PRESTRESSED CONCRETE STRUCTURES

Amlan K. Sengupta, PhD PE
Department of Civil Engineering
Indian Institute of Technology Madras

Module – 1: Introduction, Prestressing Systems and Material Properties

Lecture – 6: Concrete (Part 2)

Welcome back to Prestressed Concrete Structures. This is the sixth lecture in Module 1 on Introduction, Prestressing Systems and Material Properties.

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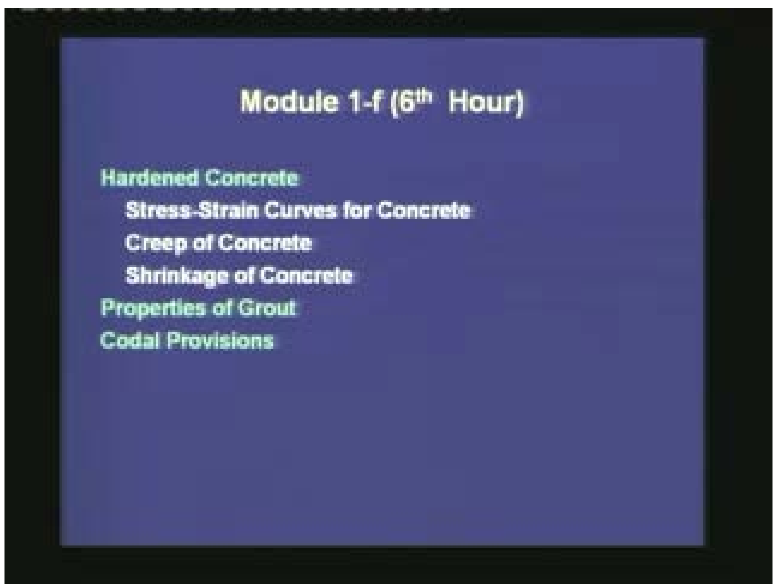

Last time, we had started to learn about the properties of hardened concrete. We studied about the strength, the stiffness and durability of hardened concrete. We also learnt a bit of the high performance concrete. Then, we learnt about the allowable stresses used at transfer and in the service load stages. Today, we are continuing with the properties of concrete. The first thing we shall learn today is the stress-strain curves for concrete. Next, we shall move on to an important property called the 'creep' of concrete. Then, we shall study the 'shrinkage' of concrete. We shall touch upon the properties of grout, and then we shall mention the codal provisions that are there in IS: 1343 – 1980. The stress-strain curves for concrete are used to study the behaviour of members.

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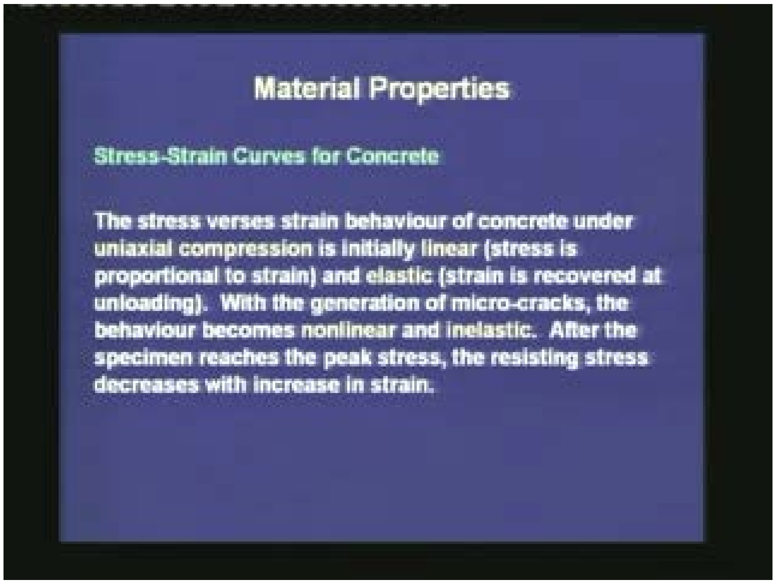

The stress-strain curve under uniaxial compression is initially linear. That means, stress is proportional to strain and in that region it can be considered to be elastic, which means that the strain is recovered if we unload the specimen. But with the generation of micro-cracks, the behaviour becomes non-linear and inelastic. After the specimen reaches the peak stress the resisting stress decreases with increase in strain. Let me explain this by a sketch.

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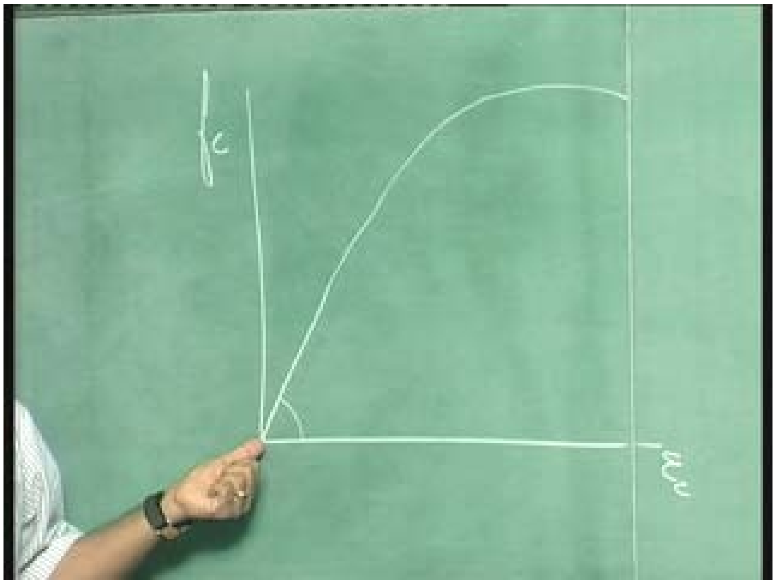

If I plot the stress versus strain of concrete, initially it will show a linear part. Gradually, it becomes non-linear and reaches a peak value. And then, depending on the type of testing, the stress drops with increase in strain. At the first part, the concrete is considered to be linear elastic. Linear means the stress is proportional to strain, and we can get the proportionality constant from this curve. Elastic means that at any point within this stage, if I unload the specimen, then it will retrace back the curve and the stress-strain state will come back to the origin. But with the increase in micro-cracks within the concrete if I go on loading, then the curve becomes non-linear. That means, the stress does not increase proportionately with the strain and finally, it reaches a maximum stress, which is the capacity of the specimen. Beyond that if we try to load, then the load drops. We are not able to sustain that load and this part of the curve depends on how we test the specimen.

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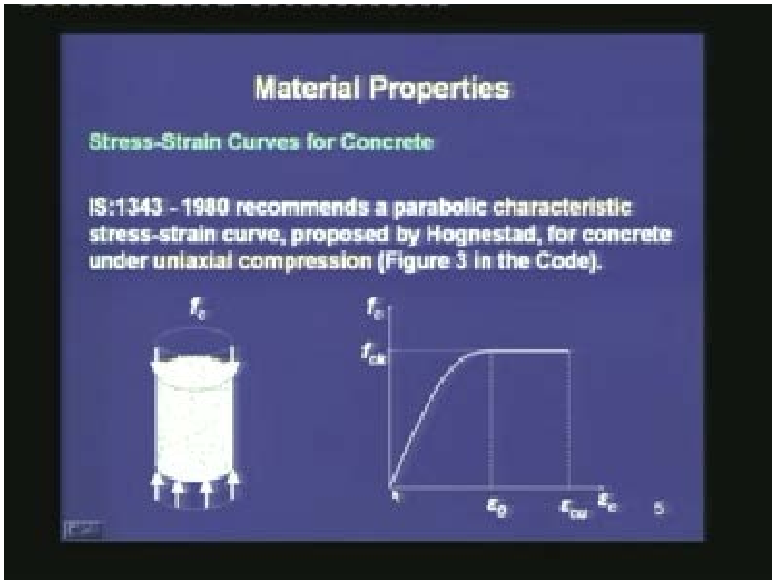

In this figure, we have schematically shown the curve that is obtained by testing a cylinder in a testing machine. The cylinder is loaded uniaxially. If we plot the uniaxial stress-strain curve, then the curve that we get for the ascending branch, that means the curve till the stress reaches its maximum value, can be approximated by a parabolic curve. IS: 1343 recommends a parabolic stress-strain curve, which was proposed by Hognestad for concrete under uniaxial compression. That means, up to the peak stress we can fit a parabolic equation to the behaviour. For flexural compression, beyond the peak stress since the stress can be sustained over a certain range of strain, the code allows the stress to be considered constant in that range.

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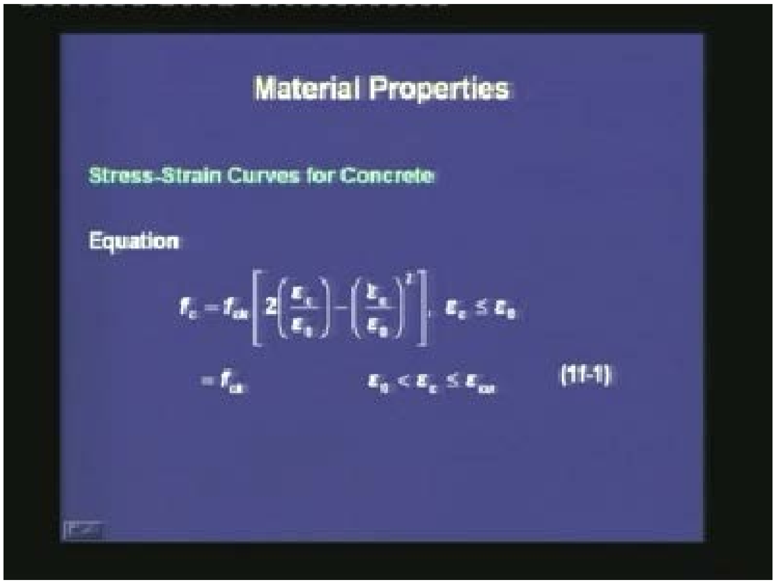

If we try to fit an equation, then the equation for the ascending branch is given by the above parabolic form. Here, ε_0 is the strain till we reach the peak stress. Usually the value of ε_0 is taken equal to 0.002. The first equation is valid in the range of $\varepsilon_c \le \varepsilon_0$. Beyond ε_0, f_c can be considered to be constant at the characteristic strength f_{ck}, and this is valid in the range from ε_0 to ε_{cu}. As per IS: 1343, ε_{cu} is equal to 0.0035.

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Just to recollect, in this equation f_c is the compressive stress, f_{ck} is the characteristic compressive strength. We had learnt earlier what is meant by characteristic compressive strength. ε_c is the compressive strain. ε_0 is the strain corresponding to reaching the strength, which is taken as 0.002. ε_{cu} is the ultimate compressive strain, which is taken as 0.0035. When the concrete reaches the strain ε_{cu}, it is assumed to fail by crushing. The curve that we have seen is termed as the characteristic curve, which corresponds to the characteristic strength.

