Maintenance and Repair of Concrete Structures
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Lecture 9
Deterioration of Cementitious Systems
(Fire attack, abrasion and erosion)

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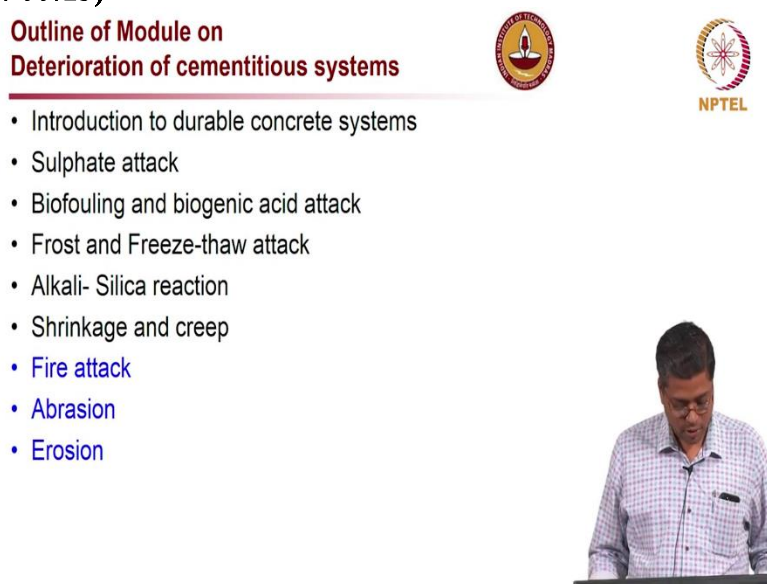

Hi, this is fourth lecture in the module on deterioration of cementitious system. In this, we will cover fire attack, abrasion and erosion. We already covered how durable systems could be, and sulfate attack, biofouling and biogenic acid attack, frost and freeze thaw attack Alkali silica reaction and shrinkage and creep. And now we will focus on these 3 mechanisms fire attack, abrasion and erosion.

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This are 2 examples I am going to show you. Some pictures showing how buildings and other structures get affected by fire. You can see that in the entire building on the left side is engulfed by the fire and on the right side also, it is World Trade Center and that led to significant damage entirely the building was completely damaged. So, fire can lead to significant damage.

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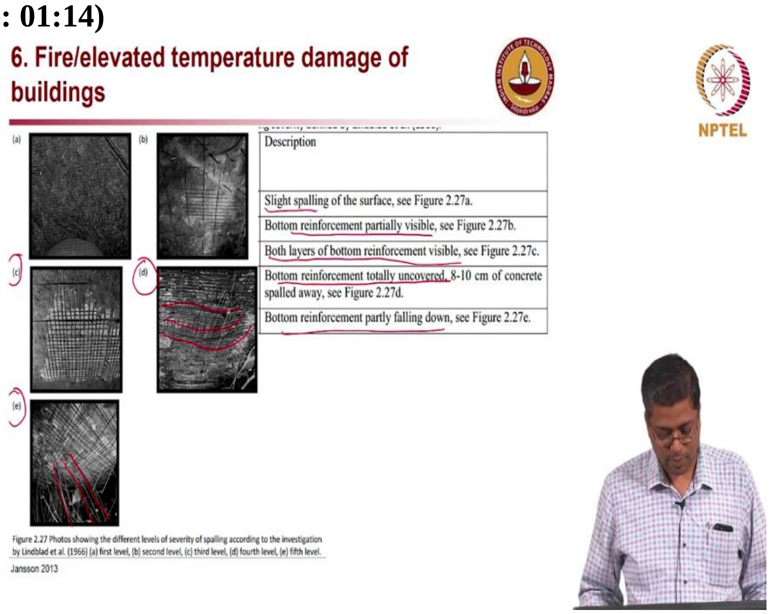

Here is picture showing what really happens or different stages of fire attack at the as you see on this when the first picture (top left) shows a slight spalling of the surface, you can see slightly rebars out there and in the second picture, it shows bottom reinforcement is now visible, that means the entire cover is lost.

And the picture 'c', shows both layers of bottom reinforcement, that means more the fire has attacked more and more concrete, more concrete is removed. And then you can see bottom reinforcement totally uncovered and you can see here is I am looking at this picture 'd', you can see here the reinforcement are also like any kind of deformed in this significantly deformed, because now the rebar is are directly exposed to the high temperature.

And then in the picture 'e' you can see bottom reinforcement, even a falling down completely. So, it's no more able to use. So, the point here is significant damage can be induced by this high temperature due to the fire.

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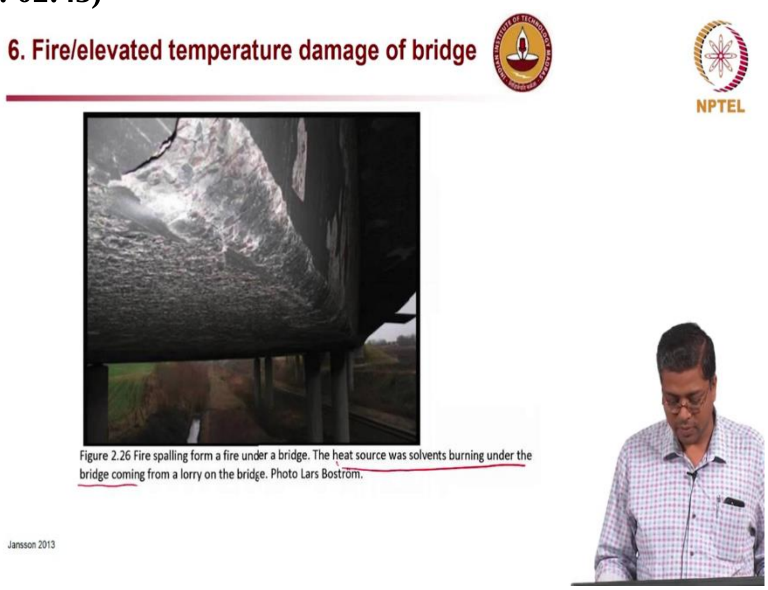

Now, this is another picture of a bridge, where actually there was a tanker or a truck with the source of heat was, solvents burning under the bridge coming from a truck or lorry on the bridge. So, you can see that significant damage even not only for the buildings, even to the other structures could be exposed to fire.

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And here this is an example which shows how crazing and spalling looks like. Crazing is like initial cracks, map cracks, which you could see on the picture on the left side. And on the right side, you can see that entire cover is now delaminated, and it is spalled exposing the reinforcement.

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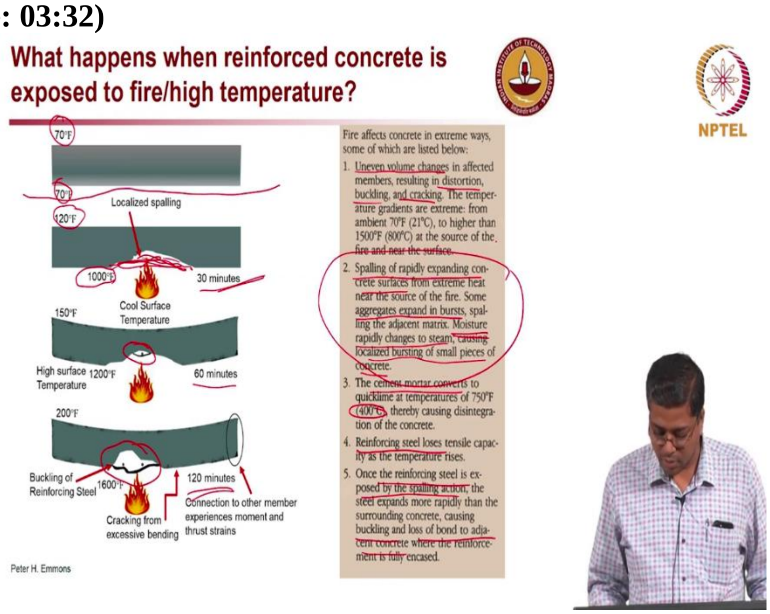

Now, let us see a little bit more detail on what happens when the concrete is exposed to fire or elevated temperature. When I am saying elevated temperature, mostly it is because of fire only. Now let us see in the beginning, this picture here in the beginning you see both the upside, top and bottom of the element is at similar temperature that is 70 degrees Celsius. And as fire damage happens, the temperature is raised up to about when it is up to about 120 on the other side of the fire, and at the side of the fire, it is at about 1000 degrees Fahrenheit.

You can see some localized spalling like some region get spall here, and which can happen in about 30 minutes. And then as time passes at about 1 hour, you can see some significant loss and as some of the rebars gets exposed. And as the time reaches like about 2 hours, that is 120 minutes, you can see that more and more damage happening and the rebar itself is now buckled you can see here.

The rebar itself is now buckled, means the rebar gets directly attacked by and it starts losing its properties. And also, the concrete element itself starts deflecting or deforming. So, all this combined effect you can say that there can be significant damage to the structural system. Now, let me go through very briefly through the text on the right side. So, what happens fire affects concrete in extreme ways, some of which are listed below uneven volume changes.

Let us say if you are talking about temperature difference at 1 side and the other side it is much higher than definitely there will be cracking and buckling and other sorts of distortions can be visible on the element. Now, another mechanism which can happen is spalling of the rapidly expanding concrete surface. So, the concrete expands because of the high temperature and it spalls, especially where the temperature is very high as it was shown in the bottom 3 images on the left side.

