Manufacturing of Composites
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Lecture - 03
Fiber Reinforcement

Welcome to lecture 3. So, in this lecture we will more focus towards Fiber Reinforcement which is the one of the major members which are added to a composite such that we get the required mechanical properties. And as I told you earlier composite is one material were in which you can selectively add mechanical properties at the required zone it can be tensile strength, it can be shear, it can be hoop whatever you want you can keep adding it. How is that getting enhanced it is; because of the fiber getting reinforced.

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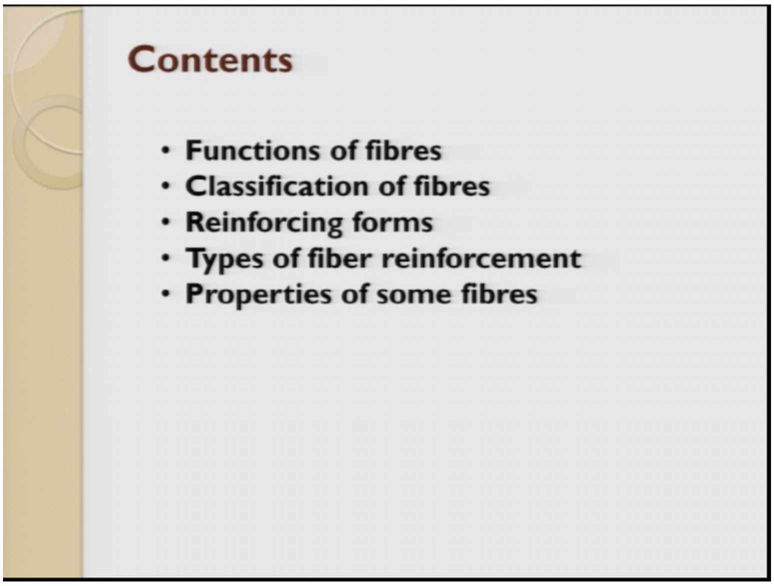

So, today we will see in this lecture we will see about functions of fibers, classification of fiber, then reinforcing fiber different types of forms what are available then types of fiber reinforcement and some of the properties of different fibers.

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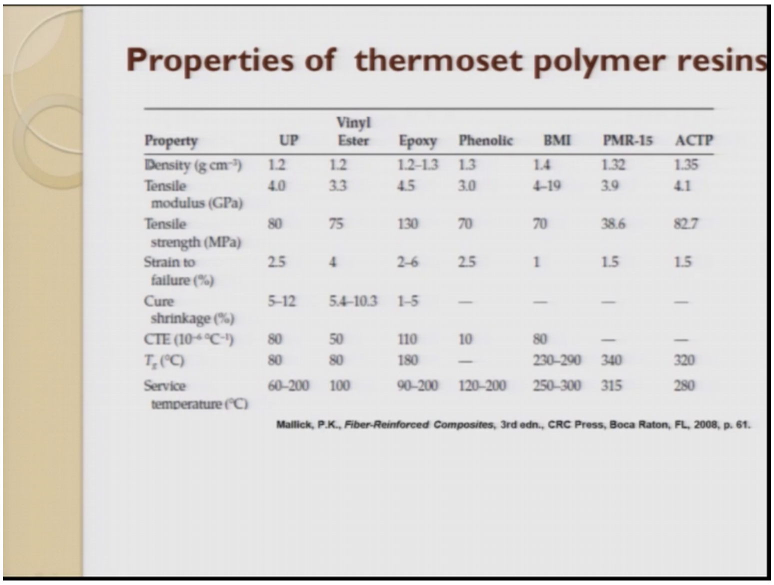

Properties of thermoset polymer resins

Property	UP	Vinyl Ester	Epoxy	Phenolic	BMI	PMR-15	ACTP
Density (g cm^{-3})	1.2	1.2	1.2–1.3	1.3	1.4	1.32	1.35
Tensile modulus (GPa)	4.0	3.3	4.5	3.0	4–19	3.9	4.1
Tensile strength (MPa)	80	75	130	70	70	38.6	82.7
Strain to failure (%)	2.5	4	2–6	2.5	1	1.5	1.5
Cure shrinkage (%)	5–12	5.4–10.3	1–5	—	—	—	—
CTE (10^{-6} °C^{-1})	80	50	110	10	80	—	—
T_g (°C)	80	80	180	—	230–290	340	320
Service temperature (°C)	60–200	100	90–200	120–200	250–300	315	280

Mallick, P.K., *Fiber-Reinforced Composites*, 3rd edn., CRC Press, Boca Raton, FL, 2008, p. 61.

So, I give an assignment in the last lecture so, where in which I asked you to take a thermoset and a thermoplastic polymer component and then or a part and then try to do the properties or compare the properties relatively.

So, here are some of the information for you. So, you can see that I have put down all the thermo sets for example, vinyl, ester, epoxy, phenolic; so what is their density, tensile properties, tensile strength, strain shrinkage and the coefficient of thermal expansion and glass transition temperature, service temperature; service temperature means these are temperatures at which the component can be kept for their usage. Generally, what happens the polymer composites over a period of time gets degradation in their strength. So, this happens because of the environmental conditions like hygroscopic present and small amount of polymer degradation which happens. So, that is what service temperature is also very important we have put here and on top of it UV exposure is also playing a very important role for their deterioration.

For example you keep a polymer chair for a longer time in the in the garden you can see the chair fails over a period of time that is because of degradation. So, service temperature is also very important where in which this tries to help us to give decide this parameter help us to decide which polymer to choose and what are the advantage of it.

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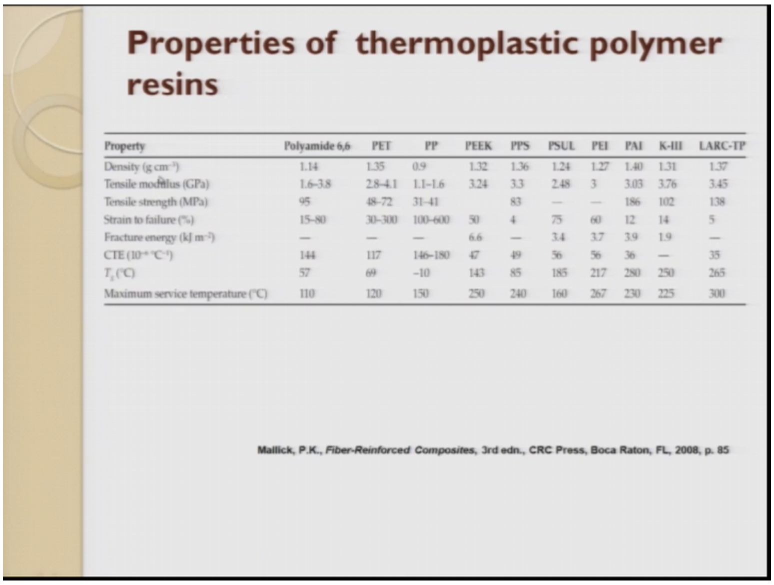

Property	Polyamide 6,6	PET	PP	PEEK	PPS	PSUL	PEI	PAI	K-III	LARC-TP
Density (g cm^{-3})	1.14	1.35	0.9	1.32	1.36	1.24	1.27	1.40	1.31	1.37
Tensile modulus (GPa)	1.6–3.8	2.8–4.1	1.1–1.6	3.24	3.3	2.48	3	3.03	3.76	3.45
Tensile strength (MPa)	95	48–72	31–41		83	—	—	186	102	138
Strain to failure (%)	15–80	30–300	100–600	50	4	75	60	12	14	5
Fracture energy (kJ m^{-2})	—	—	—	6.6	—	3.4	3.7	3.9	1.9	—
CTE (10^{-6} °C^{-1})	144	117	146–180	47	49	56	56	36	—	35
T_g (°C)	57	69	−10	143	85	185	217	280	250	265
Maximum service temperature (°C)	110	120	150	250	240	160	267	230	225	300

And here are some of the thermoplastic polymers which we discussed in the last class, I have put here Polyamide PET PP PEEK and then here again I have compared all their density, tensile modulus, tensile strength you can see tensile modulus and strength are different properties people use to swap it, but please understand there is a huge difference it is in Giga Pascal and this is an mega Pascal and this is drawn during within the elastic zone and this is drawn in the plastic zone this parameter is derived from the plastic zone.

