Concrete Engineering and Technology
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Lecture - 29
Using FRP as reinforcement in concrete structures (Part 1 of 2)

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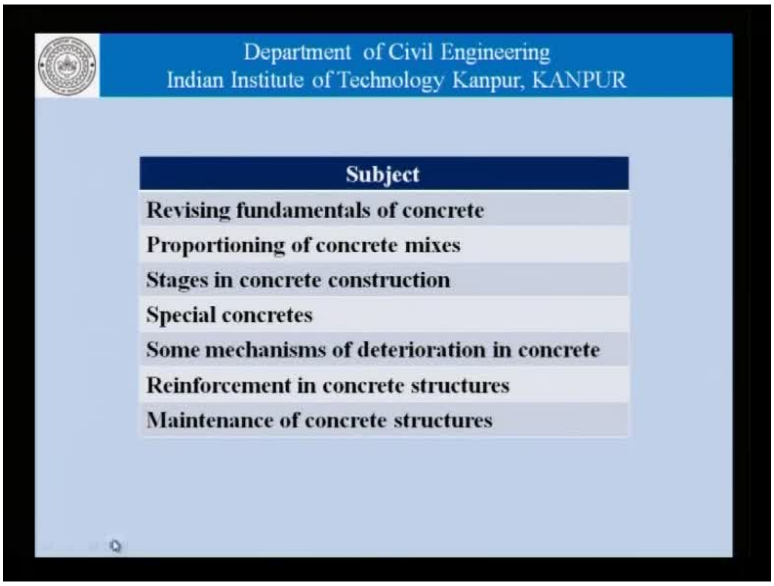

Namaskar and welcome back to this lecture series on concrete engineering and technology, where we are trying to go through fundamentals of concretes, proportioning mixes, stages in concrete constructions, special concretes, mechanisms of deterioration, reinforcement in concrete structures and maintenance.

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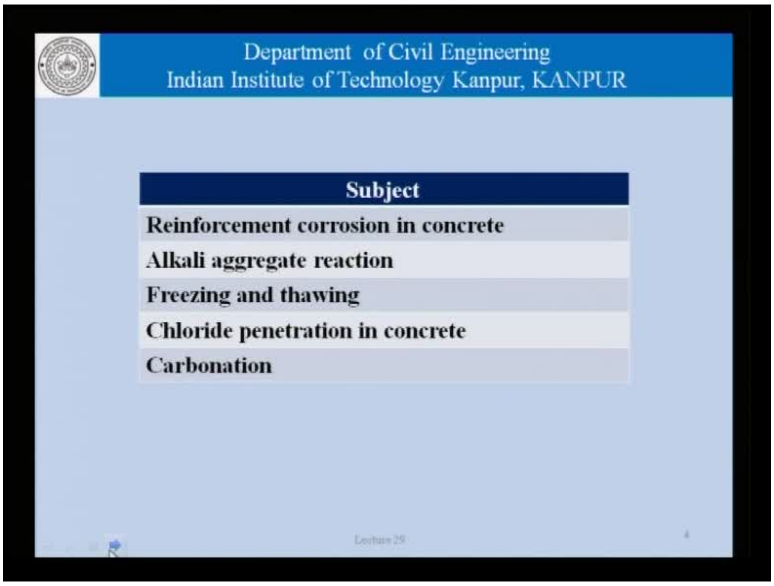

Now we have talked about some of the mechanisms of deterioration that we see in concrete structures. Some of those are listed here reinforcement corrosion alkali aggregate reaction, freezing and thawing, chloride penetration in concrete, carbonation and both these being the reasons for reinforcement corrosion.

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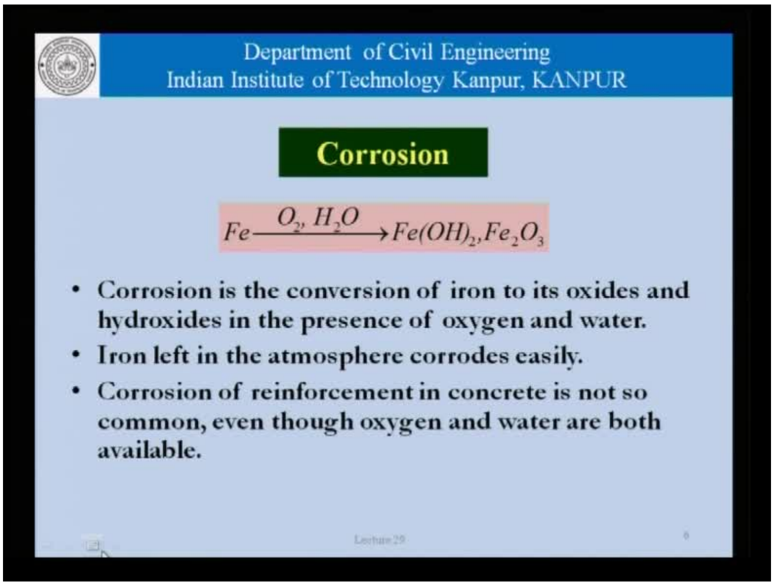

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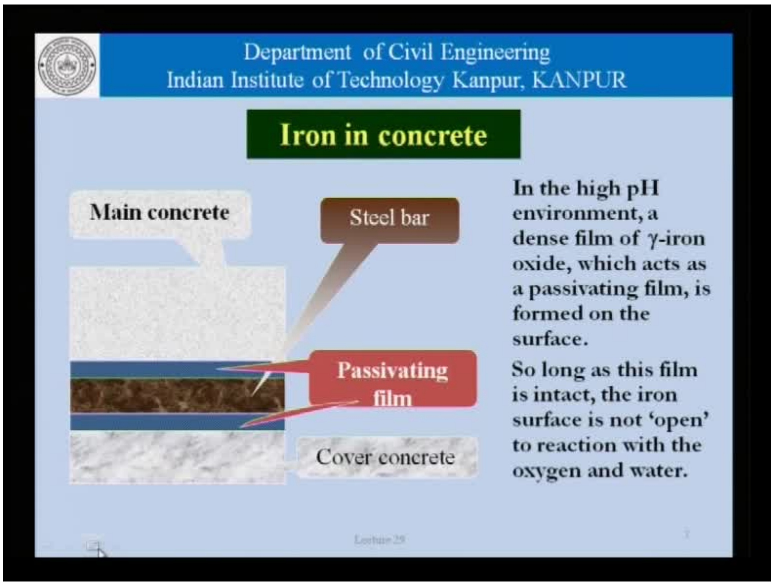

Now, as far as reinforcement corrosion is concerned we have studied that corrosion basically involves the conversion of iron to its oxides and hydroxides in the presence of oxygen and water. We know that iron corrodes easily in the atmosphere and that the corrosion of reinforcement in concrete is not so common, even though oxygen and water are available in plenty. And this slide really shows a mechanism that has been modeled to explain corrosion and concrete structures. So, we have this passivating film which forms all the reinforcing bars as a result of the high p H resulting from the formation of large amounts of calcium hydroxide in the system which is due to the hydration of cements. And so long as this passivating film is intact, the oxygen and water that may be present in the neighborhood does not cause corrosion of the bar, because the steel and the oxygen and water are not really in contact.

So that is what our understanding of concrete is and once this passivating film is damaged and so on or it becomes thermodynamically unstable. The steel bar is rendered to or it is destabilized on account of reducing of the p H as it is happens in the case of carbonation, the bar is rendered susceptible to corrosion.

