**Concrete Technology**
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**Indian Institute of Technology, Dehli**

# Lecture - 30
# Shrinkage of Concrete

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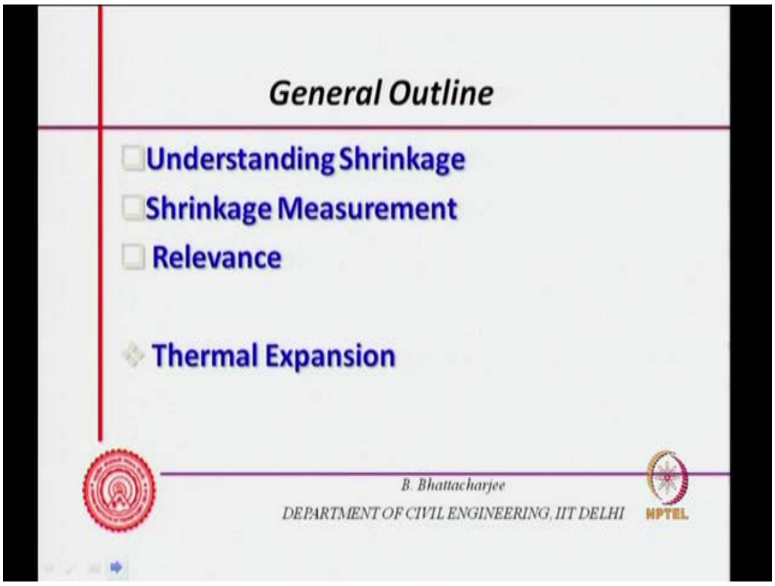

General Outline

☐ Understanding Shrinkage
☐ Shrinkage Measurement
☐ Relevance

Thermal Expansion

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Welcome to module 7, lecture 4, we shall be continuing with the shrinkage of concrete mostly of course, at the end we will talk about a little bit about the thermal expansion of concrete. So, we talked about some understanding of shrinkage earlier, we look at it at more details. Then we will look at shrinkage measurement, its relevance and as says lastly we will look at thermal expansion for a little while.

Now, like creep shrinkage is somewhat less understood, it is not fully understood, shrinkage of you know issues in concrete is relatively less understood. Of course, if you want to understand it more, then we must look into physicochemical fundamentals. And that is what we are trying to do right now. Now to start that, we must understand what happens in liquid gas interface. For example, in liquid gas interface, you know when pressure is applied on to the liquid the vapor pressure increases.

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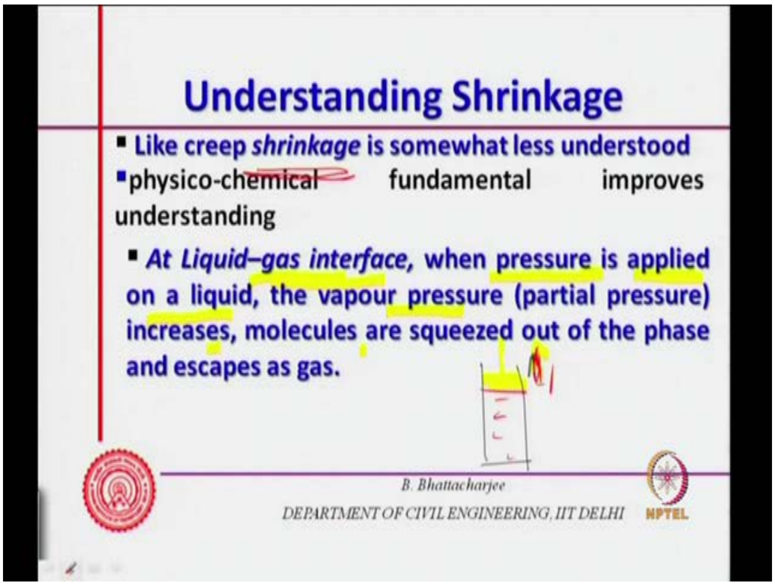

### Understanding Shrinkage

- Like creep *shrinkage* is somewhat less understood
- physico-chemical fundamental improves understanding
  - *At Liquid–gas interface,* when pressure is applied on a liquid, the vapour pressure (partial pressure) increases, molecules are squeezed out of the phase and escapes as gas.

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You know you apply pressure to the liquid; you apply pressure to the liquid this is your liquid let us say this is your liquid say. And you apply pressure here, pressure here through a piston, you apply pressure here through a piston, then vapor pressure increases molecules get squeezed out, molecule get squeezed out of the molecules will get squeezed out of the liquid phase and escape as gas. So, if you apply pressure to the liquid you know, liquid phase will get out squeeze out and escape as gas. Now, if the equilibrium then is established, if equilibrium is established, then chemical potential of the liquid and vapor must be equal.

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### Understanding Shrinkage

- Like creep *shrinkage* is somewhat less understood
- physico-chemical fundamental improves understanding
  - *At Liquid–gas interface,* when pressure is applied on a liquid, the vapour pressure (partial pressure) increases, molecules are squeezed out of the phase and escapes as gas.
- At equilibrium chemical potentials of liquid and vapour are equal.

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At equilibrium chemical, because there is no movement further, no moment is taking place. So for moment you need potential of one to be higher than the other. So you applied pressure to the liquid actually in case of potential therefore, the molecule will move out as vapor.

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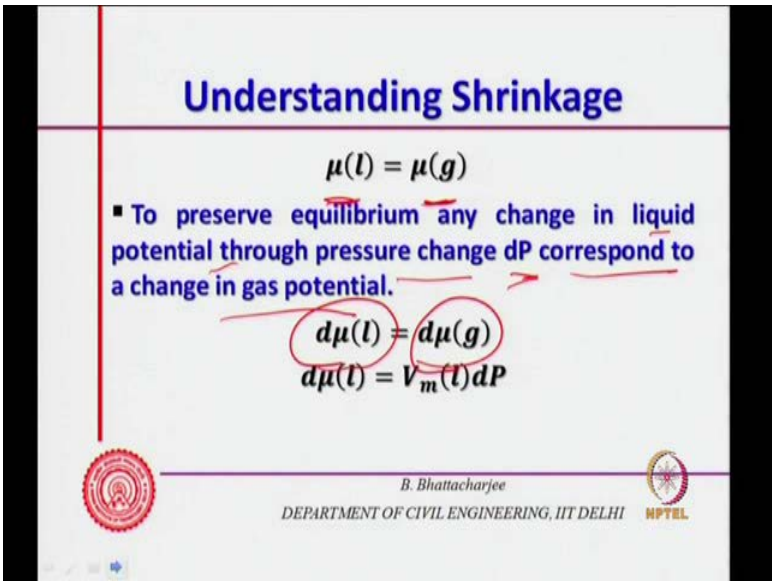

## Understanding Shrinkage

$$\mu(l) = \mu(g)$$

- To preserve equilibrium any change in liquid potential through pressure change dP correspond to a change in gas potential.

$$d\mu(l) = d\mu(g)$$

$$d\mu(l) = V_m(l)dP$$

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So therefore, if I write chemical potential chemical potential mu l of the liquid must be equals to mu g at equilibrium, and if I have to preserve this equilibrium any change in liquid potential. So, pressure change d p must corresponds to a change in gas potential So, if I have when I have applied pressure to the liquid let us say d p is a pressure I have applied, so liquid potential changed and correspondingly the gas potential must have also changed.

Otherwise equilibrium would not been there otherwise there would be no equilibrium. So, therefore, d mu l differential mu l must be equals to differential mu g where mu l and mu g are the chemical potentials of liquid and gas. Now, one can write d mu l as V m l molar volume of the liquid into d p, because molar volume is not changing so p d b you know is a work done p d b plus V d p since d V there is no volume change. So, one can write as V d p so that is the work done or there is a potential change of the liquid at that must be equals to the gas potential change so gas potential change is similarly one can write V m g that is vapor molar weight into d p, d p is change in partial pressure.

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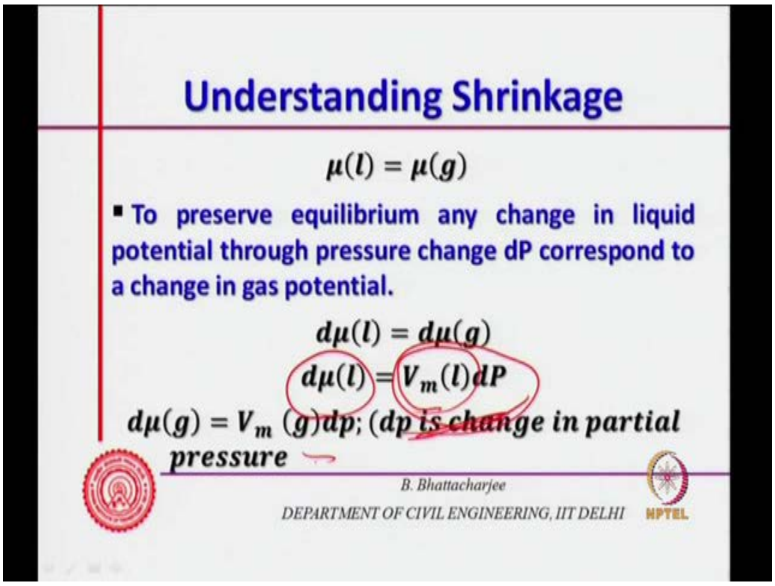

## Understanding Shrinkage

$$\mu(l) = \mu(g)$$

- To preserve equilibrium any change in liquid potential through pressure change dP correspond to a change in gas potential.

$$d\mu(l) = d\mu(g)$$

$$d\mu(l) = V_m(l)dP$$

$d\mu(g) = V_m\,(g)dp$; (*dp is change in partial pressure*

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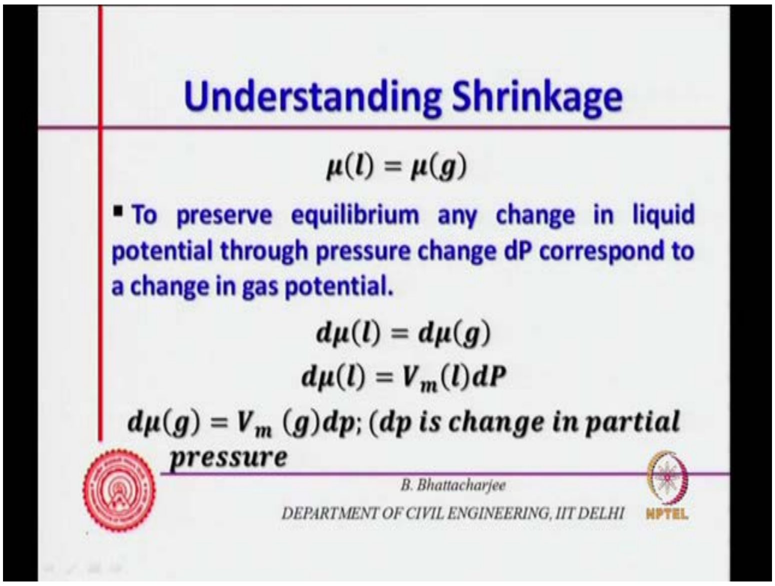

## Understanding Shrinkage

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- To preserve equilibrium any change in liquid potential through pressure change dP correspond to a change in gas potential.

$$d\mu(l) = d\mu(g)$$

$$d\mu(l) = V_m(l)dP$$

$d\mu(g) = V_m\,(g)dp$; (*dp is change in partial pressure*

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So, here when you are talking about the gas with gas it is a partial pressure, partial vapor pressure, so it is of vapor. So, we are talking of partial vapor pressure. I am assuming that you understand what is partial vapor pressure? It is a vapor pressure exerted or the gas you know pressure exerted by a gas when it occupies the full volume as the mixture so partial vapor pressure would change. Now, vapor can be thought of an ideal gas therefore, the V m can be written as R T by p for one mole actually, so R T by p d p, so d mu g can be written as R T by p R T by p d p and that is must be equal to V m l, p capital

P stands for the pressure that you applied to the liquid, this is the Partial you know vapor pressure, vapor pressure of the vapor.

