Maintenance and Repair of Concrete Structures
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Lecture 8
Deterioration of Cementitious Systems
(Shrinkage and Creep)

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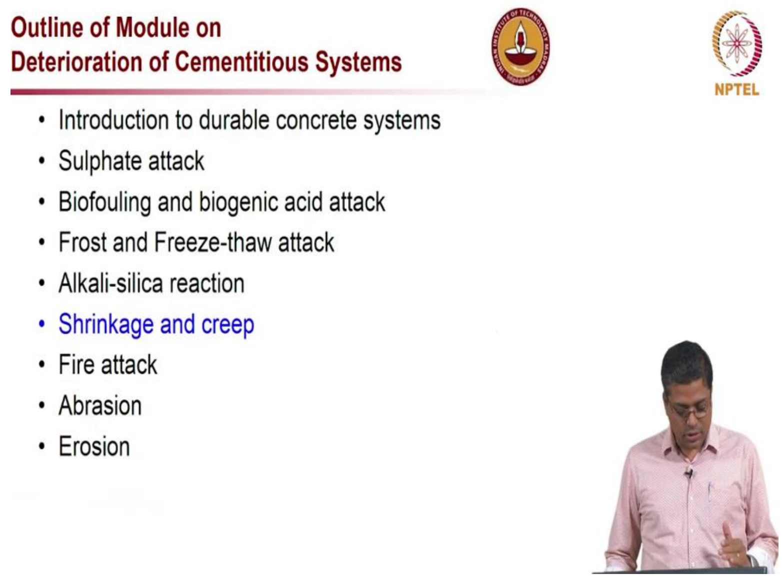

Hi, this is the second lecture in this module on deterioration of cementitious system. In this we will focus on shrinkage and creep. This is just an outline of this module. We will focus mainly on shrinkage and creep in this particular lecture.

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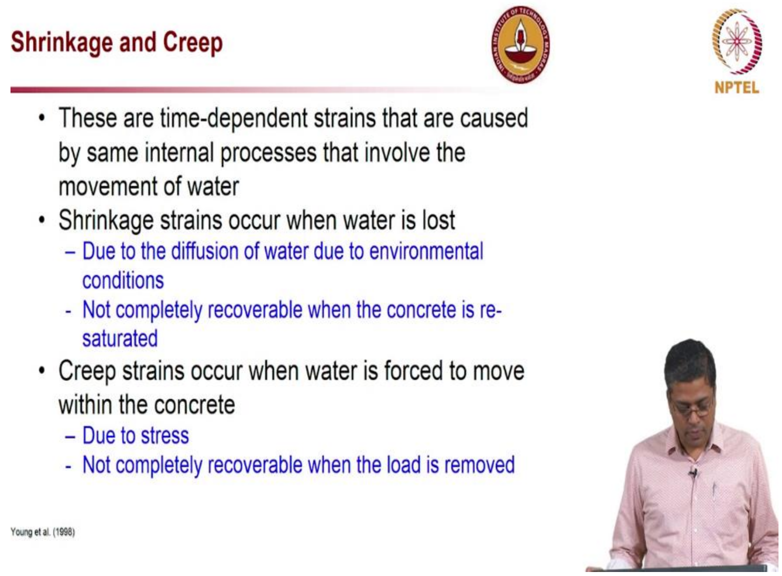

What is shrinkage? And what is creep? These are basically the time dependent strains that are caused by similar or same internal processes which involve movement of water within the concrete. And let’s see what is shrinkage and what is creeped separately. In the case of shrinkage the movement of water is happening due to the environmental conditions and which induces strain in the concrete or volumetric change. And then it effectively leads to shrinkage.

In the case of creep, it is mainly because of the load applied or the stress generated in the concrete. One thing to note here is that both the creep strain and the shrinkage strain are not fully recoverable when the load is removed or when the concrete is re saturated respectively. Once the creep and shrinkage happens, it is very difficult to recover the strain which is cost.

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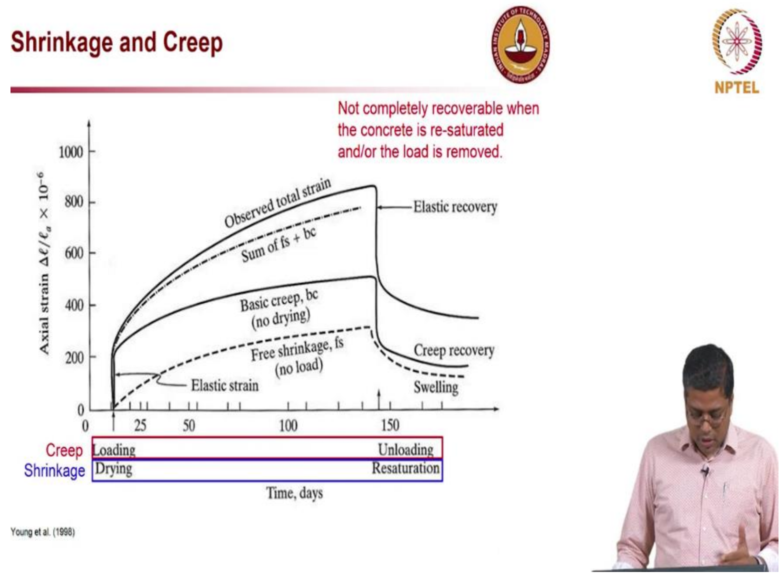

Now this graph here, it shows both the creep and shrinkage behavior. As you can see, I have put this red box at the bottom which indicates the creep. The reason for creep, which is loading and then for creep recovery, we when we unload, we can see the creep recovery. In the case of shrinkage, which is the blue box at the bottom, the loading is essentially the drying and the unloading is essentially re saturation.

So, you can see here the free shrinkage curve which is this (the 4^{th} curve from the top) and when the re saturation happens whatever the strain gain, we are able to recover some of it but not fully. And in the case of creep in the beginning as soon as the load is applied, there is an elastic strain over there. And then after that you have this creep strain. And then when at this point when the unloading starts, you recover some of the creep strain but not fully.

So, you have something which is not yet been not recovered. Now, if you look at the sum of these 2 you can see here this is that graph (2^{nd} curve from the top), where this much strain is not recovered even after re saturation or unloading. And that is the reason why it is very much important to consider the shrinkage and creep behavior, especially when we talk about large structures where the absolute deformation due to this strain could be very large in some of the structural elements.

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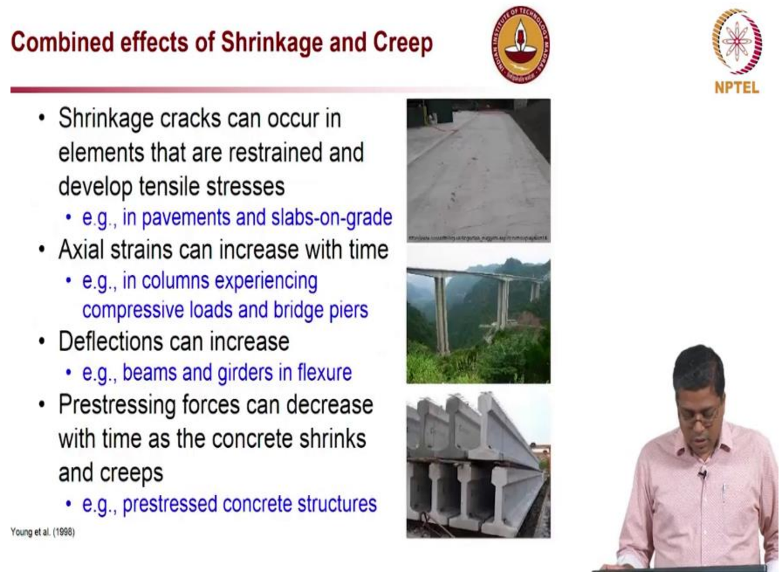

Now, combined effect of shrinkage and creep. Because it is very difficult to separate them because, as I mentioned in the previous slide, they are due to same internal processes. It is for experimental purpose probably we can, but in the real structures, both happen at the same time. So, it is very difficult to separate them and to see the effect of individual either shrinkage or creep. Now, shrinkage can occur in elements that are restraint and develop tensile stresses.

One example is pavements and slabs on grade. As you can see, here in this picture (1st picture), you have a lot of parallel cracks here which are essentially the shrinkage cracks. And then in the second photograph, where you see very large bridge with very tall piers and long span girders, you can have significant effects due to shrinkage and those effects could be in the form of compression of the columns or even on the girders, As they could have significant deflection, especially if they have prestressed concrete girders and the concrete resistance is not very high, then what will happen is eventually the because of the prestressing forces, the concrete can creep and the length of the girder could reduce and which will result in the loss of prestress, which eventually will lead to significant deflection. So, these are very important phenomenon especially when we talk about long span and large structures.

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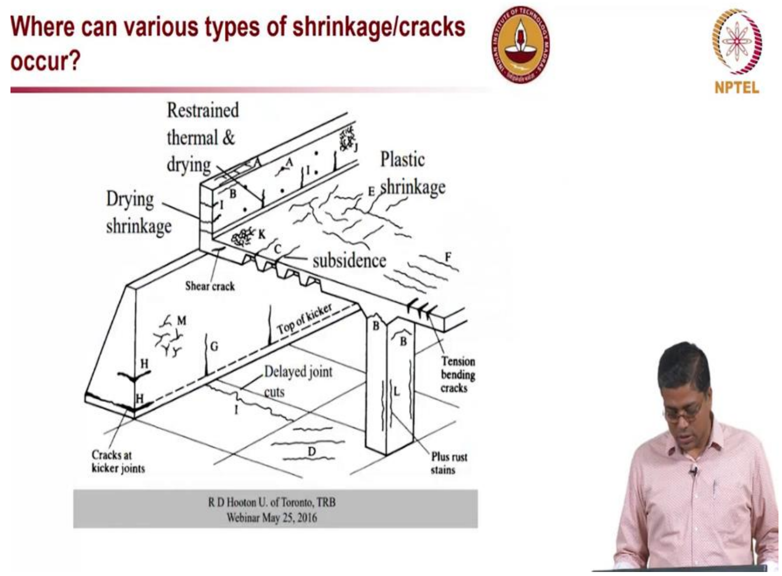

This is just one image which shows different types of shrinkage which could happen in all the different elements of structures. Where you can see a drying shrinkage on the parapet here and subsidence and then plastics shrinkage and restrained thermal and drying shrinkage combination and you can see structural cracks. So, anyway this is just showing different types of cracks which could form on concrete structures.

