Advanced Concrete Technology

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Lecture - 29
Introduction to Harden Concrete Properties

So with this we will start the chapter on Harden concrete. Now of course you know very well about typical concrete properties the fact that concrete as an excellent material in compression but it has very poor resistance to tensile stresses. Obviously, to improve the tensile capacity of concrete we need to add steel as reinforcement for making the reinforced concrete composites. Steel has an excellent bond with concrete, this bond obviously develops over time.

As concrete gains in compressive strength its other properties also increase including flexure strength as well as the bond strength. Strength is dependent primarily the water to cement ratio. But it is also affected by other factor including the aggregate to cement ratio; including the shape and size of the aggregate; including the degree of curing; the presence of mineral admixtures and several other factors which can affect the results at the time of testing itself.

Because strength of concrete is very much not a material parameter it depends a lot on external factors not just on the material factors but also on the testing factors. For example, when you test the cylinder and the cube you get completely differently strengths and that is because of the kind of forces that are at play; the kind of stresses that concrete actually undergoes while failing and so on. So there are number of issues that you need to understand with respect to strength.

You also know very well that the modulus of elasticity of concrete is typically represented in terms of the compressive strength but that is only statistical fitting it is got no fundamental relationship. In general, the higher the strength of concrete the higher will be its stiffness, there is no I mean for all material that is the case when you increase the strength you also increase stiffness but the relationship between strength and stiffness is not very easily achievable through a fundamental derivation.

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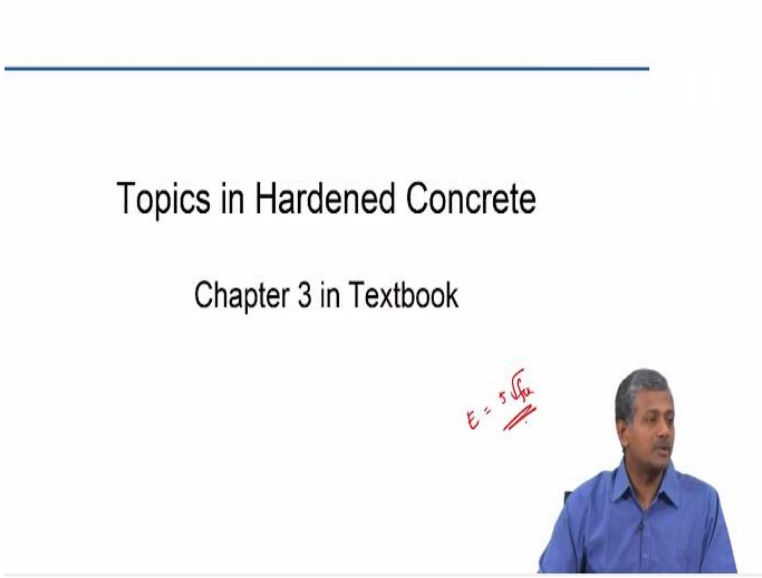

It is mostly for concrete when we use the relationship $E = 5(f_{ck})^{0.5}$ that is basically based on a statistical data fitting rather than anything else. Okay, there is no fundamental relationship why should strength, or why should modulus of elasticity vary with the square root of strength, it does not really make any sense. Just that the data seem to fit in that direction.

So all these are made with data fitting it is not essentially conveying any fundamental reason behind it. But, in general the stiffness of the concrete depends on the amount of aggregates that you have in your system because aggregates are the stiffer phase in the system, so the better packing you give to the aggregate better will be the stiffness. If the stiffness is better the resistance to deformation also is going to be higher.

So in general we want a concrete which is optimally designed to have as high a granular content as possible and as low as paste content as possible to obtain all desired characteristic of the concrete. So this again leads us back to the design of high performance concrete mixtures using the modern philosophy, that is of optimizing the packing of the granular materials and then designing just enough paste to give the desire workability characteristics.

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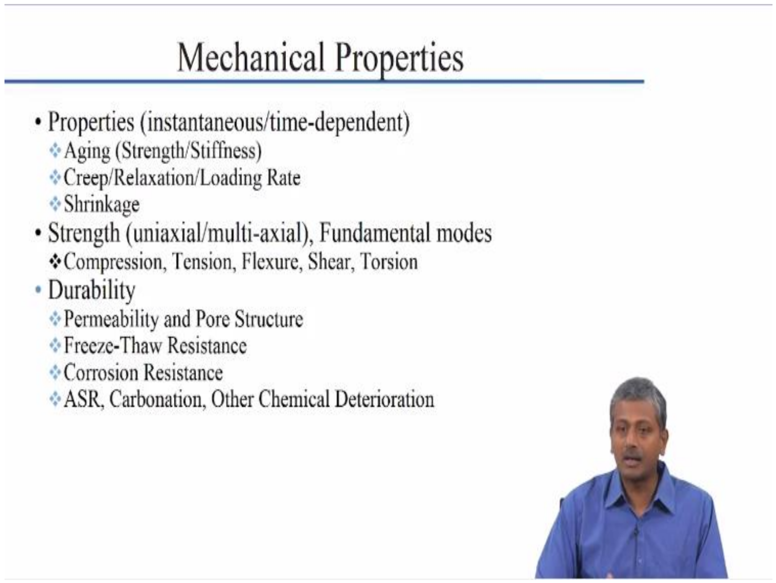

In terms of mechanical properties, of course we know that these are mostly time depended properties. Aging relates to change in strength and stiffness of the concrete with time. Then we have other aspects which are dependent on the rate of loading like Creep and Relaxation, and then we have the time depended volume deformation of the concrete which is called Shrinkage.