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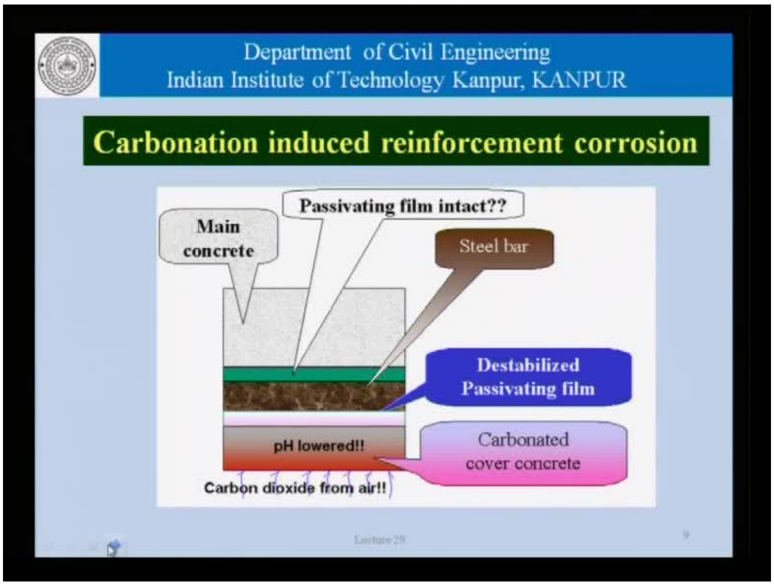

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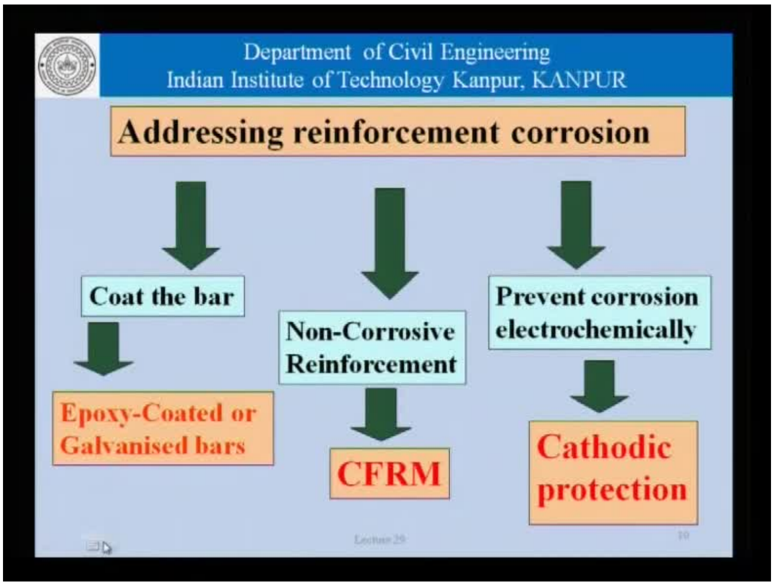

So, in a nutshell corrosion is something which is likely to happen in any case. So, there are different strategies that are listed here that can be adopted to address the problem of reinforcement corrosion. One of them is coat the bar and that is something which we do when we have the epoxy coated bars. The other is to use noncorrosive reinforcement, all together something that does not get affected by the oxygen and water or the chlorides carbon dioxide and so on does not cause corrosion, does not simply corrode. And that is where we have CFRM or continuously reinforced fiber material. Sometimes it is also call FRP or the fiber reinforces plastics. Then of course, we have the possibility of preventing corrosion electrochemically and that happens. For example, in pipelines and other structures and one of the strategy is that is adopted or that can be adopted is cathodic protection.

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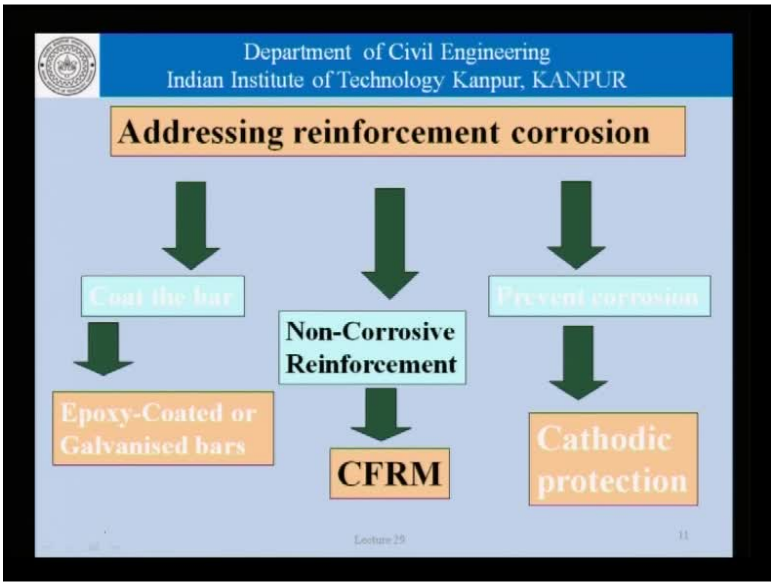

Now, as far as our discussion today is concerned it largely focuses on non corrosive reinforcement that is use of CFRM that is continuous fiber reinforced materials.

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Now, let us first examine what is the basic idea of these materials as far as application is concerned it was the age old Egyptians, another Asians civilization where they used straw in clay construction. And that probably can be seen as the first use of fibers. As far as construction materials is concerned of course, now we are used extensively in the aerospace industry, sporting goods, automotive industry, and beginning to be use now in the construction industry and concrete.

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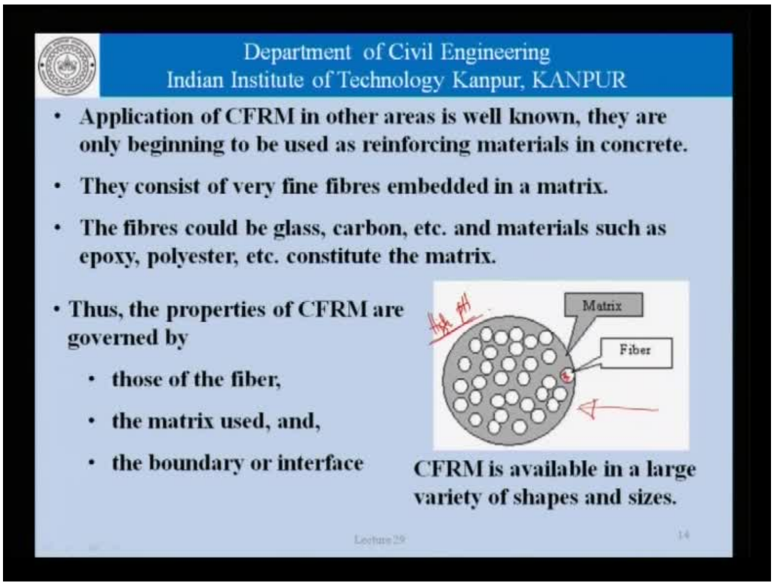

This picture shows a very simplified example of CFRM or continuous fiber reinforced material. What we have is these small fibers which are embedded in a matrix. And depending on what is the fiber, what is the matrix, what is the amount of fiber and so on? We have different properties that can be used to our advantage as far as our construction material is concerned.

So, as I stated here the CFRM consist of very fine fibers embedded in a matrix, the fibers could be glass, fiber etcetera. And the materials such as epoxy polyester and others constitute the matrix. And thus the properties of the CFRM as they stand would be governed by those of the fiber the matrix used. And the boundary or the interface as such once we use the CFRM, we must remember that as far as concrete is concerned or as far as the application of CFRM in concrete is concerned this CFRM which is shown here will be embedded in an environment which is high p H same as concrete, because that is what is going to be embedded in concrete. Another thing we should remember is that this should bound with concrete, if it is required to be bonded. For example, reinforce concrete most of the time; we would assume that there is a good bond between the reinforcing material and the surrounding concrete. So, the bound between the CFRM and the surrounding concrete is also of consequent to us in certain cases when we have unbounded construction, of course we do not really care about the bound so much.

