Civil Engineering
Indian Institute of Technology Kanpur, KANPUR

Pore size distribution

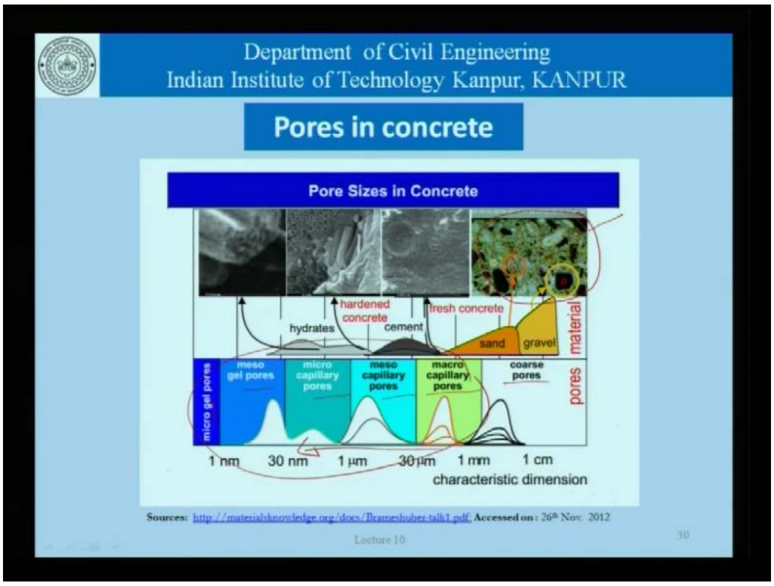
In concrete, most space is occupied by capillary pore.

It is important to clarify the property of capillary pore

When it comes to entrained air, the size is much smaller; and that is the kind of size that helps us, atleast to some extent in getting more desirable properties. Capillary pores are smaller than that, gel pores are even smaller, and intracrystalite pores are the tiniest of the lot.

If we look at the pore size distribution within concrete, again it is a same picture- entrapped air, entrained air, capillary pore, gel pores, and somewhere here would be the intracrystalite pores. We will study it a little bit more in detail a little later, that most of the space in concrete as for as pore space is concerned, is occupied by capillary pores. And therefore, it is important for us to understand the evolution of these pores as it goes, as it happen; it is important for us to understand the evolution of these pores as it happens through the hydration.

(Refer Slide Time: 31:06)



Department of Civil Engineering
Indian Institute of Technology Kanpur, KANPUR

Pores in concrete

Pore Sizes in Concrete

Sources: http://materialsknowledge.org/docs/Brameshuber-talk1.pdf Accessed on : 26th Nov 2012

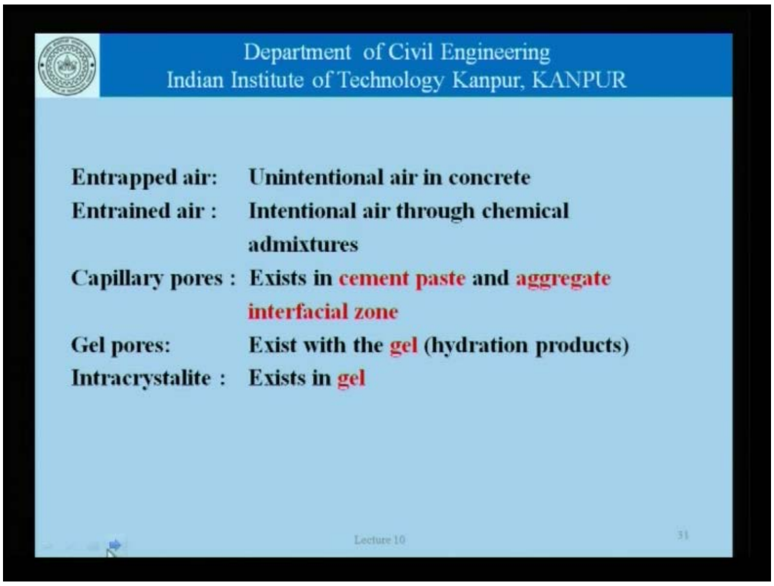
Lecture 10

30

This is what another picture showing the different pores, different terminologies- there are coarse pores, there are macro capillary pores, meso capillary pores, micro capillary pores, meso gel pores, and micro gel pores. So, what it really shows is that the porosity or the pores in concrete have attracted the attention of lot of researchers. And, they have used different tools to examine these pores, determine their sizes, try to understand their genesis and their properties, and try to give them names.