And why this shrinkage happens because there is excess water in the concrete this water dissipates either within the concrete or outside the concrete and that can create readjustment to the volume of the concrete and that leads to shrinkage. The strength can have multiple modes of action, you can have the uniaxial strength, multi-axial strength and there are different modes in which you can calculate the strength: compression, tension, flexure, shear, torsion.

So all these modes can produce different kinds of affects with respect to concrete. But for the most part we know that strength is dependent on the water to cement ratio and primarily dependent on the properties of the interfacial transition zone of the concrete because the ITZ controls to a large extent how the concrete would behave under different loading conditions. And the ITZ is one of the primary reasons why the tensile strength of the concrete is so low.

While the compression tends to close the cracks in the ITZ when you are doing tension or flexure the micro cracks in the ITZ can have a tendency of opening of much faster. So because of the heterogeneity the flexure strength and the tensile strength of the concretes becomes very low.

Durability is dependent primary on the Permeability and Pore Structure of the concrete; of course we will have a extended discussion on this later on.

And durability is composed of many different aspects like Freeze-Thaw Resistance, Corrosion Resistance. Alkaline Silica Reactivity, Carbonation and other Chemical Deterioration, which we will talk about in more detail in the later chapters.

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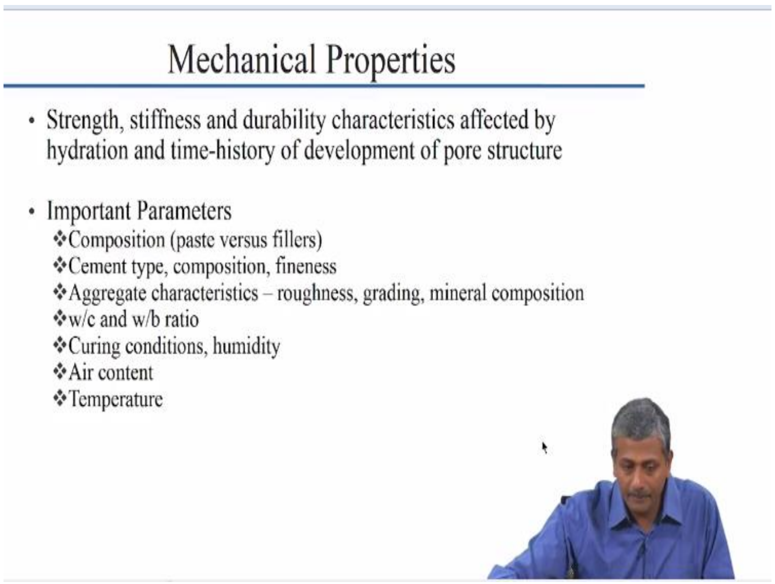

So of course the strength and stiffness and their development and evolution is dependent on the rate at which cement actually hydrates, the rate at which the pore structure around the cement grains starts getting filled up by the hydration products and the nature of the hydration products themselves.

So what are the important parameters that govern this properties of course that composition of the cement is important whether you have plain cement, whether you have blended cements. The level of filling up the pores space could be quite difference. In terms of aggregate characteristics like roughness, grading and mineral composition you know that, that affects the paste aggregate bond.

And we saw earlier when we talked about aggregate that, the paste aggregate bond can have a significant effect on the strength and durability characteristics. The water to cement or water-binder ratio obviously important. Curing conditions, Air content of the concrete if you are entraining air in the system the air content is obviously important and finally the temperature of the concrete.

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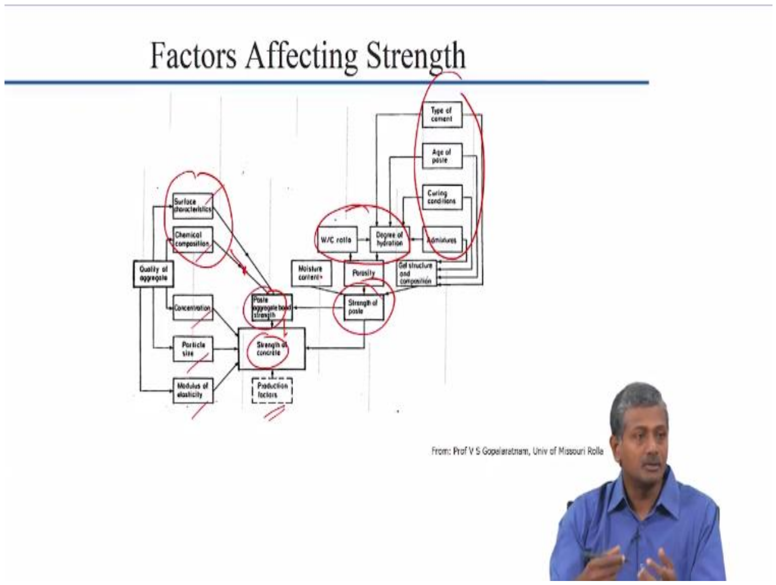