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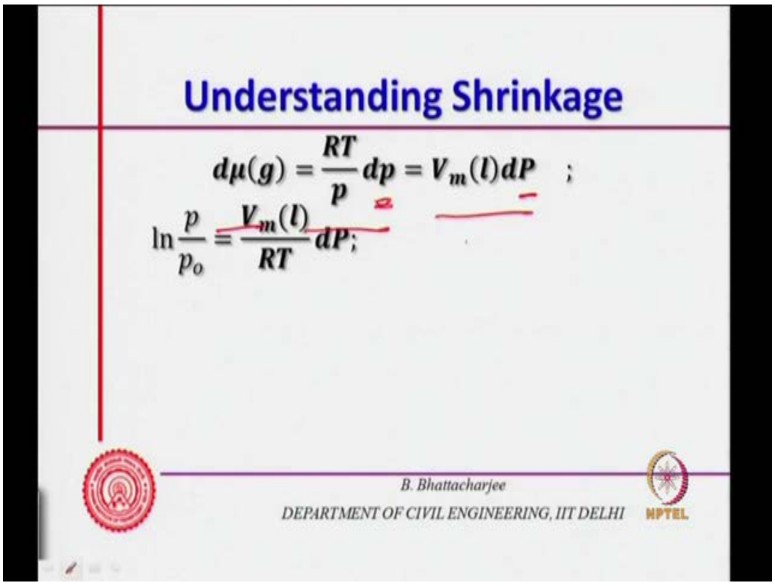

## Understanding Shrinkage

$$d\mu(g) = \frac{RT}{p}dp = V_m(l)dP \quad ;$$

$$\ln\frac{p}{p_o} = \frac{V_m(l)}{RT}dP;$$

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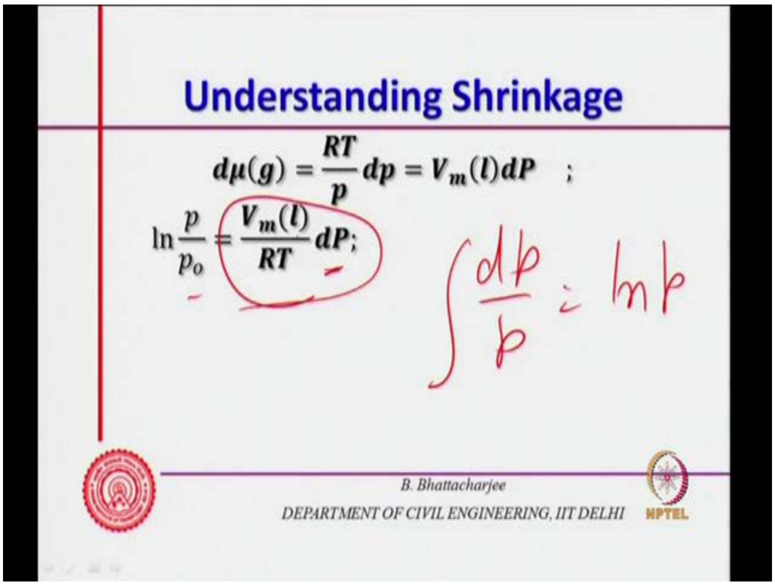

## Understanding Shrinkage

$$d\mu(g) = \frac{RT}{p}dp = V_m(l)dP \quad ;$$

$$\ln\frac{p}{p_o} = \frac{V_m(l)}{RT}dP;$$

$$\int \frac{dp}{p} = \ln p$$

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So, therefore, if you integrate this if you integrate this both sides. So, you will get l n p by p 0 must be equals to, you know if you integrate both sides you will get if you integrate this p d p by p, if you integrate you will get l n p putting the limits p 0 to p. So, vapor pressure change from p 0 to p and that must be equals to V m l by application of a pressure d p so therefore, l m p is 0 is equals to p by 0 equals to V m l by R T d p.

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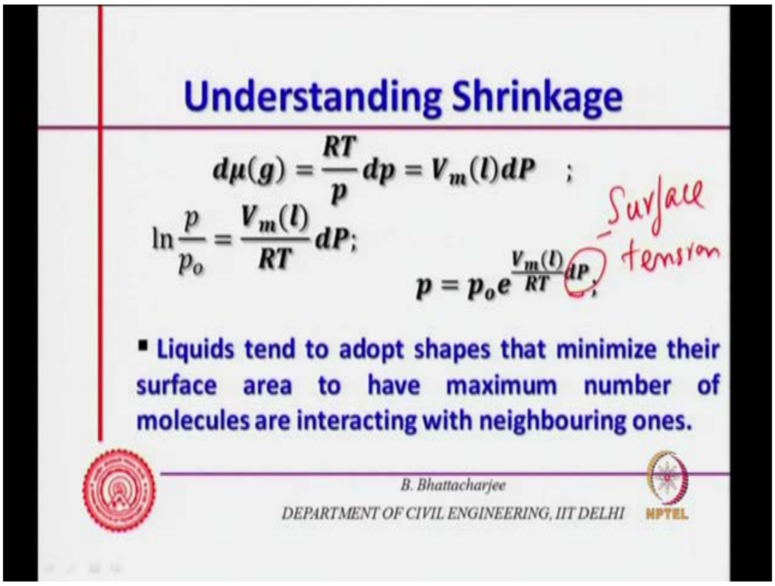

## Understanding Shrinkage

$$d\mu(g) = \frac{RT}{p}dp = V_m(l)dP \quad ;$$

$$\ln\frac{p}{p_0} = \frac{V_m(l)}{RT}dP;$$

$$p = p_0 e^{\frac{V_m(l)}{RT}\boxed{dP}};$$

Surface tension

- **Liquids tend to adopt shapes that minimize their surface area to have maximum number of molecules are interacting with neighbouring ones.**

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Now, this vapor pressure change can occur, because of applied pressure or because of things like because of phenomenon like surface tension. So, algebraically we can write it like this p by p 0 will be equals to e to the power V m l by R T d p. Now, liquid so it is if we are looking at the situations this vapor pressure; this d p can change, because of surface tension. So, just look at the fundamentals of the surface tension, you know liquid tends to adopt shapes to minimize their surface area to have maximum number of molecules interacting with the neighboring ones Liquid always try to adopt shapes that minimize their surface area that is what you have seen it takes the shape of the container and so on so forth. You know it tries to minimize their surface area and to have maximum number of molecules interacting with the neighboring ones that is the property of the liquid.

And this is what leads to surface tension. So, the work done work d w that is required work d w that is required to change the surface area by let us say d A small surface area d A is equals to gamma d A. So, d w is equals to gamma d A, this gamma is the surface e tension. So, you know this surface tension is basically the word per unit area or energy per unit area, energy per unit area, energy per unit area. You know this is of work required to change the surface area, because it has a tendency to attain a minimum surface area. So, if you want to increase it you will have to do work, at that work is proportional to the constant of proportionality is gamma. So, energy required per unit area that is actually surface tension that is actually surface tension, so that is the surface tension.

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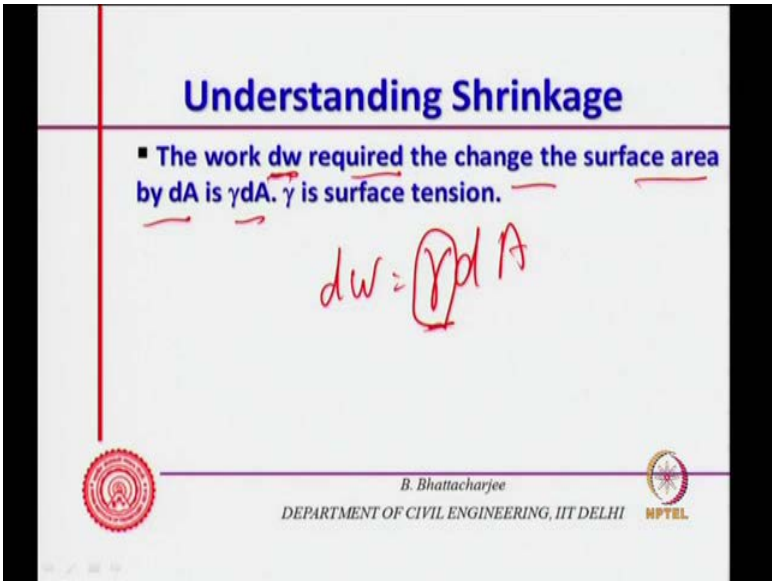

## Understanding Shrinkage

- The work dw required the change the surface area by dA is γdA. γ is surface tension.

$$dw = \boxed{\gamma} dA$$

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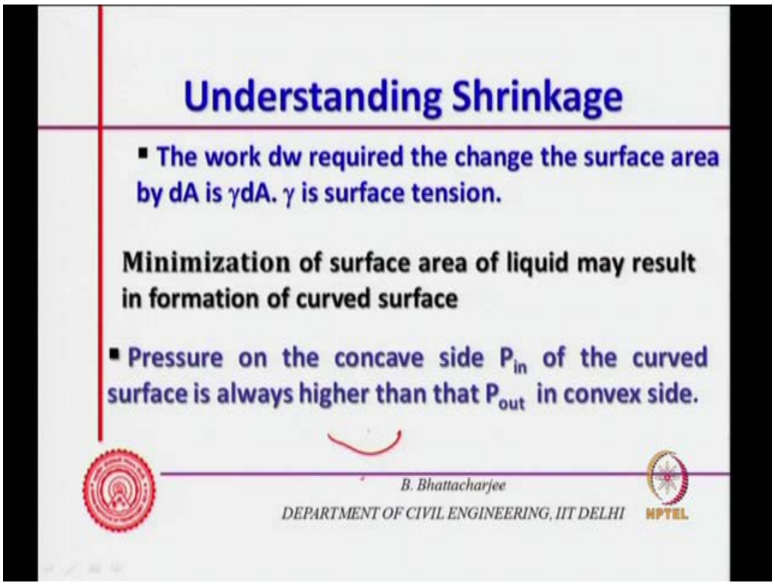

## Understanding Shrinkage

- The work dw required the change the surface area by dA is γdA. γ is surface tension.

**Minimization of surface area of liquid may result in formation of curved surface**

- Pressure on the concave side $P_{in}$ of the curved surface is always higher than that $P_{out}$ in convex side.

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So, minimization of surface area of liquid may result in formation of curved surfaces actually. So, you know because of surface tension the, you know that the surface tension property of liquid.

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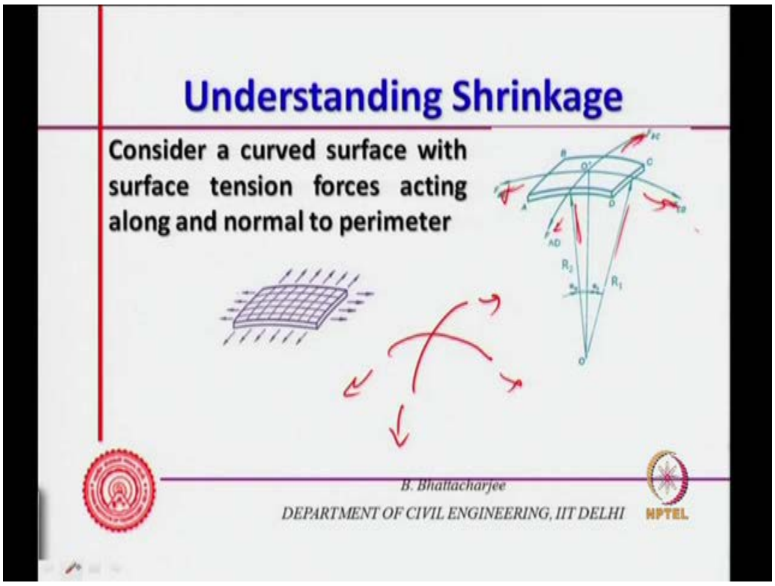

## Understanding Shrinkage

Consider a curved surface with surface tension forces acting along and normal to perimeter

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It may it results in formation of curved surface, because it tries to minimize the surface area. Therefore, when it is trying to minimize the surface area it is actually may result in formation of curved liquid surface so meniscus and so on. And usually the pressure on the concave side of the curve is always higher than that of the convex side, because you know concave side, this side the pressure would be higher than on this side always. It will be higher, because we will see that actually it will be higher, because molecules will try to pull each other in a given way and the pressure on this side is usually higher.

