Basic Construction Materials
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Module No # 09
Lecture No # 44
Polymers and Composites – Part 3

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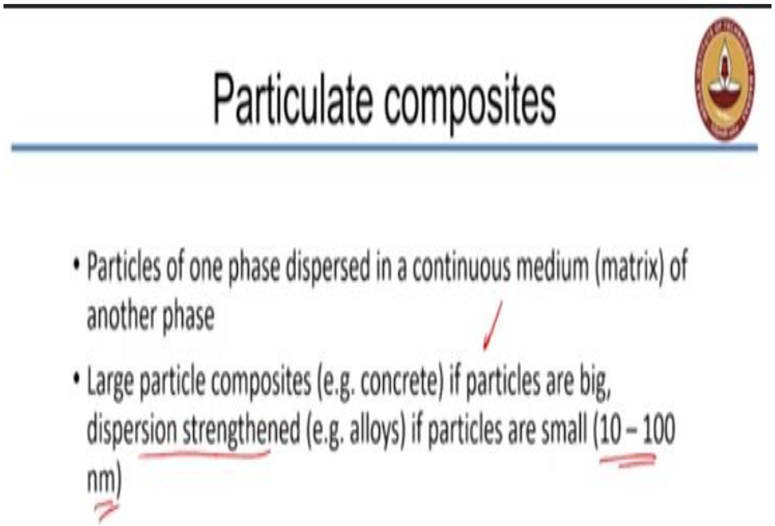

Now let us take a look at particulate composites. So as I said particulate composites imply particles of one phase which are dispersed in a continuous medium or a matrix of the second phase. So concrete for instance was a large particle composite where we had large aggregate particle which are embedded in a matrix of cement paste.

Now in alloys, the particles of carbon for instance in the iron microstructure are at the atomic level. So in those cases they are called dispersion strengthened particulate composites. For example even in stainless steel, you have nickel and chromium embedded in the structural steel but those are at atomic level. You don't have large grains of nickel and chromium embedded into steel. So these transformations or these substitutions are at the atomic scale. That is why we call them dispersion strengthened particulate composites.

Here we are talking about 10 to 100 nanometer size particles. In concrete, if you remember our particle sizes ranged from 75 microns to all the way up to 40 millimeters. So these are fairly large sized particles that are embedded in the matrix.

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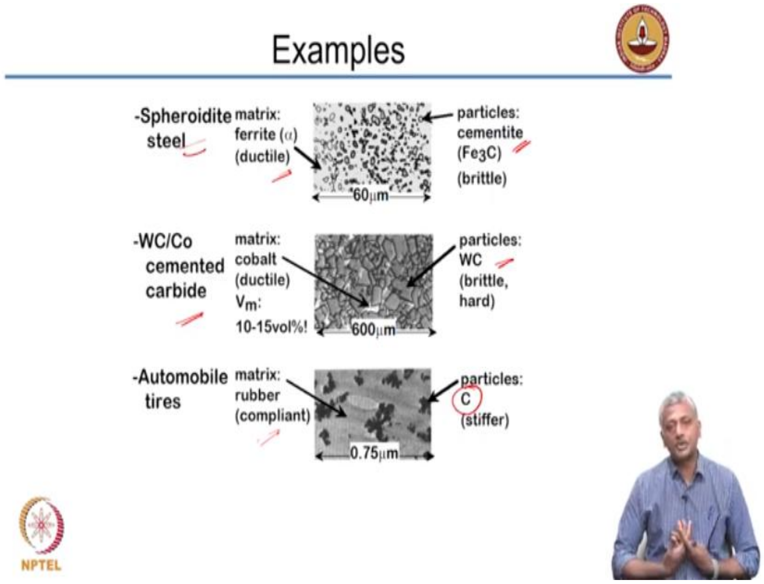

Again some examples from the steel microstructure are given here. So this is a spheroidite steel. Spheroidite steel has a matrix of ductile ferrite alpha phase, again something which you would have learnt previously in your steel lecture. And then there are particle of cementite, which is Fe_3C or iron carbide which are embedded in this matrix. When you have cemented carbide, you have a matrix which is cobalt, which is ductile and you have particles of tungsten carbide, WC which are embedded into to this cobalt.

Then you have automobile tires; please remember automobile tires are made with vulcanized rubbers. You have matrix which is rubber, which is compliant or pliable. Rubber is still stiff because of vulcanization. But you also have particles of carbon inside, which make the material lot stiffer. So, carbon black for instance; very fine particles of carbon are actually used as fillers in rubber to increase the stiffness of the material. Several examples exist from engineering applications. In civil engineering of course the most common example is concrete.