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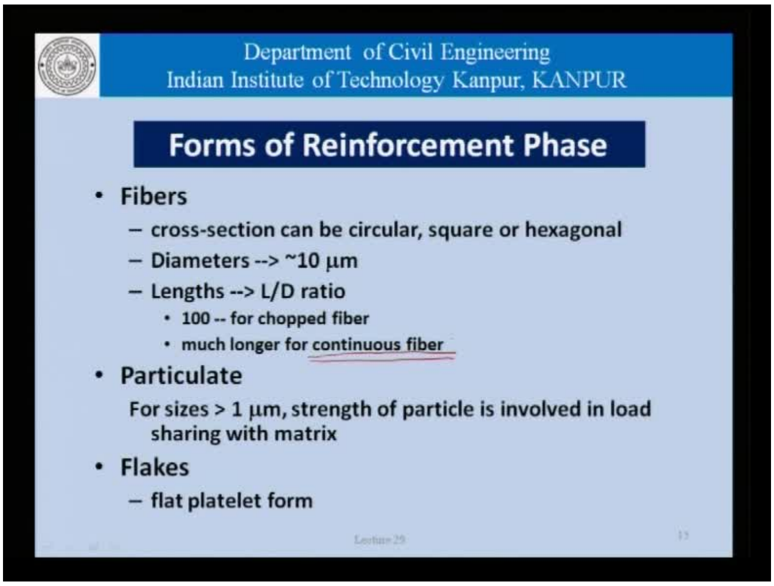

Continuing our discussion as far as the reinforcement is concerned in the CFRM it could be in the form of fibers which is cross section could be circular square or hexagonal. The diameters are very small of the order of about 10 micrometers. And then there is the length of these fibers and sometimes we talk in terms of the length as a relation to the diameter and l by d. The aspect ratio of the fibers is sometimes used in the literature and it is about 100 for chopped fibers or shot fibers that we use in fiber reinforced concretes and it is much longer for continuous fibers. So today’s discussion, we will focus on the continuous fibers of course, other than fibers the reinforcement could also be in the form of particulates which may have more than 1 micrometer size. The strength of particle is involved in load sharing with the matrix or in the form of flakes which are platelets.

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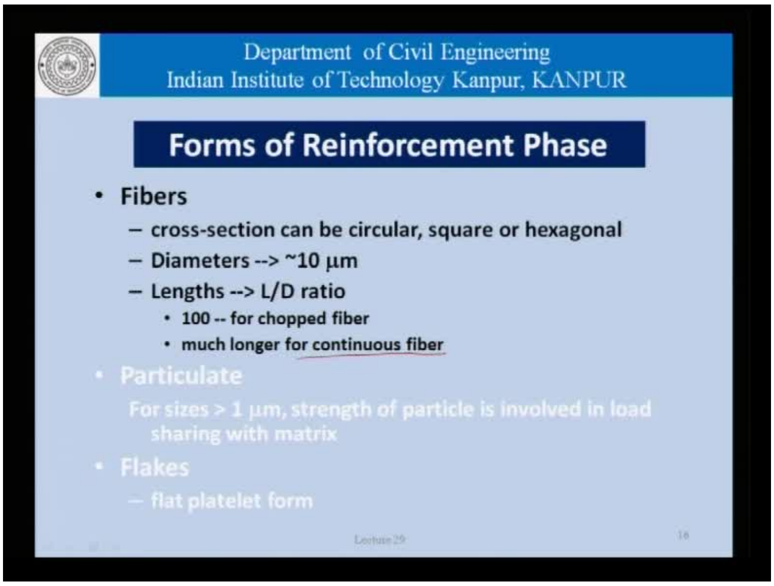

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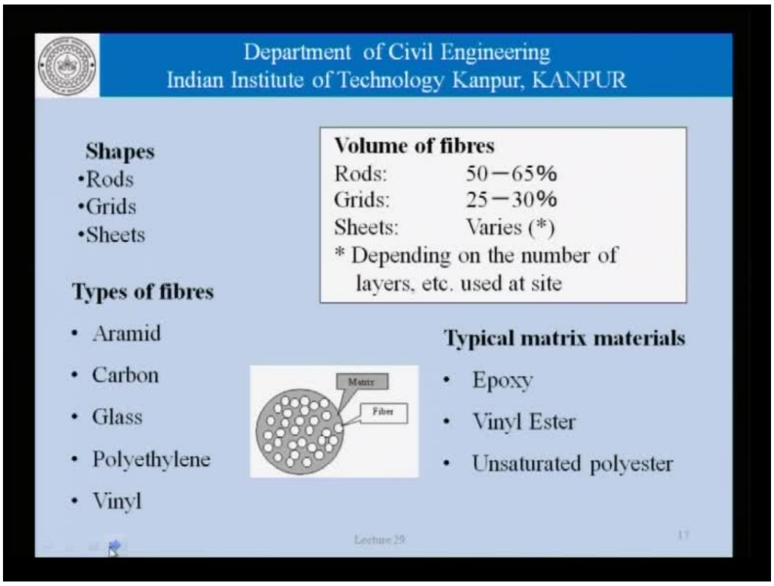

But we would be concerned today will be fibers and more particularly the continuous long fibers as we have talked about. Once again if we go back well before we go in to the discussion of the different kind of fibers, and the different products that I have made in a useful construction industry particular concrete industry. Let me show you some fibers and some products this here is glass fiber strands I hope you can make out the extremely fine long strands of the glass fiber. Now these fibers of flax can be woven into a clock which is shown here for this is a cloth made of the same glass fibers. And you can see that this cloth is woven in both directions that is in this direction as well as in this direction.

Similarly, instead of glass fibers we can take carbon fibers and these carbon fibers are black in color, and this is a unidirectional fabric made out of carbon fibers. So, the fibers are only in one direction likewise we can have a woven fabric made of carbon fibers like the one that we saw that glass fibers. And this again has long continuous fibers in both the directions. This here is a different kind of a mat and the fibers in this mat are carbon fibers which are oriented randomly. So, this is a randomly oriented carbon fiber mat, the part from glass and carbon fibers, we sometime use what is called aramid or kevlar fibers. And this is a fabric which is woven out of aramid or kevlar fibers.

So, in all these fibers or in all these fabrics we can see these extremely small few micrometer kinds of fibers which are woven into fabrics. Now having seen some of the fibers and the bar and the laminate I think we have a better idea as towards CFRM is all about. And how it can be used as a reinforcing material as far as concrete is concerned.

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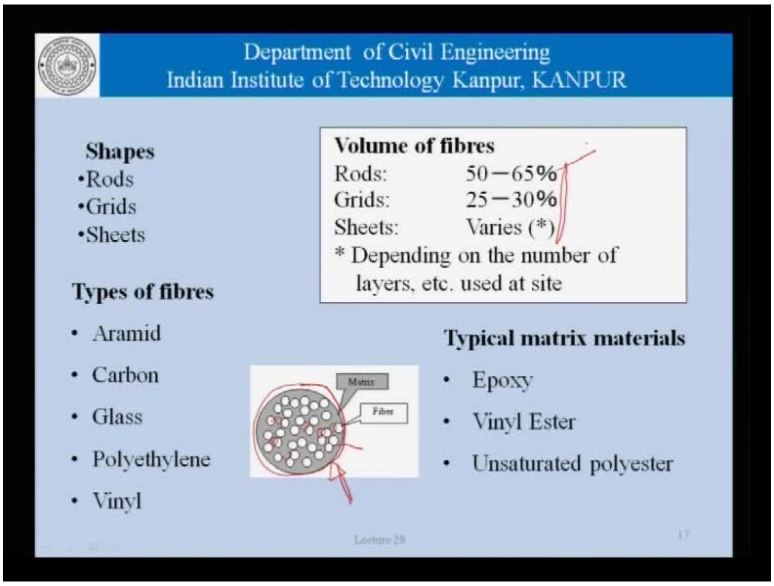

So we have seen that as far as shapes is concerned the CFRM can be in the form of rods grids or sheets or fabrics the types of fibers it could be aramid, carbon, glass, polyethylene, vinyl and so on and so forth. And the typical matrix materials we did not discuss the matrix materials so far could be epoxy, vinyl ester or unsaturated polyester. The bottom one remaining that the CFRM basically have this structure that is very fine fibers embedded in a matrix. And finally, giving a product which is of this nature, which could be a rod or it could be a flat or a laminate or a fabric.

