Advanced Concrete Technology
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Lecture - 31
Shrinkage: Mechanism and Behaviours

So let us resume our discussion on compressive and impact toughness that we were talking about in the last class. So here we were trying to investigate the influence of combinations of fibres, hybrid fibres essentially looking at combinations of steel and non-metallic fibres on the properties of concrete and we investigated through a semi deflection controlled approach the toughness of fibre reinforced concrete as they were affected by the presence of steel fibres and other non-metallic fibres in the system.

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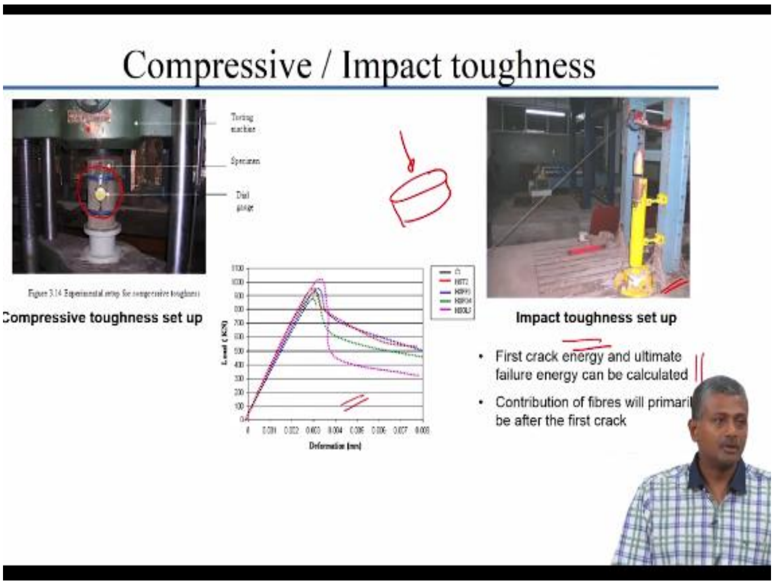

The same experiment was repeated as I said with compressive and impact test setups, but of course the degree of control in the compressive setup was not very good. As far as impact is concerned we were looking at the number of times the load of a certain level was dropped from a given height on to the specimen and the number of times it had to be dropped before the first crack appeared and beyond the first crack, the number of additional times that the load had to be dropped for completely splitting apart the concrete specimen.

So that was the impact toughness setup. Now of course there is additional studies that have been done in our lab.

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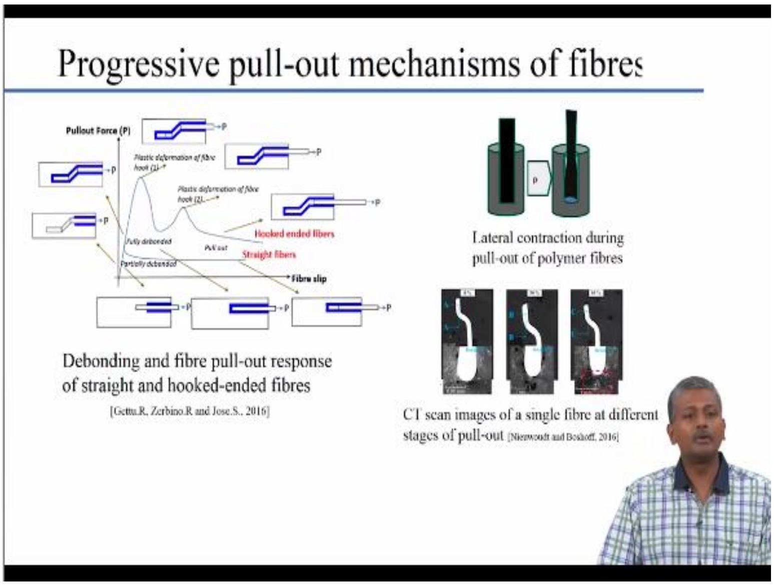

There are some students extensively working on different aspects of fibre reinforced concrete one of them is Sujatha and she has done some work on understanding the progressive pull out mechanisms of fibres. So here what this tells you is a typical pull-out force versus a fibre slip diagram. So again what you do is essentially apply a pull out load to the fibre and look at how it is actually pulling out of the matrix, okay.

So that is what is being depicted here. So you have different kinds of scenarios here especially if you have either a plane fibre or a straight fibre or a hooked in fibre. So what happens in the case of a straight fibre is that you get a complete de-bonding and then the fibre simply gets pulled out of the system. In the case of a hooked in fibre you have a slightly different sort of a system.

Because here in the initial parts you actually get a transfer of stress across the length of the hook and then the straightening of the hook will be happening towards the first part of the experiment. So here what you see because of this increase in load here is because of plastic deformation of the hook itself. So again this hook first start straightening out and then only it starts getting pulled out.

So this plastic deformation actually leads to these humps being formed in this diagram and finally there is pull out that is actually happening with the hooked in steel fibres. So again this is similar to your performance of the tie bars in a reinforced concrete column, right. If you have a tie bar which is closed like this, right. In the case of an earthquake, right, what happens to these tie bars, they will snap open and then your entire column will collapse immediately.

So what do you do for earthquake detailing you need to close these tie bars in this fashion so that any lateral force like the earthquake will first have to cause this tie bar to open up and then the collapse of the column will happen. So that would be a much better performance as opposed to if you have a 90 degree tie bar. So that is why we say that during earthquakes the detailing of the reinforcing bar is fundamentally important.

Because only that leads to a much more ductile and slow collapse of your structure. Similar to that having hooks at the end are really helpful because the straightening of the hook is able to absorb a lot of energy before the fibres starts deforming and getting pulled out of your system okay, again this is actually a x-ray microtomography study which looked at the deformation that was suffered by the fibre before it got really pulled out of your system.

Well you can conduct this under specific circumstances, for example there are microscopes in which you can actually do a test setup with a single fibre. So people have actually done microscopic studies where the specimen which has a single fibre inside the system is observed under the microscope.

So you can actually set it up like that or you can do a tomography study for example here, what is shown here is an x-ray tomography study where the entire setup is mounted inside the chamber of the x-ray tomography instrument and as the pullout is going on the x-rays are continuously scanning to get an image of the object.

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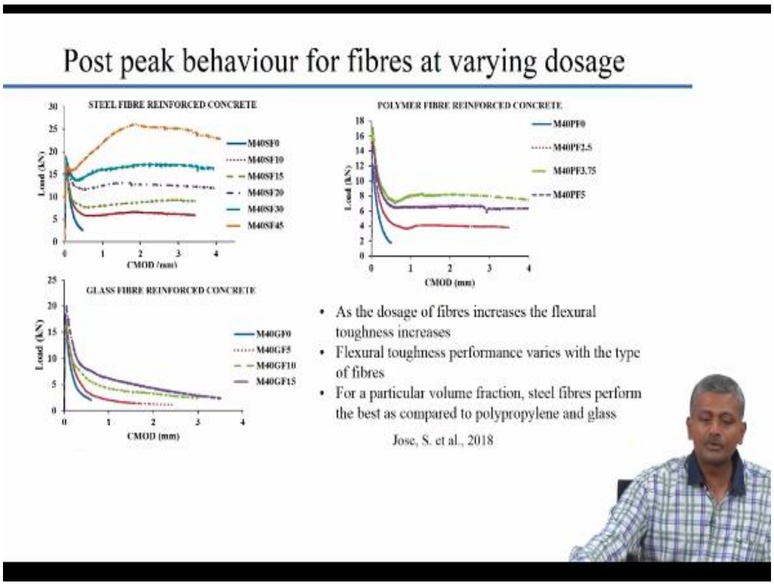

Now of course the post peak behaviour of fibres as I told you earlier can vary a lot depending upon the type of dosages that we have. Initially we had talked about the engineered cement composites when you have a very high fibre loading you may actually end up getting a strain hardening behaviour from the fibre, indeed that is what you are actually seeing in this result here.

These are M40 concrete mixes with steel fibres at different dosages starting from 0 all the way up to 45 kilograms per cubic metre, okay, in terms of volume fraction how much is that? 45 kilograms per cubic metre, the density of steel is what? 8000 kilograms per cubic metre, right, so if you have 40 kilograms per cubic metre that accounts for 0.5% by volume of the concrete, okay.

So typically fibres are used in that level when you use steel fibre you will be using around 0.5 to 1%, okay, that is probably going to be a high loading, but at the lower end for example when you want pavements and other such structural components you can actually have much lower loading like 0.25% or 0.15%, that is why this range of dosages was attempted in the study from 0 to 45 kilogram per cubic metre.