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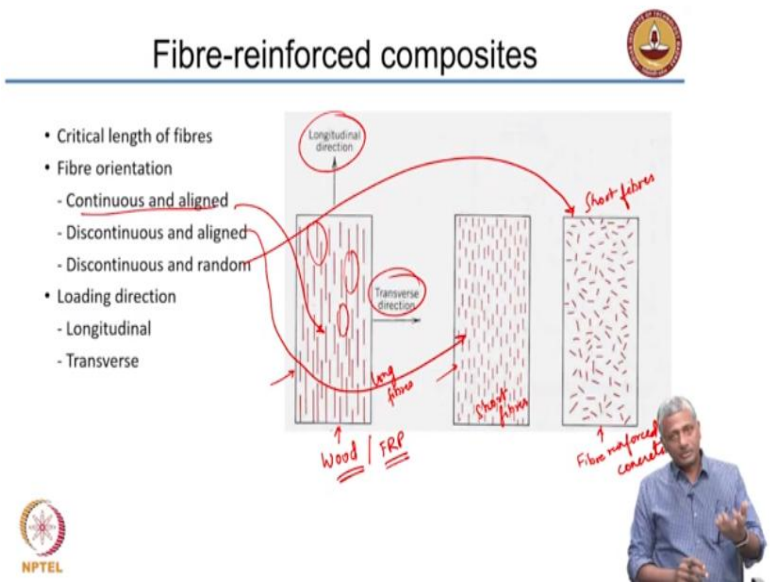

Now what about the other kind of composites? Fibre reinforced composites? Here there are fibres of one phase embedded in a matrix of another phase. For example, you consider here that this is a fibre reinforced composite where you have fibres oriented along the longitudinal direction. When you consider the longitudinal direction, it means that the direction along with the fibres are oriented. The perpendicular direction is that transverse direction. Perpendicular is the transverse direction.

Now you can also have a scale of fibres which is very small, very short fibres. So, here these are long fibres which are continuous and aligned. You can have short fibres that are still aligned but they are discontinuous. Short fibres, discontinuous and aligned. Now here, this third case is when you have discontinuous and random short fibres.

Examples of these - this one is very common in wood. You have continuous aligned fibres in wood. You have short fibres which are randomly oriented in fibre reinforced concrete for instance. Of course wood, you'll learn in another chapter. One example that we will see in this chapter itself is FRP, fibre reinforced plastic. We will talk about that a little bit later.

As I said, loading direction can be longitudinal when you are loading it in the direction of the fibre. In wood, it is extremely important because when you are loading or when you are pulling the wood in the direction of the fibre, it has got very high strength. In the transverse direction it will have a lower strength. Not just the strength, even the moisture removal properties will depend on the direction of removal of the moisture. So again wood is a very complicated material. You will learn about that separately in a different chapter.

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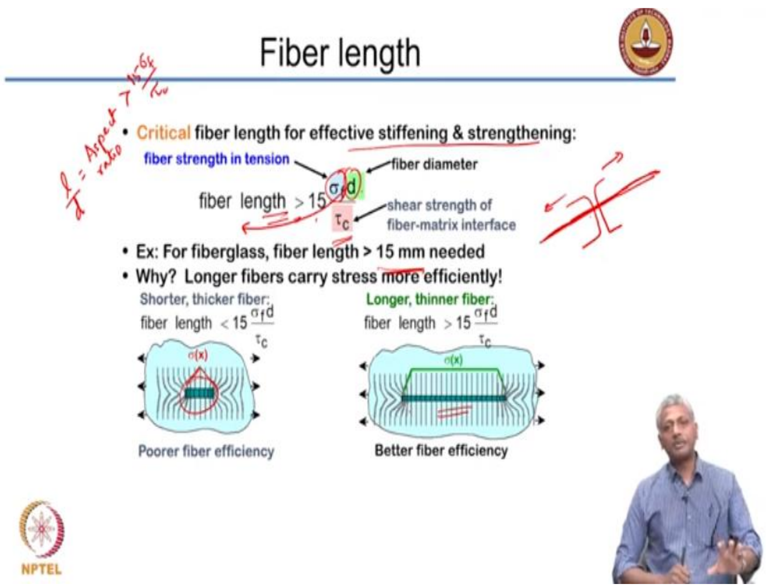

Now what are the critical parameters in the case of fibre reinforced composite? What are these fibres doing? Just imagine you have a cut on your face and they put stitches to your face. What do the stitches do? They keep the ruptured skin together so that the skin cells can grow in the gap and then you get a complete coverage of your scar. So stitches are trying to keep the tissues together and allow for growth of tissues to happen in the region that's been hurt. Similarly, fibres in a matrix.