So, it is not really the that names are important as for as this discussion on concrete engineering and technology is concerned, we are more interested that you are introduced to these ideas which are becoming so much more important in the modern de concrete technology. It is impossible for a modern de concrete engineer to be totally ignorant of some of these ideas. This picture here is nothing but a concrete slice because c coarse aggregate gravel here, there is sand particles here, and so on. And, what we are studying on this side, here, is all hydrated cement based kind of structure. So, this a very interesting dimension to concrete engineering of the twenty first century, the modern concrete engineering.

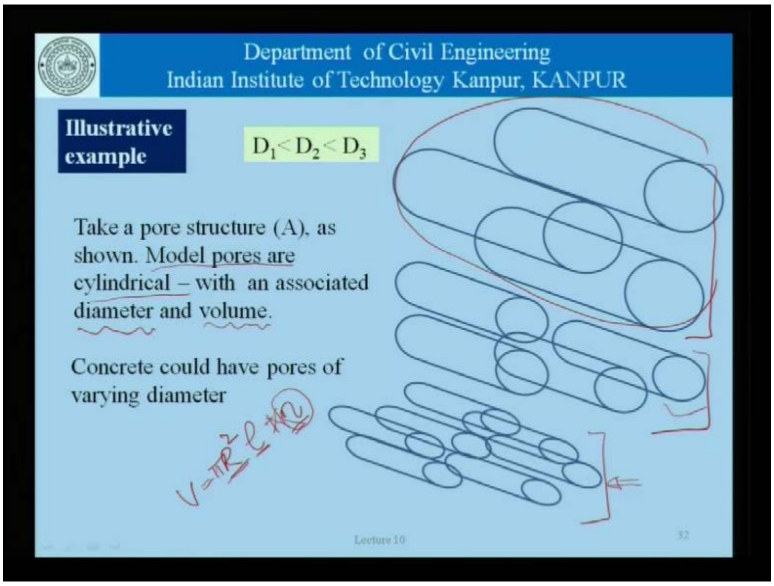
(Refer Slide Time: 32:44)



Department of Civil Engineering
Indian Institute of Technology Kanpur, KANPUR

Entrapped air:	**Unintentional air in concrete**
Entrained air :	**Intentional air through chemical admixtures**
Capillary pores :	**Exists in cement paste and aggregate interfacial zone**
Gel pores:	**Exist with the gel (hydration products)**
Intracrystalite :	**Exists in gel**

(Refer Slide Time: 33:04)



Department of Civil Engineering
Indian Institute of Technology Kanpur, KANPUR

Illustrative example

$D_1 < D_2 < D_3$

Take a pore structure (A), as shown. Model pores are cylindrical – with an associated diameter and volume.

Concrete could have pores of varying diameter

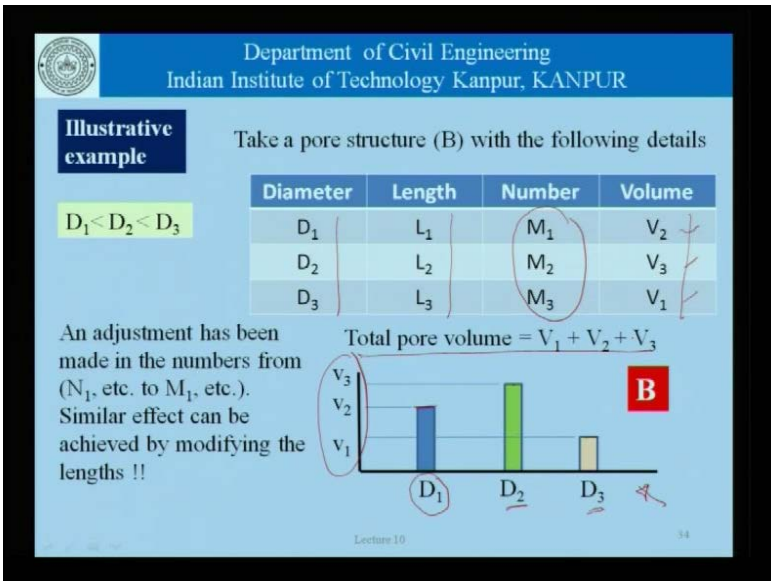
$V = \pi R^2 \ell \times n$

Entrapped air is unintentional air in concrete, entrained air is intentional air through chemical admixtures, capillary pores- they exist within the cement paste and aggregate interfacial zone, the gel pores exist with the gel in the hydration products, and intracrystalites- they exist within the gel.