And what will also happen during this time is the aggregate can expand and burst, I will show you some pictures later on some of the aggregates how it can expand because of high temperature. And moisture is another thing which is important. Moisture which is available inside the concrete will rapidly change to steam or water vapor when the temperature increases and which will exert significant pressure on to the surrounding concrete and then which also leads to bursting of concrete into small pieces.

Now, another mechanism is the conversion of cement mortar into quicklime at when the temperature is above 400 degree Celsius. Now, on top of all this reinforcement also loses it is tensile capacity because the temperature is high and it loses its most of it’s good properties. So, that reinforcement cannot take anymore the tensile loads and so, the again the structure starts deflecting.

And other mechanism is once the reinforcement is exposed that will also try to expand and it expands at a larger rate than compared to the expansion of concrete and which will also lead to significant Spalling, buckling and loss of bond. The steel concrete bond is also lost. So, these are all different type of damages which can be induced during a fire attack.

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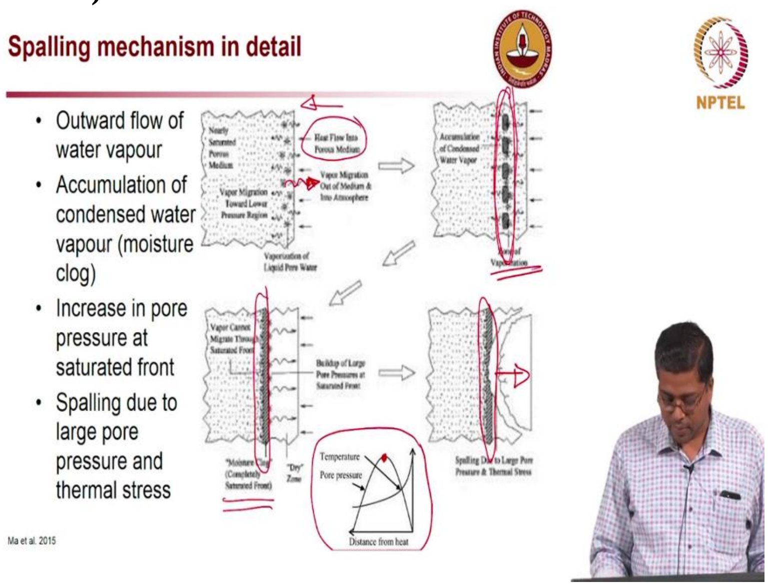

I am going to show you these things, especially the moisture action, the item number two which we were talking, I am going to show you how this moisture attack happens. You can see here on the picture on the top left, there is a heat flow through the porous medium. So, concrete is essentially a porous medium. So, heat flows into the concrete from the outside and then there is a vapor migration which happens the moisture which is available inside the concrete will migrate outward like this as it is shown here, it will migrate outward.

And but what happens is during this process their zone of saturation starts forming slightly away from the surface of the concrete. In other words, there is a condensation of water vapor which happens at a particular zone depending on the porosity of the concrete and pore structure of the concrete. But then that zone of vaporization we call it and it eventually get saturated.

And a moisture clog is formed and then that leads to building up of vapor pressure especially at that region. So, in other words, you can see here in this graph, which is basically showing what happens that showing that the vapor pressure you can see here this is the point where the highest vapor pressure and poke a poor pressure is very high and that significantly high pore pressure in this zone, which is a moisture clog or the saturated zone that will push the concrete outward, which is what we call a spalling.

So, this is a typical mechanism on how the moisture content inside the concrete will lead to a buildup of pore pressure and then eventually leads to spalling of concrete. Now spalling due to large pore pressure, so, we discussed all these points increase in pore pressure at saturated zone.

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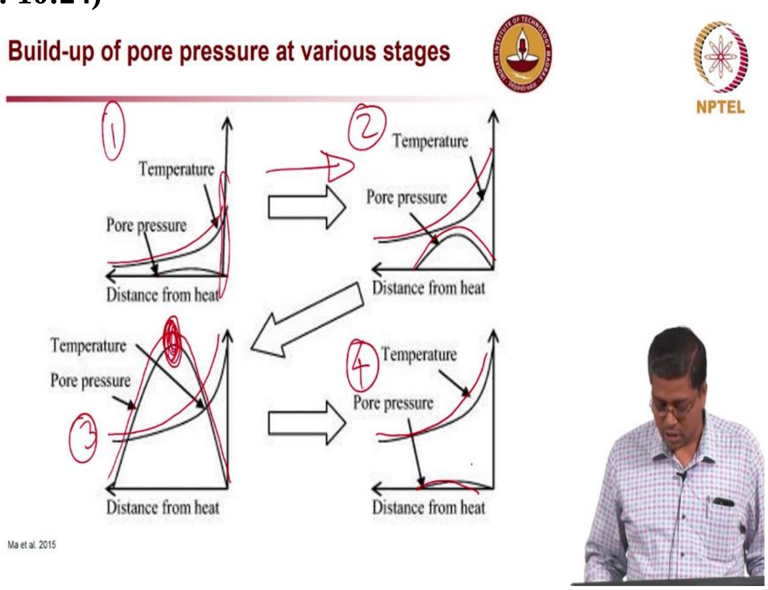

Now, just to show graphically that the change in the pore pressure, so you can see here this curve is the temperature. The right end of this graph is the surface and as you go towards left is as you go into the concrete. You can see the pore pressure is very low in the beginning, now, let us go to this graph. Now, here you can see temperature is slightly more slightly increased as compared to the first one.

Now, here you can see that the slight buildup of pore pressure is happening and then here you can see again it is increasing significantly high. Now the temperature is further increased and the pore pressure is also very high. So, this is the region which we call as saturation or the moisture clog and here you can see again significant increase in the pressure once the spalling happens that pressure is dropped. So, at this stage before the stage spalling happens.

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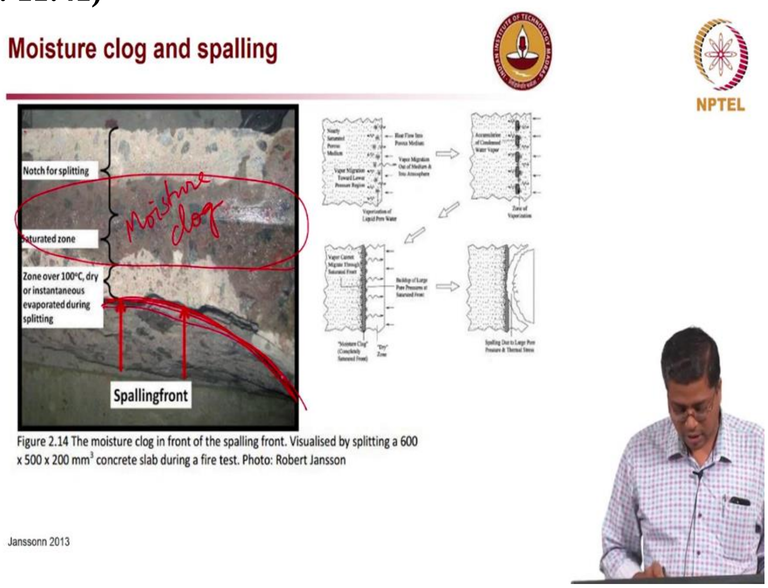

Now, one more thing this just to show that how it happened. This is from an experiment which was conducted in Sweden by Robert Johnson. I found this thesis is very informative in this case of fire attack. And now, you can see this is the inside surface and the bottom is the region which is spalled. So, this is the region which we are calling as the moisture clog. So, you can see a lot of accumulation of water or moisture in one region and that builds leads to building up of the pressure and which eventually spalls the concrete near the cover.

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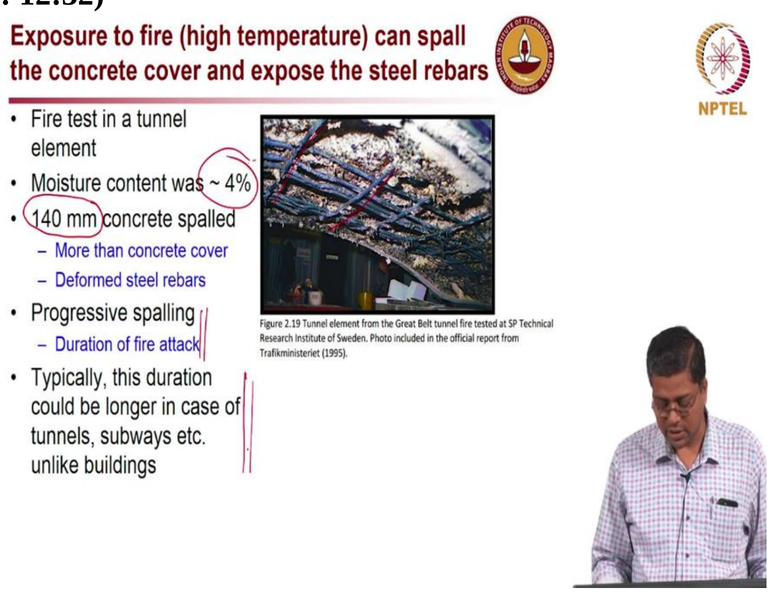

Now, this is an example of a lab experiment on a field specimen. There was a fire attack in a tunnel and they took the specimen to the lab and did another fire test. And the moisture content was maintained at the same level as it was initial, which is about 4%, very low moisture content or we can say very dry concrete. However, in this particular experiment, they could see about 140mm of concrete was spalled, and as you see in the picture here you can see significant spalling, rebars are exposed and also, they are deformed.