What they are trying to do is that if you have a material that is getting deformed, let's say a material where crack has happened. You have a fibre sitting inside the crack, bridging the crack, which is preventing the material from getting torn apart. The fibre is basically preventing the material from getting torn apart. So obviously the longer the fibre, the better it will hold the material together.

So generally the fibre length has to be good enough for effective stiffening and strengthening. So fibre length should be greater than 15 times the fibre strength in tension multiplied by the diameter of the fibre divided by that shear strength of the fibre matrix interface.

$$\text{Fibre length} > 15\,\frac{\sigma_f d}{\tau_c}$$

Very often we define the length to diameter ratio as the aspect ratio of the fibre. So if you bring this diameter here, obviously it says aspect ratio should be greater than 15 times σ_f by τ_c.

Obviously the shear strength of the fibre matrix interface will depend upon the kind of matrix that you have. For a polymer matrix, it will be different and for concrete it will be different and so on. But at the same time you need to ensure that you are choosing fibres that have a high enough aspect ratio to lead to an effective strength stiffening or strengthening of the material and effective holding of the cracks together.

For fibre glass, fibre length greater than 15 millimeters is needed, just an example of a material that is given here. So, longer fibres are able to carry stress more effectively. So here for instance, you consider the short fibre, where fibre length is less than what is required. If you have a long thin fibre, obviously the efficiency is improved. So you want a fibre with a high aspect ratio.

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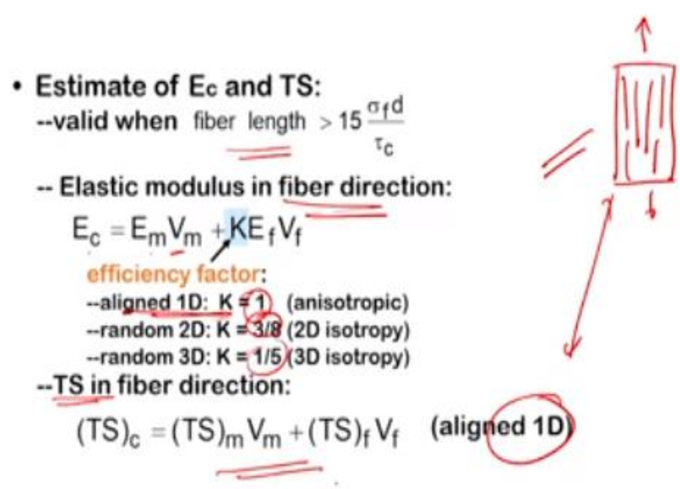

Again, you can apply similar rules as you did in particulate composites which respect to calculating the net composite modulus or net composite engineering properties. So for fibre lengths which are high enough, you can actually apply these sorts of equations in the fibre direction, that means in the longitudinal direction of loading. So in this direction, you have modulus of elasticity of composite(E_c) equal to modulus of elasticity of matrix (E_m) into volume fraction of the matrix(V_m) plus volume fraction of the fibre(V_f) into modulus of the fibre(E_f) into a factor K.

$$E_c = E_m V_m + K E_f V_f$$

And K depends a lot on the orientation. If you have perfectly aligned 1 dimensional case like what is shown here, in that case you will have K = 1. If you have continuous aligned fibres, you will get K = 1. If you get random fibres in 2 dimensions, that is in 2 dimensions if the fibres are random, then your K values reduces to 3 by 8. And if you have random in 3 dimensions, for instance when you have fibre reinforced concrete, in that case the K value is only 1 by 5. That means the component of the fibre in the composite reduces with more and more random orientation. If you have good alignment, the component of the fibre is very high. But if you have a poor alignment, the component of the fibre reduces significantly.

In the fibre direction, the tensile strength can also be calculated in a similar way for an aligned 1 dimensional case, which is continuous align case as tensile strength is equal to matrix strength (TS_m) into volume fraction of matrix (V_m) plus fibre strength (TS_f) into volume fraction of fibre (V_f), only for the aligned 1 dimensional case. This is same, we are applying the same rule of mixtures in this case also.

$$(TS)_c = (TS)_m V_m + (TS)_f V_f$$

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Fibre Reinforced Plastic in Construction

Now, let us take a look at specific construction applications of this components called fibre reinforced plastic. So as I said earlier, fibre reinforced plastic is when you have fibres which are embedded in a plastic matrix or polymer matrix.