And you can obviously see for the plain concrete there is not much deformation, but as the fibre dosage increases the extent of ductility that they can get from the system gets enhanced significantly and actually at the very high dosage you are even observing some strain hardening cementitious behaviour that causes your stress to actually go up even after that initial deformation or kink happens in the system, okay.

So in terms of polymer fibre reinforce concrete there is only a certain maximum to which you can actually go. You do not really get too much additional contribution to the polymer fibres because extent of stress that can be carried by these fibres is very small, right, polymer fibres are not that strong as far as tensile loading is concerned, steel fibres are much stronger than that. Glass fibre the problem is more related to the brittleness.

You really do not get much deformation and the fibre may start rupturing before you get sufficient pull out from the matrix. Because of that the performance of glass fibre is not really as good as that of steel fibres.

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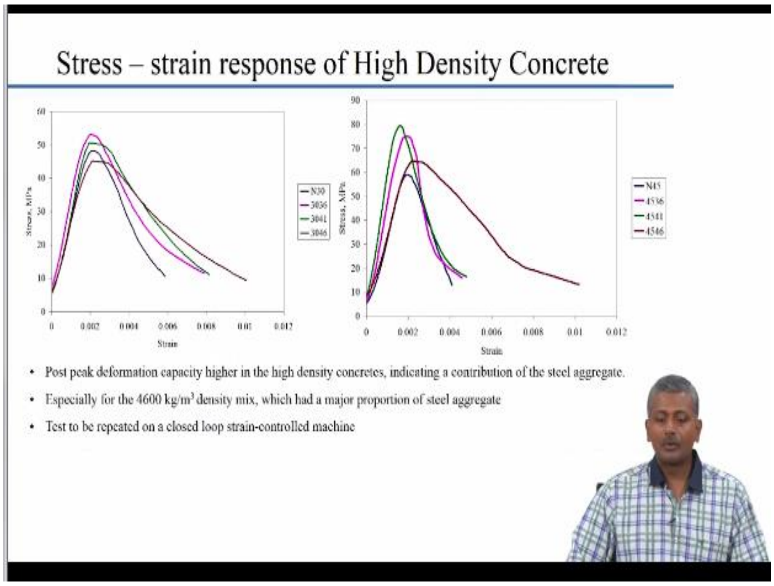

Now this is another example that we had actually done in the lab when we wanted to study the stress strain characteristics of high density concrete. Now high density concrete typically is used for very specific applications like the radiation shielding in nuclear reactors for instance. There you need density is typically in excess of 3.5 gram per cubic centimetre and generally this high density is obtained by using heavyweight aggregate.

Instead of using normal limestone or granite based aggregate which have a density of close to 2.8 to 2.9, we try to use hematite or magnetite or ilmenite aggregate where densities are typically more than 4.5 or 5, okay. So when you use these aggregate so obviously the resultant density of the concrete is also very high.

So here this was a project that we were actually doing for Indira Gandhi Centre for Atomic Research where we had to look at the structural characteristics of high density concrete because apart from the radiations shielding characteristics we also had to get some estimate of what the engineering properties of these high density concretes were. So we attempted to study this high density concrete using a compressive stress strain relationship like what I showed you earlier.

We tried to measure the compressive stress strain relationship by using cylindrical specimens and observing the deformation when the load was applied and this was exactly in the same sort of a way that I had demonstrated earlier so here the post peak deformation capacity is higher in the high density concrete. You can see that compared to normal weight concrete which is here the higher density concrete seem to have a higher post peak deformation capacity.

Now that in some ways could be attributed to the fact that we actually used steel inside these as aggregate, inside the high density concrete we actual used steel as aggregate. Now instead of using steel based raw materials like hematite or magnetite as aggregate you can also use cut rods of steel and include them in aggregate sizes. For example, here we had used 2 different rods one was an 8 mm diameter rod and one was 20 mm diameter rod.

Each were cut to a length of about 20 mm to almost get aggregate sized particles from the steel and these were included to ensure that we were able to get densities of the order of 4.6 grams per cubic centimetre also. So this 3.6 grams per cubic centimetre, 4.1 and that is 4.6 grams per cubic centimetre.

As you can see in the higher grade concrete that is M45 grade concrete that there is sufficient deformation that we actually were able to obtain with the 45 46 mix that corresponds to the 45 megapascal concrete which is achieving 4.6 gram per cc as the density. So again I do not have full faith in these numbers of course, because again these were done with the setup which was not truly deflection controlled, okay.

In the case of a compressive deflection control what you need to do is control the rate of circumferential expansion. So if cylinder is getting loaded in uniaxial compression it is not this deformation that we need to control, what we need to control is the circumferential expansion, because ultimately when the cylinder is getting compressed it is trying to bulge outwards and that outward bulging is what we need to control if you want to get a slow and steady failure rate, okay.

So for that what people have done is they have used chains along the circumference and connected a length deformation gauge to the chain, a clip gauge to the chain. So as the concrete expands laterally the chain, the clip gauge in the chain starts getting subjected to tensile strains, then we start recording the strains directly and that is sent as an input into the system to control the rate of the next load.

Now this is now possible with the equipment that we have the MTS machines that you see in a lab can actually do this strain control test for the compression of cylinders also. These were not done using the same test so there is only some limited level of information that can be actually obtained from this.

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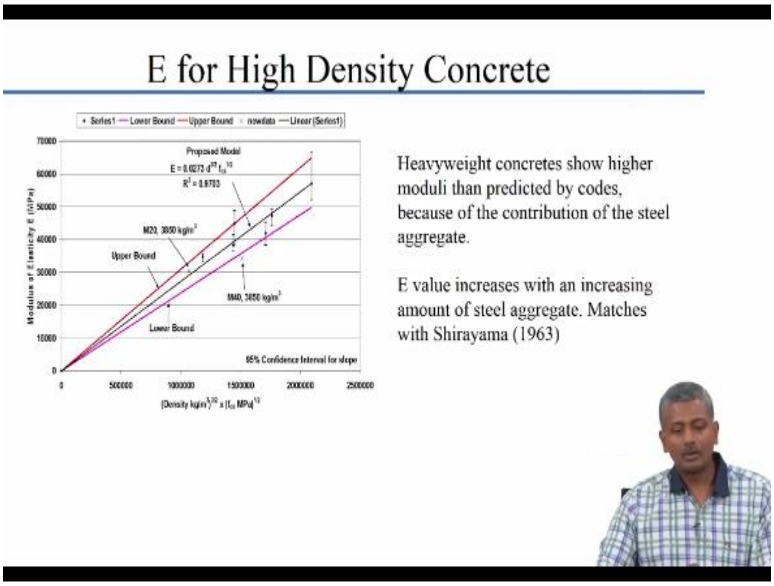

Now what we also wanted to do is look at what differences were there in the engineering characteristics of high density concrete as supposed to normal density concrete. Normal density concrete we typically assume that your modulus is equal to 5000 square root of fck. Now if you really go in to the basis for determination using this kind of an equation this is derived from an old ACI standard where the modulus is seen to be directly proportional to the density of the material to the power of 3 * 2 and strength to the power of half.

Okay again there is no science behind this relationship it is only a fundamental, sorry, it is an empirical relationship that has been derived from large data sets that have been collected by the researchers, okay. So originally when this relationship was first proposed it was based on the fact that your modulus was seen to be varying directly with the 3 * 2 power of the density multiplied by the square root of the compressive strength.

Now for normal density concretes when you convert this density into a normal density concretes like 2400 kilogram per cubic metre this entire expression translates into 5000 square root of fck, okay. So what we thought was for high density concrete we found that this relationship was really not predicting the moduli of elasticity well enough. So we actually measured the moduli of elasticity using the equipment.

But we found that the relationship was quite different from what was suggested for normal density concrete as per IS. So we wanted to see what the relationship could be so again we went back to the basics and plotted modulus of elasticity against the density to the power 3 * 2 multiplied by the square root of compressive strength.

Again there is nothing scientific or fundamental about it, it is again a way of expressing the data and indeed from this we were able to get a very good fit in terms of a straight line relationship and a new model for estimation of the E value from the strength and density of heavyweight concretes was proposed. So we actually had done this design with certain types of mixes which led us to this straight line relationship.

And then later we also made some random mixtures which were not part of the original study and saw whether they were following this relationship properly or not. So these 2 mixtures that I have marked in red those are the ones that were additionally casted which were not from the same set of mixtures that were used to actually get this relationship. So these were mixes additionally casted and we wanted to see whether they were satisfying this relationship.