So, let us say consider a curved surface which surface tension forces acting along normal to the perimeter that is what it is surface tension because its sides to pull the surface, kind of a pull you know it, it pulls the surface tries to pull the surface, say something like this. So, this is the curved surface and the surface tension puts act on to your perimeter, because it is trying to you know minimize the surface area. And it acts on to the perimeter, either you know to cause stretch it as much as possible, stretch it as much as possible, stretch it as much as possible. So that the thickness is minimum thickness is minimum, so stretch it as much as possible the thickness is minimum, so that surface area is actually minimized. So, if I exaggerate this and draw it in this manner so basically this is of force is acting along this direction on an elemental surface. This will be the forces acting along this direction; this will be the force say f A D f C D f B C and f A B. So, this is the forces that would be acting. Now, if you look at this forces the resultant force will be acting inward resultant force will be acting inward.

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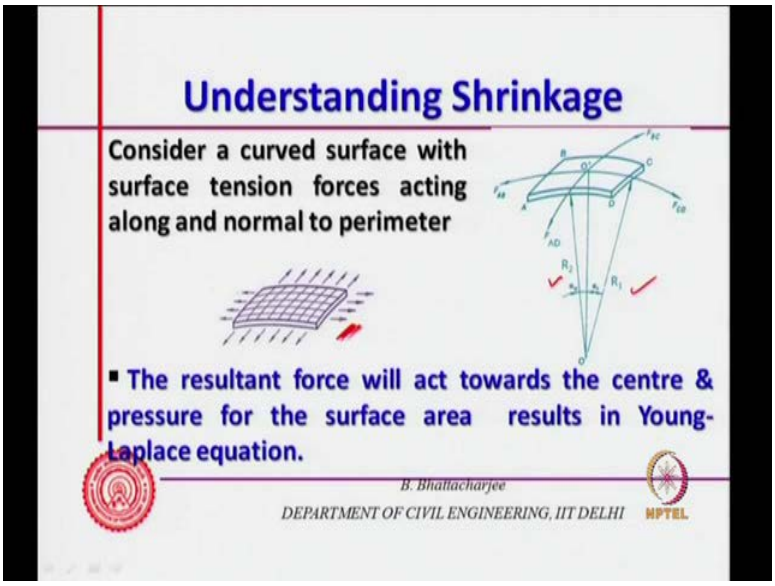

## Understanding Shrinkage

Consider a curved surface with surface tension forces acting along and normal to perimeter

- The resultant force will act towards the centre & pressure for the surface area results in Young-Laplace equation.

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This is the radius along this curvature radius along this curvature and the resultant force will be acting inward, because this is curved surface so the forces are like this and forces are like this. So, resultant forces will be acting inward and one can write possibly in this manner, one can write after looking at the equilibrium, one may write an equation. So, resultant force will act towards the center and pressure for the surface area results in what is called young Laplace equation. So, one can actually find out the resultant force acting inside and this will be a function of R 1 and R 2, it will be a function of R 1 and R 2, and gamma is the surface energy per unit area which means actually force per unit length. So, you need to of surface tension is Pascal per unit length force unit per unit length.

And multiplied by the length, multiplied by length in the perimeter and you know finding out the resultant force one can actually show for the unit area for the unit area one can show P inside is equals to P outside plus this. So, P is always higher inside that is within the comeback concave side is always higher then P outside. And this is gamma surface tension R 1 and R 2 is the radius of curvature in 2 directions that we considered. And if it is a sphere spherical surface then R 1 is equals to R 2 and I can write it as a R and young's Laplace equation turns out to be P in equals to P out y is gamma y R. So, you see the x, because of the surface tension in the inside there will be excess pressure of 2 gamma by R. And this excess pressure will result in change in the vapor pressure because we said if we changed in if you if you change the, if you; if you, you know apply a kind of pressure then there is a change in the vapor pressure as well.

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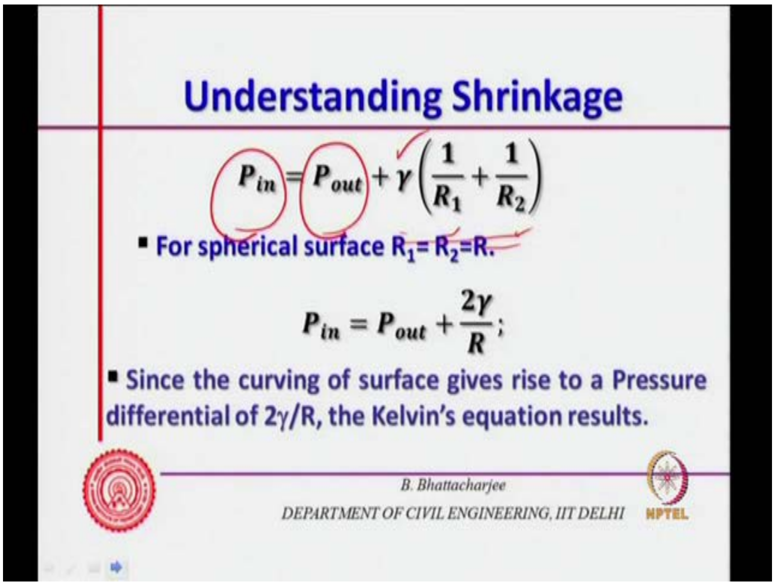

**Understanding Shrinkage**

$$P_{in} = P_{out} + \gamma\left(\frac{1}{R_1} + \frac{1}{R_2}\right)$$

- For spherical surface $R_1 = R_2 = R$.

$$P_{in} = P_{out} + \frac{2\gamma}{R};$$

- Since the curving of surface gives rise to a Pressure differential of 2γ/R, the Kelvin's equation results.

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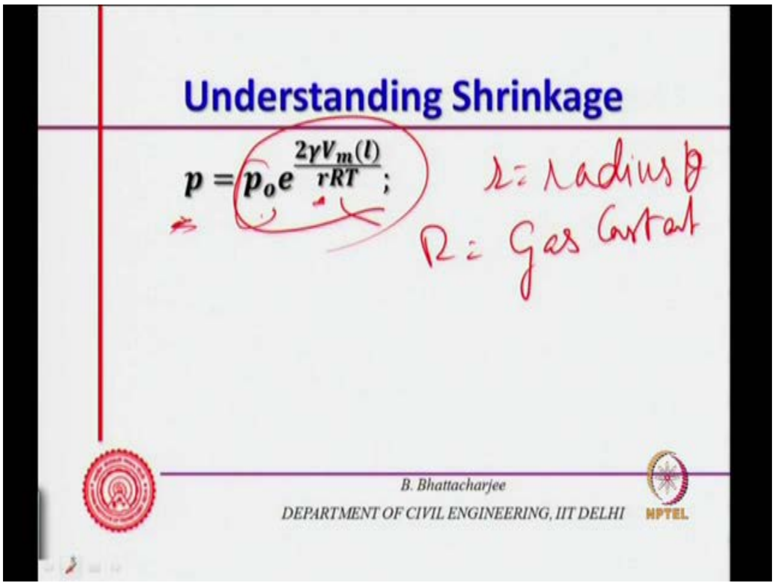

**Understanding Shrinkage**

$$p = p_o e^{\frac{2\gamma V_m(l)}{rRT}};$$

r = Radius of

R = Gas Constant

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And this gives rise to Kelvin’s equation. So, since the Kelvin surface gives rise to pressure differential of twice gamma plus R, it results in Kelvins equation which is talking of which actually you know is a model for equilibrium pressure at the interface of liquid and it is vapor liquid and vapor, so liquid and vapor. So, you see this is what is Kelvin’s equation were placed the pressure d p by twice gamma by small r I am writhing r is the radius, because capital R is a universal gas constant, gas constant, capital R is the gas constant you know gas not gas constant. So, it is the gas constant therefore, small r is a radius of the capillary so it is a vapor pressure.

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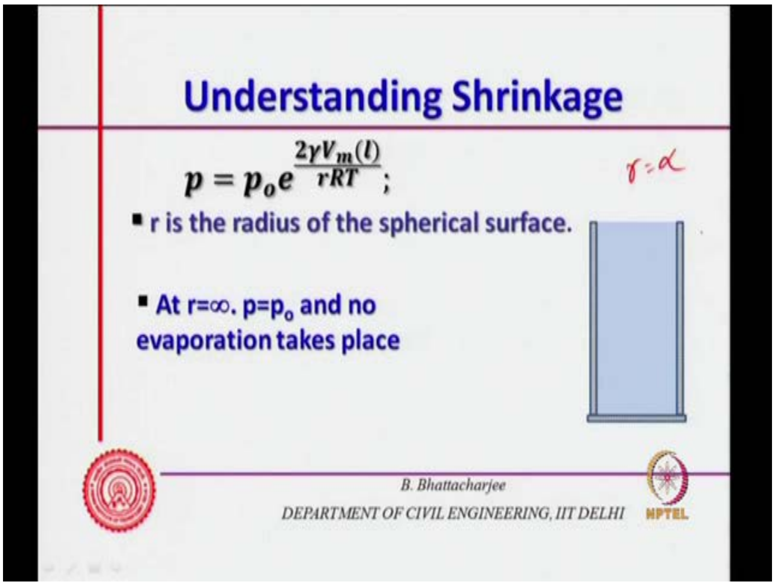

## Understanding Shrinkage

$$p = p_0 e^{\frac{2\gamma V_m(l)}{rRT}};$$

- r is the radius of the spherical surface.
- At $r=\infty$, $p=p_o$ and no evaporation takes place

$r=\alpha$

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Because of the surface tension change, change in the, you know cure radius of curvatures, because of the change in curvature p 0 was original before the formation of curvature. And now, because of formation of curvature, this will be the pressure, final pressure p 0 e to the power twice gamma by r V m l divided by R T. So that is Kelvin’s equation, that is Kelvin’s equation it can be written as some different from also, but that is Kelvin’s equation. So, r is the radius of spherical surface and at r equals to infinity when r is equals to infinity p equals to p 0 that means for a flat surface p is equals to p 0 and in under such situation no evaporation will take place I mean just let us say that this is p r is equals to infinity r is equals to infinity at this stage, right to start with.

And this no evaporation is taking place now as p changes small p changes r would decrease. Or rather r root r changes p would decrease up to the limit of the pore radius because beyond the pore radius this r cannot be smaller than this. So, therefore, r changes up to the pore radius and correspondingly p changes as well, so correspondingly p changes as well, because it cannot be of this kind maximum, you know maximum curvature would limit to r equals to the radius of the capillary tube itself. So, if you are looking in a capillary tube. So, this will be you know the radius would be simply, a simply would be equals to r. So, pores gradually becomes empty according to the size from larger to smaller pores.

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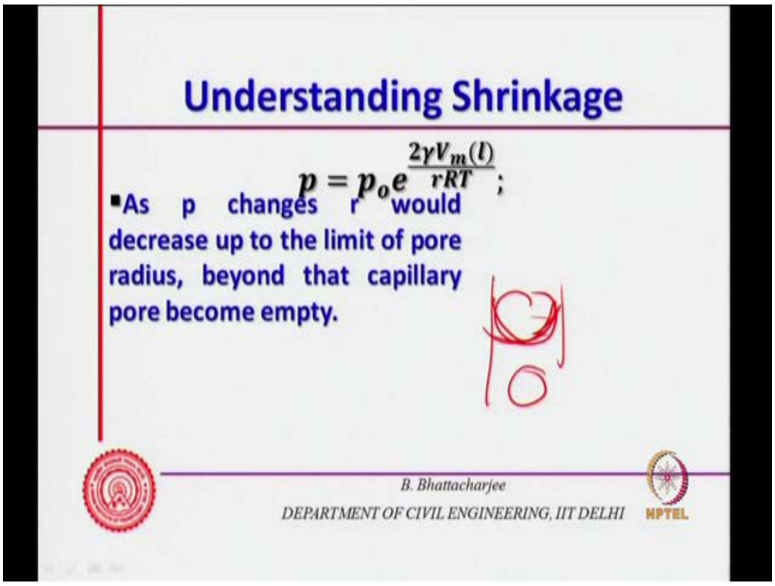

## Understanding Shrinkage

$$p = p_0 e^{\frac{2\gamma V_m(l)}{rRT}};$$

- As p changes r would decrease up to the limit of pore radius, beyond that capillary pore become empty.

