Advanced Concrete Technology
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Lecture – 33
Shrinkage: Plastic Shrinkage

Good morning everybody. So we will continue our discussion on plastic shrinkage and we have done several experiments in our lab on the influence of different fibres on cracking of concrete either in the early stages or in the hardened stages. So here I am describing to you a set of experiments that was conducted by one of our previous PhD scholar who worked on the study of plastic shrinkage of concrete as affected by a combination of Steel and non-metallic fibres.

The same study that we discussed in the last chapter on hardened concrete properties, where we looked at how the stress strain characteristics, especially the flexural toughness was affected by the combinations of the different types of fibres. So the same study was extended to fresh concrete also to look at how plastic shrinkage is affected.

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Now of course to simulate a study in the lab involving a slab that is of very large dimension could be quite tough.

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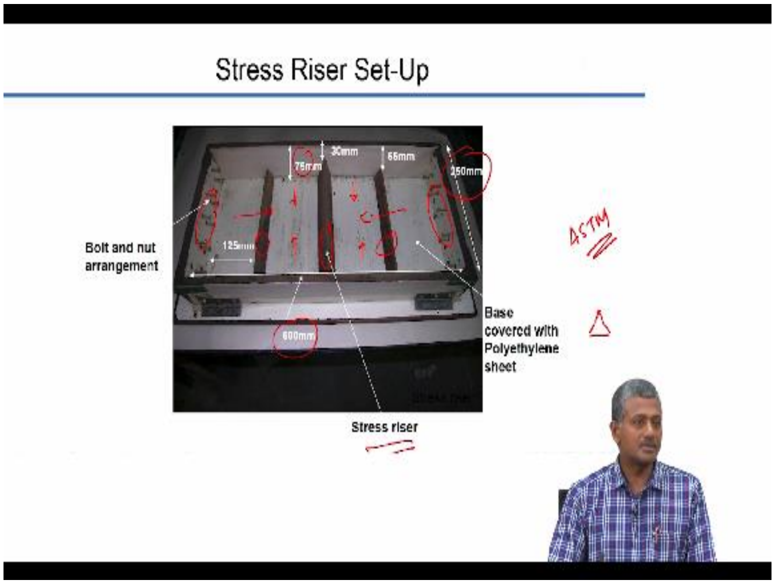

So what is typically done is a Stress Riser experiment is usually conducted to determine the plastic shrinkage characteristics of concretes and this experiment is now actually a standard, ASTM standard. I am sorry that I do not recall the exact number. This standard talks about the use of this specially designed slab. The slab dimensions are 500 mm length and 250 mm breadth and it is got a height, total height of 75 mm and in the center of the slab, you have a wedge.

It is just a wedge which is placed in the center of the slab which acts like a stress riser. So what happens now is as the concrete starts to shrink. As the concrete starts to shrink, what will happen? It will try to shrink in both directions. Concrete will try to shrink in both directions. Now because of the restraint offered by these additional wedges that are provided here and the bolts and nuts that are provided at the ends, the movement of concrete inside is going to be restrained.

So once you do that, concrete has to crack and the most probable location where the cracking will happen will be right on top of the stress riser. Why? Because we already have a stress concentration at the tip there and because of that the crack has to originate exactly at that location. So this makes the study of cracking much easier rather than looking at a very large slab where cracking can be quite random.

In that case doing a proper image analysis would require a lot of effort. In this case because of the stress riser, the cracking appears very fast and secondly it is at a predetermined location. So you can actually study the characteristics of the crack much easily. So this is basically the setup that was used.

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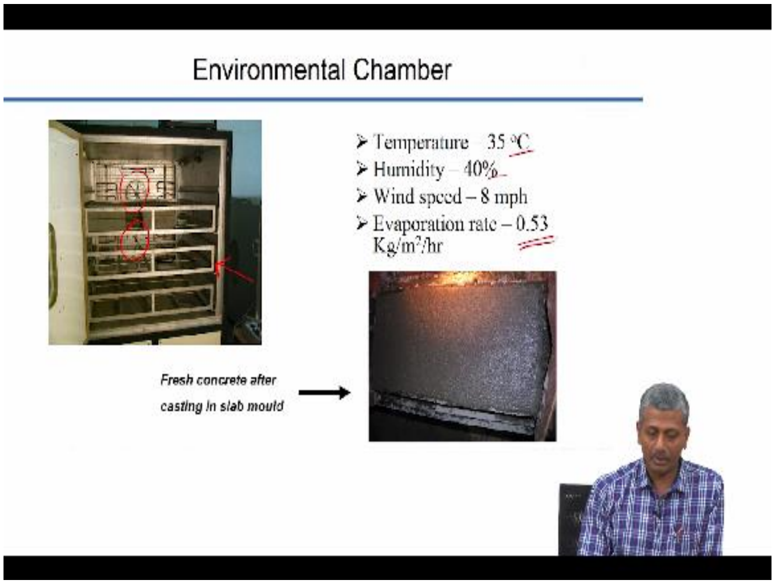

Concrete was prepared and put in into these moulds and these moulds were then transferred to an environmental chamber which is kept at a specific combination of temperature, humidity and wind speed. The temperature was 35, humidity was 40% and the wind speed was maintained with the help of these fans that you see on the inside of the chamber and that worked at about 8 miles per hour.

But still this could not really push up the evaporation rate at the critical level which I discussed yesterday was 1 kilogram per square meter per hour. So here we will replicate a 0.53 but nevertheless, we were able to conduct the experiment and demonstrate the differences between regular concrete and fibre reinforced concrete.

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So let us look at the numbers here. First, we will look at the concrete mix design. This is the same concrete that we talked about in the last chapter. Essentially it is a high performance concrete with silica fume replacing cement by about 7% and water-cement ratio is 0.4 and here, I am just describing the studies which have a combination of hooked steel and polypropylene fibres.

Although we conducted the study across the entire range of hybrid fibre combinations, steel with glass, steel with polyester and steel with polypropylene. So I am just showing you one set of the results just for clarity.

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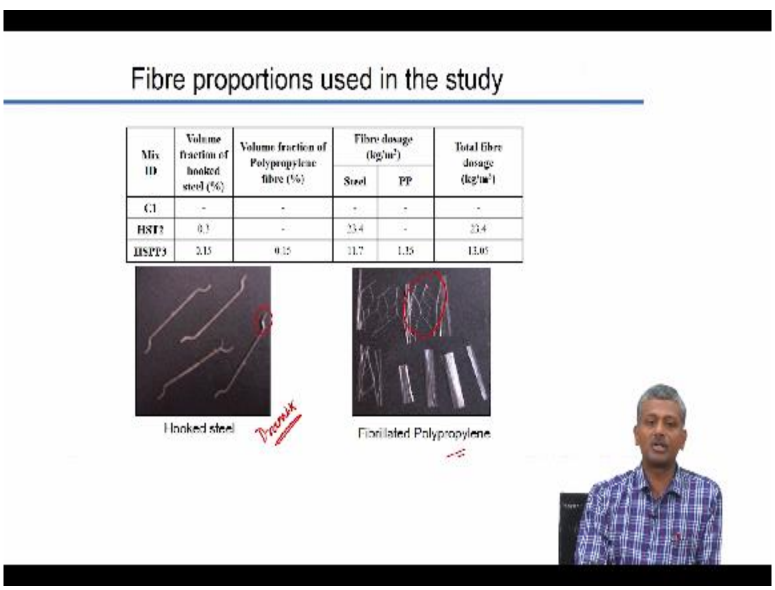

So the fibres that we used of course hooked steel, they have a hook at the end. These are well known fibres. Today, they are used almost all over the country. They are called Dramix fibres from a company called Bekaert which is probably one of the leading manufacturers of fibres in the world, and this is fibrillated polypropylene as we discussed in the last class. Fibrillation means it is not a single filament.

But there are several filaments connected in the network, and the dosage which is being discussed for this chapter here, looked at hooked steel fibres at 0.3% and that a combination of steel and propylene, 50-50% combination of steel and polypropylene, which accounts for about 0.15% of each type of fibre.

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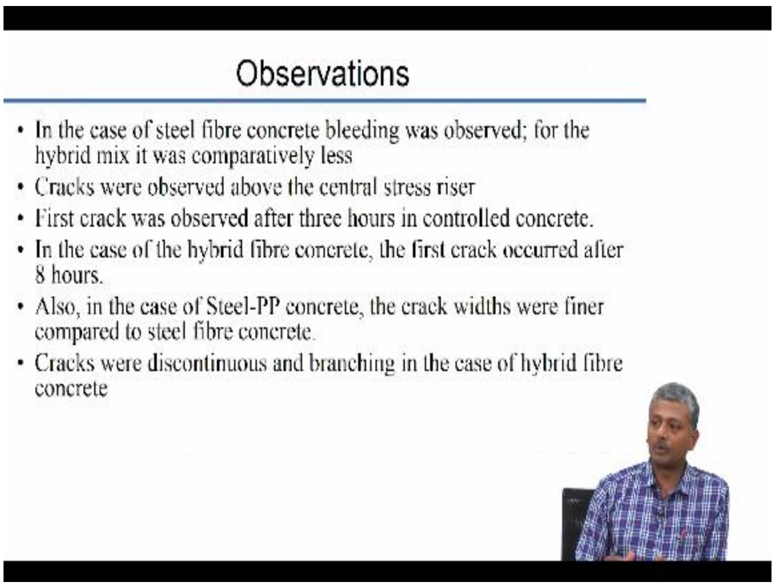

So again, now in terms of the observations obviously because of the stress rise of the crack appeared right exactly over the stress riser and the appearance of the crack happened at different times for the different types of concretes.

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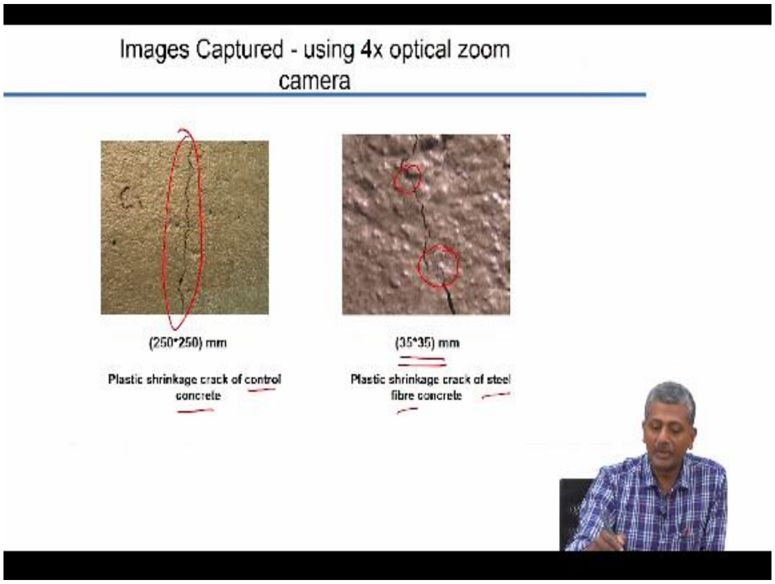

So instead of the words I will show you the actual images which correspond with the appearance of the crack. So this is the control crack concrete without any fibres and you see that this crack is almost straight. It occurs right over the stress riser and it is almost straight running across the entire length and the width is almost constant across the entire length. Of course, you can do an image analysis on this and determine the extent of crack area, maximum crack width and all the other crack related parameters.

Now for the steel-fibre concrete, the presence of fibres obviously reduces the propensity for crack opening up and as a result of that, the cracking was not uniformly all across the stress riser but it sort of started deviating at some locations and you can see some branching of cracks and overall, the crack width is also much smaller.

Please note that this is only a 35 x 35 mm area that has been imaged in this picture and that is accounting for a very small part of this entire stress riser that we are showing on the left. So the crack widths are obviously reduced when fibres are used which we expect anyway but what happens when we use a combination of steel and polypropylene?