So within certain error you can see that these are satisfying the straight line relationship also. Very often we see data that has been generated from a set of mixers that have been done, right, and a relationship that is based on the data generated in the research study and people say that for validation they choose data points from the same experimental set, that is actually not correct, that is why we wanted to avoid that and we chose 2 data points that were totally outside the experimental data set.

This was done at a different time just to look at the validity of this relationship and this was seen to have, the relationship was seen to be quite good in terms of that. So what we wanted to get at was to propose a new model for calculating or determining the modulus of elasticity based on the compressive strength, again only for engineering purposes, this does not have any fundamental background or basis, okay.

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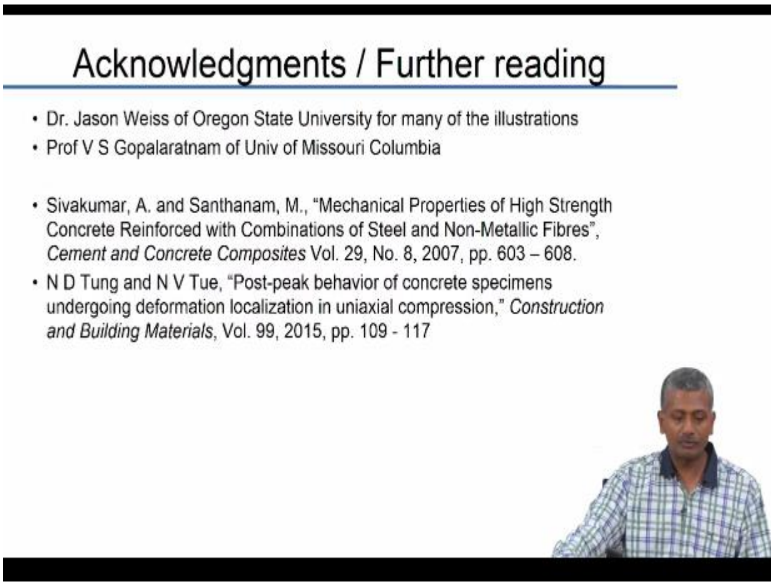

So there are of course several papers that have been published on understanding stress strain characteristics of concrete in compression and in tension in flexure. So I suggest you should do additional reading to get a good idea about what these papers are saying and also like to acknowledge Dr. Jason Weiss for much of the illustrations dealing with the post peak behaviour and of course also the lecture notes were enhanced because of inputs from Professor Gopalaratnam from University of Missouri Columbia.

So with that we come to the end of this chapter on hardened concrete, okay. So one of the important characteristics of concrete is it is ability to sustain it is volume during its entire service period.

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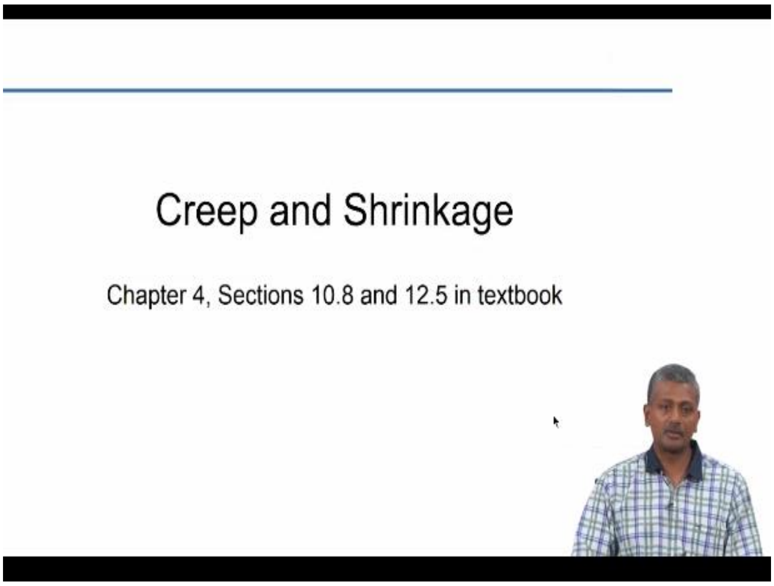

In other words, the dimensional stability of concrete becomes very important when we talk about time dependent deformations that can happen in the concrete as a material. Now concrete is composed of 2 primary phases, you have cement paste phase and the aggregate phase and the cement paste phase as we discussed earlier has different forms of water associated with it.

Some water is obviously bound in the structure of the cementitious hydration products, there is other water which is held between the layers of a calcium silicate hydrate or in capillary pores. So this water when you subjected to a sustained loading or when you subjected to external drying will have a tendency to migrate from the current location to other locations either within the material or if the drying is high enough outside the material.

So this may cause volumetric deformations of the concrete, the resistance to that volumetric deformation is essentially the basis for your dimensional stability of the concrete. So here creep and shrinkage in your text book it is covered in different chapters. Chapter 4 primarily addresses this in a large extent and then you have sections 10.8 and 12.5 which also talk about this aspect with respect to concrete.

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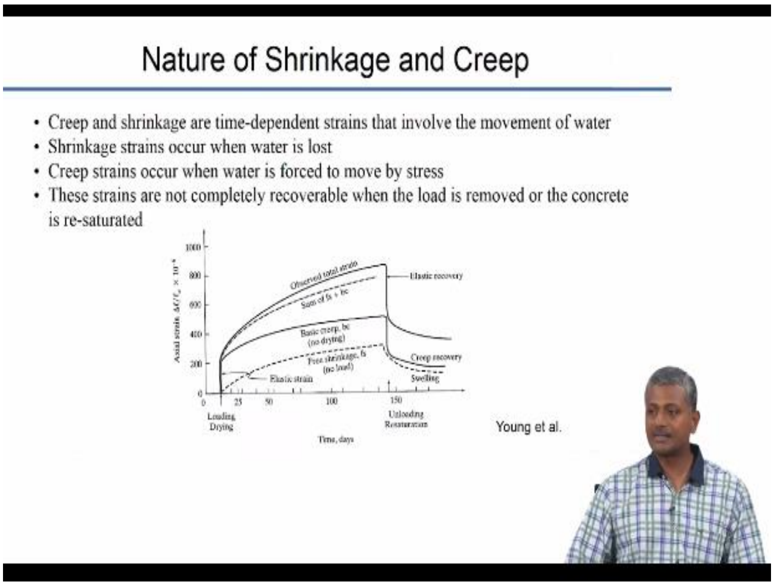

So of course as I was telling you earlier just now that water present within the concrete is responsible for the deformability of the concrete with respect to time dependent effects like creep and shrinkage. So movement of water either within or out of the concrete causes these types of defamations that you observe in creep and shrinkage. So shrinkage obviously happens when water is lost from the system, creep happens when water is forced to move by stress.

So again if you were able to compare this to some other event that happens in civil engineering they can think about this as a form of consolidation of the concrete. So consolidation of a structure on a soil happens when water starts dissipating due to the sustained loading of the structure that is exactly what is happening in this case. Water dissipates either within the concrete or out of the concrete depending upon the kind of conditions that exist.

So strains which are built up because of this deformation are not completely recoverable. What do I mean by that, if you have shrinkage and water drives out of the concrete simply rewetting the concrete may not be able to force the water back into where it was earlier, okay? So you will get some permanent rearrangement of the materials that are within the concrete. So again if you look at the general representation of creep or shrinkage it is done in terms of axial strain on the y-axis versus the time on the x-axis.

Now of course there are different ways that you can look at it, one is you can look at free shrinkage of the concrete, right, when concrete is free to shrink that means there is no restraint that is caused to it is shrinkage. So that is what is shown here at the bottom, free shrinkage without any loading in the structural member. So obviously the time that drying starts the concrete will immediately start to shrink.

And the strain in concrete will continue to build up with time. At a given point if I start wetting the concrete again it will recover some of the deformation, but there will be an overall permanent volumetric change that has built-in because of the shrinkage that happened in the first stage, okay. So this extra recovery of your volume is because of swelling when it starts absorbing the moisture again, okay.

Now in practice shrinkage would not happened on its own because most members are also loaded so you will definitely also get some creep. Creep is basically change in volume because of sustained loading and if you look at basic creep when there is no drying for example if you consider a sealed concrete element, okay, so which is subjected to loading, but there is no drying because the material is sealed.

Now basic creep is composed again of 2 or 3 components we will see the components later. As soon as you load the material you get an immediate strain that is basically the elastic response of the material. With time, you get the time dependent response of the material, okay. So even when there is no drying creep can happen obviously because of loading. You have the elastic strain and you have the time dependent creep strain which keeps on building up in the material.