Now, the most interesting part of the CFRM is that the volume of fibers can be varied. Now, if we vary the volume of these fibers here, we can vary the properties of the material putting it the other way round. If we want a certain property in the fiber reinforced material or we want the certain property in the CFRM we can design the CFRM by changing the volume of fibers apart from of course, the material of the fibers and so on. So that gives us a lot of flexibility as far as the design and the construction of CFRM is concerned, as far as the application of CFRM in the construction industry is concerned. And as far as rod is concerned the normal volume of fibers is about 50 to 60 percent grids it is about to 25 to 30 percent. And in sheet it varies depending on the number of layers which are used at site.

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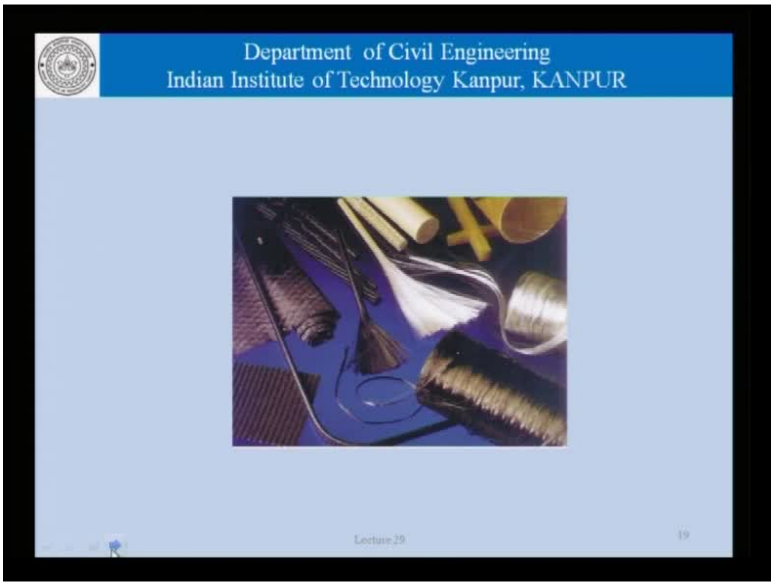

So, as we can see for example, in the case of sheets or fabrics they can be used in several layers. And if they are used in several layers; obviously, the volume content could depend on the number of sheets. So, this flexibility that we get of varying the fiber volume gives us a large advantage, as far as the use of CFRM is concerned in concrete construction.

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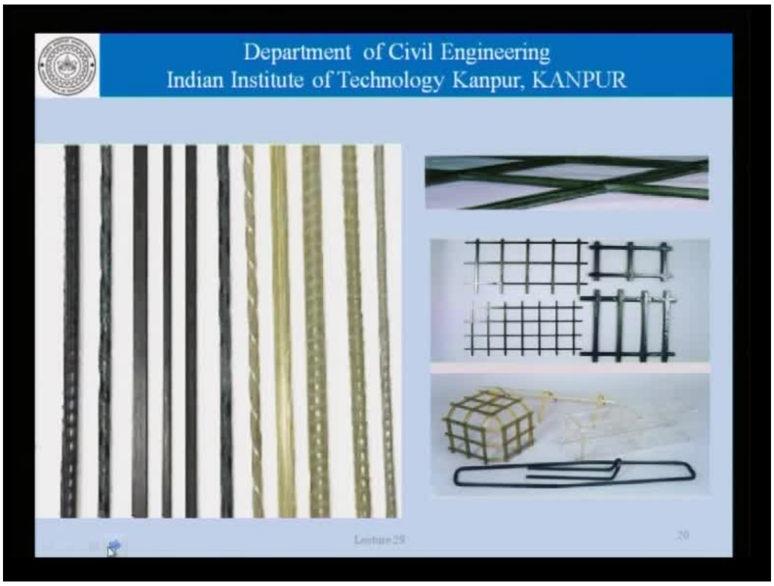

So, let us continue our discussion and try to see, what are the forms that are possible? These are the fine fibers of glass, carbon or aramid that we have already seen. These are some of the pictures of the different forms they are available in grids like this they are also available in 3d formats like this or a grid something which is like shown here and bars which are shown in this picture here. You may like to also notice that because in reinforce concrete construction we need to have the bound between the reinforcing material in the surrounding concrete.

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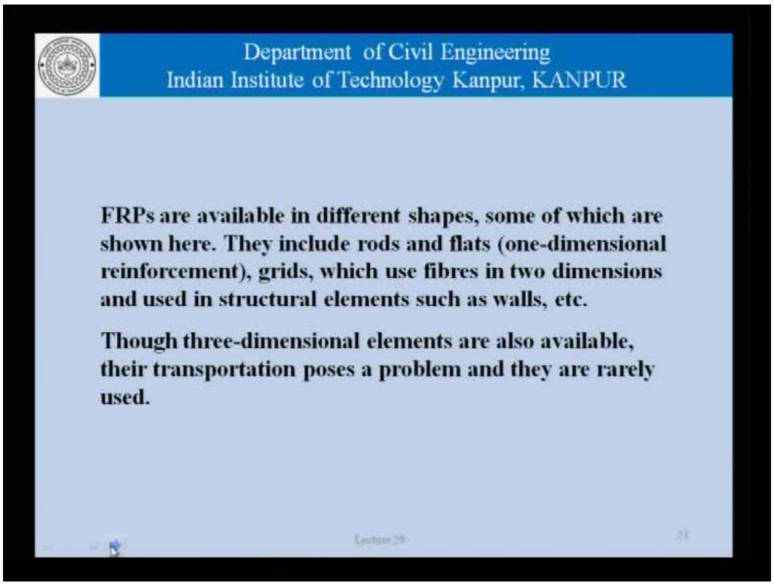

Some of these rods have especially designed ribs on the surface to increase the bound much like we have in the case of reinforcing steel, in the case of flats or strips. Of course, we may not have those bounds, because the purpose of using them in concrete for quite different.

Now to summarize FRPs are available in different shapes some of which are shown in the previous slides. They include rods and flats which may have one dimensional reinforcement grids which use fibers in two dimensions and they are used in structural elements such as walls and so on. Though three-dimensional elements are also available their transportation poses a problem. And they are rarely used.

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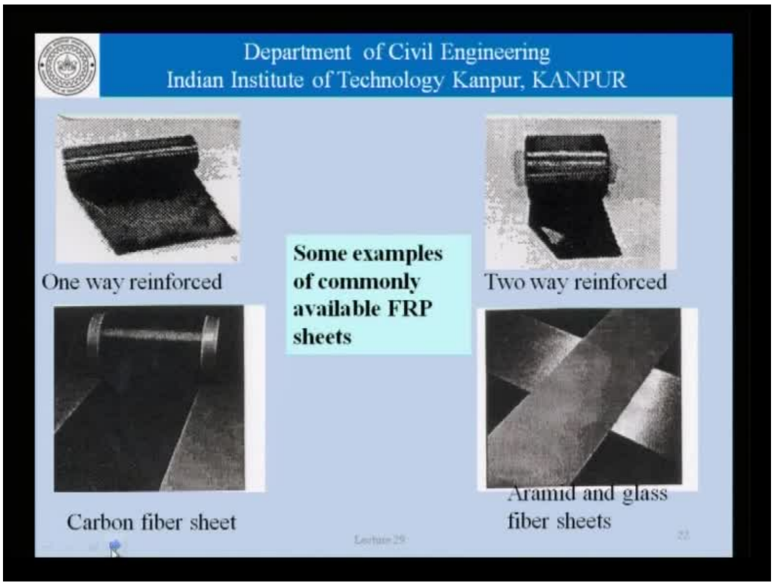

This here are pictures of one way or two way reinforced fabrics or sheets made of FRP, that is fiber reinforced plastics that is just another name for the continuously reinforced fiber material that is CFRM.

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Now, the basic properties of the CFRM are or can be summarizes given here that non corrosive. And therefore, they can be used in places where normal steel is susceptible to corrosion and deterioration. And we cannot expect or we cannot allow that corrosion, because of the criticality of the structure or any other reason they are much lighter.