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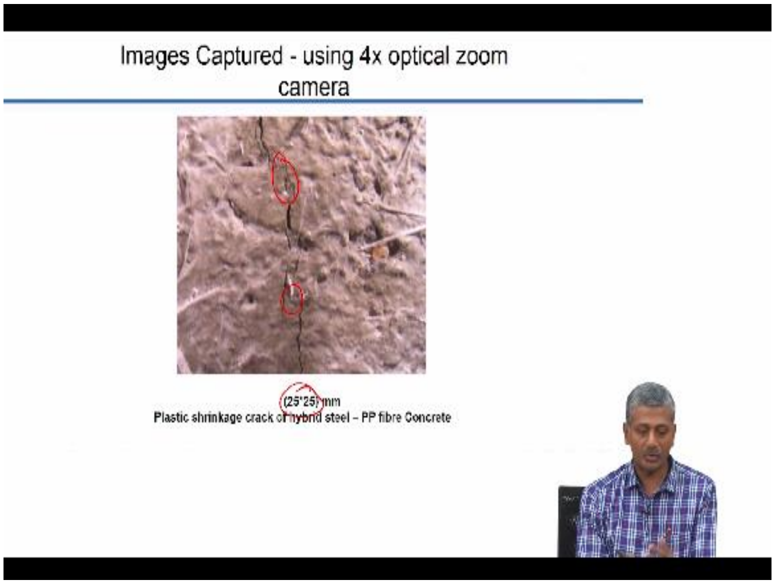

Is the performance better? And indeed this is actually even a more magnified area, 25 x 25 mm and you can see here the crack widths are even smaller than what we saw in the steel fibre case and there is a lot more crack branching which indicates that; first of all, please remember that polypropylene fibres have much lower density than steel fibres. So for a certain amount of fibres that are added in the system, you will have larger number of fibres that are available.

Higher aspect ratio and lesser density implies you have much larger number of fibres available as a result of which there will be much greater contribution to the reduction in cracking due to plastic shrinkage. So here you can actually see even some fibres on the surface of the concrete. So this fibres, there are so many number that they are actually restricting cracking tremendously and in fact, this effect was even better when we used polyester fibres which were even thinner and shorter than the polypropylene fibres.

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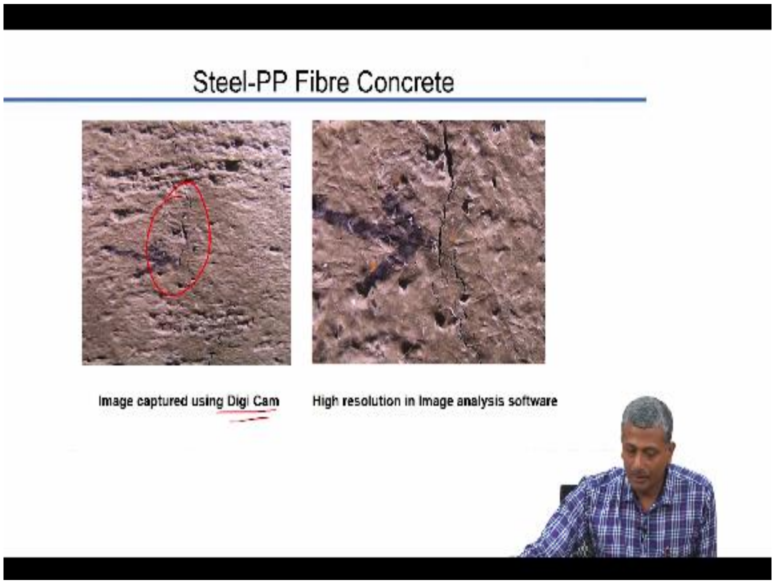

So again, here there is a combination. So how we actually capture the images and how we process the images to ensure that we were able to get the extraction of the data related to cracking. So this is the image as captured using a digital camera and this is the same image zoomed up section here where the image has been enhanced with the help of image analysis software.

Of course, it requires some level of expertise and experience handling these types of software but essentially what we want to do is get a sharper image so that we can track the progress of cracking much easier.

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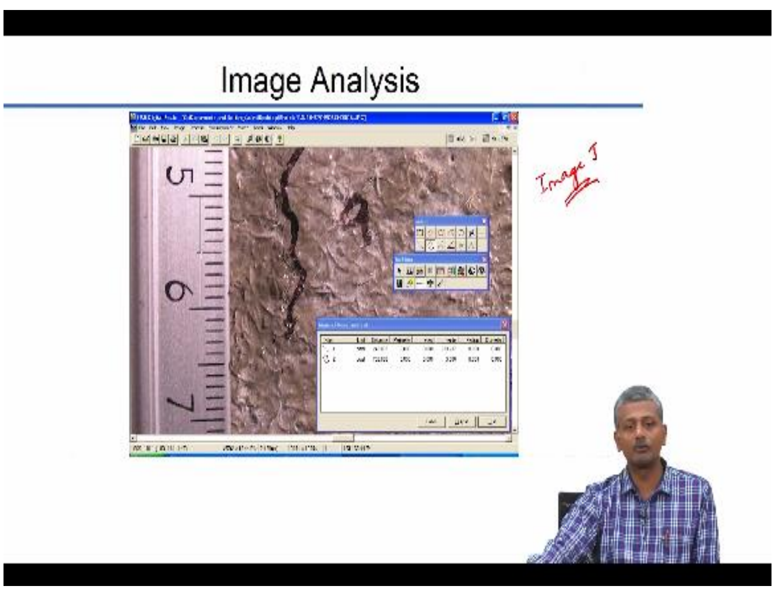

And based on this we did some measurements on the actual crack length using the tools available in the image analysis software. This is software that was available for free on the internet. It is called Image J software, name is Image J. So we can actually do the analysis in terms of determining lengths and size of the different types of features. So we determine the length of the crack and we also determine the average crack width by taking crack measurements at different locations.

Of course, you can imagine that when you deal with very fine cracks, you cannot just visually take the crack width readings. You might need to have a crack width comparator or the crack width microscope that you might have used in your structural engineering laboratory experiments.

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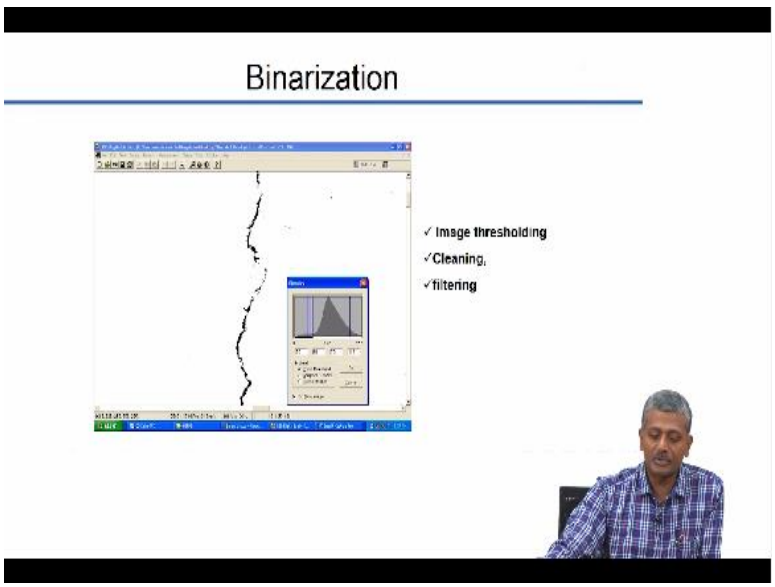

So after we do the image collection, we do the binarization which actually gets as the actual image of the crack itself. All the other parts are turned into white and only the crack part is black, and then based on that, we can actually then determine several features related to cracks.

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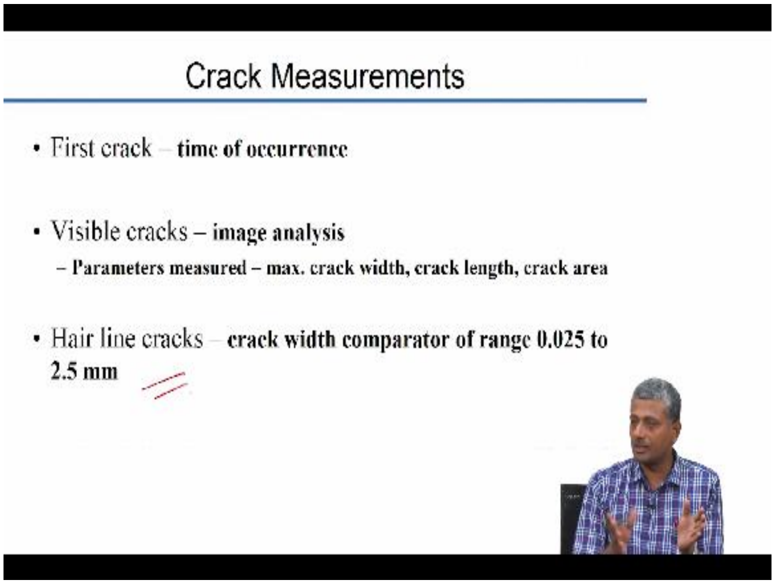

So the size of the cracks, so that we can correspond this crack size to be either a hair line crack or a large crack. There were visible cracks which could be directly obtained from the image analysis itself but for very small hair line cracks, we had to actually do the crack width comparator measurements. The other thing which we noted was the first crack occurrence time. So this was actually this entire slab was sitting inside the environmental chamber.

So of course, we had a very rudimentary setup. We had to actually remove the slab from the chamber and then visually look for any signs of cracking. You can automate this process also by putting a video camera inside and looking at the occurrence of the cracking. But in this case, it was visually done by removing the slab from time to time and checking the occurrence of crack. So then might be some errors in that.

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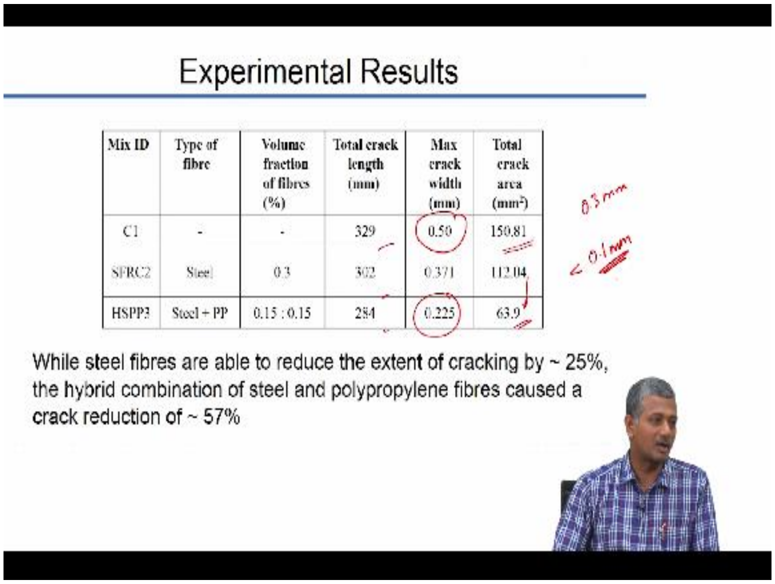

And so here, this is describing the actual results here. The total crack length is shown here. The control concrete, the steel-fibre concrete and the hybrid fibre reinforced concrete and the maximum crack width decreased from 0.5 mm to 0.225 mm when hybrid fibres were used and you can see the total crack area has been reduced significantly. So compared to even steel-fibre concrete, the total crack area has come down by almost half.

And this was actually even better when we worked with combination of steel and polyester-fibre concrete which showed reductions of crack width of almost 99% as compared to the control concrete. So you can reduce crack widths to the levels that are not significant anymore and what are the significant levels of crack widths that are typically described in the standards? Yes, for 0.3 mm in a, what type of exposure? Mild or moderate exposure that when we go to very severe or extreme conditions, you need to restrict to crack widths to 0.1 mm.

So crack width should be less than 0.1. Now of course how is this accounted for in the design? How is this accounted for in the design? How do we, do you see people going around checking crack width after the structure has been constructed? No. So this has to be accounted for in the design. So usually of course, when you do reinforced concrete design, the reinforcement is supposed to take care of this crack width.

