Concrete Technology

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Lecture - 3
Cement: Structure and Hydration

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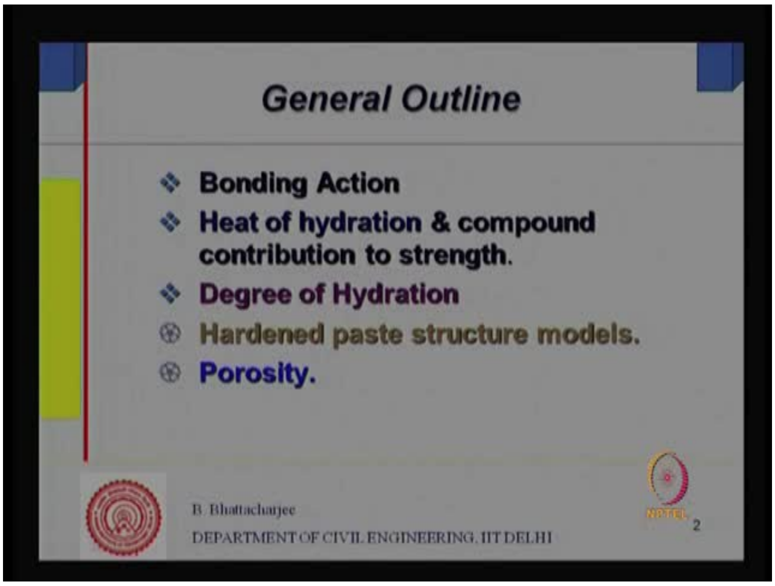

General Outline

- Bonding Action
- Heat of hydration & compound contribution to strength.
- Degree of Hydration
- Hardened paste structure models.
- Porosity.

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Welcome to module 1, lecture 3. We shall be starting from where we have stopped, that is bonding action then we shall look into heat of hydration and compound contribution to strength. Then we will look into degree of hydration followed by hardened paste structure models. And obviously from that will calculate out porosity.

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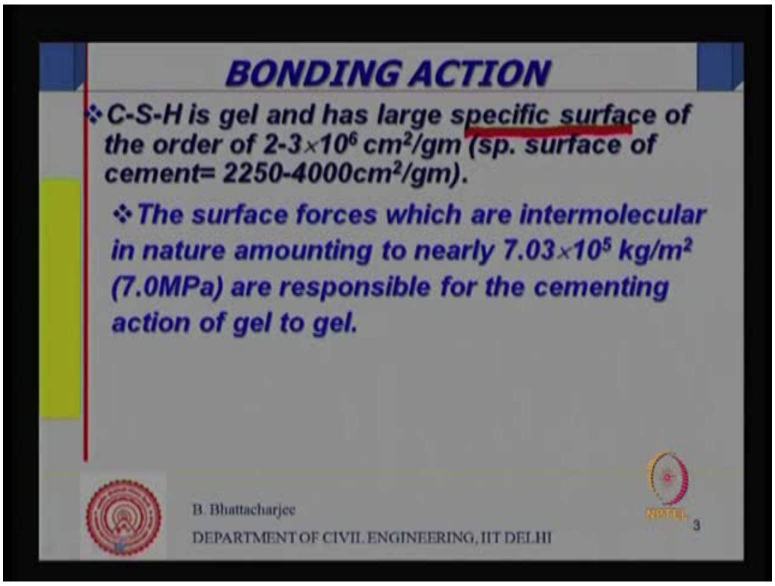

BONDING ACTION

- C-S-H is gel and has large specific surface of the order of 2-3×10^6 cm^2/gm (sp. surface of cement= 2250-4000cm^2/gm).
  - The surface forces which are intermolecular in nature amounting to nearly 7.03×10^5 kg/m^2 (7.0MPa) are responsible for the cementing action of gel to gel.

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Now, last class we are mentioning that C-S-H gel has large specific surface, it is a it has a gelatinous structure and large specific surface and the order of this specific surface is 1000 times more then there of the cement. You can see that it is 2 to 3 into 10 to the power of 6 centimeter square per gram compare to that of cement, which has 2.25 or 4 into 10 to the power 3.

The surface forces therefore will dominate, because the surface area is so large, surface forces will dominate. Now and a just as an example one can think of say if I have large size particle like stones they are not bounded. You know stones you can separate out very easily, sand well you can separate out quite easily. Come to clay the surface area is very large because particles are small, which will see that surface area is inversely proportional to specific surface, surface area part will be volume. If I say, it will be inversely proportional to the particle diameter.

So if my particle diameters become smaller, specific surface becomes large. So, in case of clay specific surface is very large, therefore you cannot separate, clay out they stick together. Cement gel is very fine gelatinous particle and therefore, very large surface area. Like clay the intermolecular forces tend to hold them together.

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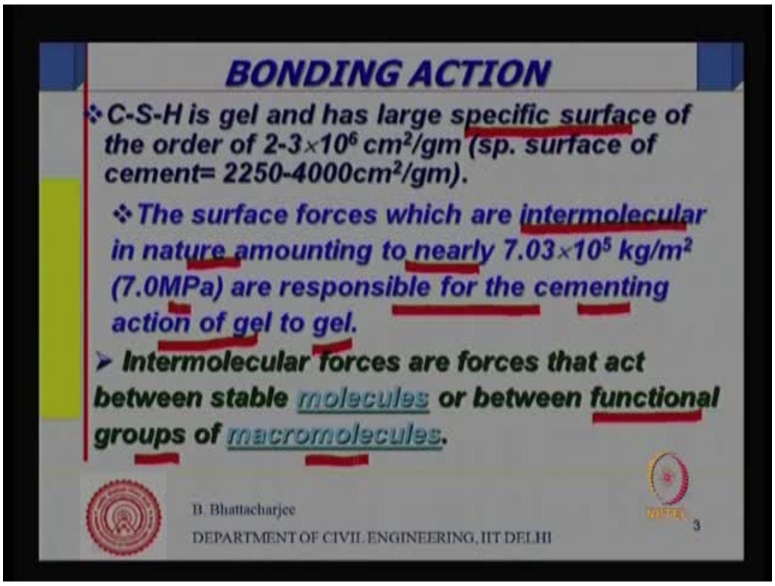

BONDING ACTION

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  - The surface forces which are intermolecular in nature amounting to nearly 7.03×10^5 kg/m^2 (7.0MPa) are responsible for the cementing action of gel to gel.
- Intermolecular forces are forces that act between stable molecules or between functional groups of macromolecules.

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So, surface force H which are intermolecular in nature, you know there intermolecular in nature there of the order of around 7 MPa are responsible for cementing action of gel to gel. So you cannot separate out gel for from gel because there are intermolecular forces. This intermolecular forces what are they? The intermolecular forces of the force that act between stable molecules or functional groups or between functional groups of macro molecules. So they are they act between molecules or functional groups.

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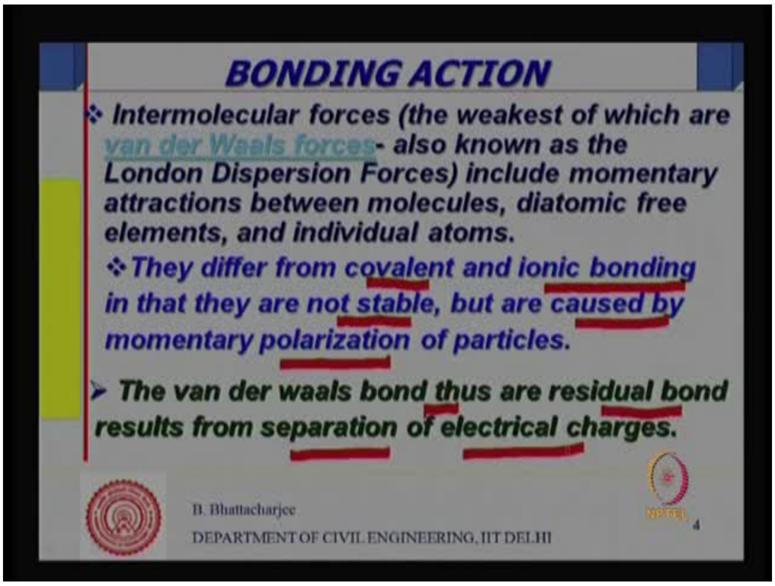

BONDING ACTION

- Intermolecular forces (the weakest of which are van der Waals forces- also known as the London Dispersion Forces) include momentary attractions between molecules, diatomic free elements, and individual atoms.
  - They differ from covalent and ionic bonding in that they are not stable, but are caused by momentary polarization of particles.
- The van der waals bond thus are residual bond results from separation of electrical charges.

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You know electrovalent or covalent bonds or between atoms to from the molecule. These forces acts between the molecule they put the molecule together they act between the molecule, so bonding action between the molecule those are the intermolecular forces.

And in cement gel this intermolecular forces help gel with gel together. The weakest of this intermolecular forces are Van der Waals forces, in a weakest of this intermolecular forces are Van der Waals forces, they are also known as the London Dispersion Forces essentially they include momentary attraction between molecules, diatomic free elements, and individual atoms. So, that is momentary attractions right? They essentially differ they differ from covalent and ionic bonding which are between atoms, where why either charge transfer takes place or sharing of electron takes place that is essentially electron transfer takes place or sharing of electron occurs. This is that is for between atoms to form compounds these are or to form molecules now this this once are intermolecular forces or they differ from this covalent and ionic bonding, because these are not stable bonds and are caused by momentary polarization of particles, momentary polarization.