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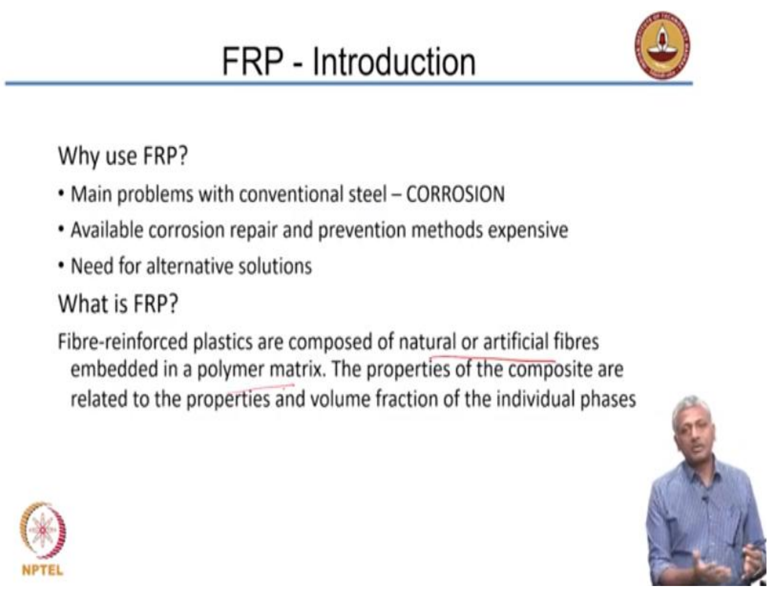

Now why would you want to use fibre reinforced plastic in construction where we use steel very commonly? The idea is that steel obviously has a life that is restricted because of its corrosion. Steel will corrode eventually and to have a structure that lasts long you need to prevent steel corrosion. So the main problem with conventional steel is obviously corrosion. You can replace this with materials that are corrosion resistant.

And you spend a lot of money trying to repair corrosion. Again, Dr.Pillai may have already talked about that in his lecture on steel. So there are obviously needs for finding out materials that are corrosion resistant and which will not degrade with respect to time. So fibre reinforced plastic is basically consisting of very high tensile strength fibres embedded in a matrix. Natural or artificial high tensile strength fibres embedded in a polymer matrix.

And again the properties of the composite can be calculated from the properties of the individual phases just like what we saw previously.

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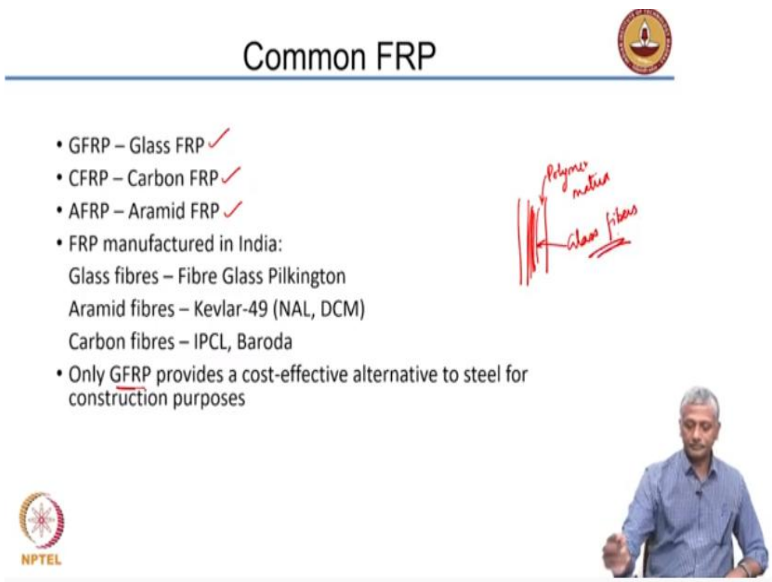

So what are the common fibre reinforced plastics? what are the common fibre types which are used here. You have glass fibres, you have carbon fibres and aramid fibres. As you go from glass to carbon to aramid, obviously your costs go up significantly. Glass is cheaper, then you have carbon and then aramid. There are several fibre manufacturers or fibre reinforced plastic manufactures in India.

But you will see later when we talk about the applications that, instead of using as a reinforcing, fibre reinforced plastic is often used for repairing and strengthening concrete structures. I will talk about that in just a minute. So as I said carbon fibres and aramid fibres are very expensive because of which only glass fibre reinforced plastic can provide a cost effective alternative to steel reinforcement for construction purposes. So here you have fibres of glass embedded in a polymer matrix. These are glass fibres.