But often times in extreme situations, we have crack widths that may be far exceeding these limits and in those cases using fibres can really help. For example, you saw that real life example of the metro decks that I showed you. The crack widths there were almost as much as 2 mm in some cases. So if they had used fibres, it would have definitely restricted crack width to even if plastic shrinkage was indeed occurring.

But of course, the use of fibres is not something which is very easy. We need to justify it. It is an expensive solution, and to a large extent, it depends a lot on the abilities of the marketing people. How well they are able to market their product to different construction companies and whether they are able to convince that the use of fibres is absolutely necessary. Now, before we discussed all this, we were talking about how to mitigate plastic shrinkage cracking.

And the simplest way is to simply reduce the evaporation of the water and that can be done by starting early curing or completely covering your concrete surface using a plastic sheet and so on which will totally prevent the evaporation of water, that is a much more easier and cost effective solution to reducing plastic shrinkage cracking but then for that people need to be present on the job site after the concreting is done and finished.

People should not pack up their bags and leave the site. They need to ensure that the first appearance of the cracks has to be detected and floating can be done to actually remove the cracks or completely covering the concrete to prevent evaporation needs to be done. Use of fibre shrinkage reducing admixtures of course, it is effective. We can show all kinds of research to prove that but ultimately it is a very expensive solution.

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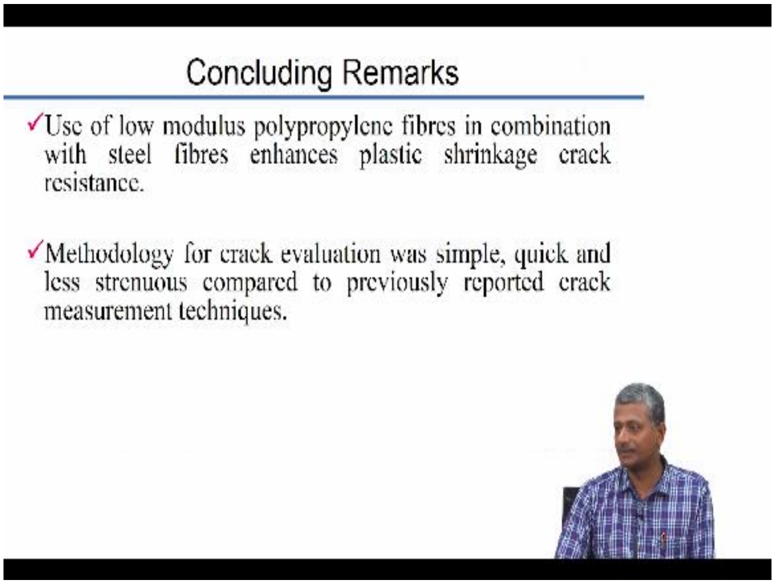

So again, use of low modulus polypropylene fibres in the study added to the benefits of already putting in steel fibres. Of course, just using the low modulus fibres like polypropylene and polyester in the concrete may not be beneficial in the long run because for hardened concrete characteristics like we discussed in the last chapter, you have to have the steel fibres present to have any significant post peak deformation behaviour.

Otherwise, with low modulus fibres, you do not really get that. So steel fibres are absolutely essential for hardened concrete behaviour but the fresh concrete behaviour can be improved by partially substituting the steel fibres with non-metallic fibres like polyester and polypropylene.

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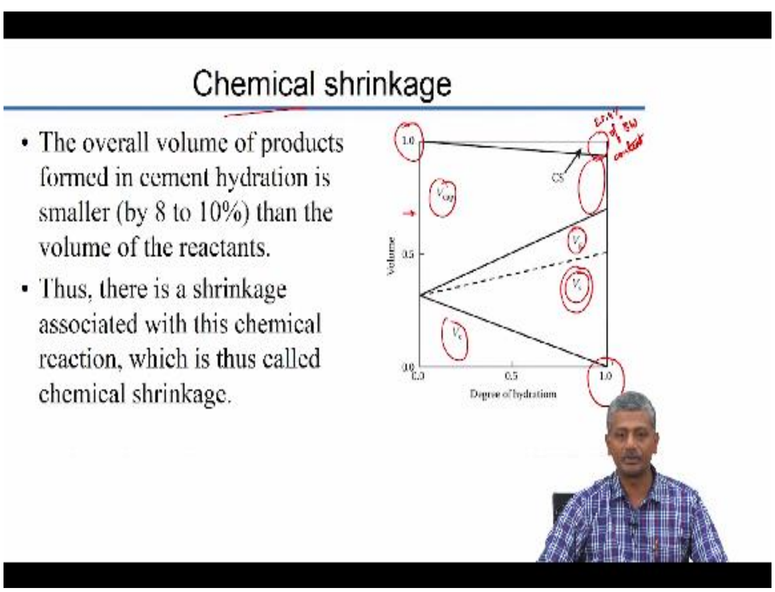

Now having looked at plastic shrinkage and we also talked briefly about thermal contraction earlier and let us look at the mechanisms of the other types of shrinkage that typically happen in the system. So one is chemical shrinkage and this is something that we have discussed when we started looking at calculation of the structure of hydrated cement paste when we did the calculation to determine how much capillary and gel pores are forming in the system.

We made an assumption that a small reduction in the volume happens when cement and water react to form solid hydration product and we generally assumed that volume to be about 25.4% of the bound water content. If you remember that calculation that we did earlier. Now how is this achieved? You can also do studies to determine this experimentally and this shrinkage that happens during the chemical reaction is simply called chemical shrinkage.

Of course, this shrinkage is also automatically contributing to any shrinkage that is happening in your system. So when you are measuring the shrinkage of your concrete, when it is subjected to drying, all kinds of processes are happening. So you have drying, shrinkage, you have autogenous shrinkage, you also have chemical shrinkage that is happening in your system. So the overall volume of the product that is forming in cement hydration is smaller by about 8-10% as compared to the volume of reactants and that 8-10% approximately is 25.4% of bound water content, that is basically a theoretical value.

The really experimentally observed values are between 8-10%. So that is why it is called chemical shrinkage. So what this is showing is again this is the initial volume of your reactants that is one, and out of that this is the volume of the cement and volume of the water which is marked as the volume of the capillary porosity. When cement and water are mixed together, all the water forms part of the capillary porosity.

As more and more hydration happens, the volume of the solid hydrated cement paste keeps growing. The volume of the gel pores proportionately grows as the hydrated cement paste keeps forming and the remaining fraction is your capillary porosity, but this solid hydrated cement paste is accompanied by a small change in volume which we correspond to 25.4% of bound water content and that exactly is what is responsible for the chemical shrinkage that happens in the system.

Of course, please remember that to attain that level of reduction in volume, that 8-10% reduction in volume, we are assuming a very high degree of hydration. Close to 100% hydration is assumed for that level of reduction in volume. So for smaller levels of hydration, you can expect that your overall reduction in volume is not that significant.

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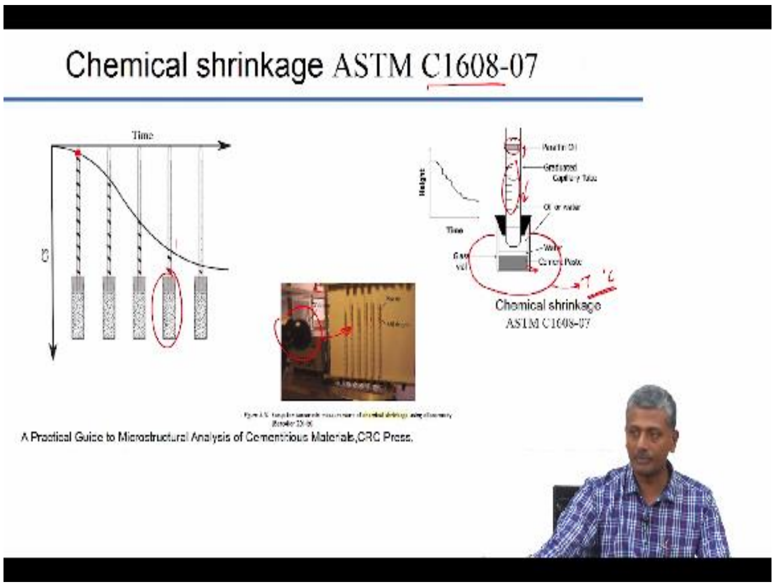

This is an experiment again which has been standardized now in ASTM C1608. So all you do is simply have a vial in which you put your mixture of cement paste and water and you have a tube, a graduated tube which is connected to this vial. You fill up this tube with water to the top and then you have a droplet of oil which is kept on the top. So there is an oil droplet which is kept on top which does not mix with this liquid here which could be either oil of water.

So what happens as chemical shrinkage happens in the cement paste, there will be some portion of its volume which will be filled up with this liquid which is here in the column and because the paraffin oil at the top is not mixing with the liquid below, you can actually note that as the drop in height of the paraffin oil and again, you can automate this process by setting up the web cam which can actually measure the chemical shrinkage directly.

So this is what people usually do to measure chemical shrinkage. It is not very difficult to setup.

Only thing it requires is that your cement paste should be in a temperature controlled chamber because you do not want the temperature to be varying during the experiment. So typically what happens is the vial of cement paste will be resting inside of water bath which is maintained at a constant temperature. So we have set this up in our lab. Those of you who are interested to see this setup can see in our microstructural lab.

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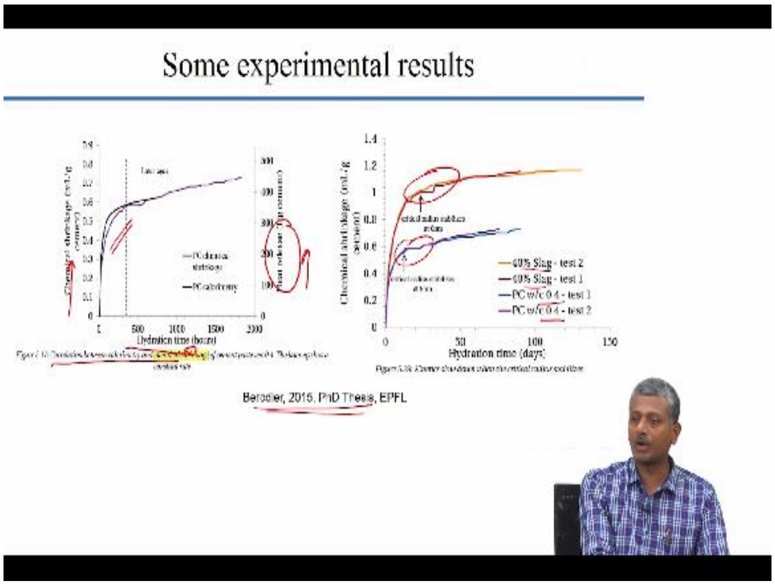

So here there is some experimental results that are given for 2 types of concrete, you have Portland cement paste with water-cement ratio of 0.4 and the same paste when it is replaced by 40% slag. So you can see here that for the plain cement paste, the extent of chemical shrinkage is going to be lower than what you observe with the slag. And then there is also correlation between calorimetry and chemical shrinkage.

So of course, calorimetry implies the study of the heat evolution pattern and the heat evolution pattern in terms of the total heat that is evolved is also proportional to the amount of hydration that is happening in the system. So as the hydration time increases, your chemical shrinkage also increases and the heat release, overall heat release also increases. You can see that the correspondence between heat release and chemical shrinkage is fairly good.

You see almost a 1:1 correspondence between chemical shrinkage and the heat release. So usually what happens in cement paste or concrete studies is that you always have alternative approaches to study any one problem. So here if you want to study hydration, you can study it through calorimetry as well as you can study it through chemical shrinkage measurements. So you get almost the same kind of trends with both types of experiments.