The strain percentage if you look at this strain percentage for thermoplastic you see they talk about 80 percentage, 300 percentage, 100 percentage and others; but whereas, when you talk about strain or failure if you see here it is 2.5 less than 10. Now, you can understand the ductility property which plays a very important role in thermoplastic then coefficient of thermal expansion glass transition temperature and service temperature generally thermoplastic composites have a higher service temperature for usage.

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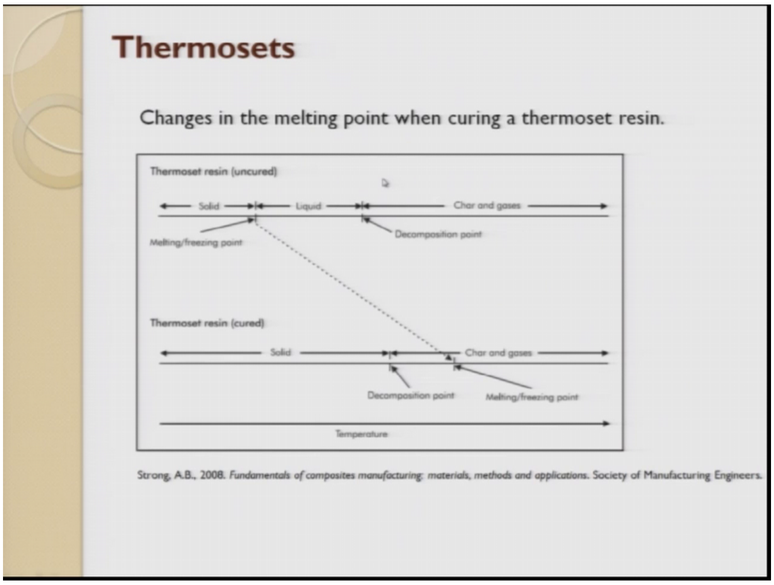

So, here is little more details about the matrix what we were discussing in the last class. So, here I have very clearly stated what happens or in the solid state and liquid state what happens and then you can see with temperature what is the influence of temperature for thermo set which is uncured and cured. Uncured is where there is still more cross linking can be done and you have not still hardened. So, when you say cured what happens is you mix an element which is a hardener you will see in details little later as and when we are fabricator composite. So, we will this cured agent is added to it. So, if there is uncured solid form here is a point where you can see melt and freeze.

Once this thermo set from uncured becomes cured you see the offset or shifting of the melting and freezing point from here to here; that means to say with respect to higher temperature this is happening. So, this is completely solid and this is a decomposition point and here is a melting point and after this what happens is the charge and gases which are happening because once you start melting thermoset polymers they are not recyclable. So, when you start burning it or heating it does not melt it just gives into char and it gets into gaseous form. So, that is happening at this point.

So, now it is very clear thermoset resin which is uncured solid form at a very low temperature once that and after this the type becomes liquid and then you have a decomposition point when it is cured it is a solid up to a very high temperature and then it undergoes directly into char it is not getting into liquid state at all.

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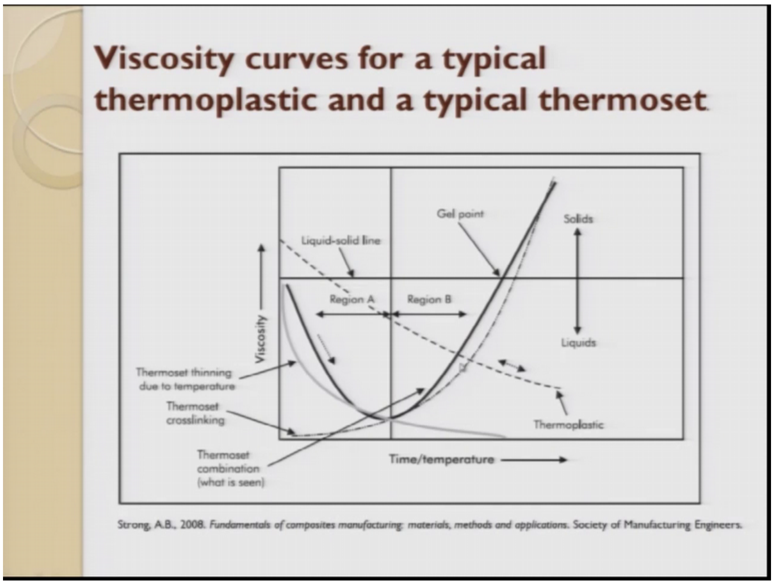

So, that is what is explained in this graph and next plot again with this is the last with respect to matrices I wanted to share an information the viscosity change with respect to temperature and time. Why is this important, because this viscous behavior dictates the flow of the resin to make to make a composite.

So, the viscosity increases as and when it becomes a solid. So, you can see here is a line which is drawn which talks about the thermoset combination and here is a point which talks about thermoset thinning; that means to say as and when you increase the temperature the viscosity of the resin thins. So, this is a very important parameter as far as manufacturing is concerned there are only 3 major parameters in manufacturing it is pressure, temperature and time.

So, you can have all 3 processes in all 3 parameters involved in a process or 2 or 1 and the biggest challenges to find out the weight ages of their influence with respect to the output product. So, you can see here the viscosity gets thinned down as and when you increase the temperature that is what is told here, why do you want to reduce the viscosity it becomes like water. So, if you want to pour it into a dye or if you want to do some process to get the output you have to take it to a higher temperature that is what is revealed out of this graph.

The next graph talks about cross linking. The cross linking can happen as and when the time increases and temperature increases in the proper ambience. So, here is a combination of these 2 we have drawn it here thermoset combination and this is a point which is called as gel point where in which it changes from liquid to solid it is in a semi solid state or in a mushy state. So, gelling point and after the gelling point you cannot do much it becomes into solid. So, like a phase diagram or like a iron-carbon diagram different phases, so, here is an important diagram which deals about thermoset polymer which talks about solid liquid line transition gel point solid where is solid and where is a liquid region form and here you can see with respect to thermoplastic the viscosity falls down as and when it goes for a higher temperature.

So, this is what we wanted to reveal from this graph with this I have coming to an end for matrices. So, matrices we have discussed about different kinds then we discussed about the properties then examples and then we have also discussed about the influence of cross linking and linking and then the viscosity parameter.

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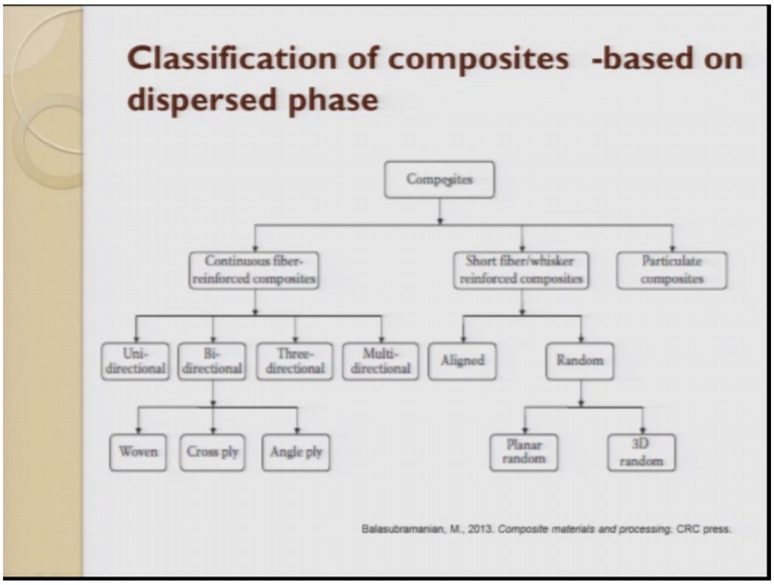

So, now let us get into the next part of composite which is the reinforcing phase. So, the reinforcing phase the reinforcing can be a continuous fiber can be a short fiber and can be a particulate fiber particulate matter.