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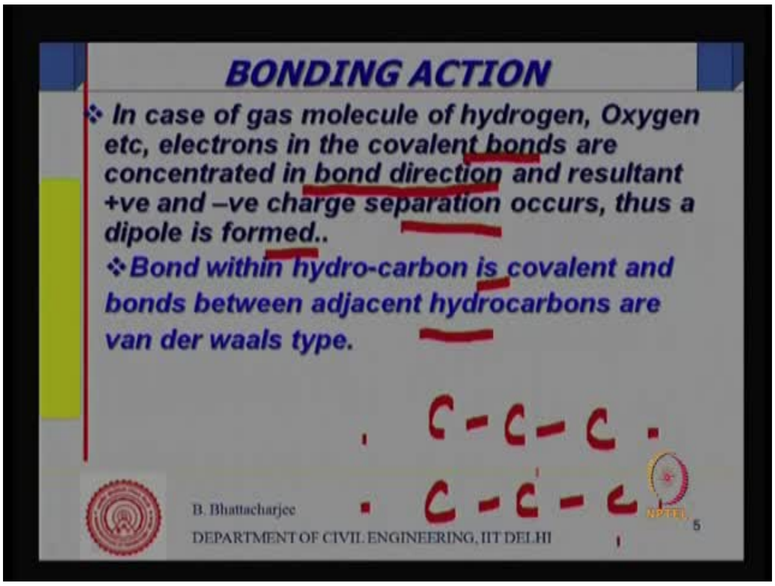

BONDING ACTION

- ❖ In case of gas molecule of hydrogen, Oxygen etc, electrons in the covalent bonds are concentrated in bond direction and resultant +ve and –ve charge separation occurs, thus a dipole is formed..
- ❖ Bond within hydro-carbon is covalent and bonds between adjacent hydrocarbons are van der waals type.

C - C - C

C - C - C

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So Van der Waals for bond thus residual bonds results from separation of electrical charges. So, electrical charges which get separated they form residual bond because of the separation of electrical charges. you know in many covalent molecules the outer shell electrons are shared, and therefore, the charges the you know the center of positive and negative charges they may not coincide from dipole. And this may results in kind of bonding forces between molecules and these are the forces which are responsible similar forces are responsible for bonding gel to gel for example, in case of gas molecule like hydrogen. H 2 there are 2 h items or oxygen etcetera electron in the covalent bond of h and h electron in the covalent bond of h and h a concentrated in the bond direction and resultant positive and negative charges separation occurs.

So long the direction of the bond electrons are concentrated, thus dipole is formed. So that is what is wherever dipole is formed you might find intermolecular forces or Van der waals forces acting bond with hydro carbons is covalent that is between say carbon to carbon in a hydro carbon these are covalent. Right but between adjacent hydrocarbons the bonds are Van der waals type for example, if you have carbon carbon chains these are all.

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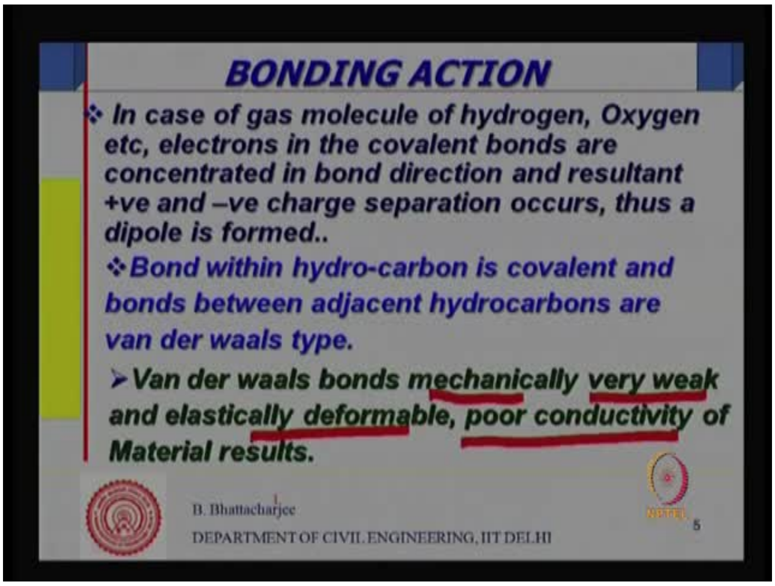

BONDING ACTION

- In case of gas molecule of hydrogen, Oxygen etc, electrons in the covalent bonds are concentrated in bond direction and resultant +ve and –ve charge separation occurs, thus a dipole is formed..
- Bond within hydro-carbon is covalent and bonds between adjacent hydrocarbons are van der waals type.
  - Van der waals bonds mechanically very weak and elastically deformable, poor conductivity of Material results.

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Covalent bonds but if I have two such chains you know in polymers fibers for example, the in that case bond between this two would be intermolecular type intermolecular type you know like a Van der waals bond, so they are bonded by this kind of action they are bonded by weak forces. So c h a gel has got this sort of bond which are not strong chemical bond but Van der waals kind. So bond and gel to gel separation requires breaking those Van der waals bond right? Many other materials do not have any bond at all for examples, sand particles between sand particles there are no forces of attraction which are holding them together or stones large surface area. A small surface area comport pertinent must of pertinent volume the forces do not act right. So this Van der waals bonds are mechanically very weak.

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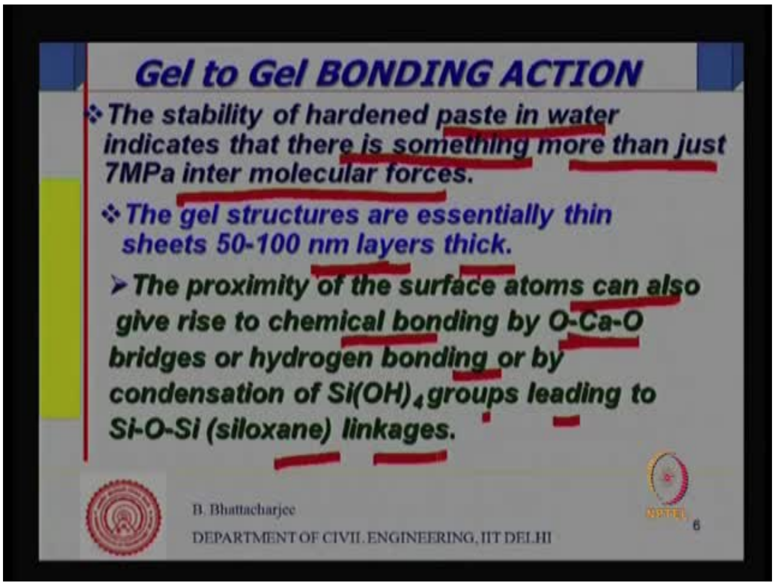

Gel to Gel BONDING ACTION

- The stability of hardened paste in water indicates that there is something more than just 7MPa inter molecular forces.
- The gel structures are essentially thin sheets 50-100 nm layers thick.
  - The proximity of the surface atoms can also give rise to chemical bonding by O-Ca-O bridges or hydrogen bonding or by condensation of $Si(OH)_4$ groups leading to Si-O-Si (siloxane) linkages.

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And they are elastically deformable exhibit poor conductivity of the resulting material. So the material where the Van der waals bonds of there there elastic elastically; that means, if you apply a load they are they deform and may come back to its original position and they have poor conductivity and c h s gel will be like that. Generally c h s gel is stable in water, now Van der waals bond or 7 MPa intermolecular forces cannot be the only force which is bonding them but by this is the force.

So stability of hardened paste in water indicates there is somewhat something more than just 7 MPa intermolecular forces which holds them. But never be less that is the measure cost or measure force understood to have in you know bond responsible for strength of gel to gel structure of gel is essentially thin sheets 50 to 100 nanometer layers thick that is, what it is you know will have a diagram a people have actually determined by some tests. And they are structure these are thin sheets like structures 50 to 100 nanometer layers thick.

So they this is been determined by varies indirect tests. Now proximity of the surface atoms can also give rise to chemical bonding of O calcium oxide to oxygen. So, the surface atoms can form bond between gel layers because that is the explanation the 7 m p a cannot be just the only thing, because it is stable in water which me use that something is more than just 7 m p a. And one of the idea suggestive it is that between surface you know calcium oxygen to calcium to oxygen bonding might be there between gel to gel sheets right gel to gel sheets.