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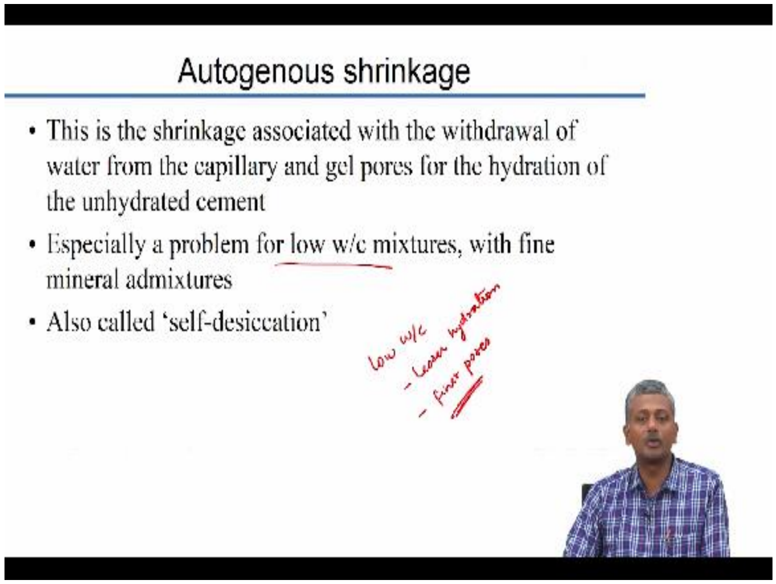

Now one phenomenon that is a little bit difficult to comprehend is autogenous shrinkage or self-desiccation because the concrete is not really subjected to any external drying. It is drying from within. Okay, one of the aspects that you need to think about is not all of the cement inside the concrete gets hydrated. Some cement remains unhydrated and it starts pulling the rest of the water towards it for undergoing hydration and this water now has to travel through porosity which has been reduced because of hydration of other cement particles.

So whenever there is travel of water through thin pores, there is going to be high capillary pressure associated with it that causes shrinkage. Alternatively, you can also think about the fact that the unhydrated cement, when it reacts with the water, there will be a chemical shrinkage associated with it, that will also correspond to overall self-desiccation or self-drying of the system.

So basically there are 2 components, one is the movement of water through thinly constructed capillary pores and the other is the formation of hydrated cement paste which results in the reduction in volume. So essentially autogenous shrinkage is a little complex because of that but it is generally a problem primarily for low water-cement ratio mixtures, because you can imagine when you keep on reducing the water to cement ratio, what happens to the level of unhydrated cement in the system?

It goes up. Low water-cement ratio, more unhydrated cement. Another factor is low water-cement ratio also means that the pore sizes are smaller. If the pore size is small, then the travel of water through these pore size is will be generating lot higher capillary pressures that will lead to more shrinkage. So essentially low water-cement ratio is responsible for lesser hydration and then second, it produces finer pores.

So both these factors contribute to autogenous shrinkage. In fact, when you think about high strength or high performance concretes, the extent of autogenous shrinkage can be much higher than the extent of drying shrinkage. Why should drying shrinkage be low in low water-cement ratio systems? There is no water to evaporate out of the concrete. There is very little water that can actually go out of the concrete.

So there what is actually happening is the water is moving within the concrete only. So that is why we call it an autogenous shrinkage. So this concept of autogenous shrinkage is something that people are not yet fully confident of handling as far as the design of concrete and curing, subsequent curing of concrete is concerned. So let us think about a curing situation in which you start membrane curing.

When you do membrane curing of concrete, there is no external water that you are providing from the outside. So again the strains generated because of movement of water to hydrate the unhydrated parts of the cement is going to be significantly high. When you do water curing, there is external water also that possibly can enter the concrete and reduce the autogenous shrinkage by a significant level.

So if you do long-term water curing for concrete that is having low water to cement ratio, that can actually significantly reduce your autogenous shrinkage characteristic. When you do a greater extent of wet curing, the amount of autogenous shrinkage keeps reducing, because water is available from the outside, it reduces the amount of capillary pressure that is felt by the system upon self-desiccation.

Again, it is called self-desiccation because there is drying happening from within. You do not necessarily need to dry it outside. So even in a sealed specimen, you will actually get shrinkage and that is because is autogenous shrinkage.

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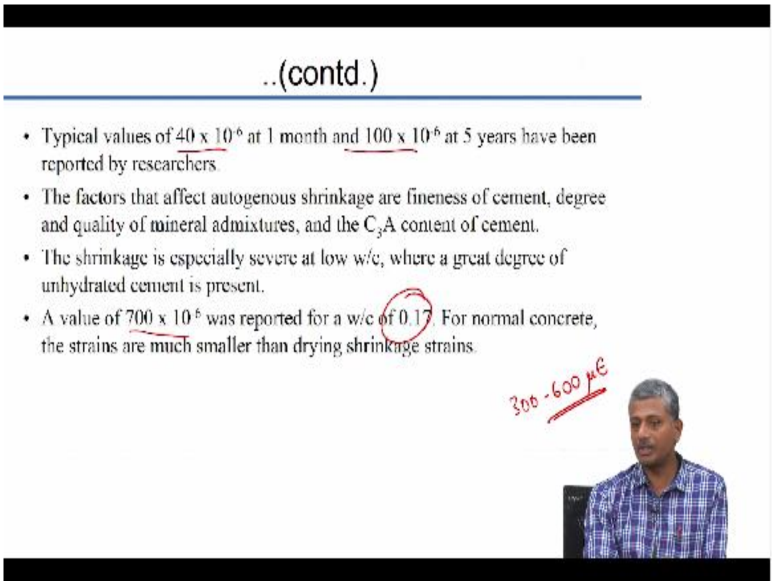

Again several different values for autogenous shrinkage for normal concrete are reported, 40-100 microstrains. 40-100 microstrain is very small. What is the typical drying shrinkage value? We are talking about 300-600 microstrains for normal concrete but then when you go for very low water-cement ratio systems, people have even reported as high as 700 microstrains. So that is a significantly large amount of strain that you have in the concrete.

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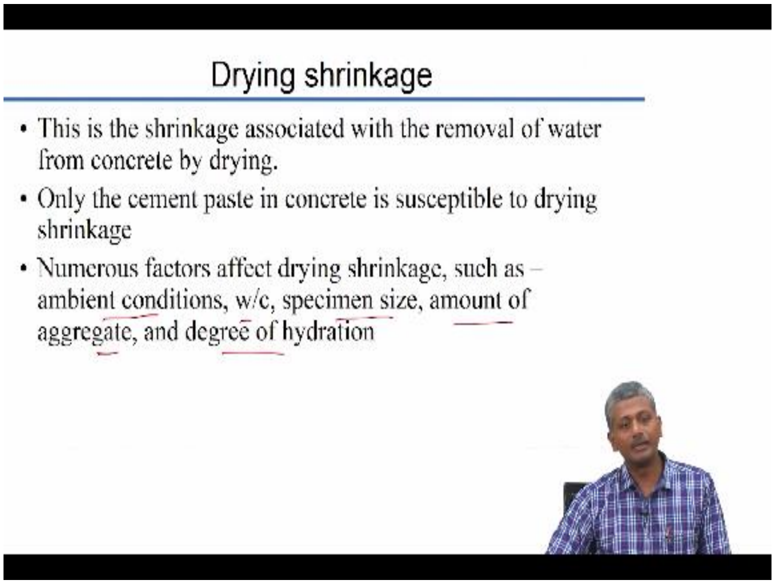

Now of course all the different components of shrinkage like chemical shrinkage and autogenous shrinkage, ultimately contribute to the overall shrinkage of the concrete which is worsened when there are drying conditions prevailing outside of the concrete. So all this totally we call it as drying shrinkage and generally the component of shrinkage that is associated with drying of water to the outside environment is called drying shrinkage.

And of course, we know that only the cement paste in concrete are subjected to shrinkage not the aggregate. Even the other forms of shrinkage also happens in cement paste and there are several factors which we have already seen before as to how they affect shrinkage in the ambient conditions that is temperature, humidity, water to cement ratio, specimen size, amount of aggregate and degree of hydration.

All these affected creep in the same way that they affect shrinkage. So for example if I take the amount of aggregate, how does it effects shrinkage? More aggregate implies lesser shrinkage obviously. So again, the move towards this new mix design philosophy where we optimize the aggregate content to minimize the pore volume that is a good approach to take to reduce the overall shrinkage in your system.

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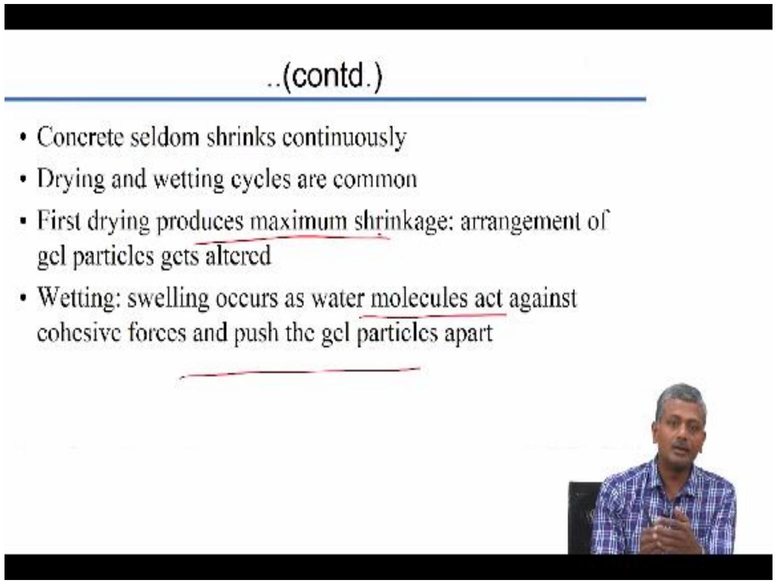

Of course, one thing you need to understand is in practice, concrete does not shrink continuously. Because there are cycles of drying and wetting. So what we need to understand is how this cycle of drying and wetting changes the concrete microstructure in such a way that overall shrinkage or swelling actually happens in the system. In a laboratory study, we saw the kind of protocol that is usually followed.

You have concrete that is prepared and stored in an ideal condition like a wet curing or a moist-curing for 7 days and 28 days as the case may be and then subjected to a drying environment. But there we do a continuous drying at low relative humidity to make the concrete shrink continuously. But then in reality, this concrete shrinks for some time and then there may be a rain after that because of that, there is rewetting and then there is going to be drying again and rewetting again and so on.

There will be multiple cycles of drying and rewetting. So how does this affects the concrete structure? As you can readily imagine when the concrete is just removed from your moist-curing environment and subjected to the first drying, you can expect the maximum amount of water to leave the system. So first drying usually produces maximum shrinkage and this is because if the conditions of drying are bad enough.

That means your temperatures are high and relative humidity is very low, you can actually start removing water from your gel pores like the interlayer in the adsorb spaces when you start removing water from those pores or the very fine capillary pores, the associated capillary pressure is extremely high that result in very high shrinkage strain. But then what happens upon wetting?

Water re-enters the pores and causes swelling. But because of the size of the pores, there is only some pores which can be filled again with water. So rewetting can only fill up certain pores. So that is why the swelling amount is not equal to the first shrinkage amount. There is always a permanent shrinkage that has built up in the system. So again the water molecules act against the cohesive forces and push the gel particles apart but this can be only to a certain extent. You cannot re-alter the entire system. You cannot bring it back to 0.