So, when it is added to composite it is called as continuous fiber reinforced composites short fiber reinforced composites or particulate type composites. So, the difference between continuous fiber and the short fiber is the aspect ratio. What is aspect ratio; length was divided by diameter the length can run for few meters few centimeters and the diameter will always be in microns. So, that is continuous fiber. So, the continuous fiber can exist as a single fiber or as a bundle of fibers or a bundle of fibers viewed into a matter.

So, the fibers can be in the further classified into unidirectional, bi directional. Unidirectional matters in one direction in one direction there will be lot amount of fibers in the cross; that means, to say perpendicular direction there will be only lesser amount of fibers to hold these fibers. In bi direction fibers both directions you will have both direction of a mat you will have uniform amount of distribution of glass fibers.

Today there is a big push towards 3 dimensional. I will show you what is that and then you can also see multi dimensional. When you talk about short fiber I have also put a bar and I have said whisker. Whisker is a defect less, if it is the diameters are much smaller the lengths are also smaller as compared to short fibers, but there is no defect at all so; that means to say, it has a very high strength, but the length of the whisker will not be more than few tens of microns or few hundreds of microns few hundred I have said few tens of microns.

So, this short fiber can be aligned or it can be random. So, here by direction as I said it can be woven cross ply or angle ply.

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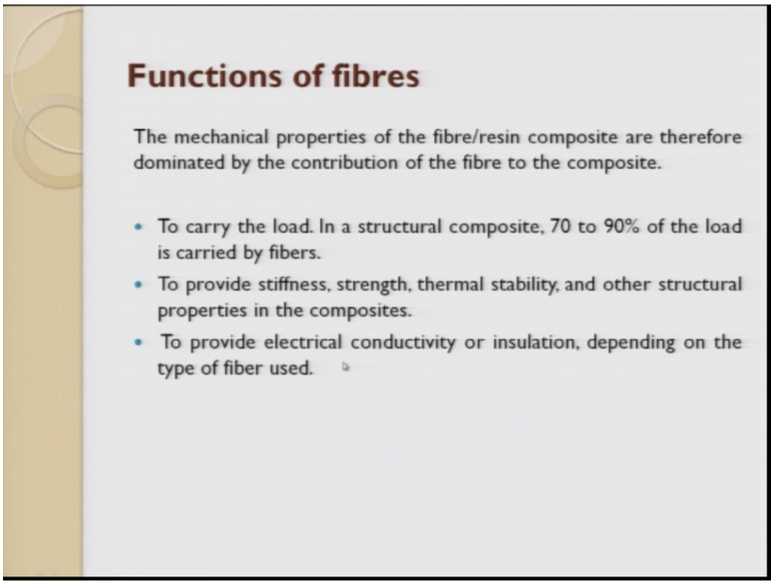

So, now let us go a little further and first let us understand; what is the function of a fiber. As I told you last time it itself, composite as a synergetic property matrix is to hold the fiber and matrix is to distribute the load. So, who takes the load the fiber takes the load the important function of a fiber is to carry the load. The next thing is it provides the required stiffness, strength, thermal stability and other structural properties of a composite. It can also provide electrical conductivity or insulation depending upon the choice of fiber.

So, in a nutshell the fiber the function of a fiber dictates or besides the mechanical property of the given composite.

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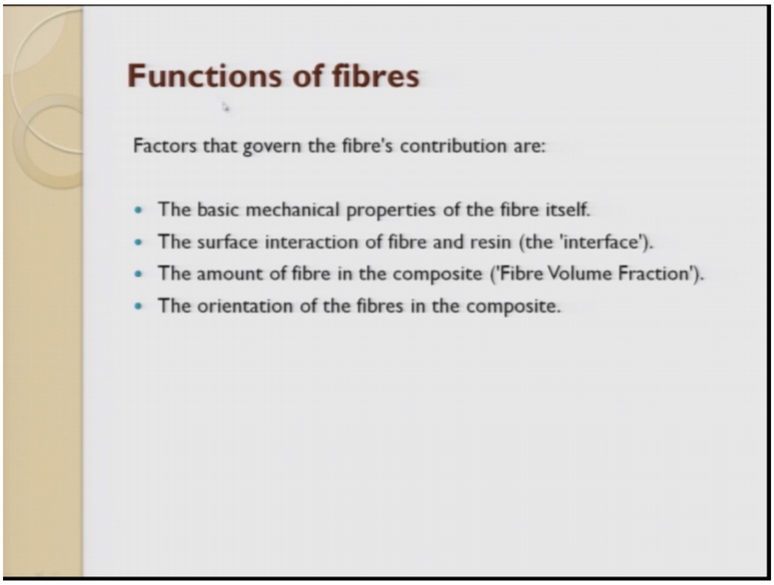

The factors which govern the fibers contribution is one the basic mechanical properties of the fiber itself plays a very important role for deciding the factor is one of the factors; next is the surface interaction generally the fiber is a very thin diameter material and it is made out of ceramic when you talk about glasses it is the ceramic material and polymer is an organic material. So, connecting these 2 guys is always a big challenge; that means, to say the wet ability of the polymer on top of the glass fiber is always a big challenge.

So, they always try to add one more coating on top of the glass fiber. So, that they have a proper adhesion between the polymer and the fiber. So, there when you make a fiber you always try to have a directional property and this directional property when you try to make the wet ability becomes very less. So, we always use a word called as sizing factor or we as this silent coating we used to give this coating tries to have a surface interaction between the fiber and the resin. Next the amount of fiber the fiber amount can vary from 2 percent it can go up to even 90 percent.

Today, we make 90 percent reinforced composites for special types of application. So, the amount of fiber is always called by term called as fiber volume fraction the amount of fiber present in the composite. The last thing is the orientation of the fiber also plays an important role I can try to orient my fiber in the required direction. So, that I get the best property out of it. So, I summarize here. So, the function of the fiber the factors that govern the fiber contribution are one the mechanical property of the fiber itself whether it is made out of glass, whether it is made out of ceramic, whether it is made out of polymer, whether it is made out of a natural material so, that property dictates that is first thing. Second thing is the surface interaction between the fiber and the resin. So, that is very important, locking of the fiber with the polymer matrix is very important. So, it forms a term called as interface the interface should be always good that is one another governing factor.

The third governing factor is going to be the fiber volume fraction amount of fiber present in the composite and the last one is orientation of the fiber when I talk about orientation now you are very you should be understanding that I can orient the fiber in any direction I want 0, 45, 90, 30 whichever direction you want you can try to orient and get it. When I say orientation of the fiber you can also wind the fiber around the composite. For example; for the solid fuel which is stored in rocket they have a vessel and this vessel the roving is spun around it to get the required property. So, orientation of the fiber also plays a very important role.

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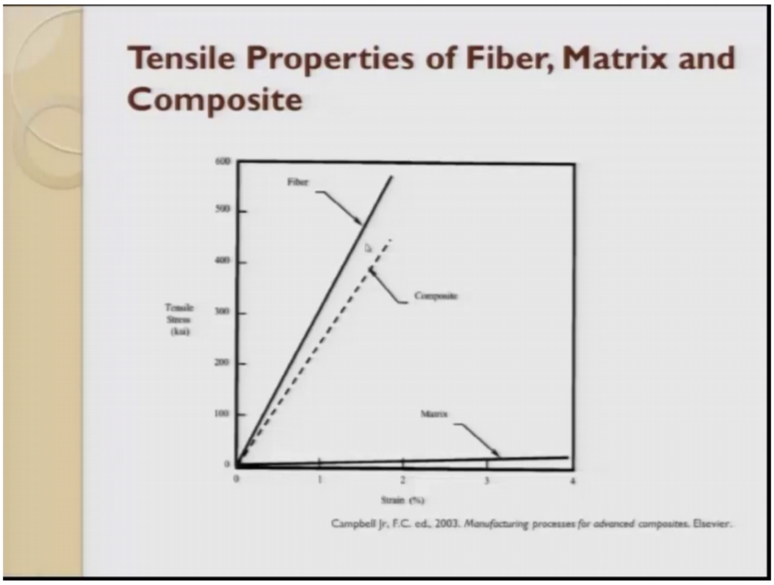

So, a little bit of understanding about the mechanical properties suppose you here you can very clearly see the influence of matrix with respect to tensile stress and strain. The matrix has lot amount of strain, but the strength or the stress is very low. When you talk about a fiber, the glass fiber, there is not much of strain, but the strength goes very high. So, where is a composite, a composite is somewhere in between these 2 you can see a composite which has a property less than the tensile stress of the fiber glass and above the matrix.