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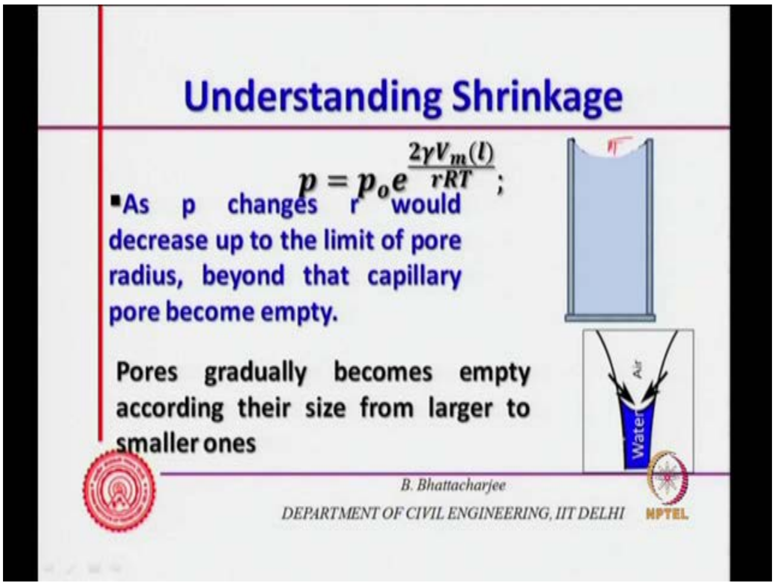

## Understanding Shrinkage

$$p = p_0 e^{\frac{2\gamma V_m(l)}{rRT}};$$

- As p changes r would decrease up to the limit of pore radius, beyond that capillary pore become empty.

Pores gradually becomes empty according their size from larger to smaller ones

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Now, once this reaches r further change in the vapor pressure you know would result in pore becoming empty. So, in the drying case of drying vapor pressure changes as the vapor pressure changes the pore you know curvature will change. And a time will come when curvature radius of the capillary of this curvature of the surface. And the radius of the tube is same beyond that the radius of the tube is same beyond that if still pressure changes then what will happen? The pore will become completely empty. So, this is the phenomenon of drying you know, so drying actually suppose gradually becomes empty according to the sizes. So, larger pores part get emptied and then comes to the smaller pores. So, typically this is the large neck, first this will get emptied and this is the inside you know at equilibrium of course, this will depend upon the vapor pressure existing and this size. So, capillary size and that is how actually drying takes place that is how drying takes place.

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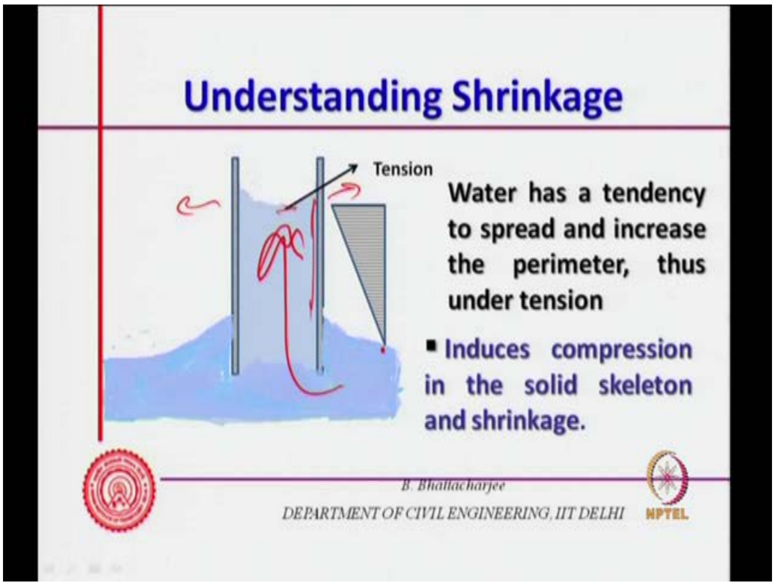

## Understanding Shrinkage

Water has a tendency to spread and increase the perimeter, thus under tension

- Induces compression in the solid skeleton and shrinkage.

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Now, how it is relevant to our shrinkage this is what it is when such drying is actually taking place you know this is the capillary; this is my capillary; this is my capillary. The equilibrium is existing at this point, now a tension would exists here, a tension would exist here. Water has a tendency to because water has a tendency to water has a tendency to spread, water has a tendency to spread, water has a tendency to spread, it will try to spread along this direction. So, if tries to spread the radius would like to increase it is you know perimeter will like to increase, in other words there is a tension acting in the water.

So, the tension acting in the water is something like this and this tension is maximum just to the bottom of the meniscus, and gradually reduces down up to the surface of the water outside. So, if you have a capillary water rises along this direction, water raises and the tension in the liquid is of this kind, because liquid would like to spread, liquid would like to spread here there is no tension, because it is already spreaded here liquid would like to spread so from here to the within the capillary in this one there is a tension. Now, this in other words will actually exert a kind of compression on to this glass tube. So, it induces compression in the solid skeleton, now if it is within concrete or paste, cement paste then it will exert on to the paste interface, paste capillary interface. So, the compression will be the paste matrix or paste skeleton we actually under a kind of compression, paste skeleton will be under a kind of compression under a kind of compression.

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## Understanding Shrinkage

- A molecule well below the surface is equally attracted by all surrounding molecule.

Molecule at the surface is acted upon by a resultant inward force and surface tension results.`

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So, this will be under compression; this will be under compression. So, therefore, a molecule you know if this, this compression now let us look at this if you look at the surface tension properties for the gel, same thing similar kind of like as liquid. So, a molecule will, well below the surface is equal related by surrounding molecule. For example, a molecule below the surface it is attracted by molecules in the surrounding attracted by molecules in the surrounding.

But the one up there, one you know one up there actually one somewhere there will be attracted only downward it will be attracted only downward, upward there is no force. So, therefore, if I bring in a liquid here if I bring in some liquid here liquid molecule here which gets adsorbed at the surface then the force downward force will get reduced, this downward force will get reduced, downward force will get reduced, so downward force will get reduced, downward force gets reduced, downward force gets reduced.

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### Understanding Shrinkage

- A molecule well below the surface is equally attracted by all surrounding molecule.

Molecule at the surface is acted upon by a resultant inward force and surface tension results.`

- For colloidal particle such as C-S-H gel this is significant and compressive force induced may be as high as 250MPa.

Adsorbed water reduces this inward compression & surface tension & swelling results.

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So, molecular the surface is acted up on by a resultant inward force and surface tension results and when I for colloidal particles such as C H S gel this; this significant you know for C H S system also there is significant and compressive force induced could be as high as 250 M p a. So, if it is a dry there is a compressive force acting downward into the skeleton and this could be as high as 250 M p a. Now I bring in adsorbed water reduces this inward compression and surface tension and swelling results.

So, what will happen? It reduces down the inward compression, in other words surface tension of the C H S system as reduced. So, swelling will result, you know there are no molecule if there are no molecule at adsorbed water then the molecule of the C H S or particle C H S system will pull the surface once inner inside and it, it would induce a kind of compressive force. Now, if there is an adsorbed water this compressive force will get reduced, in other words surface tension would reduce and swelling will result, swelling will result so absorption of molecule results in swelling.

Absorption of molecule results in swelling, absorption of molecule results in swelling and swelling strain is proportional to the surface tension the itself and its like this. So, the strain that results in let us say, because of water being adsorbed would be proportional to surface tension force and from constant of proportionality is K which can be reduced related to modulus of elasticity, modulus of elasticity of the gel which can be related to modulus of elasticity of the gel. So, you see the change in surface tension, because of a adsorbed water results in swelling strains and this is this, this is energy per unit area can be related to strain therefore, this must be related to the stiffness of the modulus of elasticity of the system.

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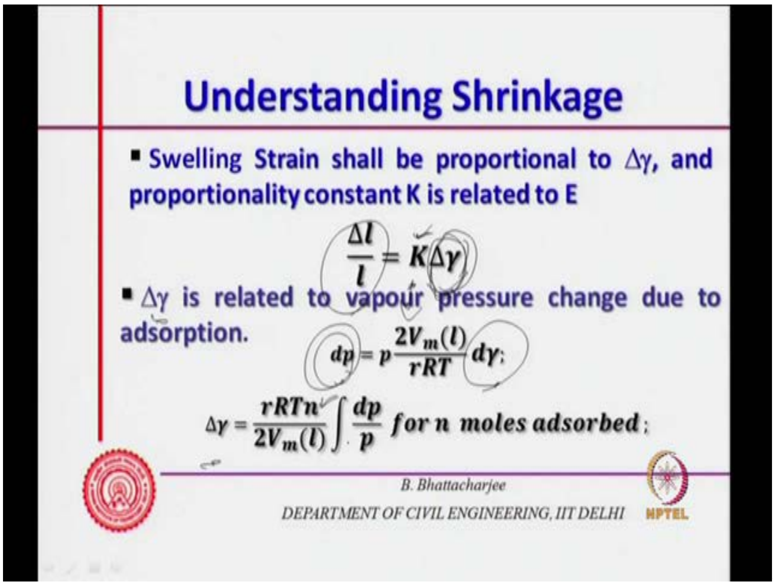

## Understanding Shrinkage

- Swelling Strain shall be proportional to $\Delta\gamma$, and proportionality constant K is related to E

$$\frac{\Delta l}{l} = K\Delta\gamma$$

- $\Delta\gamma$ is related to vapour pressure change due to adsorption.

$$dp = p\frac{2V_m(l)}{rRT}d\gamma;$$

$$\Delta\gamma = \frac{rRTn}{2V_m(l)}\int\frac{dp}{p}\ for\ n\ moles\ adsorbed;$$

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So, this one is again related to vapor pressure if we remember this one is related to vapor pressure. So, if this is a vapor pressure change this surface tension would change you know vice versa if there is a change surface curved surface results in change in vapor pressure. And if there is a change in delta y change, because of water being adsorbed it will also change the in the vapor pressure.

So, when, when, when, when I some water reaction absorb, absorb there is a change in vapor pressure and change in vapor pressure there is a change in vapor pressure and this change in the surface tension results in swelling. Now, if I withdraw if I withdraw the water reverse will actually occur so delta y one can write it like this, this is for the moles you know n moles adsorbed if n mole s are adsorbed one can find out how much is that delta y from the change in vapor pressure or rate of change of vapor pressure and so on so forth.

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## Understanding Shrinkage

- Swelling takes place when moisture is adsorbed
- Shrinkage takes place when drying occurs.

Adsorbed water reduces surface tension i.e., surface energy, hence critical stress initiating fracture from pores would be lower, hence moist specimen exhibits lower compressive strength due to dilation

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So, therefore, swelling takes place when moisture is adsorbed, swelling takes place when moisture is adsorbed. And shrinkage takes place when drying occurs when drying occurs drying occurs you know it will come to drying occurs it will, r will become smaller. As the moisture is withdrawn r will become smaller, r will become smaller and my vapor pressure change would be you know it would vapor pressure change would actually occur, vapor pressure changes occur and r would become smaller. And at this smaller r the compressive forces onto the skeleton that would generate would actually compress the system. It will compress the system surface tension will change and it will actually compress the system more, compress the system more.

So, there is a compression, because of the capillary itself there is also compression, because of the you know adsorbed, adsorbed water being withdrawn, adsorbed water being withdrawn. So, this results in drying shrinkage, this results in drying shrinkage. So, adsorbed water reduces surface tension, surface energy, hence you know, hence, hence critical stress initiating fracture from the pores will also be lower. So, since the surface energy becomes low if you recollect when we are talking of strength you know strength is fun critical strength is a function of e t under root e t divided by pie into half of the crack with or pie r. Now, surface energy is reducing when actually moisture it becoming moist. And therefore, critical stress reduces therefore, more specimen exhibit lot of compressive strength due to this dilation effect. So, this is going back to our situation 2 things; first of all if you if water comes in and it is adsorbed to the surface, surface tension reduces and the compressive force which was pushing, you know the gels, matrix together now it it there will be a dilation so it expands. But at the same time surface energy reduce therefore, moist specimen shows lower strength.