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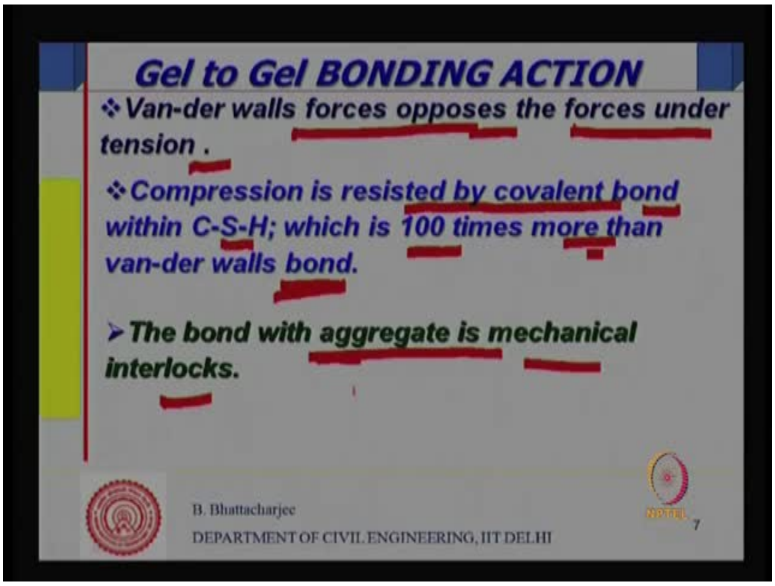

Gel to Gel BONDING ACTION

❖ Van-der walls forces opposes the forces under tension .

❖ Compression is resisted by covalent bond within C-S-H; which is 100 times more than van-der walls bond.

➢ The bond with aggregate is mechanical interlocks.

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This bonding may also be present because of the surface items which right or a hydrogen bonding or by condensation of silicon hydroxide will tetra 4 is O H 4 groups leading to S I O S I linkages. So other kind of chemical bonding is also thought to be responsible for bond between gel to gel in addition to the Van der waals bond because it is stable in water. So gel to gel bond is Van der waals kind or some sort of chemical bonding also may be present. And that is what results in strength of gel well if the tension is applied this forces will oppose the tensile force.

So separation will be opposed by this forces which are bonding the gels compression on the. Other hand compression on the other hand is resisted by covalent bond within C-H-S so you try to push them. Now you are pushing the sheet against one sheets against another, if you trying to push them you are pushing one sheet against another. If you are trying to push the sheets c h s under compression you are actually pushing one sheet against another which means, that you are trying to compress the c h s gel itself c h s bond itself which is not possible.

So that is for that is way they are strong in compression because you cannot compress c s h bond so easily but if you pull it would be is you know it can separate out of the sheets or c s h from one to another. Only the forces responsible for they are the bonding that is of the intermolecular forces you know they will hold them together. So, they weak in tension because it is intermolecular forces. Opposes the tensile force where as covalent bond in c h s opposes the compression forces right. So there much stronger and they are 100 times stronger than this compression forces are 100 times. You know compress compressive a the bond under compression the bond that has to be that has to be you know the bond the force resisting the compression or is 100 times more than Van der waals bond that is way they are strong in compression. Well bond with aggregate is essentially mechanical interlocks. So will come that some time later on bond with aggregate is mechanical interlocks. Let us see so first of all Van der waals forces opposes the force under tension or intermolecular forces of all kind compression is resisted by covalent bond within c h s and that is 100 times more than Van der waals bond. So therefore, they are strong in compression not so strong in tension.

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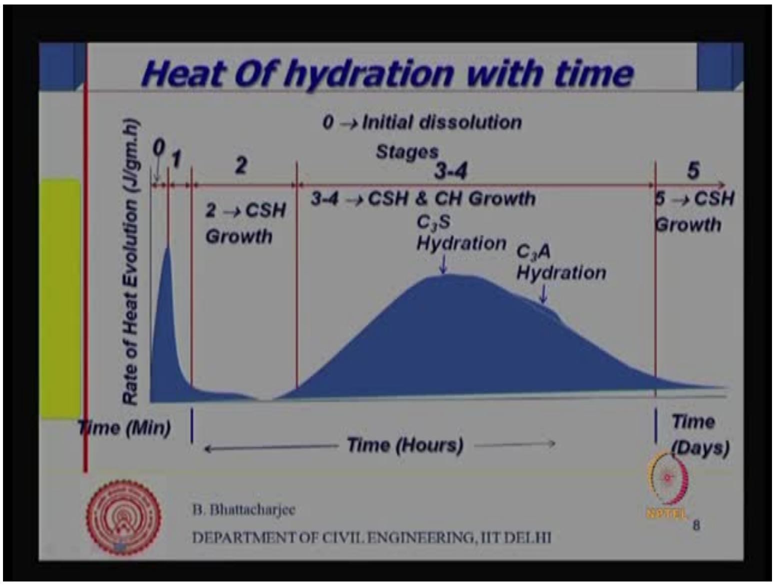

Heat Of hydration with time

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And of course, when it is comes to aggregate so it is gel to gel, gel to aggregate is of course, mechanical interlocks right. Gel to gel is mechanical interlocks right. So that was the bonding action white cement can bond a itself cement paste you know you cannot separate out cement paste itself, that is the reason but they are bonding with aggregates of course is mechanical interlocks will look into sometime later on. When you look into concrete strength, next we look into heat of hydration with time. Let us see heat of because we have seen other contribution of each compound of cement to heat of hydration but with time how heat of hydration is evolved let us look at it. This side is time in hours let us say and that side is rate of heat evolution rate of heat evolution well. Initial face is of course in minutes, then in hours, then in days. Now if you look at it, this is how the heat of hydrations look like you have pick right in the beginning quick initial dissolution period followed by rate gets reduced down, then rate picks up again and then the small hump here and that it you know follows that way. So the stages I can say first is stage 0 followed by stage 1, stage 2, 3 and 4 and 5. First zero stage is initial dissolutions so at that stage there is quite a rate of heat evolution, rate of heat of evolution is high then in the stage one you know government it will relate to government period. C 3 S hydration occurs here, when rate of heat evolution of heat is very high and C 3 hydration occurs next stage.

So this stage just stages one will see that it is impingent formation 2 C H S growth 3 and 4 also c h s growth and 5 is further c h s growth. So this stage initial c h s growth occurs, this is initial dissolution period, one stage one is impregnate formation stage one is estrange of formation, stage two is some c h s growth 3. And 4 c h s growth and 5 is again c h s growth C 3 S hydration occurs at the pick well heat of hydration is pick C 3 hydration occurs. And next level of C 3 hydration occurs later on that gives another small hump. So that is heat of hydration.

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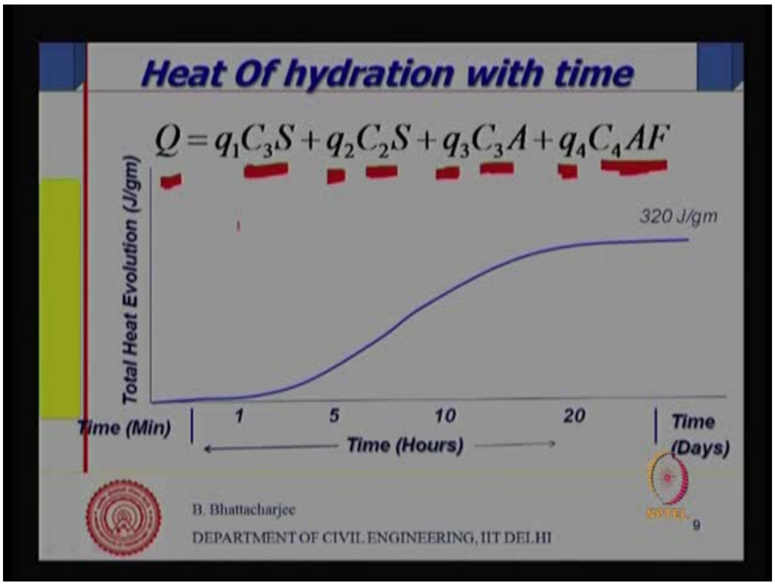

Heat Of hydration with time

$$Q = q_1C_3S + q_2C_2S + q_3C_3A + q_4C_4AF$$

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Rate of heat evolution you can see rate of heat evolution that is heat of evolution per unit time, that is not we are looking at joules per gram per hour you ((.)) Now total heat of evolution total heat evolution if you look at it, that would again with the same time so it majority of the heat evolution really takes place in the initial this 20 hours so and the order is of the total order doing 320 joules per gram etcetera after a after complete. You know 24 hours or so.

So pick heat of rate of heat evolution will be 4 to 6 hours as we have seen in the last same here about 7, 8 hours, 10 hours at that time and after that it becomes stabilizes out. So initial there is the speak but that is small period so if you submit up. It is not very large but then therefore the rate of heat evolution will increase and tends a pick somewhere there at this stage and after that rate of heat evolution reduces so total heat evolution also reduces.

Total heat of course you can find out from q 1 that is the heat of hydration C 3 S multiplied by the amount of C 3 S. q 2 is a heat of hydration of C 2 S multiplied by the quantity of C 2 S per unit mass, q 3 C 3 A heat evolution of C 3 A. And the amount of C 3 A per unit mass in the cement q 5 is a heat of hydration of C 4 A F and this is a quantity. So you can sum this up to find out total heat evolution at any stage or even in totality complete heat of hydration.