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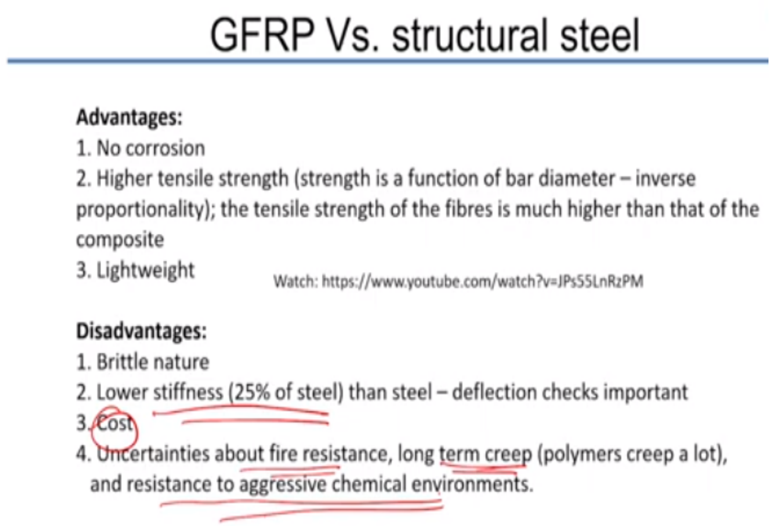

The advantage obviously of glass fibre reinforced plastic is that it will have no corrosion because it will not degrade like steel. Now I will touch upon that again because corrosion can have a different meaning when you are talking about polymers.

Again glass fibre reinforced plastics can be made into very high tensile strength materials. The glass fibres themselves are extremely strong and the tensile strength of the fibres is generally much higher than that of the composite. The glass fibre reinforced plastic is much more light weight as compared to steel. You are talking about densities of GFRP, which are in the range of 2.5 to 2.7. Steel has a density of nearly 8. So for the same size of bar, you can imagine that it is much easier to lift a GFRP bar as compared to a steel bar. So you have a very high strength to weight ratio in the case of GFRP.

The problems with GFRP are its brittle nature. So it experiences brittle fracture, brittle behaviour as compared to steel. It’s even got lower stiffness, only about 25% of the steel. So that means even at low load levels there will be a lot of deflection. This is elastic deflection mind you, if you remove the load, it should spring back because the material does not have much plasticity. It does not exhibit a yielding. So it has a brittle failure.

Cost is high as compared to steel. GFRP is comparable, the other type of fibres which are much more effective but they are not cost effective at all.

Now the problem with fibre reinforced plastic is that since it is plastic, its fire resistance is going to be poor. Of course that does not mean steel has good fire resistance. It's also got poor fire resistance but plastics can start degrading at much lower temperatures.

You will have long term creep. In the case of metals like steel, the creep effects are very less but here we are talking about a polymer matrix, so there will be creep effects. And the problem mainly is that reinforced concrete is a highly aggressive chemical environment for the polymer. Because as we talked about this earlier, the pH of cement paste or concrete is 12 to 13, that is very high level of pH, highly alkaline pH.

We don't know what will happen to the polymer in such high pH levels. Many polymers tend to degrade at such high pH levels. Again this is one reason why when people talk about adding plastics to concrete, main problem is these plastics would tend to degrade inside concrete and they may let out some toxins into the atmosphere. We do not want that to happen, so we need to treat them well before we use them.

So coming back to GFRP, polymer may degrade in the aggressive chemical environment of the concrete.

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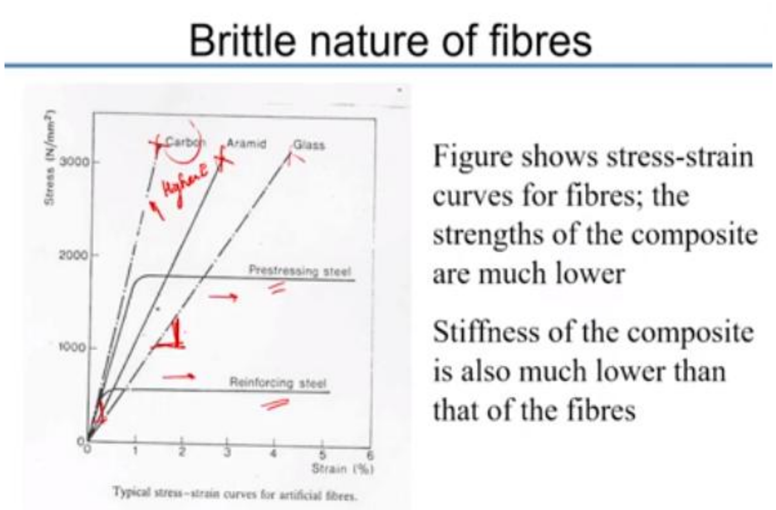

Again just to show the brittle nature, what I have shown you here is the behavior of reinforcing and prestressing steel. So you can see that they have a very long ductile region of deformation whereas your fibre reinforced polymers are simply breaking apart in a brittle fashion. There is no deformation, there is no ductile elongation of the material.

