Maintenance and Repair of Concrete Structures
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Lecture 15
Strategies and Materials for Surface Repair
(Compatibility of repair materials with Substrate)

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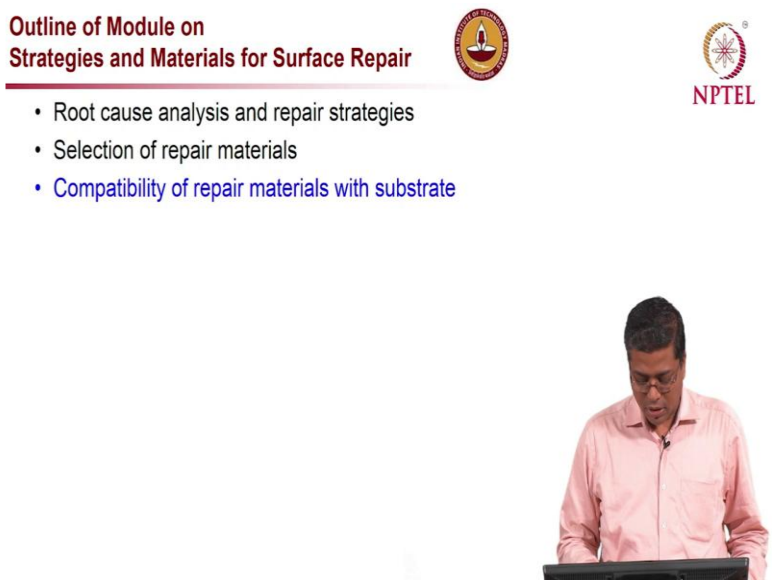

Hi, this is the third lecture in the module on strategies and materials for surface repair. In this, we will talk about the compatibility of repair materials with substrate. And also we will look at some of the stuff which we already discussed in the previous slides.

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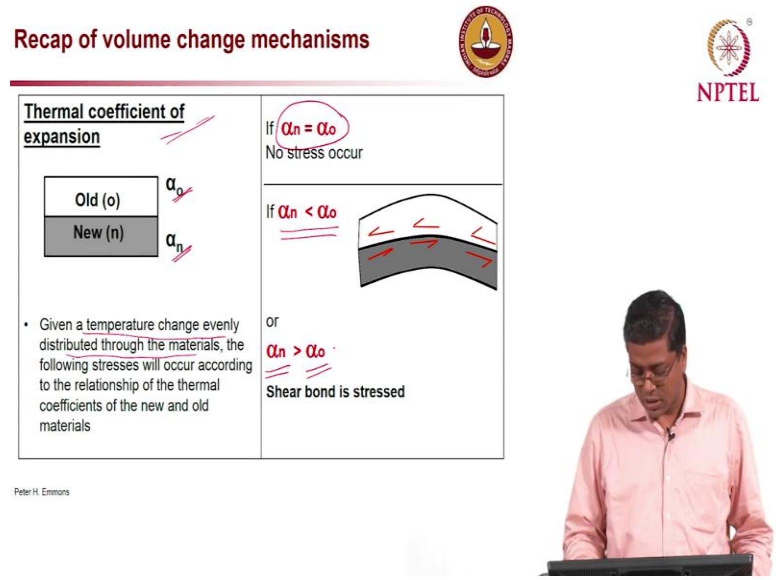

So, this is the recap of volume change mechanisms. I will show you 4 major material parameters which really influence the volume change; one which we discussed was coefficient of thermal expansion. You can see if alpha is the coefficient of thermal expansion, this o here indicates old material or existing concrete or substrate and then n indicates the repair material. So, let us assume that given a temperature change evenly distributed through the material.

The following stresses will occur according to the relationship of the thermal coefficients of new and old materials. So, as you see on the picture on the right side in above picture, if alpha of the new material is equal to alpha of the old material, then there will be no shear stress in the layer between 2 materials. But, if in this case, let us say alpha of the new material is less than that of the old material.

Then that means the new material will shrink less than the old material, as it is shown in the picture or in other words, because the volumetric change is different for these 2, there will be development of shear forces then you will have shear stress and then that might lead to failure or Delamination. If the bond strength between them is not really good, especially the shear bond mechanism.

So, we will talk about this later also and if the new material has higher coefficient of thermal expansion than the old material then also this will happen. So, as long as there is a difference in coefficient of thermal expansion between the 2 materials then there could be generation of shear stress and then the shear bond will get stressed in that case.

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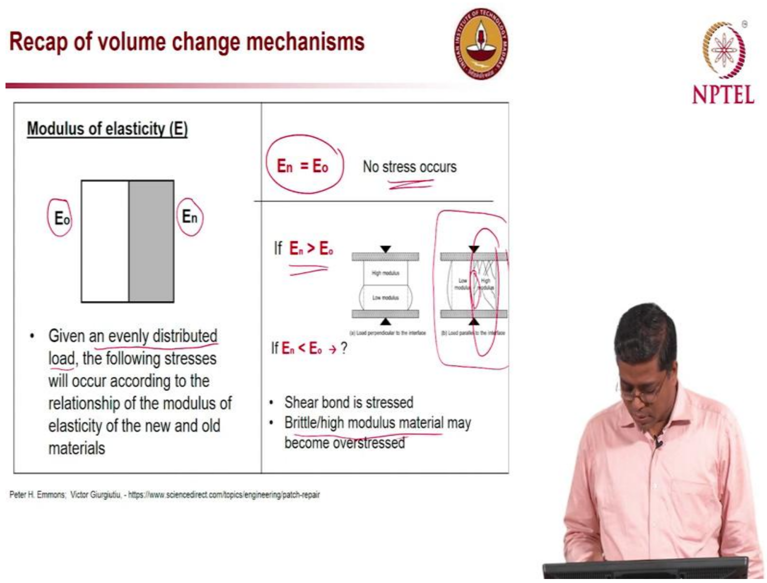

And the other parameter we looked at was modulus of elasticity and here is E_0 indicates modulus of the old material and En indicates modulus of the new material or the repair material. Now, let us say at a particular time instant after the repair or during the repair, let us say given an evenly distributed load, the following stress will occur according to the relationship of modulus of elasticity of the new and old material.

If both the modulli are equal or almost equal, then there is no generation of stress. But if one of that is different, let us say En is greater than modulus of the old material, then the material with higher modulus will experience a higher stress at the same strain level or deformation level, then that means that material with more modulus will probably lead to crack at an earlier time.

So, as you can see here, this is that case when you have a high modulus, then that material will go into the plastic stage, when you talk about the stress-strain behavior and then it will experience higher stress and then experience cracking where the material with low modulus is still experiencing a lower stress level. Now, shear bond can be stressed depending on whether this load is applied in which direction.

In this case as in the second drawing here, you can again say that the shear bond between the 2 materials gets stressed and you might have a failure along that plane. This I already discussed brittle or high modulus material may become overstressed at the same strain level and then lead to cracking.