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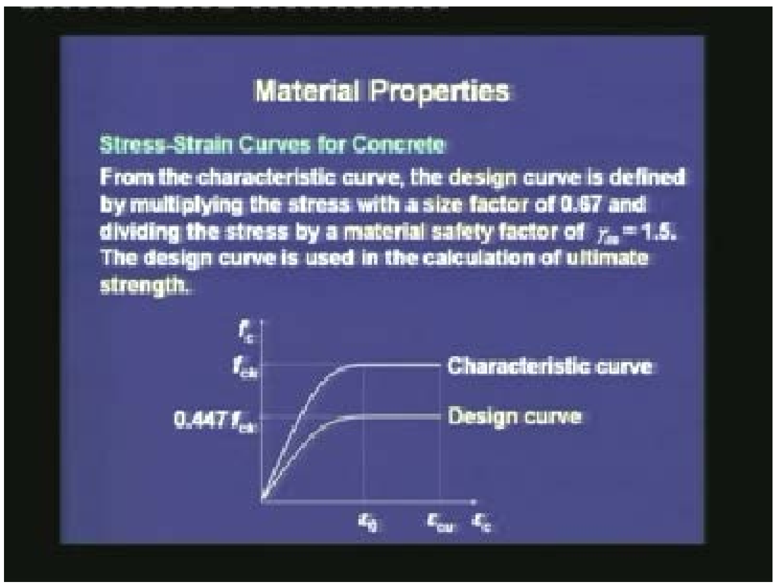

From the characteristic curve, the design curve is defined by multiplying the stress with a size factor of 0.67, and dividing the stress by a material safety factor of γ_m = 1.5. The designs curve is used in the calculation of ultimate strength in a member.

Let me explain this again. The first factor, that we are multiplying the stress is a size factor. We test specimens of cubes or cylinders in a testing machine. However, the concrete that exists in a member may fail at a lower stress, because of the larger size of the member. In order to take account of the lower failure strength in a member, a size factor is multiplied to the characteristic strength. The size factor is 0.67, when the characteristic strength is determined from cubes.

In the limit states method, we also use a material safety factor, which considers the variability of the concrete properties cast under different conditions. This material safety factor is taken equal to 1.5. When we divide the stress from the characteristic curve, we get the design curve. We can see that the design curve has a lower slope at the initial region, and it has also a lower strength whose value is 0.447 $f_{ck.}$ It is even less than half of the characteristic strength.

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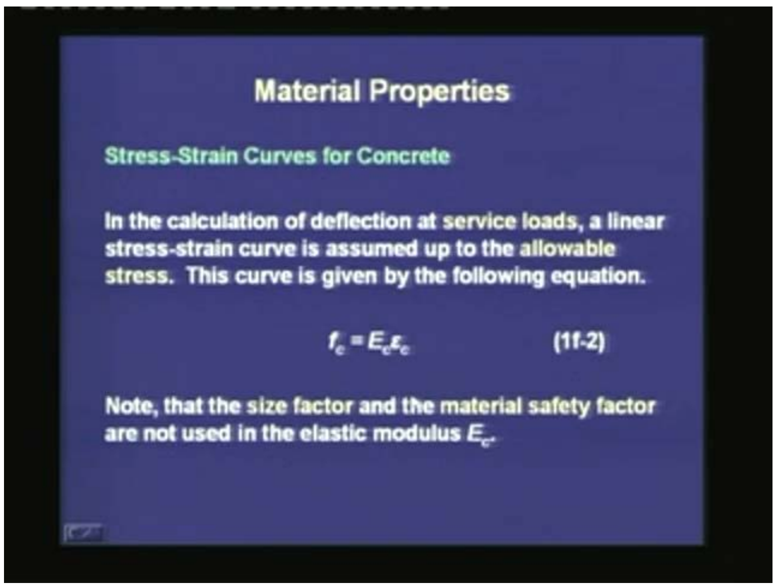

This previous design curve is used to calculate the strength of a member at the ultimate state. But we also need to calculate stresses and deflections under service loads. Under service loads, we assume the concrete to behave linearly, as if it does not go into the non-linear range. In the calculation of deflection at service loads, a linear stress-strain curve is assumed up to the allowable stress. Usually, the allowable stress is about one-third of the characteristic strength and in that region, the concrete behaves linearly. This curve is given by the equation, which is similar to the Hooke's law, where $f_c = E_c\varepsilon_c$. That means, the stress is equal to the modulus times the strain. Note, that the size factor and the material safety factor are not used in the elastic modulus $E_{c.}$ The elastic modulus E_c is given as $5000\sqrt{f_{ck}}$. That means, the material safety factor and the size factor are not considered in the modulus because: first of all, we are calculating the deflections at service loads, and second, the factors are applicable only for the strength. They are not used in the calculations of deflections at service loads.

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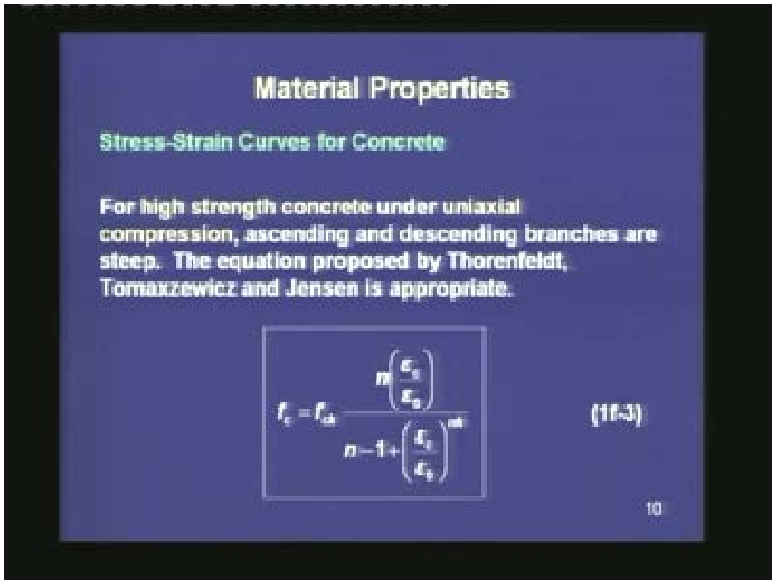

The curve that is given in the code is suitable for normal grade concrete, say up to the grade M60, where the characteristic cube strength is 60 N/mm^2. But if we are using high strength concrete, then it is found that this equation is not suitable. For high strength concrete under uniaxial compression, the ascending and descending branches are steep. In that situation, the Hognestad parabola is not suitable. The equation proposed by Thorenfeldt, Tomaxzewicz and Jensen is appropriate. This equation is more involved, but it can replicate the stress-strain behaviour more accurately than the Hognestad parabola. Here, the stress is equal to the characteristic strength times a function, which we shall explain now.

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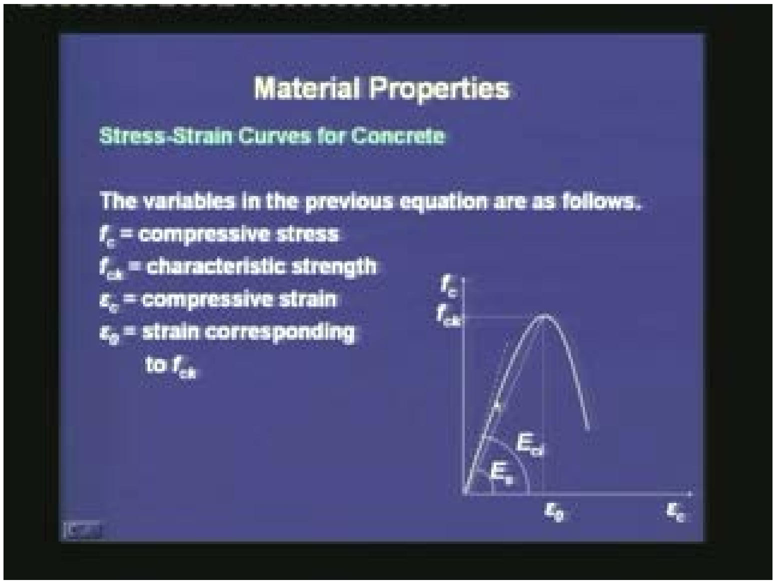

This equation is expressed in terms of two moduli. The first one is the initial tangent modulus (E_{ci}), which is the tangent to the curve at the origin, and the second is the secant modulus at the peak stress. If the grade of concrete is say 100 MPa, then we have to find out the secant modulus at the peak stress, and that is represented by the notation $E_{s.}$ Just like last time, f_c is the compressive stress, f_{ck} is the characteristic strength, ε_c is the compressive strain and ε_0 is the strain corresponding to reaching f_{ck}.

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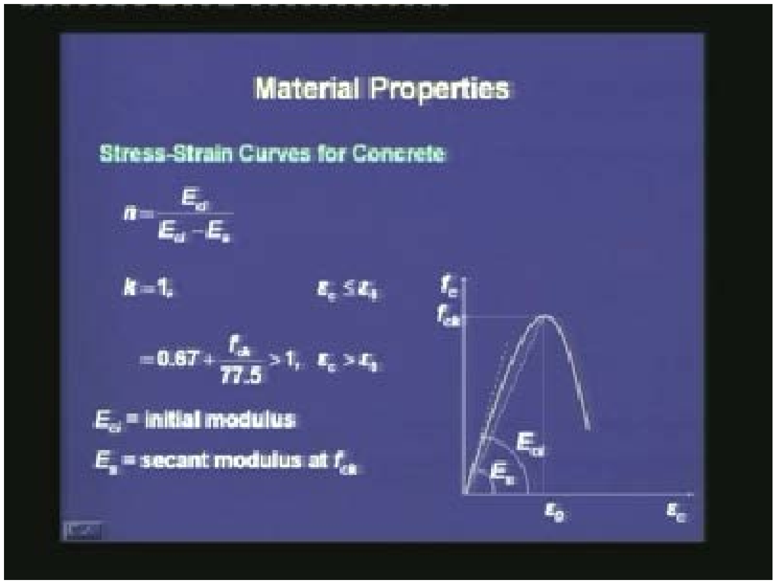

A variable that is used in the equation is a parameter denoted as 'n'. The value of n depends on the two moduli, and it is given as E_{ci} divided by the difference of E_{ci} and E_s. The other parameter 'k' is a shape factor, which is equal to 1 for the ascending branch, that means when $\varepsilon_c \le \varepsilon_0$. Beyond the ascending branch, for the descending branch k is given by an expression, which is a function of f_{ck}. If the grade of concrete is high, that is if f_{ck} is high, k will be larger and the curve will drop more rapidly. Thus, here is an equation which can model both the ascending and the descending branches, and also is able to model the different values of slopes for each of the two branches. Remember for high strength concrete, the drop in stress beyond the peak strength is rapid compared to that for normal grade concrete.