Stiffness which is the slope of the stress strain graph also is lower than that of steel. So steel has a high stiffness whereas the glass fibre reinforced plastic has a low stiffness. When you go to carbon fibre, stiffness is increased. You get higher stiffness which is closer to that of steel, but the problem is its extremely brittle behaviour and simply no plastic deformation before failure. So in construction we always want to design structures to have a ductile and slow failure. When you compromise on the ductility, it is not really an acceptable civil engineering solution. So this is something that you need to worry about when you start using alternative materials.

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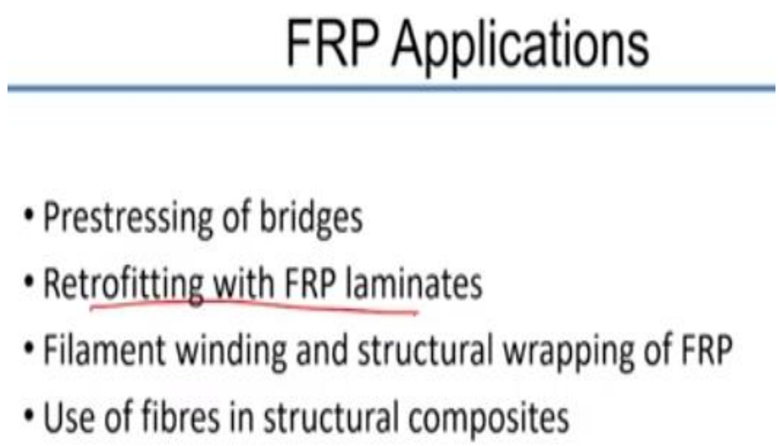

Now given that its use as the reinforcement could be highly limited, there are other applications that have come about of the use of fibre reinforced plastic. One of the common applications is prestressing of bridges, but more commonly you have retrofitting with laminates of fibre reinforced plastic. Again please remember laminate basically means several sheets of fibre embedded in plastic which are in different directions.

So you get a composite which is much stronger because it has got fibres now aligned in all kinds of directions. So these are laminates. What they do is they take these laminates and wrap them around the concrete. Supposing you get a fracture what do they do? they wrap it with a plaster. Plaster ensures that you cannot move your hand. Your hand becomes very stiff. You cannot move your hand or the joint which has got fractured until it heals. In the case of concrete, if there is a lot of cracking, you put this wrapping around it. So what it will do is, it will strengthen the concrete within the wrapping area.

So again fibres can also be used in structural composites but for the most part we are talking about FRP applications in construction, which are mainly for retrofitting with FRP laminates.

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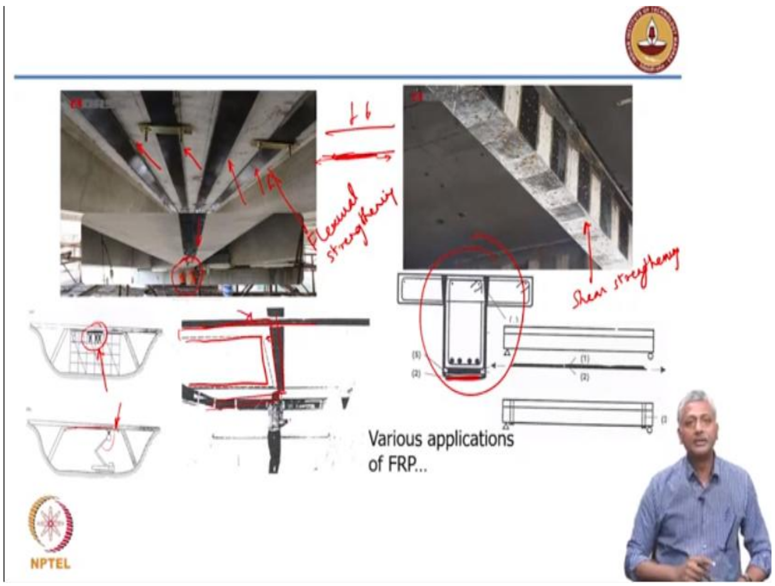

What is shown here is again these two workmen are basically fixing this FRP laminate on the underside of the bridge here. So you can see these laminates which have been fitted. These are strips of fibre reinforced plastic laminates which are stuck on like a glue. So what will happen is, if you have a beam like this and you are fixing this here to the bottom; for example this is a cross section of the beam and you are putting the laminate at the bottom.