So what are the factors that affect strength this is actually giving an overall picture, this is more of a review of what you have had before in your general discussion on concrete technology. So you have the quality of aggregate, which is a surface characteristic, the chemical composition the aggregate; the amount of aggregate that you have in your system, the particles size and the modulus of elasticity aggregate.

So out of these the surface characteristics and the chemical composition seen to affect the bond of the paste and aggregate and that obviously has an effect on the concrete strength. The concentration; amount of aggregate, the particle size and the modulus can have a direct influence on the strength of the concrete. And of course these are also affected by the factors which are involved during the production of the concrete.

Like for example, compaction that you can give to the system; the degree of packing that you can get from the concrete and so on. And the paste aggregate bond again has a direct affect on the strength of the concrete. Now, the paste aggregate bond can also get affected by the paste itself. And what determines a characteristic of the paste it is a moisture content, the porosity and the gel structure and composition all these are dependent on the cement chemistry as well as the degree of hydration and the extent of water cement ratio in the system.

So now this is a very complex sort of a relationship which ultimately puts together a composite that ends up having a very good compressive strength property but a poor flexure strength property.

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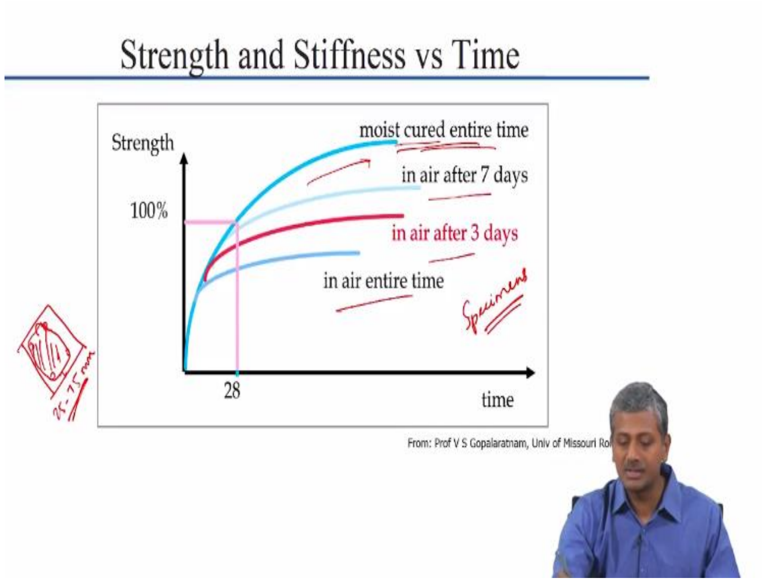

Now if you look at the growth of strength and stiffness versus time you know that as more and more hydration occurs the strength first grows at a rapid rate and then the rate of growth of strength slows down. And you know very well that concrete which is cured for an entire time moist cured for entire time will attain a very high maximum strength.

And if you continue curing there is going to be continuous marginal improvement in the strength because not all of the cement gets hydrated completely. So there is still unhydrated cement left in the concrete even after a substantial period of time, so if you continuing to cure this unhydrated cement will continue to react and fill up the hydration; products in this space available.

Now if you are curing less and less and absolutely not curing at all then your potential to develop that maximum strength is going to be lowered. Now whether this creates a problem for your concrete structure or not is debatable. For instance, when you are looking at a column; if you are thinking about a column you have the reinforcing bars on the outside which are put together by the tie bars, the concrete that is inside the reinforcing bars which is in the heart of your column that is truly not being subjected to any drying.

So the water-cement ratio that you would have used in that concrete would be maintained throughout anyway, because this is, the cover to the column can vary as much as 25 to75 millimeters. You cannot imagine that with the fine pore structure that concrete has the drying atmosphere prevalent in the outside can start drying out water from 30 to 40 millimeters into the concrete that may not happen.

So the concrete that is sitting inside the reinforcement is something that is continuing to gain strength because of its continuous hydration process. It is only the cover concrete which is responsible for that poor pore structure that develops when there is no curing. But the cover concrete is not really responsible for strength it is responsible for the durability of the concrete. The strength which is governed by core concrete may not truly get affected.

So these are results for cubes or specimens of concrete. But the real structure itself may not reflect this kind of a behavior. If you really to go the interior of the structure you will still get concrete that is properly cured and which is developed its potential strength. So again you need to understand how the perspective changes when you move from specimens to the actual concrete on the site.