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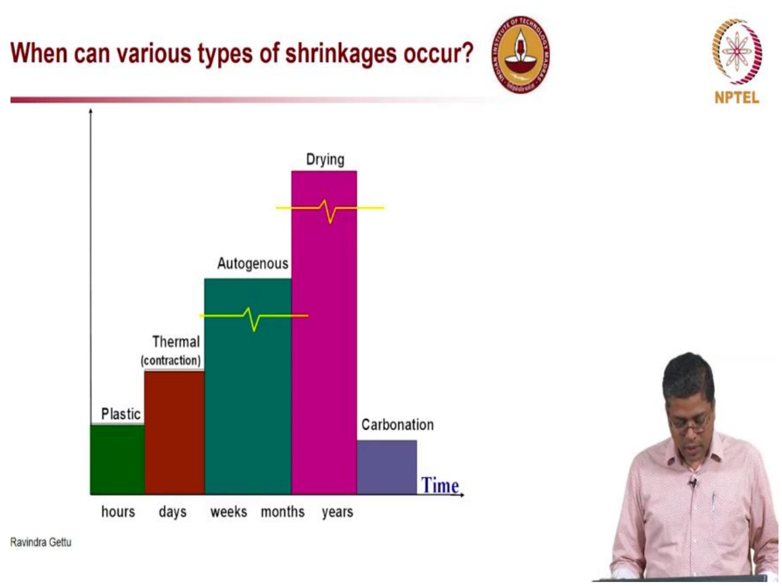

And what are the different types of shrinkage? And when do they actually occur? Plastic shrinkage, thermal shrinkage, autogenous shrinkage, drying shrinkage and carbonation shrinkage are the 5 different types of shrinkage which we will discuss in this lecture. And when do they occur? Mainly if you are talking about plastics shrinkage it happens in the first few hours and then thermal shrinkage right after the final setting and you can start seeing thermal shrinkage and then autogenous shrinkage in the first few weeks. And then drying and carbonation shrinkage it happens in the long run or long term process whereas carbonation shrinkage might take much longer than all the other four.

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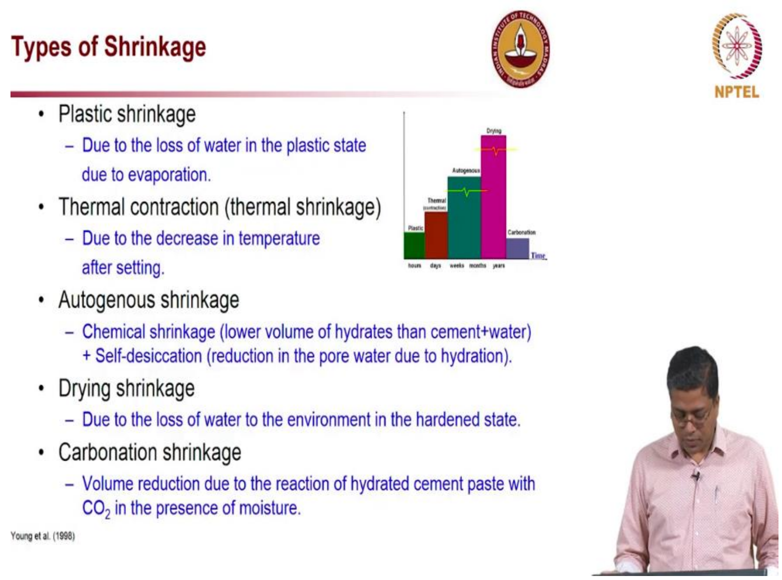

Plastic shrinkage is mainly happening because of the loss of water when the concrete is still in plastic state. That means, it is still a fresh concrete. And thermal contraction or thermal shrinkage happens when there is a decrease in temperature especially after the setting. Autogenous shrinkage is mainly because of the chemical shrinkage and the self-desiccation, which could happen in the first few weeks, from days to weeks. Dying shrinkage, it is mainly due to the loss of water in the concrete after the concrete already has hardened, and loss of water, basically due to the drying of the hardened concrete.

And carbonation shrinkage, it is mainly because of the reaction of the cement paste with the carbon dioxide in the presence of moisture. Calcium carbonate which gets precipitated in these space available within the concrete and even free space available within the concrete which eventually leads to shrinkage.

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Now, before we talk about shrinkage, there is one type of crack which is not because of the shrinkage, but because of the settlement of concrete during the fresh states or in the plastic state. So, it is not due to shrinkage, but I just wanted to cover this aspect also, as you can see here on the picture on the top left shows how it is manifested as you can see there, they are actually forming right above the rebars here.

Also, you can kind of see a pattern which is parallel to the or right above the reinforcement. Now, how is it happening which is shown in the sketch on the left side, you can see these white circles which are the reinforcement and then the bleed water from the bottom of the slab moves upward and what happens is the concrete which is on either side of the reinforcement, it starts settling and but the concrete right above the reinforcement, it gets obstructed by the reinforcement and it does not get a chance to settle vertically down. But there could be some horizontal movement, and some horizontal movement which also leads to crack on right above the reinforcement, and this is depicted very clearly in these 2 photographs on the right side. So, you can see this crack pattern, which is just above the reinforcement. And if that is the case, maybe the concrete has a lot of water than what it is required and a lot of bleeding and that is why it is leading to this kind of settlement, which is called either plastic settlement or subsequence.

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Now, this is plastic shrinkage cracking, the first type of shrinkage crack which we discussed, and you can see here, very clearly parallel cracks and it is on slab on grade.

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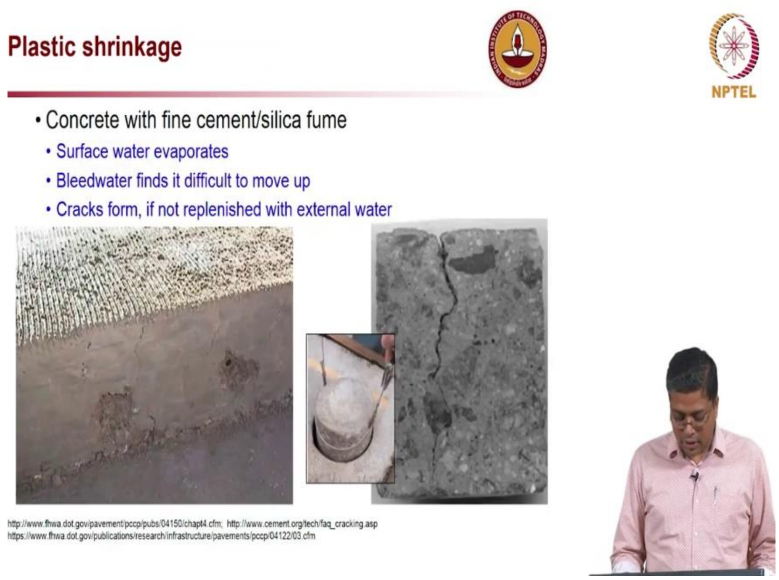

And this is another example of plastic shrinkage cracking. Where you can see again the slab on grade, where you can see here slight crack at the top mainly more cracking at the top and less as you go down. Now, why this is happening or the mechanism is clearly seen again on the photograph from the second photograph, where you see this crack happening here this is the crack and you have more crack width at the top.

And as you go down the crack width is less. why I am showing the cylinder photograph here is this picture on the right end is actually a cut section of a cylinder which is cored from the slab. So, you can see the top of the slab has more crack width than the bottom. What is the mechanism, especially these kind of crack happen when the you know the pathways for the bleed water to come upward is blocked. Which happens when the cement, let's say for example, if it is having silica fume, they actually block or clog all the pathways and it prevents the bleed water from coming upward. And at the same time, if the surface of the concrete is relatively dry, then you will have evaporation or loss of water from the top surface of the concrete. But that does not get replenished with the bleed water which is prevented from coming up.

So, multiple actions; one is the surface water evaporates, and then, at the same time bleed water finds it difficult to move upward and then this condition creates a cracking or leads to the formation of cracking, especially when you do not have enough water available at the top surface. So, the top surface or near the top surface cracks more than the underneath.

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And this is another example of a roof structure where significant shrinkage cracking was observed. You can see lot of cracks over here and then what are these white patches which you are seeing is actually the water during the curing the top surface of the same slab. Water from the curing actually seeps in through these cracks, which are present.

And then therefore, the salts are leaching out and you can see this white patch on this surface. Sometimes you can even see like a long crystals being formed through this crack. And one thing to note here is these are not structural cracks. Because, you can see very clearly that there is no particular shape for it and it is from the top of the slab to the bottom of the slab, the crack is continuous.

And that is why you see these white patches also forming and if it is a roof slab then definitely you will have issues during the rain. So, it has to be protected or treatment has to be done before you can go further.

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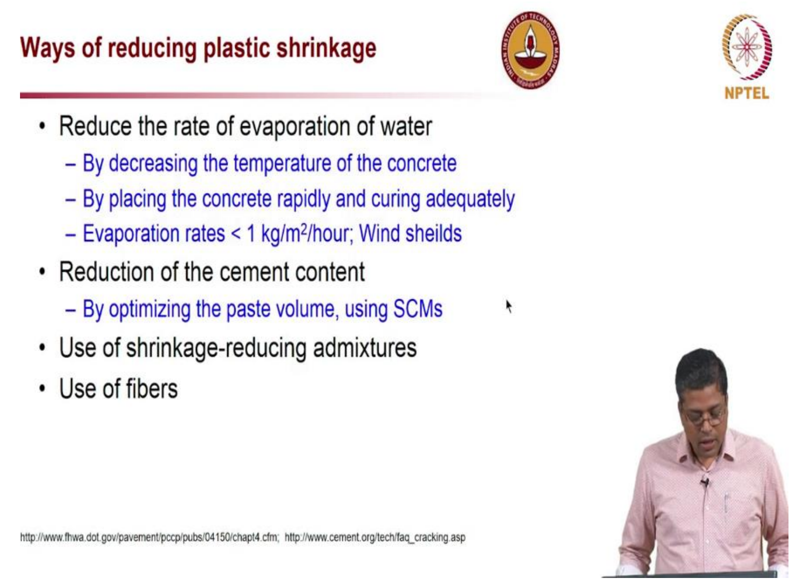

Now, how do we reduce plastic shrinkage? The first thing is that we have to reduce the rate of evaporation of water. How we can do that by decreasing the temperature of the concrete or by placing concrete as soon as it is mixed and providing adequate curing. And if there is a wind conditions we have to ensure that the air movement above the concrete surface is less, because if you have more air movement, it will carry more and more moisture from the concrete.