These are all what happens and once the rebars are exposed and deformed. It cannot really have the structural strength as desired, and progressives spalling that depends on how long fire exposure happens and it is basically showing layer by layer removal. In other words, initially some spalling can happen then further, the new a new surface gets exposed and then the temperature rise in temperature inside the concrete is more, and then which eventually leads to spalling.

And typically, the duration could be in longer in case of tunnels because it is like a closed system or a long structure where once there is a fire, it is not like a building where you have Windows doors and open space where the heat is dissipated. But in case of a tunnel the heat is contained inside and it takes very long time to dissipate that heat. So, fire attack could be very severe in case of tunnels and such structures.

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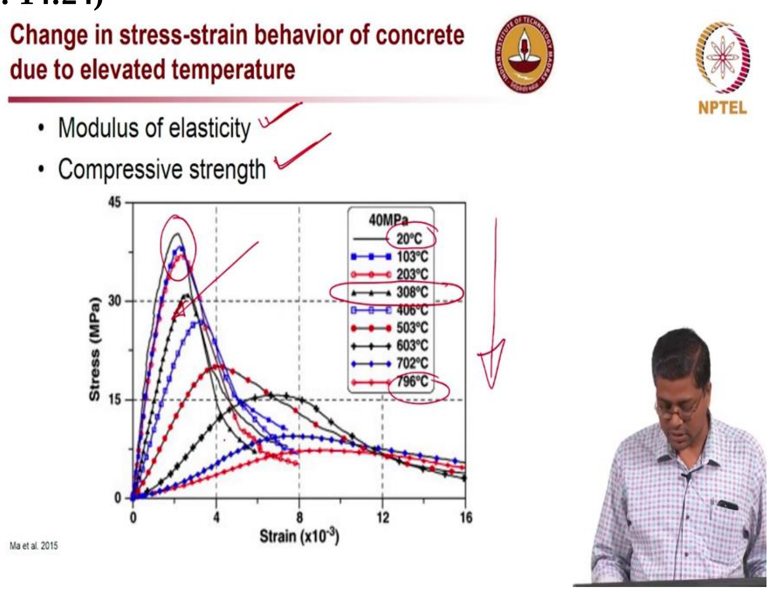

Now, what happens to the concrete or the stress train behavior of concrete due to elevated temperature. You can see here; this graph shows the behavior from about 20 degrees Celsius to about 800 degrees Celsius. And you can see the first 3, it is about 20 degree which is Ambient and then 100 and 200 degrees Celsius, not significant change in the property we can say at that stage first 3 graphs for practical purposes we can say they are more or less same.

Now, one when you reach 300, the triangular markers here this graph, that one you can see that there is a significant decrease or something happens at about 300 degrees Celsius. And after that you can say that the graph is significantly changing by the reduction in both the modulus that means the slope in the initial region and also in the Compressive strength. That means the height of the graph or the peak of the graph both are actually decreasing significantly.

So, point is once the elevate the temperature is above 300 degrees Celsius, then the concrete starts losing it is mechanical properties. Now, so, what does that mean? If the Concrete starts losing its mechanical properties then we have to probably replace the concrete or do significant repair work so that the structure can retain its capacity.

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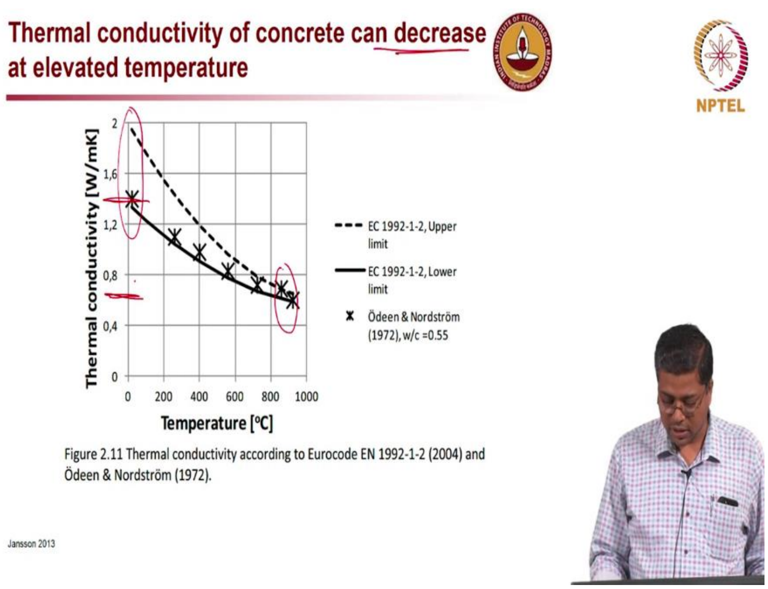

Now, what happens to the thermal conductivity of concrete? That can also decrease at elevated temperature as you see here, when the temperature is let us say from the ambient conditions, which is here, and it goes to about 800 plus degrees Celsius, you can see there is this about 1.5, this is about 0.6, almost 50% reduction in the thermal conductivity. So, that is also a significant change.

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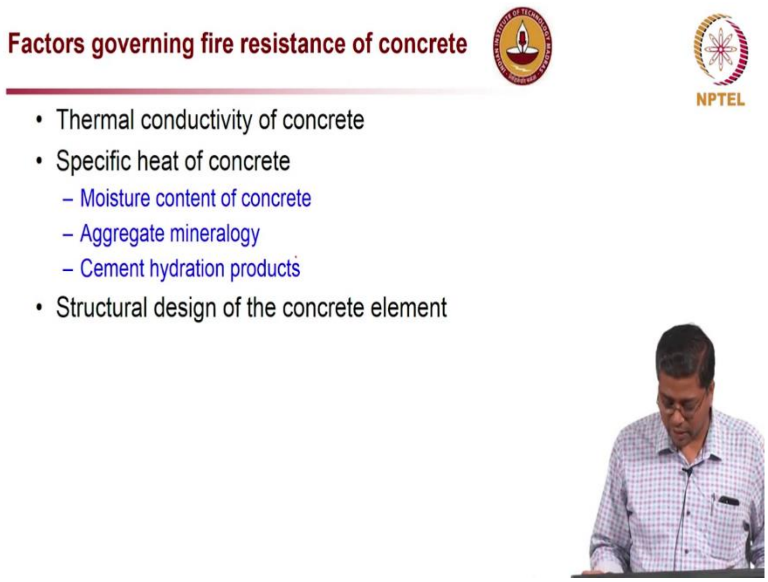

Now, what are the factors which govern the fire resistance? Until now we were looking at what are the changes because of the elevated temperature, and now let us see how to address those things. So that we will have less change. First thing is thermal conductivity and then specific heat of concrete. specific heat of concrete means, how much heat can be absorbed by the concrete before it penetrates into the concrete.

And moisture content of concrete matters and then mineralogy of the aggregate matters and then the type of cement hydration products also and of course, the structural design what it means is the size and shape of the structural element. And what are the design features for dissipating the heat energy also.

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Now, aggregates play a significant role on the fire resistance. Aggregates constitute maximum volume about 75 or even 80% of this concrete could be aggregate considering both fine and coarse aggregates. If they can absorb the heat without rapidly increasing the temperature of Concrete it is very good for fire resistant. So, absorption of heat by the aggregate is something very important.

If they can absorb more heat, then per unit volume, that is very good. And aggregates with high thermal conductivity are poor performers, what that means? If there is a little bit of fire or the higher temperature and it will be easily conducted into the concrete that means, the internal temperature of concrete will also rise very easily. So, that is not very good. Now, what is good is with high specific heat that means, if they can absorb heat the per unit volume they perform very well under fire and that is dependent on the mineralogy of the aggregate.

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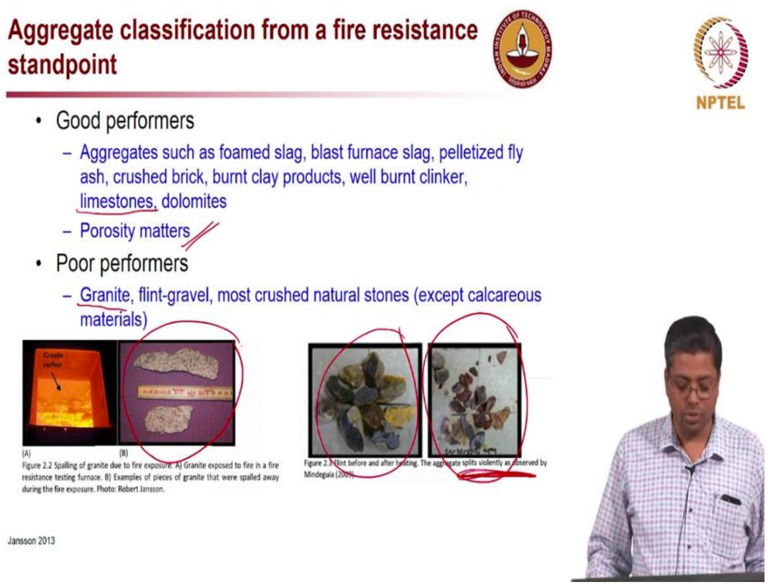

Now, what are the good performers and bad performance in case of aggregates? Anything which we say as with really reasonably high pore structure, high porosity then they will perform better. When you talk about fire resistance, so for example you can say limestone, it definitely has more pores as compared to granite stone, which is why the granite is not a good performer in case of fire.