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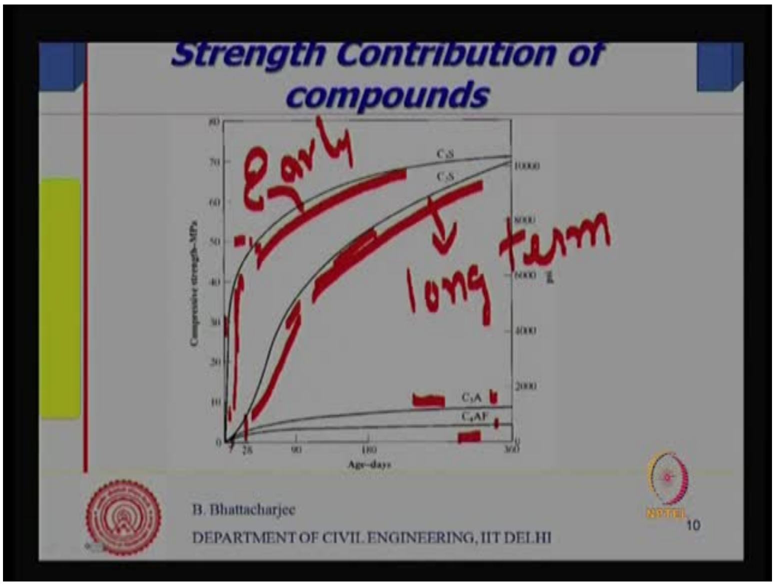

Strength Contribution of compounds

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This you know this quantity you know and this I have given you earlier some time the quantity of heat the sliverated per unit mass from the C 3 S and similarly, from C 2 S, C 3 A and C 4 A F, another important aspect is strength contribution. So we have seen that actually C 3 S hydration takes place in the beginning when we looked at the a when we earlier looked into the a you know a various phases, that is found a various product that is form with time and we have seen that is first stage that in reaction followed by formation of c h s after about 6 hours.

So and then calcium hydroxide also comes out in this case actually C 3 S reacts earlier C 2 S reacts late. So therefore strength development if you see C 3 S. It is responsible for early strength development C 2 S initially does not rate of strength of development is not much right. It follows like this and C 3 A contribution to strength is less and C 4 A F contribution to strength is even less. So initial strength normally comes out within seven days because we are talking of days would be from C3S. 28 days C2S contributes, but it is do contributes significantly to long term strength.

But, see you if you see C3S after about 28 days hardly any strength the rate of strength gain as reducing significantly for C3S. On other hand C2S fix up here. The rate is increasing and you know so long term strength comes from C2s long term long trim early strength. This has got less strength contribution..

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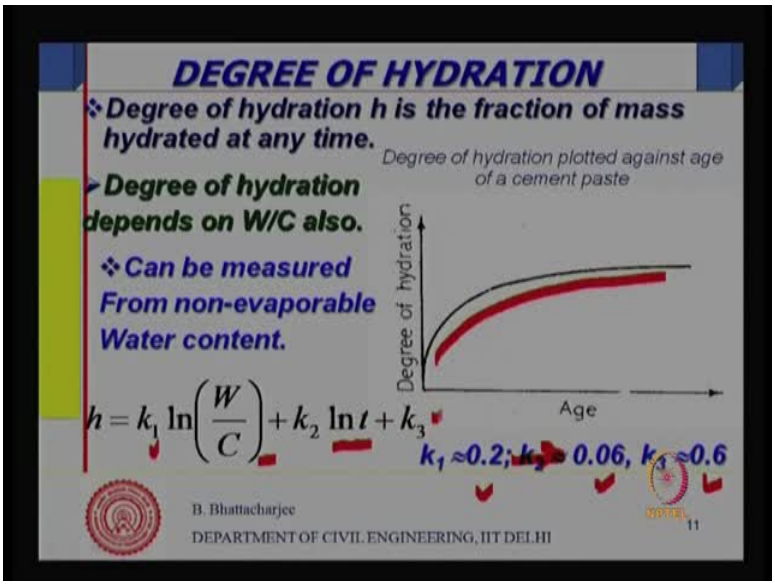

DEGREE OF HYDRATION

- Degree of hydration h is the fraction of mass hydrated at any time.
  - Degree of hydration depends on W/C also.
- Can be measured From non-evaporable Water content.

Degree of hydration plotted against age of a cement paste

$$h = k_1 \ln\left(\frac{W}{C}\right) + k_2 \ln t + k_3$$

$k_1 \approx 0.2; k_2 \approx 0.06, k_3 \approx 0.6$

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So the length contribution was it is C3S which give early strength, C2S gives latest strength. And we have seen a that because C S H that will combination is the beginning would come from C3S and related only C2S reaction take place. We define the term degree of hydration. Degree of hydration is the fraction of mass hydrated at any time. We you know case denoting it by h. So degree of hydration h is the fraction of mass hydrated at any time; that means well just for our understanding if c dash is the mass of cement hydrated. C is the original mass, so h is given by this.

So mass hydrated quantity of cement hydrated divided by original. So therefore h is a fraction it is a fraction. So h is the expressed the degree of hydration is exposes of fraction. It is a fraction of mass hydrated at any time. And this is this is function of time this is the function of time and as you can see with age degree of hydration integers and then tends to become steady. As we have seen, you know because cement consists of four major compounds, C2S, C3S etcetera.

So, they will a portion of it will hydrate up to certain period of time and later on the hydration rate is strength development is slow. So naturally hydration it also slow. So it picks up statistically of this kind of carbon but recently this a few more measurements you know that experiments many reasons a experiment demonstrated that this degree of hydration is function of water cement ratio as usual. A even even for water cement ratio high water cement ratio like 0.5, 4, 0.5, 0.6 etcetera is a function of water cement ratio itself.

And a one can measure this from non evaporable water content. So you take the cement paste at any age under controlled condition you have prepare the paste configuration hydration. And then block the hydration by some treatment. Actually isopropyl alcohol if you put it return that will absorb all water and stop the hydration. So at any age you can stop the hydration. Then you can heat it up to find out the non evaporable water content..

Evaporable water content you go however 110 degree centigrade but after that if you heat it up you can find out the non evaporable water content. And from that non evaporable water content measurement one can find out what is the you know degree of hydration. And one can possibly relate this to the water cement ratio that age in this manner. So it is a function of log of age also function of log of water cement ratio and this coefficients are of the order of around k1 is 0.2 of the order k2 is 0.06 k3 is around

0.6 or a so I think a these you know now one can obtain this constant. from actual measurements. So some values are available in literature one kind find in values.

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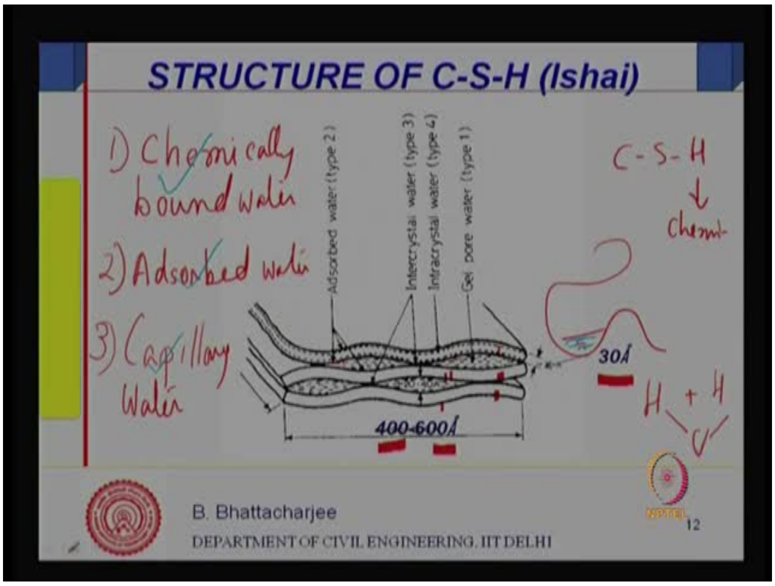

STRUCTURE OF C-S-H (Ishai)

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Right. So that is degree of hydration. Now let us look at structure of C H S, C H S structure. Now several modules have been proposed, this one is proposed by Ishai. These are sheets so you got sheet one sheet, another sheet and the other sheets. So this sheet like structures seven thickness of order around 30 armstrong. This is 400 to 600 armstrong, sheet length. And the space in between 10 to 40 micron inter layer inter layer space inter layer space. So and the water is there.

Now you know in forus material water can be held, in forus material you can hold the water first is chemically bound water, that we have seen chemically bound water. And chemically bound water at the CSH so this is chemical bound. That we have seen, then besides that since surfaces have surfaces can have intermolecular forces that will be polarities, so water being H2O being a polar liquid it is got a dipole.

So center of positive charge and negative charge they may not be at the same point they may not coinciding. So therefore it is polar, so it can get absorbed at the surface. So you have got absorbed water absorbed water at the surface absorbed water, right absorbed water. Now between two layers he actually called it inter crystal water between two layers.

So other then chemically combine water of course, you can have adsorbed layer absorbed water. And the besides that of course, you can have capillary water which is taken up by section capillary section, right. If you larger size of course, or relatively you know some vespers not very small force fine force fine particles their force absorbed layer would be there. But, slightly larger size force water can penetrate by capillary such. So the third type of water held is capillary water capillary water and in some cases there can be water held simply by mechanical action, for example, if I have a pole like this here water comes in here water comes in and is water comes in is just stuck here.