Now when you I withdraw the water what will happen? This surface tension in the gel will actually increase and there compression in the system you know it will compress the gel particles inside therefore, its fragment change would occur so during drying. Besides that in the capillaries there is a tension in the liquid itself which tries to in, in which in turn tries to kind of compress the skeleton. So, capillary when there is capillary water depending upon the capillary size it would actually there will be a compression. So, this compression you know this ten this compression results you know d p changes in the liquid which in turn would actually cause a kind of compression into the skeleton, both you know could be could provide explanation to drying shrinkage.

So, first of all when drying occurs a resolved water is moved out there is a you know the pool by the gel particles at the surface by the inside particles becomes more is a kind of compression. so there is a shrinkage. And also there is a tension at the, you know at the in the liquid itself which wants to spread and it pushes the particle out. So, when there is a drying, this phenomena actually pushes this phenomena it comes to the final and final pore. And this pressure is actually twice gamma by r, so r becomes smaller this pressure would increase and it would actually exert more compressive force on to the skeleton.

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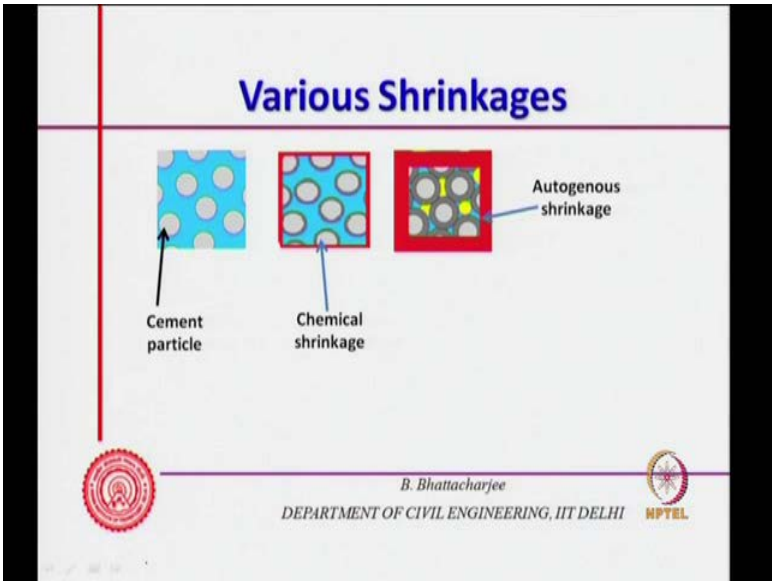

Various Shrinkages

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Therefore, these are the phenomena's through which we can one can explain the drying shrinkage of cement paste or concrete. And also by using same phenomena we are able to explain why moist specimen shows lower compressive strength? If you recollect we said that when specimen is moist it, it exhibits lower compressive stress strength that is because you know the stress it can withstand is less, that is because the kind of a you know dilation would occur surface tension reduces gel particle expands gel I mean system expands and it can it can actually the surface energy is re reduced. Therefore, it requires lesser force or lesser stress to actually cause fracture. So, both two phenomena's this same phenomena understanding gives us the, you know why moist specimen is shows lower strength, but it also gives us some understanding of shrinkage drying shrinkage process, so what is it?

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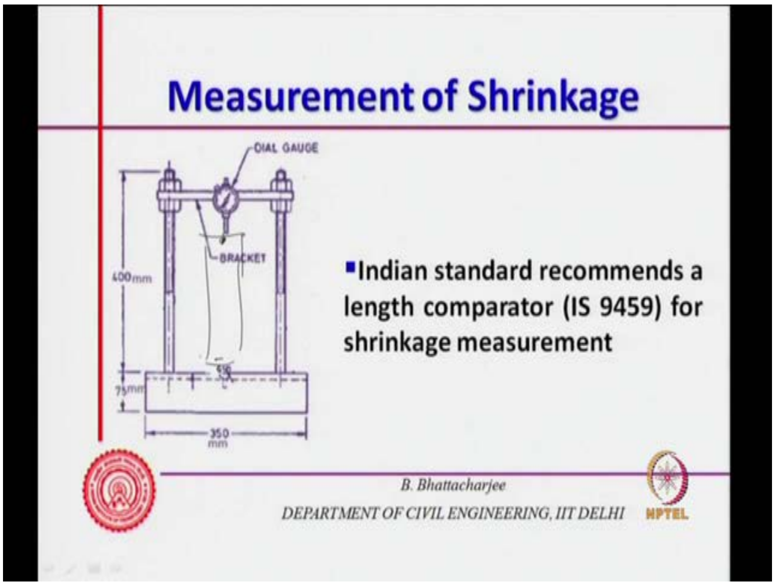

## Measurement of Shrinkage

- Indian standard recommends a length comparator (IS 9459) for shrinkage measurement

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First is a chemical shrinkage is a small quantity in the beginning and nitrogenous shrinkage is larger quantity drying shrinkage would follow. So, this is various shrinkage we looked and then measurement must then carter for all these types of shrinkages which we discuss earlier in our pervious lecture, while Indian standard recommends a length comparator some something of this kind for shrinkage measurement. So, you have basically you know this there is a dial gauge you put your specimen here and there is a standard you put your specimen here and any length change you can measure. Basically there is a standard reference which is which, which first is used to find out what is the dimension. And you have actually a d mac point here on the specimen d mac point here on the specimen. So, there is a tip which comes and matches in this dial gauge can tell you is the dimensional changes. So, this, this can be used for measuring length change.

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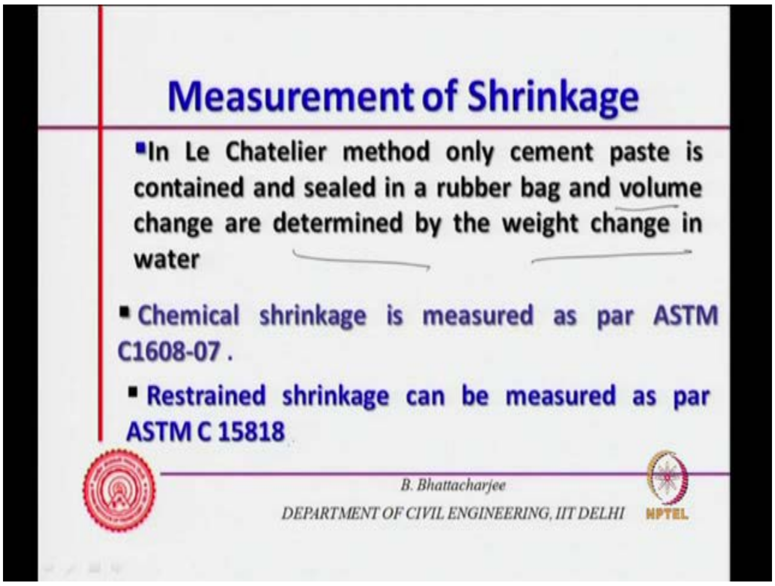

## Measurement of Shrinkage

- In Le Chatelier method only cement paste is contained and sealed in a rubber bag and volume change are determined by the weight change in water
- Chemical shrinkage is measured as par ASTM C1608-07 .
- Restrained shrinkage can be measured as par ASTM C 15818

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And if it is sealed specimen then that would give you a kind of chemical and autogenous shrinkage may be together, while if you look at Le Chateliers method which is also measuring dimensional change in cement paste. And it is in contend in sealed rubber bag contend and sealed in a rubber bag and volume changes are determined by the weight change in water. So, whole sealed bag you can put it in water and then you change in volume together the rubber bag, because rubber will expand or contract according to you know it is because it can expand or contract.

So, as far as according to the expansion or contraction of the specimen, so as the specimen contracts rubber bag will also contract and its volume change you can find out that is Le Chateliers principle. However, chemical shrinkage can be measured by ASTM C1608 method. And restrained shrinkage cab be measured as far as par ASTM C1581 you know this, this method so one 15818 method.

Now, chemical shrinkage method, how do you measure? While you measure it like this; you measure it like this; you have actually cement paste here. And then you fill it with water and then there is a capillary which is graduated and you put in excess water just after mixing you know after mixing, all this is happening after mixing. So, you fill this with water and this is all water and there is a paraffin oil added at the top to minimize any evaporations. So, there will be no evaporation loss and as the shrinkage of this one occurs this capillary will come down, and from the cap graduated capillary you can actually measure the amount of chemical shrinkage, so chemical shrinkage is because of the volume change of this one.

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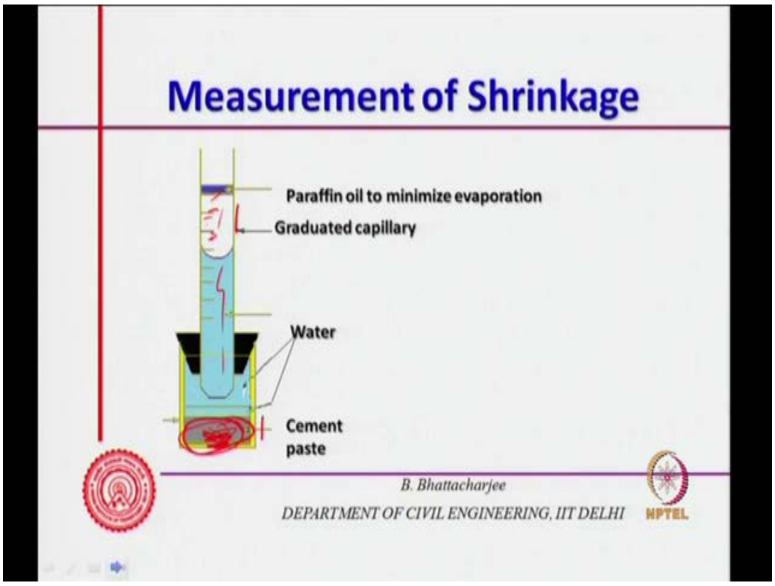

Measurement of Shrinkage

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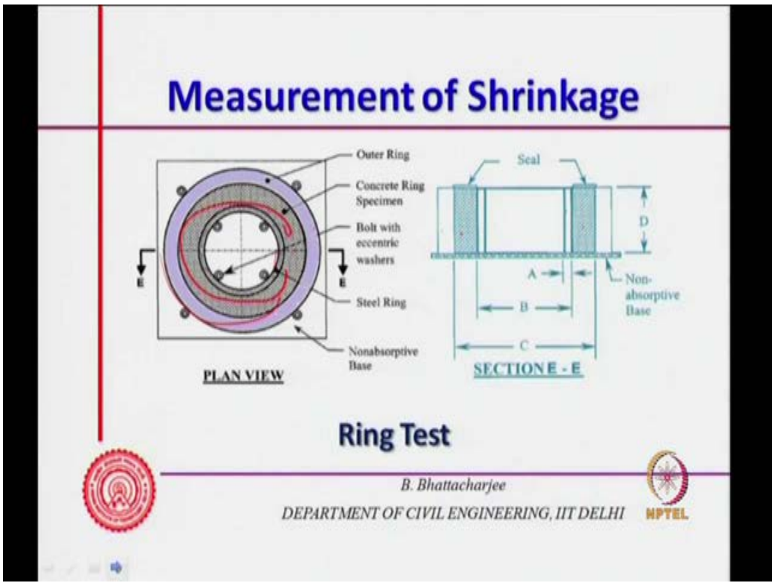

Measurement of Shrinkage

Ring Test

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So, volume change of this one so as the volume of this one shrinks this can volume change full water is there, there is no evaporation loss nothing no drying, nothing is occurring. So, volume changes as we discuss the stroy symmetrically you can find out how much volume change or the product would occur. So, you can measure this chemical change; this is done in the r d stage. Now, the other one is through or shrinkage measurement is through ring test you know this is called ring test where you have this is your outer ring and this is the specimen has it one and this is the inner ring; this is inner, inner ring actually and then you can use strain gauges to measure. So, this is the ring test it looks like this, outer ring concrete inner ring and various kind of arrangement is of course, there is a base here. And this is your concrete; this is the inner ring and this is the outer ring, some dimension d etcetera, etcetera this is given in the code itself.