Now, this is an illustrative example of the kind of pore space that exists within concrete. I am going to use this example to illustrate several concepts of pores and pore sizes in concrete. If we take a pore structure, A, which is shown here, the model pores are cylindrical; that is, there is a diameter associated with them, and there is a volume associated with them. So, the diameter of these pores is the largest; the diameter of these pores is smaller; and this is the smallest.

The volume for a cylinder, we know is related to the diameter and the length. And, if there are more than one cylinders we can multiply this by a number n, to get that total volume. Now, in this case, we can try to determine the volume of these pores which are the largest, the volume of these pores which are slightly smaller than that, and the volume of these pores which are the smallest, provided we know the numbers and we know the lengths.

(Refer Slide Time: 34:25)



Department of Civil Engineering
Indian Institute of Technology Kanpur, KANPUR

Illustrative example

Take a pore structure (B) with the following details

$D_1 < D_2 < D_3$

Diameter	Length	Number	Volume
D_1	L_1	M_1	V_2
D_2	L_2	M_2	V_3
D_3	L_3	M_3	V_1

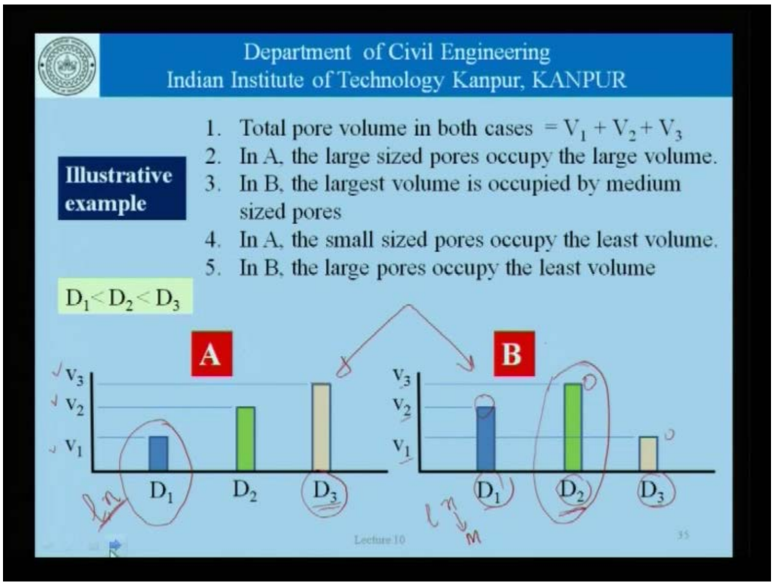
Total pore volume = $V_1 + V_2 + V_3$

An adjustment has been made in the numbers from (N_1, etc. to M_1, etc.). Similar effect can be achieved by modifying the lengths !!

If we have pore diameters D 1, let us say the total length corresponding to that is L 1, the total number corresponding to that is N 1, the volume associated with that would be V 1. And, V 1 would be related to this diameter, length, and the numbers. Similarly, we can have an expression for V 2 and V 3. And, this is a schematic of these volumes and the diameters, that there is a V 1 which is associated with D 1, there is a V 2 associated with diameter D 2, and the V 3 which is associated with D 3. The total pore volume in this system is V 1 plus V 2 plus V 3. So, we have a pore system or a pore structure, A, which has diameters of pores D 1, D 2, and D 3. The individual volumes of pores of these sizes is V 1, V 2 and V 3. And, the total pore volume is V 1 plus V 2 plus V 3. So far, so good.