So once you start bending, once the beam starts bending, the laminate will take a lot of tension that happens at the bottom and your beam will be protected. So here the laminates are wrapped around in the other direction. So this is for shear strengthening. This is for flexural strengthening, that means bending strengthening and that is for shear strengthening. So there are various ways in which you can do this.

The same thing could be also done with the steel plate stuck to the bottom of your concrete. But again steel will corrode, even a plate will corrode. Secondly, steel is very heavy. If you can imagine workmen trying to put the steel plate at the bottom of the beam, that will require significant amount of effort. And that’s what exactly is shown here, for affixing steel laminates, you have a full scaffolding and many workers who are trying to put that up. In this case a continuous application of the FRP laminate can be executed by just 1 worker. And you don’t really need any heavy scaffolding to support these things.

So these are applications that are commonly done with fibre reinforced plastics. Again this is an example where these strips are being added so that an opening can be cut out from the slab. So for example, if you want to create a new staircase inside your building but you don’t have a beam to support the weight of the floor if the slab is removed. So you are basically putting the laminate in a square arrangement and then removing the slab from within that. So that all the load that comes will now be taken by the laminate.

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So finally let’s talk briefly about structural composites. We talked about structural composites earlier when we had a discussion on, for example prestressing. We talked about structural composite because prestressing is also a form of structural composite. There are also steel tubes that are filled with concrete. That is another example of structural composite.

So here the materials are not intimately getting combined, they are still separate but they form a structure together and function together.

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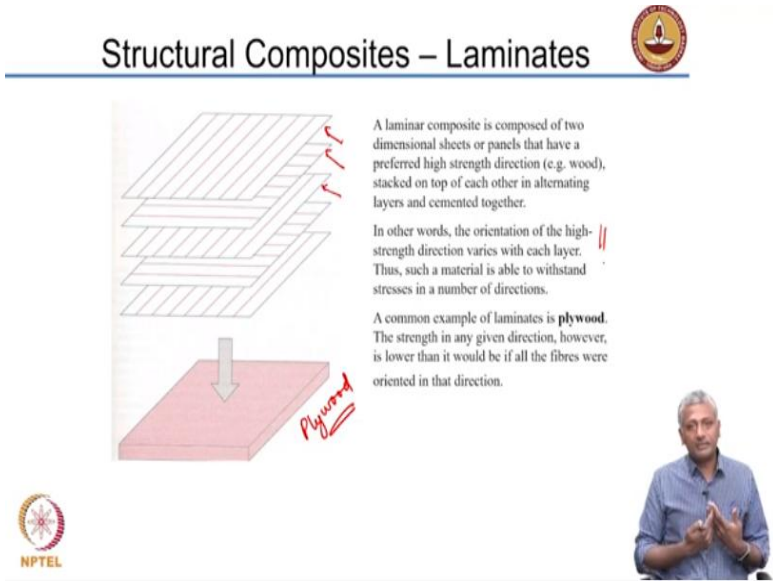

One of the common ones as I said is a laminate. So here you have fibres oriented in orthogonal directions which are stuck together with a glue. So that's a laminate basically which is composed of 2 dimensional sheets or panels which are having a preferred high strength directions. In which ever directions the grains are oriented or fibres are oriented, for example wood, in whichever direction the grains are oriented, it will have a very high strength.

So when you put different orientations together and stick them together to form plywood, you will have a material that is strong in all directions. So plywood is a very common construction material. Especially for formwork it is used extensively. Generally the orientation of the high strength direction will vary with each layer. But when you put them together a composite material will have very high strength in all directions.