Now, you should be able to appreciate the properties of a composite with respect to fiber and matrix. You can keep changing this strength properties moving towards this side or this side you can keep doing it depending upon the volume fraction. So, volume fraction also plays a very important role.

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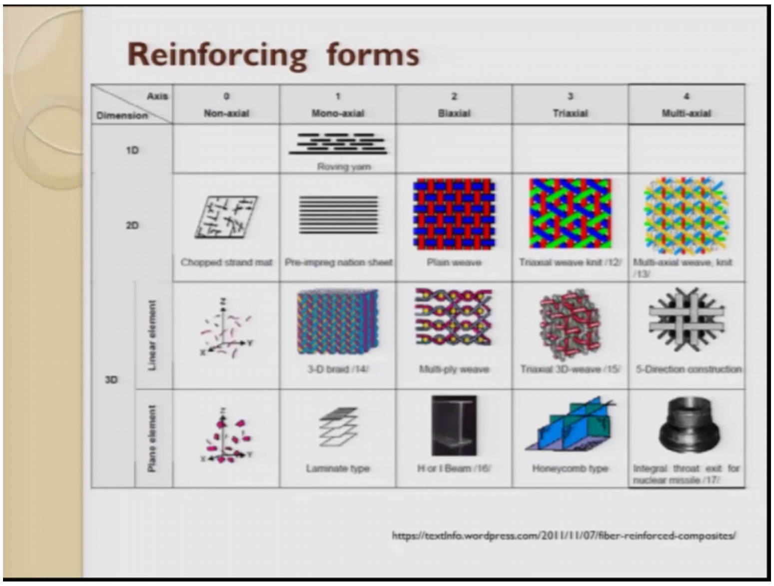

So, now here are some of the forms of reinforcement. So, here we have given 1D. 1D is a roving; that means, to say a thin thread like structure which runs for kilometers. So, it is 1D. So, this 1D can be cut and then it can be used for weaving and it is weft and then you try to get a 2D. So that means to say, I take x direction of 1D then cut this and then create a y direction of 1D then you try to view this 2 1D s you get a 2D.

So, if it is a continuous fiber we try to get something like plain weaves like this if it is a short fiber what we do is we cut all the short fibers they can be random or they can be oriented in one direction we stack them and then we press them. So, here you see here it is called as chopped strand mat. It is like your foot mat which you put at the entrance of the door you can see coir. So, in the similar way you will have a glass or a carbon fiber chopped strand mat generally we use glass chopped strand mats for making composite.

So, several of these lamellae join together to form a laminate, which we discussed last time.

So, here you can see pre impregnated national sheet so, what were notions sheet. So, this is nothing, but here it is not the fiber alone, a polymer is also injected and it is something like a readymade laminate which is there. So, what you do is you remove the top cover bottom cover you stack them in whatever directions you want and you make a laminate. So, this is the second thing which is also in mono axial. So, here you can see biaxial the unidirectional mat the bidirectional mat which I was talking to about this is what it is you can see this is weft direction and this is warp direction and both direction can have uniform volume fraction, the thickness of the bundle of the glass fiber or it can also have lesser in one direction and the other direction it can have more.

So, this is plain weave, you can also have tri axial weave knit. So, you can see here the mat is made in 3 direction. So, one direction is straight which is flowing the other direction is at 45 degrees plus and the blue one is assume it is minus 45 you can have 3 directions weaving and to make a 2D mat then let us move to the next. So, this is multi axial weaving. So, why is the difference between 3 axial and multi axial why is it required the as you want to enhance your strength properties you will always go for this if it is a plain simple geometry we always go for plain weaving or we can even go for pre-impreg notion sheet 1D mono axial sheets we can go.

But moment it becomes higher strength and you would like to have a complex part we used to go for tri axial or multi axial. So, today there is a big push towards 3D composites. Till now we are enjoying 2D composites and now the market is pushing towards 3D composite why because when you try to stack all this lamina and make a laminate that can be a defect called as delamination. Delamination means there is not a 100 percent proper bonding between the 2 layers. Moment there is a small defect and you put it in a service condition, the crack keeps growing very fast.

In order to avoid this now people have started using triaxial weaving or 3D composites. 3D composites are here you see that the fiber reinforcement is done weaving in all 3 directions this is called as 3D braid. So, you completely make a pre form of the required product and then you try to infuse resin you make a composite material. So, the advantage is, it has very high strength and it has also the proper reinforcement at the required spot this can be done by the 3D composite. So, here there are some of the variants you can say multiply weaves you can also see tri axial 3D weaves. So, this is slightly complex this one 2D and now it is becoming 3D.

Now, you see 5 directional construction is also there. So, 5 direction means it is xyz then any 2 axis rotation; rotation about x, rotation about y or rotation about z you can do and then you try to make it. So, here you can these weavings are more focused towards the product of very high strength. So, you can see here this is a linear element and you can also see plane elements, so, laminate which I have explained. So, you can see here directly they make an eye beam, directly they make a honeycomb structure and then directly they make a throat exit for the nuclear missile they make it. This is all reinforced now. So, now, what they do is they just like try to infuse resin to give a shape to it.

So, reinforcement it should be clear that it can exist in any of these 3 forms one is 1D, 2D and 3D. So, 3D is the need of the r. So, people are working on 3D composites people are trying to understand the failure mechanisms in 3D composites. 2D to a large extent people have understood. So, 1D you can make 2D, so, 2D is a sheet from seeps several of the sheets stacking together and then stitching these sheets will always lead to 3D. 3D will have very high strength properties.

So, now let us see the classification of fiber reinforcement. Here, what we have classified is only the form. So, this can be made out of glass fiber, this can be made out of carbon fiber, it can be made out of Kelvar fiber, it can be made out of graphite. So, these are different type materials which are involved, but these materials are different and the form is different both try to influence the required output that is what I have explained here the mechanical properties of the fiber itself. Apart from these 3, mechanical property of the fiber itself influences the property.

So, please keep that in mind. Here are some of the different types of reinforcement.

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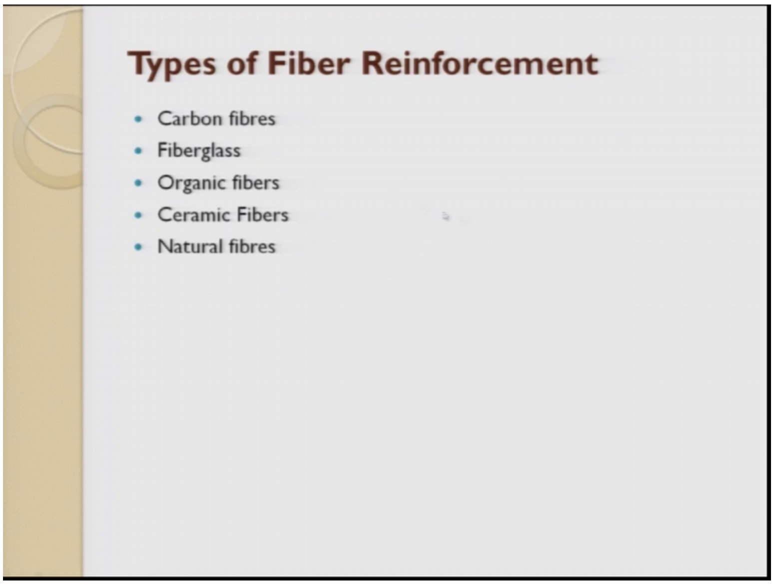

One is carbon fiber, next is fiberglass which is very exhaustively used. We also can have organic fibers, we can have ceramic fibers. Today, there is a big push towards natural fibers also.