At a given point when you unload the material what happens, it instantaneously recovers the elastic strain, right, but then it cannot recover fully the strain which was associated with the time dependant factor, okay. So some volumetric deformation is built-in into the material. In reality, creep and shrinkage are going to happen together. So if you sum up these 2, if you sum up the free shrinkage and the basic creep you will get this dashed line.

Sum of basic creep and free shrinkage, but in reality the actual deformation that you observe for materials that are undergoing both loading and drying is much higher than the sum total of your free shrinkage and basic creep. This suggests an additional mechanism which is governing your deformation, what is that? see the sum total of free shrinkage and basic creep is lesser than the actual deformation that the material suffers when it is loaded and is drying at the same time, right.

So there should be some additional contribution which is leading for this curve to be higher than that of the sum of free shrinkage and basic creep, what is that additional contribution? When you mix the 2 words drying shrinkage plus basic creep you get, when you combine the 2 words you get something called drying creep, okay, you have drying creep.

Please remember your structure is not deforming in response to the applied load and water is getting driven out of your system, okay so because of drying, water is driven out of your system, so not only is the water dissipating within the material, it is also getting driven out because of the drying conditions. So this additional contribution that you see is because of drying creep.

So creep that happens in drying conditions is more than creep that happens in sealed conditions, okay. So that is what you are actually observing when you see the higher strains as opposed to the total of your free shrinkage and basic creep.

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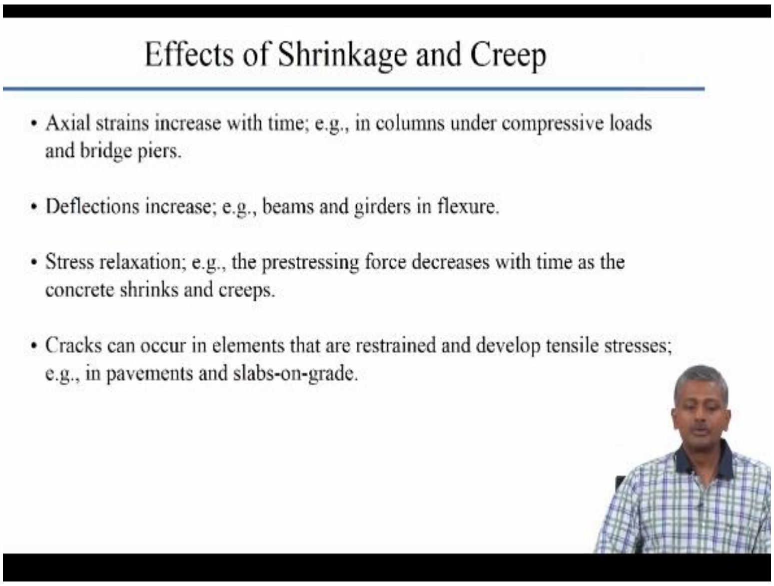

So what happens because of shrinkage and creep? Obviously if you are looking at a compression member the axial strains are going to be increasing with time, right? In the case of a flexural member like a beam you may have creep and shrinkage happening in the opposite direction. So flexure is going to pull your material right, if you look at the bottom most fibres which are in tension, the fibres are getting pulled because of flexure. So creep will additionally increase the strain in that direction but because of the shrinkage what is happening? water is getting lost and your volume is reducing and so you may have a different opposing direction of shrinkage as opposed to creep. So there are situations in which creep and shrinkage can result in a collaborative plus effect or a collaborative minus effect, okay.

So deflections can increase obviously because of creep in beams if flexural deflection is happening because of creep the deflection is going to be much higher, okay. Stress relaxation can happen in the case of prestressing steel. So prestressing force decreases with time as the concrete shrinks and creeps, concrete goes in so the extent of prestress that is transferred by the steel keeps getting reduced with time okay.

And cracks can occur in elements that are restrained because of the movement of the concrete in response to the volumetric deformation, right? So especially when you have a pavement for instance which is sitting on soil the restraint offered by the soil to the volumetric movement of the pavement can result in cracking in the pavement.

Indeed, if you do a pavement which is a continuous slab of plain concrete on top of soil you let it dry for a couple of days what happens? what do you observe? so if this is your long slab that you put as a pavement on soil, if you let it dry on its own it will develop regularly spaced cracks, okay, that is because over a certain length the tensile stresses that are developed due to drying are exceeding the tensile strength of your concrete okay.

So what do we generally do in the case of pavements, we give joints exactly these locations which are likely to crack we actually make joints and then we seal those joints to ensure that moisture does not get into the pavement right, so the joints are created primarily because of the effect of shrinkage.

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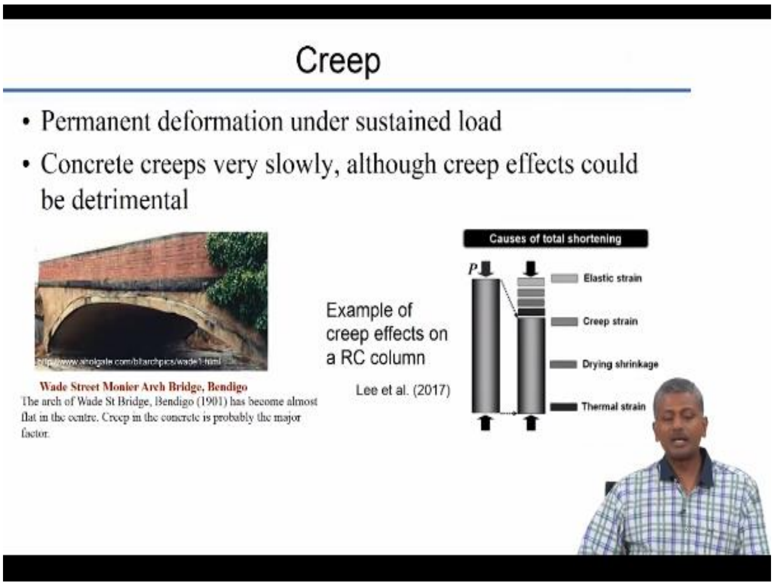

Now creep is obviously related to the permanent deformation under sustained load. Concrete creeps extremely slowly, but then creep effects can be detrimental to the performance of the concrete. So you see here there is sustained loading on this arch has completely flatted the top surface and this has happened over many years obviously, this is not something that happens very quickly.

Concrete even at moderately high temperatures 40 to 50 degrees Celsius will have a very low rate of creep. Compare this to a polymer, the creep rate of a polymer is going to be extremely high. You see on an asphalt concrete pavement surface that when you get to summer you start seeing the deformations under the wheel path. What do we call that as? the deformation under wheel path? rutting.

And that rutting is basically happening because of the very highly viscoelastic behaviour of asphalt. Cement concrete on the other hand is not as viscoelastic as a polymer but still the effect of creep can be substantial in cement concrete because we are talking about deformations over a very long period of time. In a polymer we talked about very short term deformations and which are highly sensitive to the temperature.

Because you know asphalt is a material that has a very high viscosity at room temperature but if you increase the temperature to 60 degree Celsius that viscosity reduces nearly 1000 times or no more than that 10000 times. So such drastic changes in viscosity can happen in that material, not in concrete. Concrete is not going to be so highly viscous, but still it is much higher than that of a metal.

Metal in response to regular working temperatures will not creep as much as concrete and concrete does not creep even a fraction of polymers, but then still the resultant stresses could be substantial. So creep in any material happens because of an internal rearrangement of the structure. In concrete the internal rearrangement is primarily because of dissipation of water. For example, if you think about CSH, we talked about Feldman Sereda model right, water was present in different forms within the CSH. So as consolidation happens the layers of CSH will get closer together, because this water starts dissipating to other areas, right. Similarly, in metals you have proper crystalline structure, with time the bonds will start getting strained and because of creep you will have an internal rearrangement that will send the metal back to it is lower energy state, right.

So again internal rearrangement of molecules leads to creep. The strength may not increase because of that, of CSH yes, when you talk about CSH the strength will increase because of consolidation, but the overall deflections are so high that your failure strains are going to get reached much easier than without any creep.

In the case of metals, the internal rearrangement can lead to reduction of stress concentrations which may actually lead to an improved performance in certain instances. But that depends on the type of loading on the type of stress that is actually existing in the material and so on, okay, so here this is an example of what is happening in the case of a column which is loaded in compression.

So we have several different components as we are talking about, you have elastic strain, you have creep strain, drying shrinkage and you may also get thermal strain depending upon the temperature at the time of concreting and the temperature subjected to in the long term. But the thermal strain as you can imagine will happen much earlier in the life cycle of the material as opposed to creep strain which takes years for that to accumulate.