You can see a picture at the bottom left where granite during a fire test the picture here it shows like flakes of granite or in a knife like edges are also visible on this that can this actually granite stone broken into pieces. So, under fire, and now on the right side you can see a flint before fire and this is after fire. The same aggregate pieces are broken into and 1 word here is interesting to note it splits violently.

They break violently into smaller pieces. That means then if you use flint or granite in concrete, they can also break like these inside the concrete. So, it is not just the cementitious part which is breaking, but the aggregate itself also can break into pieces. So, we have to be careful in selecting, we may not be able to change the aggregate, depending on what is available, we will have to use those aggregates. So, what we have to do is; what are the other ways by which we can protect the concrete structures which are vulnerable to fire damage.

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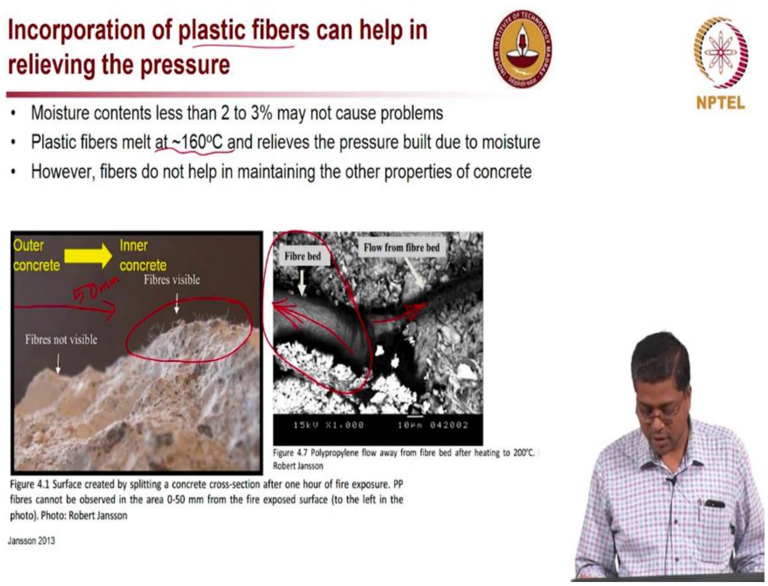

So, one way of doing that is incorporation of plastic fibers. They can help in relieving the pressure because the Spalling happens because of the pressure buildup as we discussed earlier the moisture clog and then it increases the pore pressure and then leads to spalling. So, here is the picture on the left side, you can see region on the left side of the picture is the cover concrete.

So, if you go up to here about 50 mm thickness, there is no plastic fibers visible but at beginning there was plastic fibers. So, you can see here some air like fibers visible in that region. Now, what it means is during the fire attack from the left to the right, as the temperature increases and reached about 160 degrees Celsius, the plastic started melting and it leaves that whatever the space occupied by the plastic fibers.

They help in providing pathways for the water vapor to go out of the concrete, that way they prevent the building up of the pressure inside the concrete. So, this is a good practice which people used to do especially for tunnel linings and structures like that picture on the right-side shows this, on the right side the there was a fiber bed, that is a place where the fiber was kept originally.

And after exposure to fire or an elevated temperature, you can see that the fiber started flowing, that means the molten fiber molten plastic it started flowing and started occupying another space. So, when it starts flowing into the other space available in the concrete that means, this part is now available free for release of pressure. So, this is how the plastic fibers can help in controlling fire damage or minimizing fire damage.

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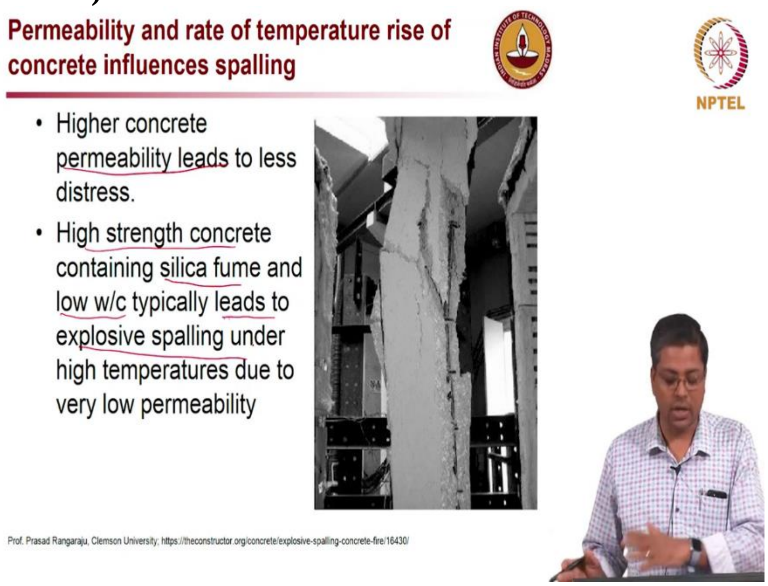

Now, permeability of the concrete and the rate at which the temperature rise of concrete happens, they also influence spalling. Higher concrete permeability leads to less distress, why because then you have more pathways for the water vapor to get released from the concrete. Now, higher strength typically high strength concrete will have more compact micro structure.

Especially when you use a silica fume, or low water cement ratio or any other SEMs witch we use today. They might have a more compact micro structure, which can lead to explosive spalling under high temperature, because they do not release this, when they do not provide pathways for the water vapor to move outward. So, then eventually the pressure builds up significantly and eventually, it leads to explosive kind of spalling.

If we are talking about fire if the structure is probably vulnerable for fire attacks, then we should make sure that there are sufficient ways by which the heat does not get into this, there are a lot of coatings available nowadays, which prevent the rise in the temperature inside the concrete So, that is probably one way to go for because if you are talking about taking a lowering the permeability or increasing the permeability of concrete, then the problem would be there will be durability related issues.

So maybe the better way would be to use good quality concrete, but at the same time, provide a coating which will kind of function as an insulator, and it will prevent the temperature rise inside the concrete even if there is a fire attack.

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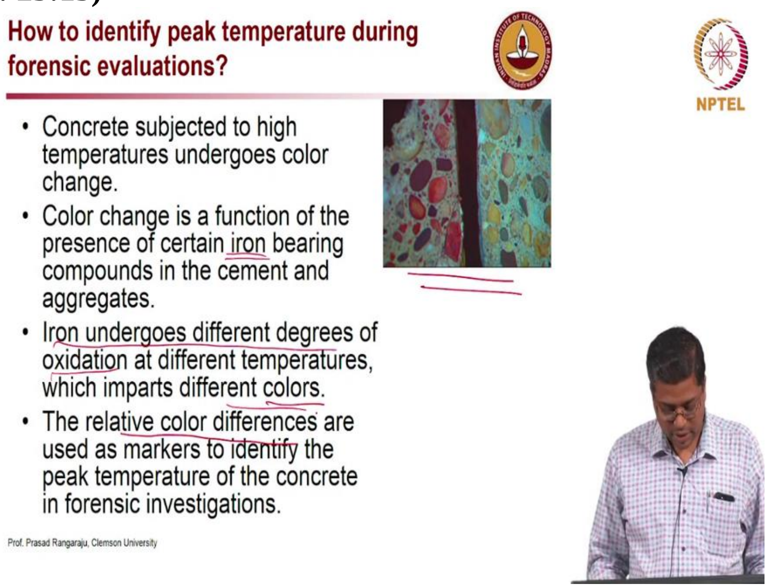

Now, let us say you are seeing a structure where it is already experienced a fire damage and we need to know what was the maximum temperature which was experienced by the concrete. So, how can we do that? By looking at the color change in the aggregates we can identify what is that maximum temperature and this is possible because of the presence of iron wearing compound in the cement and aggregates.

And iron undergoes different degrees of oxidation at different temperatures leading to different colors. So, I will show you a graph on the next slide. And so, this color differences can be an indicator for the temperature.

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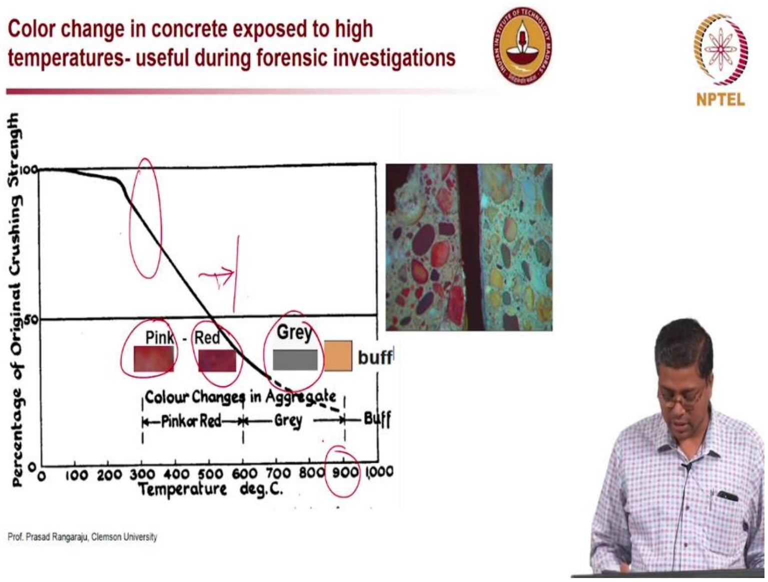

The maximum peak temperature, which the concrete was exposed to as you see here. If you see a pink color, then that we can say temperature was probably somewhere in this range that is about 300 plus and if the color changes towards red, then that is up to 600 degrees Celsius and then, if it is grayish in color then 700 to 800 degree and if it is Buffish color than it is about 900 degrees Celsius.