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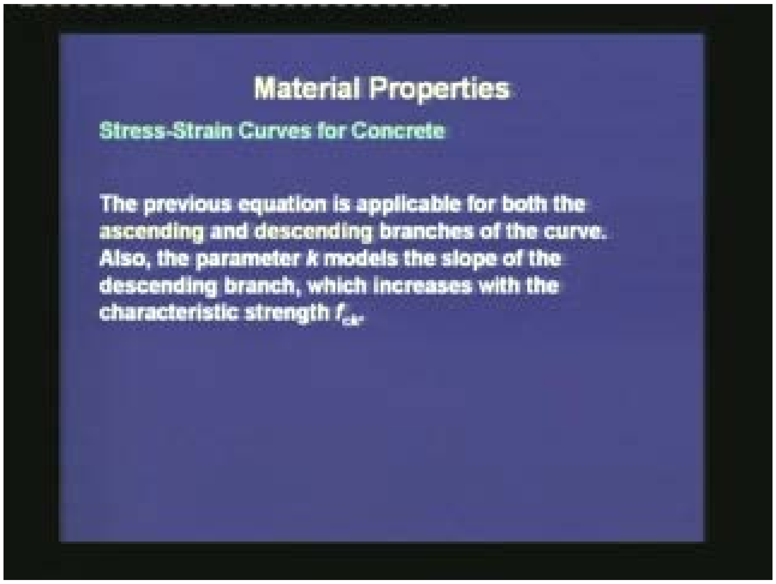

Just to summarize, this previous equation is applicable both for the ascending and the descending branches of the curve. Also, the parameter k models the slope of the descending branch, which increases with the characteristic strength f_{ck}.

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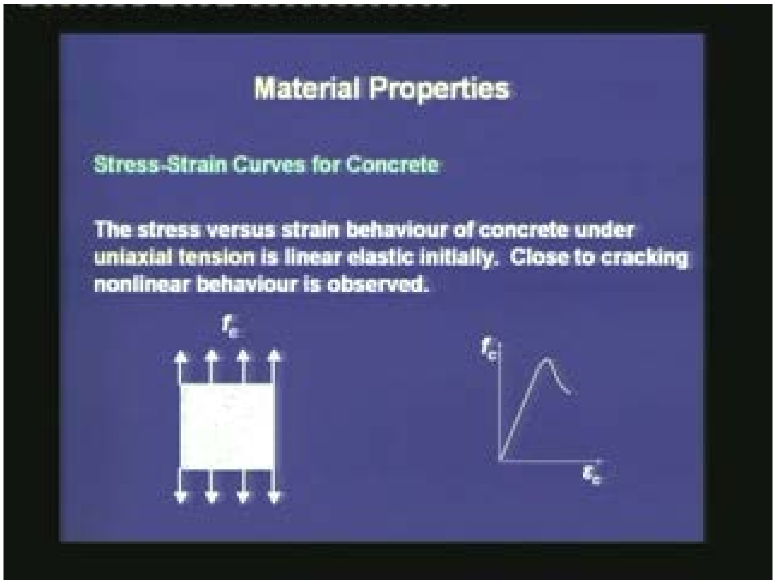

Next, let us move on to the stress-strain curves for concrete under tension. For tension as I said earlier, there are three ways to find out the strength. The first one is a beam under two point bending or sometimes it is called four point bending. The second one is the spitting test, where a load is applied along the diameter of a cylinder, and the third one is the direct tensile strength. If we have to find out not just the strength but the stress-strain curve, then the direct tensile test is more appropriate. Although this test is difficult to perform, stress-strain curves have been developed based on this test. Here, it is seen that the behaviour is linear elastic almost till the peak; but close to cracking, we observe non-linear behaviour and then, there is a drop in the curve, which is because of the enlargement of the fracture process zone. The explanation of the descending branch can be given in terms of fracture mechanics.

For design purpose or for conventional analysis, we do not consider this descending branch. We consider a straight linear elastic curve up to the cracking value, which is sufficiently accurate for the property that we are looking for.

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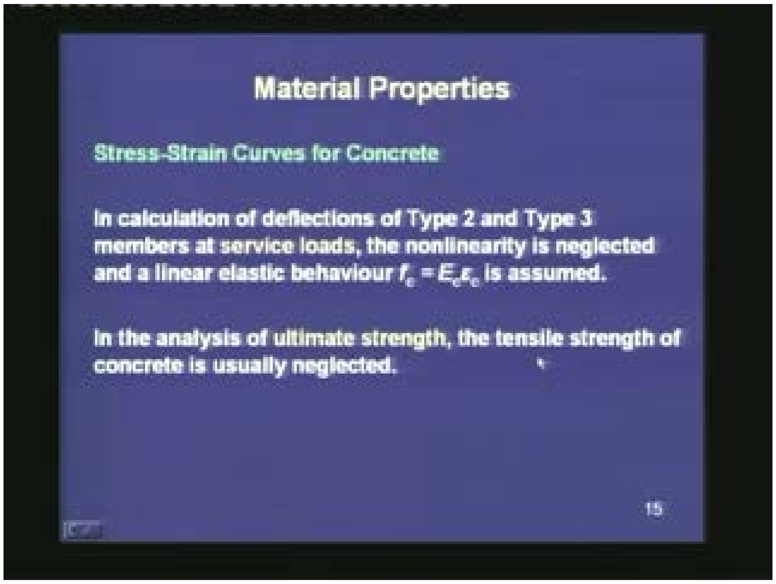

Where do we use this curve? In the calculations of deflection for Type 2 and Type 3 members at service loads, the non-linearity is neglected and the linear elastic behaviour $f_c = E_c\varepsilon_c$ is assumed. Remember that in Type 2 and Type 3 members we allow tension in the concrete. In Type 1 members, we do not allow any tension in the concrete under service loads and hence, this equation is not needed for Type 1 members.

In the analysis for ultimate strength, that means when the concrete reaches crushing under compression, in that limit state the tensile strength of concrete is usually neglected. Although, the concrete below the neutral axis may have some tensile stress, the stress is neglected in the conventional calculation of the ultimate strength.

Next, we are moving on to a very important property of concrete, which is called the creep of concrete. What is creep?

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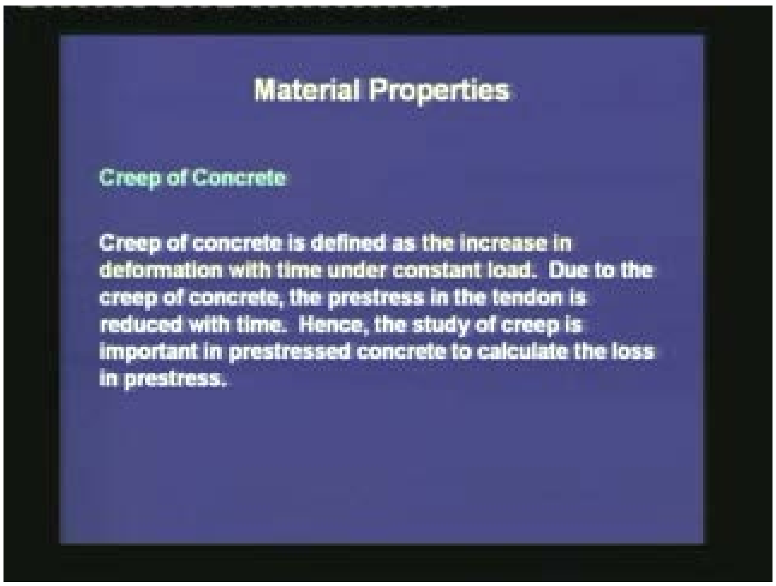

Creep of concrete is defined as the increase in deformation with time under constant load. Due to the creep of concrete, the prestress in the tendon is reduced with time. Hence, the study of creep is important in prestressed concrete to calculate the loss in prestress. Although creep exists for reinforced concrete, we do not put much emphasis on creep, because we are not concerned about any loss of prestress there. Sometimes, creep may be of concern in reinforced concrete structures leading to differential settlements. But otherwise, in our first course of reinforced concrete usually creep is not covered. But creep is a very important phenomenon in prestressed concrete, because with time as the concrete increases its deformation, there is a drop in the prestress and hence, the effective prestress is less than the initially applied prestress. To recollect the definition, creep is the increase in deformation with time under a constant load. The strain is not just a function of the stress anymore, it is a function of time also.

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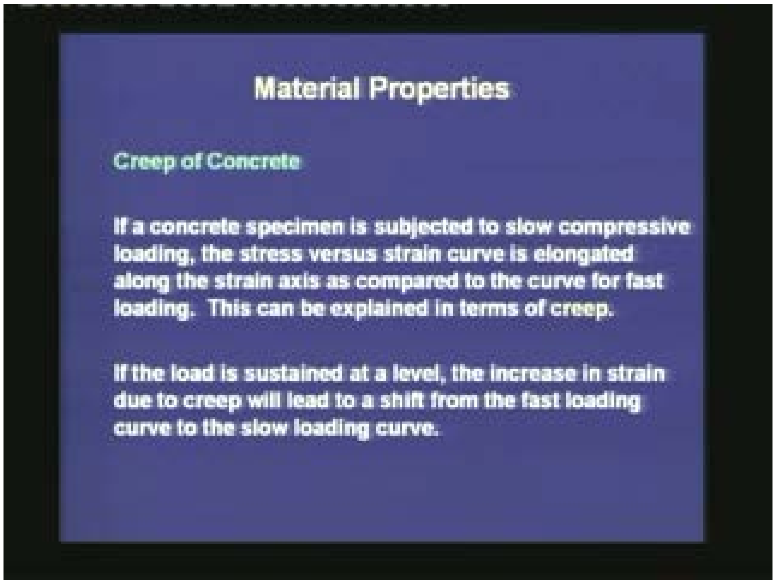

If a concrete specimen is subjected to slow compressive loading, the stress versus strain curve is elongated along the strain axis as compared to the curve for fast loading. This can be also explained in terms of creep. If the load is sustained at a level, then the increase in strain due to creep will lead to a shift from the fast loading curve to the slow loading curve. Let us explain this by a sketch.