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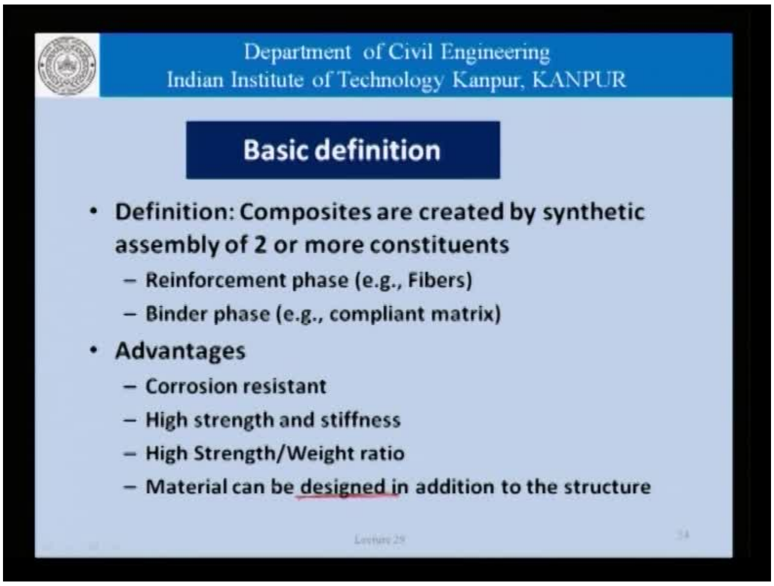

They are much lighter to steel having a specific gravity for 1.3 to 2.7 and specific gravity of steel we know it is about 7.8. So that makes it about one fourth or may be even less sometimes of steel. They have high tensile strength and with the higher tensile strength then steel, they become very useful for being applied as tendons in pre stressed concrete constructions. In some other applications, we use the fact that the FRPs are non magnetic in nature. So in examples like this property is useful in places such as MRI chambers and so on where we do not want magnetic materials in the neighborhood of certain equipment sometimes we also use their properties against microwaves.

So, we have these special applications for use of CFRM in normal civil engineering construction using concrete. And this slides is again just a recapitulations of what we have done the composites are synthetic assembly of 2 or more constraints comprising of the fiber phase which is the reinforcement and the matrix they having the advantage of being corrosion resistance, high strength and stiffness, high strength to weight ratio. And the material can be designed in, in addition to the structures so it is the… We are familiar with the concepts of structural design, but use of CFRM gives us the flexibility of actually designing the material itself by varying the fiber content and the material.

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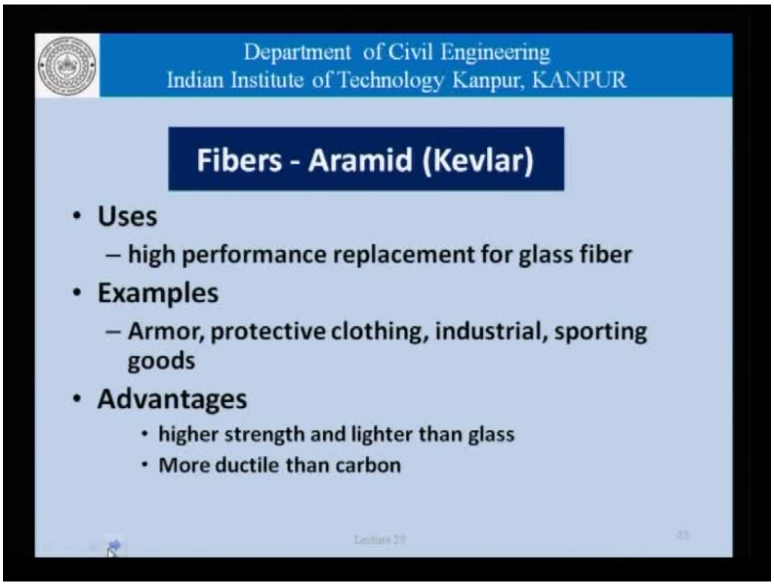

Now, let us take a look at some of the fibers and the matrices and their properties. As far as aramid is concerned it is a high performance replacement for glass fibers, examples could be in armor, protective clothing, industrial and sporting goods. It has the advantages of high strength and the fact that it is lighter than glass; it is more ductile than carbon.

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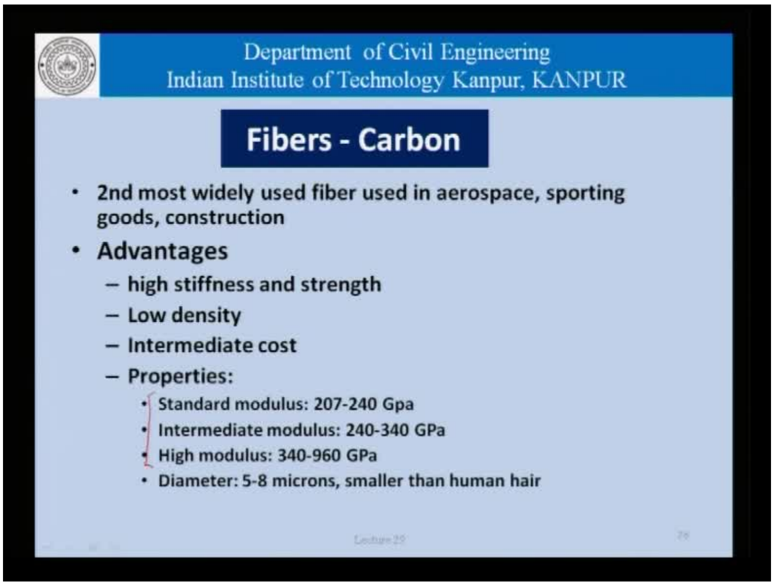

Coming to carbon fibers it is a second most widely used fiber used extensively in the aerospace, sporting goods and the construction industry with the advantages being high stiffness and strength, low density, intermediate cost and as standard modulus of 207 to 240 Gpa, intermediate modulus to 240 to 340 Gpa and high modulus 340 to 950 Gpa. So, basically carbon fibers give us the flexibility of choosing one or the other depending on what the stiffness? We want the diameters is about 5 to 8t micron which is smaller than human hair.

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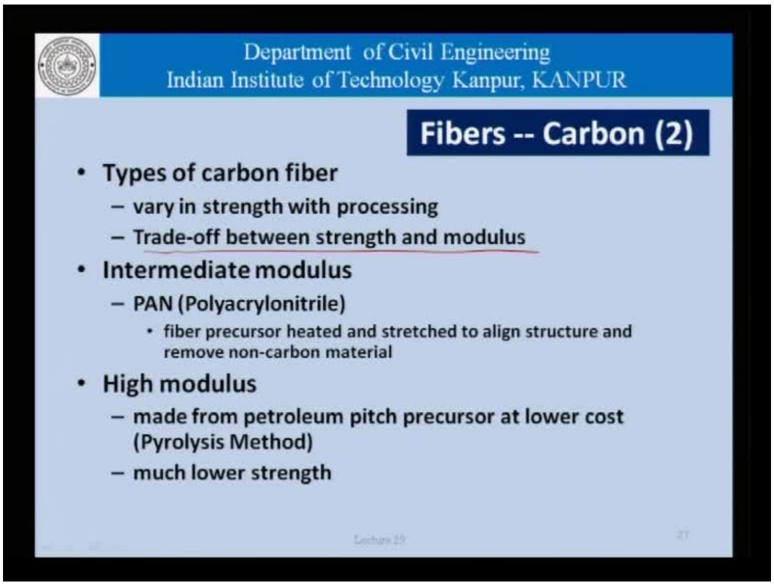

Continuing with our discussion on fibers or carbon fibers they vary in strength with processing. And there is a tradeoff between strength and the modulus elasticity for the intermediate modulus carbon fibers we have the pan or the polyacrylonitrile fibers in the case of pan, the fiber is precursor heated and stretched to align the structure and remove non carbon material from there. And in the case of high modulus material it is made from petroleum pitch precursors at low cost. And pyrolysis method is the one that is used it has the much lower strength, but high in modulus. So that is what we talk of when we talk of this tradeoff between strength and modulus.