So, there are charts like this which shows or helps us to determine what was the peak temperature. And now, once you know the peak temperature then you can say what is the probable decrease in the modulus of elasticity, and the compressive strength of concrete. So, as I showed here the how the stress strain behavior will be different. If you go for this increase in temperature here.

And the stress strain graph, significantly changes are stressed and behavior changes. So, all this is required, we need to know what was the peak temperature or then you have to go and take cores or take specimens from the concrete and then do some testing, but the point here is you may not be able to get core because they are all now spalled and cracked.

So, getting cores also may not be a good idea. So, you have to have these tools available to be able to relate then to the color and then residual mechanical properties could be.

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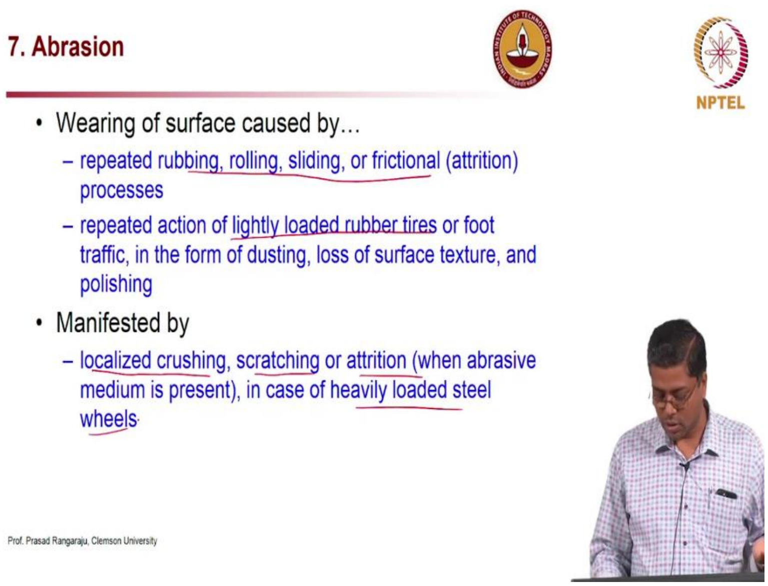

Now let us look at abrasion damage. What is abrasion it is basically wearing of surface because of repeated rubbing, rolling, sliding or frictional or attrition processes. And repeated action of lightly loaded rubber tires or foot traffic even in the form of dusting loss of surface texture excess and polishing so, these are all ways by which we can define what is wearing and how it is manifested by localized crushing, scratching or attrition and in case of heavily loaded steel wheels. So, where do we see this? Most often it is visible on either industrial flooring where you have heavy vehicles moving or on highways, road structures.

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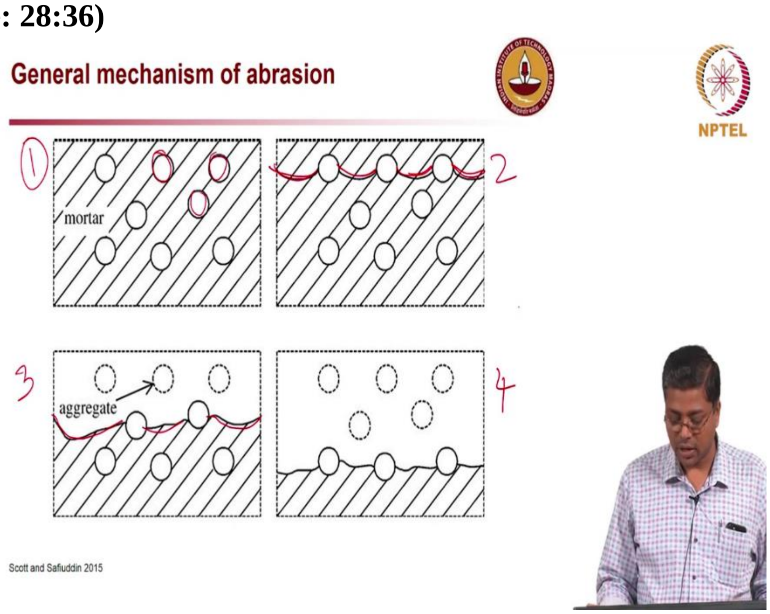

Where you have vehicle movement, that is where we see this abrasion most often. And let us talk about a little bit what happens. The first step would be you have an intact mortar or a concrete with aggregate these round circles. You can see they are all representing aggregates. And then on the second stage here, what you see is some part some portion at the top is lost and then you have aggregates are partially exposed.

Now, in step 3, you have some aggregates which are completely lost and then this the surface starts moving downward, the abraded surface, it keeps moving downward and then more and more of such aggregates are lost and the entire, so, you can see here the progression of the abrasion in concrete structures. So, first the fine particles are lost, then you have small aggregate particles gets exposed, and then more and more aggregates gets exposed and eventually has significant loss.

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Now, this is a picture on the right side very clearly shows this. You can see that aggregate particles are likely visible and this can also lead to pot holes.

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Now, after this is a picture showing where a significant amount of aggregates has been removed, you can see here in this portion, it is only the cement paste is removed, but here you can see significant amount of aggregates are also removed. So, this is the initial stage and this is the final stage or later stage.

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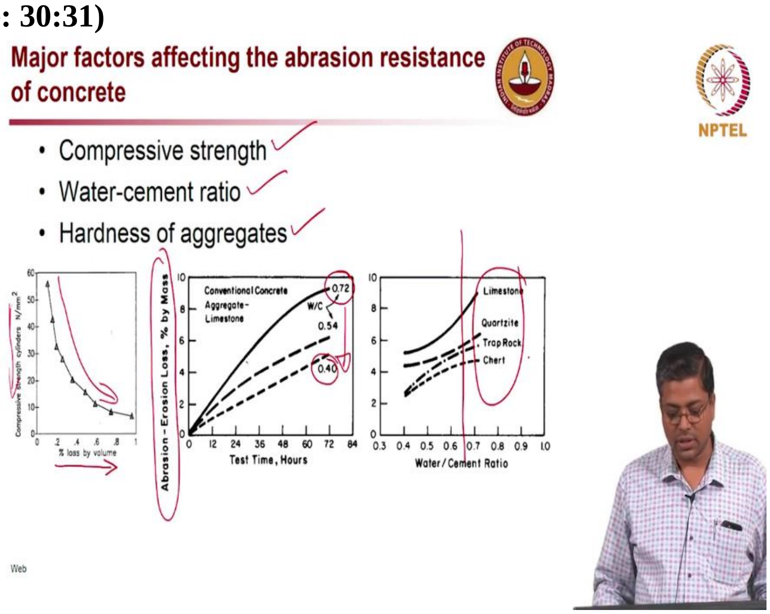

Now, what are the major factors affecting the abrasion resistance of concrete? So, compressive strength, water cement ratio and hardness are the 3 major factors which affects the abrasion resistance. You can see here on the picture on the left side, the percentage loss by volume it going here and as the compressive strength of the concrete is less you have more and more percent loss.

Now, on 2 graphs on the right side this is abrasion erosion loss, again all these studies are done based on the amount of material loss.

So, here you can see water cement ratio changing from 0.4 to about 0.72. So, as the water cement ratio is lower, less amount of material is lost. And here you can see for the same water cement ratio if you draw any line over here, you can see how different aggregates perform with limestone showing maximum damage and quartzite, trap rock and chert showing less damage. So, definitely water cement ratio plays a role and the aggregate and its hardness plays a role and also the compressive strength of the entire concrete also plays a role.

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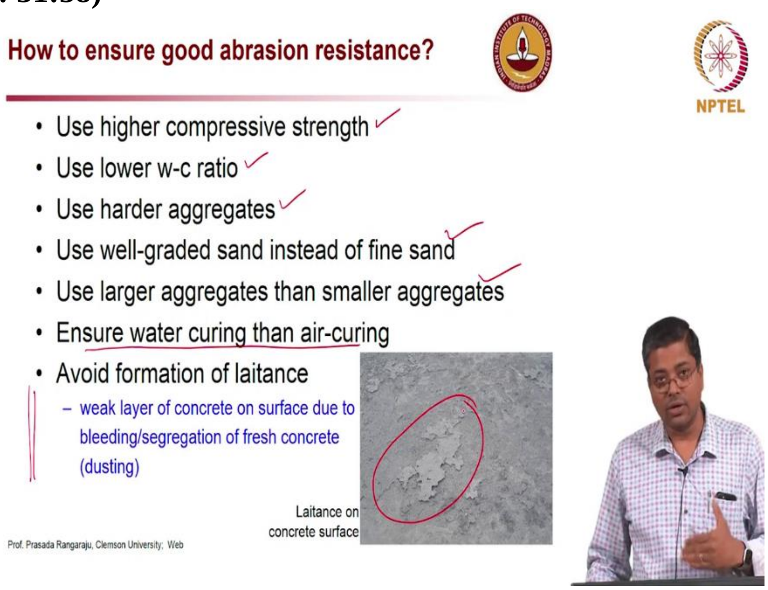

Now, how to introduce good abrasion resistance? Use high compression strength concrete use lower water cement ratio, use harder aggregates and well graded sand and instead of fine sand, and then larger aggregates than smaller aggregate and make sure that the concrete is very well cured especially that will ensure that the top layer of the concrete is hard enough because when you talk about abrasion it is mainly the top layer which matters.