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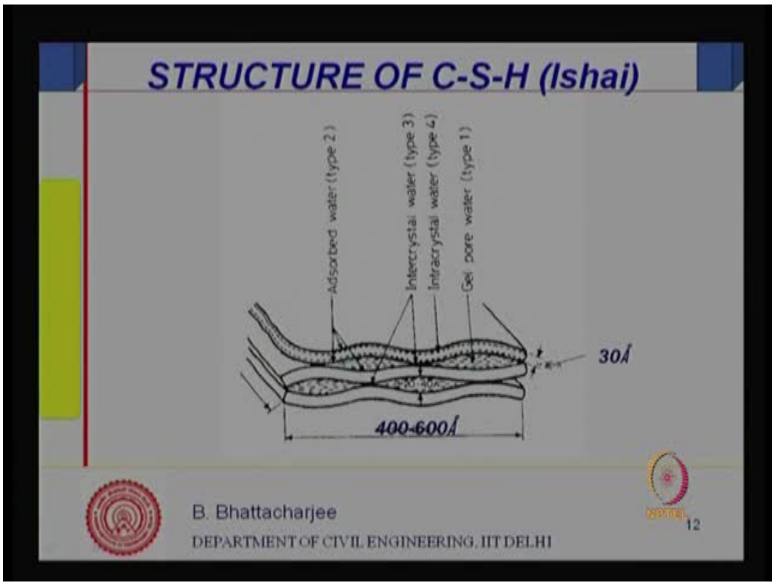

STRUCTURE OF C-S-H (Ishai)

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So this is mechanically held here. Now in concrete or cement paste you will have chemically bound water absorbed water and capillary water can also be there if it is saturated, all right. Now in his module in this module in the module is talking of the sheets adsorbed water. Adsorbed water are from layer of water it is the surface and density is not one density of this water is not one right, it has got a different density.

So the absorb layer will be some there at the boundary. So the surface then this water is calling inter-crystal water which is between which is between the layers, layers of CHS. And then still there will be some water between the space, between the sheets it is being called as gel water..

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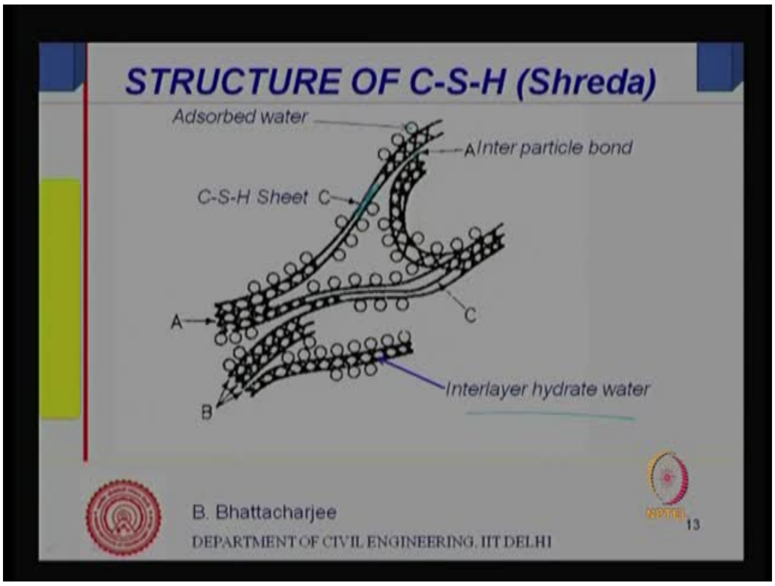

STRUCTURE OF C-S-H (Shreda)

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it is being called as gel water So this was the module propose one module proposed. There is another module of the Shreda, and hare you can see is adsorbed water again in the surface this on the sheets. So C H S sheets are here, the adsorbed water of the surface inter particle bond is between this of particle another sheet. Adsorbed water this is the sheets so they are not in exact layers parallels layers but they are in different orientation, this x cross r interlayer hydrate water.

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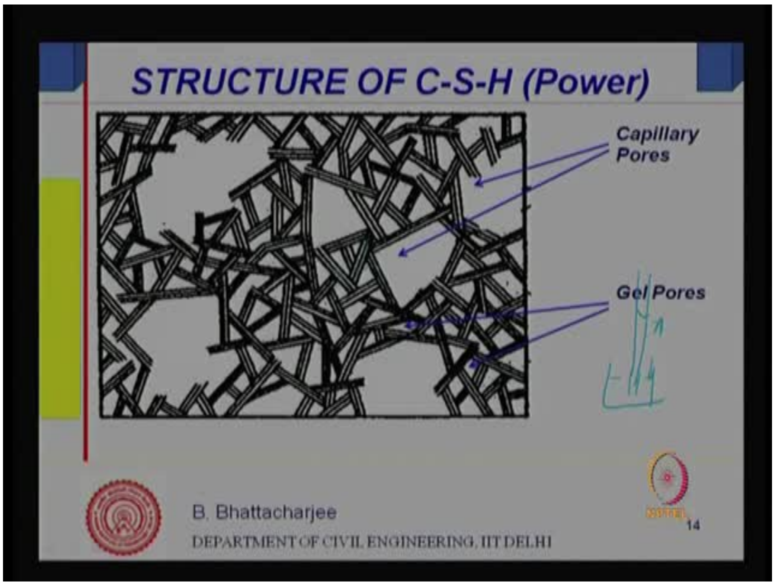

STRUCTURE OF C-S-H (Power)

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So in you know interlayer hydrate water is in the so less cross so these are all interlayer water adsorbed water is here this is the layers. And within the layer there is interlayer water, right. So inter particle bond is here adsorbed water. C-S-H sheets is interlayer water and you know this is the C-S-H sheet these interlayer hydrate water. So this is another module and this is the module proposed by Power. In this module these are the C-S-H these are the C-S-H sheets you can see and capillary pores there are large space which he call as capillary pores as I was telling where relatively larger pores this once water can by inter capillary section right, following because of the surface tension forces, because of the surface tension forces.

As you know at the inter face there be surface tension forces like you deep a capillary if you deep a capillary into if you deep a capillary into water there is capillary rise as you know capillary raise and this is because of surface tension forces. So water can come here because of surface tension forces and this forces is large and these are called capillary pores. And gel pores are smaller once between the gels between the gels. So these are the C-S-H sheets and thus between this C-S-H sheets the space which is there where they are be gel pores gels cannot this he calls a gel force which is in here top the gel system. Now larger force are capillary pores. So this is how the Powers module looks like. We have capillary pores and layer of C-S-H layer soft c s h and within the layer of C-H-S the smaller pores are been called as gel pores. So these are the modules which represent the herndon paste structures.

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PORES IN PASTE

- Gel is colloid sized particles having 28% characteristic porosity involving pores of average width15Å, called gel pores

Gel pores: micro pores (0.5nm -- 100nm)(Shrinkage & Creep)

Capillary meso pores (5 nm-5000nm) (Mechanical & Durability)

Macro pores due to air entrainment

Macro pores due to poor compaction

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So having done that now we can think of pores in the paste. Gel is a as we have explained earlier gel is colloid sized particles having 28 percent characteristic porosity involving pores of average width as 15 armstrong. And these are the gel pores. So they are gel pores are gel pores are micro pores or you can say even nano pores 0.5 nano meter to 100 nano meter size. These are generally considered to responsible for shrinkage and creep. Capillary pores there are slightly larger size called meso-pores and size would be 5 nano meter to 5000 nano meter.

They are responsible for mechanical strength; that means you know low or load caring capacity and durability property of the cement paste and then concrete. Then that would be pores coming because of pure compaction. So these are the macro pores or because of air entrainment. Air entrainment is deliver at entrainment is used in some cases in order to provide better (( )) or registrants. We look into that sometime later on. And poor compaction can also results in large size pores.

So there for what we see is the cement paste has got a structure, it is porous inherently porous hydraulic cement paste has got a hydro paste and structure which is inherently porous. And a it is crush two types of pores. That is been recognized, one is gel pores it has got a (( )) structure each is that is the major compound which is from after hydration as got sheet like structures and it is inherently porous with 28 percent characteristic porosity twenty eight percent characteristic porosity has been determined from indirect experimental evidences.

Similar the size of the gel pores that is mean also determined from experimental evidences nitrogen adoption technique etcetera. Then the other type of pores which can be they are is a capillary pores which are large size pores and if you recall the hydration process that we looked into we said that they are inner you know product of hydration which is within the original grand boundary, we have outer product because hydration product occupies more.

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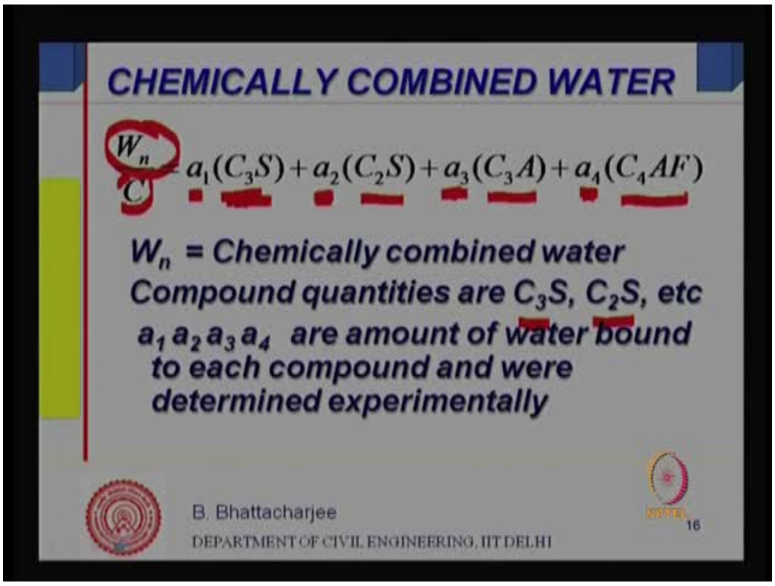

CHEMICALLY COMBINED WATER

$$\frac{W_n}{C} = a_1(C_3S) + a_2(C_2S) + a_3(C_3A) + a_4(C_4AF)$$

W_n = Chemically combined water

Compound quantities are C_3S, C_2S, etc

$a_1\, a_2\, a_3\, a_4$ are amount of water bound to each compound and were determined experimentally

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Volume then the original cement. Therefore some of those water field space will be field in by hydration product and those we call as outer product. Calcium hydroxide also stays outside the original grand boundary and originally water field place, which remain vacant after hydration forms capillary pores. So you can recall that you know you can seen that those pores of the largest size and are responsible for durability and mechanical properties namely strength etcetera.