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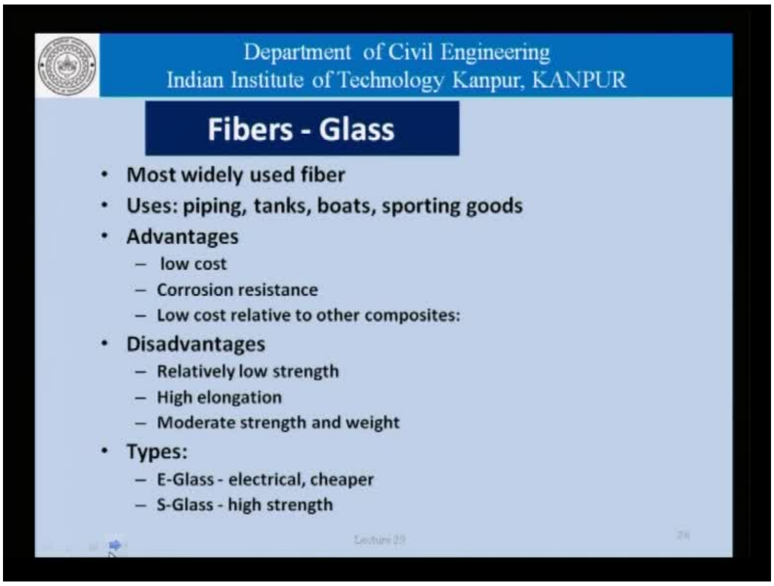

As far as glass fibers are concerned, they are most widely used fibers used in piping tanks boats and sporting goods. And have the advantage of low cast, corrosion resistance, low cast compared to other composites. But it has a disadvantage that they are relatively low strength, have a high elongation and have only moderate strength and weight.

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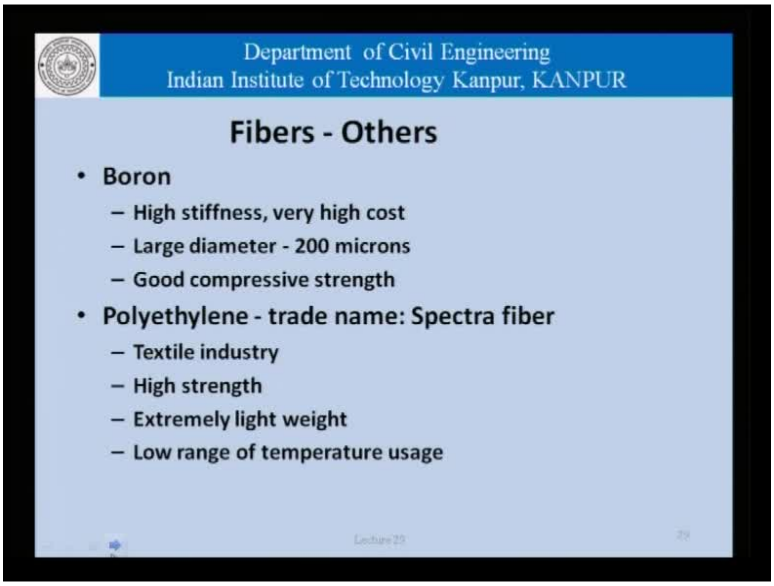

We have E glass and S glass fibers and they have slightly different properties. And one has to choose the fiber depending on the application that we have. As far as other fibers are concerned than glass carbon or aramid we have boron fibers which are high stiffness. But very high cast large, they have much larger diameters of about 200 microns, they have a good strength. Then we have of course, polyethylene fibers which are used from the textile industry have high strength, very light weight. But they have the disadvantages, as far as we are concerned in construction that the range of temperature over which they can be used is quite small.

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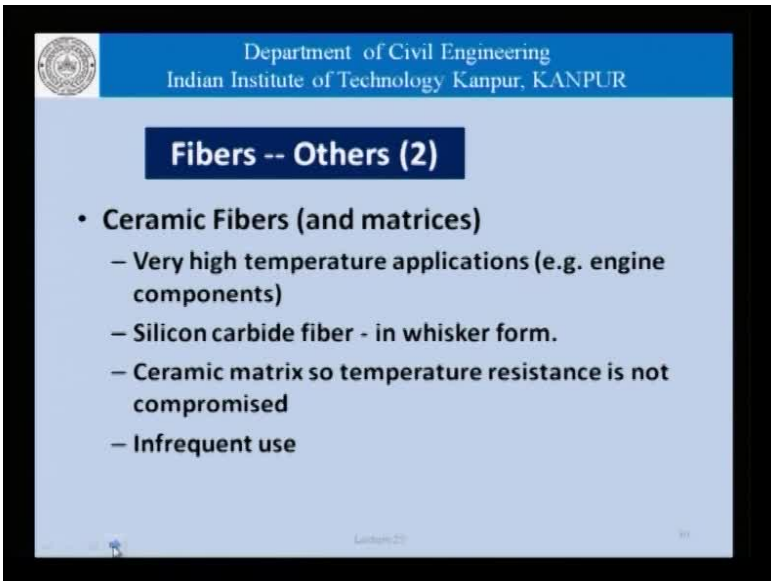

Other than these, we also have ceramic fibers and matrices which are very high which are useful for very high temperature applications. For example, in engine components silicon carbide fibers in whisker form is a part of this a ceramic matrix is so temperature resistance, one must remember the however that fibers alone rarely used. Now, with this background I think we have seen the different types of fibers that are available to us. And through the applications in the different cases we also see the large variety of applications or how the CFRM is used in the different walks of life beginning with sporting goods, protective wear and the automobile industry, high temperature applications other than the construction industry.

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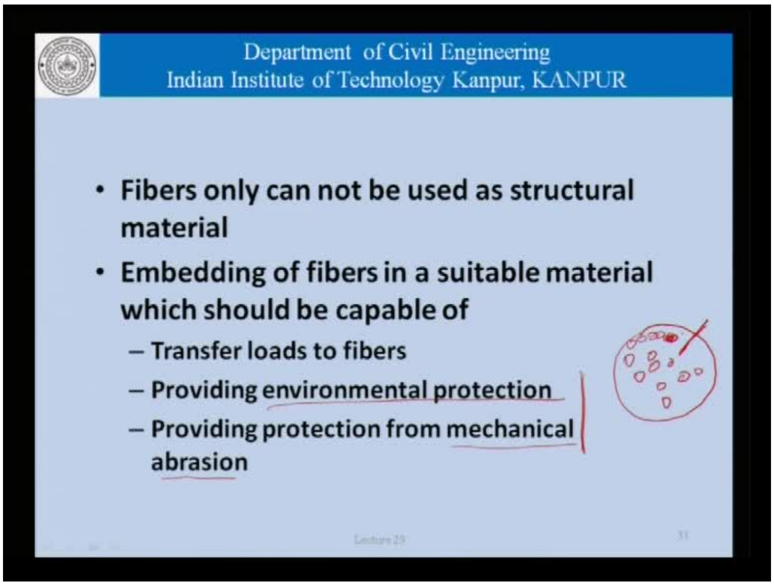

But one must remember that fiber alone cannot be used as a structural material what needs to happen is that they are embedded in a suitable material. And what should be the properties of that material? The embedded or the material in which these fibers are embedded should be such that it is able to transfer the load to the fibers provide environmental protection to the fibers and provide protection from mechanical abrasion. So, this is environmental protection here that is the fiber should be protected from p H the temperature and so on. And at the same time the fiber should also be protected from mechanical abrasion and mechanical action that may occur in the neighborhood of the fibers. We must remember that as far as a fiber reinforced plastic is concerned or CFRM is concerned, it really consists of these fibers which are embedded in this matrix. So, this matrix is supposed to protect these fibers from the external action which is being talked about here. At the same time the, the matrix should be such that it is capable of transferring the load to the fibers.