Now, if we consider a similar structure which is slightly different, let us say, B. And there the relative volumes of pores having the same diameters, the same lengths, but the volumes are different. And, this can happen if we just change the number of those pores. Initially we had N 1, N 2 and N 3, and if it becomes and if that becomes M 1, M 2, and M 3, then the volumes will change. And for the, and for the sake of illustration I have made it V 2, V 3, and V 1. Now, how that picture is represented here, is that now for pores having a diameter D 1, the volume involved is V 2; for the pores where diameter D 2, the volume is V 3; and the pores with the diameter of D 3 has a volume of V 1. In this case also the total pore volume is V 1 plus V 2 plus V 3.

(Refer Slide Time: 36:42)



Department of Civil Engineering
Indian Institute of Technology Kanpur, KANPUR

Illustrative example

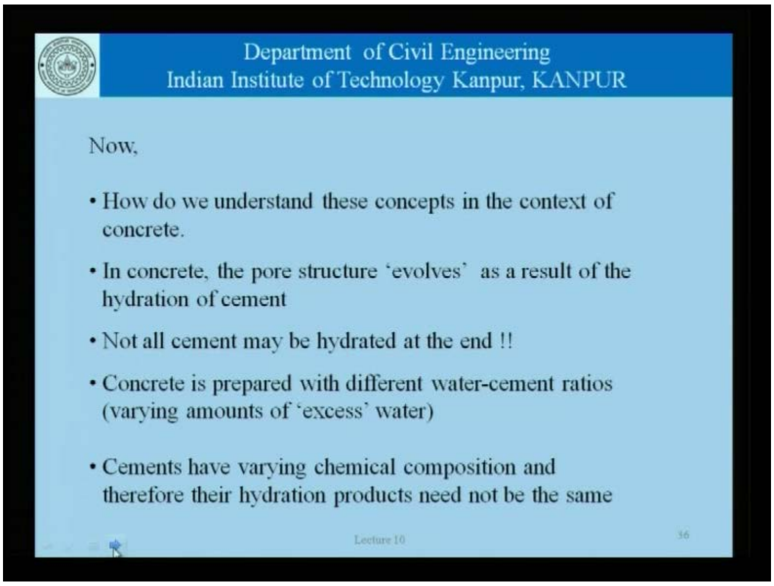
1. Total pore volume in both cases $= V_1 + V_2 + V_3$
2. In A, the large sized pores occupy the large volume.
3. In B, the largest volume is occupied by medium sized pores
4. In A, the small sized pores occupy the least volume.
5. In B, the large pores occupy the least volume

$D_1 < D_2 < D_3$

Now, if we compare these 2 pore structures, A and B; let us recall what was A. A is a situation or a pore system where D 1, D 2, and D 3, have the lengths and the numbers of pores such that the volumes are V 1, V 2, and V 3. In the pore system of B, the numbers have been so adjusted with the same length that the pore volumes for D 1, D 2, and D 3, have now become V 1, V 2, and V 3, as shown here. So, D 1 has V 2, D 2 has V 3, and D 3 has V 1. Now, if we are asked to compare these 2 pore structures, what are the kind of comments that we can make. The first thing is that the total pore volume in both cases is V 1 plus V 2 plus V 3. So, there is no change in the total pore volume of the 2 pore structures. So, the pore structures are the same as for as the total pore volume is concerned. However, in A, the large sized pores occupy a large volume; large size pores because D 3 is the largest pore size. And, in A, D 3 has a volume V 3 which is the largest.

So, if we want to calculate a percentage of volume contributed by the larger pores, it will be the largest as far as the larger pores are concerned for A, whereas, for B, the largest volume is occupied by the medium sized pores. The largest volume here is V 3, of course, that is the way we have defined; that is the way we have modeled. That is now contributed by pores which are medium sized. In A, the small sized pores occupy the least volume. That is, the contribution, the relative contribution of the small pores as for as A is concerned is the least. Compared to that, in B, the large sized pores occupy the least volume. So, we can make any such statement. We will have to study this pore sizes, we will have to study the relative contributions, and then we can make a statement as to how one pore structure is different from the other.