And larger pores could be there if you have deliberant entrainment, why you do it will come to that is some time later on? And if you have a poor compaction then also you can have large size pores. Let us see how much is chemically combined water.

Right to do that people have done test experiments on individual compounds right, so if you want to find out the chemically combined water all right, we must know how much is a amount of waters C3S will c three s will require for full hydration. How much the quantity of water C2S require for full hydration. You know so this is the quantity of water required by one gamma C2S for its full hydration. A3 is the quantity of water required by one gamma C3A for full hydration and A4 similarly, A4 is a quantity of water, required by one gram of C4AF for full hydration. So then this is the chemically combined water.

So chemically combined water per unit mass is Wn c is amount of water, that will combined with c cement c is the quantity of cement, so quantity of water that will combine per unit mass is Wn by c. And if I know the that quantity of C3S proportion C3S proportion of c two sC2Sproportion C3A and proportion of C4AF. Then I can find out chemically combined water for C quantity of cement. The compound quantities proportion of C3S, C2S etcetera. Now people have actually done experiments very long term, very long term experiments done by people.

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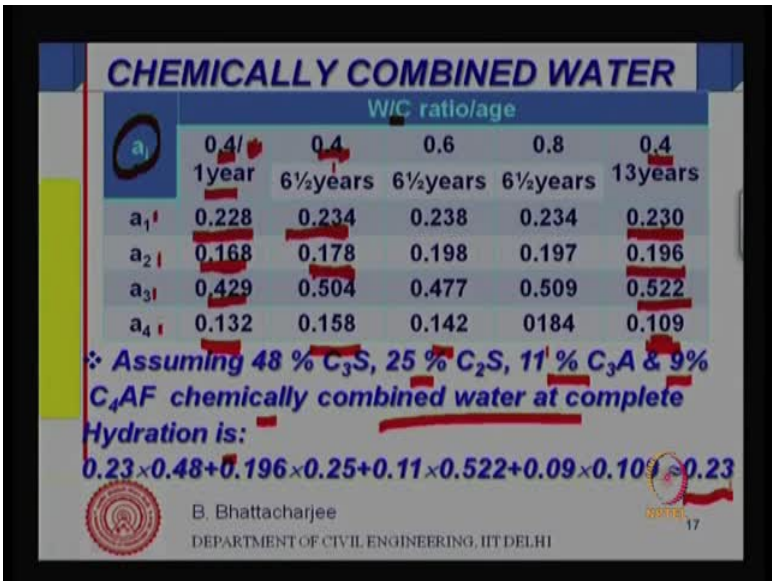

CHEMICALLY COMBINED WATER

a_i	W/C ratio/age				
	0.4/ 1year	0.4 6½years	0.6 6½years	0.8 6½years	0.4 13years
a_1	0.228	0.234	0.238	0.234	0.230
a_2	0.168	0.178	0.198	0.197	0.196
a_3	0.429	0.504	0.477	0.509	0.522
a_4	0.132	0.158	0.142	0184	0.109

- Assuming 48 % C_3S, 25 % C_2S, 11 % C_3A & 9% C_4AF chemically combined water at complete Hydration is:

$$0.23\times0.48+0.196\times0.25+0.11\times0.522+0.09\times0.109\approx0.23$$

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To find out the amount of water bound to each compound and this results are actually given in this table. If you look at it these are a i this a1, a2, a3, a4 with a water cement ratio water to cement ratio and age. So water cement ratio of 0.4 in one year it was absorbed that one gram of one gram of C3S consumes around for 0.228 grams of water for 0.4 water cement ratio. 6 and half years this becomes 0.234 and in thirteen years this became 0.230. So complete hydration nearly one can assume thirteen years is very long time.

And the test have been performed on individual compound in this manner. a2 is that was for C2S and in one year 0.168 grams of water reacted with one gram of C2S in 0.4 years I mean in 6 and a half years 0.178 and in thirteen years 0.196 all this 0.4 water cement ratio. Similarly, A3 you know you can see that in 13 years 0.5 to 2 grams of water reacted with one gram of C3A and A4 that is one gram of C4AF reacted with 0.132 grams of water in 1 year in 6 and half year 0.158 and 13 8 why it are something like this.

But if the water cement ratio change. 0.6 and 0.8 in 6 an half years the variation was something like this I think there must be some mistake in this figure. Whatever it is, what we see is that different quantities of water are declared by different compounds of cement for their complete hydration. Because 13 years one can assuming to be a full hydration. Now suppose you have assumed 48 percent C3S, 25 percent C2S, 11 percent C3A and 9 percent C4AF chemically combined water at complete hydration is given by this formula.

0.23 into 0.48 because 2 3 into 0.48 because 48 percent is C3S, 0.25 into 0.196 0.11 percent C3S so it is like this and approximately this value comes out be 0.23. So it is 48 percent C3S 25 percent C2S 11 percent C3A 9 percent. C4F 100 grams or one gram of cement you know containing this quantity. Because one gram of cement we have then 0.48 grams of C3S, 0.5 grams of C2S etcetera. So one grams cement will be react approximately with 0.23 grams of water. If this proportion changes slightly this may change a little bit.

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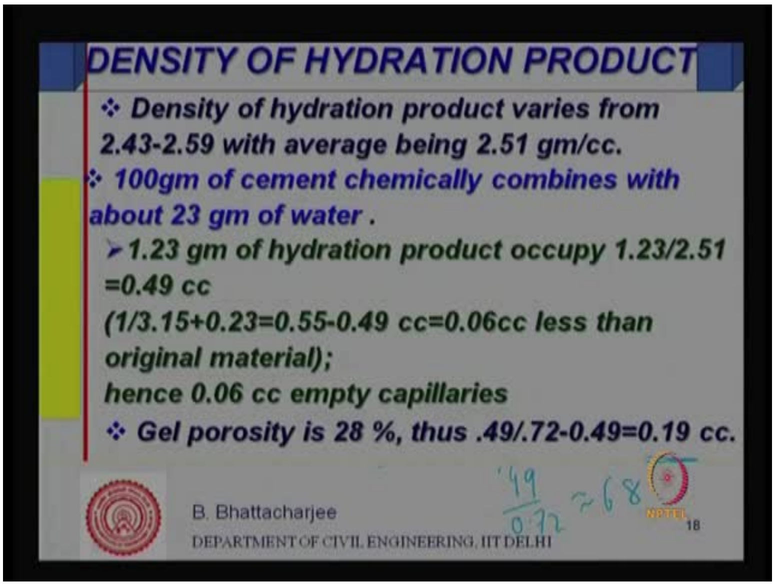

DENSITY OF HYDRATION PRODUCT

- Density of hydration product varies from 2.43-2.59 with average being 2.51 gm/cc.
- 100gm of cement chemically combines with about 23 gm of water .
  - 1.23 gm of hydration product occupy 1.23/2.51 =0.49 cc
    (1/3.15+0.23=0.55-0.49 cc=0.06cc less than original material);
    hence 0.06 cc empty capillaries
- Gel porosity is 28 %, thus .49/.72-0.49=0.19 cc.

$\frac{.49}{0.72} \approx 68$

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That is why I written approximately, so generally supposing you consider this is 55 and this is 22 and this is may be somewhat less etcetera. This value will change but round 0.23 only but round about 0.23 only. So round about point two three only, so values would change. Approximately therefore one gram of cement reacts with 0.23 grams of water in for complete hydration 13 years is a very long time after those practically no hydration..

So stichiomatrically we can say that one gram of water, one gram of cement requires 0.23 grams of water for complete reaction, all right. So this is one information, other information that was that become available from early experiments in 1950s is that density of hydration product, solid product of hydration varies from 2.43 to2.59 two point four three two two point five nine and if you look at the average it will be 2.51 grams per cc. So 100 grams of cement therefore chemically reacts with 23 grams of water, one gram with 0.23, so 100 gram with point you know 23 gram of water and would it produce 1.23 gram of hydration product.

Which can occupy 1.23 divided by 2.51 0.49 cc. Because this grams per cc. This is the grams, so 0.49 cc. So the hydration solid product of hydration will occupy 0.49 cc right. Now if you look at cement is specific realties generally taken to be 3.15 on an average. So one gram of cement will occupy 1 by 3.15 that is point you know 0.32 this will come out as 0.32 so 0.32 plus 0.323, and water occupies the same volume, sums up to 0.55. And that is 0.55 and the product solid product of hydration occupies 0.49 therefore this occupies less than the original volume of water right original material. This is assumed to be some empty space.