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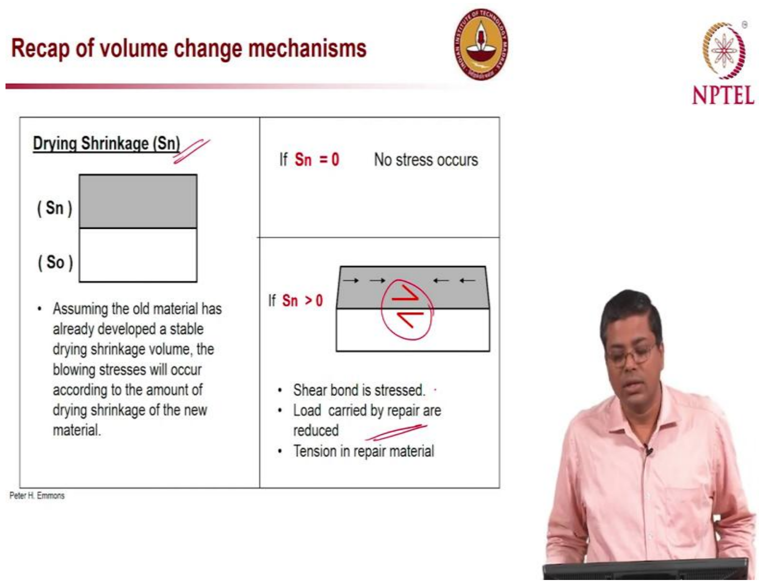

Another one was drying shrinkage. Again, if you have one material if it is going to shrink more than the other or if you have one material expanding more than the other then but when you talk about shrinkage, it is shrinking. But if you are talking about the swelling mechanism, why I am telling about swelling also is because it is also something to do with the moisture.

So, either way, if there is a volumetric change then the shear bond here gets stressed or the shear stress will be generated. Now, load carried by a repair might become less so the integrity of the system will be lost and that is something which we don't want to happen. So very important to make sure that there is no stress generated along the bond.

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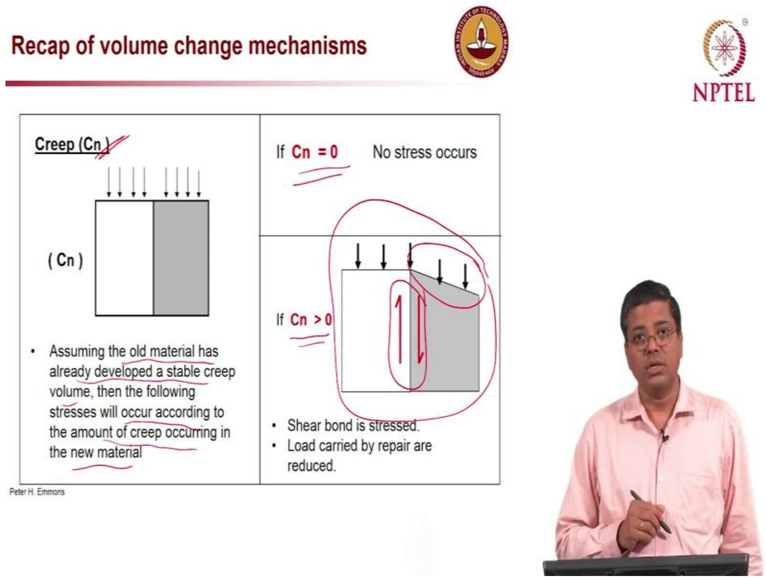

Also we talked about creep. Again, assuming that the old material has already developed a stable creep volume, that means no further creep and then the following stress will occur according to the amount of creep occurring in the new material. So, if there is no creep, then there is no stress generated, but in the case as you see here, Cn if it is greater than 0 or a significant number.

Then you might see that there is a significant deformation and then once there is a deformation or in other words there is a movement then you can actually experience shear stress along this plane, which is not that good.

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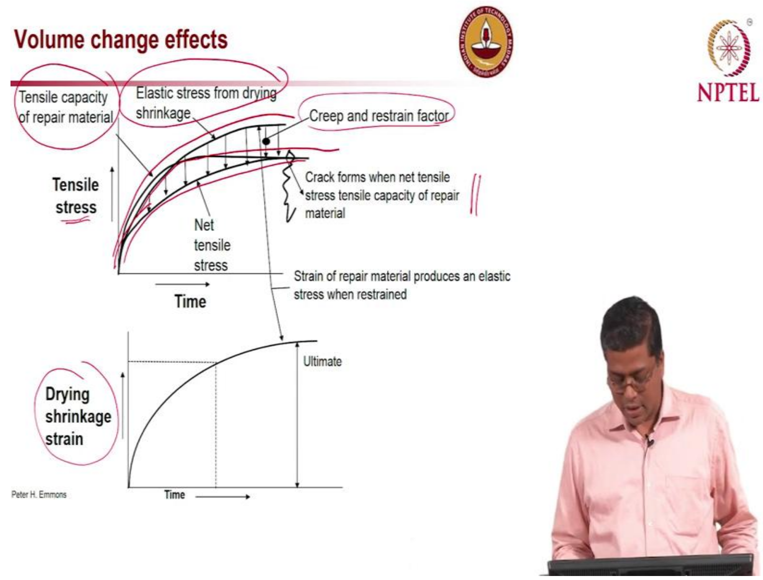

Now, let us look at how the strength is developed inside the concrete or the material? And at the same time how the stress is generated because of various actions and then how the combination or how it leads to cracking. So, look at this curve here that is showing the capacity of the repair material or how the tensile strength of the repair material is increasing or evolving.

Another curve which is this curve showing the elastic stress from the drying shrinkage. So, one is capacity and the other one is demand there is stress generated because of the drying shrinkage. And there is also a relaxation factor because of the creep and restraints. There will be a reduction in the applied stress and so the net tensile stress is actually this. So, this reduction is indicated by these vertical arrows in the sketch.

So, basically the crack develops or the crack is formed when the net tensile stress is actually more than the tensile capacity of the repair material. So, the moment when there is more tensile stress than the stress which the material can take at that moment the material starts to crack. And the graph at the bottom shows the drying shrinkage strain as a function of time. The one on the top shows the tensile stress as a function of time and the one on the bottom shows the strain as a function of time.

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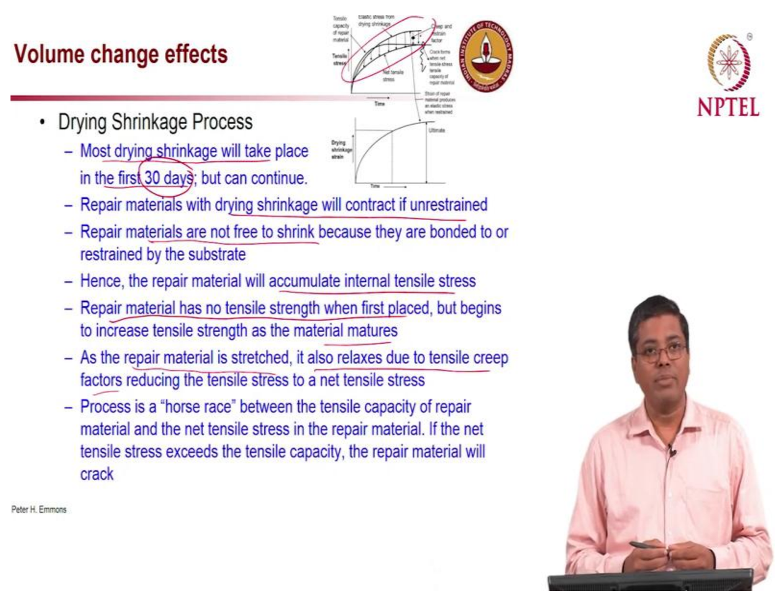

Now, this is the same thing what I just discussed, written in text. I will just go through it very briefly. So, most drying shrinkage will take in the first 30 days, maybe even few months. I would like to say not just 30 days, but least some months, but it will continue to happen and then repair materials with drying shrinkage will contract if unrestrained, but without cracking.