(Refer Slide Time: 39:31)



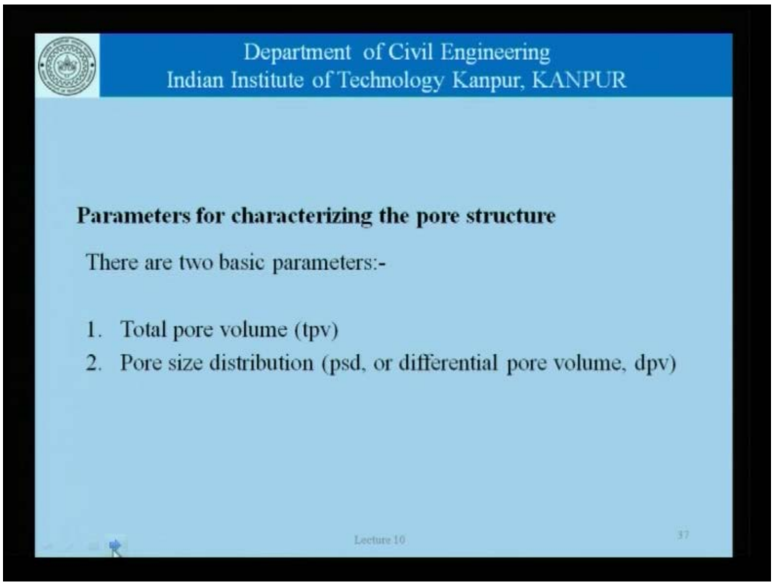
Department of Civil Engineering
Indian Institute of Technology Kanpur, KANPUR

Now,

- How do we understand these concepts in the context of concrete.
- In concrete, the pore structure 'evolves' as a result of the hydration of cement
- Not all cement may be hydrated at the end !!
- Concrete is prepared with different water-cement ratios (varying amounts of 'excess' water)
- Cements have varying chemical composition and therefore their hydration products need not be the same

Now, how we do understand these concepts in the context of concrete, where the pore structure evolves as a result of the hydration of the cement, not all cement is hydrated at the end of the day, concrete is prepared with the different water cement ratios which leads to a varying amount of excess water, cements have varying chemical compositions and therefore their hydration products need not be the same.

(Refer Slide Time: 40:05)



Department of Civil Engineering
Indian Institute of Technology Kanpur, KANPUR

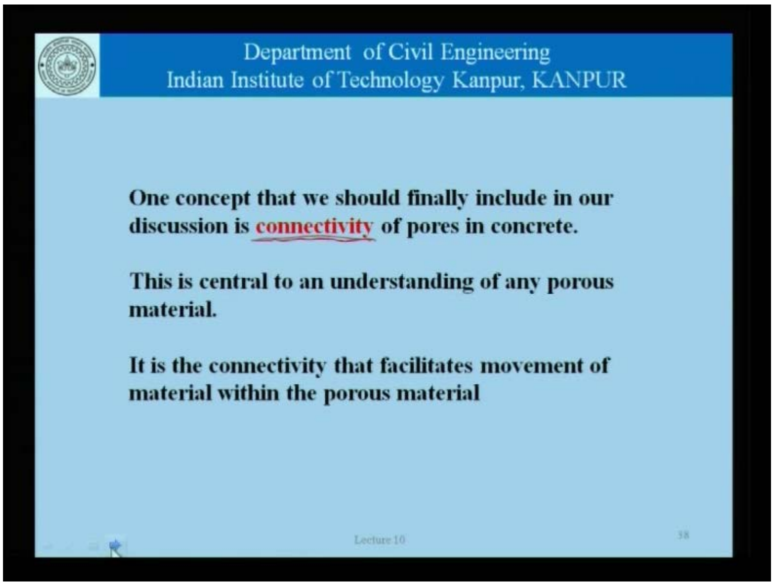
Parameters for characterizing the pore structure

There are two basic parameters:-

1. Total pore volume (tpv)
2. Pore size distribution (psd, or differential pore volume, dpv)

Basically what we use in concrete is 2 parameters to characterize the pore structure- the total pore volume and the pore size distribution, the differential pore volume.

(Refer Slide Time: 40:22)



Department of Civil Engineering
Indian Institute of Technology Kanpur, KANPUR

One concept that we should finally include in our discussion is connectivity of pores in concrete.