So the difference is assumed to be some empty space. It is this difference is assumed to be so 0.32 plus 0.23 makes it 0.5. This is what it is, minus 0.49 gives 0.06 cc and therefore assumed to be this is assumed to be some empty space. But this 0.49 actually has got internal pores internal pores and this is typically 28 percent. So it has got internal pores 28 percent 0.06 cc of water remains aside but this 0.49 actually will occupy much higher than 0.49. Because 28 percent characteristic porosity is there 28 percent characteristic porosity is there.

And therefore 0.49 divided by 0.72, which will give you roughly for 0.68. You know and therefore this different give us 0.19cc. So the gel porosity is 0.19 0.19cc. Gel porosity is 0.19cc or I mean gel pores is 0.19cc. So if I take one gram of cement if I take one gram of cement and allow it to hydrate fully, then it will occupy actually 0.49 cc the solid product hydration will occupy but 0.19cc will be occupied by the gel pores within you know enclosed within this product of hydration plus you may have a capillary pore space of 0.06cc. Empty capillary sized pores.

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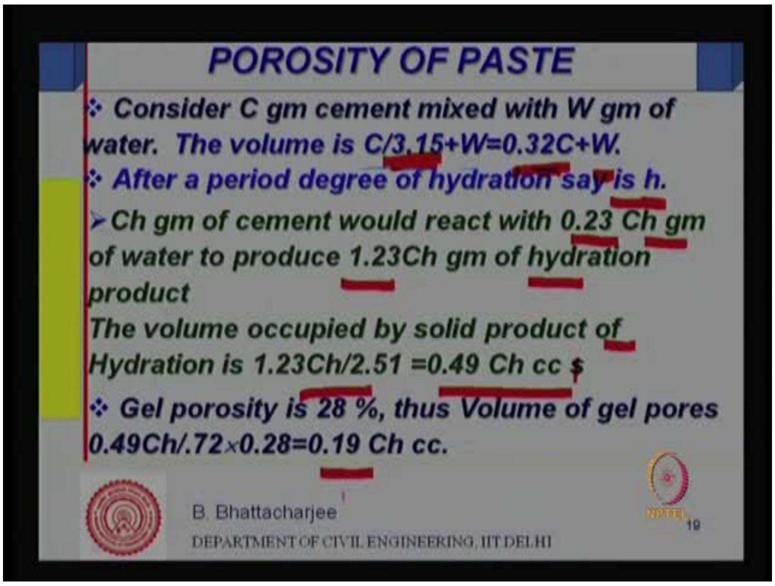

POROSITY OF PASTE

- Consider C gm cement mixed with W gm of water. The volume is C/3.15+W=0.32C+W.
- After a period degree of hydration say is h.
  - Ch gm of cement would react with 0.23 Ch gm of water to produce 1.23Ch gm of hydration product

The volume occupied by solid product of Hydration is 1.23Ch/2.51 =0.49 Ch cc

- Gel porosity is 28 %, thus Volume of gel pores 0.49Ch/.72×0.28=0.19 Ch cc.

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So this is what comes from the previous modules and if I consider c gram of cement mixed with w gram of water the volume would be C3C divided by 3.15 plus w 0.32c plus w 0.32c plus w 0.32 c plus w right, because specific gravity or density of cement is taken to be 3.15 grams per cc. After a period of hydration say degree of hydration being Ch gram of cement would react, because h is defended the fraction with 0.23 Ch gram of water to produce 1.23 Ch gram hydration product.

The volume occupied by the solid product of hydration therefore is 0.49 Ch cc. So this is cc basically 0.49 Ch cc. Same calculation follows because 1.23 grams occupied 0.49Ch is the amount of the cement that is reacted. So therefore 0.49Ch. Gel porosity 28 percent thus volume of gel pores would be 0.19Ch. Same thing same calculation is being repeated only now I add c h, which it solider everything was one gram is taking.

If I take is c grams of cement and h is the degree of hydration then c h grams cement will react and everything has to be multiplied by c h and that is why I get it. So again 0.49Ch is solid from volume of solid product of hydration, 0.49Ch cc. 0.19Ch cc is a gel pores volume right. So that is how I can just calculate out the volume pores, gel pores. The mass of hydration cement of course, will be c into one minus h.

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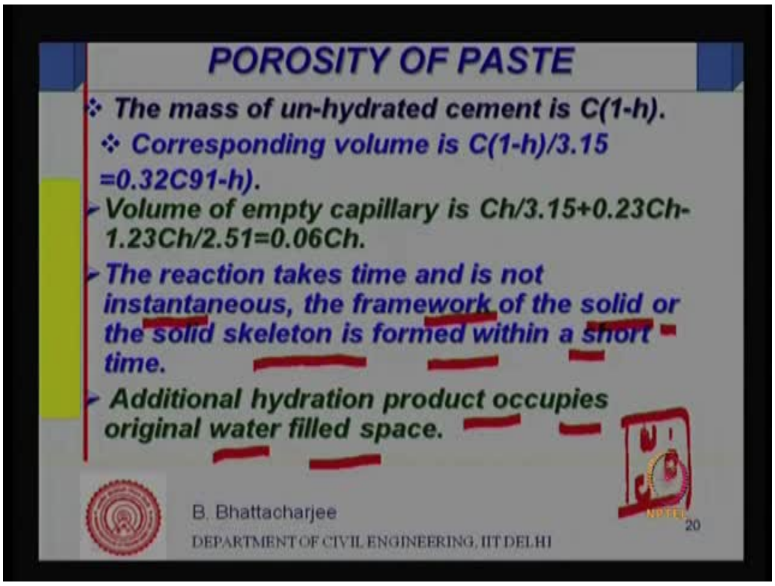

POROSITY OF PASTE

- The mass of un-hydrated cement is C(1-h).
  - Corresponding volume is C(1-h)/3.15 =0.32C91-h).
- Volume of empty capillary is Ch/3.15+0.23Ch-1.23Ch/2.51=0.06Ch.
- The reaction takes time and is not instantaneous, the framework of the solid or the solid skeleton is formed within a short time.
- Additional hydration product occupies original water filled space.

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Mass of because c h hydrated originally C, C minus C h is nothing but C minus 1 minus h. So that is what it is mass of un-hydrated cement will be only this much and corresponding volume because density of cement is 3.15. So will be 0.32 c this should be bracket C h 0.32 c into 1 minus h into this should be bracket 1 minus h 0.32 c 1 minus h that would be the mass of and volume of un-hydrated cement volume of un-hydrated cement, and volume of empty capillaries will be same 0.06 c h like earlier we have done it will be 0.06 c h now reaction.

Takes place reaction take place you know it takes time, it does not occur instantaneously, it is not instantaneous but the frame work of the solid is form quite quickly. So within half an hour time you know initial set so frame works forms very quickly you cannot disturb it any further. So solid skeleton is formed within a short time, since solid skeleton is formed within a short time, the rest of the hydration product occupies only the space available within that solid skeleton.

So additional hydration product occupies original water filled space within the skeleton, the structure is formed very quickly. This is the structure form but some space are blanked. So those blanked spaces are filled in by additional hydration product because solid is formed but a products solid structures form once.

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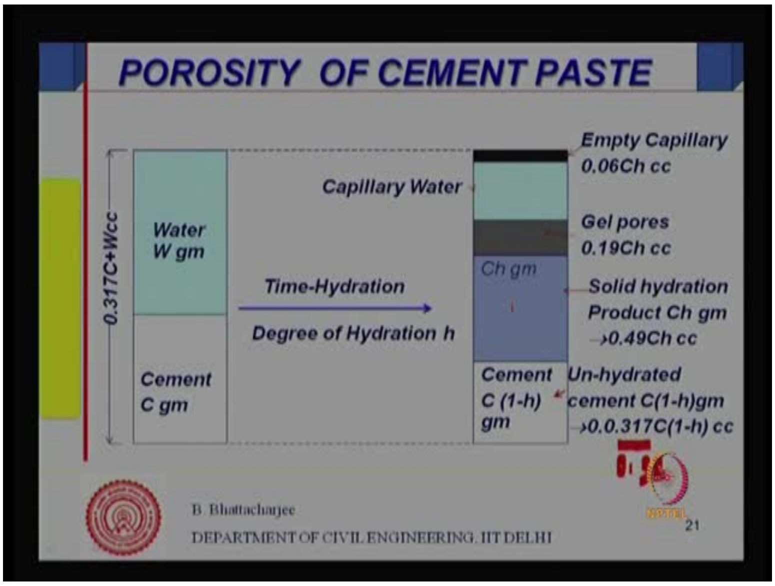

POROSITY OF CEMENT PASTE

0.317C+Wcc

Water
W gm

Cement
C gm

Time-Hydration

Degree of Hydration h

Capillary Water

Ch gm

Cement
C (1-h)
gm

Empty Capillary
0.06Ch cc

Gel pores
0.19Ch cc

Solid hydration
Product Ch gm
→0.49Ch cc

Un-hydrated
cement C(1-h)gm
→0.0.317C(1-h) cc

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It solidifies and this porous remember we had blue colored water which outer product filled in living some more filled space those space are the space available for hydration products those are generated in the later stages of hydration, because solid skeletons found in within short period of time. And the prose the force of hydration the volume expansion pores of hydration is not so high. It is to cause disruption of the structure, therefore they only fill in the original space that mean, no change in the total volume. So this if you look at into look into this will look into it will look like this schematically cement C grams, water W gram time let us say hydration is occurred degree of hydration is h now you know un-hydrated cement remaining is C into 1minus h gram.