But if there is a restrain which is the case in most cases, if they are not free to shrink, because they are bonded to the substrate or restrained by the substrate, then there will be tendency to crack the material rather than just letting the material to shrink completely. Now, in this because of the restrain, the stress will accumulate and then that will lead to significant strain.

And then repair material has no tensile strength, when first placed basically in the fresh state as time passes the material will mature itself and then gain more and more strength which we already discussed in the previous slide. But as the material is stretched, it also relaxes due to the creep factors that is the vertical arrows in the graph, which is this one here, the vertical arrows indicate that reduction in the stress due to the creep effects.

And there is a fight between this tensile stress developed and the capacity which is also developed. So, whenever there is a crossing over point that is at this point when there is more stress applied than the capacity of the material, then the material will lead to cracking.

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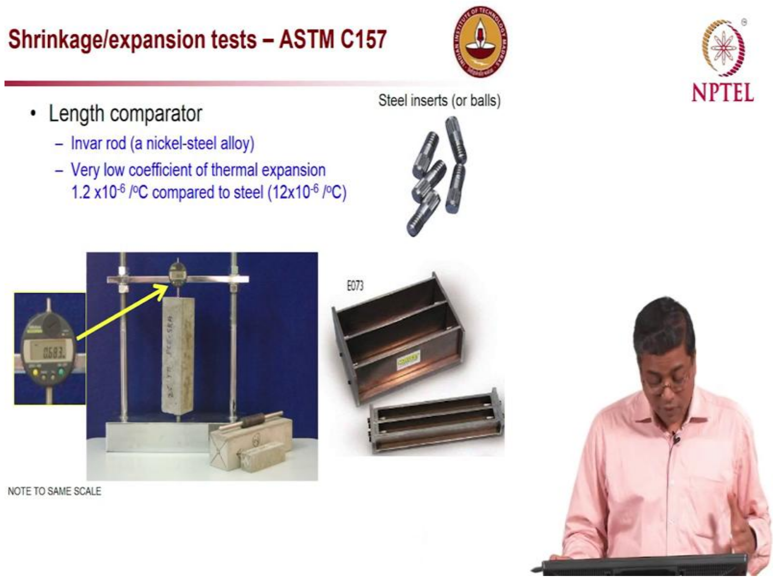

This are some photographs from our lab where it is showing how to test the shrinkage behavior in a concrete system we can see it is a length comparator, where you have a prism of concrete with plain concrete and with this we can expose the concrete specimen to environmental conditions and then measure the change in the length of the specimen.

And that change in length will indicate the resistance of the material against free shrinkage, there is no reinforcement in this concrete. So, it is essentially looking at free shrinkage mechanisms and we assume that if the free shrinkage is very high then definitely you may have other problems. Even if you provide reinforcement in concrete you will see cracking because of significant potential for shrinkage of the concrete.

So, we have to make sure that the concrete or the repair material, which is used is having sufficiently high resistance again shrinkage or sufficiently low shrinkage.

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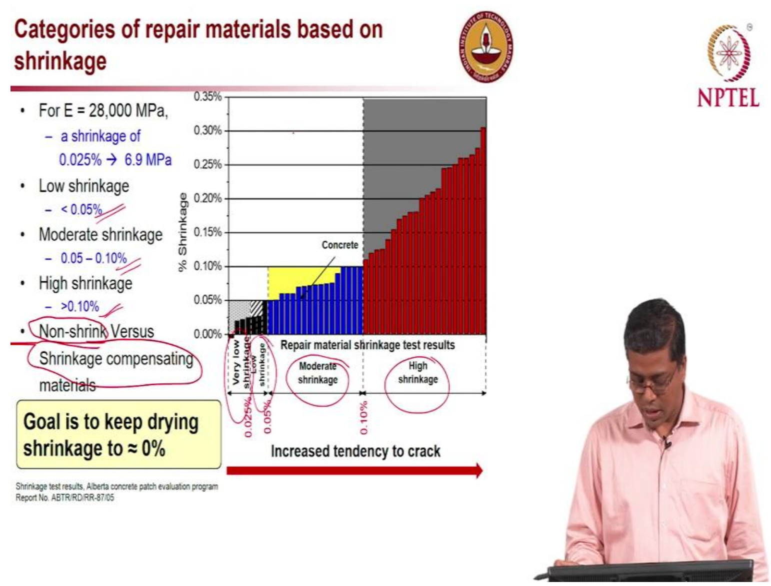

What is that sufficiently low shrinkage? So we will see some example here these numbers here need not be taken as fixed numbers, it is up to the engineer and for the specific case, you have to decide what is good for a particular application and what is bad for a particular application those have to be decided, but this is just a guideline to tell you what can be called as a low shrinkage, moderate shrinkage and high shrinkage.

If the shrinkage is less than 0.05% then we can say it is low shrinkage. If it is between 0.05 to 0.1 then we can say it is moderate and if it is greater than 0.1, then we can say it is high shrinkage and may be that kind of material should not be used. Now, another thing which I wanted to tell is the availability in market. Many places the goal is to keep drying shrinkage almost 0 as written in the yellow box at the bottom left, but when I say 0 so anyway it is very low that is what is the idea.

So, 2 types of shrinkage or 2 types of materials are available in the market one is called non shrink materials and the other is shrinkage compensating material. So, the non-shrink is basically does not shrink. So, for example, if you add shrinkage reducing admixture, then it acts at the microstructure level by reducing the surface tension of the material of the liquid phase and it does not allow the material to shrink whereas in the case of shrinkage compensating materials or grouts or shrinkage common setting mortar. What is the idea? There will be some kind of expansive agent provided in the material. So, when you provide an expansive agent the role of that is it allows shrinkage, but at the same time there is something else which is happening in parallel which compensates for the shrinkage which has happened. So, these are the 2 types of materials if you want to categorize available.

So, one is non shrink the other one is shrinkage compensating. Now this graph shows what this range is as I listed on the left side very low shrinkage, low shrinkage, moderate shrinkage and high shrinkage. So, as the shrinkage is more and more the tendency to shrink & the tendency to crack is also more.

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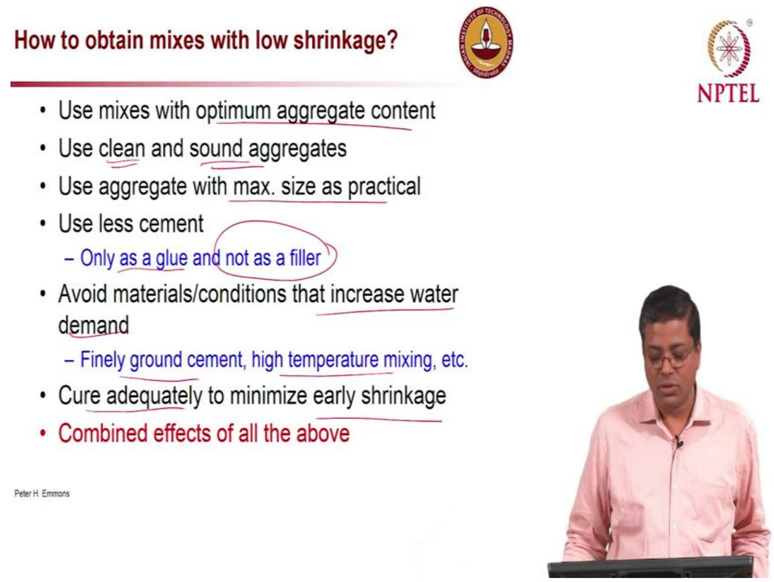

As you go towards the right, the tendency to crack is more. Now, how to obtain mixes with low shrinkage? We can use maximum possible aggregate. So, that means, an optimum aggregate content is best and then of course use clean and sound aggregate, clean means there should be no unwanted dirt or unwanted material in the aggregates and use aggregates with maximum size as practical because you will have to think about the spacing between the reinforcement you cannot keep on increasing the size of the aggregates so whatever is the practical thing. And then as per the codes you have to see what the maximum size allowable is and use maximum of that. The idea is to use less amount of fine powder or the cement. So, that the maximum space is occupied by the aggregates whether it is fine aggregate or coarse aggregate the maximum space in the concrete should be occupied by the aggregate.