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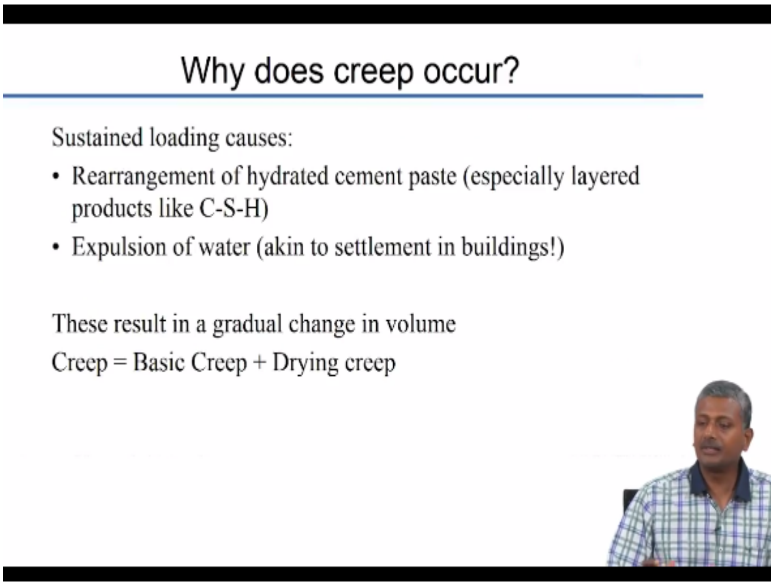

So obviously this is the rephrasing of the same thing, sustained loading basically causes rearrangement of the hydrated cement paste primarily because you have layered characteristics of CSH and there will be expulsion of water from the system either from the concrete itself or within the concrete water is occupying other spaces than it was earlier. So this results in a gradual change in volumes.

As I said creep is composed of 2 components, you have the basic creep and the drying creep. Basic creep is entirely because of internal rearrangement, drying creep happens when this is exacerbated because of removal of water from the concrete because of drying conditions existing.

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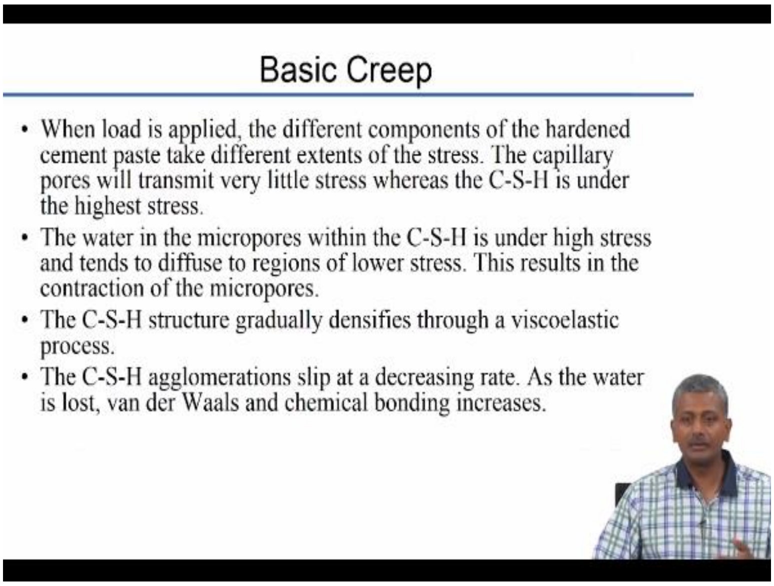

So again the mechanism is explored in more detail on the slide. So when load is applied different components of the cement paste take different extents of the stress. The capillary pores obviously being almost capable of taking no stress will not take much of the stress but CSH being the strongest component will take maximum level of the stress. So water in the micropores or the interlayer and adsorbed water in the CSH is under very high levels of stress.

So it starts getting dissipated towards the lower stress regions like the capillary pores for instance. So CSH gradually densifies because of the viscoelastic rearrangement and again the agglomerations of CSH will start slipping that means there will be some sliding happening between the layers and that will lead to lot more volumetric deformations. So when water gets lost your chemical bonding will start increasing.

The CSH itself will much increase very highly in strength, but your overall concrete deformation will be high which will lead to failures straining approach much faster.

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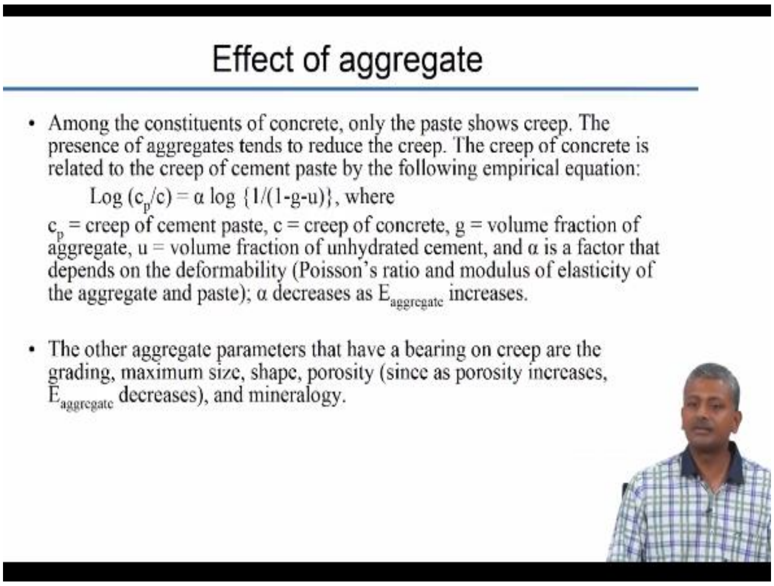

Now we know that it is only the cement paste which is going to be subjected to volumetric deformation. The aggregate for the most part is going to be inert to the effects of conventional working temperatures and the extent of drying that happens in real conditions. So what research has shown is that the creep of concrete is inversely proportional to the amount of aggregate that you have in your system.

The greater the amount of aggregate, the lesser the creep in your system and this exactly shows why we want to move towards the particle packing based mixed design system where we are able to maximize the extent of the granular component and minimize the amount of paste in the system, okay.

So again this is just a relationship proposed based on some research studies where a logarithm is taken off the component in the left that is creep of cement paste divided by creep of concrete that is given by a function of the volumetric fraction of the aggregate. So here g is the volume fraction of aggregate and u is the volume fraction of unhydrated cement.

Please remember that not all of the cement hydrates, the unhydrated cement actually will work positively when it comes to volumetric deformation because this is a component that is not going to deform, being extremely stiff, as opposed to the hydrated products which are not having the same level of stiffness. So this alpha is basically a constant or a factor which depends on the deformability of the material.

Again deformability depends on the modulus of elasticity or stiffness of your material, so as aggregate modulus increases alpha decreases. In other words, if you transform this into a creep of concrete expression in terms of creep of paste, okay. So whatever you get on this side will decrease as alpha decreases that means with higher modulus of elasticity of aggregate this alpha factor will decrease and the resultant creep of concrete also will decrease.

Irrespective of the creep of the past, what is creep of paste dependent on? obviously the water to cement ratio. The lesser the water to cement ratio, the lesser will be the extent of creep in the paste, okay. The other parameters that can have a bearing on creep are grading of the aggregate, we looked at that earlier from the particle packing perspective, the size of the aggregate, shape and porosity of the aggregate also.

Because if aggregate is porous it will have low stiffness. If it has low stiffness obviously the overall resistance of concrete to deformation also will be lower, okay and mineralogy of the aggregate that we have seen in terms of the effects that it has on other properties of the concrete also like strength.

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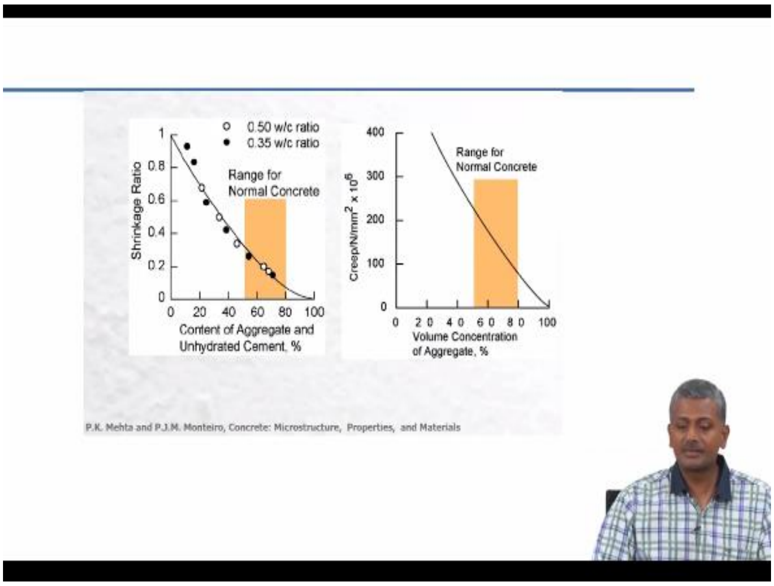

So this is data from your Mehta and Monteiro book which plots the shrinkage and creep in terms of the content of aggregate and unhydrated cement in your system. You can clearly see for different water/cement ratios you can see a major drop in your creep coefficient as well as your shrinkage ratio that you get in the system. So here shrinkage ratio is the ratio of the shrinkage of concrete to shrinkage of paste.