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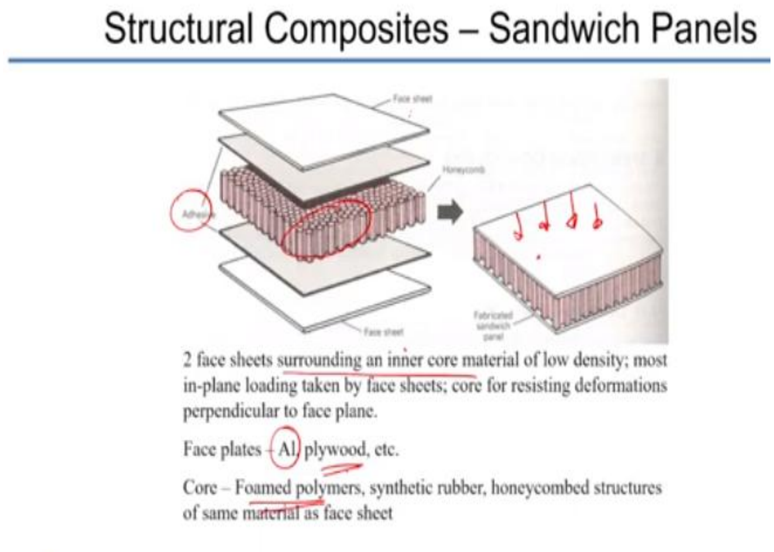

Now a composite sandwich panel is something that is formed out of external layers that are of a different stiffer material and internal layers that can be light weight and less stiff. For instance, here you have sheets of aluminum on the faces joined together with adhesives to an internal structure that is a honey comb structure. Honeycomb structure will provide very low weight but at the same time what happens is, when this material is loaded, because of the bulk that is provided by the interior material, the sandwiched material, it will have ability to resist large deformations.

So there are 2 face sheets that are surrounding an inner core material which is having low density. Mostly what we do is, we use honeycombed material or we use foamed polymers at the core. So the face plates are typically aluminum but we can also use plywood.

So these are called structural composites and this is because the materials are combined to work structurally together. They are not intimately mixed together.

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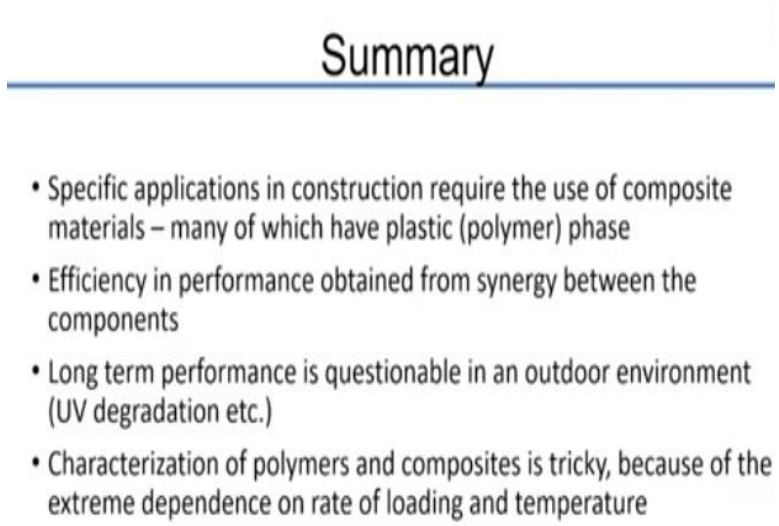

So to summarize this chapter on polymers and composites, we have specific applications in construction that requires the use of the composite materials. And in many instances we have plastic as the phase that is present in the composites, the binding phase or the matrix phase that is present in the composite.

So efficiency in performance is obtained from the synergy that different components exhibit when they come together. Individually they are performing differently but when they come together there is synergistic effect that results in the performance of the composite.

Again when you apply polymers and composites in construction in an outdoor environment, their stability will be governed by their resistance to ultraviolet degradation. They will degrade with respect to ultraviolet conditions, however the rate of degradation will determine what is the suitability of a particular type of composite for a given environment.

Characterization of polymers is extremely tricky. You need to be sure that you are applying the correct rate of loading and the right temperature is being used for doing the test, as opposed to concrete. Of course in concrete also we want to test everything at the right rate of loading, however it is not as sensitive to the rate of loading as polymers.

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References

- William D. Callister, Jr., "Materials Science and Engineering – An Introduction," 5th Ed., John Wiley and Sons, New York.
- Various web sources

So with that we complete this chapter. There is a good reference book by William Callister. It is a must have for all engineering students I think. Although it talks primarily about material science approach but even civil engineers should have a significant understanding of the coverage of materials that you have in William Callister.

So this book is called material science and engineering - an introduction. There is an Indian version available which is fairly low cost. For the kind of material that it provides you, it is actually a real treasure trove to have. Any material scientist, any budding civil engineer should have that book to understand the basic properties of materials. With that we end this chapter. You will see that much of our discussion on polymers will also be valid when we discuss bituminous pavements in one of the last section of this course. Thank you very much.