And provide only that much cement which is necessary to bind or glue all this aggregate and not to add any cement as filler. Sometimes, not necessarily in Indian practice, but in other parts of the world people actually use finely ground limestone or limestone powder as a filler material which essentially not react much like the cement.

But it will occupy that very fine space which is available between the aggregates. So, that is also something which is important to know and avoid materials that increase water demand. So, if you put too much of fine materials then there will be more water demand. So, you will end up in using a higher water-cement ratio, which is also not good, when you talk about resistance against shrinkage.

Now, finely ground cement is probably not a good idea all the time and high temperature mixing is also not a good idea all the time. Because high temperature mixing means the water loss will be there and then that means drying will happen even at the early stages of concreting so which will lead to cracking. Now, curing adequately is very important to minimize especially plastic shrinkage or early shrinkage.

Now, it is all these points there should be taken with understanding the combined effects of all the above. So, it is not that just use maximum aggregates or use very limited cement. But we have to really look at how the combination of these selections will affect the shrinkage. So, that has to be studied and then trial mixes must be tested before going for large scale repair works.

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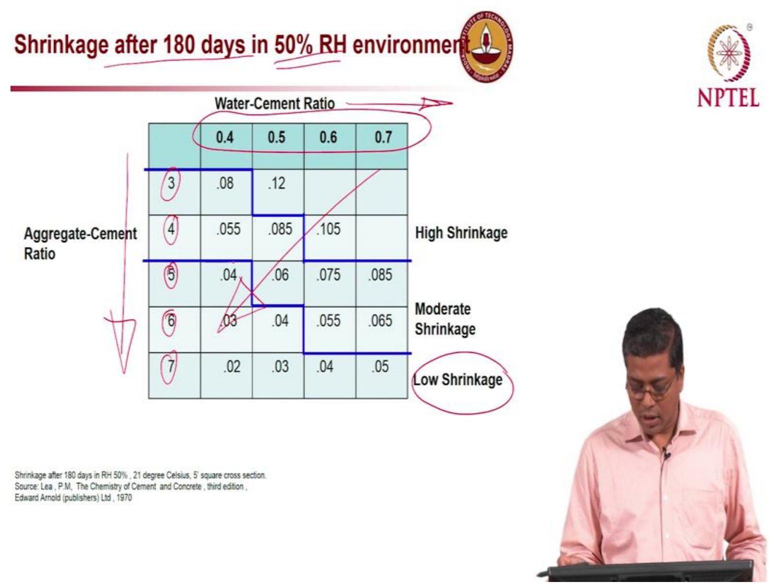

Now, this is just an example showing how shrinkage after 3 months of exposure to about relatively dry environment with 50% relative humidity. So, as you go down on this table, you can see the aggregate-cement ratio is decreasing, that means, as you go down on the table, the lower the position, the more the amount of aggregates.

So, you can see here 3, 4, 5, 6, 7 so, this number is increasing as you go down and then you have water-cement ratio. This four water cement ratios you can see 0.4, 0.5, 0.6 and 0.7. So, here again as you go to the right, the water-cement ratio is increasing. So, what is the expectation when you have higher aggregates and lower water-cement ratio?

Then you will have higher aggregate content and lower water-cement ratio, you will have a low shrinkage that is what is observed here. So, as you go to the table in this direction diagonally to the bottom left if you go you will see low shrinkage. If you go to the top right corners, then you will see high shrinkage. So that is a general idea of how the water-cement ratio and aggregate-cement ratios interact and influence the shrinkage resistance.

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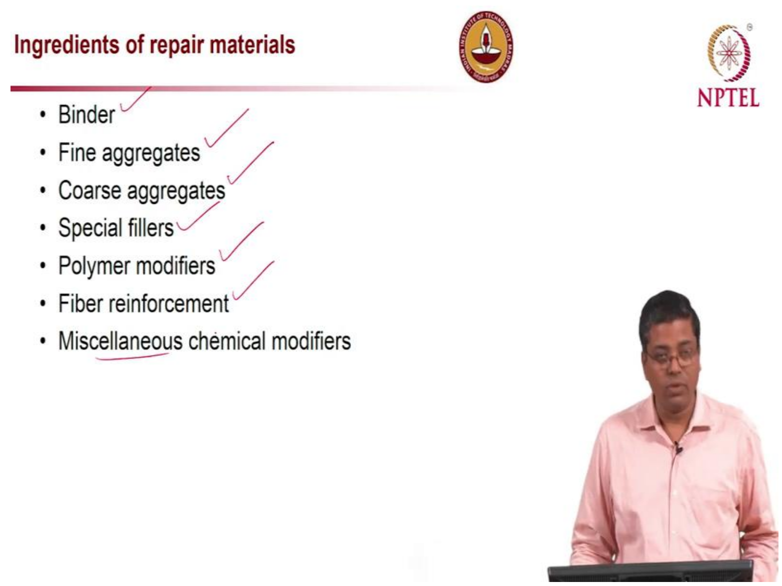

Now, let us also look at what are the different ingredients which you can observe in various repair materials available today, definitely there are binders it could be cementitious and polymeric binders also and depending on the need and the performance requirements and of course, you have fine aggregates and coarse aggregates and also some special fillers and then polymer modifiers and then fiber reinforcement and then some miscellaneous chemical modifiers. So, we will go through each one of these in at least one slide on each of these.

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So, let us talk about the binders definitely Portland cement is there and these kind of binders are which widely used in general repair or patch repair work where no special performance requirements are expected. However, if you are talking about special applications, where some chemical resistance or very thin application that means, where the high shrinkage resistance is expected in such cases you will see that the repair material will have epoxy or acrylics or some other polymers are used.

They are integrally mixed or integral part of the material. It is not like a coating or something which you provide but you are actually mixing these materials along with the cement powder.

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Sometimes the quantity will be significantly high in that case also. Now, fine aggregate this is a different type I mean this photo shows, what is the idea to reduce the amount of binder which is used and enhance mechanical and durability properties. We cannot skip durability in any cases it is very important. Now used without the addition of larger size aggregates in some cases, especially if you are talking about high flow requirements etc.,

Then you will see that the larger sized aggregates are sometimes avoided or only in small quantity. And this kind of fine aggregates; fine means it is not like a powder, but up to about 4.75 millimeter size. Sometimes we will also see coarse aggregates which are with a limiting range of about 8 mm we will still use, the idea is the smaller the aggregate size which is used comparing fine and coarse.

The flow properties will be influenced by the proportion of these aggregates and then especially for repair materials where flow is very important because you most often work with confined spaces or there are restrictions on space and the flow path etc., So, in such cases you need a material which flows very well and in such cases the smaller size aggregates are used.