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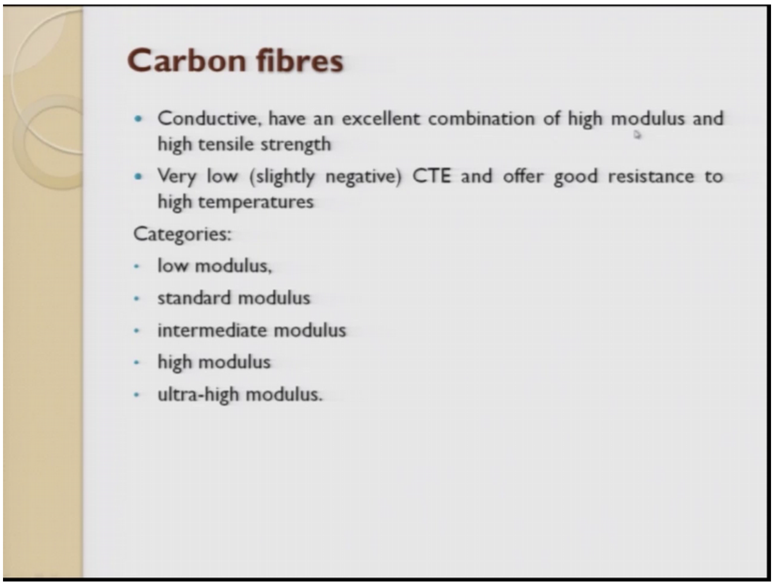

Carbon fibers have very excellent modulus and the very high modulus and very high strength it has very low coefficient of thermal expansion and offers a good wear resistance of very high temperatures. That is why carbon fibers are today exhaustively used in aerospace application, it is very expensive, but it also gives excellent modulus and strength on top of it is lightweight it finds lot of applications in these properties the coefficient of thermal expansion plays a very important role, it is slightly negative.

So, you can understand that there will not be any expansion of the part when it is put in assembly. They are categorized into low modulus, they can also have low modulus, standard modulus, intermediate modulus they have high modulus and ultra high modulus. These are some of the categories you can use, what we do is, we try to tweak around the starting raw material of the carbon fiber so that, we try to fit in any of these modulus what we want and try to get a required output.

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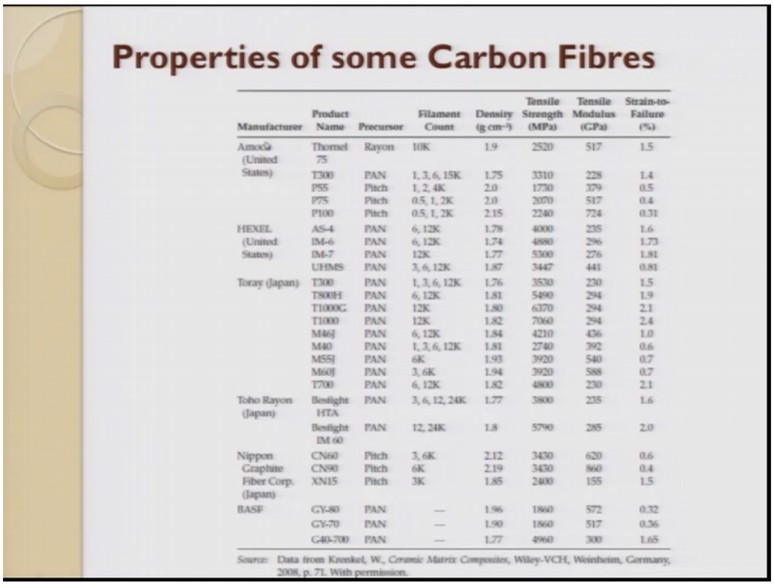

Manufacturer	Product Name	Precursor	Filament Count	Density ($g\,cm^{-3}$)	Tensile Strength (MPa)	Tensile Modulus (GPa)	Strain-to-Failure (%)
Amoco (United States)	Thornel 75	Rayon	10K	1.9	2520	517	1.5
	T300	PAN	1, 3, 6, 15K	1.75	3310	228	1.4
	P55	Pitch	1, 2, 4K	2.0	1730	379	0.5
	P75	Pitch	0.5, 1, 2K	2.0	2070	517	0.4
	P100	Pitch	0.5, 1, 2K	2.15	2240	724	0.31
HEXEL (United States)	AS-4	PAN	6, 12K	1.78	4000	235	1.6
	IM-6	PAN	6, 12K	1.74	4880	296	1.73
	IM-7	PAN	12K	1.77	5300	276	1.81
	UHMS	PAN	3, 6, 12K	1.87	3447	441	0.81
Toray (Japan)	T300	PAN	1, 3, 6, 12K	1.76	3530	230	1.5
	T800H	PAN	6, 12K	1.81	5490	294	1.9
	T1000G	PAN	12K	1.80	6370	294	2.1
	T1000	PAN	12K	1.82	7060	294	2.4
	M46J	PAN	6, 12K	1.84	4210	436	1.0
	M40	PAN	1, 3, 6, 12K	1.81	2740	392	0.6
	M55J	PAN	6K	1.93	3920	540	0.7
	M60J	PAN	3, 6K	1.94	3920	588	0.7
	T700	PAN	6, 12K	1.82	4800	230	2.1
Toho Rayon (Japan)	Besfight HTA	PAN	3, 6, 12, 24K	1.77	3800	235	1.6
	Besfight IM 60	PAN	12, 24K	1.8	5790	285	2.0
Nippon Graphite Fiber Corp. (Japan)	CN60	Pitch	3, 6K	2.12	3430	620	0.6
	CN90	Pitch	6K	2.19	3430	860	0.4
	XN15	Pitch	3K	1.85	2400	155	1.5
BASF	GY-80	PAN	—	1.96	1860	572	0.32
	GY-70	PAN	—	1.90	1860	517	0.36
	G40-700	PAN	—	1.77	4960	300	1.65

Source: Data from Krenkel, W., *Ceramic Matrix Composites*, Wiley-VCH, Weinheim, Germany, 2008, p. 71. With permission.

So, here are some of the manufacturers which are available. Manufacturing of carbon fiber is not a easy task because the carbon has to be maintained it has to be carburized at a very high temperature getting a carbon precursor, purifying it to a highest level and then processing it at the higher temperature continuously, puts a huge challenge in carbon fiber.

So, India has been working on carbon fiber manufacturing for quite a long time and recently we have achieved it, now we have some factories in India which makes carbon fibers. Here are the product names which are available and these are the precursors, if you see there are 2 types of precursors; one is 3 types. In fact, Rayon, PAN and Pitch these are the 3 types of precursors these are all petroleum product precursors and then you can see the filament count. So, this K starts for 1000, 2000 counts and you see that density is very light. So, it is number at 1.8, 1.75, 2.0 and something like that. Tensile strength very high, tensile modulus very high, strain to failure is also very low. So, this makes carbon fiber a good alternative material for bulletproof jackets, rocket applications, helmets which is used by defense personalities all these places carbon fiber plays a very important role. Understanding the process of making carbon fibers from PAN itself is a big topic of discussion, we will not get into that.