And its volume is well this is 3. 0.32 I will say 32 c 1 minus h cc approximately and you know this is the un-hydrated volume, this is the solid hydration products which is 0.49 c h cc; that is what we have seen, this will be the gel pores corresponding gel pores, which is 0.19 c h cc and some space of water still not filled by the martial remain as capillaries we can call it as capillary water, we can call it as capillary water and empty capillaries will be like this. So this is the empty capillary and this sums up whatever we have discussed now original.

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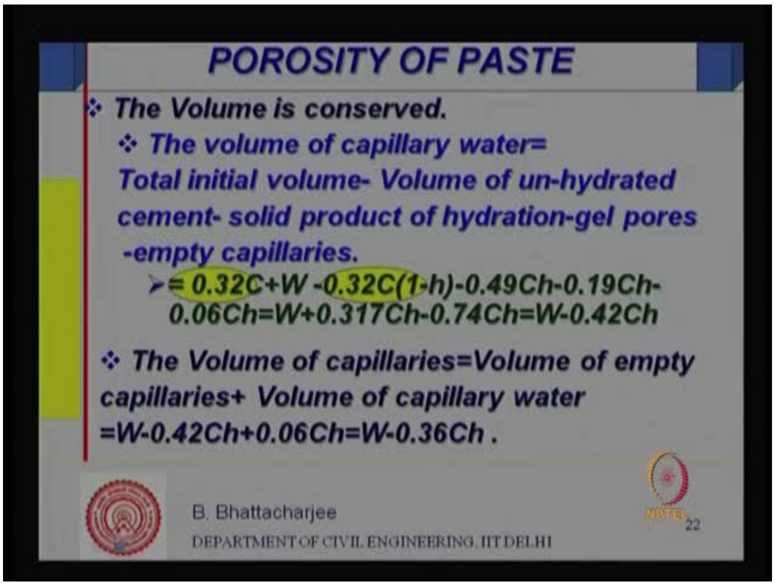

POROSITY OF PASTE

- The Volume is conserved.
  - The volume of capillary water= Total initial volume- Volume of un-hydrated cement- solid product of hydration-gel pores -empty capillaries.
    - $= 0.32C+W-0.32C(1-h)-0.49Ch-0.19Ch-0.06Ch=W+0.317Ch-0.74Ch=W-0.42Ch$
  - The Volume of capillaries=Volume of empty capillaries+ Volume of capillary water $=W-0.42Ch+0.06Ch=W-0.36Ch$.

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Volume is this much how much? 0.32 c plus W cc and this volume is conserved this volume is conserved this volume is must be same as this volume, this volume is conserved. So therefore, this volume must be same as this volume therefore using this concepts I can calculate of the porosity. So porosity of paste I can calculate out, the volume is conserved, the volume of capillary water will be total initial volume minus volume of un-hydrated cement.

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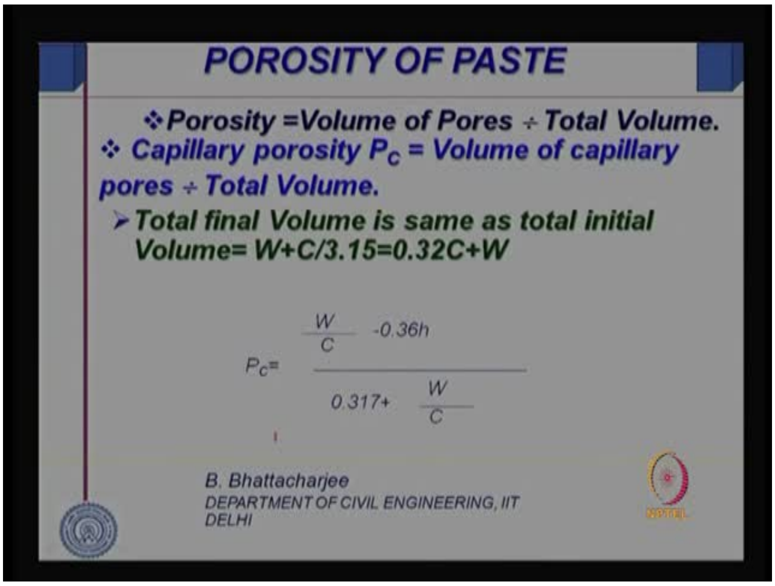

POROSITY OF PASTE

- Porosity =Volume of Pores ÷ Total Volume.
- Capillary porosity P_C = Volume of capillary pores ÷ Total Volume.
  - Total final Volume is same as total initial Volume= $W+C/3.15=0.32C+W$

$$P_C= \frac{\frac{W}{C} -0.36h}{0.317+ \frac{W}{C}}$$

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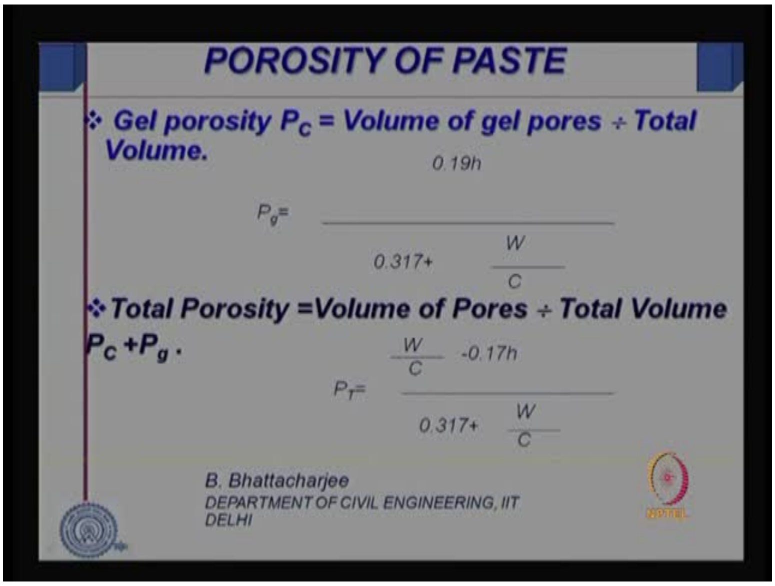

POROSITY OF PASTE

- Gel porosity P_C = Volume of gel pores ÷ Total Volume.

$$P_g = \frac{0.19h}{0.317 + \frac{W}{C}}$$

- Total Porosity =Volume of Pores ÷ Total Volume $P_C + P_g$.

$$P_T = \frac{\frac{W}{C} - 0.17h}{0.317 + \frac{W}{C}}$$

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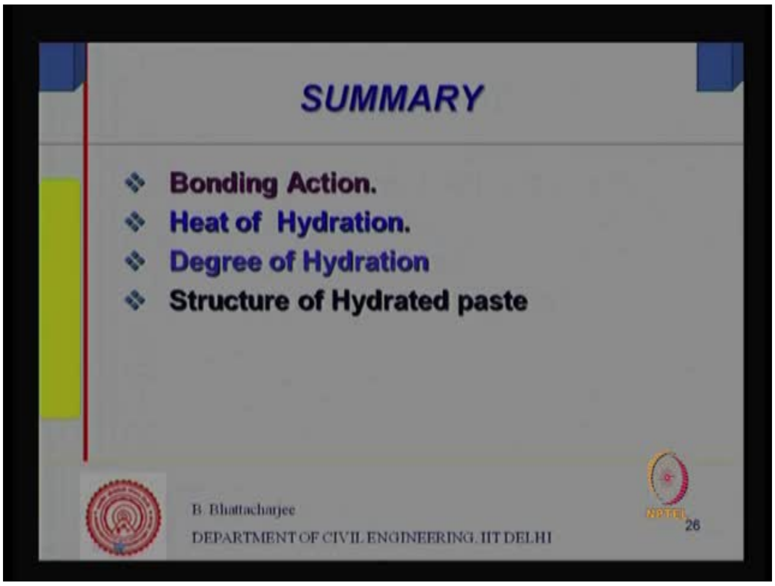

SUMMARY

- Bonding Action.
- Heat of Hydration.
- Degree of Hydration
- Structure of Hydrated paste

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And empty capillaries I can I can just find out the capillary pore water volume by finding initial total initial volume is known and other component volumes are known I separate them will look into this in the next class in the beginning the equations etcetera.

will find out there the volume of capillaries, volume of capillary empty capillaries would work out to be W minus 0.36 h, therefore porosity I can calculate out get an expression for the porosity based on this will repeat this in the next class and gel porosity I can find out I can find out total porosity. So this will look in the next class. So summarizing today we have looked into bonding action, heat of hydration, degree of hydration, structure of hydrated paste and we tried to find out the porosity which we shall looking into in the next class. So that is what. So next class will look into the total porosity and followed by a properties you know tests and various kind of properties of cement paste cement paste.

Thank you very much.