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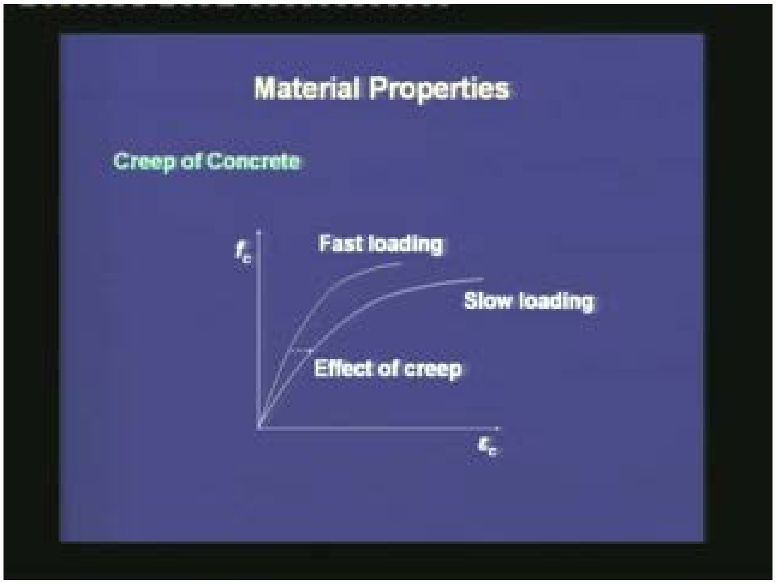

Here, we have plotted the stress-strain curve for two different types of loading. The left one is a fast loading. That means, the load is applied quickly till the specimen reaches its ultimate strength; whereas, the second curve is under a slow loading. That means, the load is kept sustained and it is gradually increased with time; and what we see is that, the two curves are different. Here, we see an important feature that the stress-strain curve of concrete is dependent on the time of loading. The only difference between the two loadings is the way they are applied, and the difference in the curves can be explained in terms of creep. If we load the specimen up to a certain stress and maintain the stress at that level, that means we are sustaining the stress with time, then over a period we shall see that the strain in the specimen has increased, and that is the effect of creep. From this we can understand that creep is the increase of strain with time, under a constant load, and the horizontal shift is called creep. The change from the fast loading curve to a slow loading curve can be explained by this phenomenon of creep.

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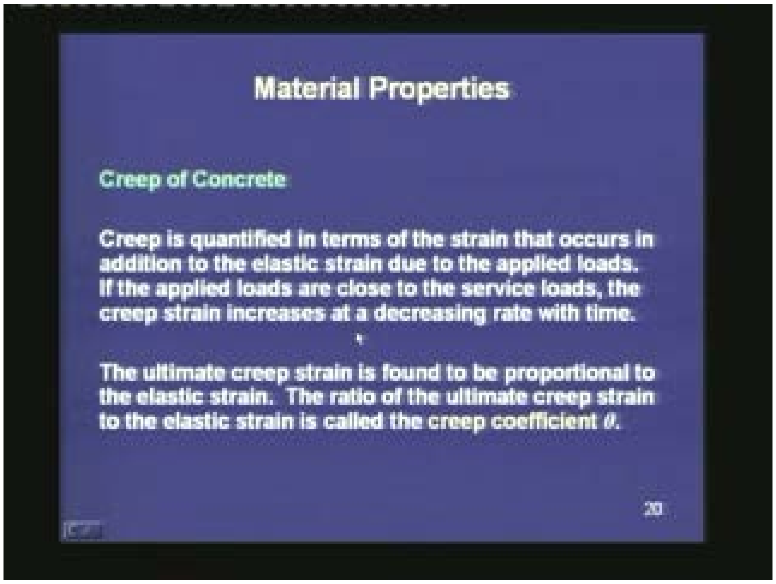

How do we quantify creep? The creep is quantified in terms of the strain that occurs in addition to the elastic strain, due to the applied loads. If we apply some load, there will be an instantaneous strain which is called the elastic strain and then, with time the strain will increase. The additional strain is termed as the creep strain. If the applied loads are close to the service loads then, the creep strain increases at a decreasing rate with time. This is a nice feature for design, that if the loads are sustained within the serviceable value, then the increase of strain with time gradually tapers off. If it did not taper off, then it would have been a problem. We will not be able to stop the deflection of the member; but luckily if the stresses are within the allowable service stresses, then the creep strain gradually tapers off and reaches a final value.

The ultimate creep strain, i.e. the maximum creep strain that occurs after several years is found to be proportional to the elastic strain. The ratio of the ultimate creep strain to the elastic strain is called the creep coefficient. To summarize, what we are most interested in is not the variation of creep strain with time, but the ultimate creep strain; that means the additional strain which occurs over several years, that is what we want to quantify. What we have observed is that if the stresses are within the serviceable values, then this ultimate creep strain is proportional to the instantaneous elastic strain. The ratio of these two strains, i.e. the ultimate creep strain divided by the elastic strain is defined as the creep coefficient θ.

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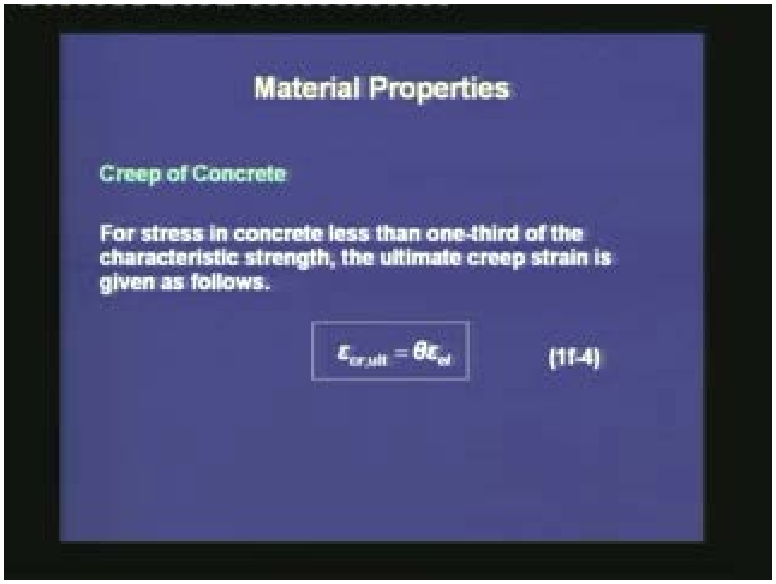

To summarize, for stress in concrete less than one-third of the characteristic strength, the ultimate creep strain is given as: $\varepsilon_{cr,ult} = \theta \varepsilon_{el}$. The code specifies that if the stress in concrete is less than one-third of the characteristic strength, then the ultimate creep strain is equal to a proportionality constant, which is called the creep coefficient, times the elastic strain which is much easier to calculate. This equation is thus very helpful for us, because we are able to calculate the elastic strain easily. From that, if we know the creep coefficient, then we can calculate the additional ultimate creep strain.

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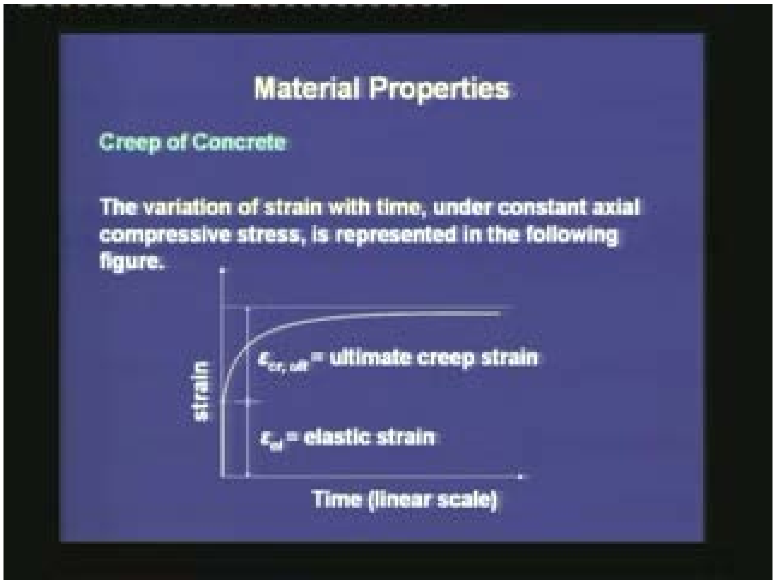

This curve will explain the creep in a different way. Here, we have plotted the strain with respect to time. The variation of strain with time, under a constant axial compressive stress is represented in this figure. When we apply the stress there is an instantaneous strain, which is called the elastic strain. This elastic strain is given by the Hooke's law, if the stress is limited to about one third of the characteristic strength. But then, with time the strain increases, and this additional strain is called the creep strain. This additional strain gradually tapers off to a value, which is called the ultimate creep strain and is represented by $\varepsilon_{cr,ult}$. This is a typical variation of the creep under a constant axial compressive stress. Thus, there is an initial elastic strain which occurs instantaneously, and then that strain increases with time till it almost stabilizes to a maximum value.

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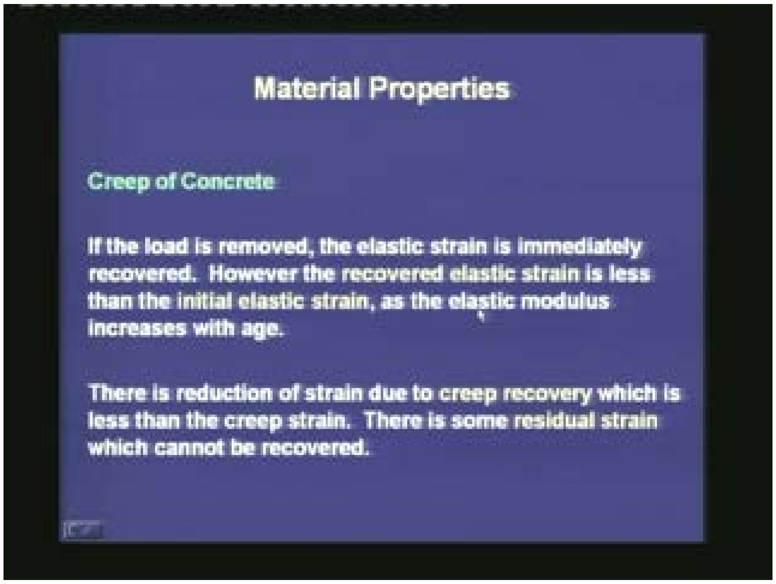

What happens if the load is removed? If the load is removed, the elastic strain is immediately recovered. However, the recovered elastic strain is less than the initial elastic strain, as the elastic modulus increases with time. This is an important phenomenon: if we have loaded the structure over a certain time and then, if we unload the structure, first there is an elastic recovery. That means there is an instantaneous drop in the strain. But this elastic recovery is not same as the initial elastic strain, because the modulus has increased over the period and hence, the elastic recovery is less than the initial elastic strain. There is additional reduction of strain due to creep recovery, which is less than the original creep strain. Thus, once we have unloaded the specimen, after the elastic recovery there will be further reduction of strain, which is called the creep recovery. But the creep recovery is not equal to the creep strain that has occurred earlier. There is some residual strain, which cannot be recovered. That means the residual strain is a permanent phenomenon, which cannot be recovered completely after it has been unloaded. There is a plastic deformation of the specimen.