So, you have to ensure that the top layer is of very good quality and avoid laitance you can see here what is laitance, it is a weak layer of concrete on the surface due to excessive bleeding of fresh concrete you can see so, these kinds of things indicates that the near surface will have very porous structure. So, that will lead to significant abrasion damage.

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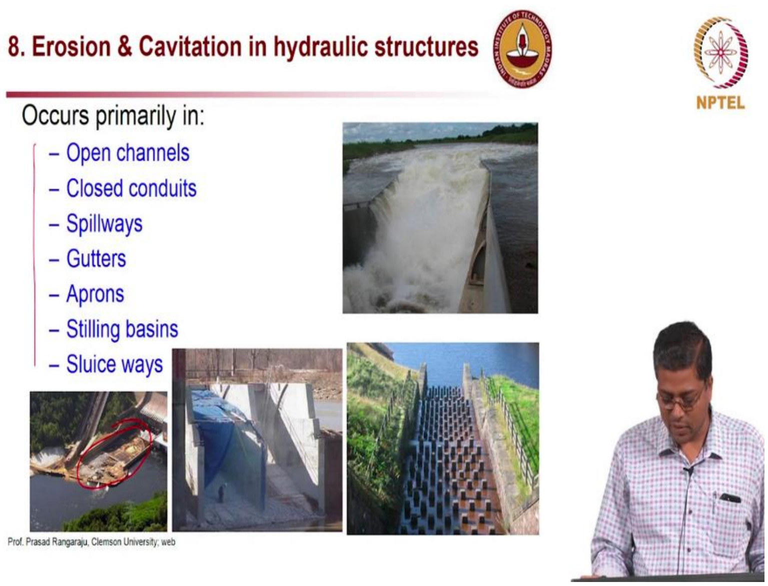

Now, erosion and cavitation especially these are happening in hydraulic structure because you are talking about water body there. So, these are the typical structures where this will happen. Open channel, closed conduits spillways, gutters, Aprons, stilling basins, sluice waves, all these are part of hydraulic structures, you can see here significant damage on this. So, these are type of structures, where there is a flow of water along with debris etcetera you can expect a significant erosion and cavitation.

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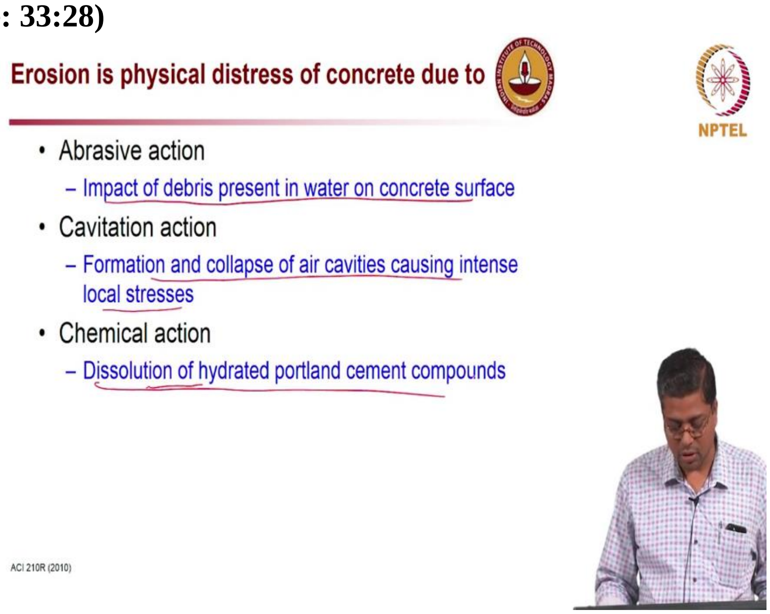

Now, how this erosion happens? There are 3 actions in this one is abrasive action, the second one is cavitation and then there is also a chemical action. Abrasive action is because of the presence of debris in the water which is flowing and the cavitation is because of the intense local stresses which are formed due to the air cavity formation and collapsing of those air cavities. And we will discuss that detail later. Then chemical action is basically dissolution of the hardened cement concrete which can happen so, all these in combination gives this erosion damage.

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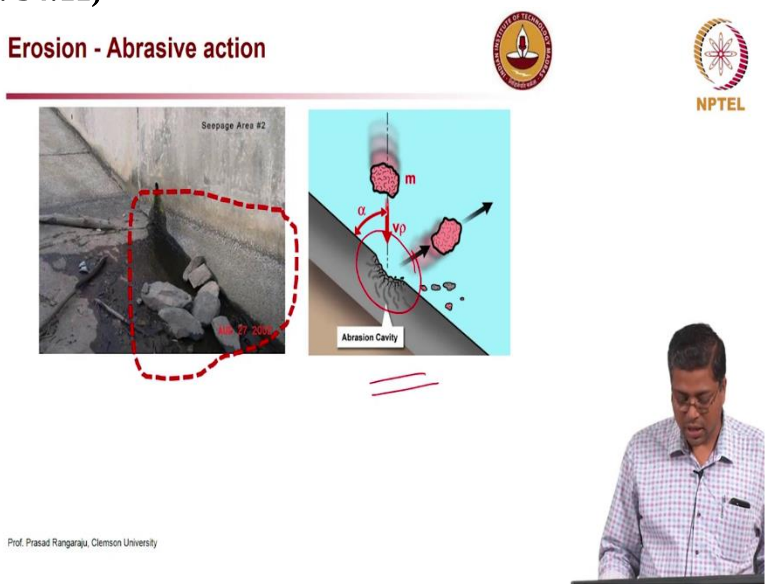

So, what is the abrasive action? You see on the picture here, there are huge rock boulders which are percent on the, this is a bottom portion of a spillway, you can see large boulders, they actually abrade on the concrete surface and lead to damage as is shown in the picture on the right side here. You can see a large particle hitting the concrete it locally damages the concrete and when multiple actions come and then eventually the entire concrete surface get eroded or the abraded and get damaged..

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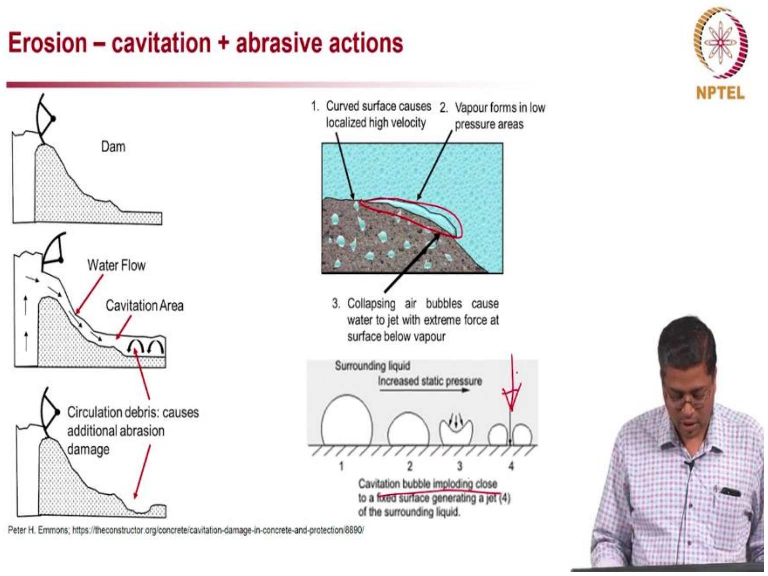

This is a cavitation plus abrasive action because all this water you might also have either debris or sand particles. So, particulate matter will be present in the concrete and if that is the case you can have abrasion. Now, let us see what is cavitation? mainly this happens When there is a change in the shape or, if there is an irregularity in the concrete surface.

So, because of these irregularities, so, for example, here as you see on the picture on the top right, you can see there is a small region which is a air void formation or vapor forms in low pressure which leads to formation of the air bubbles. And then eventually, some of the air bubbles will coalesce and then become a large air bubble. And then what happens eventually is that they start imploding like you see here in the 3 and 4.

This air bubble because of the water pressure, it collapses into 2 smaller air bubble and then there is a jet of water which is hitting the concrete surface as is seen on the Case 4 here you can see here, there is a jet of water which is hitting locally and that kind of action leads to significant damage to the concrete or cavitation damage.

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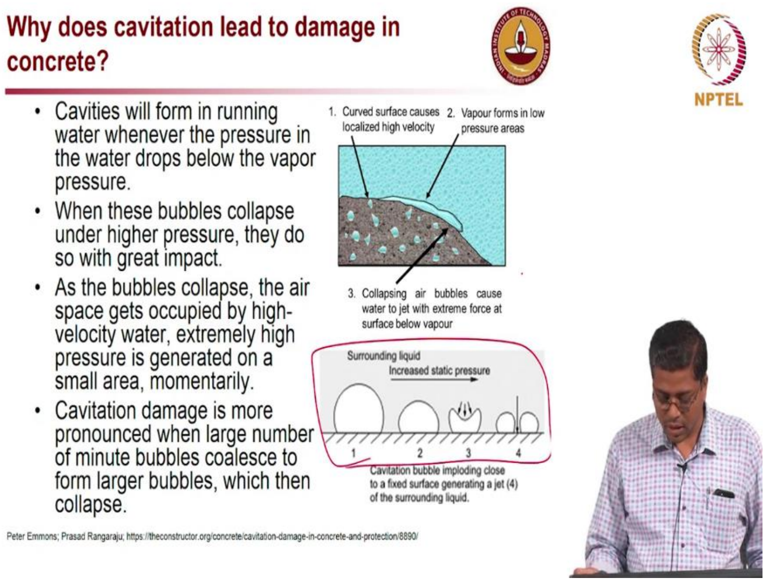

So, again the same thing what I just discussed them putting it in text. Cavities will form in running water, whenever the pressure in the water drops below the vapor pressure. And when these bubbles collapse under high pressure they do so with great impact. And as the bubble collapse the space gets occupied by high velocity water extremely high pressure is generated in a small area for a fraction of a second or momentarily and then cavitation damage is more pronounced when large number of various small bubbles coalesce is to form large bubble which then collapse as shown in this sketch over here.