Of course, the shape and gradation of aggregate will affect the compaction and special aggregates can be used. If you are talking about abrasion resistance that means harder aggregates and which will abrade less.

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Now, this is about coarse aggregate, last slide I also told sometimes we tend to avoid very large coarse aggregates a maximum size of up to about 6 to 8 mm is typically used for micro concrete or most of the screed concretes because you do not want very large aggregates, which will affect the flow and then costs more difficulties in placing the concrete. Now, idea here is again reduce the amount of binder which is used and enhance general mechanical and durability properties.

Because the quality of the aggregate is also very important. And when you talk about durability, the interface between the aggregate and the cement paste which plays a significant role, which we call ITZ (Interfacial Transition Zone) between the aggregate and the cement paste. So, the quality of aggregate is very important when you talk about durability. Durability of repair material is also important in addition to the mechanical properties.

More the aggregate you have, less the shrinkage and then special aggregates, if you are talking about abrasion resistance, then you have to use special aggregates which will have good resistance against abrasion.

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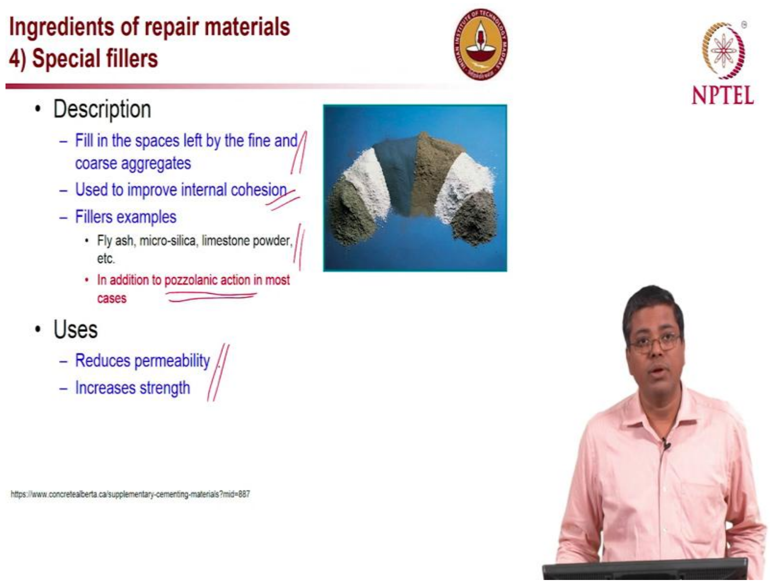

Now, special fillers, the main idea here is they fill the space left between the fine and coarse aggregates used to improve the internal cohesion. And the examples are, very fine powder, fly ash, micro silica or micro limestone powder. And one thing to note here, it is not that even though there are special fillers, they also might have a role in pozzolanic action and mostly the more important role and then they also function like a filler and then they enhance the permeability and the strength of the material.

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Now polymer modifiers examples are Latex, acrylic, polyvinyl acetate or PVA widely known name and also epoxy emulsions. And these materials again enhance various properties. Latex is used to reduce permeability that means it resists the entry of water into the concrete and then enhances the bond. One thing which I would say here is, we should not always go with, because the cost of these modifiers, depends varies significantly.

For example, acrylic might be, for example is very expensive sometimes and latex might be relatively cheaper. But again we should not go and select a material because sometimes we have a tendency, if a particular material cost more then probably that is better. That is the intuition sometimes, which we have. It is not always true. So, you have to really look at the bond mechanisms. Instead of looking at the cost of the material look at how the performance especially in long term.

If you are talking about using of this repair materials for an exterior element, you have to really look at how they perform under sunlight or UV exposure in long term, long term what I mean is at least multiple 2 to 3 years you should wait, you will say so, but what you do, you cannot really wait for long term. So, there are accelerated tests where we can prepare the specimens and then put it inside a chamber.

And which can be like, UV chamber and then test how fast the materials degrade or how resistant they are against the UV radiation, especially when you talk about polymeric materials we must do or check the effect of polymeric materials which are also exposed to sunlight, we must check how the UV resistance of those materials are and if they start degrading, you might lose the bond and at the same time, you might also lose the mechanical properties like modulus, strength, etc.

So that is something very important to check. The point here is higher the cost does not mean that the performance is also going to be better you might find a better performing material at a lower cost.

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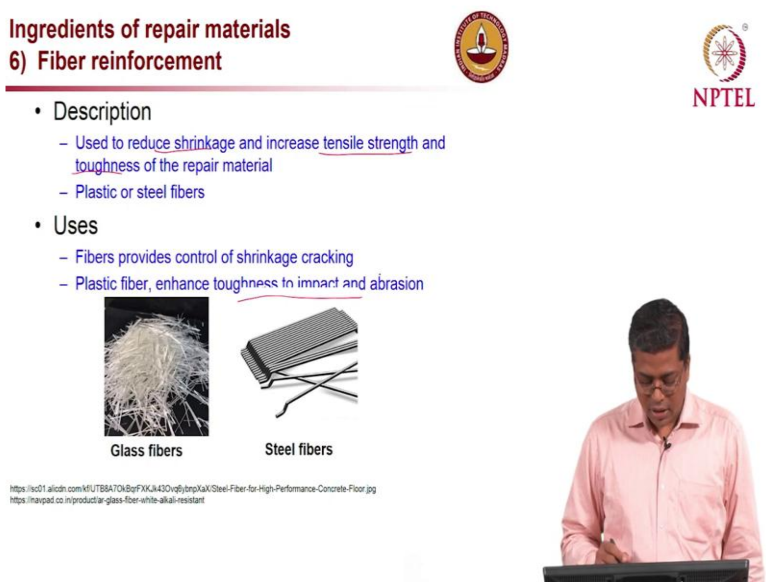

Now fibers also play a significant role in reducing plastic shrinkage especially and also they help in increasing the tensile strength and toughness of the repair material. Essentially, they help in controlling the crack. So, you can see here steel fibers, there is an impact of the fibers on both plastic shrinkage and it can also, positively affect or enhance the tensile strength and toughness of the concrete system.

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Now, miscellaneous or chemical modifiers this modifies various properties depending on the case what you are talking about. So, for example, you have accelerators, retarders, shrinkage compensating admixtures, water reducers, flow enhancing agents, expansive agents and air entraining admixtures all these different type of materials are available and they change various properties as desired.

You should have all these materials, but depending on the necessity, you have to choose, so that is where the point is, we need to know exactly what we want, when you talk about a repair material. Otherwise, many cases are there where unwanted chemicals are also added and then just increase the cost of the repair. So the engineers must be like I said in the last class engineers must be able to dictate what is required or what properties are required for the materials which they use.

Not the people who sell these products should dictate on what to do, engineers should be able to tell and they provide what is required, they will tailor make the product and provide it.