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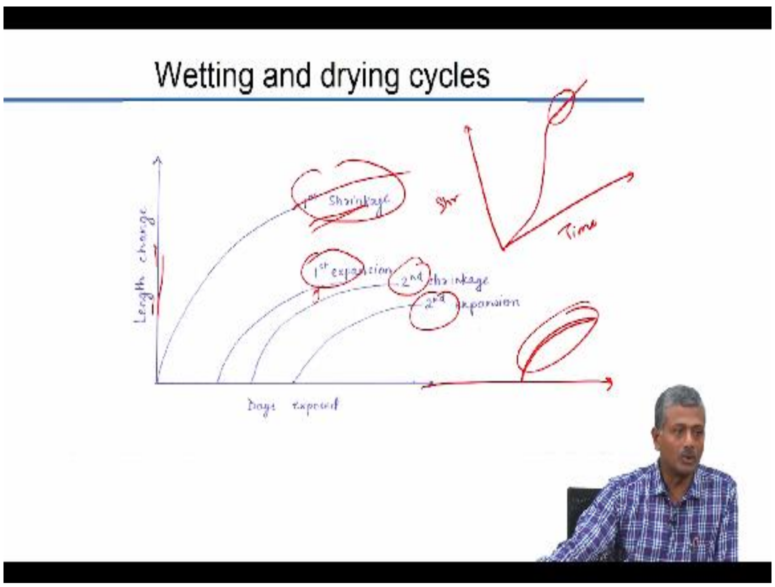

So what happens with multiple cycles. The first shrinkage produces the maximum change in length or change in volume of the system. The first expansion little bit smaller. Then next time that it dries out, the level of shrinkage is again smaller than the expansion because then only part of this water now can get pulled out at the same levels of drying conditions and subsequent expansion again on rewetting, is again lower than the shrinkage that actually happens.

In the long-term, what do you expect? If I extend this to thousands of cycles, what do you expect? Negligible what? Change in length. Change in length will keep reducing but what do you expect in terms of the magnitude of shrinkage and expansion? Beyond a certain point, your structure would have been altered so much that the water that enters will be the same water that leaves.

There is not going to be any extra shrinkage or expansion. What you will end up happening is both the curves will coincide. Shrinkage curve and the expansion curve will start coinciding after multiple number of cycles. That means that the water is now capable of only entering certain pores and leaving those pores and those pores may be large enough to really not lead to a major alteration in the microstructure.

So beyond that point, you do not really see a change in the structure and you do not really see a difference in the performance as far as shrinkage and swelling is concerned. Nevertheless, it is important for you to understand, what happens during this first shrinkage. The first shrinkage as we discussed, re-alters or alters the gel structure which causes the water from the interlayer in adsorb spaces to start getting removed, going towards the capillary pores and the capillary pore water obviously goes out to the external environment.

When the first drying happens, what type of water will first come out of the system? Water held within the fine capillary pores or coarse capillary pores? Obviously the coarse capillary pores which is not held by very high capillary pressures, that will be the first to dry out but that water drying out will not really cause much shrinkage because it is going out of coarser pores. It is only when you start pulling out from finer capillary pores, shrinkage increases.

But if your system is saturated, a lot of water may be there in your coarse capillary pores. So if you measure the weight loss along with your length change, you might see an interesting trend.

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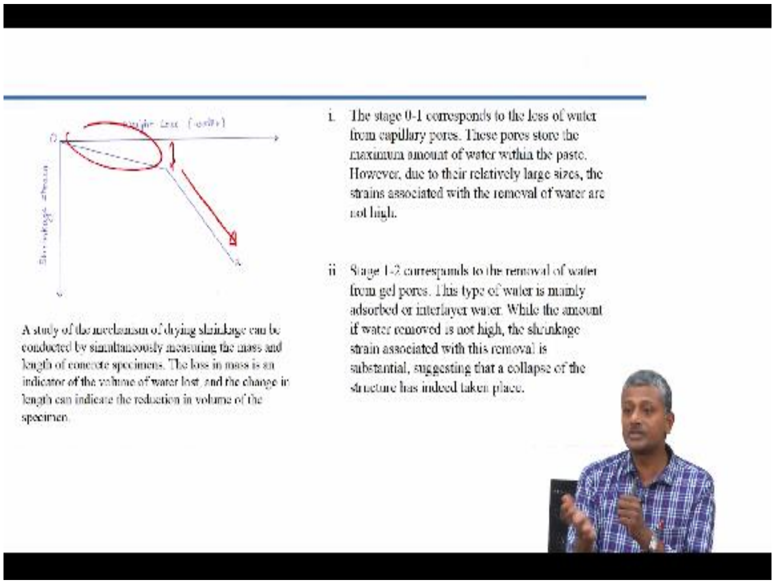

You will basically see that, sorry, I should come to that picture here. The weight loss is very high in the beginning but the shrinkage strain is quite small. That is because you are pulling the water out of the coarser pores but once you overcome that and you start pulling out the water from the finer pores, the extent of shrinkage goes up very rapidly but the extent of water loss does not change significantly for the same extent of shrinkage.

So generally shrinkage can be looked at as a 2-phase mechanism. The first phase is where water goes out of the coarser pores and does not really produce much shrinkage. Second phase is when you start pulling out water from the finer pores which produces lot of shrinkage but lesser amount of weight loss. So once again when you look at shrinkage related experiments that are described in papers, if people are only studying shrinkage for 2 weeks or 3 weeks, they may not even be reaching a significant part of the second phase.

So because of that, it is always essential when you conduct shrinkage experiments, you need to do it for at least 6 months to 1 year to really get any realistic assessment of shrinkage. Now of course, I talked about the fact that this shrinkage itself will start stabilizing. The rate of shrinkage will keep reducing and generally if you plot this on a log scale, your shrinkage level versus the time, if you plot it on a log scale, you will get some sort of a relationship like this.

An S-curve will generally be obtained when you do a log scale plot on the same points. So what we need to do is control or continue the experiments until at least this ascending branch starts stabilizing. If you do not do that, then the result is not really representing the true shrinkage of your specimen. Again, how much time do you need for this? 6 months to 1 year. So when you are taking up a new mix design for a special concrete, you need 6 months to 1 year.

I was in this conference once. The presenter before me talked about the special concrete they design for some project in Turkey and they got nearly 18 months to do the full mix design for the concrete. I was the next speaker, I talked about the project in Chennai Airport and for us, we were given one day to come up with the mix design which I was able to push to 2 months at least so that at least I could be confident of obtaining the strengths.

But then this is the kind of preplanning that goes on with concrete in our country. So concrete is not given good preference. People think that concrete is well known. It should just be produced and used directly on the site without thinking too much about the design. As long as workability and strength is obtained, everything is fine but there is so much to concrete beyond workability and strength.

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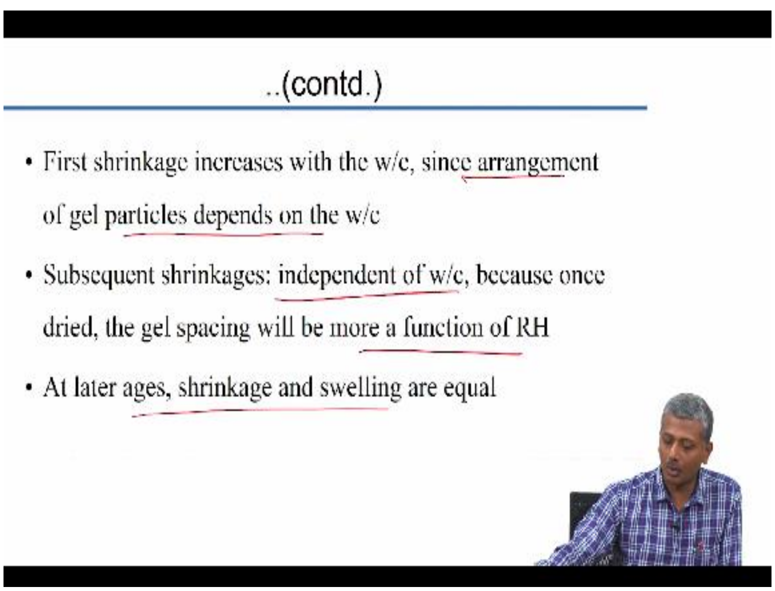

So the first shrinkage, the extent of the first shrinkage increases with the water to cement ratio and that is quite obvious because there is more water present in the capillary pores and these are going to get removed because arrangement of the particles, arrangement of the gel particles depends on the water to cement ratio. Why do I say that? Because your distribution of the extent of capillary porosity and gel porosity depends on the water to cement ratio.

The higher the water to cement ratio, the higher will be the drying shrinkage. Subsequent shrinkages become independent of water-cement ratio because once you dry the gel and alter the gel structure, there is only so much you can do to the same structure. It is only going to be a function of the relative humidity in the environment. Subsequent shrinkage is only be a function of the relative humidity. At later ages, once you come to the long-term, the extent of shrinkage and swelling will become almost equal.

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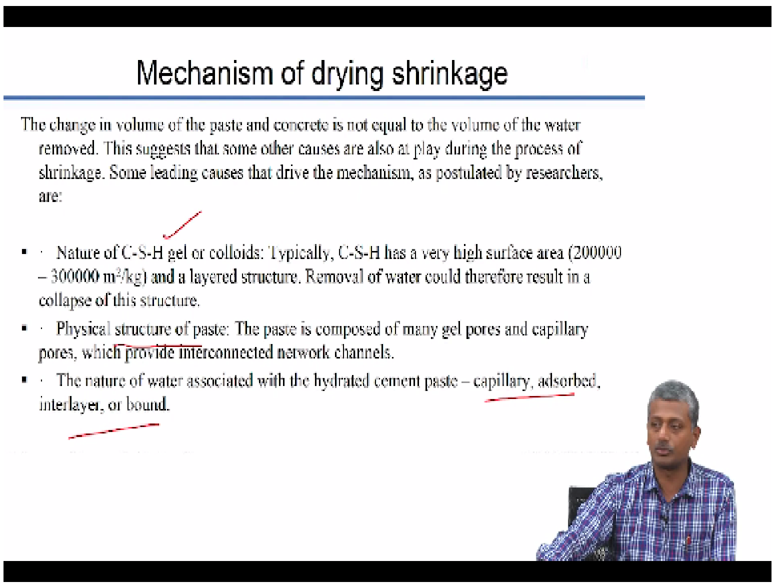

Of course, if you really go into the depth of understanding why shrinkage happens is obviously because of the nature of CSH gel. We have also seen the structure of CSH as described by the Feldman-Sereda model and when we were discussing that, we also saw what type of water would really lead to high level of shrinkage. The physical structure of the paste is also responsible for shrinkage. Again, the interconnectivity of the porosity determines how much of this water can actually get out of your system.

The more interconnected the pores, the greater the extent of water loss from the system, and again this we discussed when we talked about the structure of the CSH. The different forms of water would lead to different levels of shrinkage. And which is the water that is not evaporable? The chemically bound water is non-evaporable water. All the other waters at different stages of drying can get removed from the system leading to shrinkage. This we talked about already.

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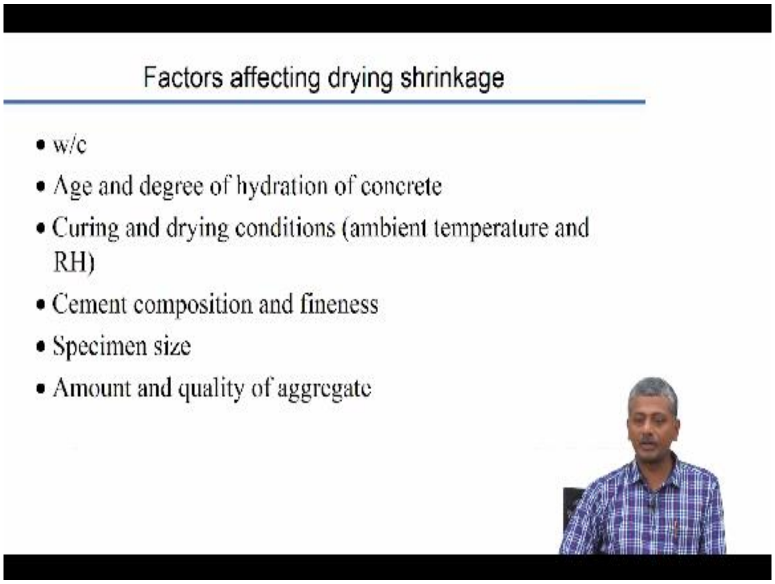

So again, I will recapitulate the points which are, the factors which are affecting drying shrinkage. You have water to cement ratio. Age and degree of hydration of the concrete. At younger ages, there is lot more water in the system, so more shrinkage can happen. If you do long-term moist-curing, then the extent of drying shrinkage can be reduced significantly. Curing and drying conditions in terms of ambient temperatures and relative humidity are important.