And which will eventually lead to fast drying, which is not recommended. And also, we can go by reducing the amount of cement or optimizing the paste volume especially by using supplementary cementitious materials like fly ash or slag or those kinds of materials and also shrinkage reducing admixtures are available, which can also reduce the shrinkage. And then also the use of fibers is also helpful in reducing plastics shrinkage cracking.

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You can see here this is an example of concrete without fibers or plain concrete on the left side. And on the right side with the addition of fibers very clearly you can see the concrete on the left side has significant cracking, the one on the right side has very less cracking.

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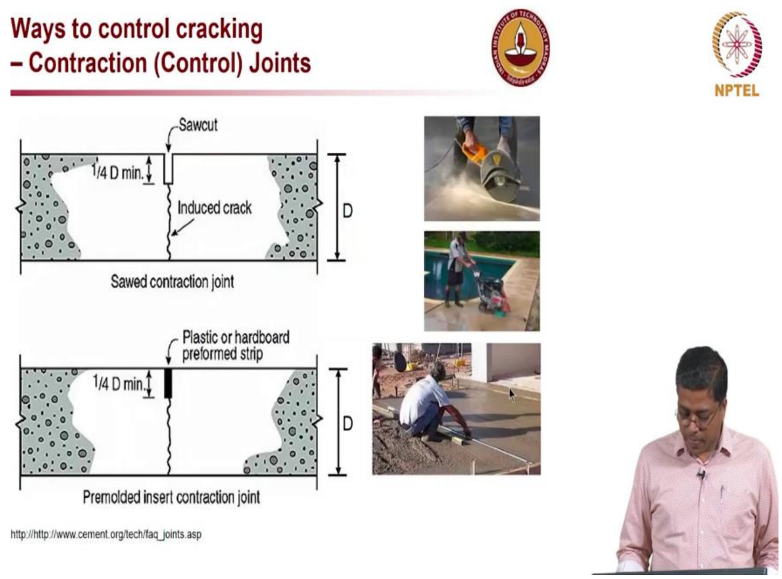

And how do we control shrinkage cracking in concrete. Look at the word, I'm talking here 'controlling' the crack not preventing the cracking. So, you can see on the sketch, where we are providing or a sawcut. If you have a concrete slab, a very long slab, it will lead to cracking so it is very difficult to prevent cracking in such case especially for a road or highway or slabs as you see on this pictures over here.

You can see people are making sawcut in or in other words, once the concrete gain sufficient strength, you cut the top surface of the concrete, like make a cut like that. Now, essentially what you are doing is you are creating a section with smaller area. That means, when there is a particular tensile stress generated, what will happen is the concrete will start cracking across that thinner section. Here, right below the sawcut, whatever the area available is less than the total cross-sectional area of the slab.

Because of the sawcut you are reducing the area available. That means for the same force, because the area is less, you will have more stress, and wherever the stress is more concrete is going to crack there. So, essentially we are controlling the location or we are defining the crack location by doing this saw cutting. And to prevent other issues, we should also ensure that the sawcut region is protected because otherwise if there is a crack, and if you have rebar going like this, it might actually or it will rather corrode right here. So, you have to protect this sawcut or that joint also from moisture. So, providing a good sealant is always a good idea in such cases.

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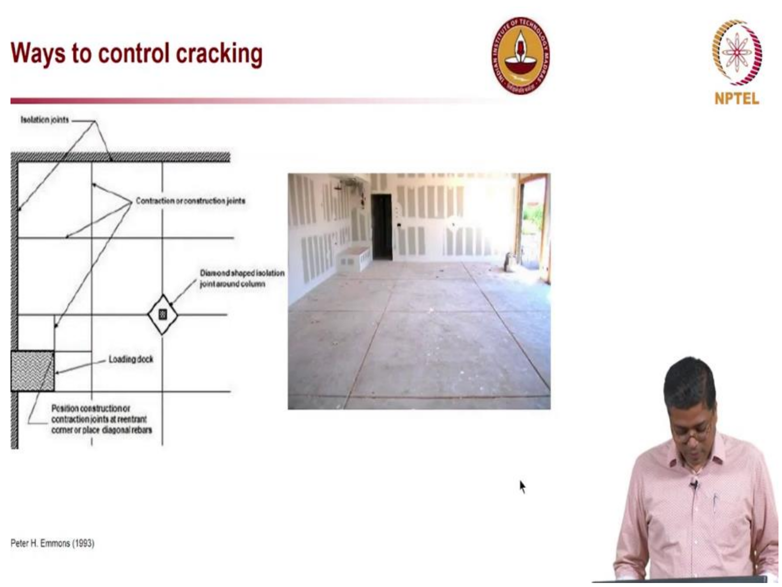

Now, this (Picture on the right) is for an interior structure you can see here a slab, large slab you have saw cuts made like this, and which will ensure that the crack is right below those saw cuts and it is not forming randomly on the concrete surface. So, this sketch (Picture on the left) also shows similar thing, some typical plan on how we can make contraction or construction joints and force the crack to happen right below such joints or such saw cuts.

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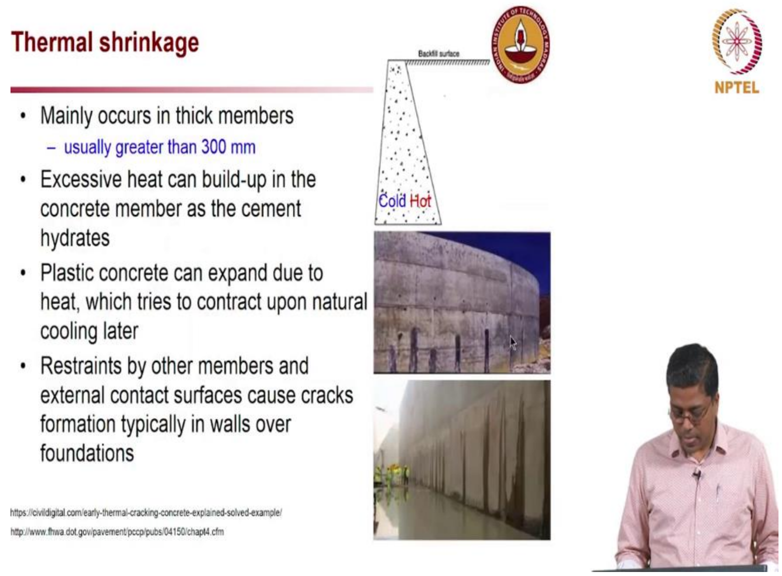

Now thermal shrinkage, it happens mainly in thick members, as you see on the picture on the top right, I am showing a typical cross section of a retaining wall, where you can see as you go down, the thickness of the member increases. And so there will be excessive heat generation, especially at the bottom portions.

And what will happen is the portion which is mark here like a hot region, and then here maybe near the surface, it is relatively cold because heat will dissipate into the environment from the outer surface. Whereas the concrete inside or towards the right side in this sketch will still remain at higher temperature. Now, this differential temperature condition will lead to cracking. It is very clearly observed on the bottom 2 images, you can see 2 retaining wall photographs.

Where at the bottom portion of these retaining walls, you are seeing cracking that is it is similar to this region. So, you can see here this portion is cracked and here also the bottom portion is cracking. So, very clearly this is due to differential temperature conditions. Now, it is not necessary that it happens uniformly everywhere on the structure. Before I go to the next slide, let me explain at what time and why this kind of crack happens.

One thing is excessive heat which we already discussed. And now, other thing is when this heat generation happens in the beginning, the plastic concrete expand due to the high heat generation in the beginning and as concrete cools down, it tries to contract or shrink and because there is restraint, or in other words, it is not a free shrinkage which is happening, there are reinforcement in the concrete and also this concrete is resting on earth or some foundation and on the other side the backfill is there.

So, there is a lot of restraint provided by the surrounding elements and also the concrete itself. If you look at the concrete which I showed in the picture, you can see the other concrete can also provide restraint to this portion. So, effectively there are some region or the bottom portion of this structures are restrained by the other concrete and the foundation and which leads to cracking. And that is the main mechanism. If there is no restraint, then you will not see cracking, but you will see only shrinking, but most of the structures that is not the case, you have a restraint.

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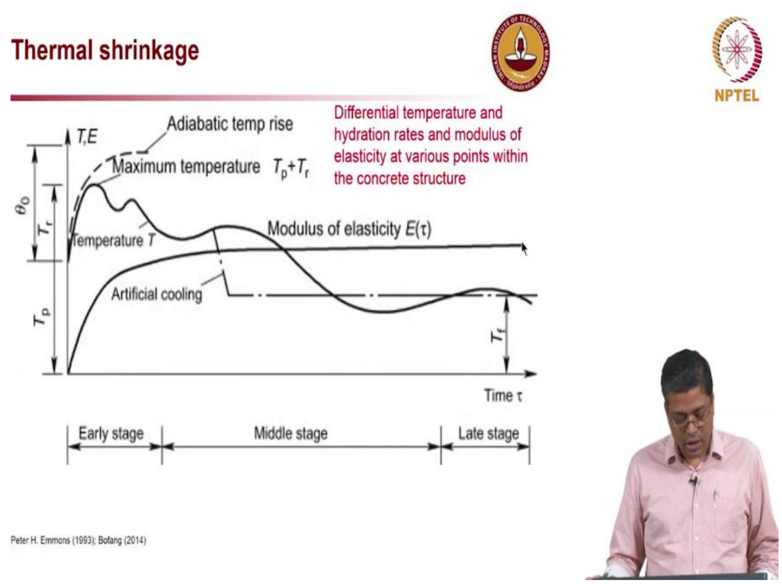

This is just a graph showing how the modulus of elasticity builds up in concrete, and how the temperature variations happen in the concrete. As you can see here, in the beginning until about this stage, you have significant rise in temperature, then as time passes, the concrete starts cooling down.