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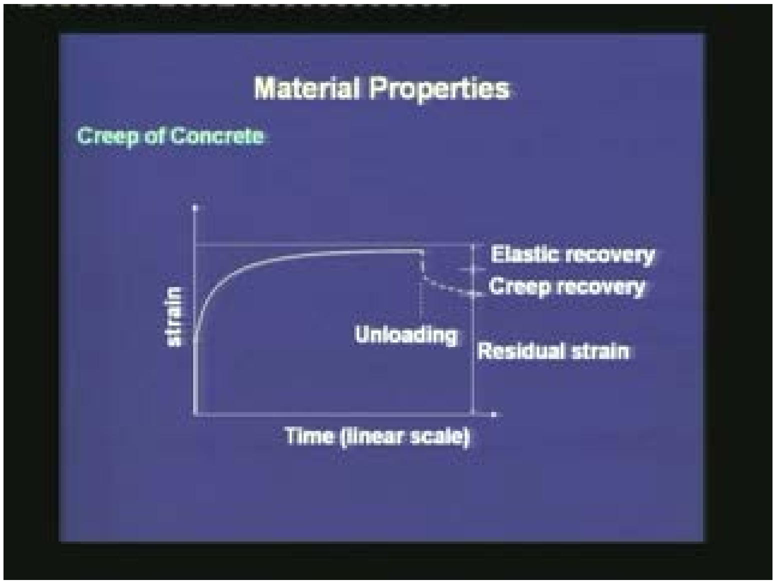

This is a plot, which is a continuation of the previous plot. First, you have an elastic strain. Then we have the creep strain, which gradually stabilizes to a maximum value. If at a certain time we are unloading the specimen, then there will be an elastic recovery, which is less than the original elastic strain. Then with time there is creep recovery, which is also less than the ultimate creep strain. The strain that remains after several years after the unloading, is called the residual strain of the specimen.

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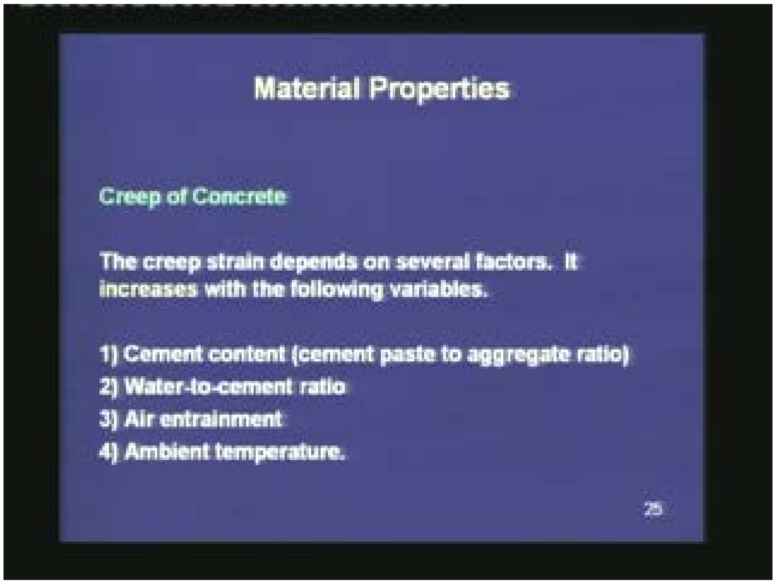

The creep strain depends on several factors. It increases with the following variables. First is the cement content, which can be quantified in terms of the cement paste to aggregate ratio. That means, the more cement paste we have compared to the aggregate we tend to have more creep. Second is the water-to-cement ratio. If the water-to-cement ratio goes up then the strength of concrete goes down, and it is observed that the creep of concrete also increases. Third is the air entrainment. If we have more air within the concrete, then due to the constant load we find that the air pockets are closing and hence, creeps strain is increasing. That means, with increasing air entrainment we have increased creep. Fourth is the ambient temperature. For higher temperature it is observed that the creep is higher.

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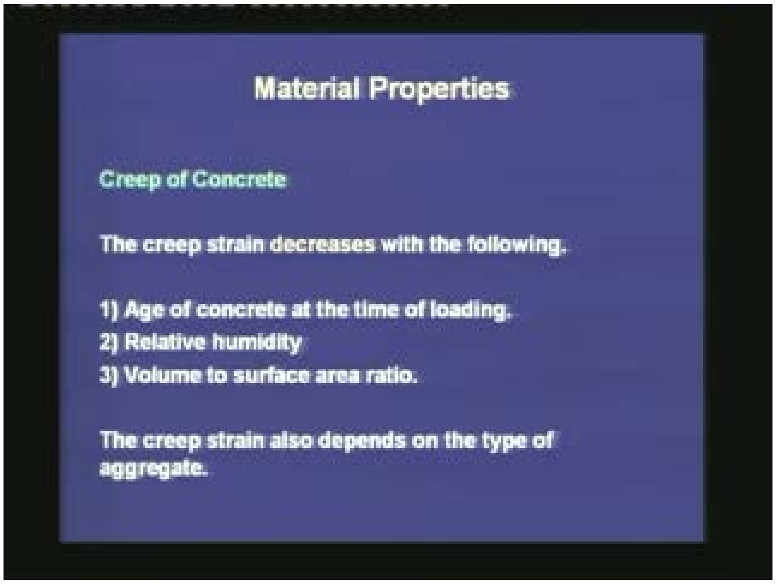

There are some other factors, where the creep strain decreases with those factors. First one is the age of concrete at the time of loading. In prestressed concrete this is a very important parameter. The code specifies that the concrete has to gain a minimum strength before the prestress is applied and then, there has to be a minimum time before the member is also subjected to the service loads. This is because if we delay the loading in the concrete then, we can observe that the creep strain is less. Hence, one way to reduce the creep strain is to load the concrete at a later period.

The second factor, which can reduce creep, is the relative humidity. If the relative humidity is high then creep reduces. The third is the volume to exposed surface area ratio for the member. If the volume to surface area ratio increases, in other words, for the same volume if the surface area decreases, the loss of water decreases and hydration is better. In that situation the creep is reduced. The creep also depends on the type of aggregates. There can be aggregates from natural sources, and there can be synthetic aggregates. It is found that the creep depends on the type of aggregates.

The calculation of the creep strain can be very involved. IS: 1343 gives guidelines to estimate the ultimate creep strain, in Section 5.2.5. This is a simplified estimate where only one factor has been considered.

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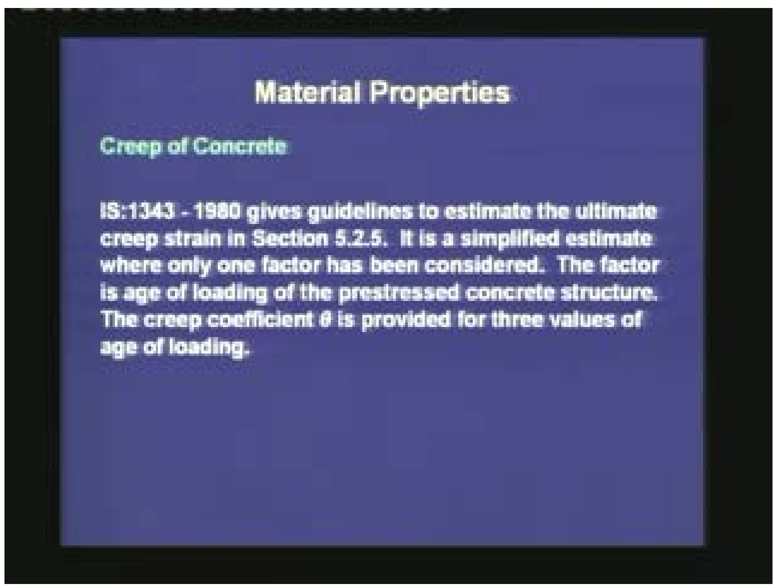

As I mentioned before that the creep strain depends on several factors. The code gives us a very simplified approach to calculate the creep strain, wherein the expression depends on only one factor, and this factor is the age of the concrete at loading (in short, age of loading). The creep coefficient θ is provided for three values of age of loading.

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To summarize, the expression in the code is a very simplified expression. It depends only on one factor, which is the age of loading of the concrete structure. The code gives us a table to calculate the creep coefficient, which is a ratio of the ultimate creep strain divided by the elastic strain. The creep coefficient θ is given for three ages of loading. When a specimen is loaded at seven days, we see that the creep coefficient is 2.2. That means, the ultimate creep strain is more than twice the elastic strain. If we calculate deflection just based on the elastic strain, the total deflection can be more than three times that value.

If the concrete is loaded at twenty eight days, then the ultimate creep strain is 1.6 times that of the elastic strain. Finally, if we apply the prestress at one year then, the ultimate creep strain is slightly greater than the elastic strain. From this table we can understand that one way to reduce the effect of creep is to delay the application of prestress in the structure. Sometimes, this can be a problem. Especially in a pre-tensioned member when there is a demand for the members, there is a tendency of applying the prestress quickly. But for the benefit of long term deflection, if we delay the application of prestress, and if we hydrate the specimen over a longer period, then we shall gain in terms of long term deflection due to creep. It is recommended to delay the loading of the structure, to delay the application of prestress so as to have the long term benefit of reduced creep deflection.

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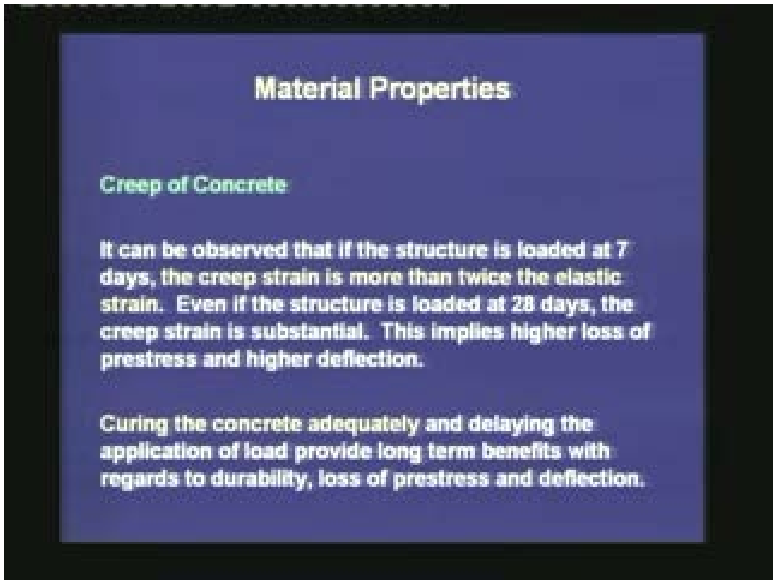

To summarize, it can be observed that if the structure is loaded at seven days, the creep strain is more than twice the elastic strain. Even if the structure is loaded at 28 days, the creep strain is substantial. This implies higher loss of prestress and higher deflection. Curing the concrete adequately and delaying the application of load provide long term benefits with regards to durability, loss of prestress and deflection. Here, there should be an understanding between the designer of the prestress member and the supplier of prestress member or the contractor, that let the specimen be cured properly; let it gain substantial strength before the prestress is applied, so that we have long term benefit of reduced creep. A reduction of creep will mean a reduction of loss in the prestress, and a reduction in deflection. It also will give good durability properties of the concrete.