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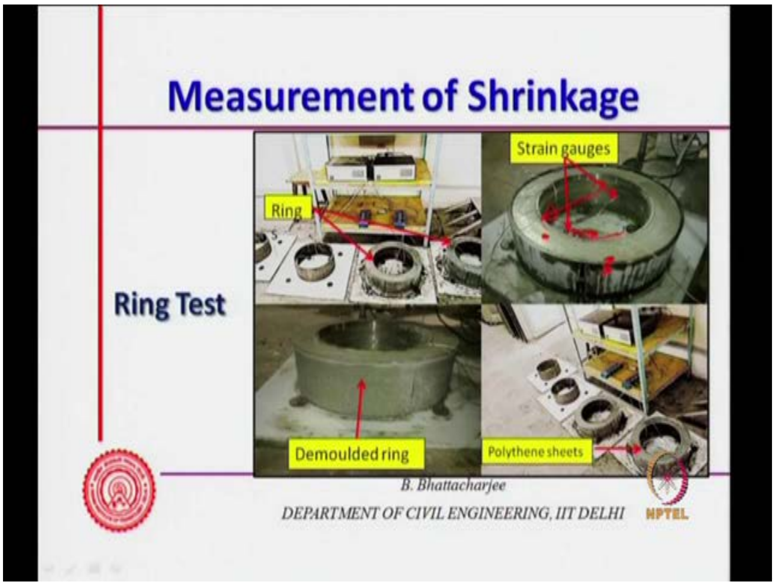

Measurement of Shrinkage

Ring Test

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This is called ring test and in this one typically it looks like this you see you can see the concrete here and outer ring outer ring the inner ring inner ring some where there. And inner ring you put in strain gauges, inner ring you can put in strain gauges. This diagram is showing actually demoulded specimen, you know polythene then they are covered with polythene sheets they are covered with polythene sheet to the inner ring still intact they are covered with polythene sheet, sheet and this is also showing actually the ring situation and this is the demoulded ring so covered with polythene. Now, you have strain gauges and you can go on recording the strain, because as the shrinkage occurs this dimension will try to reduce, because this you know this inter inner periphery will try to reduce. And therefore, in a in, in, in turn it will exert a kind of pressure inside, this you know the perimeter of this one will try to reduce.

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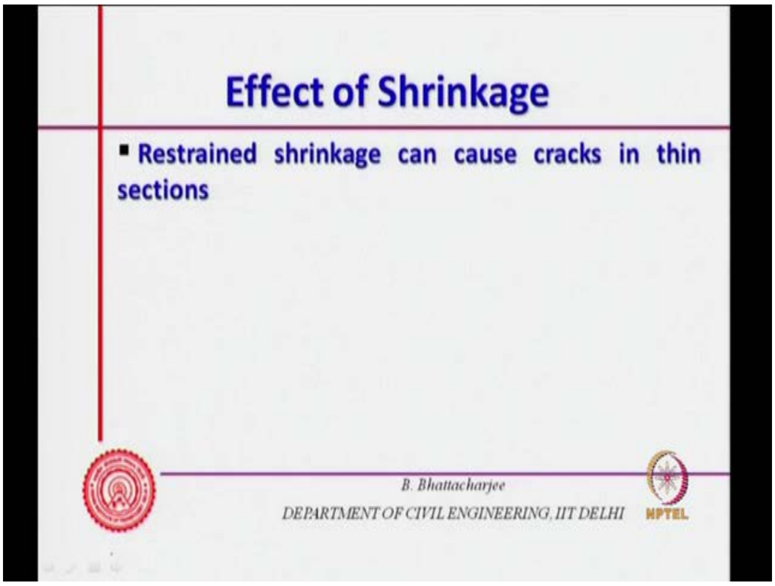

## Effect of Shrinkage

- Restrained shrinkage can cause cracks in thin sections

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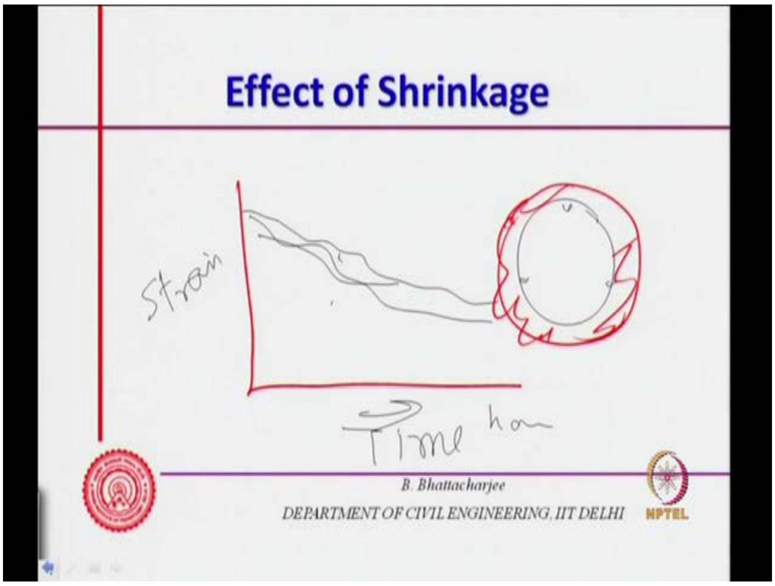

## Effect of Shrinkage

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There is, and inward it is just opposite of a kind of hoop action inward, you know trying to reduce the, since it  Is shrinking perimeter length is trying to reduce. So, radius will try to reduce and there will be strains and this strain you can go on measuring with time and that will give you all kind of shrinkages. For example, autogenous shrinkage and in the long run if it is a shrinkage drying shrinkage after cracking if you have auto, autogenous shrinkage means you actually covered it with polythene no moisture loss would be there. But if you allow it to dry in a given environment then you can find out what is the time required for cracking. So, this is an STM’s test and that is how you measure

So, restrained shrinkage of course, now typically before that I can just draw a figure draw a figure a can draw a figure you know essentially figure would be something like this, before this effect of shrinkage. So, you have actually shrink strain shrinkage strain with time you plot for ring test and this is with time it will vary for different conditions and you can find out. So, it is time, you know hours in terms of hours so days as much as you want to measure and this strain can be related to shrinkage. So, this strain is a kind of can be related to shrinkage.

So, in your ring test the inner ring shows you inner ring shows you, you know this is your concrete; this is your concrete, the strain gauges have been put in there strain gauges have been put in there. So, this strain gauges for this strain gauges you can measure the strain and that will tell you how much is the shrinkage actually occurring from this you can calculate out the strain that would be occurring so that is called the ring test. Now, what is the effect of shrinkage? So, that is how we do the test, so chemical shrinkage is measured by change in volume through a graduated capillary and autogenous shrinkage as well as drying shrinkage up to.

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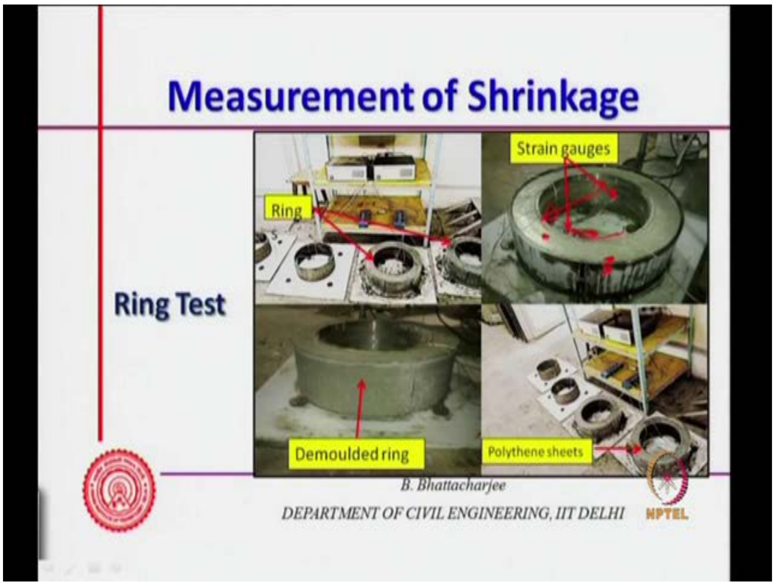
Measurement of Shrinkage

Ring Test

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### Effect of Shrinkage

- Restrained shrinkage can cause cracks in thin sections
- Tall building differential shrinkage in inner & outer column may results in additional moments

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Cracking can be measured by ring test that is what I just mentioned you can go on recording this. So, this is what is the, you know ring test from which you can measure. Now, what is the effect of shrinkage? Effect of shrinkage is restrained shrinkage causes can cause cracks in thin section.

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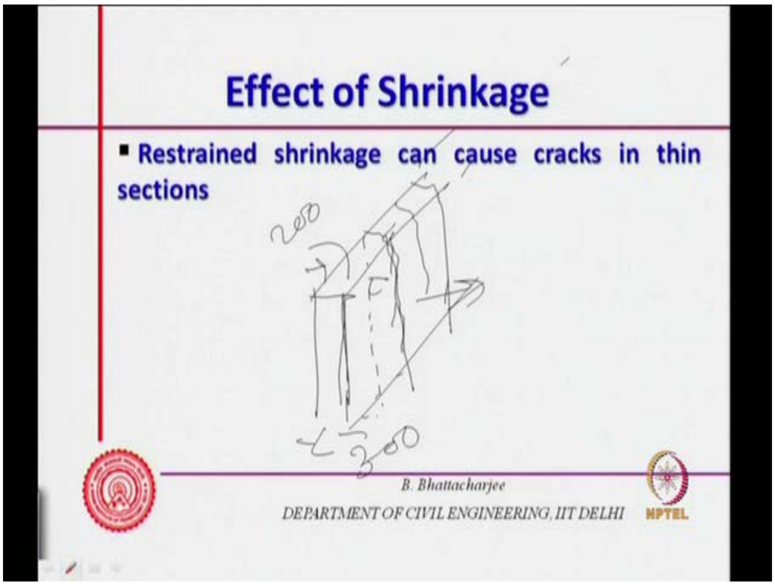

### Effect of Shrinkage

- Restrained shrinkage can cause cracks in thin sections

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For example, if you have a wall if you have a wall you know a wall like this thin wall thin wall and is restrained construction joints are not given have not been given let us say. You might find cracks like this, you might find cracks like this at regular spacing especially if the curing is improper, this is not very un common in thin section something like 200 m m thick to let us say 200 to 300 at the bottom, because if you remember we said it depends up on volume to surface area ratio. So, if the curing is not adequate and drying is occurring in a thin section and there is no construction joint is a long one. Let us say basement wall 30 40 meters without proper construction joint. This can result in this can result in cracks coming in all through, thin section this comes pre cast elements thin very thin per cast element.

If it is shrinkage is restrained cracks can come and it could be through and through it could be simply through and through up to certain depth with a large the larger crack here and final at the bottom or may, may not go up to full depth something of this kind. So, this is this, this is a phenomena seen in northern India specially when you cast the concrete around May, June when relative humidity is very low ten to about forty percent and the curing if it is not done properly this can results in cracking. And this cracks you see normally within 2 to 3 months of the construction rank shrinkage crack hats fairly common.

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## Effect of Shrinkage

- Restrained shrinkage can cause cracks in thin sections
- Tall building differential shrinkage in inner & outer column may results in additional moments

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High strength concrete are susceptible to autogenous shrinkage high strength concretes are susceptible to autogenous shrinkage, because you have lot of cement past in the system. And therefore, there may be you know susceptible to shrinkage. So, one has to see that one has to you k therefore, this is studied for low water cement ratio system autogenous shrinkage studies are important. Tall building you know very tall building this is your outer column, let us say outer columns and where you have somewhere here you have got inner columns. Now drying here drying is different than drying here you know drying in this one drying there will be different. So, this could be shrinking more if it is drying more or depending upon the situation. So, if one shrinks if there is a differential shrinkage differential shrinkage or strain due to the shrinkage in a very tall building like creep differential creep because in case of creep.