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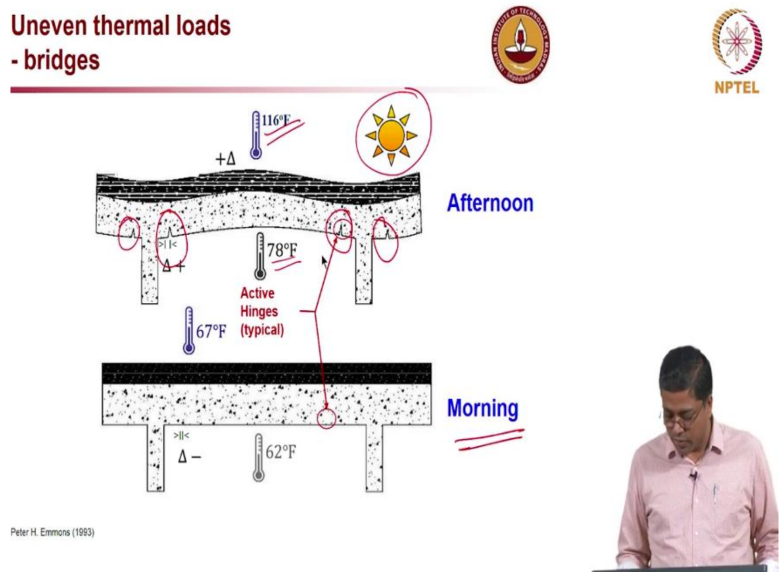

Now, this uneven thermal loads in bridge structures can actually lead to cracking. As you see in this picture, first look at the bottom portion of the picture which is indicating how the structure of the temperature conditions. In the morning the top surface and bottom could be of similar could be experiencing similar temperature, but afternoon where you have you know if it is a really hot climate you will have the top surface of the concrete bridge might experience a higher temperature is something like more than 100 degrees Fahrenheit.

Whereas the bottom side could be at low temperature (make sure this is in not in Celsius so, please that it is in Fahrenheit). Because of this change in the shape, it induces some cracks like this you can see at the bottom here wherever there is a flexure happening and because of the shrinkage or expansion of the top surface there is some kind of buckling which is happening and which induces this type of cracks.

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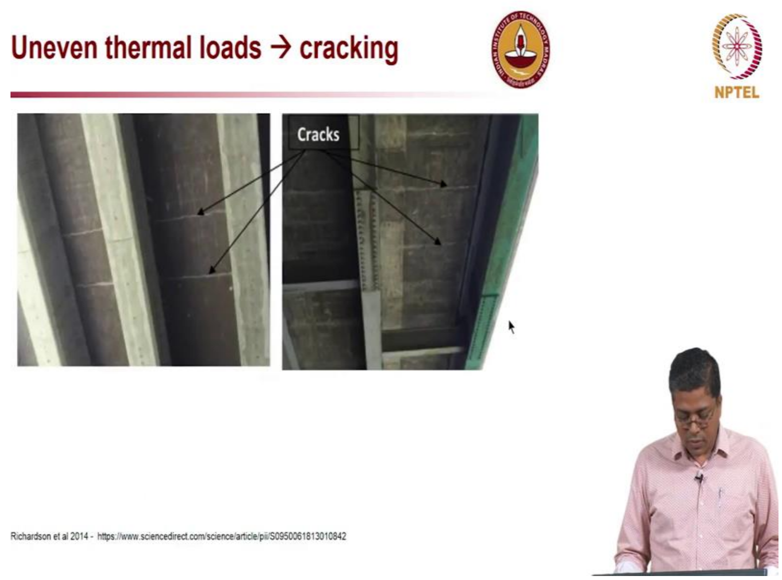

Now, this is demonstration of such cracks which is visible at the bottom of this bridge deck. Here you can see some cracks, these kind of damage mechanisms happen especially on large structures, imagine in this particular bridge, you have a crack there and there are actually reinforcement, which goes like this in these cracks. And when you have a crack, definitely that rebar is going to experience localized corrosion right here. So, definitely this kind of damages will lead to long term performance issues.

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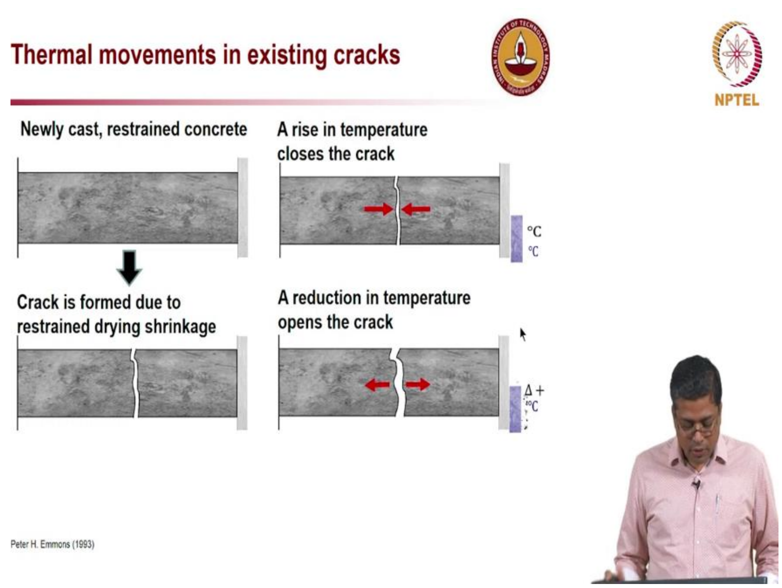

I mentioned earlier sometimes again because of the temperature variations this crack might close open, close open, all that might happen. So, this particular example, you can see on the top left image, it is newly cast concrete with restraint on both sides. So, what will happen, crack is formed when restraint drying shrinkage happens.

So, this you can see the crack forming right almost at the center. And on the right-side image you can once the crack is formed, if the there is a rise in the temperature, the crack width decreases. So, comparing to the second step here on the third case you have a reduction in the crack width, because the concrete is going to expand or it is expanding. So, of the concrete on the left and right side is expanding and the crack is being closed.

Now, what will happen if there is a reduction in the temperature, the same concrete will now move outward or in other words it is shrinking, both left and right side concretes are going to shrink and then it is going to open the crack.

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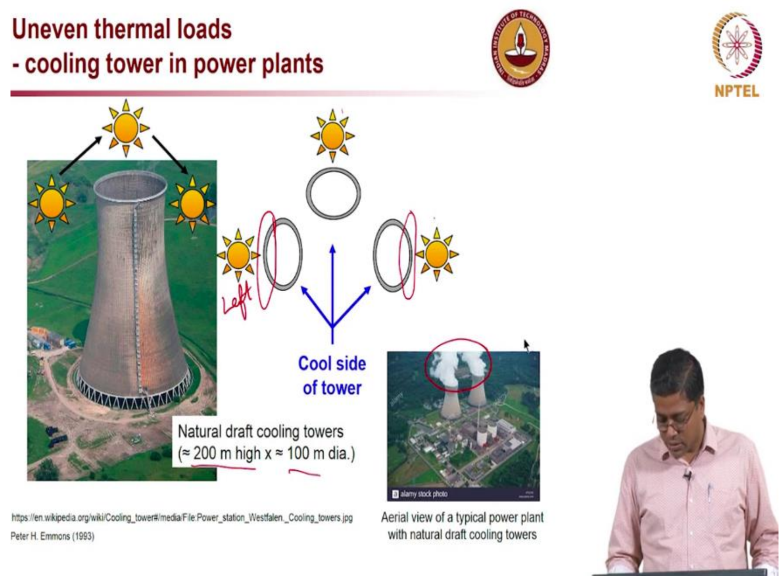

This is another example, depending on the position of the sun. So, if the sun is on this left side as you see here, so, this portion of the cooling tower will be at experience at higher temperature than this portion. So, this is left side is going to expand and that expansion will induce a change in the shape. So, the expansion on the left side will induce a change in the shape that means, the entire cooling tower will in a slightly deviate from the circular shape to an elliptical shape.

Likewise, you may also see if the sun moves to the other side, if it is on right side like here again then the expansion will be on the right side of the cooling tower. So, this essentially what it is showing is all the portions of a cooling tower could experience change in thermal loads which will induce the movements or shrinkage and it might lead to cracking etc. On this the significant cracking could happen on these type of structures.

So, the hot side, the warmer side of the element will experience expansion, which will lead to change in shape. This is just bottom right side you can just see a typical power plant, you see this thing is basically the water vapor which is coming through this natural draft cooling towers, very large structures and you know very important structures especially for power plants.

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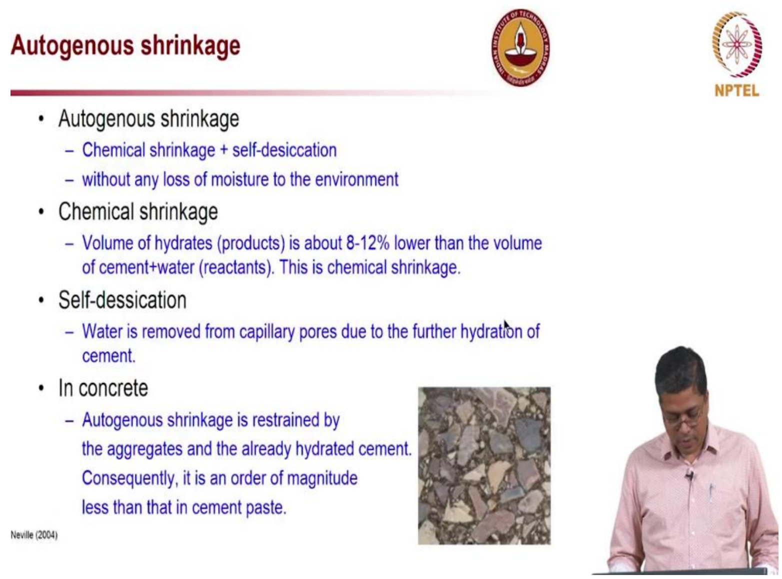

Now, another shrinkage mechanism is autogenous shrinkage where it is typically a combination of chemical shrinkage and self-desiccation, 2 processes. And main thing to note here is that this happens without any loss of moisture to the environment. There is no drying or anything like that happening. It is happening without any loss of moisture. Now, what is chemical shrinkage? And what is the self-desiccation? Chemical shrinkage, the name itself suggests it is due to some chemical reaction which involves reactants and products of course.