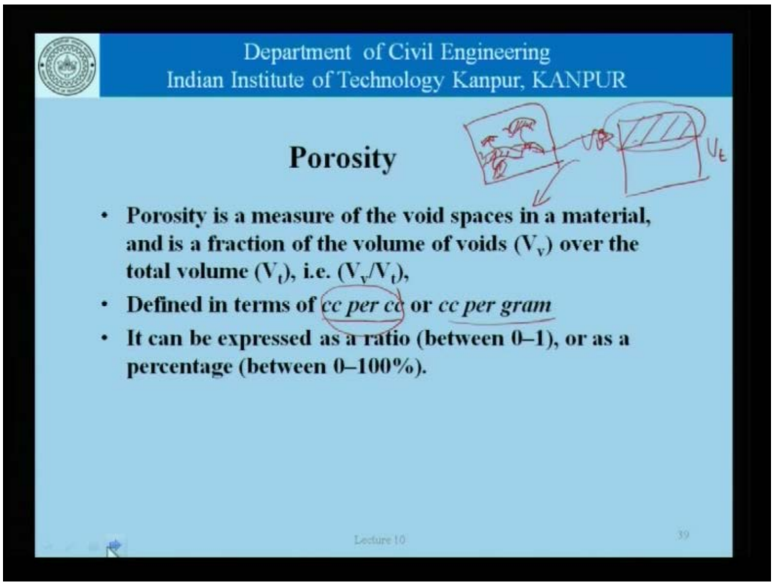
This is central to an understanding of any porous material.

It is the connectivity that facilitates movement of material within the porous material

In our discussion today we have talked about total pore volume and the pore size distribution, what we have not talked about is the connectivity of these pores. Now, if we look at this slide once again, it shows the different diameter pores, we must understand that we showed them as not connected. The connectivity of these pores is a very important idea that is important for us to keep at the back of our mind which is central to understand any pores system or any porous material. It is also important to understand the connectivity facilitates movement of material within the pores.

So, stand alone pores which are not connected to the pore spaces are not particularly harmful, are not particularly harmful as for as movement of deleterious material within the pore structure is concerned. It is only when the pores are part of a continuous system that they become harmful from a durability point of view as for as concrete is concerned. So, these are some things which we will talk about later.

(Refer Slide Time: 41:44)



Department of Civil Engineering
Indian Institute of Technology Kanpur, KANPUR

Porosity

- Porosity is a measure of the void spaces in a material, and is a fraction of the volume of voids (V_v) over the total volume (V_t), i.e. (V_v/V_t),
- Defined in terms of *cc per cc* or *cc per gram*
- It can be expressed as a ratio (between 0–1), or as a percentage (between 0–100%).

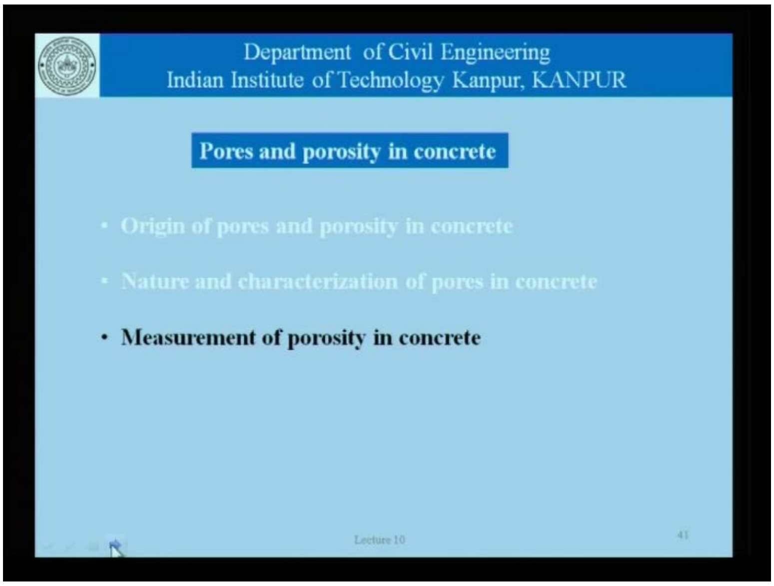
Lecture 10

39

As for as porosity is concerned, now porosity is a measure of the void space in a material and refraction of the volume of voids which is V v, over the total volume V t. If we have a material which is a total volume of V t, which is a consolidated pores space of V v, then the porosity of this material will be V v upon V t. We must remember that this V v is a consolidated pore space which we have put here. Actually what could be happening is that, as far as this material is concerned there is a total volume V t and there are pores of different sizes which are which are present in this material, and they are all contributing a little bit towards this volume of the voids. And, they have to be continuous in order that they become part of a continuous pore system.