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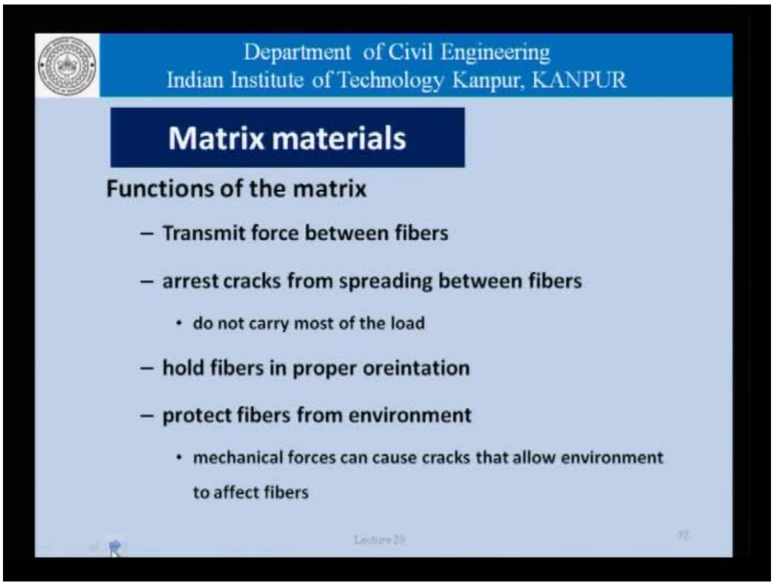

Reiterating the functions of the matrix materials transmit forces between fibers, arrest cracks from spreading between fibers. But at the same time they do not carry much of load hold fibers in proper orientation, protect the fibers from the environment. Mechanical fibers that can cause cracks and allow the environment to affect the fibers that should not happen as far as the fibers are concerned. And the matrix should be able to protect the fibers to that extent does a matter of fact we can draw analogy from what happens in the case of reinforce concrete itself. One of the functions of the concrete is also to provide a cover to the reinforcing bars so much as the concretes provides the cover to the reinforcing bars.

But it must also ensure that the bars carry the load. So there is a transport of stress that happens from the concrete to the steel the same thing should happen as far as the CFRM is concerned. The matrix surrounding the fibers place the role of the concrete and the fibers themselves individually play the role of a reinforcing bar. It is a different matter that as for as an application is concerned it is the rod itself which is a conglomerate of millions of fibers which are all embedded in a matrix that rod becomes a single load carrying member embedded in concrete. But as far as the analogy is concerned one must remember that the matrix serves more or less the purpose of concrete in normal reinforced concretes.

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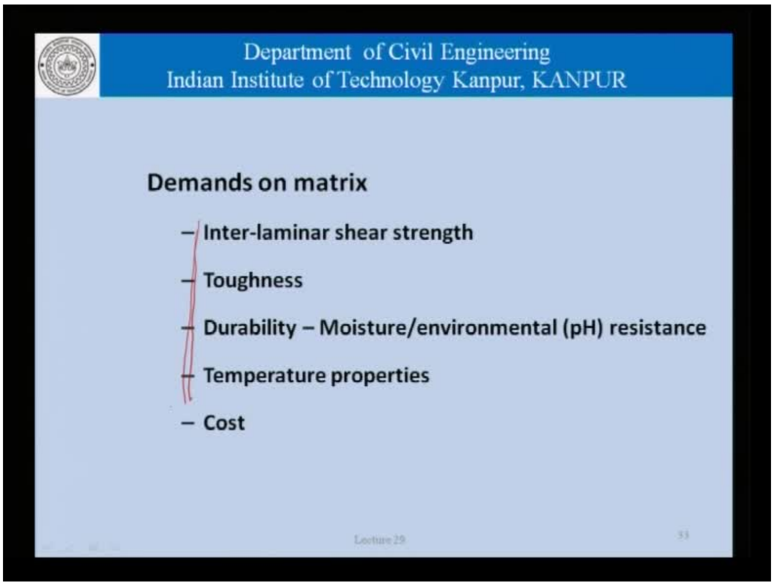

So, now continuing with our discussion, as far as matrix material is concerned the demands on the matrix are inter laminar shear strength, toughness, durability in terms moisture and environmental p H resistance, because the matrix itself also needs to be durable. If the matrix is not durable sooner and later the fibers will get exposed and that is precisely what we do not want. And therefore, durability of the matrix material is of at most importance when we are designing a CFRM. It should have the required thermal properties it should be stable in the range of temperature that we expect the material to be used. Of course, it should be cost effective.

In fact, some of these properties are so important that one must remember these properties when we are designing tests for ensuring durability and structural action as far as CFRM is concerned. In the case of concrete applications if we do not want or do not expect concrete to be exposed to very high temperatures. Then thermal properties have a certain important or a certain degree of importance, but in cases where we expect the CFRM even if it is embedded in concrete it is likely to be exposed to high temperatures then it has to be tested accordingly.

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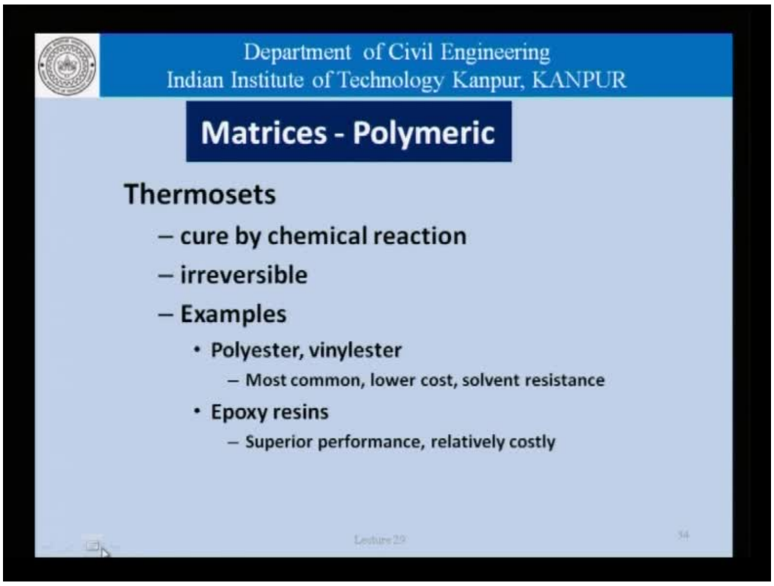

The same is the case with moisture the p H and so on and so forth. Now, coming to the different matrices or the different materials for matrices, for example, that are for example, there are polymeric materials which are thermosets, they cure by chemical reaction which is irreversible in nature. And the examples of these are polyester or vinylester and they are the most common low cost solvent resistant matrices. There can also be epoxy resins which have a superior performance what are relatively costly.

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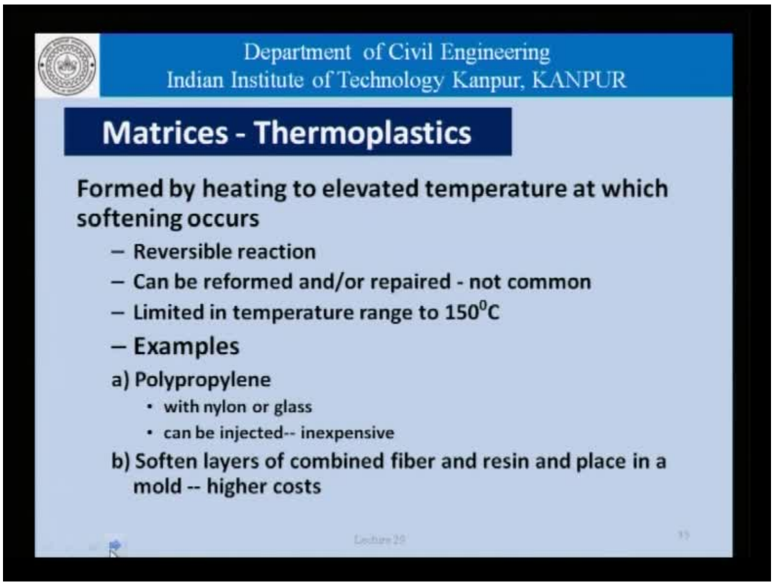

Similarly, there are thermoplastics which are formed by heating to elevated temperatures at which the softening occurs. And this reaction is reversible, and they can be reformed and or repaired, but that is not very common. But then that also limits the range of temperatures up to which they can be used, because after that this softens. The examples for this could include polypropylene with nylon or glass, they can be injected and are inexpensive the soften layers of combined fiber and resin and place in a mold and that is higher cost.