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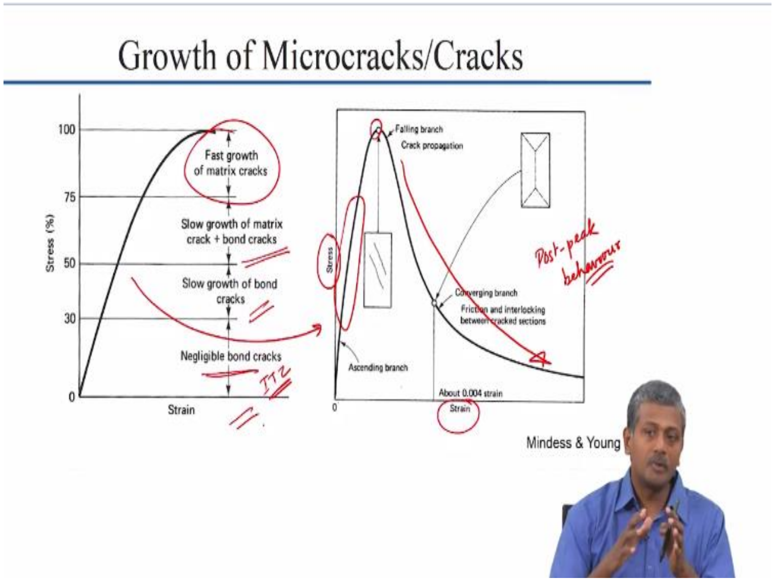

Now the micro cracks or cracks within the concrete can grow at the steady rate, you know already that we have at a very low stress level we can have some bond cracks which may or may not be negligible. There can be some significant cracking. If there is substantial difference between the aggregate and paste characteristics specifically. Why do I say that, so you know that concrete has two phase system, you have aggregate and the paste, both have extremely different stiffness characteristics.

So when you start loading this material the stiffer phase is going to attract more of the load, so the aggregate attracts more of the load which slowly will get distributed to the paste as more and more loading is done. But initially, when the loading is done your aggregate surface attracts much higher load than the paste. So you can imagine that the ITZ which is already a weak phase, is already been subjected to a very high level of stress because the aggregate is attacking more load.

So the ITZ cracking can happen at very low levels of loading itself. Around 30% of load itself can cause cracking at the ITZ. As you increase the loading further the bond cracks will start growing further and then beyond 50% of loading this bond cracks may start extending into the matrix that means your paste away from the aggregate also will start cracking. And then when you have a fast growth of the matrix cracks then you have a condition that leads to failure.

And looking at this from a stress-strain response perspective, so this is a stress and that is strain looking at it from that perspective, the ascending branch is what is plotted here, this is basically your ascending branch which is happening until you reach the peak load or peak stress. But beyond that your complete failure of the specimen actually happens because of the crack that have formed across the micro structure will now open up and then the specimen splits into two.

But because there is sufficient amount of aggregate present in your concrete there is going to be some interlock which will prevent the cracks form opening up at an instance. It will take some time in some extended deformation for the crack to completely open up, and that is what it is responsible for this Post-Peak behaviour. I will discuss this in more detail in the subsequent slides.

So because we have cracked sections which are interlocked the opening up of the concrete after the peak load is reached does not happen suddenly. Now as opposed to this if you just check paste, if you have some cement paste that you test in compression there is nothing holding it. So the failure of cement paste will be brittle. So once it reaches peak stress there is no more deformation, it just breaks apart.

Whereas in concrete there is some ductility introduced into it because it is a multi-component system and the non-linearity again; the non-linearity of the stress-strain curve is also because of the fact that you have the ITZ in action. You do not have two phases that are perfectly matching with each other, you have two phases that are not matching that creates a third phase called the ITZ and that leads to the non-linearity of the stress-strain curve.

So beyond peak also there is substantial deformation that can actually happen in concrete. What is the level at peak strain? Typically, what do we assume the peak strain to be concrete? 0.0035 or 0.003. About 0.0035 or 0.003 is what we assume as the peak strain in concrete.

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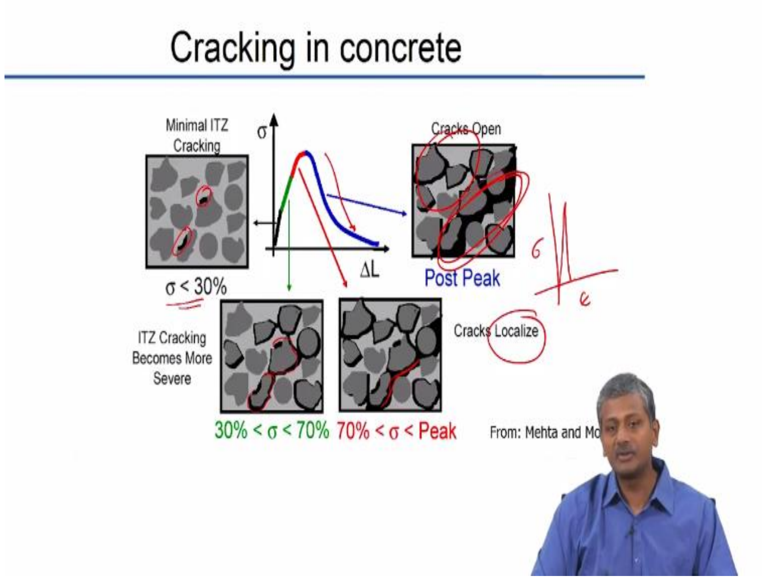

So again just to reiterate this picture. So you have very low levels of stress < 30% at that level the only cracks that were existing are the ITZ cracks which could be negligible but then this is where your failure will start to initiate because already there is a crack here, obviously if there is a crack that needs to grow, it will grow from same point. As you increase the level of stress, the cracks are tending to increase around the bond.