So obviously when there is no aggregate in the system your ratio is 1 that means you are getting shrinkage of paste. As you increase the extent of aggregate and the paste, the shrinkage drops drastically. The range for normal concrete is given here, typical we have 60 to 80% aggregate content in your cement. So if you look at the extent of shrinkage we are talking about shrinkage of concrete being about 20 to 30% of the shrinkage of cement paste, okay.

Shrinkage of concrete is about 20 to 30% of shrinkage of cement paste. Creep on the other hand again decreases significantly with respect to the increase in aggregate content of your system. For normal concrete your creep can be 25 to 35% of your overall creep of the paste. So the higher the aggregate content, the lower will be the creep, but for the normal concrete you will get about 25% of your paste creep, so 100 as compared to 400.

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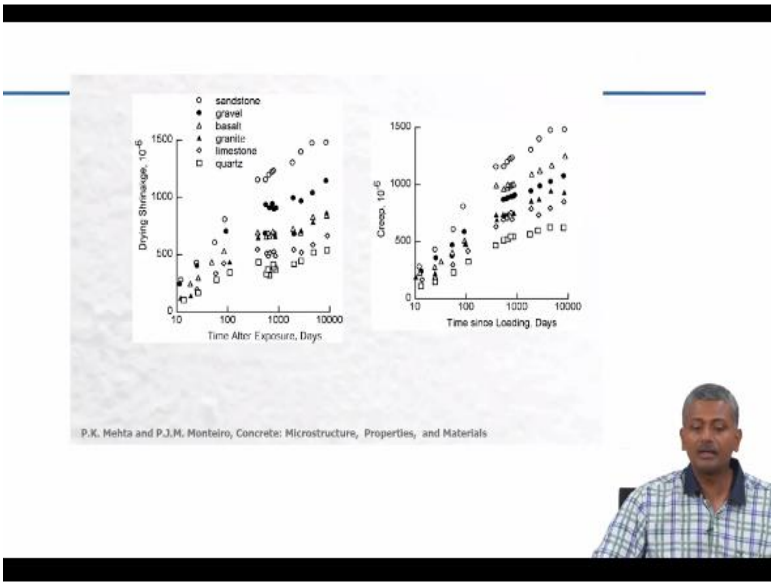

Again this is actually research data that shows you the creep with respect to different types of aggregate. Again we talked about this earlier also from the perspective of the interfacial transition zone characteristics, right. So again shrinkage and creep can be severely influenced with the type of aggregate that is also used in the system. So you can see here for example the extent of shrinkage with sandstone is extremely high as is the creep with sandstone, okay.

On the other hand look at quartz aggregate, you get very low shrinkage and creep as compared to the other types of aggregates. So the type of aggregate obviously affects the modulus of elasticity of the aggregates and it also has a bearing on the ITZ. So there is not much research which shows very clearly the role of the ITZ as far as creep and shrinkage is concerned.

But definitely you can imagine just like it effects the strength and modulus it will also affect the tendency of concrete to deform volumetrically.

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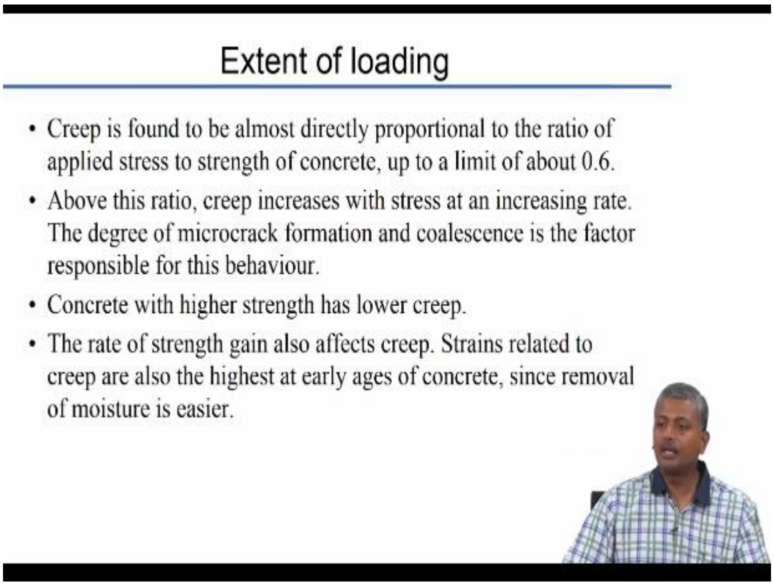

Now creep will be higher if the extent of load that you are applying to the concrete is higher. At low levels of loading or low levels of stress compared to your ultimate strength your creep is going to be small. So generally what is seen is creep is found to be linearly proportional or directly proportional to the ratio of applied stress to strength of concrete up to about 60%. Okay this is again linked to the fact that up to about 50 to 60% of your loading your cracks which you see inside the concrete are mostly in the where?

When you load your concrete in compression up to 30% or 40% you have only minor cracks in the ITZ. When you increase this load to about 50-60% your ITZ crack only starts getting bigger and bigger. So since your cracking is still located only in the ITZ, your creep does not increase drastically. So it is almost directly proportional to the extent of applied stress to strength ratio.

Now when your applied stress to strength ratio exceeds 60% we saw that the cracks also start propagating into the matrix. So when that starts happening the creep increases at a much faster rate, okay it is not linear anymore, it starts increasing at a much faster rate beyond 60% of the ultimate load. So again the degree of microcrack formation and coalescence is the factor responsible for this behaviour.

And that is again associated with the behaviour we saw during loading of concrete in uniaxial compression. So concrete with higher strength obviously has lower creep, not just because of it is strength, also because of its higher stiffness. When the stiffness is higher the resistance to deformation also is higher and rate of strength gain also affects creep obviously. In the early stages your strength of concrete is much lesser because of which creep can be higher if you are transferring the load to concrete at an early stage.

So that is why we want to wait for a certain period of time before the load transfer can happen to the concrete because it is not just a strength, but also the resistance to deformation that is very important as far as concrete is concerned. At early ages there is more water available to move around, at later ages this water would have completely got used up in the system.

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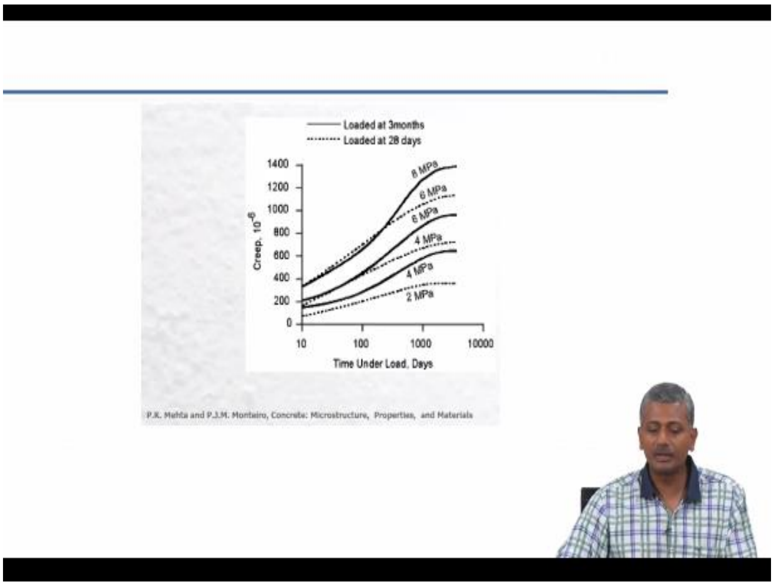

Again this is showing you the creep with time for different levels of load in the material. So as the loading goes from 2 megapascal to 8 megapascal your creep can increase by a factor of nearly 6 times that is a huge level of increase, okay. So what you need to do is understand beforehand what the expected level of loading in the material is and take into account when you design the material or when you design the structure take it to account the extent of creep that is possible at that level of load.