The cement composition and fineness is important, why? Again, cement composition and fineness will have an effect on the amount of hydration that actually happens and the development of your capillary pore space can depend on that. The specimen size, the larger the specimen size, lesser will be the shrinkage but then the larger the specimen size, more possibilities of differential rates of shrinkage on the outside and the interior and the amount and quality of aggregate again is very important.

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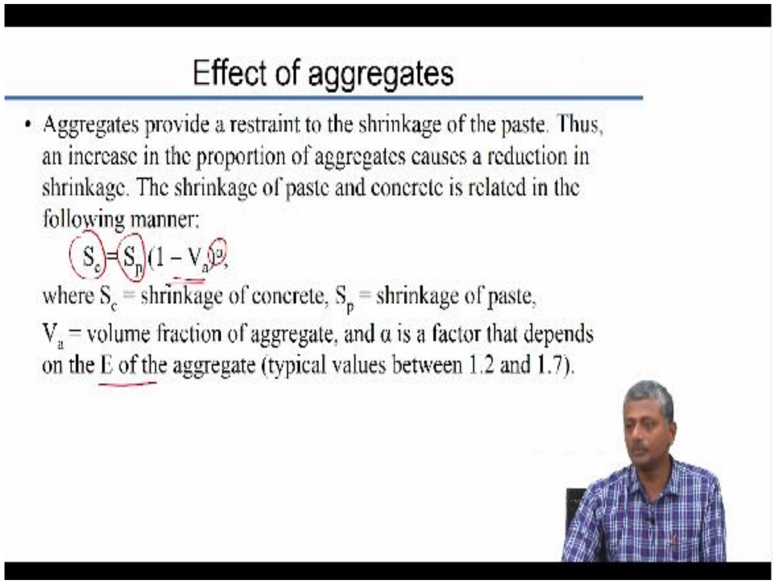

Of course, the same sort of relationship that we saw in creep. Shrinkage of concrete is given in terms of shrinkage of paste and the factor which is inversely proportional to the amount of aggregate in the system. So shrinkage of concrete depends on shrinkage of paste obviously but then the aggregate acts like a restraint.

So the greater the amount of aggregate that you have in the system, the greater will be the restraint and there is also this another factor alpha, which is similar to what you saw in the creep expression also and this alpha depends on the modulus of elasticity of the aggregate. The higher the modulus, the higher the value of alpha. Stiffer aggregate will provide more restraint as compared to less stiff aggregate.

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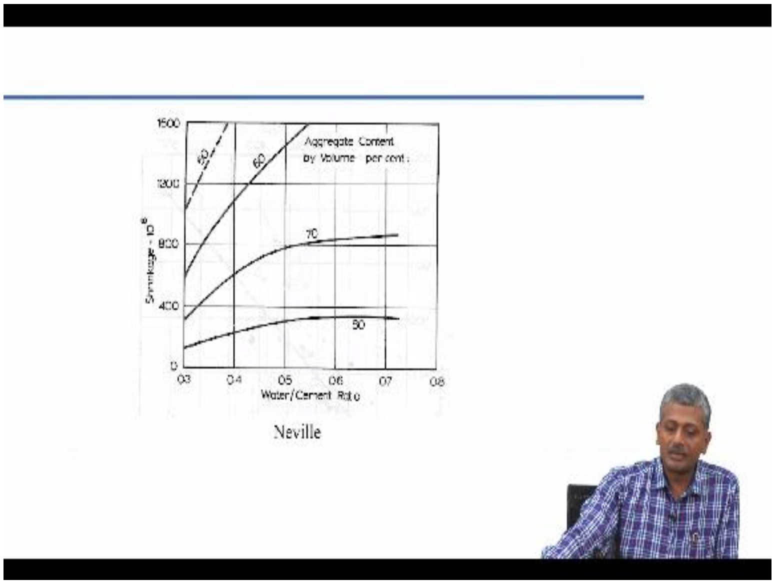

Again, these are results that are from your book by Neville, again talking in terms of water to cement ratio. The extent of shrinkage is being shown here at different levels of aggregate, 80-50%. So when you increase from 50-80%, you can see that the shrinkage extent has been brought down by a factor of 4-5, that is a significant amount.

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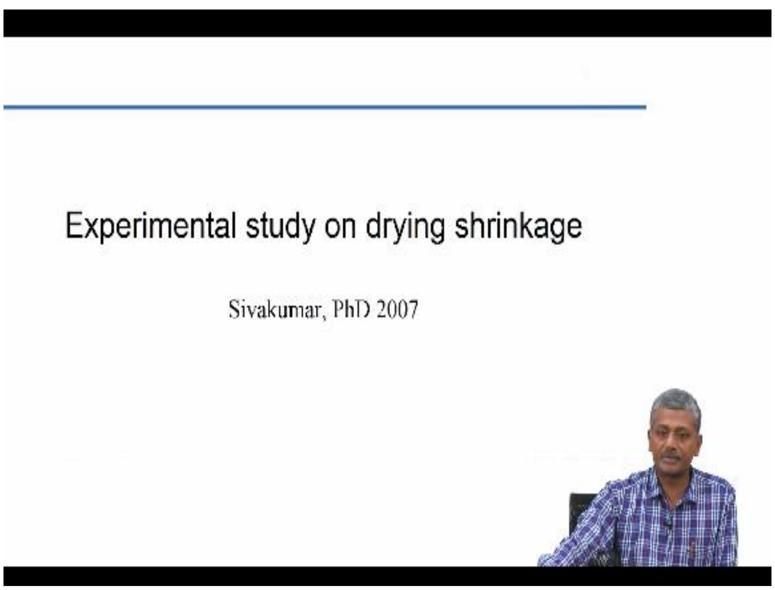

And again the same study that I described earlier was also done for drying shrinkage where we were trying to measure the free shrinkage of prismatic specimens but there is only so much you can learn from that. As far as fibres are concerned, the ability of the fibre is to restrict cracking. If you allow the system to shrink freely, it will never crack.

Because there is no stress. Strain is continuously increasing as the length change happens but there is no stress because there is no restraint. So what you have to setup with respect to drying shrinkage is a measurement of the restrained shrinkage that means when shrinkage happens, if there is a restraint, how does it leads to the generation of cracking.

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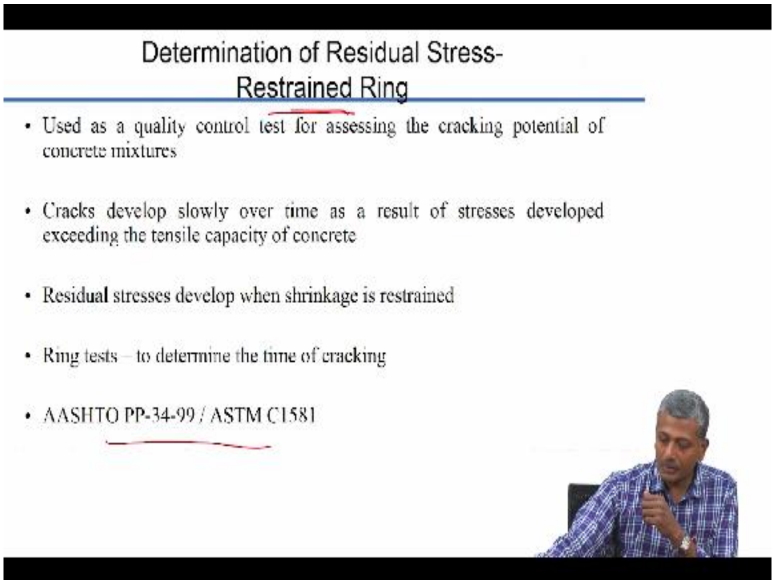

And for that, there is called, there is a test called the Restrained Ring test which is again an AASHTO and ASTM specified test.

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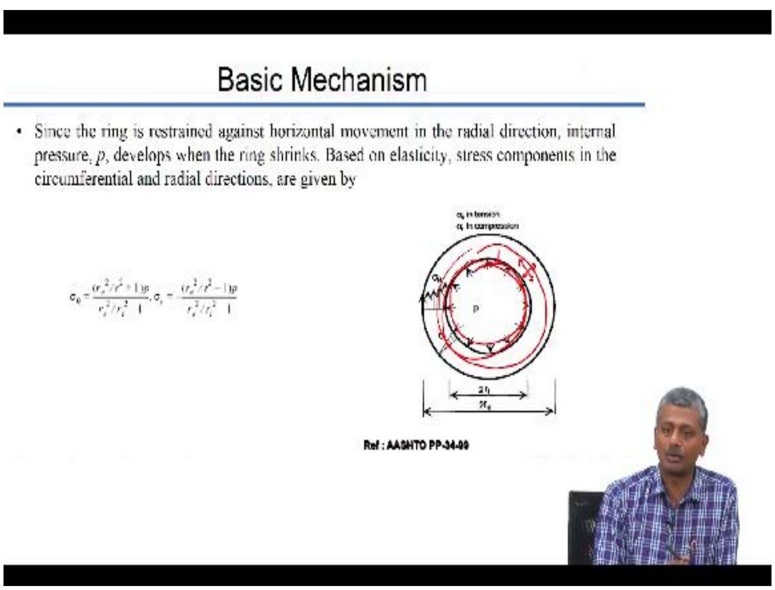

So here what happens is, you have a concrete ring. This is the concrete ring and there is a steel ring inside of the concrete ring. So this concrete ring, because of the nature of concrete, will start shrinking. So as it shrinks, because shrinkage will produce volumetric deformations in both directions. As it is shrinking, the resultant stress because of the restrained offered by this steel ring will be translated into the development of strain in the steel.

Now because steel, at that level of stress, steel will be in its elastic state, nothing will happen to the steel. So once you measure the strain in the steel, you can automatically measure the stress in the concrete which is causing the cracking. So that is what is restrained ring test. I am not going into the details of this. I will show you the results in more detail.

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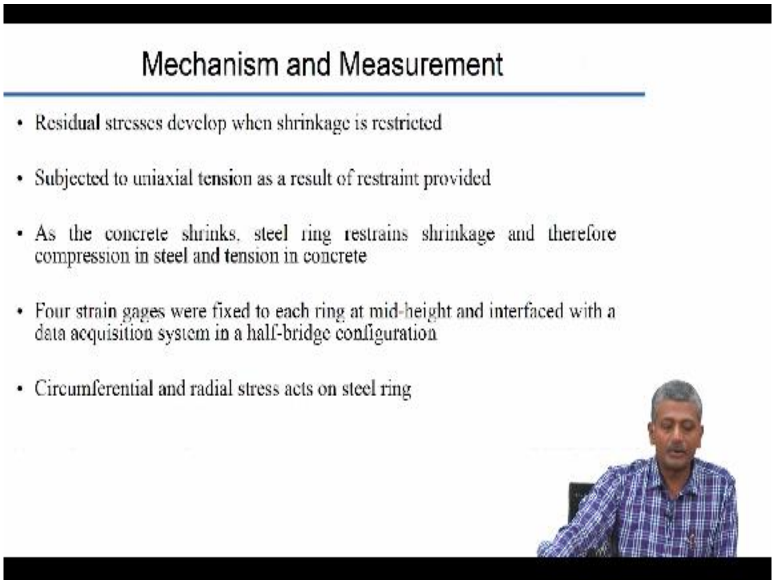

So again what you do is measure the residual stresses that develop in the concrete when the shrinkage is restrained by the steel ring that is inside.