And then the cracks will start to spread across the matrix and tend to localize. Now what you mean by localization of cracks? What you think is meant by localization? Interconnection that leads to a larger crack being formed at a particular location not throughout the structure but there may be a weaker point where a large number of cracks have joined together and form sort of a crack bend. So now if a localize crack is formed beyond peak the crack that opens up will be that localized crack that is actually formed.

The other sections may or may not be experiencing anything after the peak load is being reached. In other words, the other sections that are away from this localized crack maybe already undergoing unloading after the peak stress has been reached, because, you know that once the cracking happens there is a stress relief.

But this stress relief here is not instantaneous because this crack continues to open at a slow rate, thanks to the interlocking that you get between the aggregates. So that is why you get this unique post-peak behavior with concrete. If you take chalk for instance, what will be the stress-strain behavior of chalk? It will go up and fracture and then suddenly fail, there is not going to be any post-peak behavior.

But when you talk about metals you will end up with the slightly different post-peak behavior.

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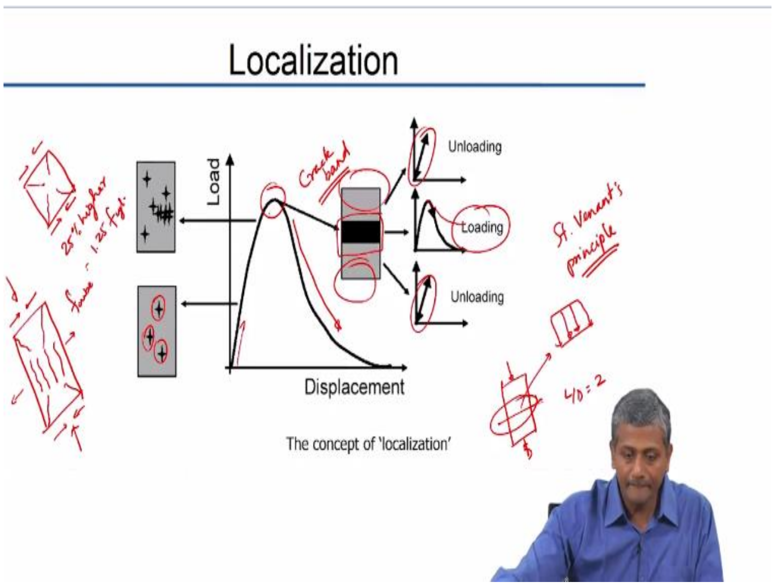

Okay, before we get to the understanding of in general post-peak behaviors once again the concept of localization is explained here. So take the case of a cylinder which is much better to consider than a cube, why because in a cylinder, because the length to diameter ratio is what 2, length to diameter ratio is 2, so when you are loading this cylinder in compression, exactly at the center of the cylinder we have a perfectly uniformed compressive stress distribution. Why?

You remember the principle which tells you that the end effects are felt up to a distance of lateral dimension, that's St.Venant's principle. So according to this principle, the end effects during loading will be felt up to a distance equal to the lateral dimension of the object. So for a cylinder the lateral dimension obviously is a diameter so L/D is 2, so exactly at the center at least you have a zone which is subjected to pure compression.

And this compression is the cause for development of initiation of the cracks at the center of the cylinder which then spread up and because of the friction at the ends start branching of like that.

You have seen a cylinder cracking, when a cylinder cracks you start developing the vertical cracks in the center first, and then towards the top they will start branching out like that, because of the friction that is present at the end, sorry.

Because of the end friction the cracks start branching out towards the edges on the top. What happen in the cube? The end friction effects are felt throughout the height of the cube, so actually the entire crack itself is like that. You do not get any vertical cracking in the cube. Vertically cracking is an indication that you are getting pure compression, if you are getting these inclined cracks that means your end friction is affecting the result.

And you know very well that in a cube the end friction can affect the result to as much as 25% higher, so the cube is approximately 1.25 times the strength of a cylinder, which is why when you do reinforce concrete design to calculate the structure capacity of columns you multiply the f_{ck} as a concrete with a factor of 0.8, that multiplication is done to convert the cube strength back to cylinder strength.

Why? Because the cylinder represents a true compression member and cube is not truly a compression member. We just do a cube strength primarily from the point of view of doing the test easily, because all you need to do is turn the cube on the side and you get a perfectly flat surface. For a cylinder, you have only one way to test it and you need to cap it properly on the top to ensure that you have a very plain section on the top and bottom.