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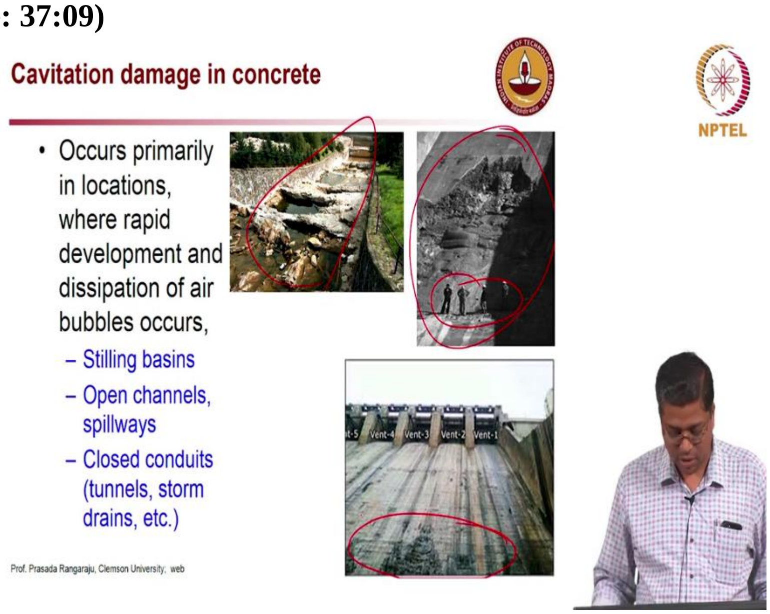

Now, these are some examples showing how big this cavitation damage could be, you can see some people standing here and the size of the damage and this is also a large significant damage, here also you can see significant damage on a spillway.

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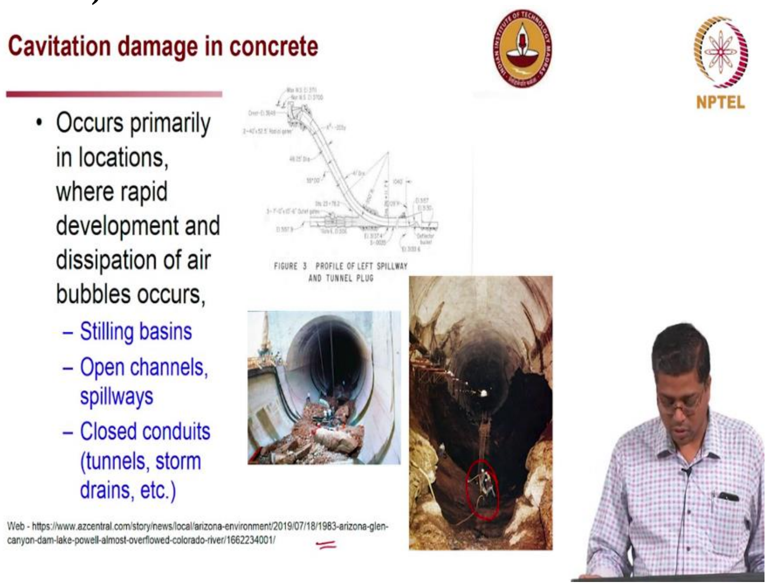

And this is a very huge such damage experienced in this Glen Canyon Dam in Arizona in 1980s. And that significant damage you can see people standing here and the size of this damage is so huge.

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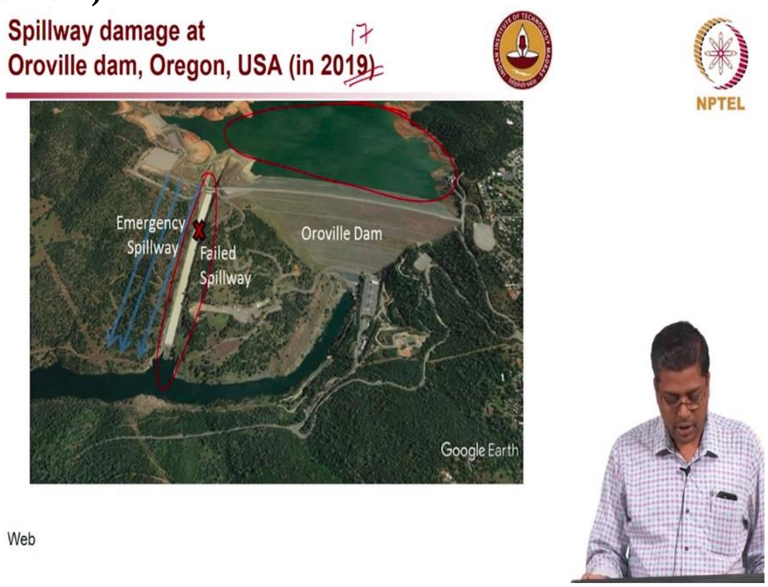

Now, this is another example, this happened in 2017. And there was a spill way you can see the dam structure here and there is a spillway here which was failed, and you can see.

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How the damage started, initially there was very small damage here and then it eventually led to significant damage. The bottom portion of the entire spillway was completely lost.

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And this is repair of that structure. You can see the entire spillway was removed and then now rebuilt. Now it is looking good, but a lot of money spent. So, you can see here the damage started from here and then led to huge damage the entire spillway was lost.

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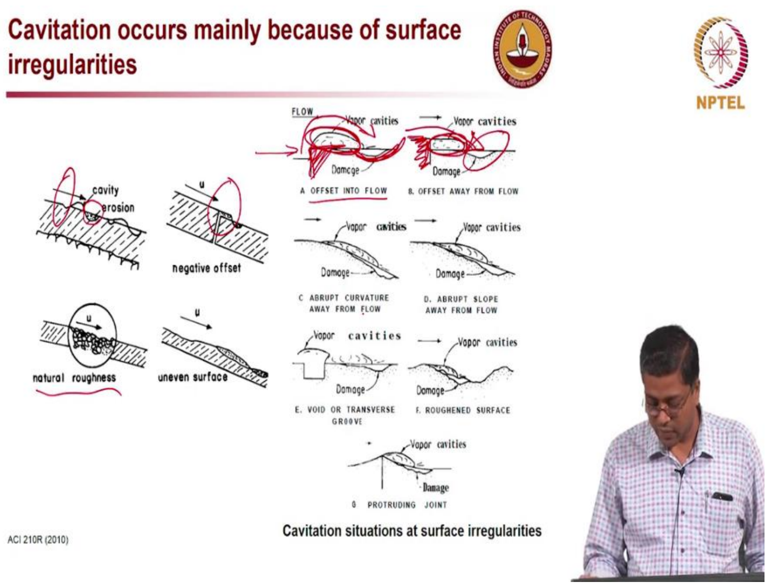

Now, some sketches showing the details on how this cavitation can happen. You can see here, there is some erosion at the bottom portion here and then cavitation. This is happening because of this irregularity on the surface over there and then natural roughness of the surface can also lead to cavitation. And here you can see a change in the surface profile that also lead to cavitation.

So, any uneven surface or irregularities on the concrete surface which will lead to cavitation. Even if it is very small, because of the high velocity of the water, it can lead to colossal damage. So, it is something very important especially for hydraulic structures to be taken care. These sketches on the right side also shows offset into the flow. So, flow is from here, you have a projection of the structure here that leads to flow of water like this.

And which leads to formation of cavities like this and which eventually lead to damage in the downside here. So, like that here, you have flow and the structure is like this. And there is a sudden moment of downward creating cavity here and which leed to damage here below. So, likewise in all these pictures you can see surface irregularities lead to significant damage on the concrete.

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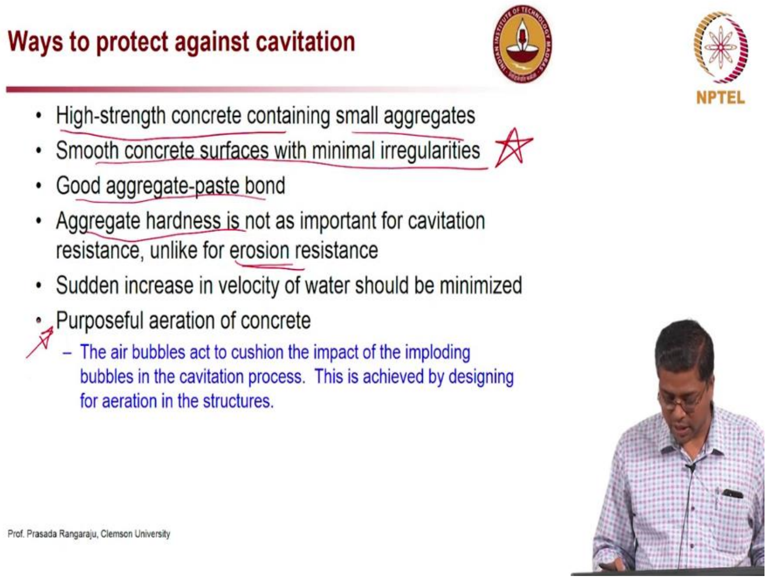

How do we protect concrete structure against cavitation? High strength concretes containing smaller aggregates and then smooth concrete surface with minimal irregularity this is the most important thing I believe, because that will prevent the formation of cavities and good aggregate paste bond, the aggregate should not get dislodged from the concrete and hardness is not as important for cavitation resistance unless erosion or abrasion resistance.