And the reactants have volume which is more than that of the products how much about 8 to 12% so, essentially the cement and water which are the reactants, has a combined volume, which is larger than the volume of the hydrates. Or in other words, the cement hydration reaction tends to a reduction in the volume by about 8 to 10%. let us say 10% volume reduction.

And self-desiccation is mainly when water is removed from the capillary pores, but not to outside the concrete system. In other words, the especially this kind of mechanism happen in low water cement ratio concrete, where you will still have some unhydrated cement left in the concrete. So, that is why here we are seeing further hydration of cement or you do not have sufficient water available for the full hydration of the cement system.

So, as and when it is available, it will use. So, the water which is present in the capillary pores is also used for this hydration purpose and that lead to something called self-desiccation. And here very clearly water is not lost to the environment. The water from the pores are used for further hydration of the cement paste. Now in concrete what happens is autogenous shrinkage, when you talk about cement that is different when you talk about concrete there is a major ingredient which is aggregate.

So, about 75% or even more 75% of the concrete might have coarse aggregate and then you also have fine aggregate present in the concrete. Now, look at this picture here you have a lot of course aggregates and they are actually providing restraint, and which will also you know restrict or in other words this because of this restraint the overall shrinkage might still be less. So, the magnitude of shrinkage in concrete could be significantly less than that in the cement paste of 1 order of magnitude or $1/10^{th}$ we can say.

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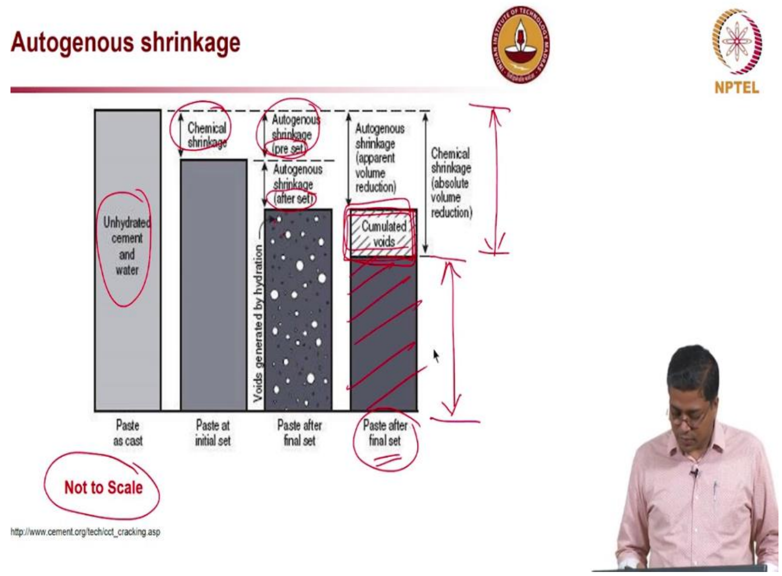

Now, this is just a schematic showing this volume reduction. Here on the bar on the left side, you have the volume of unhydrated cement and water and the right side you have paste after the final set. So, this is the volume, the final volume and so, you have this much shrinkage, note that this is not to scale, it is not that there is a 50% reduction in volume. It is not like that, because this looks almost 50% on the right side, but that is it is not that not drawn to scale.

So, there is some chemical shrinkage and then autogenous shrinkage preset and after set and then this is the final after the final set. How much reduction in accumulative voids are all shown here. Basically all these white circles on the third bar is that particular volume is accumulated in this to show you what is the absolute volume of the final products, which is the gray box here.

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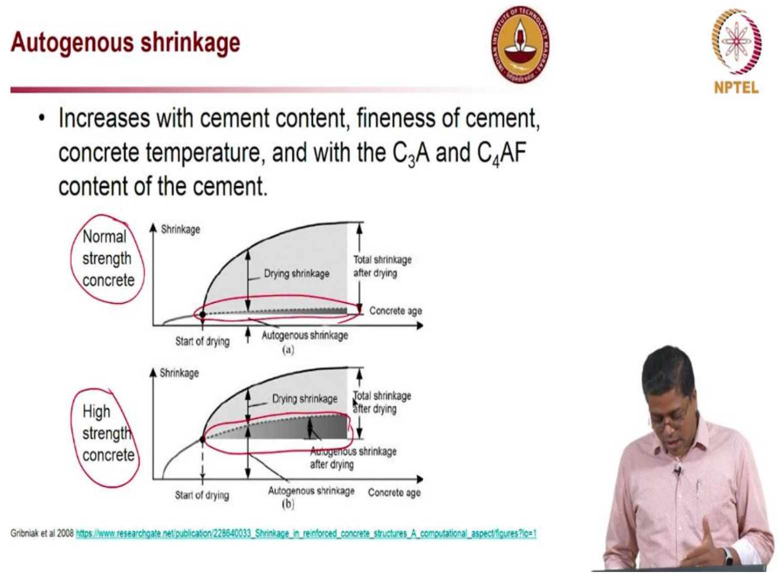

Now, autogenous shrinkage increases when the cement content is increased or when the fineness of the cement is increased or the concrete temperature is increased. And also, when you have C3A and C4AF content in the cement. So, these are typically the reasons for increase in the autogenous shrinkage as you see here, the picture the graphs on the bottom you see a normal strength concrete and a high strength concrete.

In the normal strength concrete this dark gray region which is this, is the autogenous shrinkage which is very less as compared to the dark gray region in the bottom graph. So, definitely in the high strength concrete, we usually go for low water cement ratio, and that eventually leads to this significantly high autogenous shrinkage.

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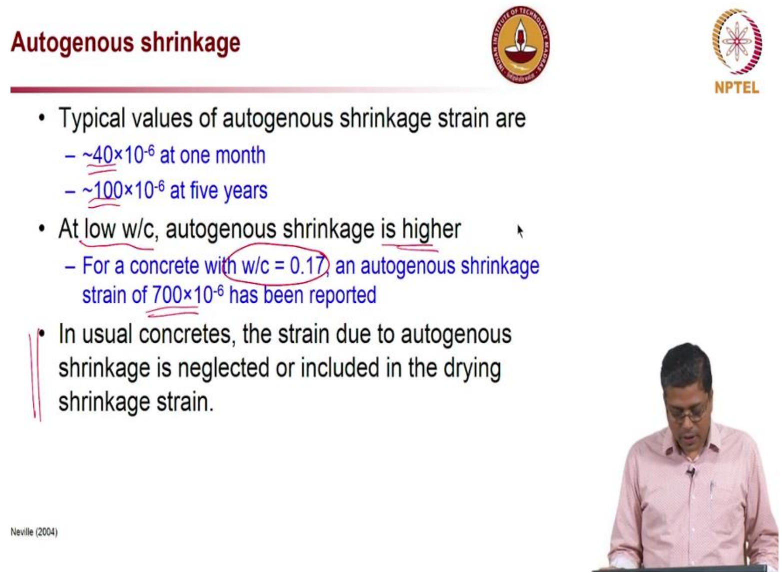

Now, what are the typical values? If you are talking about autogenous shrinkage strain, it is about 40 micro strain in 1 month and about 100 in 5 years. So, most of this is happening in the very beginning, almost 50, 40% is happening in the first month itself. Now, if you are talking about a low water cement ratio concrete, autogenous shrinkage is higher. For example, the water cement ratio with 0.17 this is for experimental purpose.

Because we hardly use 0.17 water cement ratio concrete but you can see here autogenous shrinkage with 700 micro strain has been reported. Now, but usually when you talk about concrete autogenous shrinkage is usually neglected or it is included as part of the drying shrinkage strain because of the difficulties in the measurement. So, total shrinkage is what is reported usually.

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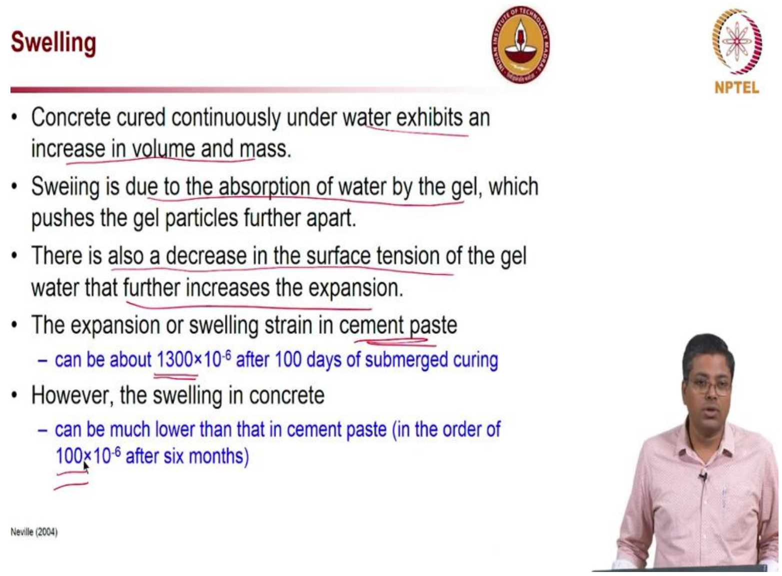

Now swelling; concrete also swells when it is exposed continuously to water. So, water gets into the concrete and then definitely there is an increase in the volume and mass and why because it is absorption of water by the CSH gel which pushes the gel particles further apart. So eventually the volume of the concrete itself increases.

And another mechanism is there is a decrease in the surface tension of the gel water that further increases the expansion. So surface tension decreases and which leads to expansion. Now, it could be in this range about 1300 micro strain after 100 days of submerged so, significantly high strain could be observed depending on the type of cement paste, when you talk about concrete it could be in this range.

So, what one thing to notice is when you look for numbers, make sure that you are actually looking for numbers which are relevant for the concrete system which you are using and not just for the cement paste.