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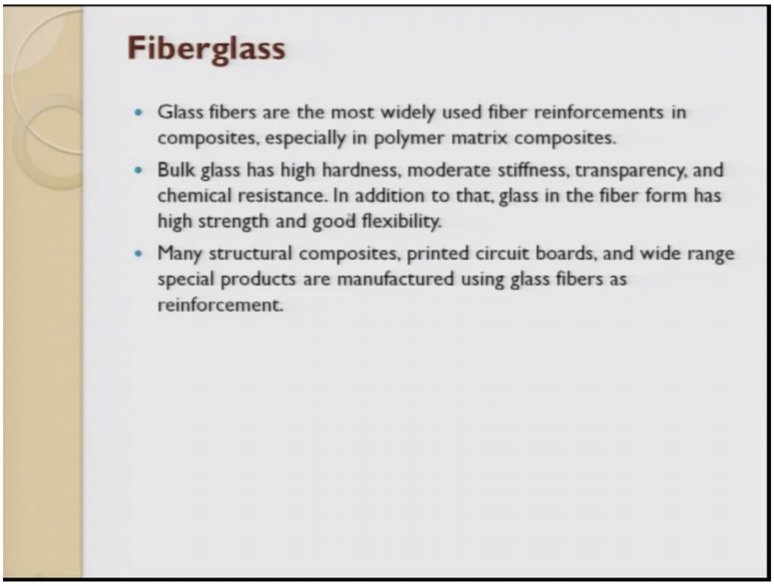

The next most common fiber which is used is glass fiber. Glass fiber is very economical and it has been in the market for quite a long time. Glass fiber is the most widely used fiber reinforced composite. It can be in a roving, it can be in a in a sheet form, it can be in a 3 dimensional form also. The bulk glass has high hardness, moderate stiffness, transparency and chemical resistance. In addition to that, the glass in a fiber form has very high strength and good flexibility. So, because of this high strength and flexibility glass fibers are used in polymer matrix composite. As I told this glass fiber, when it is wetted with polymer they do not have a good adhesion. So, we always do a silent coating on top of this glass fiber so that, they get locked to the cross linking and get a proper adhesion.

Many structural components like PCBs and other wide range of products are manufactured using glass fiber reinforced composites.

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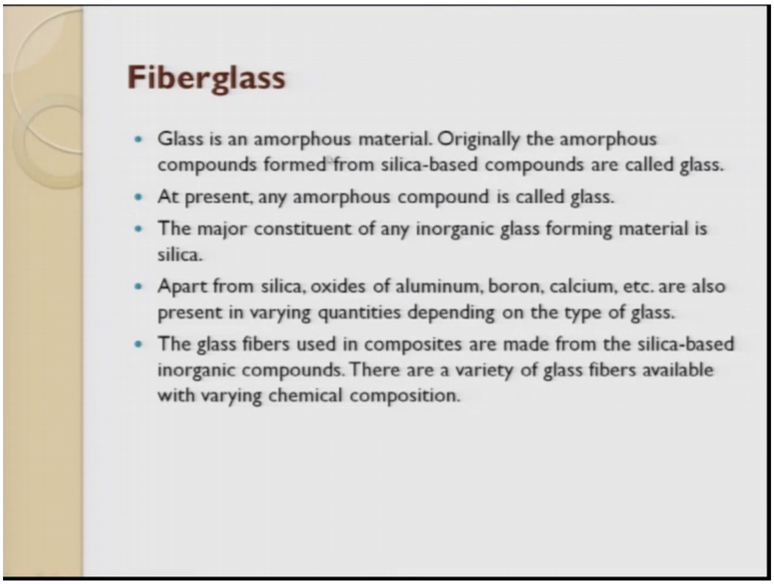

The glass is an amorphous material. Originally the amorphous compound formed from silica based compounds and are called as glass. At present, any amorphous compound is a glass. The major constituent of an inorganic glass forming material is silica. So, apart from silica, oxides of aluminum, boron, calcium, etcetera are also present in varying quantities depending upon the type of the glass. Based upon the ingredients present, the properties changes, you can also try to make it electrically conductive, electrically insulating all these things can be played around by adding this ingredients. It is not exclusively glass, it is also with the ingredients which makes the glass fiber more hybrid property has more hybrid makes it more hybrid property.

The glass fibers used in composites are made out of silica based inorganic compound. There are a wide glass fiber available with varying chemical compositions; this chemical compositions leads to different mechanical strength properties.

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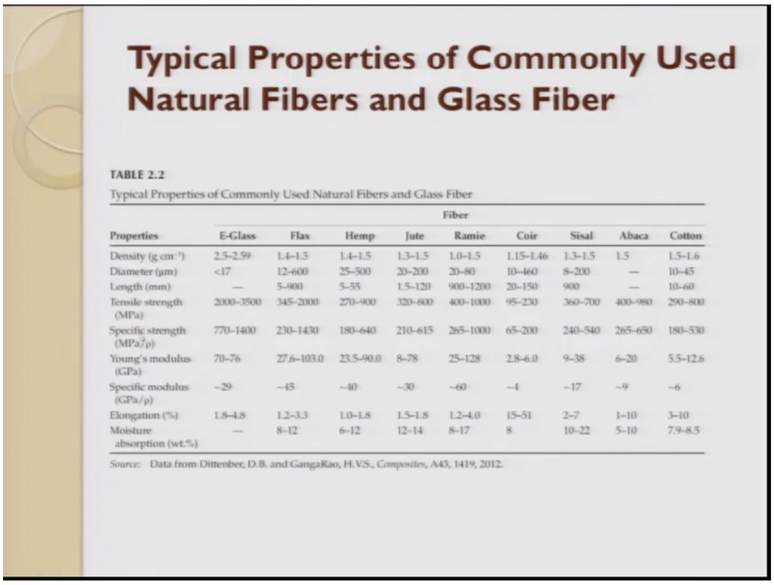

Typical Properties of Commonly Used Natural Fibers and Glass Fiber

TABLE 2.2

Typical Properties of Commonly Used Natural Fibers and Glass Fiber

	Fiber								
Properties	E-Glass	Flax	Hemp	Jute	Ramie	Coir	Sisal	Abaca	Cotton
Density (g cm^{-3})	2.5–2.59	1.4–1.5	1.4–1.5	1.3–1.5	1.0–1.5	1.15–1.46	1.3–1.5	1.5	1.5–1.6
Diameter (μm)	<17	12–600	25–500	20–200	20–80	10–460	8–200	—	10–45
Length (mm)	—	5–900	5–55	1.5–120	900–1200	20–150	900	—	10–60
Tensile strength (MPa)	2000–3500	345–2000	270–900	320–800	400–1000	95–230	360–700	400–980	290–800
Specific strength (MPa/ρ)	770–1400	230–1430	180–640	210–615	265–1000	65–200	240–540	265–650	180–530
Young's modulus (GPa)	70–76	27.6–103.0	23.5–90.0	8–78	25–128	2.8–6.0	9–38	6–20	5.5–12.6
Specific modulus (GPa/ρ)	~29	~45	~40	~30	~60	~4	~17	~9	~6
Elongation (%)	1.8–4.8	1.2–3.3	1.0–1.8	1.5–1.8	1.2–4.0	15–51	2–7	1–10	3–10
Moisture absorption (wt.%)	—	8–12	6–12	12–14	8–17	8	10–22	5–10	7.9–8.5

Source: Data from Dittenber, D.B. and GangaRao, H.V.S., *Composites*, A43, 1419, 2012.

So, here are different types of glass or here is a E-glass in front of you here are the densities, diameter. It is all in microns look at it 17 microns, length, it can run to few I put a dash here, but it can run up to meters then tensile strength specific strength Young's modulus, Specific modulus then you can see elongation and moisture absorption. Moisture absorption is one of the very important parameter which should be noted while deciding which fiber which matrix to choose, because this moisture present in the service condition tries to dictate the performance of the composite. So, here apart from E-glass I have put the other natural fibers which are also available today you get from flax, you get from hemp, you get from jute, you get from coir, you get from cotton.

These are some of the fibers, of course, there is a huge sacrifice in the strength properties, but people are looking forward for natural fibers because they wanted to use free cycling of composites and they also wanted to make products which are sustainable. E-glass fibers are not so easy for biodegradable. You can also have organic fibers. So, organic fibers means they are they have basically made out of c and h.