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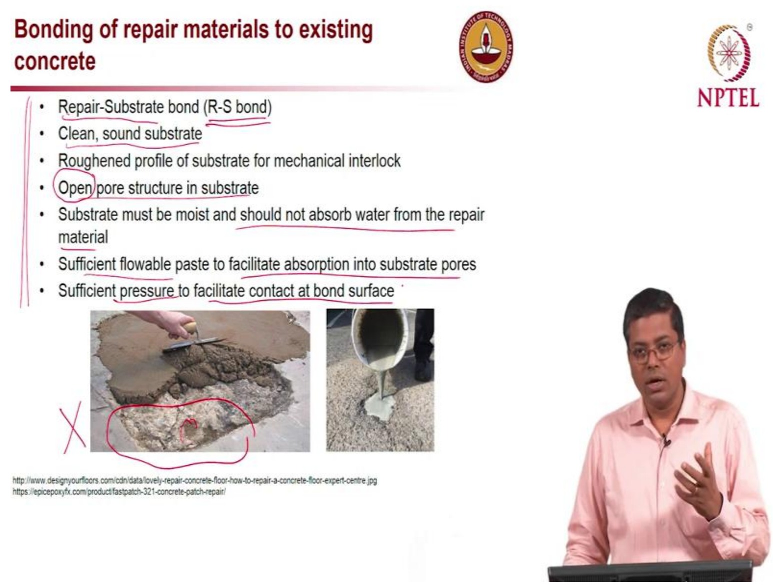

Now, bonding of repair materials to existing concrete, what are the important things to consider when we talk about bonding? So, I am going to call the bond is between the repair material and the substrate. So, we are going to call it RS bond, because there is also another bond which is steel concrete bond so, I do not want to confuse between the two. So, in this lecture when we talk about bond it is the bond between repair and substrate concrete.

Now, the clean and sound substrate, the surface preparation means where you are going to place the repair material that surface should be very clean that means no free or loose particles should be there. I put this picture here just to show you that, this is not something which is a good practice, you can see that there is a lot of dirt or loose materials present in this. The surface is not well prepared.

So that is something which is not good and also here you can see it is very dry substrate. So, what will happen is the moisture which is available in the repair material will be absorbed by the substrate. As soon as it comes in contact, which is not a good idea rather what we should do is, we should make the substrate surface in saturated surface dry condition or SSD condition. Not too much of water but at the same time, not too less water.

So that there will be no absorption of moisture from the repair material to the substrate that is something which we should not allow. Now, open pore structure in the substrate is available. Because if it is available then it provides better interlocking, I am saying open pore structure. It is not the pore structure inside the substrate.

But at the surface of the substrate you need to have uneven surface so that there will be good interlocking or roughened profile for mechanical interlocking and also the sufficient flowability, the repair material should have sufficient paste which can flow and facilitate absorption into the pores, the open pores in the substrate. And also when you apply the material we should provide sufficient pressure.

So that it helps in making good contact at the bond surface all these small pores available, either the material flows and reaches there or if it is relatively dry repair material, then you should pack it very well or compact it very well. So that the mechanical interlock between the substrate and the repair material is very good.

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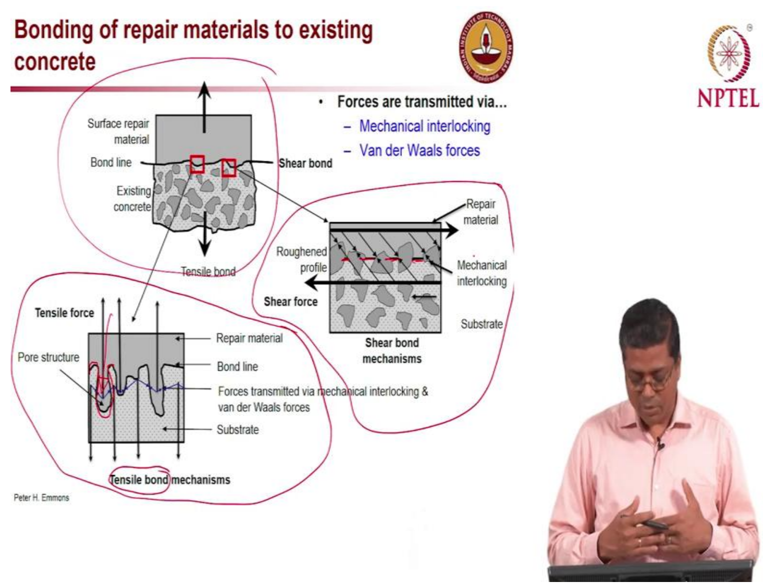

I will show this is the detailed image showing what I just discussed. You can see here, first image to look at and which is generally that bond region and you see 2 red boxes there. So, that is my larger zoomed image of this first red box is this, which is basically talking about the tensile bond mechanism. You can see here there are some regions where basically it ensures mechanical interlock in the perpendicular direction to the bond line or you are talking about tensile forces here and the tension bond mechanisms.

You can see here there is a nice interlock happening here bulb like repair material. The repair material flows into the open pores. So the open pore which we discussed in the previous slide is this, this is an open pore here. And so the repair material goes in and fills inside and then it then hardens and then it is very difficult to pull it out of that.

So, definitely there is a good resistance against the tensile forces. And similarly, when you talk about the shear bond, which is this sketch here, you can see that bond line. It is crossed by the aggregates. So, if you have sufficient amount of aggregate of reasonably large size, then you will get very good resistance because aggregates will provide a good resistance against the shear or they have good shear resistance.

So that when aggregates come on that path, the red line which I have drawn they provide very good mechanical interlocking and it helps in providing much better shear resistance.

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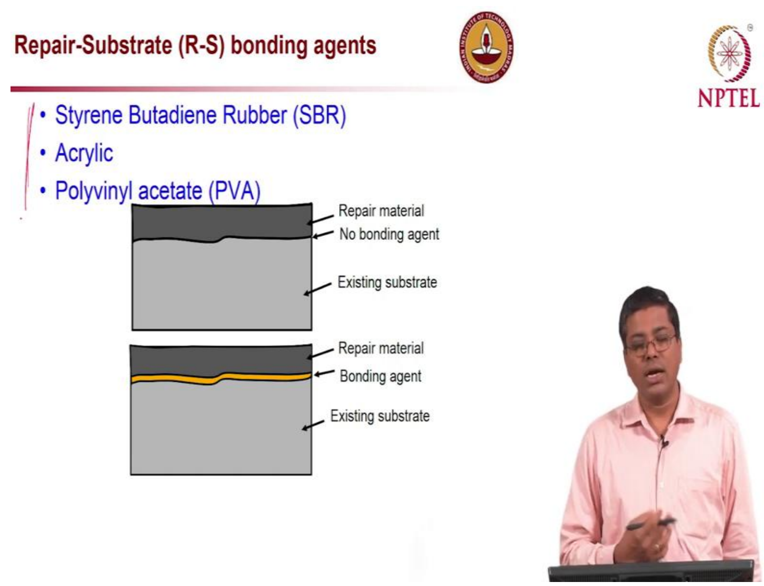

Now, as we discussed, these are the 3 widely used repair bonding agents available when you apply this bonding agent they also helps in chemical bonding. That is also something important it is not always only mechanical interlock but chemical bond, if the good adhesives are there, that is essentially the bonding agent that will also help in enhancing the bond behavior.