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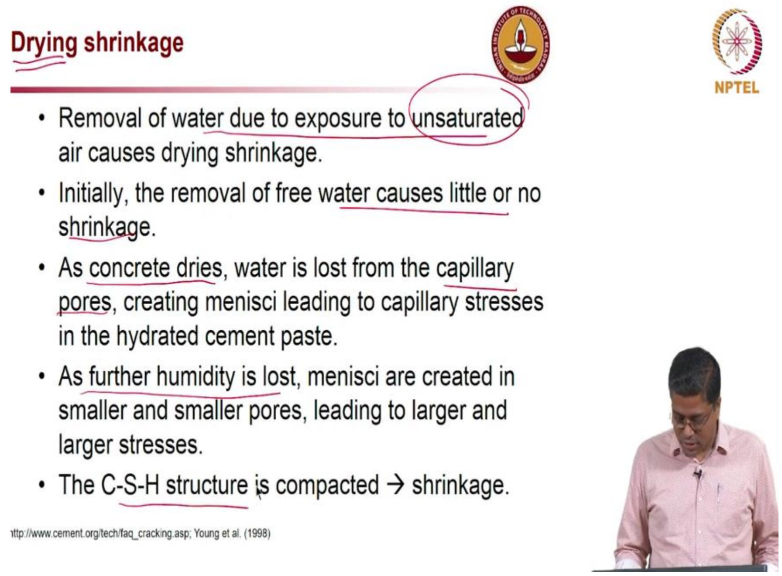

This is an example showing drying shrinkage of a slab, above an asphalt pavement. Actually, because of the asphalt pavement below, the restraint provided by the pavement is relatively less, which leads to this type of shrinkage and this is actually a slab which is about 40 feet long and only 1 crack was is visible on this slab and what you see here is a culvert here and this is actually on 1 side of the culvert the slab is provided.

If you have a hardened concrete and the air right above the concrete surface is not having sufficient humidity or it is in a relatively dry or not really humid environment. That is what I mean by unsaturated condition.

So, what will happen the water which is present inside the concrete will try to diffuse outward and get into the environment outside or drying happens. And initially this removal of water does not cause much damage to the concrete. But as more and more water evaporates or as more and more drying happens, the water which is present in the capillary pores, the water which is present in the capillary pores are also lost.

And what this leads to is, it forms menisci leading to the capillary stresses in the hydrated cement paste. Now, you will have multiple locations this is happening, multiple locations within the concrete this could happen and as further humidity is lost the size of these menisci are reduced. When the size is reduced, that means, you know the stresses are going to be more and more. So, as the size of the menisci smaller the larger will be the stresses generated, which leads to shrinkage cracking.

And also this C-S-H structure eventually gets compacted that means the entire concrete system tends to shrinkage and which will lead to cracking because there are presence of aggregates and rest other restraints which are provided by either the steel reinforcement or the surrounding earth or wherever whatever the concrete is in contact with. So, all as long as there are restraints, then this could lead to cracking. If there is no restraint this could just lead to shrinkage.

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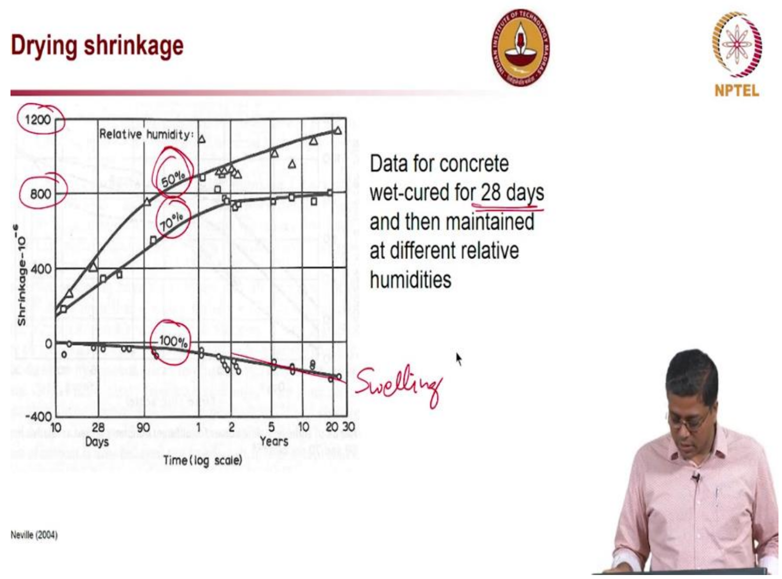

Now, this graph showing drying shrinkage at where the 3 concretes all the 3 were cured for 28 days. And you see here this is 50%, 70% and 100% after 28 days of wet curing, when the concrete was exposed to these 3 different humidity conditions, we could see that very clearly the amount of shrinkage or drying shrinkage is significantly high in case of dry environment.

In this case, which is 50% humidity about 1200 micro strain, when the humidity was about 70%, the strain is only about 800. That is about 30% reduction, and then when you look at 100% humid environment actually the moisture from the air was absorbed by the concrete and you can see or the from the water was absorbed by the concrete and it actually leads to swelling. This is actually case of swelling. So it is very clear that the ambient moisture condition or the humidity condition really plays a role in drying shrinkage.

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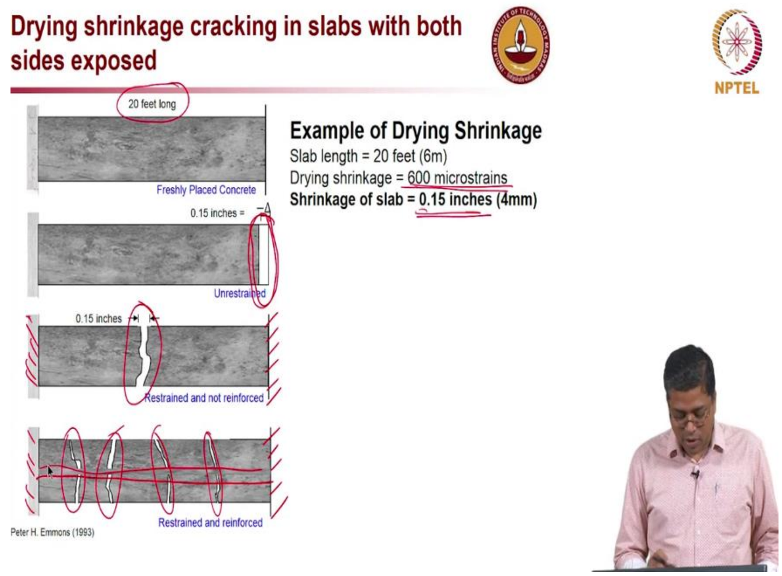

Now drying shrinkage cracking in slabs with both sides exposed. See the slab which I showed here, this was slab on grade. That means the below or the bottom side of the slab is not exposed, it is in contact with the asphalt road at the bottom. Whereas there may be if you are talking about a roof element or a bridge deck, where the both sides of the slab are exposed to environment and this particular example showing here.

It is example from Peter Emmons textbook. You can see here it is a 20 feet long if the length of the element is 20 feet long and the drying shrinkage is about 600 micro strains, the shrinkage or the defamation or change in the length could be about 0.15 inches that is shown here, this is the reduction in the length.

If free shrinkage is allowed, then the length change will happen. But if it is restrained on this side also if the both the sides are of the concrete restraint are held then what will happen the crack will form at almost at the center. And so, the same crack width, but 1 crack will form at the center. Now, if you provide a reinforcement as you see in this picture here there is a rebar which is going at the center right here.

Then there is an additional restraint provided by the reinforcement and that will lead to multiple cracks like in this picture, you see 4 cracks, but the crack width of each of them is relatively less than the 0.15 inch or 4-millimeter crack.

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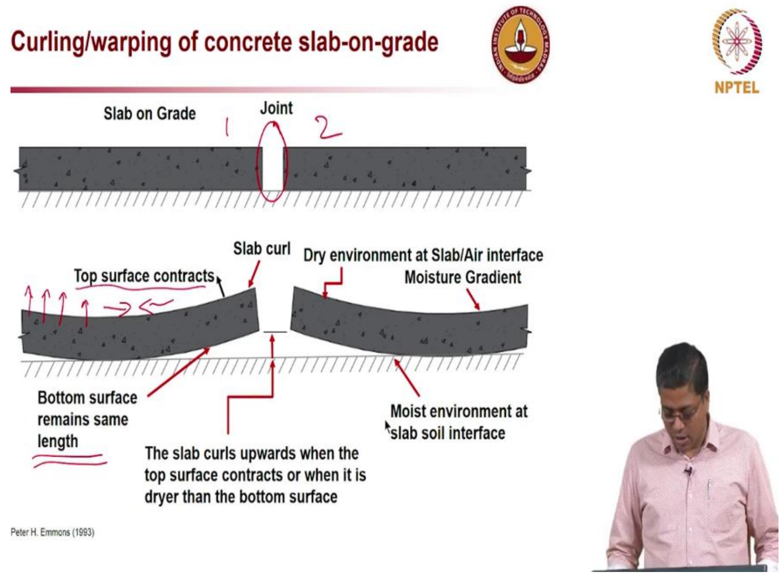

Okay, now, this is an example, showing how this curling or warping of concrete slab on grade happens like highway or a concrete pavement. You can see here 2 slabs 1 and 2 and there is a joint at the center. Now, what will happen if the top surface is relatively you know, if they are in a dry environment, the top surface will actually try to contract whereas the bottom surface I am talking about here the top surface contracts. And whereas the bottom surface remains at the same length.

So, the moisture from the concrete is actually getting out and which leads to drying and shrinking of the concrete and shrinkage means this is going to contract here, whereas, the bottom portion is at similar length. So, there is the effectively the ends of the slab will get lifted up. And if this happens on multiple slabs like this, as you see, when you ride on this road you will feel the moment, the wheel moves from 1 slab to the other. You will feel that the sound if you have these kind of problems, then definitely that will need to be taken care.

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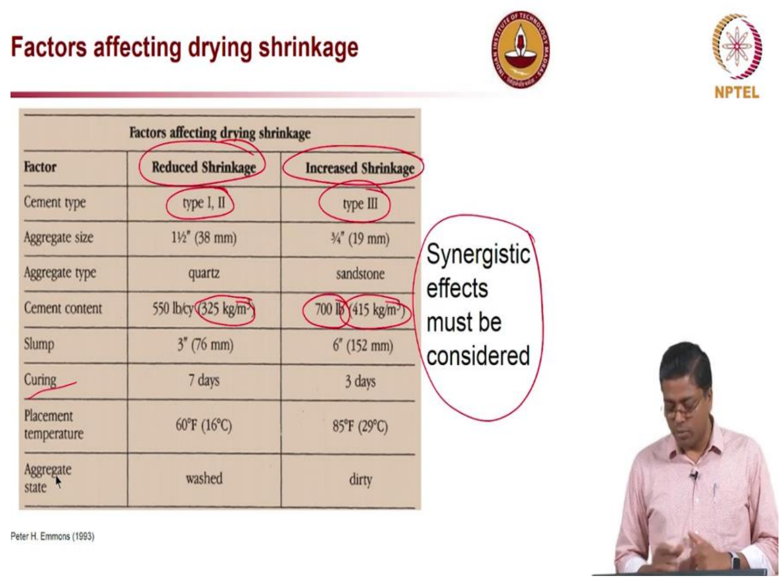

Now, some of the factors which affect drying shrinkage. So, this is just an example to show in the second column here, these are the cases where shrinkage is reduced and the case in the third column it shows where more shrinkage was observed. But, I would like to mention 1 thing that do not look at only 1 parameter. For example, if I say type 1, 2 cement it is going to have less shrinkage and type 3 to have high shrinkage.