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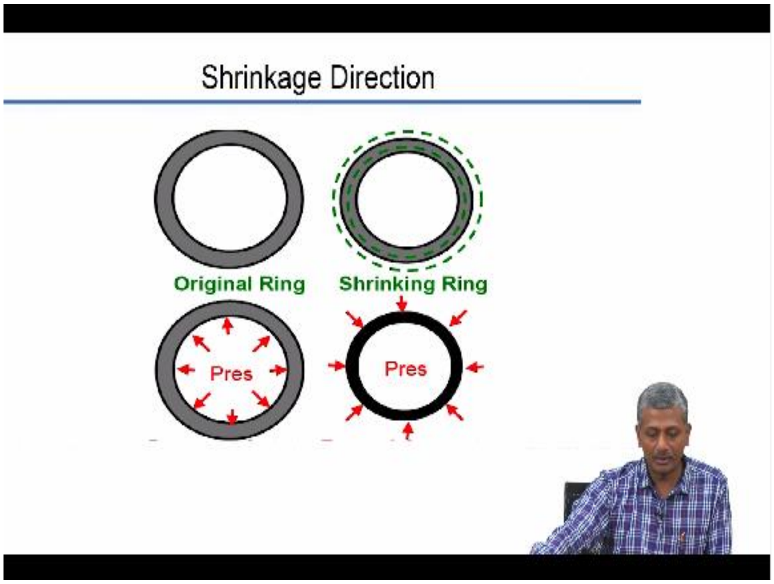

So again, this is your original ring and when you have a shrinking ring, essentially the concrete tries to shrink inwards and that creates pressure on the steel ring and that pressure is almost equal to the pressure that is on the concrete ring, restrained pressure because every action has an equal and opposite reaction. So pressure on the steel ring is equal to the pressure which is restraining the concrete from shrinking.

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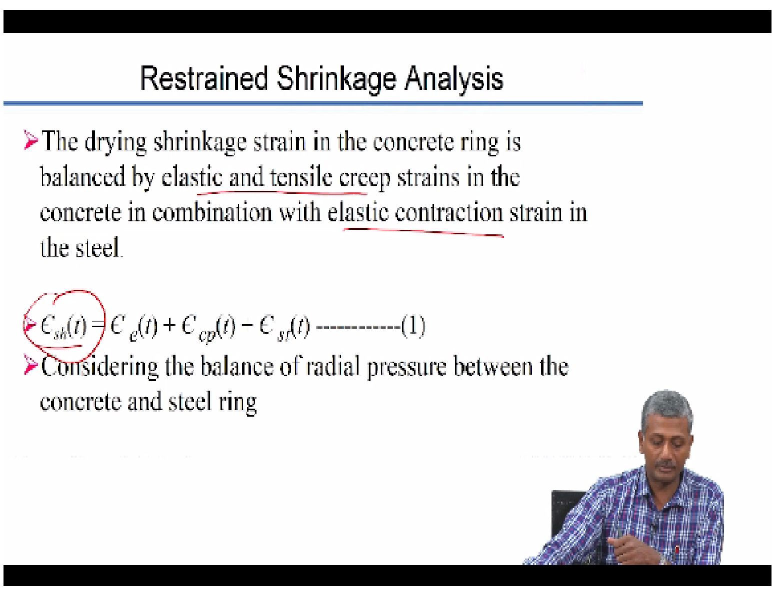

And the steel ring pressure can generate strains in the steel ring which can be measured in terms of the hoop strains and those hoop strains can be then converted to the actual stress in the steel. Of course, we consider that overall shrinkage which happens in the system is equal to the strain that is getting produced from the steel. So here we consider the shrinkage to be a function of several different factors which is because of the different elements that are involved in the system.

So again here, so here you have the total shrinkage in the concrete ring is balanced by the elastic and tensile creep strains in the concrete, in combination with the elastic contraction strain in the steel. So your overall strain is considered to be a component, a mixture of 3 different components.

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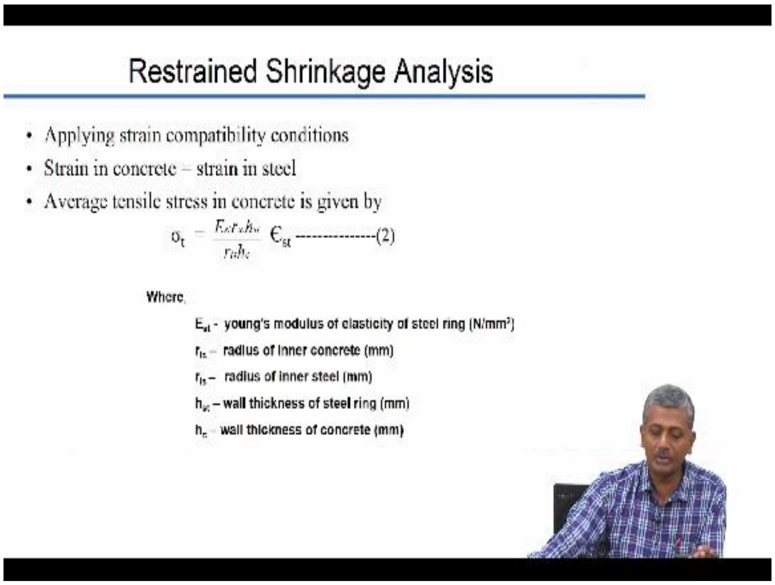

And based on this, you can actually workout the tensile stress generated because of shrinkage in the concrete as a function of the strain generated in the steel. Based on some boundary conditions that you need to apply in the system and considerations of drying happening either circumferentially or from the top and bottom, you can actually workout this kind of a system by assuming certain things like strain in the concrete is equal to the strain in steel.

You apply the strain compatibility criterion, you can actually obtain the stress in the steel as a function of the, sorry stress in the concrete as a function of the strain in the steel. All the other factors, modulus of elasticity of steel, inner radius of the concrete ring, inner radius of the steel ring, height of the steel and height of concrete are predetermined by your experimental combinations.

Yes, of course, the height of the steel and concrete will be most likely equal. It is not going to be any difference there. So all you need to do is look at the radius, inner radii of steel and concrete and it will be dependent on the modulus of elasticity of the steel because steel is still under the elastic condition.

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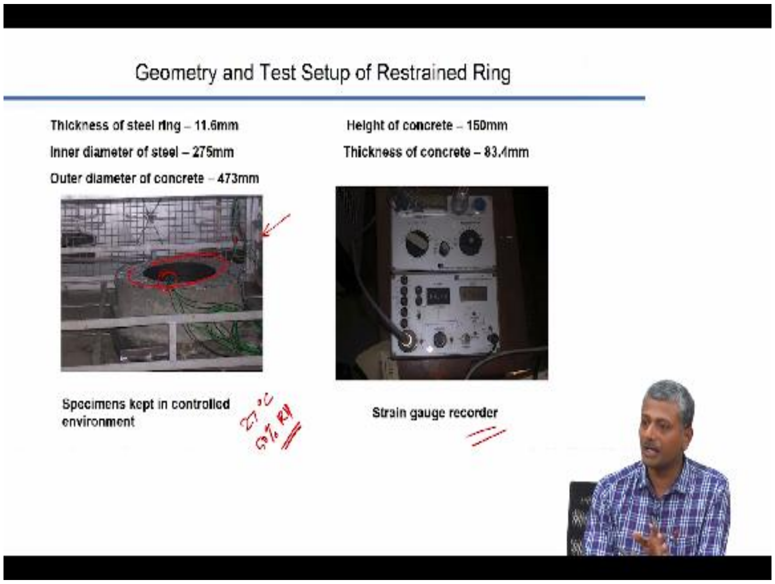

This is the same environmental chamber that we used earlier of the plastic shrinkage study. So here, this has to be done in a temperature and humidity controlled environment again because depending on the temperature and humidity, your extent of shrinkage that happens in the concrete will vary. So here the concrete was, the measurements were done at 27 degree Celsius and 50% relative humidity.

So this control has to be maintained using the environmental chamber and again this is the ring here. So you see the ring, the top of the ring has been completely sealed. The concrete ring, the top has been sealed and the periphery or circumferential surface of the ring has been exposed to start drying out. So the equation that I showed you was essentially for circumferential drying and not drying from the top and bottom.

And we had a strain gauge recorder which had to be manually operated to collect the strain data from time to time. So there were strain gauges. You can see the wires that are coming out. These strain gauges were pasted on the inside surface of the steel in the hoop direction, not in the upward direction or longitudinal but hoop direction and there were, I think, 3 strain gauges pasted on every steel surface and we were actually monitoring the strains using the strain gauge recorder.

In those days, we do not have a data acquisition system which could automatically acquire the strain data. So we had to manually collect strain data from time to time. So again, some error may have crept in because of manual collection because the appearance of the crack, what it will do? If the crack happens in the concrete because of drying, what will happen to the strain in concrete? It will be released.

The strain will be released once cracking happens. So it should fall to somewhere close to 0. So when it falls very close to 0, the exact time-location where it actually falls to 0 has to be visually only observed in this case. So only visually you see that the crack has appeared and then take the strain reading. So the crack may have appeared before the time then actually was visually detected.

So if you have a strain data acquisition system, you can actually measure the exact deformation of the system. But here we were actually doing it visually, so there was some error that may have crept into the data.

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So here this shows you the control concrete without any fibres. You can see the crack that has appeared all along. You see the crack that has appeared all along. Of course, the crack width is not completely large because you have aggregates which are across the crack which are bridging the crack. So they are preventing the crack from opening up tremendously. Now in the case of the steel fibre concrete, you do not even see the crack clearly but you can just briefly make it out between those 2 lines.

It is not very clear but yes, the amount of cracking is obviously controlled because once the crack appears, there are fibres bridging the crack and these fibres are now taking the stress that is generated because of restraining the shrinkage. In the controlled concrete once the crack appears, there is only aggregate interlock because of which some level of stress can be still maintained in the system.

Mostly it will be close to 0. But when fibres are present, fibres are bridging the crack and once the crack appears, the stress is transferred to the fibres and there is no further change in the stress level or rather stress may continue to build up because of more and more shrinkage but then steel fibres are not going to deform. So the residual stress will keep on getting built up in the fibres with time.

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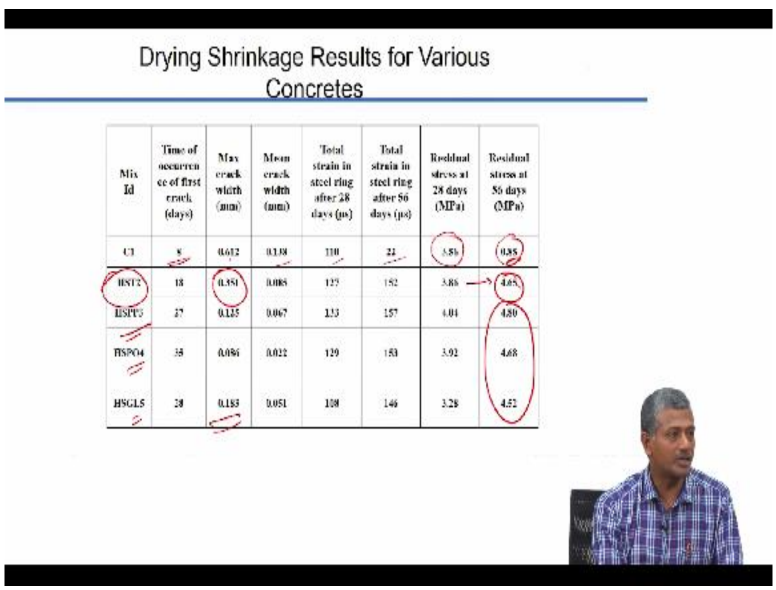

So here this is showing you the measurements. So for the control concrete, the time of appearance of the first crack was 8 days. The maximum crack width was 0.6 mm, mean crack width was 0.13 mm. Total strain in the steel ring was 110 microstrains after 28 days. Strain in the steel ring was 22 after 56 days. Residual stress at 28 days is 3.5 Mega Pascals. This is the concrete which supposed to be M60 concrete, M60 concrete that means the flexural strength will be around 5-6 Mega Pascals.

So even at 3.56 and at 56 days, it is 0.85, that means there is absolutely no residual stress because the crack has appeared and there is no change in the system. When you have steel fibre concrete, you have a higher residual stress at 56 days as opposed to 28, that means the shrinkage of the concrete keeps on building up the stress which is going on being taken by the steel fibre component.