So because of the ease of the testing we test cube. So essentially this vertical crack means that the tensile strain capacity in the lateral direction is getting exceeded. In true compression how will be the failure be-- if I, it will be crushing, so your concrete should come into; turn into a powder. So for example if you do a tri-axial compression of concrete you will not see any of these cracks developing. So beyond the certain point of time the concrete should just crumble into a powered.

For example, when you do concrete testing under hydrostatic conditions, so all stresses are equal in that case. So in that case you can actually get strengths from regular concrete of 30-40 megapascal as much as 300 to 400 megapascal. When you test under tri-axial conditions your concrete strength will get severely enhanced because of that. And we talk about that also later. So here I wanted to explain this concept of localization with the example of a cylinder.

So let us say you starting to load the cylinder we know that the cracks start growing beyond about 30% to 50%, at the peak load or at the peak stress you have a zone exactly in the center of the cylinder which consist of the maximum concentration of the cracks which leads to bend forming, so that's called the Crack band.

So those of you who are interested in fracture mechanics can take additional courses and you learn about crack band theory in concrete, so that is where this localized crack which is forming exactly in the center of the cylinder, starts to grow. So as a crack starts to open up, the specimen displaces more and more with lower and lower levels of load. So you do not need to give higher levels of load to make it displace the same amount.

So the displacement is registered now at lower and lower levels of load, the crack continuous to open. So essentially what is happening in it, this segment is still undergoing loading, although the level of load is continuously reducing. The crack continuous to grow and the crack width continuous to increase, beyond a certain point if the crack width is very high this specimen cannot hold itself, it just crumbles; falls apart.

But the other segments where the pressure has already been relieved may actually be undergoing unloading. They are not going to have any stress after the peak stress has been reached whereas in the local zone right in the center you have a continuous loading that leads to a slow development of the crack level. And this is where we can adopt the use of fiber reinforced concrete. What does fiber do?

It will bridge the crack and prevent the crack from opening up fast. So instead of getting a behavior like this you will get a much more slower growth to failure, so the crack will not open up suddenly, even in the case of regular concrete it take some time to open up but still with the fiber reinforced concrete the time can be extended tremendously, so you can get extremely good post crack behavior.

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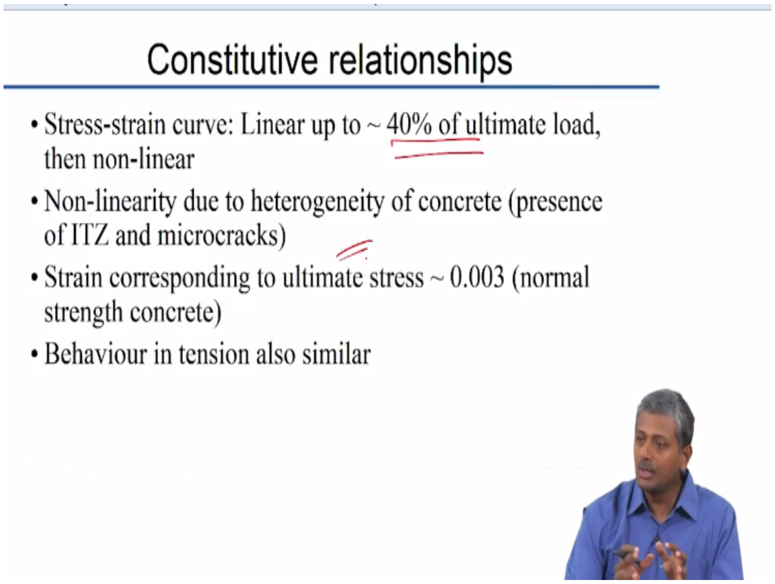

So again as far as understanding stress-strain characteristic of concrete are concerned, we know that at very low load levels concrete is almost elastic, typically we assume that the elastic nature of concrete or sometimes the linear nature of concrete both are not the same, you understand that linear and elastic is not one and the same thing. What is linear? What is elastic?

Elastic means it has a capability of coming back to its original shape, linear simply means the graph is linear or proportional. The stress is proportional to strain that makes a linear graph. So up to 40% of the ultimate load the stress to strain relationship of concrete can be assumed to be mostly linear, but even there, there is non-linearity primarily because of your interfacial cracking that happens.

Then, non-linearity of course is throughout your stress strain diagram primarily because of heterogeneity. Then strain corresponding to ultimate stress is typically taken at 0.003 for design purposes or 0.0035. The behavior in tension in terms of the shape of the stress-stain graph is also similar but the failure strain will be much lower as oppose to the failure strain in compression.

So there are no unique values because you cannot do a proper direct tension test in concrete. You typically do a flexure strength test, because that is much easier to perform. The tensile strength means you need to grip the concrete and pull it apart the gripping can create too much compression at the ends which may lead to local failures even before the material gets pulled apart from tension.

So doing a tensile strength of concrete is not an easy task. So that is why we do an indirect tensile strength which is a splitting strength or we do the flexure strength which actually represent the case of concrete bending.