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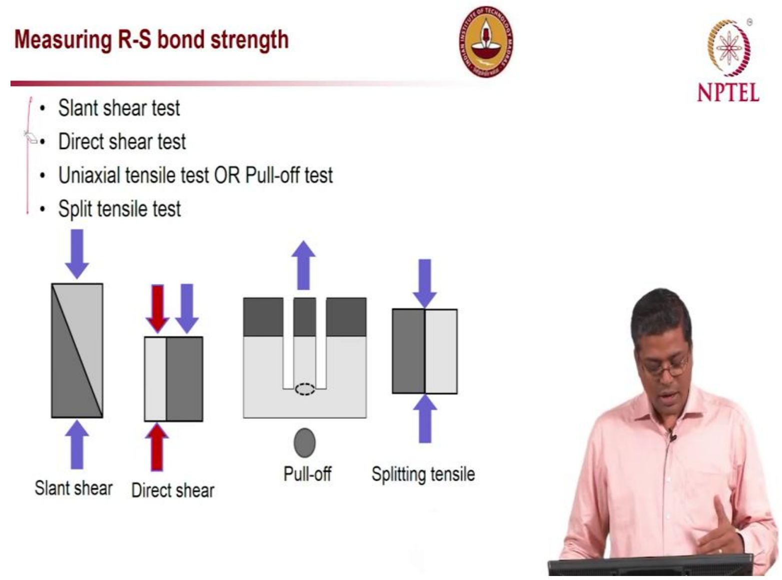

There are a lot of materials available for performing repair work. And then one main requirement is that there should be very good resistance against the bond failure or the bond strength of the repair material. The bond strength of the interface between the repair material and the substrate should be very high and how can we check them these are 4 typical tests available slant shear test, direct shear test, uniaxial tensile test or pull off test and the split tensile test is a just schematic diagram. I am going to show you the schematic again and we are going to discuss more detail on each of these tests.

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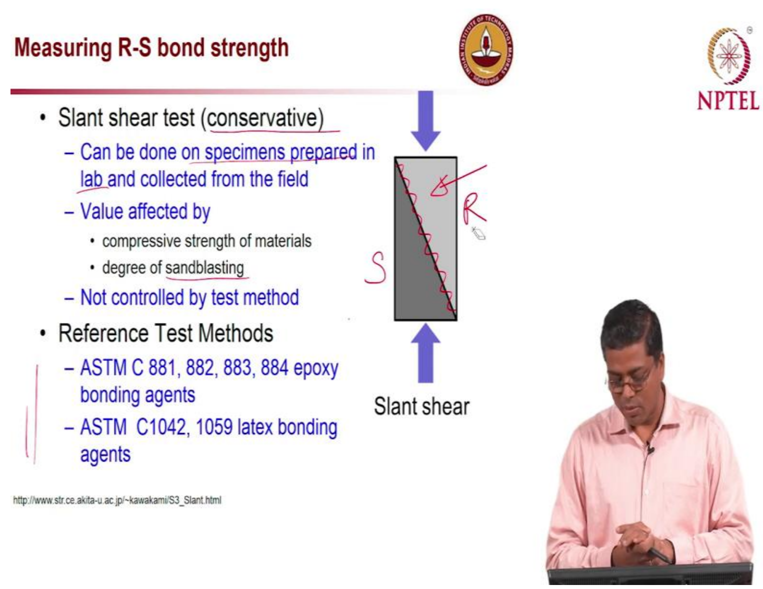

Slant shear test. It gives relatively most of the time a conservative result and how it can be done on specimens prepared in lab and also those core specimens which are collected from the field and then what we can do is you take the substrate and then cut the core and then replace that top part with the repair material and you actually roughened this surface here.

You know, how do we roughen that surface, there are ways best thing is by sandblasting or in other words, using some grits you can spray the grit onto the surface and then roughen the surface and sometimes we have also seen people actually chiseling the surface, but that may not be a good idea all the time. Because when you chisel, this is my opinion.

I have observed this in some of the specimens when you chisel you think you are actually roughening the surface in a macro level may be it is true, you will have uneven surface depending on the size of the chisel. But when you really look closer in a millimeter scale, then you can say or even smaller scale, maybe the powder which is coming at the time of chiseling we get, the powder will fill this open pores available on the surface, which is probably not something good.

But at the same time when I say this, if the real practice at site is also by chiseling, then you do or follow the same practice for making the test specimen that is very important you don't want to recommend chiseling in the field and then do a much better practice in the lab to test. So, that preparation of the substrate is this and this is the repair material here.

So, the surface preparation like the preparation of the specimen is very important in this particular case the entire test results depend on how rough the interface is. So, if you want to really see what is actually happening at the site, prepare the surface of the substrate concrete in the same way as you will practice in the field and then you can say in such case how the system behaves and these are the reference test methods available.

So, let me just say this once more, you can take a core from the field and then cut diagonal along that core specimen or a cylinder specimen and replace one half, the top triangle in this slide in the sketch, replace that with the repair material. You can use the same cylindrical mold to cast the specimen and do this test.

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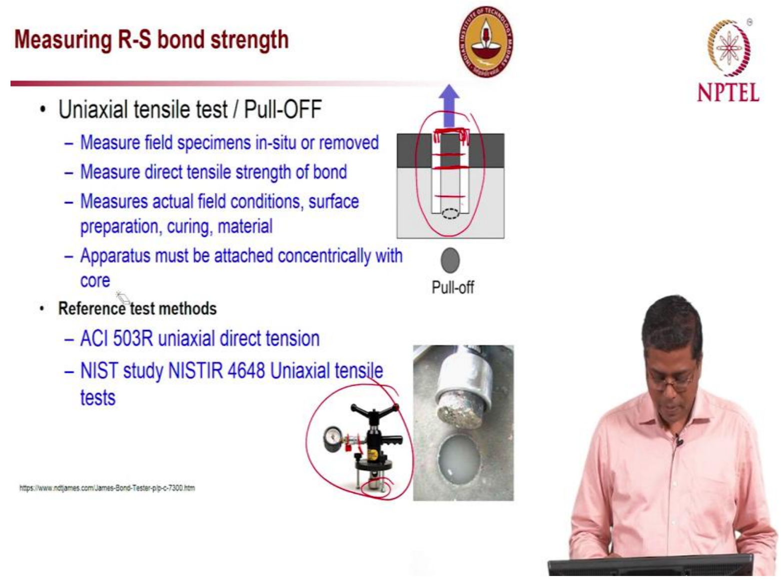

And then another way is on site if you want to test something without really taking a specimen to the lab and all that. This is nice equipment available. So, uniaxial tensile test or pull off test can be conducted on field specimens directly in the field itself, where you can actually connect this; you can see the instrument here, you can connect this, the bottom portion that hold on to the concrete surface or the surface of the repair material.

And thus essentially you are doing a tensile test like this. So, you take a core and then connect this, the holder on to here you will hold. You can see here like that and then you pull the cylinder prepared and if the cylinder is failing here at the bond line, then you can say the bond strength is not good. I mean, you can actually assess what is the bond strength.

And if it is failing here, then you can say the bond and the material repair material is very good, actually the substrate is weaker and if it is failing here then you can say that the bond material itself has a lower tensile strength than the RS bond, bond line and also the substrate. So, you can make a lot of meanings out of this test. Because it is done actually on the site, it really tells you what is actually affecting? Or what is the real behavior of the system in field structures?