So the strength consideration should not only be from the structure perspective, I mean in terms of load carrying perspective, it should also be from the long term deformation perspective, okay, so for example, if 8 megapascal is the extent of stress that you expect will happen in your material, right. If you choose a material of M30 concrete as opposed to if you choose M40 or M50 concrete the response to creep is going to be quite significantly differ.

All this is obviously for the same concrete. What is also shown here is the time at which loading is done, right, when you load at 3 months versus when you load at 28 days. So at 3 months what happens? at 3 months you have much greater strength, much lesser moisture available for movement. So you expect that as opposed to 28 days you should have, no as opposed to 28days, at 3 months you will have much lesser water in the system.

So the creep, when you do loading at 28 days, is higher than when you do loading at 6 months. So if you compare 6 megapascal stress at 3 months you have the lower curve, at 28 days loading you have the higher curve okay. So applied stress to strength ratio and the age of loading both will determine the extent of creep that will happen in your system.

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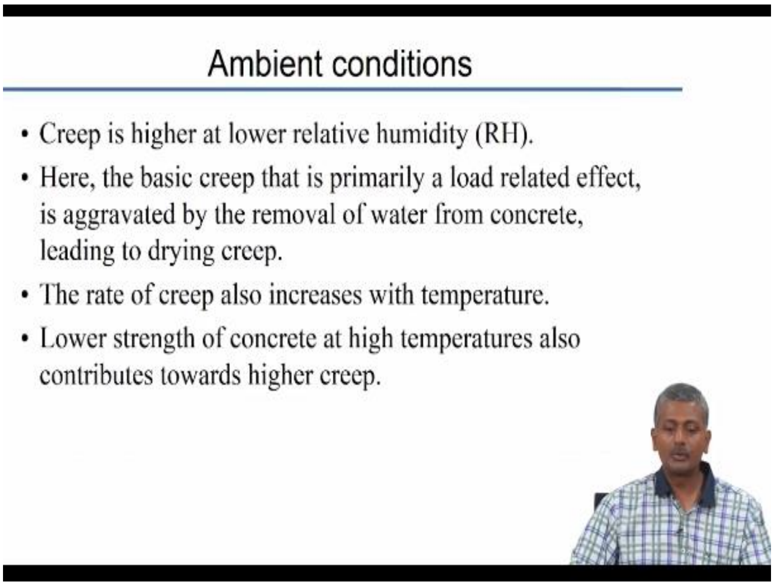

So the ambient conditions again have an influence obviously because the more drying the condition is the greater will be the effect of drying creep. If you have very lower relative humidity and high temperatures that will increase the rate of removal of water from the system and your drying creep obviously is going to go up okay.

Basic creep is primarily a load related effect and should not be subjected to any changes if there is change in the external environment, okay. The rate of creep also increases with temperature. The higher the temperature, the higher the rate at which creep will happen and lower strength of concrete at higher temperatures also contributes to greater creep. So there is a lot of factors that work together in unison to change the behaviour of concrete in the long term.

So it is not just the temperature but a combined effect of the strength which is lowered at high temperatures and the fact that temperature increases the rate of strain during creep, okay, so all these factors together will lead to an overall increase in the creep capacity.

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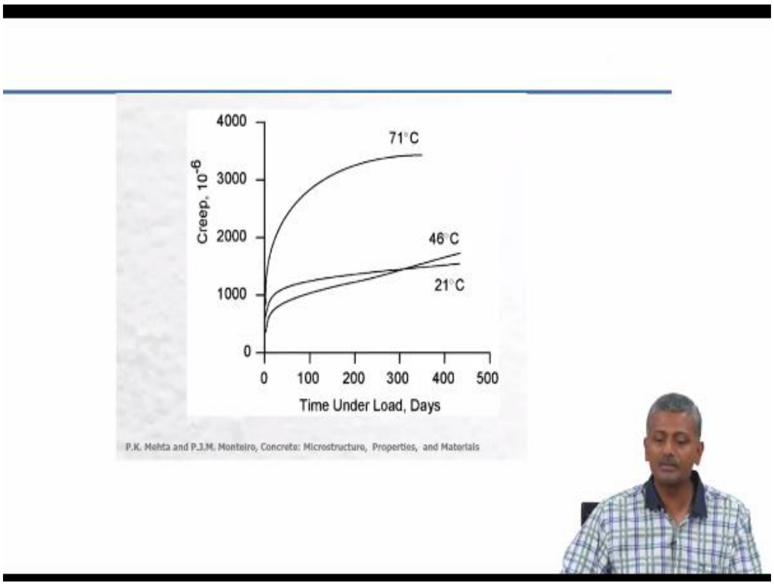

Again this is showing your results which are there in your text book. At 21 and 46, there is not that much distinction in the extent of creep, but when the temperature is very high up to 71 degrees you can see that the creep is changed by a factor of nearly 2.5 to 3, so that is a major increase in your creep.

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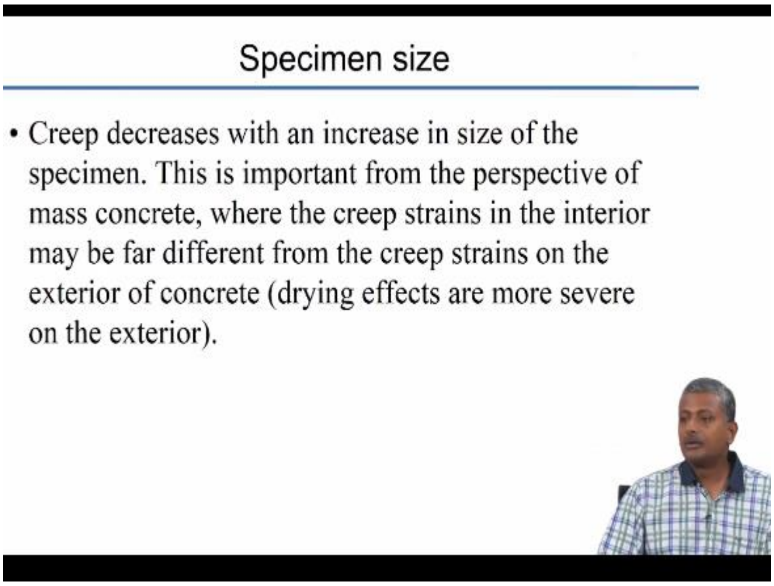

Now you can rightly imagine that when you are going from small to large specimens the effect of creep could be quite different. As the size increases you have lesser and lesser creep that actually happens in the system, okay, so again this could have different connotations.

When you have very large specimens, the creep which is in the interior of the specimen could be quite different from the creep strain at the exterior of the specimen.

So you create what is known as the strain gradient and that can lead to cracking in your system. So creep strains on the interior maybe far different from creep strains in the exterior. Because in the exterior it is not just the load related effect it is also the drying effect which can increase the level of creep on the exterior. So within the same material or within the same structure you can now have a region with lower creep and a region with higher creep.

So there is differential strains that are created because of creep in the system and that may lead to cracking okay. So even a large structures where the overall strains due to creep maybe low, the difference in strains in the interior and exterior can lead to substantially large risk of cracking because of creep. In smaller structures you will have almost an equal rate of creep throughout the cross section of the structure, okay.

But then the extent of creep that happens in smaller structures will be much greater than the extent of creep in larger specimens.

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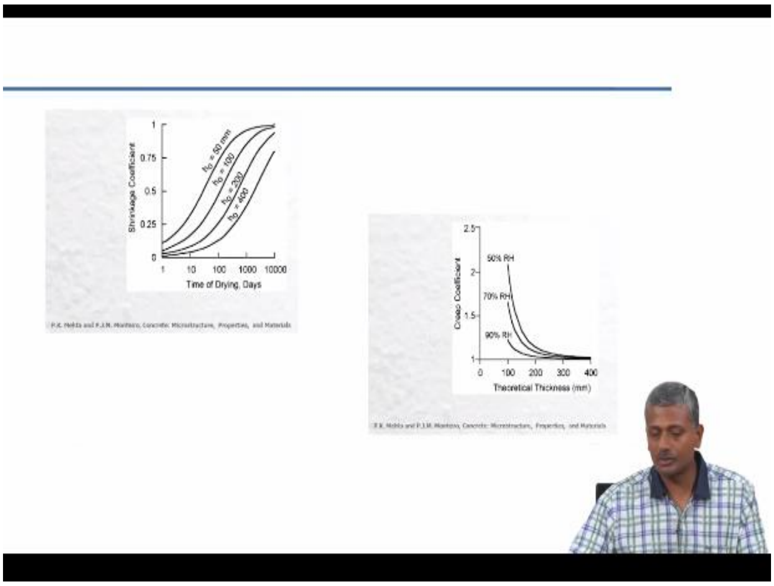

Again this is showing you similar results here. In terms of shrinkage and creep coefficients with respect to the thickness of the material. So again as the thickness of the member increases you are getting lower and lower rates of shrinkage. As the thickness of the material increases you are getting lower and lower rates of creep at different relative humidities, okay.