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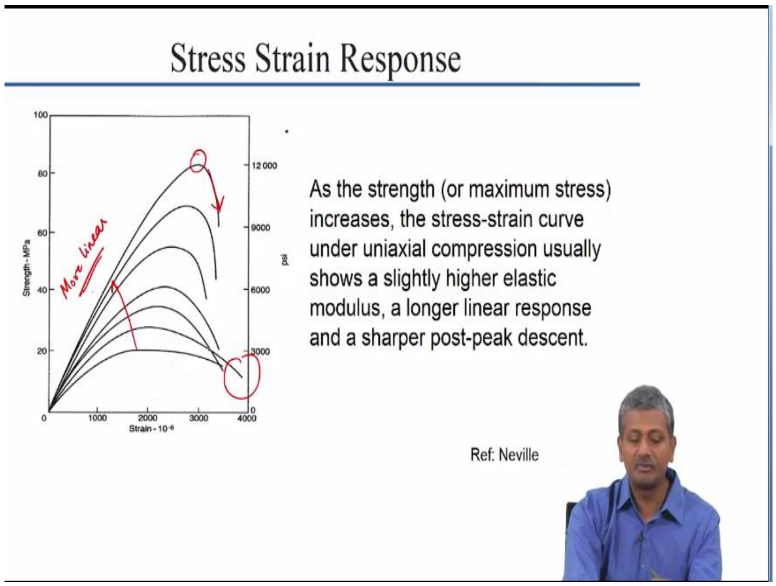

So the Stress Strain Response of concrete depends obviously on the level of strength that the concrete has. You know very well that as concrete becomes stronger and stronger it gets more and more brittle. And in fact as concrete gets more stronger and stronger what is that strengthening in the concrete to make it stronger? Aggregate or paste? The paste is getting stronger. So what happens to the ITZ?

ITZ continuous to also become stronger as a paste become stronger. In other words, you reduce the heterogeneity of the concrete to a large extent. So paste gets stronger and stronger and the ITZ gets stronger so there is no real boundary between these two phases. So that is why you see that as the concrete strength increases the graphs become more and more linear, the graph is becoming more and more linear.

And primarily because your heterogeneity, that is the ITZ, is getting reduced as the paste phase become stronger and stronger. But then obviously your brittleness is increasing as soon as the peak strain is reached we have a sudden drop and then this specimen can fall apart. And when it does that obviously you get explosive failure, you get a very brittle failure. On the other hand, for low strength concrete there is sufficient deformation even after the peak strain is reached.

So you will see this to be a very common factor that when you increase the strength of any material it will tend to increase the brittleness of the material, it will reduce the deformation capability of the material. Of course concrete will not ductile by any means but still it has some ductility because of the slow growth of the post-cracking behavior. But when you become; when you increase the strength of the concrete more and more you tend to offset that behavior and cause a sudden failure of the concrete.

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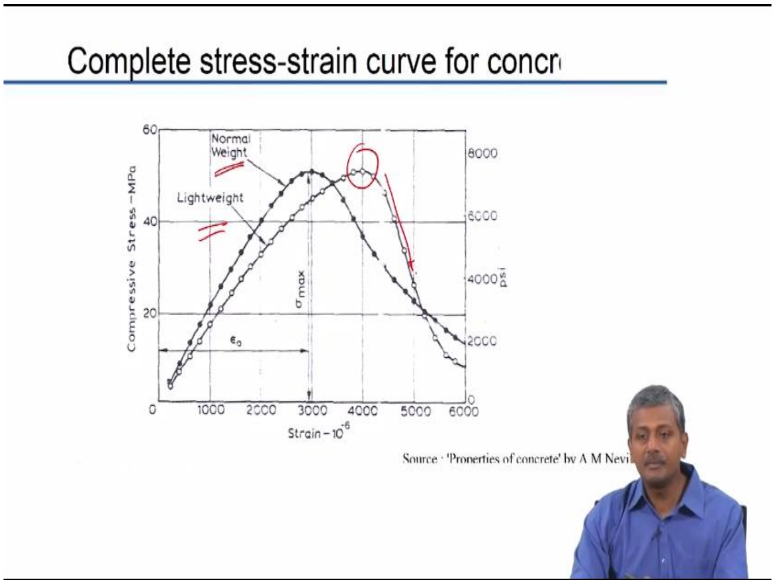

Again this is an example of Stress Strain behavior of a concrete for normal weight concrete and lightweight concrete. A lightweight concrete obviously deforms a lot more before it reaches the peak, primarily because there is lightweight aggregate present in it. So there is much more deformation that it can actually take before it fails. But post-peak may not be the same as a regular concrete in the case of a lightweight concrete.