And similarly, when you have the combination of steel polypropylene polyester glass, you have high levels of residual stress which are still being taken because the fibres are still bridging the crack. But interestingly, the crack widths are significantly lower as compared to even the steel fibre concrete that means the polymeric fibres and the glass fibres are contributing in a big way to the restriction of cracking during drying shrinkage.

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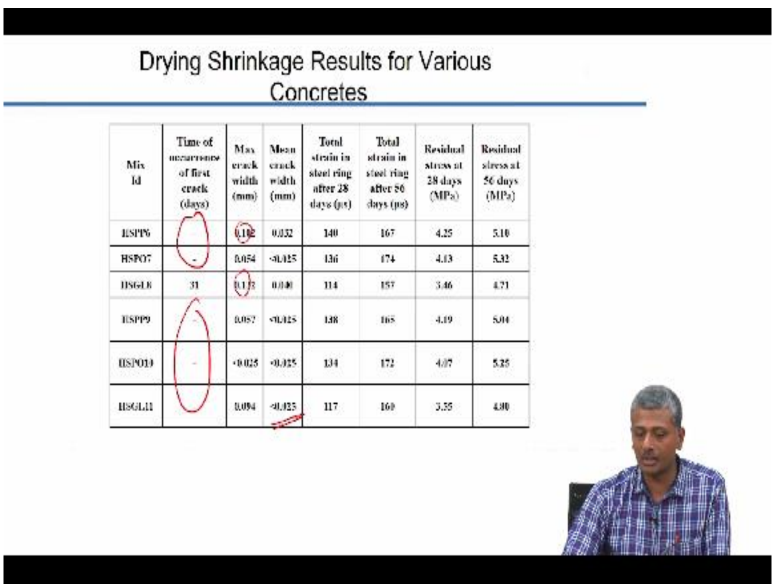

Mix Id	Time of occurrence of first crack (days)	Max crack width (mm)	Mean crack width (mm)	Total strain in steel ring after 28 days (με)	Total strain in steel ring after 56 days (με)	Residual stress at 28 days (MPa)	Residual stress at 56 days (MPa)
HSPP6	-	0.102	0.032	140	167	4.25	5.10
HSPO7	-	0.054	<0.025	136	174	4.13	5.32
HSGL8	31	0.113	0.040	114	157	3.46	4.71
HSPP9	-	0.087	<0.025	138	165	4.19	5.04
HSPO10	-	<0.025	<0.025	134	172	4.07	5.25
HSGL11	-	0.094	<0.025	117	160	3.35	4.80

Again, these are different types, so when you see a dash, that means that no cracking was seen in these systems which are at higher extent of the polymeric and glass fibres as opposed to steel fibres. And the mean crack width is very low in many of these cases. So that indicates all these, even the maximum crack width and only in some cases is greater than 0.1. So the hybrid combinations are actually leading to a condition where crack widths can be controlled tremendously. So you have a significant improvement of the ability to resist drying shrinkage cracking.

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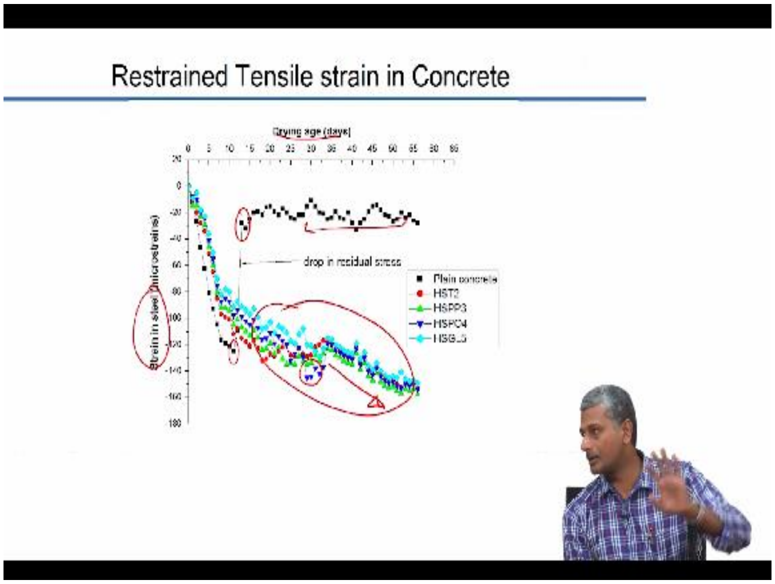

This is just showing you the residual stress or rather sorry, this is the strain in steel versus the drying age. For the control concrete as soon as the crack appears, you have a major reduction. There is some level of residual strain which is built up because of the interlock between the aggregates but in all the other systems, you may see some small kinks at which there is a drop in strain.

But as soon as the stress gets transferred after cracking to the steel fibres or to the polymeric fibres, there is again a build up of your residual stress in the system. So concrete is continuing to shrink at the same rate. The control concrete and fibre-reinforced concrete has the same ability to shrink. It is only the fact that once the cracking appears, the stress is now transferred to the fibre because of which it can continue to shrink without resulting in significantly large amount of cracking.

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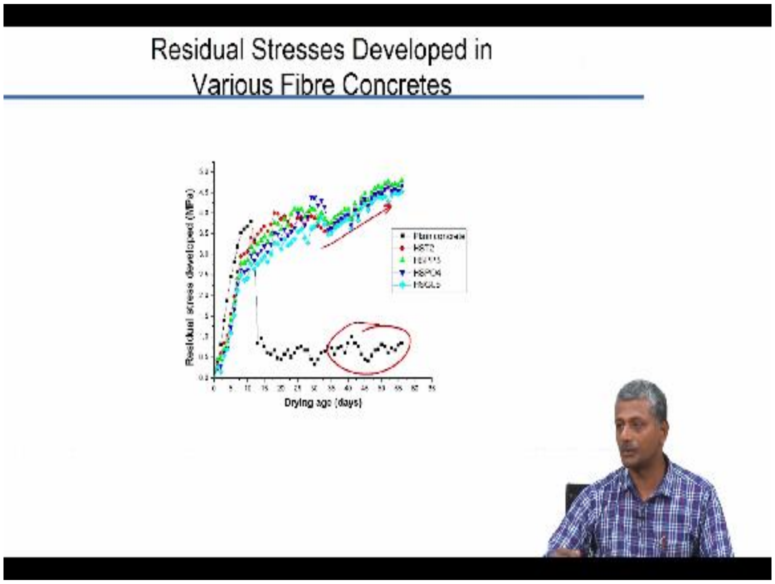

Again, this is the development of residual stresses in various fibre concretes. So with the fibre concretes, the stress continues to develop. With the plain concrete, your stress is almost down to 0.

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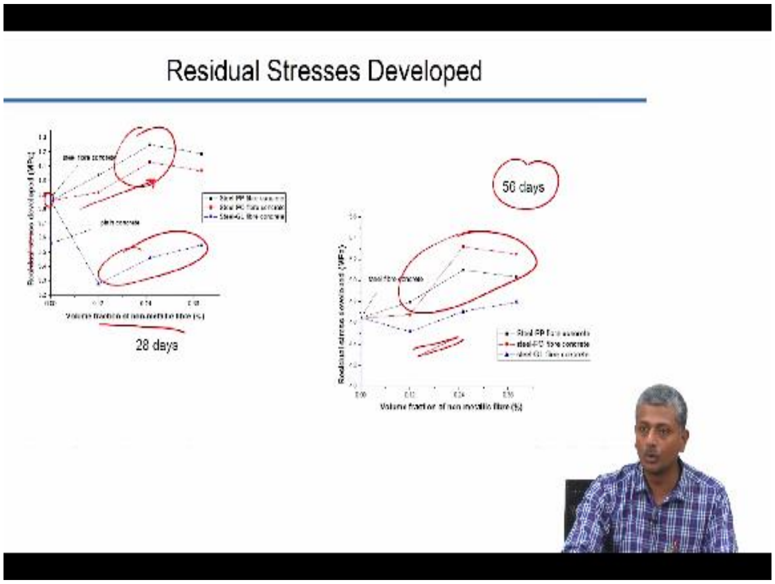

So in terms of residual stress developed as the volume fraction in non-metallic fibres, you can see that for steel fibre, we are here. As we increase the extent of polyester or polypropylene fibres, we are seeing an increase in the residual stress developed. With glass fibre, you do not see as good a performance as with steel fibre concrete. So glass fibres, possibly because they are extremely thin, may be even breaking as the crack appears.

So because of that the capacity is actually going down. On the other hand, if you look at residual stress in terms of 56 days, you see a performance which is similar to what you have at 28 days for the polyester and polypropylene concretes. For the glass fibre concrete, you still have a system that is showing a low residual stress than the steel fibre concrete.

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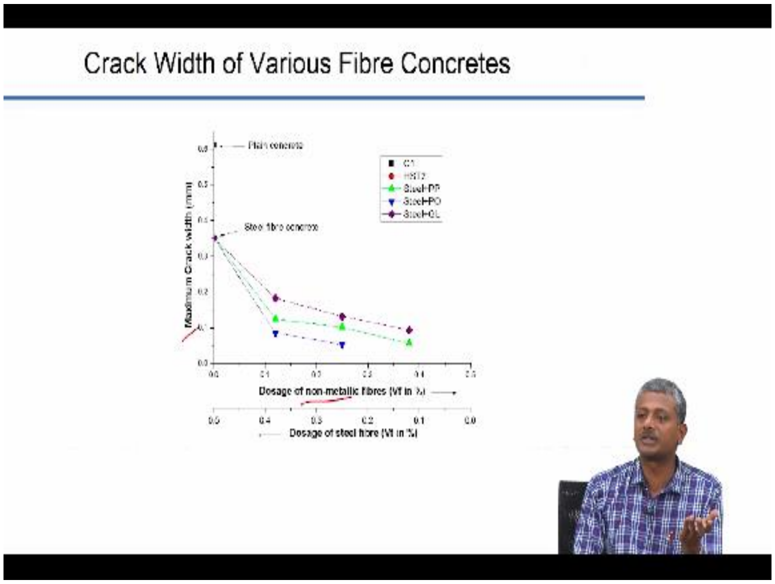

Again, this is showing the maximum crack width versus dosage of non-metallic fibre. As you increase the extent of non-metallic fibre in the system, your maximum crack width is getting lesser because you have more number of fibres bridging the crack. Glass, polyester, polypropylene, these are lower density as compared to the steel. So for a given mass of the fibre, there will be lot more fibres which are actually present and these will be bridging the crack that is why the overall crack width is going to get reduced.

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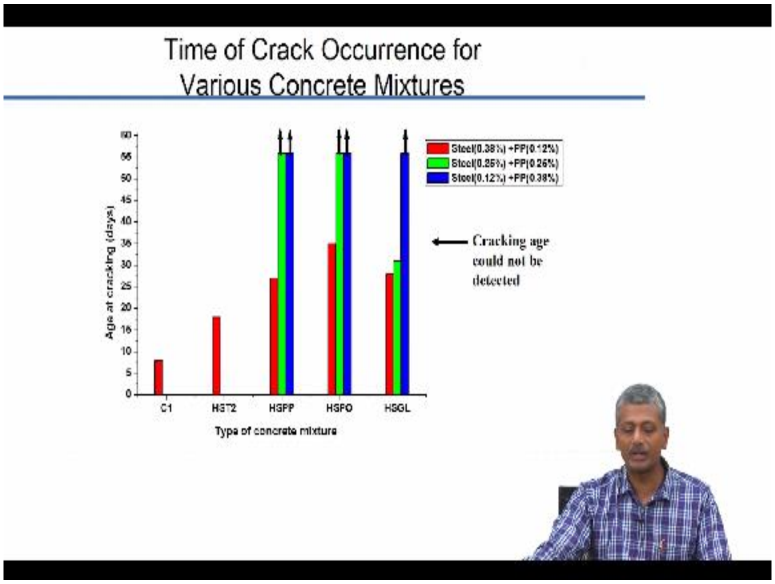

And again time to occurrence of cracking increases as you substitute the steel fibres with the non-metallic fibres. Thank you.