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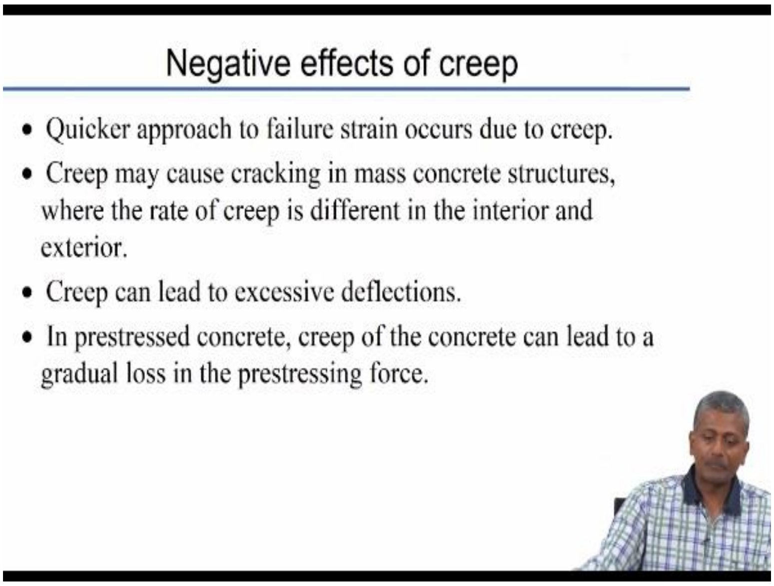

Now obviously a quicker approach to failure strain occurs when there is creep. Mass concrete structures when there is difference in strains in the interior and exterior can get the cracking because of that and excessive deflections can happen because of creep which we saw from that example of the arch bridge which was shown in the first slide. In prestressed concrete creep of the concrete can lead to loss in the prestress force.

So you do not have the same effectiveness maintained throughout the performance of your prestressing members okay. So you need to account for those prestress losses beforehand by understanding the extent of creep coefficient that you have in the concrete and this can be a valid factor in the design of prestressed concrete members.

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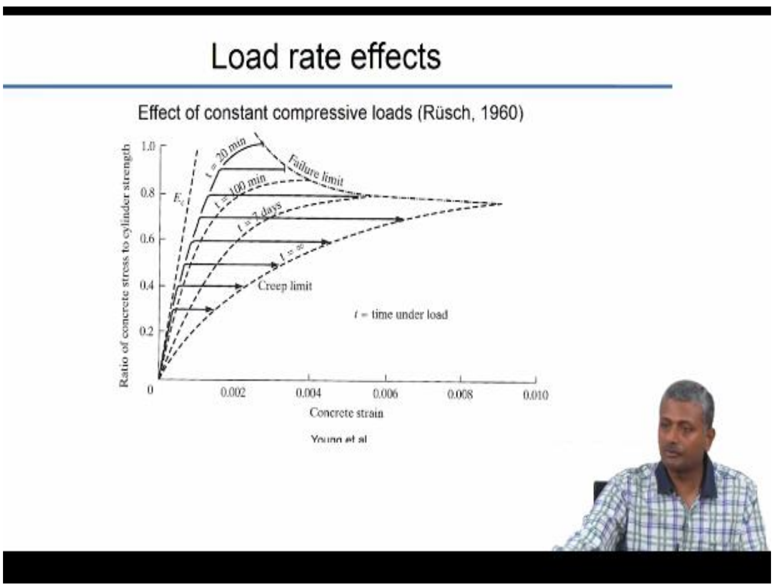

Of course this is something that you have observed in the lab, when you test concrete very fast that means if your loading rate is very high, you get actually higher or lower strength? higher the loading rate, the higher the strength of the concrete, okay. The lesser the loading rate the time dependent deformation effects also start playing a role in increasing the extent of strain.

So what is shown here the ratio of concrete stress to the cylinder strength, okay, when you have a time of application that is very less for example when you are at 20 minutes which is a short term test when you start increasing the time over which you are applying the load the overall stress that the concrete can take keeps on reducing, right? Over a long term the extent of stress that the concrete can take keeps on reducing.

And that is basically called the effect of constant compressive loads here, so what you get out of this is this curve which is called the creep limit, okay, when you are applying the loading over the infinite time your stress to strength ratio as a function of your concrete strain will start, will go as per that curve described by the creep limit okay. So the greater the amount of time that your system is under load, the lesser it can perform with respect to it is ultimate compressive strength, okay.

So for instantaneous loads or for sudden loading or impact loading the strength that you get from your concrete is very high, but then when you increase the rate or when you reduce the rate of loading by increasing the time that the loading is given to the specimen your extent of strength that you get from the specimen is lower. So that is why when you do the compression test or a tension test on concrete you need to very clearly specify the rate of loading.

Now all the more so when you test polymers this is even greater of a factor. Not just the temperature but also the rate of loading has to be very clearly specified when you are testing polymers. So there the effect can be even more drastic than this. With concrete you see some effect, but if your test varies between 5 minutes and 10 minutes, it is not going to make much of a difference.

In the case of a polymer even 5 to 10-minute difference can be quite significant because of the effects of creep that are coming in at slower loading rates.

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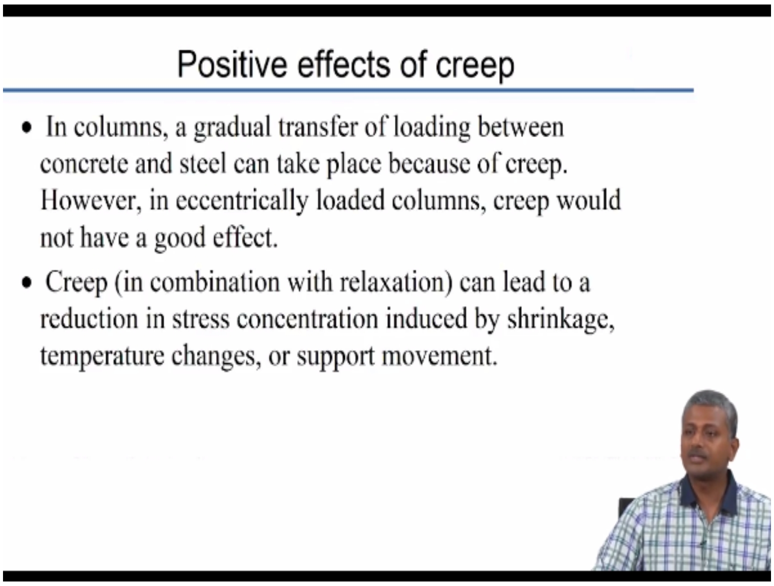

Now in some cases you can also get positive effects of creep because internal rearrangement can lead to reduction of stress concentrations and in columns you can have a gradual transfer of loading between concrete and steel because of creep. Because there is deformation happening in the material, the stress transfer can happen much slower and overall in eccentrically loaded columns you will have a problem though.

In regular columns it is alright, the transfer can be alright, but in eccentrically loaded columns what you will do is you will probably solve the problem in one part of the column whereas add to the problem in the other part of the column, because you get different combinations of loading in different parts of the column okay. So depending on where you are in an eccentrically loaded column you can actually get a situation that is better than no creep situation or a situation that is worse than the no creep situation, okay.

Now in combination with relaxation, creep can reduce the stress concentrations which are induced by shrinkage, temperature changes or support movement. Now what do you understand by relaxation? what is creep? increase in strain because of sustained loading. Relaxation is basically reduction in stress because of sustained levels of deformation, okay. Now if you stretch a material between 2 points, okay.

So the strain is constant, but with time what happens? you have seen this in the clothesline also when you stretch a clothesline between 2 points and you let it be there for certain period of time, with time the internal stresses in the material keep reducing and there is slackening of your clothesline, okay, the strain is kept constant, but the internal rearrangement leads you to have lesser and lesser stress in the material, here that is called relaxation.

So creep and relaxation usually happen together in materials. You do not get conditions which only cause creep or only cause relaxation, so both these effects can be seen together in materials. So generally with creep and relaxation happening together we will actually lead to a reduction in stress concentration which is caused by other factors which are leading to movement within the concrete like shrinkage or thermal movement or support movement which happens in the system.