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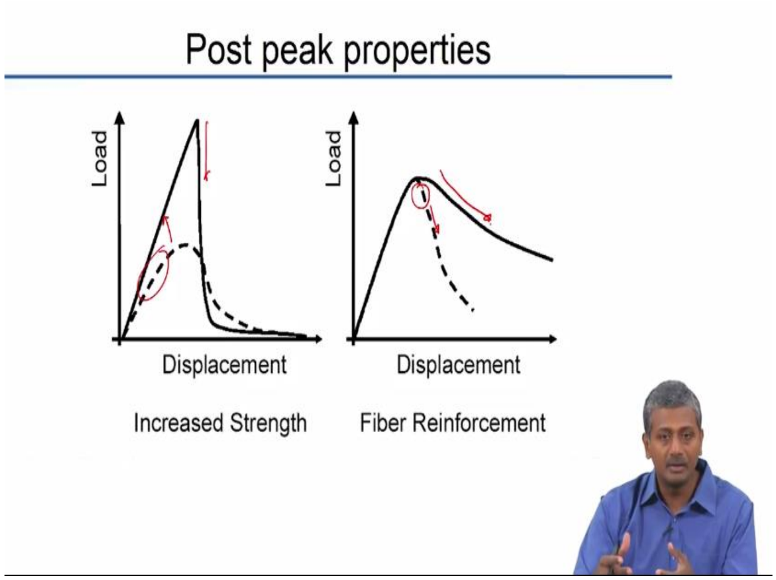

So what is interesting for us to understand are post-peak properties, primarily because we start dealing with special concrete like Fiber Reinforced concrete where we can actually do something to the rate at which the cracks are growing. So post-peak properties in general can help us understand, what does increased strength do to the system, as we saw earlier the graph become more and more linear and the failure becomes more brittle as the strength increases.

With fiber reinforcement, what we essentially do is, we stop this post-peak branch from descending very rapidly and cause a very slow dissent of the post-peak branch. This means that we are introducing fibers to observe the energy during failure and preventing the cracks from spreading rapidly, so that is a very desirable behavior from the perspective of how a building should fail.

We don’t design a building to fail but when the failure happens we wanted to fail in a slow and steady manner, so fibers helps to control the rate at which the failure actually will happen.

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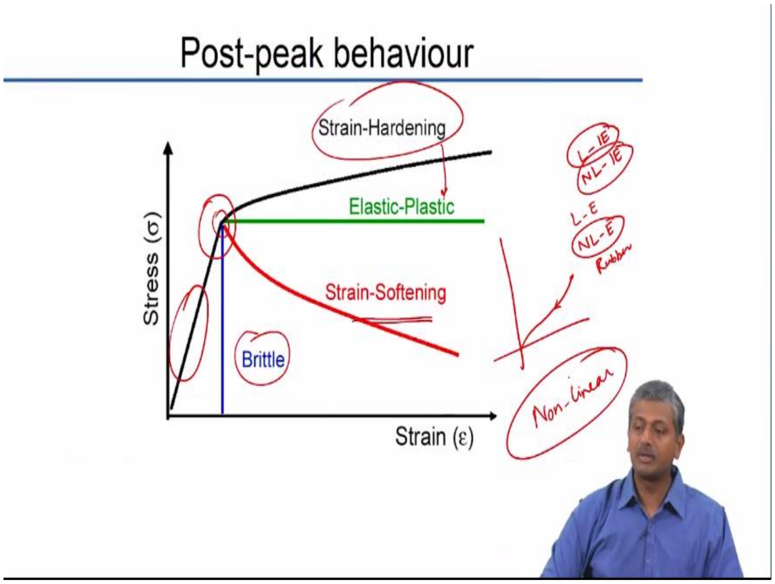

So I will stop with this for today. Post-peak behavior is different for different types of systems. So obviously, the Brittle behavior exhibited by materials like chalk, where after the peak stress is reached there is no more deformation capability in the material and then you have a complete collapse. You have this Strain-Hardening behavior that will typically associate with steel, mild steel and other metals.

But for design purposes we assume that to be a Elastic-Plastic behavior; we assume that the yield strength will be what you get maximum and not really go into the strain hardening region. With concrete, we call the behavior as Strain-Softening behavior, with increased level of stress or with increased level of displacement beyond the peak stress there is a reduced level of load that is registered that is called Softening, concrete is one of the Strain-Softening material.

Now, at this stage you should also understand the distinction between linear and plastic or linear and elastic. So if you look at a graph which is like this and if you unload, if it comes back perfectly what kind of behavior would that classify into? Linear and Elastic. Now if you have a behavior like this and then when you unload it comes back exactly back to this, you call it? Non-linear and Elastic. And give me an example for that, rubber, yeah. Rubber is non-linear elastic material.

Because rubber has this polymer chains that are entangled so as you increase the stress on it there is some disentanglement and some order that, that is brought about in this structure, but when you release the load it is able to comeback. Then of course you have the other combinations linear and inelastic and finally non-linear inelastic. So concrete mostly is linear and inelastic in the beginning and non-linear inelastic once it reaches the higher levels of stress.

So mostly we say that concrete behavior is Non-linear. Concrete it is mostly having a non-linear behavior and as you strengthen it you make it more and more homogenous increase the strength of the ITZ and that causes the behavior of concrete to become more and more linear. Okay.