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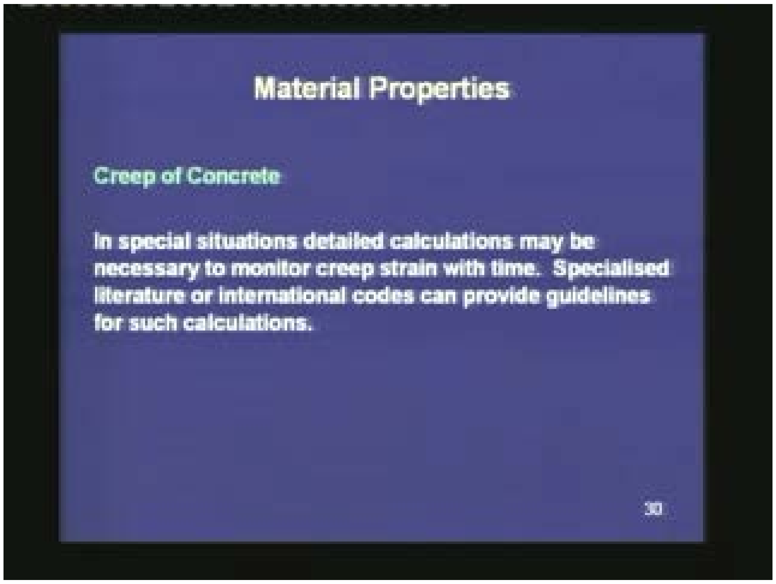

In special situations, detailed calculations may be necessary to monitor the creep strain with time. The procedure that is given in the code is independent of time. There we are able to calculate only the ultimate creep strain, which occurs after several years. We are not able to monitor the creep strain with time. In case, if we need to monitor the creep strain, then there are more involved expressions. We need to check specialized literature or international codes, which can give us guidelines to calculate the creep strain with time in a more detailed fashion.

Next, we are moving on to another important phenomenon of hardened concrete, which is the shrinkage of concrete.

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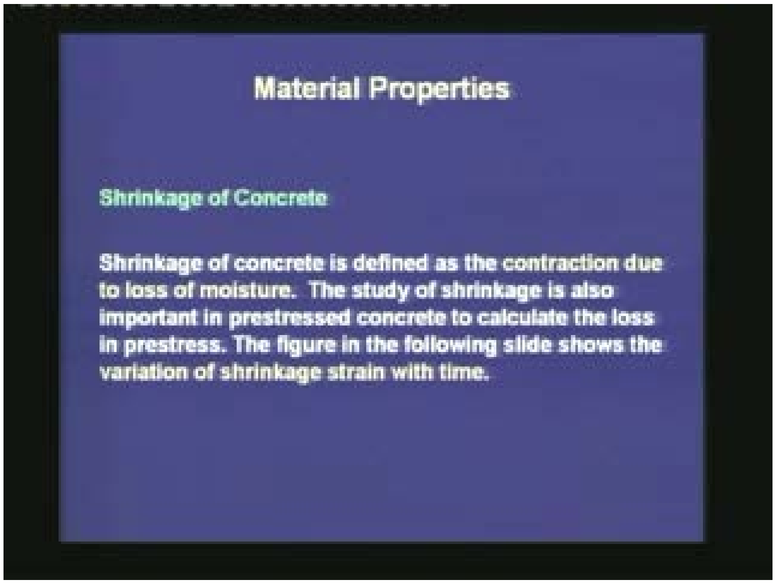

How do we define shrinkage? The shrinkage of concrete is defined as the contraction due to loss of moisture. The study of shrinkage is also important in prestressed concrete to calculate the loss in prestress. Just like creep, the shrinkage is also a phenomenon which varies with time. It has also the same effect, i.e. it will have a reduction in the prestressing force with time, and also it will lead to an increased deflection. Hence, the study of shrinkage is important in prestressed concrete. The following figure will show the variation of the shrinkage strain with time.

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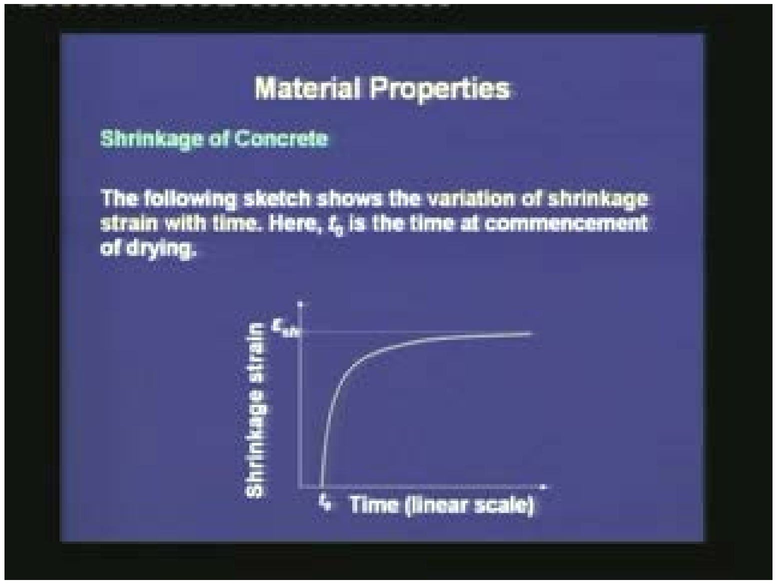

In this case, t_0 is the time at the commencement of drying. If a concrete specimen is properly cured, then during the curing period we do not observe shrinkage strain. The shrinkage starts due to the loss of moisture after the curing period. After t_0 we see that the specimen gradually reduces in length, and with time this reduction in length stabilizes to a maximum value, which we shall represent as ε_{sh}, the ultimate strain due to shrinkage. Its value depends on the time when the specimen is subjected to drying. Like creep, the shrinkage also depends on several factors.

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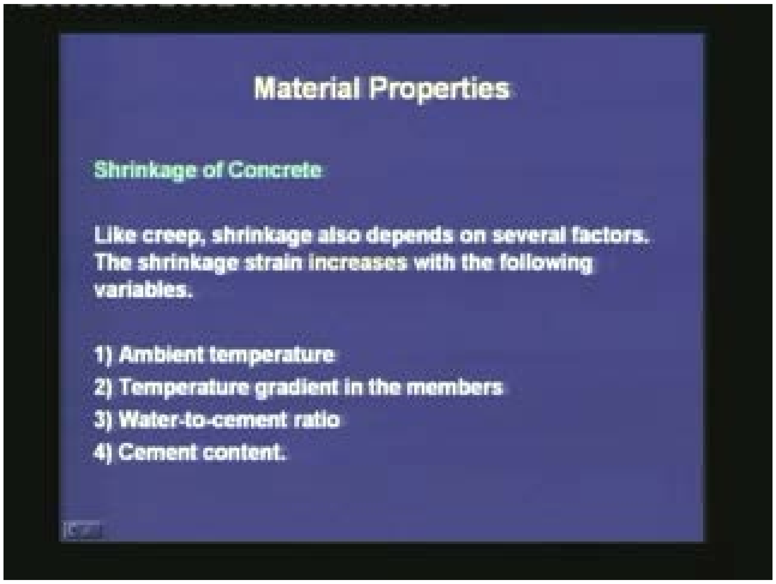

The shrinkage strain increases with the following variables. First one is the ambient temperature. If the temperature increases, then the loss of moisture is increased and the shrinkage strain increases. Second is the temperature gradient in the member. If a member is thick, then the loss of moisture from the interior parts of the member is low, and hence shrinkage is low. But if the member is thin like a slab, then the temperature gradient is less, and the loss of moisture is more and shrinkage is higher. Third is the, water-to-cement ratio. If we have higher water-to-cement ratio, then the strength of concrete reduces and during the drying period the loss of moisture is higher, and the shrinkage is higher. Fourth is the cement content. If the cement content is high compared to the aggregate, then also the loss of moisture leads to higher shrinkage.

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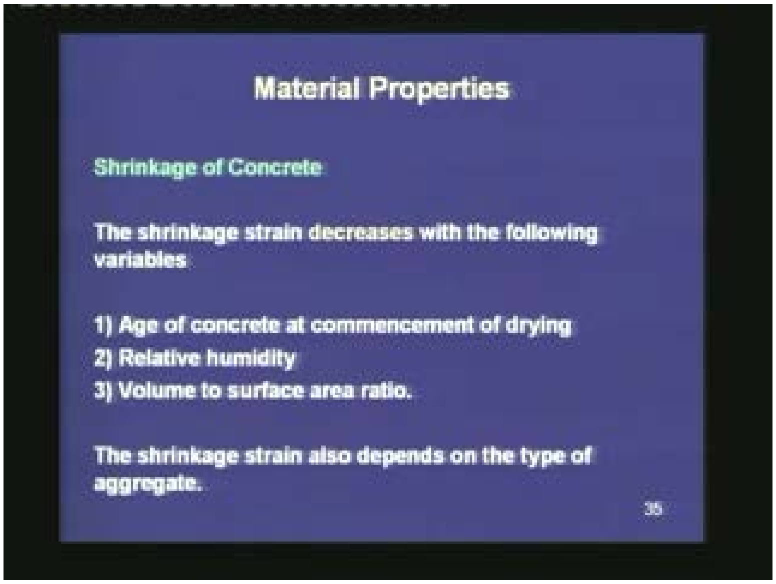

The shrinkage strain can decrease with the following variables. First one is, the age of concrete at commencement of drying. As I mentioned earlier that the variable t_0 (means the time when the drying starts) is an important parameter for determination of the creep. If the drying starts early then the creep will increase; but if the drying is delayed or in other words, if the age of concrete at commencement of drying is increased, then the shrinkage strain will reduce. Next is the relative humidity. If the relative humidity increases, then the loss of moisture decreases and hence, the shrinkage strain decreases.