It is not like that, you have to really look at the synergistic effects of various parameters must be considered while deciding whether which system will have high or low shrinkage, but this table just gives you a rough idea of some factors which will affect. Aggregate size also, if you are going for smaller size aggregate, you might have a higher shrinkage.

If you go for a large cement content like 415 kg/m^3 instead of 325 kg/m^3, you will definitely have more shrinkage. See, the cement is the ingredient in concrete which leads to shrinkage. So, if we can reduce the amount of cement in concrete definitely you can reduce the amount of shrinkage, and curing definitely, if you go for a shorter curing here in this case, 7 day and 3 days.

The 3 days case is experienced exhibiting higher shrinkage and also the quality of the aggregate. So, all these factors must be looked at, but synergistic effects must also be considered when you look at shrinkage.

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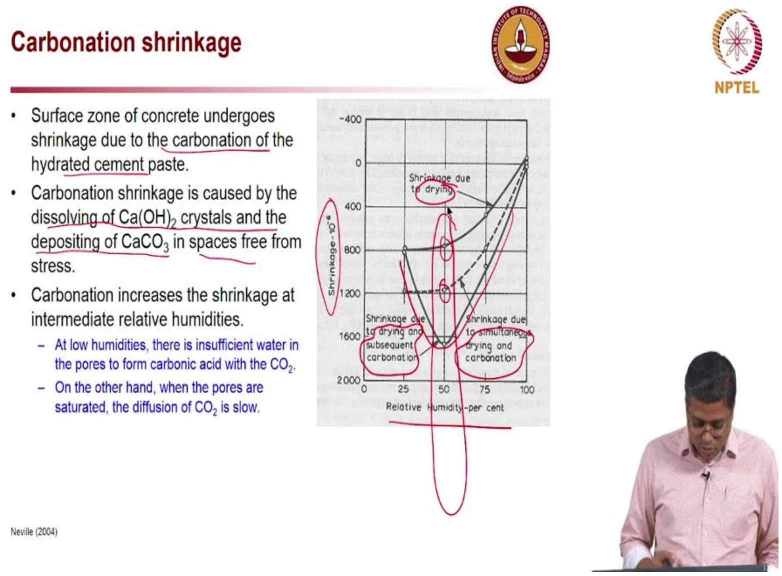

Now carbonation shrinkage is the last form of shrinkage we are going to discuss. And this is observed in some concretes in the very long run, because after a long time when the concrete undergoes carbonation then it leads to a products which are having smaller volume or it leads to shrinkage. Let us look at the mechanism. Here the near surface concrete will undergo shrinkage due to the carbonation.

Because that is the region which actually gets carbonated first and how is it happening? It is caused by dissolving of calcium hydroxide crystals and the deposition of calcium carbonate crystal in the space which is free from stress. So, you have calcium carbonate and this is the product of this carbonation reaction between calcium hydroxide and carbon dioxide, forming calcium carbonate. And then they occupy spaces available within the concrete which are free from stress and eventually they lead to shrinkage.

Now, at what humidity level this can happen as you see on the graph here you can see this is humidity and this is the shrinkage. If in 1 case when the shrinkage was due to drying and subsequent carbonation, then it showed maximum shrinkage. But when it was simultaneous drying and carbonation slightly less shrinkage that is here, and then when it was only drying then it was significant it was further less.

So, point to note here is at about 50% shrinkage you have maximum carbonation and that is the humidity level you have maximum carbonation and probably maximum shrinkage also which is due to the carbonation.

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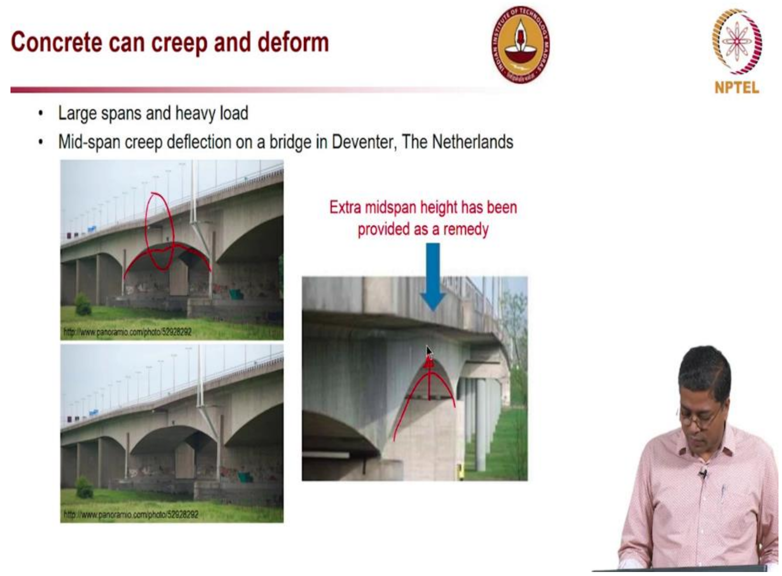

Now, concrete can creep also and the significant deformation can be experienced in this case here, when you have large span and heavy load, you can see the size of this concrete, I mean dead load of this particular bridge is very high. And this picture here as you see, you have a dip at the bottom here, there is a deflection at the center span, which actually is an indicator of significant creep because that deflection happened over a period of time.

And what the repair procedure they actually see here lifted up the center portion and provided midspan was raised a little bit and repaired so that vehicles could drive without a dip on the concrete.

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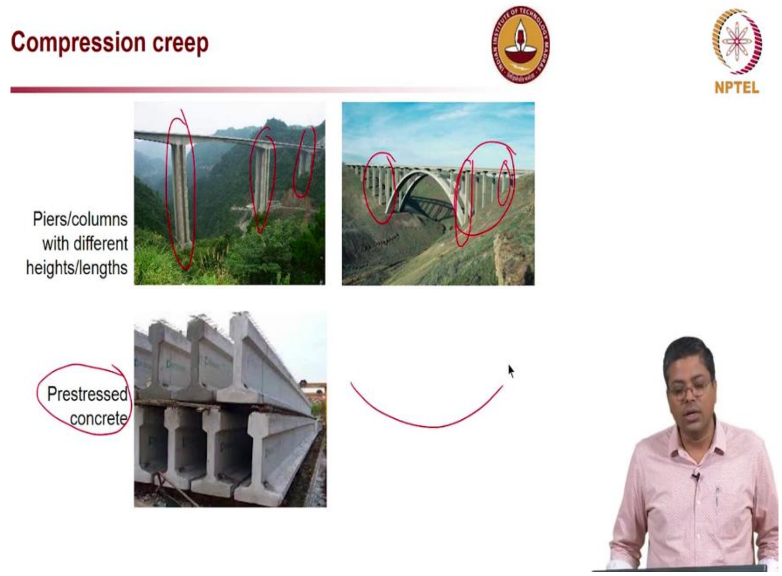

Now, these are some other examples showing compression creep, you can see the 2 pictures. On the top 1 here have a very tall column, or a pier and this it is probably slightly less tall than that and this is also slightly less and then here also you can see all these columns have different height. Now why I am talking here is when you have these different heights, the deformation due to creep, and these are very large structures. So, the dead loads are the loads acting on these columns are also very high.

Now the deformation on each of these columns, due to creep. Smooth ride on the deck is not going to be possible because then there will be differential settlement or the deck will not be at the same level. So, it is very important to make sure that the creep effects are very minimal on these type of structural elements. In other words, the tallest column here the deformation experienced by the tallest column and the shortest column should be maintained at a similar level otherwise you will have uneven riding surface which is not a good thing.

And also in the case of prestressed concrete the because of the prestressing forces the concrete experiences significant compression and over a long period of time, what will happen is, because of this compression the concrete will undergo creep and simultaneously as the concrete gets creep or the length of the element decreases. There is a significant loss in the pre stress which will then induce deflection of the girder. So, there are long term and important impacts of this creep phenomenon.

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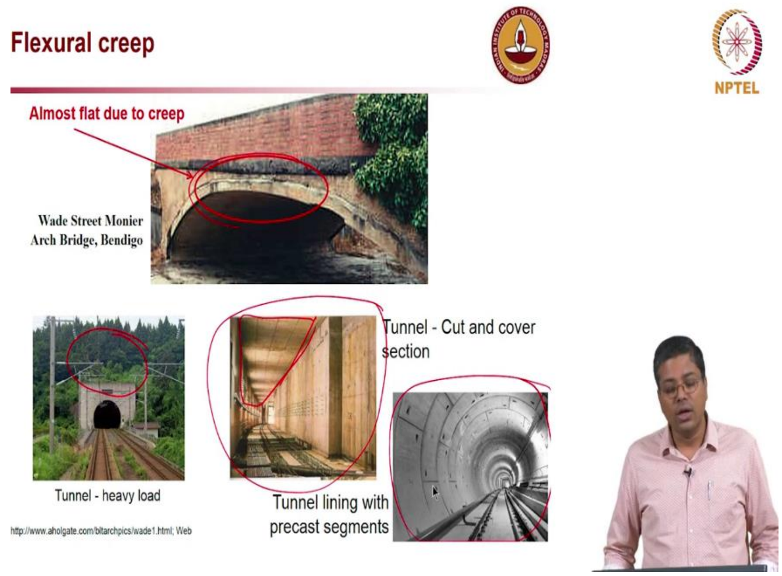

Here is another example of flexural creep, until now we were talking about compression creep. Here you can see an arch bridge, which is now no more an arch. It is not really an arch almost flat at the center, you can see here and the center span and other places where flexural creep becomes very important is tunnel elements or because of the huge heavy load acting on the tunnel segments for the entire life of the structure.