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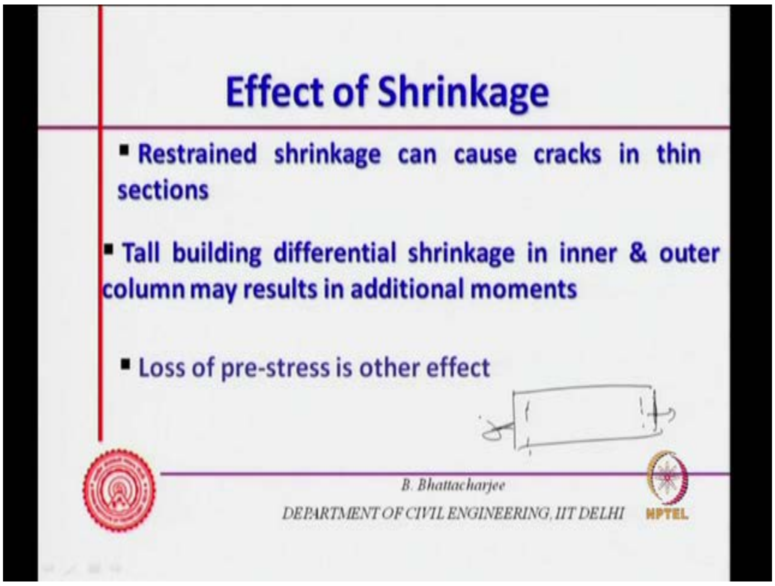

## Effect of Shrinkage

- Restrained shrinkage can cause cracks in thin sections
- Tall building differential shrinkage in inner & outer column may results in additional moments
- Loss of pre-stress is other effect

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Loads were coming differently internal columns were highly loaded were external columns were less loaded. So, in tall buildings loading, because of loading the creep effect comes in, but external columns may be drying differently than the internal column depending upon of the of course, the climatic situation. And if there is a differential stream coming in, in very tall building 30 to 30 fourth 40 story building then you might find there are secondary, you know because of this there are secondary moments that is coming in. Because of differential shrinkage this may result in additional moment like we discussed related to creep. Lot, loss of pre stress is of course, the other effect loss of per stress is of course, the other effect, because shrinkage means shrinkage it the natural dimension of the concrete would become smaller. So, there will be some amount of you know it will if, if it is restrained then there will be this would cause.

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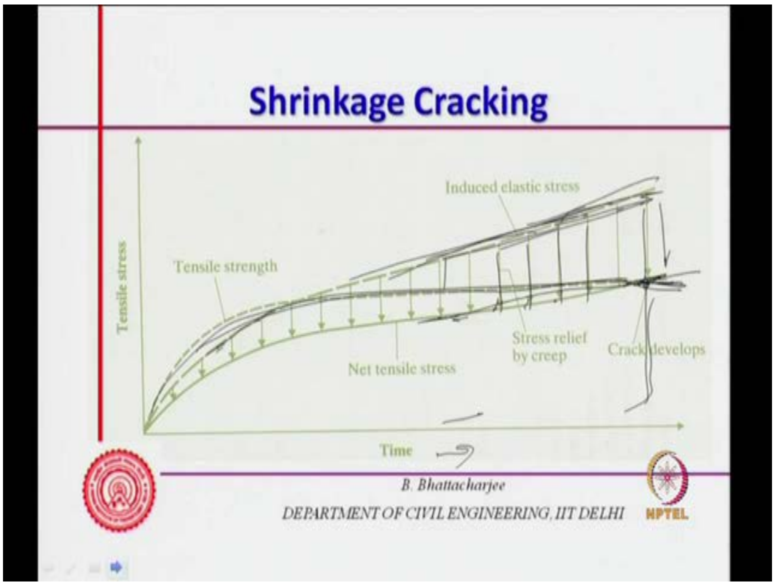

Shrinkage Cracking

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Loss of some per stress, because you know it is it, it would have it would have tried to come to this dimension, because of shrinkage, but you have restrained it in other words you are actually applying a kind of tension. So, this pre stress can loss can be there, because of shrinkage of the concrete itself shrinkage of the concrete itself, because the shrinkage of the concrete itself so this is another effect. But most important of course, is the cracking, shrinkage cracking you know if it is restrained if it is restrained then tensile stress may be increasing like this, this might be the induced tensile stress, because of the restrain. And this will change with time, because shrinkage will increase with time therefore, stress will increase with time shrinkage will increase with time therefore, stress will increase with time and this is the tensile strength. So, in the beginning shrinkage is less than the tensile strength shrinkage could be less than the tensile strength.

But if the shrinkage crosses the tensile strength cracking would come, fortunately there is some amount of relaxation because of creep because you have a tensile stress which is sustained with time. So, there will be some relaxation due to the creep effect, because there is a sustained tensile, because this is restrained structure restrained structure shows shrinkage cracking the, I was talking about the thin structures earlier very thin sections you know in the similar sections actually. This is long, long there is no construction joint in the basement wall thin basement wall evaporation rate is higher v by s you know volume to surface area ratio v is small sis large.

So, v by s is small thickness is less therefore, v by s is less you know and there the evaporation rate is high curing is not been done properly one might have used even an accelerator to accelerate the strength gain similar kind of thing. So, basically, basically where curing is not proper this scenario is seen much a particularly in the hot dry deserts sort if climate where relative humidity is very little or in a composite monsoon climate during the hot dry desert season. So, shrinkage will increase with time tensile strength also increases with time, but since it is sustained and restrained therefore, there will be some relaxation. Sustains stresses would be generated, because the restrained shrinkage, but this also get relaxed due to the creep, creep relaxes you said that if you sustain loading if it is de strain then there is a relaxation. So, this is the relaxation; this is the relaxation due to creep; this is the relaxation due to creep; this is the relaxation due to creep. Now, tensile strength increases in this manner, the moment tensile strength is less, then this, because Shrinkage increases with time.

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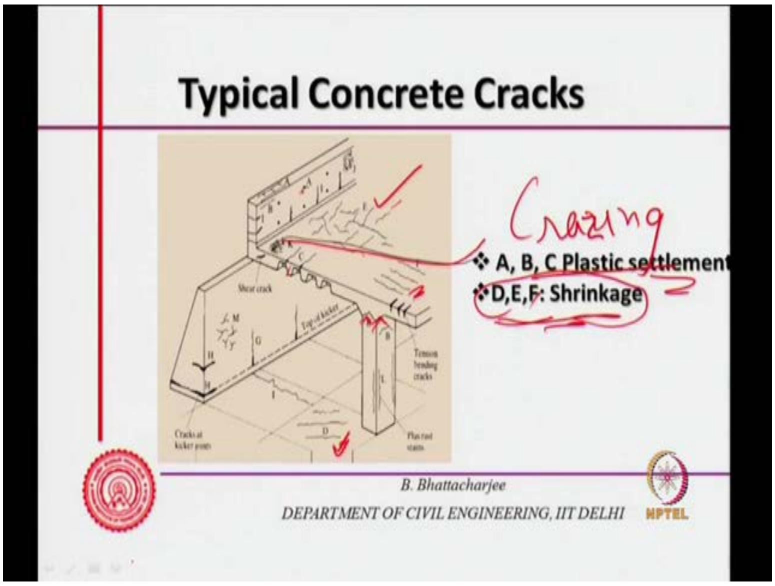

**Typical Concrete Cracks**

Crazing

- A, B, C Plastic settlement
- D,E,F: Shrinkage

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Relaxation is also increasing in time, but time comes when actually this you know net tensile stress over takes the tensile strength, the cracks actually develops that time. So, this can take some time, but normally all this cracks comes in within about month or 2 of the construction this is drying shrinkage cracks particular not even in normal strength concrete this may be quite a bit of this could be there. Other kind of cracks comes out of shrinkage could be seen in this diagram typical concrete cracks. For example, this is K is fine crazing; this is crazing; this is called crazing you know this is called crazing, crazing you can see very fine cracks, surface cracks, crazing, crazing, crazing, crazing fine crazing these are the surface cracks this also comes because of shrinkage.

But D E F so this E this D where is D D E F. So, this is E and D is here D E and F is here these are shrinkage cracks. So, shrinkage cracks might appear like this, this will be largely surface, this might look at the surface they might look like this. But if the section is thin you might get them through and through also. So, these are the shrinkage cracks actually A B C are plastic settlement cracks but I think I will not discuss them, because I am not really discussing the cracks here that is because of initial settlement you know as I said when bleeding occurs bleeding occurs as the solid subsides and water as a tendency to come. If the reinforcement is actually restricting the subsidence there will be a crack on top of it so these are plastic settlement crack A B C.

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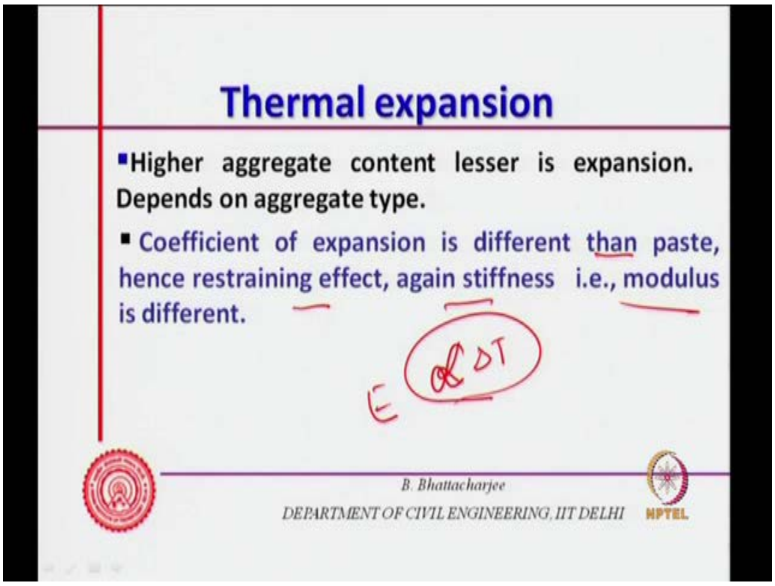

## Thermal expansion

- Higher aggregate content lesser is expansion. Depends on aggregate type.
- Coefficient of expansion is different than paste, hence restraining effect, again stiffness i.e., modulus is different.

$E \; \alpha \Delta T$

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You know a horn chares where dimension changes occuring you might see this kind of any way that is not for interest much. But shrinkage cracks and crazing these are of our important, you know interested at the there are other kinds of cracks which I am not discussing that would be part of some other discussion. So, this is the importance of shrinkage and shrinkage cracks. Now, now next you can look into thermal expansion which is almost a related matter to shrinkage and expansion, because this is also a kind of dimensional change. And this is the coefficient of thermal expansion, basically it is is important because particularly.

For example, if I am using a reinforcement let us say steel of course, we do use and this coefficient of expansion should be similar as the concrete fortunately it is with respect to steel we almost match. And therefore, there will be no, you know if there is a differential thermal expansion that will induce kind of tensile stress in one material with relative to the other or compression in the other one. So, depending up on what is the coefficient of expansion? So, thermal coefficient of thermal expansion of concrete is important, aggregate does not expand much it will of course, depend upon a aggregate type. And cement paste can expand, aggregate expansion coefficient is different than that of the paste and it has got a kind of restraining effect. So, stiffness of this modulus of elasticity are different therefore, one issue is coefficient of thermal expansion are there is the modulus of elasticity. So, net effect is you know it is actually alpha delta T is the alpha is the coefficient of expansion which is length change per unit length.