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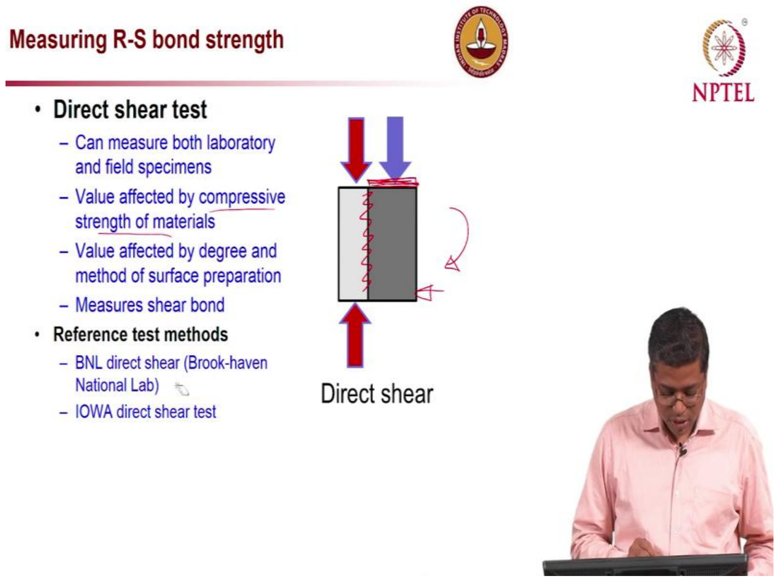

Now, direct shear test, where you prepare a specimen and then you see as shown in the sketch here the red arrows on the left side is holding the substrate in place and typically there will be a plate here and then you apply a load on to the repair material and you enforce the material to experience direct shear failure along this plane here. So, this is a very good test again to do typically in the laboratory and also on the field specimens.

But, you have to see for the case by case which is good and affected by the compressive strength of both the materials because, depending on the size, there could be some other actions also coming like this. There will be compression happening here. So, those factors are also there. That is why it is not widely used test method because of these other mechanisms which will affect the test results. It is not very easy to do this test.

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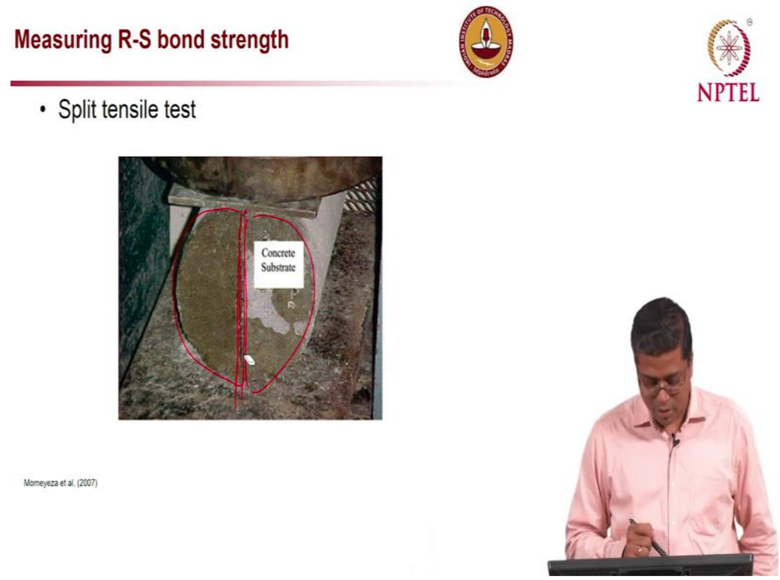

And also there is a split tensile test, this is a photograph showing one half of the cylinder is a repair material and the other half is the concrete substrate. And just like the typical split tensile test, there is no difference between the tests you do exactly. You take a cylinder, which has both concrete substrate and repair material.

Make sure that the surface or the interface between the repair material and the concrete surface is perpendicular or it is just like this, it is in the same plane as the load is applied. Otherwise, if the cylinder is slightly rotated, then you may not be actually doing a right test. So, that is something important precaution to be taken while doing this test.

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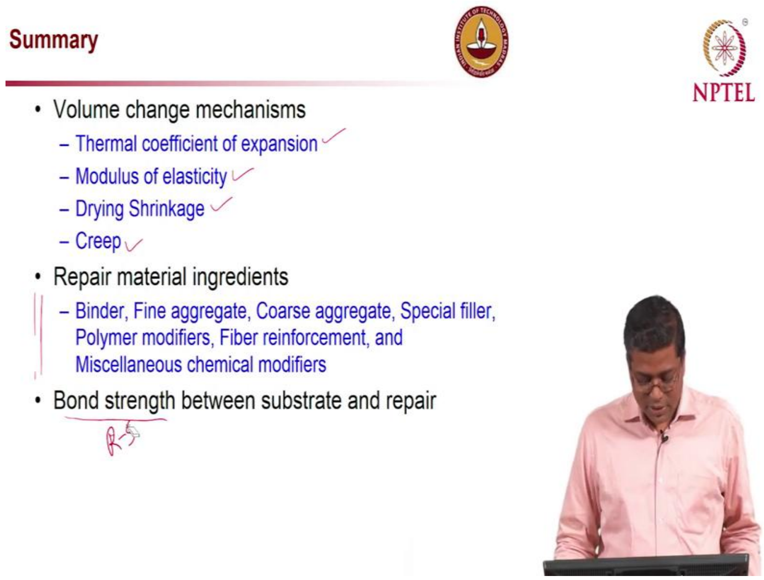

Now, to summarize, in this lecture, we looked at various volume change mechanisms, we summarized about how the coefficient of thermal expansion, modulus of elasticity, drying shrinkage and creep coefficient etc., can really influence the behavior of the structure and why it is important to keep these also at a minimum level, especially the coefficient of thermal expansion, drying shrinkage and creep.

And modulus of all these should be comparable with that of the substrate or the existing concrete element. If you have difference between these properties; if there are difference between the substrate and the repair material, then that will induce a lot of issues or the changes in the volume of the repair and concrete substrate and that will induce shear stresses at the interface which may have additional problems.

We also looked at what are the ingredients, typical ingredients for repair materials and how these ingredients affect various properties and what are the qualities and how do we select these ingredients what are the key properties, how they affect the material behavior also and then finally, we looked at the bond strength and how they can be tested, bond strength between the substrate and the repair.

We talked about RS bond, repair material and substrate not the steel concrete bond in this lecture that is not the point. So, how it can be tested both in the field and in the laboratory and which can help in ensuring good performance over the long period and make sure that you prepare bond strength test specimens, you follow what is actually happening at site and similar practices and then do the test for this lecture.

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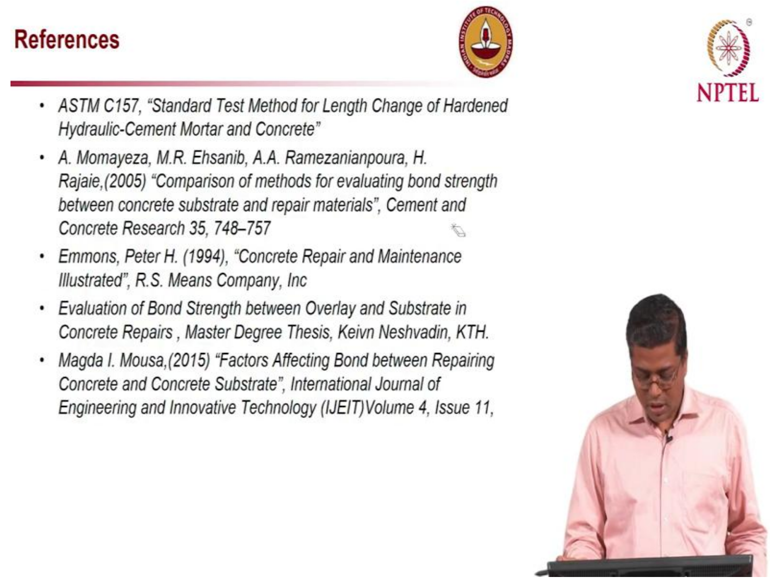

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And thank you that ends this module.