The third is the volume to exposed surface area ratio. If the volume to surface area ratio increases, it implies that for a given volume, the surface area is reduced. That will lead to a reduction in loss of moisture, and hence the shrinkage will reduce. A specimen in which the exposed surface area is large, there will be higher loss of moisture. The shrinkage strain also depends on the type of aggregate. We see that if we use natural aggregates then the shrinkage can be less compared to, if we use synthetic aggregates.

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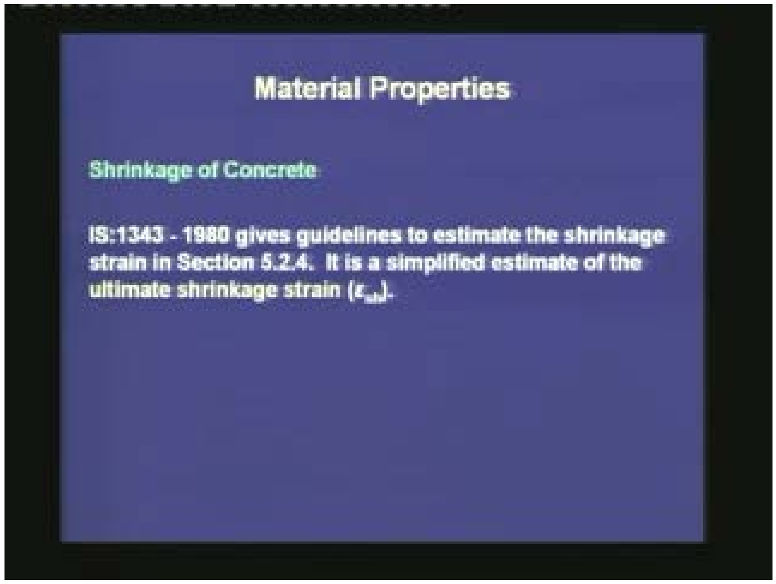

The IS: 1343 gives guidelines to estimate the shrinkage strain in Section 5.2.4. It is a simplified estimate of the ultimate shrinkage strain.

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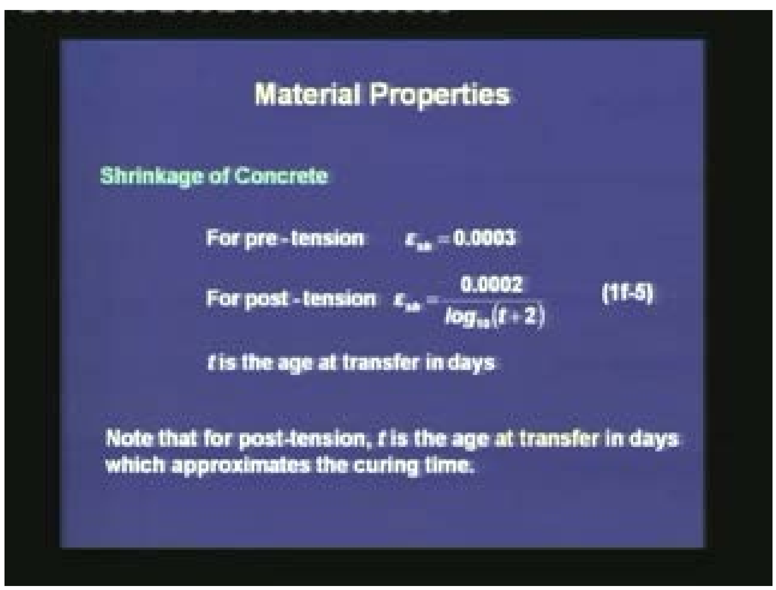

As I said before, that the shrinkage strain is a function of time. But the code gives us a simplified expression, which is independent of time, and which is an estimate of the ultimate shrinkage strain. For a pre-tensioned member, the shrinkage strain is given as

0.0003; for a post-tensioned member, the shrinkage strain is given as a function of the time (t), where ‘t’ is the age at transfer in days. It is assumed that t is the approximate curing time. If we delay the transfer of prestress, then the shrinkage will be reduced and that will be beneficial for the prestressed member.

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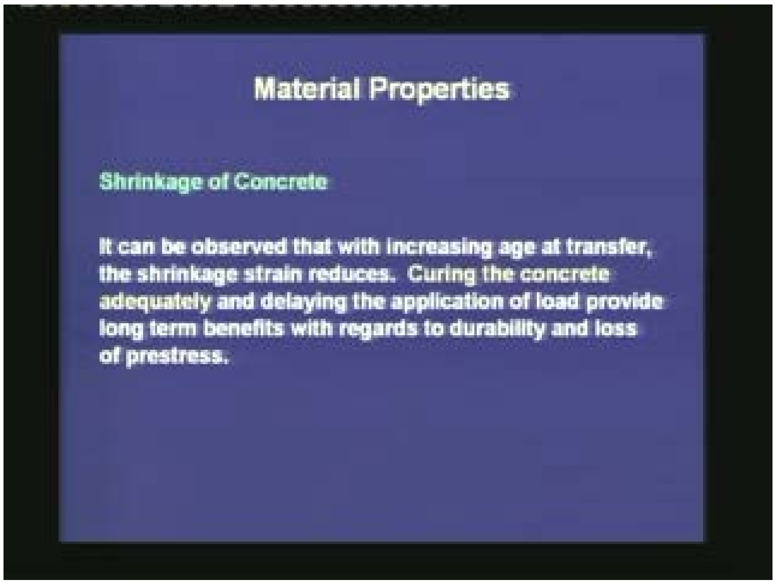

Thus, it can be observed that with increasing age at transfer, the shrinkage strain reduces. Curing the concrete adequately and delaying the application of load provide long term benefits with regards to durability and loss of prestress. This observation is similar to creep. That means, if we cure the specimen properly and if we delay the prestress, then although we may lose a few days initially, in the long term it will have added benefits of reduced creep, reduced shrinkage and hence, a reduced loss of prestress and a reduced deflection. Thus, for the long term benefits it is always advisable to cure the specimen properly and to delay the application of prestress.

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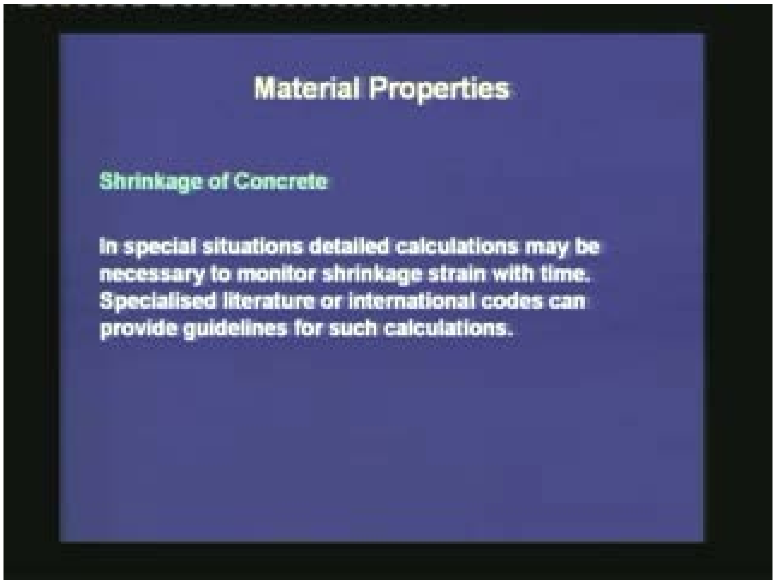

In special situations, detailed calculations may be necessary to monitor shrinkage strain with time. The expression in the code is independent of time; it gives a value of the ultimate shrinkage strain. But if we have to monitor the loss of prestress with time, we may have to estimate the shrinkage strain with time. In that case, specialized literature or international codes can be referred to for guidelines.

Next, we move on to the properties of grout.

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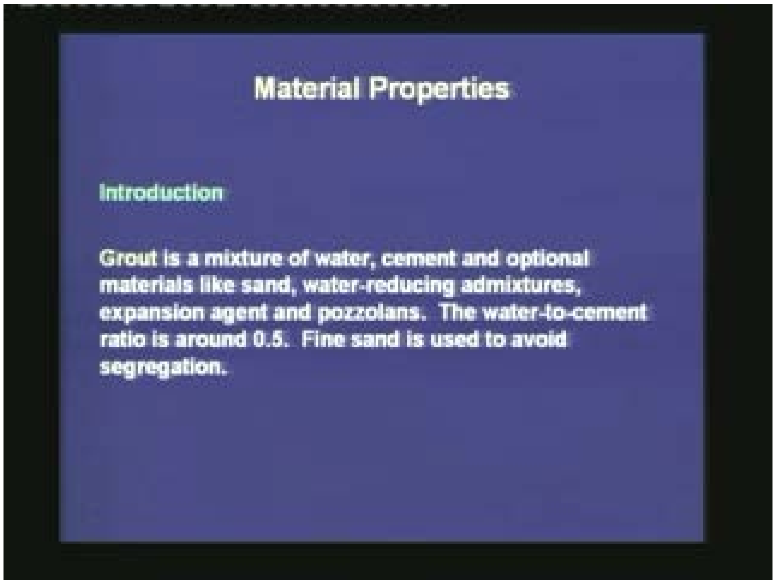

In our previous lectures, we have mentioned that for post-tensioned members it is advisable to grout the tendons, which helps in transferring the stress from the tendons to the concrete over the length of the members. The grout also has an anti corrosive environment for the tendons, and the grout should be strong enough to sustain the load over time.

What is grout? A grout is a mixture of water, cement and optional materials like sand, water reducing admixtures, expansion agents and pozzolans. The grout is primarily a mixture of water and cement. We may add sand or some admixtures or some expansive agents and pozzolans. The water-to-cement ratio is around 0.5. If we are using sand then the sand should not be coarse. We should always use fine sand to avoid segregation. Unlike concrete, grout has to be very fluid, because it is pumped through a long distance of the prestressed member. During the pumping, the materials should not segregate and for that fine sand is recommended instead of coarse sand.

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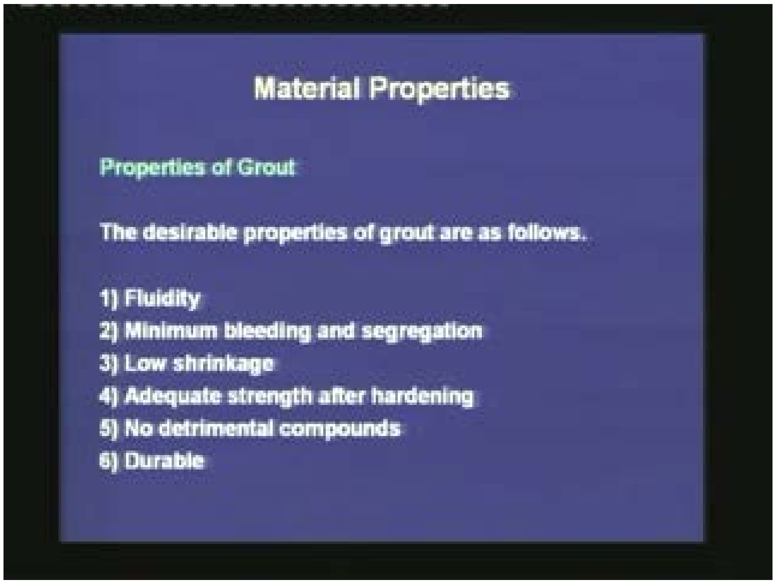

The first desirable property of grout is fluidity, i.e. it can be pumped. Usually the post-tensioned members are larger and longer. Hence, if we are pumping the grout from one side it has to reach the other side, and excess amount of grout should flow out to make sure that the full annular space between the tendon and the concrete has been filled.