Porosity therefore will be defined in terms of cc per cc, or cc per gram. So, in any case, the pore space will be defined in terms of volume. It could be defined in terms of a volume percentage of the pores to the volume of the material, or it could be defined as volume space of pores to the mass of that material. It can be expressed as a ratio which would be between 0 and 1, or a percentage which would be between 0 and 100.

(Refer Slide Time: 43:16)



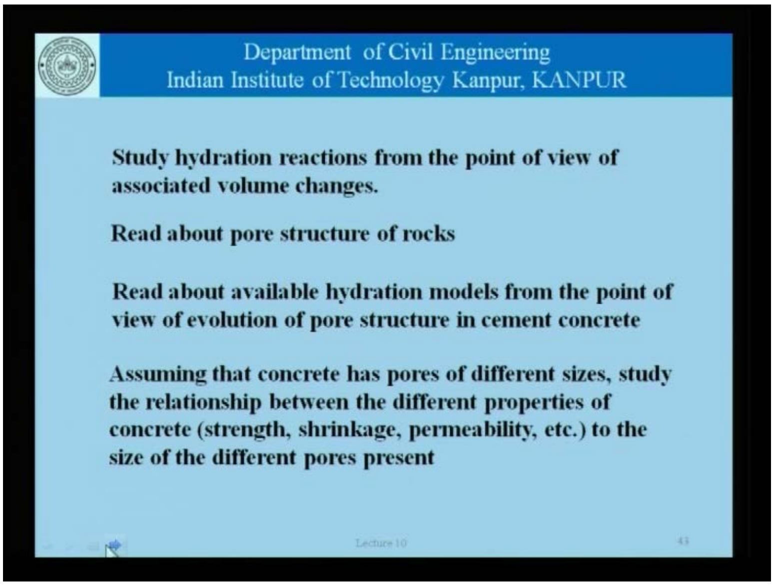
Department of Civil Engineering
Indian Institute of Technology Kanpur, KANPUR

Pores and porosity in concrete

- Origin of pores and porosity in concrete
- Nature and characterization of pores in concrete
- **Measurement of porosity in concrete**

So, having completed our discussion on the nature and characterization of pores and concrete, we need to talk a little bit about the measurement of porosity in concrete, and that is something which we will do in the next discussion.

(Refer Slide Time: 43:33)



Department of Civil Engineering
Indian Institute of Technology Kanpur, KANPUR

Study hydration reactions from the point of view of associated volume changes.

Read about pore structure of rocks

Read about available hydration models from the point of view of evolution of pore structure in cement concrete

Assuming that concrete has pores of different sizes, study the relationship between the different properties of concrete (strength, shrinkage, permeability, etc.) to the size of the different pores present

We will close the discussion today with some homework, and that could include study of hydration reactions from the point of view of associated with volume changes, what we gave examples; we did give, we did give 2 examples of C 3 S and C 2 S hydration. I would like you to look at those hydration reactions a little more closely, and also try to understand what is happening with C 3 A and C 4 F.

We could read about the pore structure of rocks. After all, rocks have their own porosity, except that in the case of rocks the porosity is does not evolve over time, the weight evolves with concrete. It does evolve with time because the rocks are formed under different processes and the pores spaces of different rocks are different. So, that is something we would, so there is something which would be interesting to compare, the porosity in pore structure of rocks verses that of concrete which is an artificial rock.

We could read about available hydration models from the point of view of evolution of pore structure in cement concrete. There are different hydration models available, as far as simulating the hydration of cement is concerned. These models have been developed with different objectives. Sometimes they have been developed in order to understand, what is the best size distribution of particles of cement, in order to ensure maximum hydration. They were developed to study the heat liberated, and so on. But, we could also study it from the point of view of volume changes and evolution of pore structure.

And now assuming that concrete has pores of different sizes, we could study the relationship between the different properties of concrete- that is strength, shrinkage, permeability, durability, and so on, to the different sizes of pores present. May be we will find that the larger sizes contribute to something, the smaller sizes are more important for some other property, and so on. With this we come to an end of our discussion.

Thank you.