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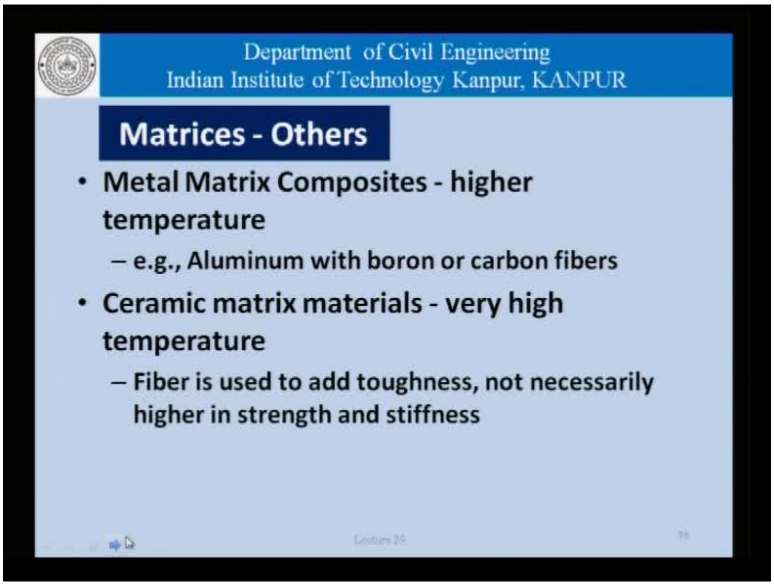

Then of course, there are other matrices such as metal matrix composites which are good for high temperature applications aluminum with boron or carbon fibers. There are ceramic matrix materials which are very high temperature resistant. And these fibers used to add toughness and not necessarily higher in strength and stiffness. And now with this we have prepared the background for our discussion on the properties of the CFRM.

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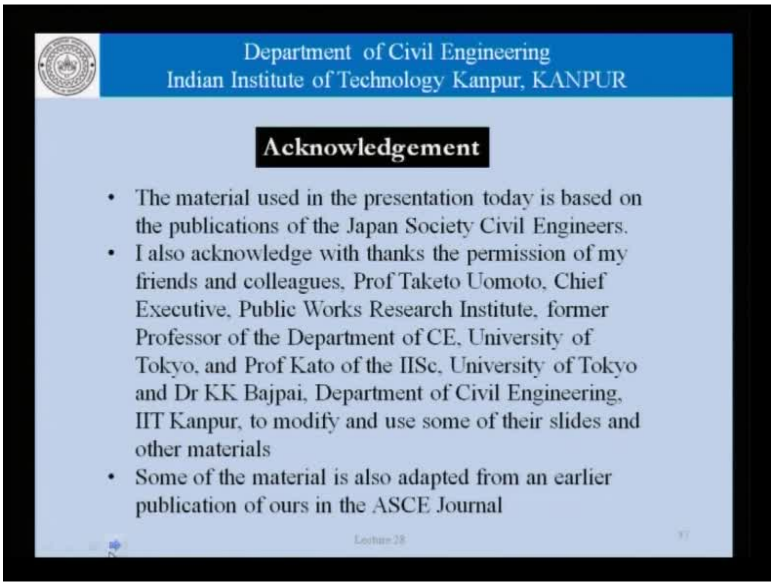

And before we close the discussion today I would like to acknowledge the support or the permission from the JSC to use some of the material which we have based on JSC publication. And I would also like to acknowledge with thanks the permission of my friends and colleagues professor Uomoto, who is the chief executive of the public works research institute, formally professor of the department of civil engineering university of Tokyo. Professor Kato of the IISc University of Tokyo and doctor K K Bajpai of the department of civil engineering at IIT Kanpur, who have kindly agreed that I may modify and use some of their slides and other materials for today's presentation. And some of the material that I used here today is adopted from an earlier publication of ours in the ASCE journal. So, with these acknowledgements let us come to some of the points that we can ponder over before the next discussion.

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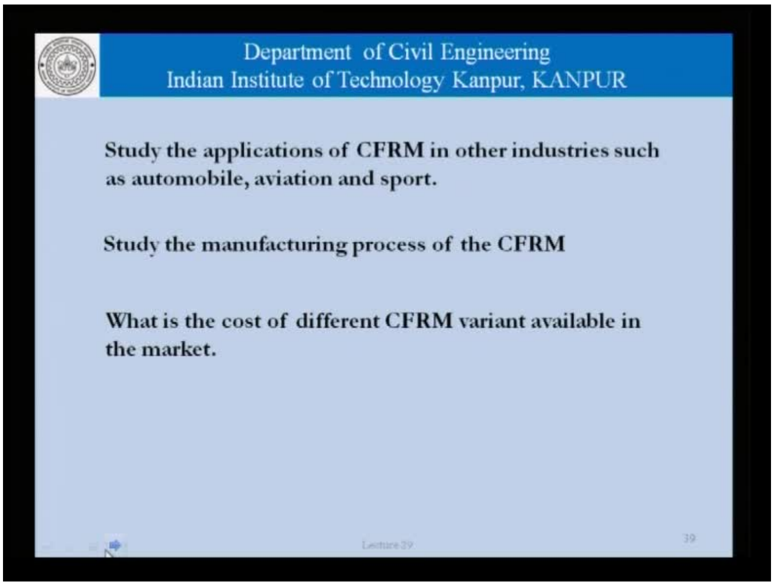

One can study the applications of CFRM in other industry such as automobile aviation sport protective personal gear and so on. Study the manufacturing process of the CFRM, how the CFRM how the CFRM is manufactured beginning with the manufacture of the fibers in the first place. And then how these fibers are made into the CFRM? That is the reinforce materials, that is including the matrix and what is the cost difference or what is the cost of the difference CFRM variants available in the market? So, before we go into studying the properties or looking at the different CFRM materials which are available in the market for construction and so on. Let us take a look at some of the fibers and a few of the products which are used in construction. So, here is the strand of the continuous glass fiber. So, we can see that these are extremely fine fibers which are all over into a single which could be over into a single strand.

And this is strand can be embedded in a matrix to give you a fiber reinforced product made from glass fibers this here is a glass fiber woven cloth. So, we can see that it is woven in both directions it is woven in this direction as well as in this direction and it is a same glass fibers which have been used in both these directions. This here is a unidirectional carbon fiber fabric the carbon fibers are all oriented in this direction and have the same characteristics as glass fibers except that these are made of carbon. And therefore, we will behave differently we saw the woven fabric of glass. Now, this is the woven fabric for carbon, so these are carbon fibers which have been woven into a fabric both in this direction as well as in this direction. This here is a fabric made with aramid or Kevlar. And here again we can see that they are fibers which are oriented in different directions though not necessarily perpendicular. This is a slightly different form of carbon fibers where the fibers are not oriented in a particular direction.

So, this is a randomly oriented carbon fiber mat. This here is made from carbon fibers which are not particularly oriented in a certain direction. So, this is a randomly oriented carbon fiber mat. Now, this is an example of a glass fiber rod here we can see that the glass fibers have been solidified or embedded in a particular matrix. So it is difficult to make out that this rod is really made up of, it requires some imagination to understand that this rod is made up of fibers which look like this. But indeed depending on how much fiber you put in here into this rod, we can actually design the properties of this rod or we can get a rod which meets our requirements as far as strength and so on is concerned. Apart from rods, we can also have laminates and this here is an example of a carbon fiber laminate.

Similarly, this is an example of a unidirectional glass fiber laminate and this is an example of a unidirectional aramid or kevlar fiber laminate. So we have seen individual fibers, glass, aramid, carbon and we have seen and we have seen unidirectional fibers; we have seen woven cloth; we have seen woven cloth made with glass, fibers, aramid and we have seen a rod or a laminate. Now, depending upon what we want to use or what are the properties that we want from the reinforcing material? We can actually combine these fibers. There is no reason that in both directions we should use only glass fibers; we can use a combination of glass and carbon depending on our needs. So this flexibility in using different fibers and different directions in different amounts helps us design materials which can be very useful when we are doing construction, when we are doing the design of a structure where we want to use these materials. With this we come to a close for the discussion today.

Thank you.