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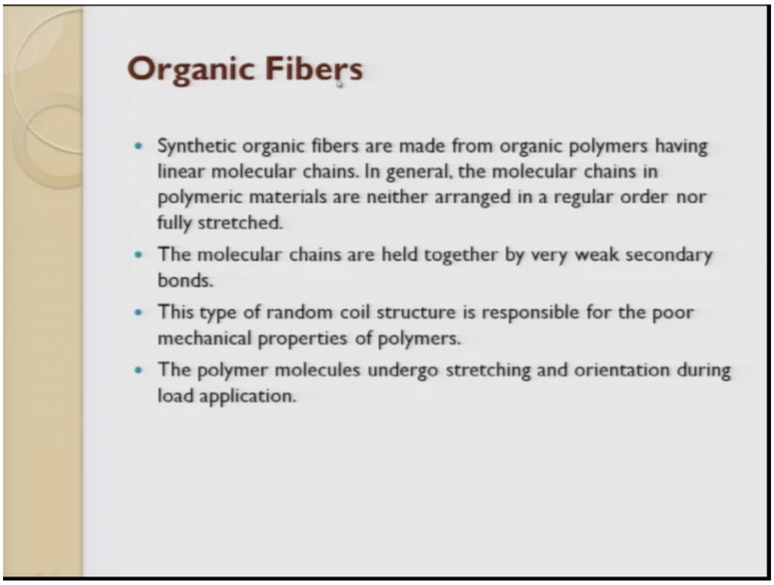

So, synthetic organic metal are made out of from organic polymers having a linear molecular chain. So, what happens is the chains will be spread in multiple directions when you try to pull the chain in one direction, all these the chains molecules will be arranged in one direction. In general, the molecular chain in the polymeric matrix is neither arranged in an order the nor fully stretched. So, what happens is when you try to make it to the fiber form all these things move in one direction and try to give us the property.

The molecular chain are held together by very weak secondary bonds. The type of random coil structure is responsible for poor mechanical properties that is what I said when you try to stretch it they all get to align in one direction and then give a very high strength. The polymer molecules undergo stretching and orientation during the load application. This is how you convert a normal polymer into a fiber by applying load in the in the required direction, the fiber gets their required mechanical properties.

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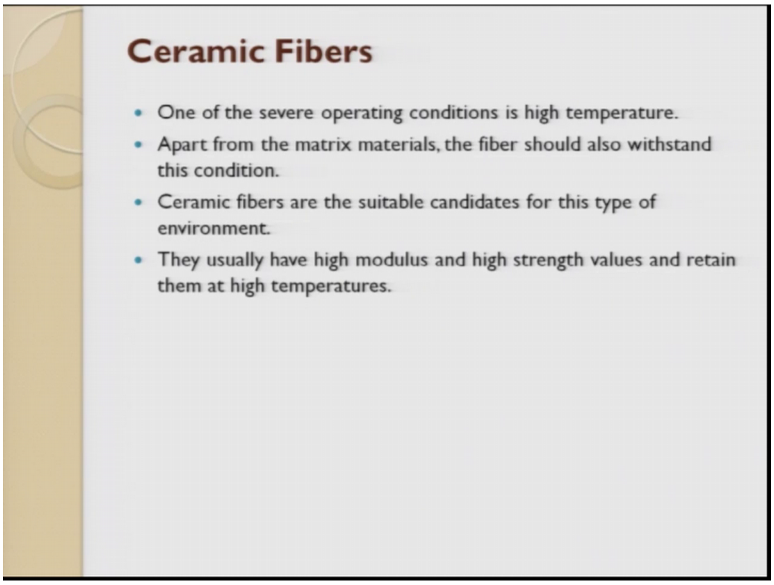

You also have ceramic fibers. Ceramic fibers are gaining popularity slowly, but it has its own limitations as far as processing and making a composite one of the severe operating conditions are very high temperatures you always go for ceramics.

Apart from the matrix metal the fiber should also withstand very high temperature. The ceramic fibers are suitable candidates for very high temperature applications. Usually high modulus, high strength at higher temperatures we go for ceramic fibers. Again the ceramic fibers are of 2 classifications. Generally ceramics are classified into oxide or non oxide. So, here the ceramic fibers are also classified into 2. 1 is called as oxide and another one is called as non oxide. Oxide, basically are alumina-silica systems including alpha alumina. So, what they do is they try to tungsten carbide on top of it they try to coat alumina or silica. For example, if you want to do a non oxide fiber they predominantly take SIC material that is coated on a boron carbide on a tungsten carbide wire and then they call it as a ceramic fiber.

So, they are polycrystalline fibers with a grain size of less than 1 micron and generally provide with a diameter of less than 20 microns. The production cost of these fibers are significantly lower than those of a single crystal fiber or a whisker because to a large extent they do not they are fabricated easily. So, it has made the roll to roll. So, a wire is pulled out of one in a in spool and then it is getting coated in a PVD system or a CVD system and then it gets predominantly to CVD for economical reasons, then it is wound on a out spool or a completed spool where in which they have a coating of this ceramic fibers.

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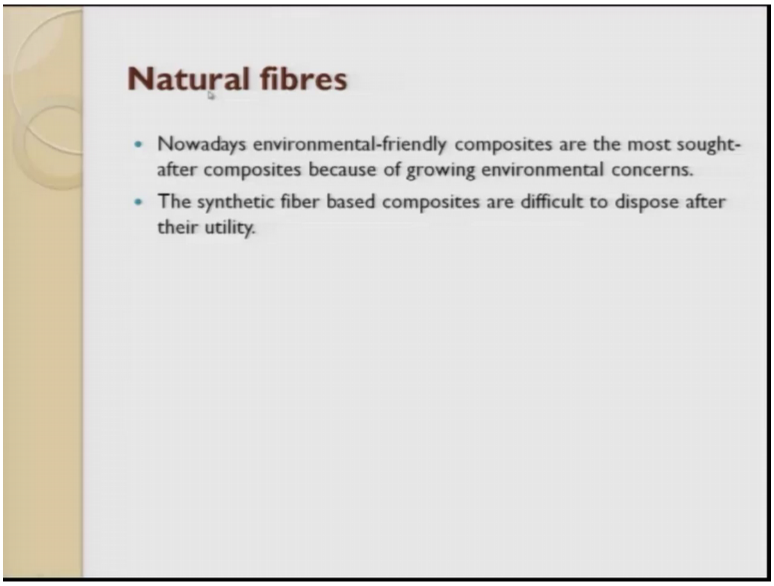

So, natural fibers we saw the properties natural fibers today people have started extracting from banana, coir, coconut coir and all these things for sustainable products people are looking forward for solutions and the polymer which is used in this natural fiber composite they are also trying to use recyclable. So, basically they are using for thermoplastic natural fiber reinforced composite.

But, however, since they are having lot of processing difficulty even today people use epoxy on polyester and use natural fiber for reinforcing. The natural fiber reinforcing composites here they are not looked forward for primary strength application they are always looked for secondary structures. For example, rooftop, then what you see in the dive boards used in an amusement park, the boat hull where there is a secondary structure so; that means, to say they do not take major strength, but it is used for a covering.

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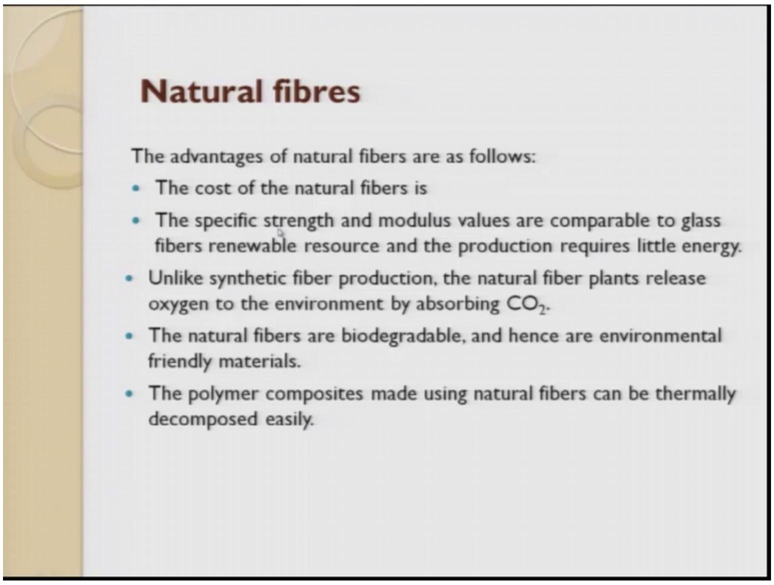

So, all these places now they are started using this natural fibers. So, they have the advantage one is cost is a major advantage; that means, to say it is economical, specific strength, modulus varies as compared to glass fiber and the fiber renewable resources and the production requires lesser energy. Unlike synthetic fiber production, the natural fiber plant releases oxygen to the environment by observing CO 2. The natural fibers are biodegradable and the polymer composite made out of natural fibers can also be made can be thermally decomposed easily; that means, to say people are looking forward for recyclable parts.