The second important property is, minimum bleeding and segregation. Bleeding means the floatation of water over the sand and the cement. In the grout, the constituents should not segregate in order to maintain its property and in order to have a minimum strength. Hence, the grout should be such that we have minimum bleeding and segregation of the constituents. The third is low shrinkage. If the grout shrinks, then there may be voids in the duct, which may lead to the ingress of water, and hence to corrosion. Thus, the grout should be of low shrinkage such that voids are not created, and it fills the annular space completely during the service life of the structure.

The fourth important property is adequate strength after hardening. A grout is a medium through which the prestressing steel is transferring the stress to the concrete. If the grout itself is weak, then it will not be able to transfer the stress. Hence, it should have adequate strength after the hardening. The fifth property is no detrimental compounds in the grout. The grout should not have any compound which will lead to the corrosion of the prestressing tendon. The grout should maintain an alkaline environment for the anti-corrosive property and finally, the grout should be durable with time. That means the properties of grout should not change during the service period of the structure.

IS: 1343 specifies the properties of grout in Sections 12.3.1 and 12.3.2. Out of these specifications, a few are mentioned here which are more important.

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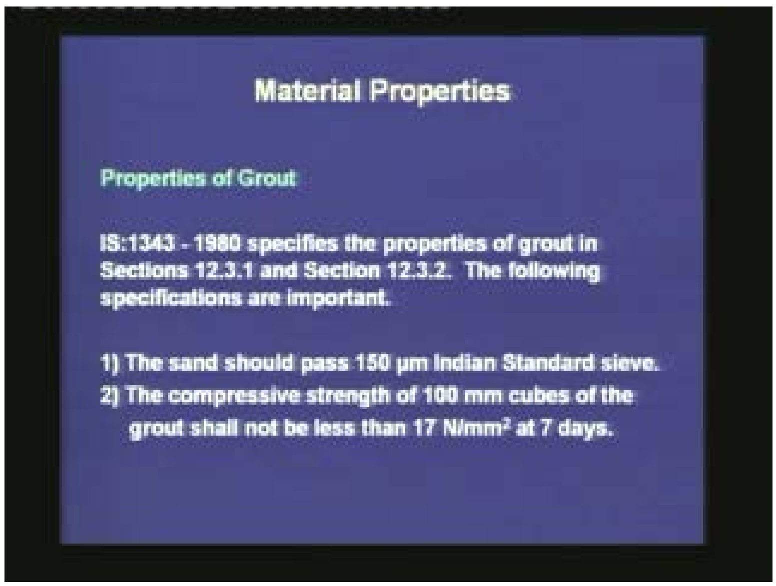

The first one is that the sand should pass a 150 μm Indian standard sieve. As I mentioned before, that in order to avoid segregation in the constituents of the grout the sand should be fine. To ensure that, the code recommends that the sand should pass through a sieve of 150 μm. The second necessary property of the grout is that the compressive strength of 100 mm cubes shall not be less than 17 N/mm^2 at seven days. The code specifies a minimum compressive strength of 17 N/mm^2 for 100 mm cubes made of the grout and after seven days of curing.

Besides these, the code also specifies some other provisions for concrete.

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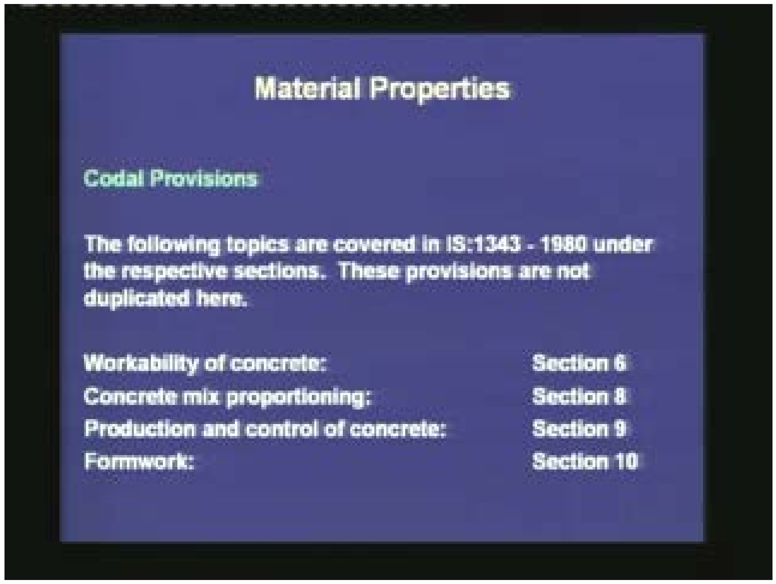

These provisions are not mentioned in detail in this lecture. The provisions are self explanatory, and they can be referred to whenever they are needed. We are just summarising the properties. The code specifies the workability of concrete in Section 6. The concrete mix proportioning is specified in Section 8; the production and control of concrete in Section 9. The specification for formwork is given in Section 10.

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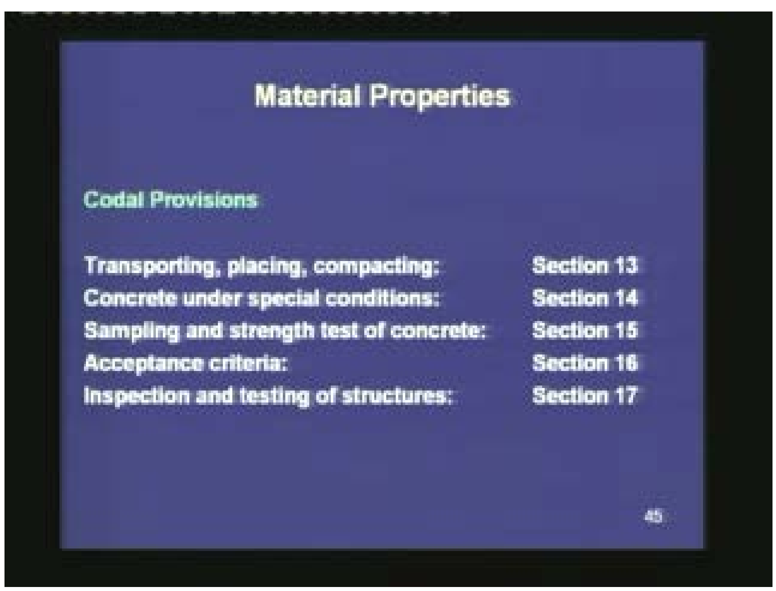

Transporting, placing and compacting concrete are very important for the durability of the concrete and the prestressed member. These provisions are given in Section 13. For concrete under special conditions, like under cold temperature or very high temperature, the specifications are given in Section 14. The sampling and strength test for concrete is given in Section 15. As we mentioned earlier, concrete inherently has variable properties. There is a particular way of testing the concrete specimens, which is specified in the code in Section 15. The acceptance criteria are given in Section 16. During concreting of the specimen, it is recommended that proper inspection is done.

Prestressed concrete members are more susceptible to damage if the concrete is not done properly. Hence, the acceptance of the concrete is very important for prestressed members. Especially, the concrete should be of good quality during the transfer of prestress, both for pre-tensioned and post-tensioned members. The inspection and testing of concrete structures are covered in Section 17. Again to repeat, the inspection of the casting of concrete is more important in prestressed concrete members as compared to reinforced concrete.

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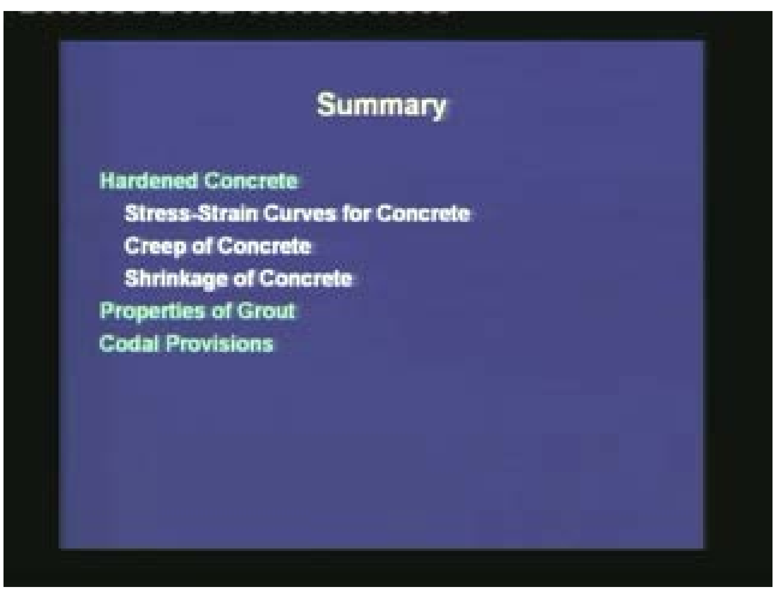

In today's lecture, we had started with the continuation of the properties of hardened concrete. First, we studied the stress-strain curves for concrete. We learnt that we need these curves if we have to understand the behaviour of the concrete members. We had studied two types of curves. One is the stress-strain curves for concrete under compression and next, the stress-strain curves for concrete under tension. For compression, the simpler curve is the Hognestad model, which is applicable for normal grade of concrete. But if we are using high strength concrete beyond 60 MPa characteristic strength, then the Hognestad parabola may not be suitable. We found that there is another expression, which can model the ascending branch and the descending branch of high strength concrete better. Next, we moved on to the creep of concrete. We have learnt that the creep should be minimized in order to reduce the loss of prestress. We understood the phenomenon of creep, the factors affecting creep and how to reduce the creep strain.

Next, we moved on to the shrinkage of concrete. There also we understood the parameters of shrinkage, and how to reduce shrinkage so as to reduce the loss of prestress. We studied the properties of grout, and we know that the grout has to be of good quality in the post-tensioned members. Finally, we summarised the codal provisions that are there in the code. Most of these provisions are self explanatory. They are to be followed during the casting of concrete, and during the curing of the concrete, before the prestress is transferred.

Thank you.