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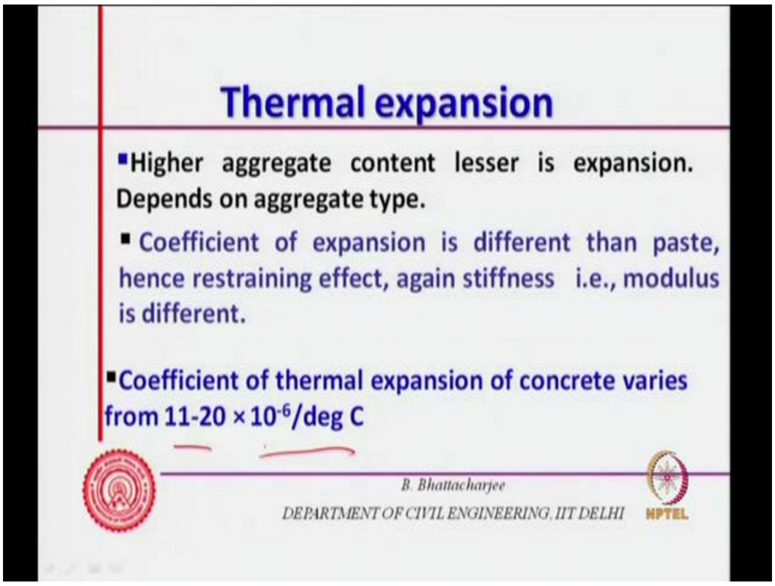

## Thermal expansion

- Higher aggregate content lesser is expansion. Depends on aggregate type.
  - Coefficient of expansion is different than paste, hence restraining effect, again stiffness i.e., modulus is different.
- Coefficient of thermal expansion of concrete varies from $11\text{-}20 \times 10^{-6}$/deg C

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So, this will be kind of a strain this will be the kind of strain. And stress induced would be would depend up on stress this is the strain and stress induced alpha is the coefficient of thermal expansion. And stress induced will depend up on the modulus of elasticity stress is multiplied by E actually this multiplied by E will be the stress induced on to the other material. So, if it induces tensile strain in the concrete system then it would actually cause cracking. So, it depends up on aggregate type as I said and aggregate content aggregate content. Coefficient of thermal expansion of concrete varies within this and steel is also somewhere there you know 14 13 14 11 depending up on type of steel they are also within this range. So, coefficient of thermal expansion generally varies this.

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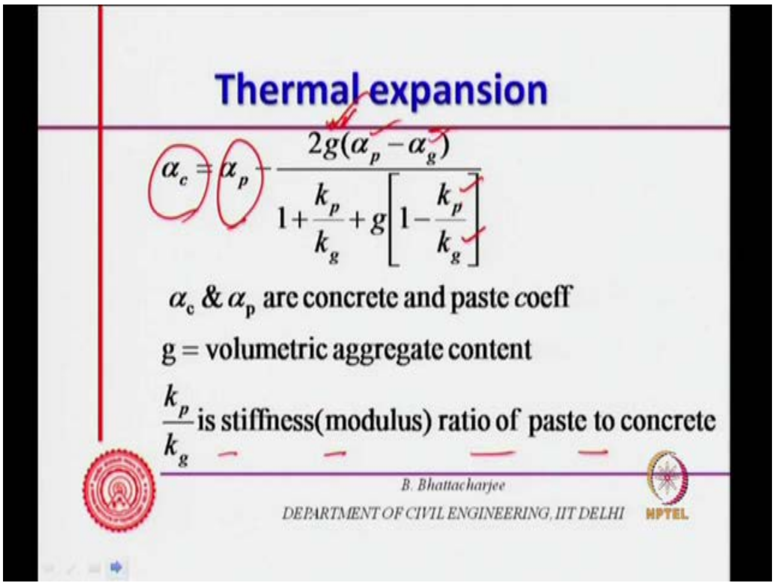

## Thermal expansion

$$\alpha_c = \alpha_p - \frac{2g(\alpha_p - \alpha_g)}{1+\frac{k_p}{k_g}+g\left[1-\frac{k_p}{k_g}\right]}$$

$\alpha_c$ & $\alpha_p$ are concrete and paste coeff

g = volumetric aggregate content

$\frac{k_p}{k_g}$ is stiffness(modulus) ratio of paste to concrete

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The factors those affect are actually moisture content, strongly effects moisture content and also the, you know the volume of aggregate, because you can see from this expression. This is the thermal expansion of concrete; this is the thermal expansion of paste, paste and aggregate, this is the thermal coefficient of thermal expansion of aggregate this is the volume of aggregate g is the volumetric aggregate content and k p is the stiffness ratio of paste and concrete. So, modulus of elasticity of the paste to aggregate so this is also a function of this, so this 2 factors modulus of elasticity, fraction volume and paste aggregate expansion coefficient. All this actually effects the coefficient of thermal expansion of concrete you know coefficient of thermal expansion of concrete so this is an empirical sort of equation.

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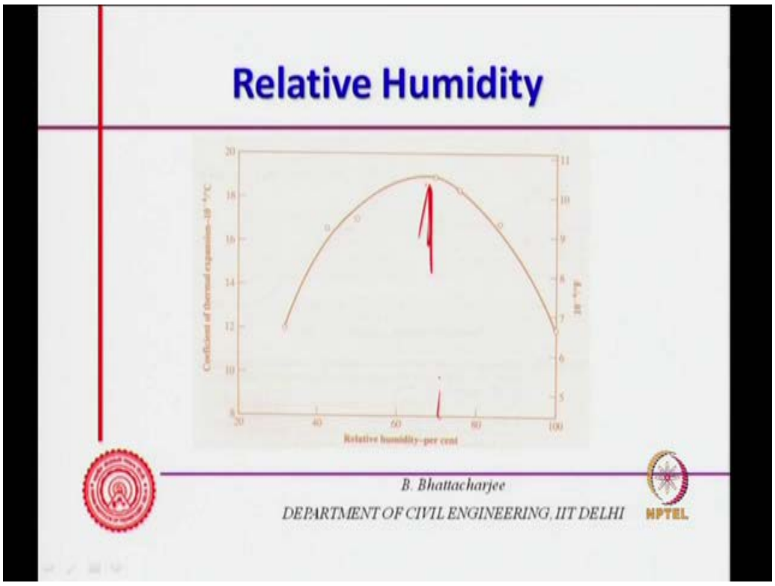

Relative Humidity

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So, this is this is what it is. Another factor which very strongly effects is the moisture content or relative humidity, moisture content or relative humidity, it depends up on a in like moisture content effects, most of the properties of concrete system, because you know there like thermal properties particularly, because if you look at thermal conductivity, conductivity when you put in moisture. Actually air is being replaced by air gets replaced by moisture itself, air gets replaced by moisture itself the properties of air and water is quite different. And therefore, whenever there is a moisture or you know the moisture content of the concrete changes most of the properties changes. So, in a relative humidity and temperature again temperature also affects the coefficient of thermal expansion.

So, relative humidity let us look at it now it seems that when you have a moist relative humidity is somewhere around 60 percent or somewhere around 60 70 percent. Or so coefficient of thermal expansion is maximum when it is saturated it is somewhat less it will depend upon stiffness it will depend upon stiffness and stiffness of the one which is saturated of course, the expansion gets reduced. It will depend up on besides that you know when it is actually its relative humidity is saturated the, the, the stiffness also would change stiffness of the system will also change. Because you know as we discussed earlier, the adsorbed water actually changes the properties of the gel itself. So, depending upon the relative humidity coefficient of expansion, so it is actually observed that a coefficient of expansion is maximum at about 70 percent relative humidity.

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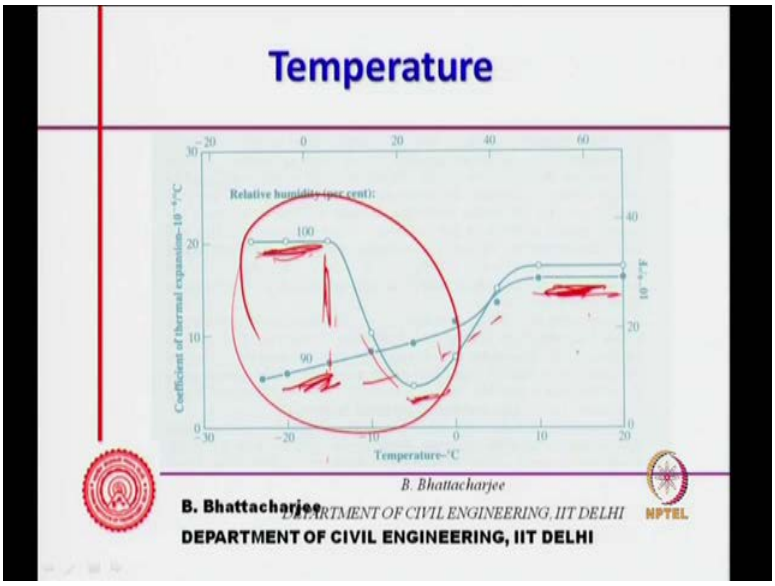

# Temperature

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So most important properties which are there are the aggregate content modulus of elasticity of aggregate, modulus of elasticity of the paste and paste thermal coefficient of expansion and which is again gorverned by relative humidity or moisture content and also dependent on temperature so also dependent on temperature. So it is of course there is some sort of a you know some sort of observed experimental results relative humidity 100 percent, coefficient of expansion is something of this kind and as, as my temperature at of course, it depends up on minus 20 at lower temperature. Now, this is more, more or less water will be mobile, you know this although, although properties of gel water is different it is not same as free water it would not be free water getting frozen this may not get frozen at all but properties are different.

But as the temperature increases close to 0 degrees centigrade, this is lower at 100 percent relative humidity, but at higher temperature which are important for us. This could be important if you are looking at the frost action but as far as we are concerned in Indian scenario temperature will be higher than this and this temperature does not have effect. So, low temperature has got some effect and this effect depends upon again relative humidity. So, at 90 percent humidity you can see the results are required by different, but as at high temperature this is a more or less similar; this is a more or less you know the values are more or less similar. So, this is what effects the this is what effects the, you know this, this what actually effects the coefficient of thermal expansion or concrete system coefficient of expansion of you know thermal coefficient of expansion of thermal expansion of concrete system.

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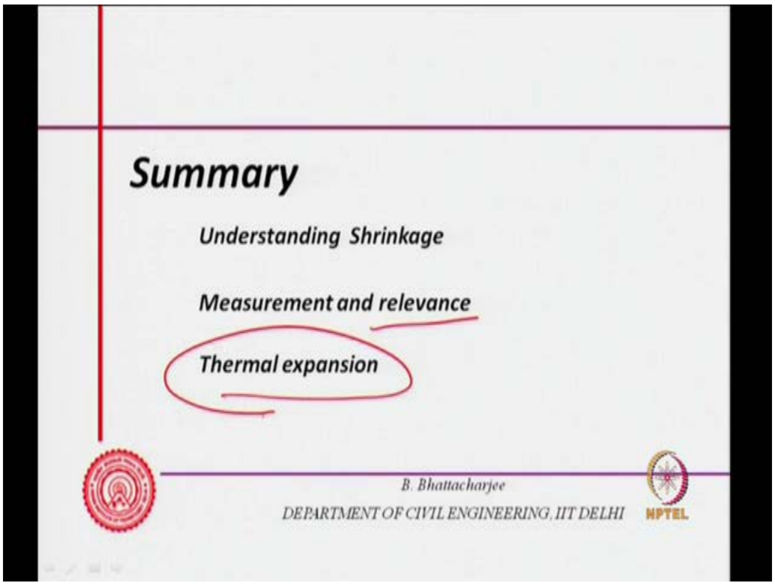

## Summary

Understanding Shrinkage

Measurement and relevance

Thermal expansion

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So I think a, we have looked into so far we have looked into so far tried to understand shrinkage a little bit from the fundamentals. So, in the process what you looked into we looked into we know we tried to derive basically Kelvin’s equation. And then we have tried to explain how surface tension properties can result in compression in the skeleton, because of the surf you know nature of the water itself. Then we looked into as the drying occurs it occurs from larger pores to the final pores. And in the process you know it would exert pressure into the skeleton. And therefore, this compression result in drying this is what one issue we looked into.

Then we looked into swelling mechanism because of the adsorbed water how the surface tension of the gel itself will change. And how it is related to shrinkage when you have moisture? When you have moisture you know withdrawal or drying. And also by the way we just also explained that why compressive strength of concrete is low or when moisture is adsorbed of course tensile strength increases, tensile strength of dry specimen is more that is because there will be no shrinkage cracks that is we talked earlier. And then we looked into various measurement method and their relevance of shrinkage in cracking. We tried to look into types of crack and lastly we looked into thermal expansion of thermal expansion of concrete system, the factors those effect the thermal expansion. So, with this actually, we you know complete the module 7 where we have discussed largely about creep shrinkage and related phenomena and tried to also, understood the creep behavior as much as possible then the shrinkage behavior of concrete and cement wage material. So, I think that with that it finishes our discussion on module 7.

Thank you.