Now, sudden increase in velocity of water should be minimized but that will happen because of this shape or irregularities on the concrete surface. So, if we take care of this concrete, ensure that the concrete surface is very smooth and there are minimal irregularities, probably the risk for cavitation is less, or the probability of cavitation to occur is less. The purposeful aeration this is something new technique which have been really you know, adopted in many structures nowadays, I can show you some pictures.

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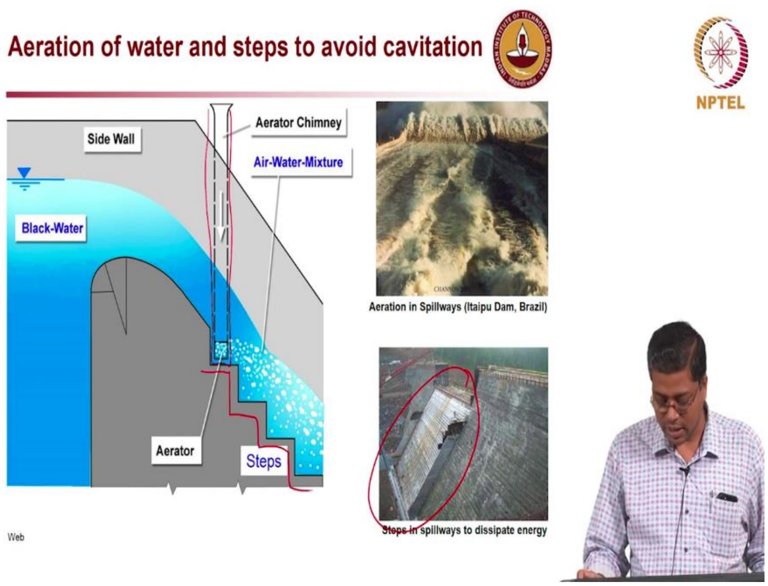

So, this is how it is you can see here, you are basically pumping air into the water body so, that there are more air bubbles and also introducing steps like this so, it is the see on the right side picture here there are steps on the spillways, which helps in dissipating the energy and so, that the pressure which is acting on to the concrete is relatively less and it avoids the damage due to cavitation.

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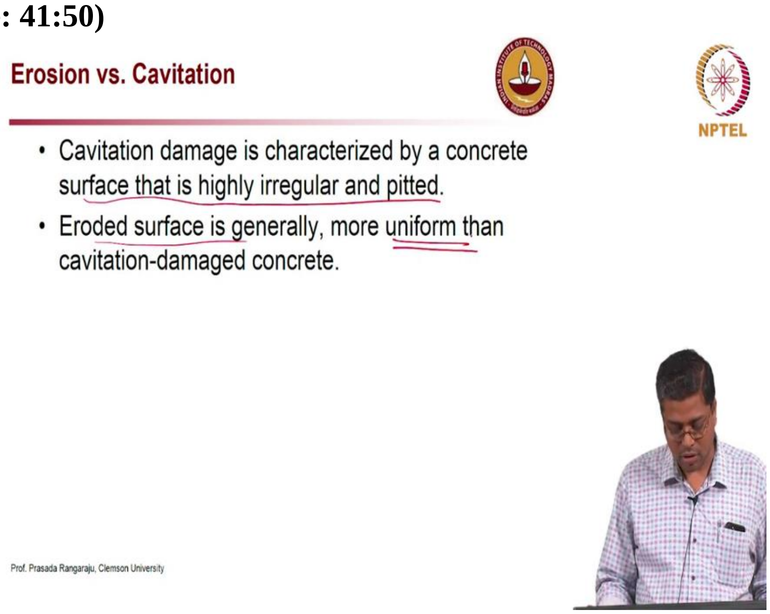

So, major difference between erosion and cavitation is, in cavitation surface highly irregular and pitted whereas in case of eroded surface, it is more or less uniform or more uniform than the cavitation damaged concrete.

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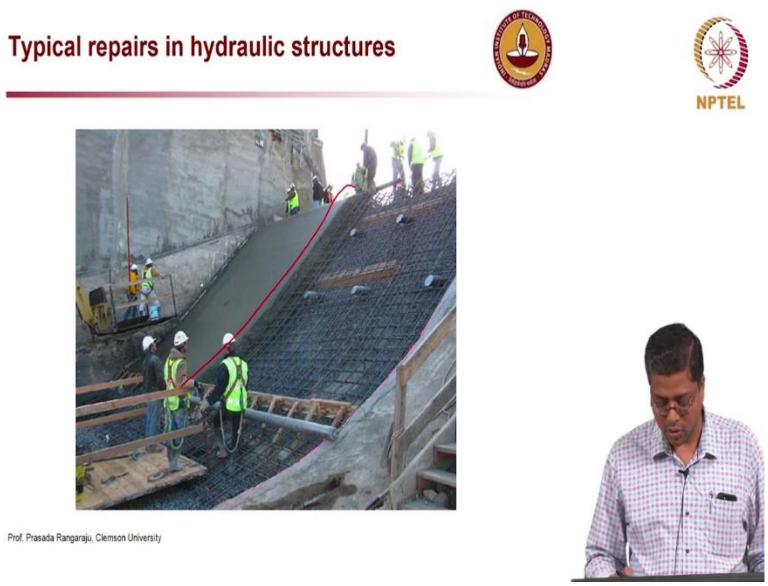

This just showing another repair, you can see here, again, they are making sure that the surface is very smooth, because that is the one which is very important to ensure there is no cavitation damage, very smooth transitions no irregularities should be there.

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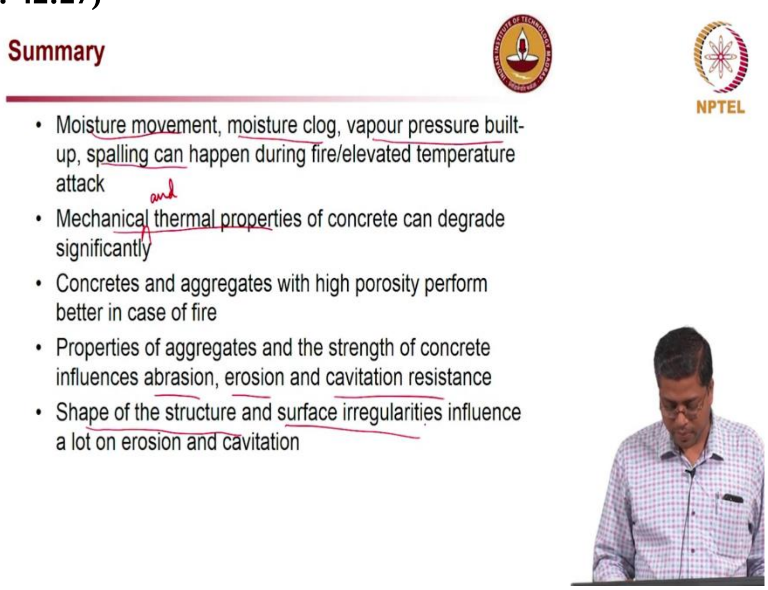

To summarize, now, first we talked about fire damage. And moisture movement, we discussed about how moisture moment happens in concrete during elevated temperature. And then we talked about moisture clog, which leads to building up of pressure inside the concrete which eventually leads to spalling at high temperature conditions, or especially when there is fire, mechanical and thermal properties of concrete can get affected because of fire attack and concretes and aggregates with high porosity perform better in case of fire because they provide pathways for the moisture to get released from the concrete.

And strength of concrete influences abrasion, erosion and cavitation resistance and shape of the structure and minimal irregularity. These are the 2 things which we have to really worry about to prevent erosion and cavitation in hydraulic structures. I think with that we will stop today.

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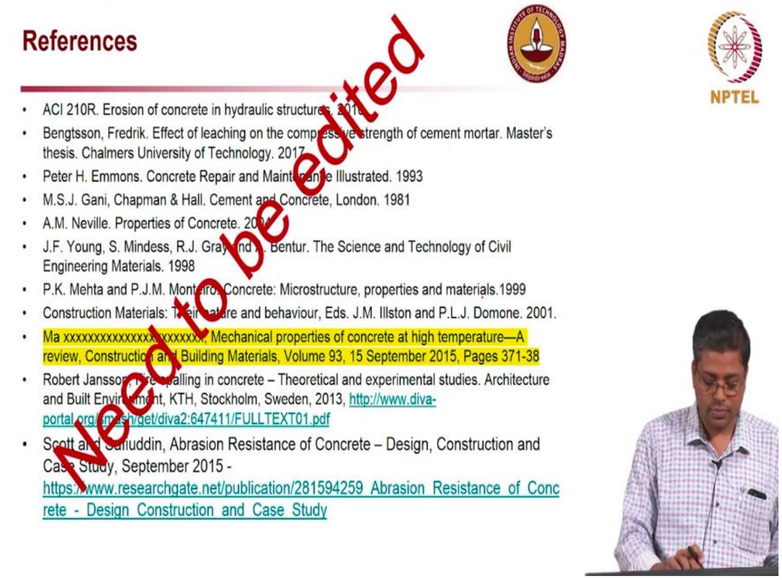

These are the references used for making this lecture. Thank you.