The segment or the concrete has to be designed for creep resistance, this one is an example of cut and cover section that cut and then cover means above this, this concrete over here, you have either a soil or a significant load is there. And here also it is another tunnel, where again you will have significant load on top of the tunnel.

They are expected to last very long, not just couple of decades, but much beyond that so in the long term, how these type of structures will perform under creep must be studied before we decide.

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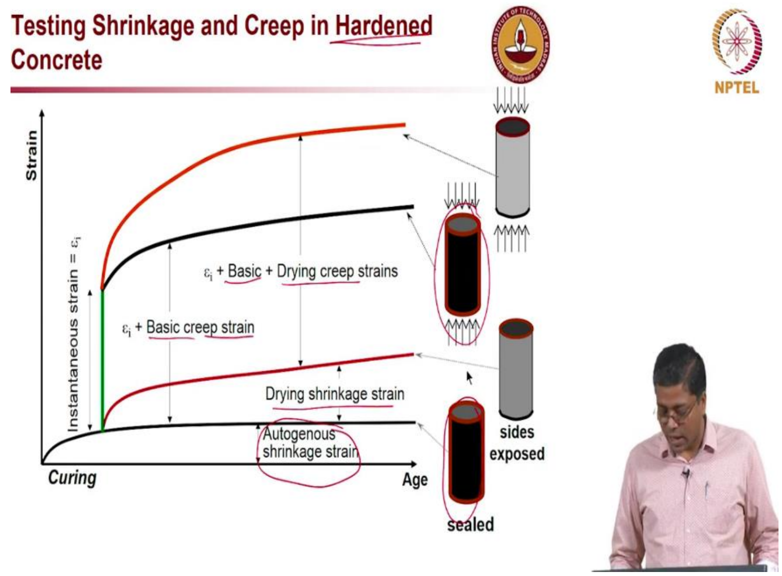

It is not just the immediate structural performance long term performance must be looked at how we can test shrinkage and creep. This is just a similar graph I showed in the very beginning, you can see here autogenous this is on hardened concrete the first graph which I showed was slightly different. So, you can see autogenous shrinkage and then drying shrinkage strain here basic and dry creep and basic creep strain.

Now, how do we check this mainly when you talk about the autogenous shrinkage, you will seal the concrete with aluminum wraps I will show that in the next slide. Whereas, when you talk about drying shrinkage or drying creep, we test the concrete element without covering them.

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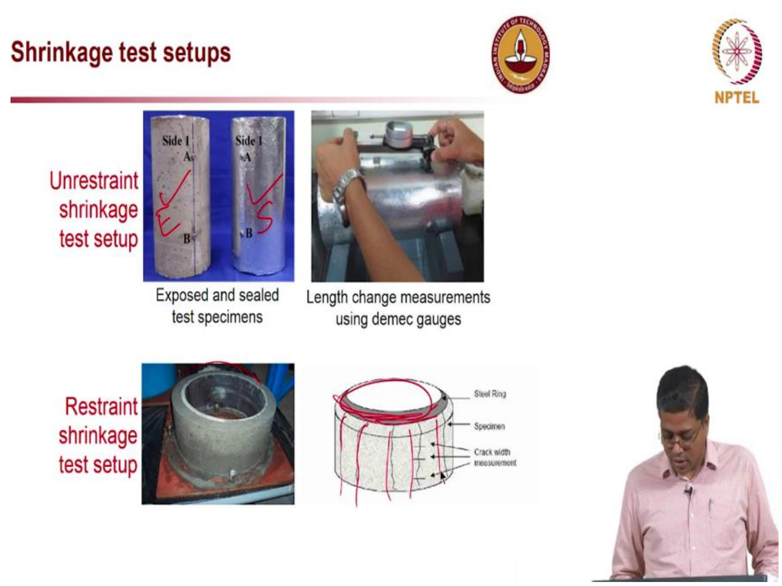

You see the picture here on the left, 2 cylinders, one is exposed cylinder, and other is a sealed cylinder. And we look at the change in the length as time passes and then see what is the shrinkage. Once it is sealed that is mainly for autogenous shrinkage which is exposed is mainly for total or drying shrinkage. And for restraint shrinkage test we suggest to do this ring test, where the steel ring which is the inside is gray portion here, this one that steel ring provides the restraint.

And then concrete tends to crack like this, see the sketch on the right side and then we look at how much is the crack width and how the pattern is and all that.

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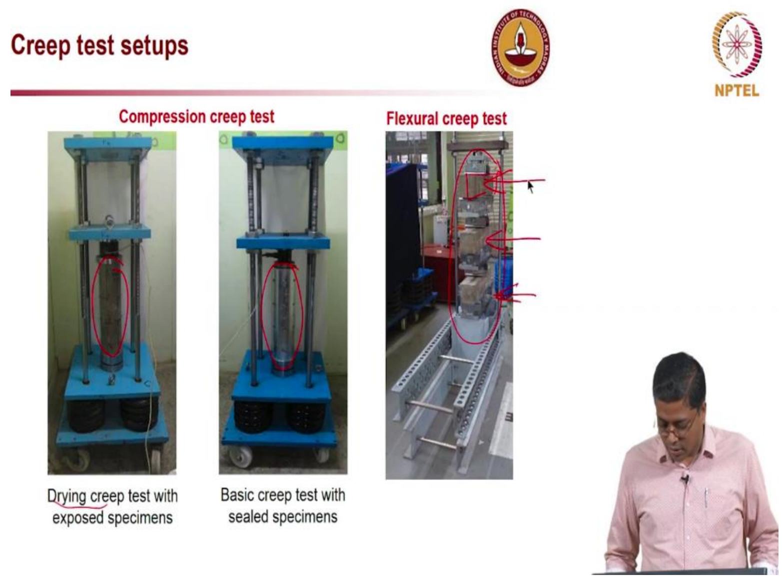

For the creep test setup, you see here these are typical creep test setup where you can see concrete cylinders on the right side. This is actually sealed that is mainly to study the basic creep, whereas on the left side it is exposed concrete specimen which is not sealed. So, you can study the drying creep in this case and like I mentioned flexural creep is also very important.

So, here is the test setup which we have in our lab, where you can see flexural creep test setup where 3 concrete beams beam specimens are kept one above the other, 3 beams just to look at the flexural creep.

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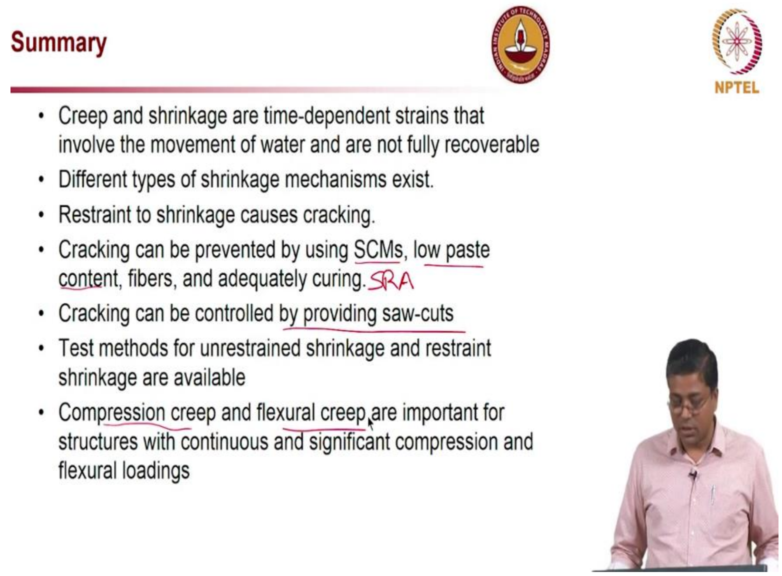

Now, to summarize, we looked at creep and shrinkage and found that they are actually time dependent strains that involved movement of water and are not fully recoverable. And different types of shrinkage mechanisms exist we looked at 5 different types and then restraint into shrinkage causes cracking in other words if there is no restraint, there will be only shrinkage but no cracking, but when concrete cracks, it is not something which is good for this structure.

So, we want to prevent cracking. How do we prevent cracking? maybe by using SCMs or low paste content or cement content and use of fibers and definitely by adequate curing, also shrinkage reducing admixtures can be used and shrinkage reducing as admixtures forgot to mention that in this bullet and cracking can be controlled not eliminating tracking but by controlling cracking can be controlled by providing saw cuts at defined distance.

And then test methods for unrestrained shrinkage and restraint shrinkage are available and compression creep and flexural creep are also very important. Usually we talk about compression creep but flexural creep is also very important when we talk about long span structures, especially long span structures and tunnel elements, which are meant to last for a long time or in 100+ years of life is expected in case of tunnel even, maybe more is expected.

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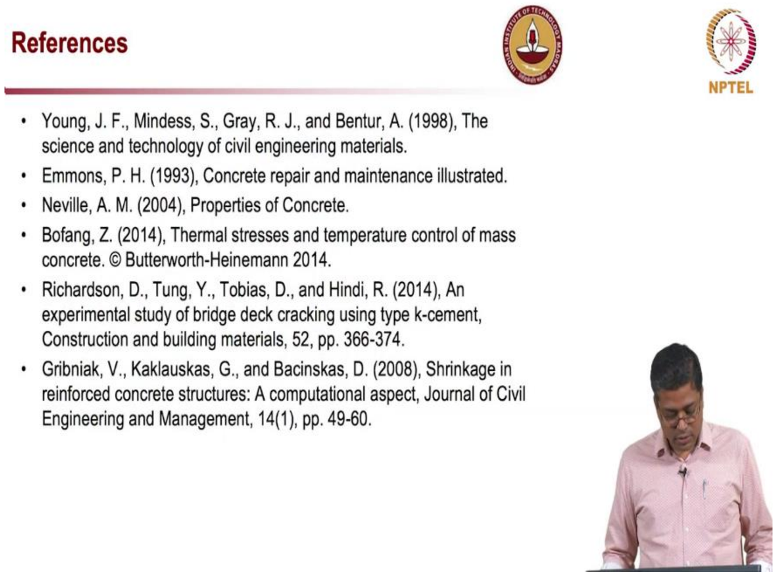

Thank you these are the references used for making this particular presentation.