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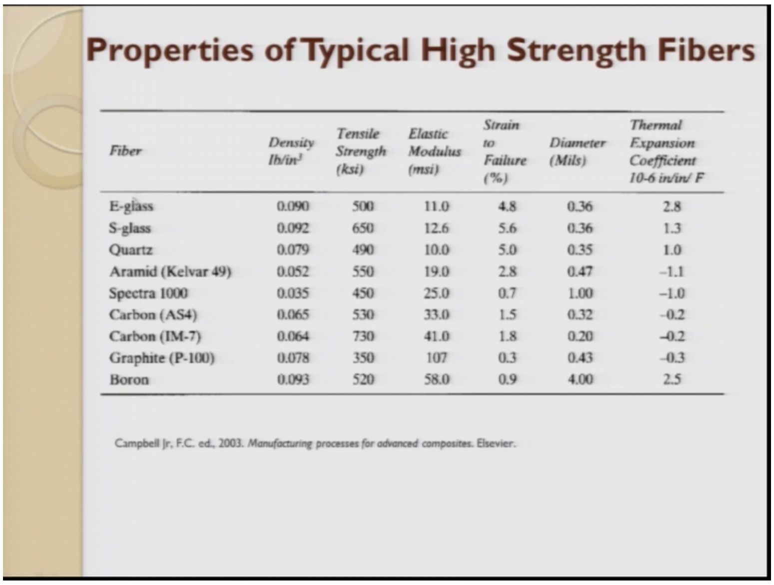

Properties of Typical High Strength Fibers

Fiber	Density lb/in^3	Tensile Strength (ksi)	Elastic Modulus (msi)	Strain to Failure (%)	Diameter (Mils)	Thermal Expansion Coefficient 10-6 in/in/ F
E-glass	0.090	500	11.0	4.8	0.36	2.8
S-glass	0.092	650	12.6	5.6	0.36	1.3
Quartz	0.079	490	10.0	5.0	0.35	1.0
Aramid (Kelvar 49)	0.052	550	19.0	2.8	0.47	–1.1
Spectra 1000	0.035	450	25.0	0.7	1.00	–1.0
Carbon (AS4)	0.065	530	33.0	1.5	0.32	-0.2
Carbon (IM-7)	0.064	730	41.0	1.8	0.20	-0.2
Graphite (P-100)	0.078	350	107	0.3	0.43	-0.3
Boron	0.093	520	58.0	0.9	4.00	2.5

Campbell Jr, F.C. ed., 2003. *Manufacturing processes for advanced composites*. Elsevier.

So, here are some of the glass fibers, carbon fibers, here are their density here are their strength, the elastic modulus, strain, diameter and then the thermal expansion. You see the carbon, it always has negative coefficient of thermal expansion. There is a new material which is an offshoot of carbon which is called as Aramid Kelvar. The starting carbon is the precursor is a different material. So, Kelvar 49 this is used for bulletproof jackets you can see the thermal expansion is a robot minus 1.1 percentage, whereas, E-glass the thermal expansion is 2.8. That means, you say as and when the temperature goes high they come the product also slightly expands. So, I told depending upon the impurity there can be different types of glass fibers. So, it is E-glass fiber, S-glass fiber and quartz they are basically a compositional difference coming here. So, these are carbon and carbon fiber when it is taken to a very high temperature it gets graphitized.

In a very high temperature where there is no oxygen pyrolysis you do it converts into graphite. Graphite has a density of this is the graphite density and then it has a tensile strength. So, you can see the elastic modulus, you can also see the thermal expansion. So, here this is also used for lubricating effect. So, what happens as graphite they have if you have several stacks of layers of graphite there, in between these layers there will be a very weak bond. So, graphite can easily slide in this shear direction. So, boron as I told you tungsten which is given a boron coating. So, you can see these are the fibers which has very high strength boron 520.

So, you can see which is close to carbon fiber it is used for very high temperature applications and here polymer also is not it is not in a polymer stage the matrix gets converted into carbon so that, it is very easy to withstand very high temperatures.

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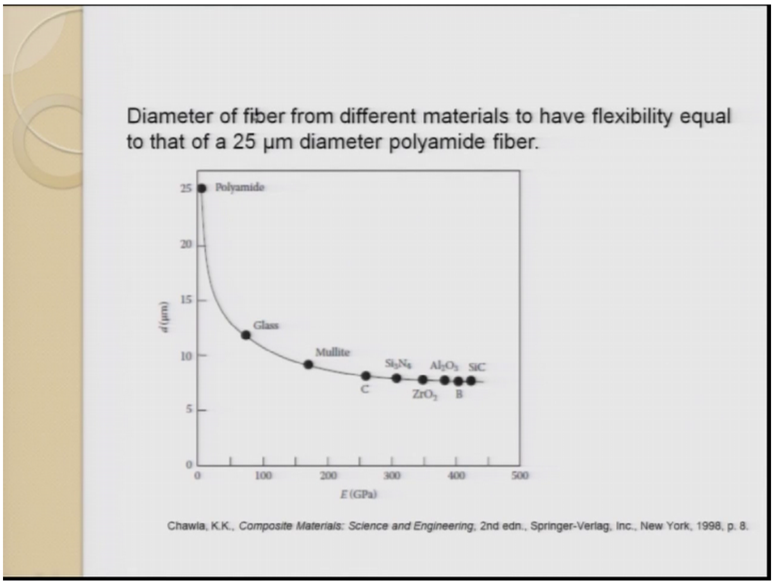

Here is a graph which compares the diameter of the fiber for different reinforcing material to have a flexible equal to around about 25 diameter polyamide. So, here we can take this as a d diameter polyamide starting from 25 diameter, you can see the e is the Young's modulus. So, you see E, polyamide has around about very low E, Young's modulus, glass fiber is better than mullite is a is a offshoot of glass. Then you have a carbon then silicon nitride zirconium, alumina and you see SIC.

Today, people are talking about SIC reinforced composites for high temperature and high strength application. So, this is a graph which compares and tells with respect to d and E which is diameter and E. So, this we are all talking about an individual fiber several of these fibers stuck together to form a roving. So, several of the roving put together forms a mat several of the mats put together forms a laminate. So, please keep that in mind. So, this is a graph which talks about diameter and E.

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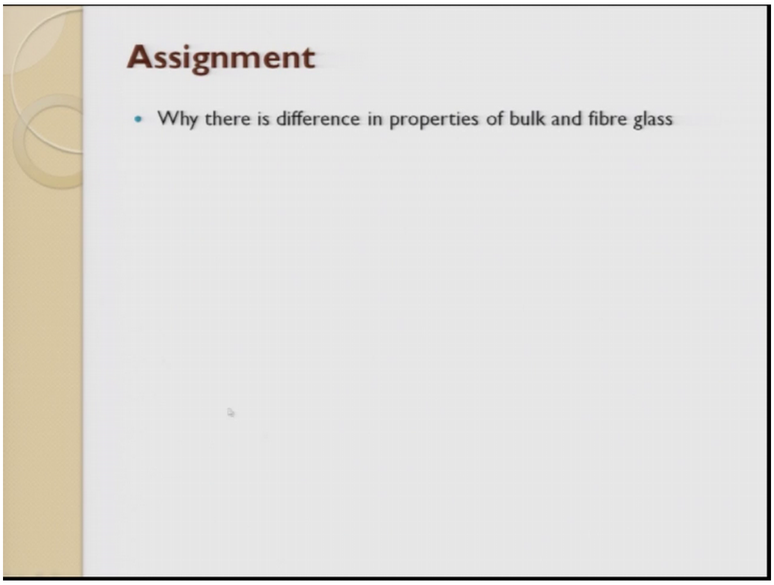

So, with this we come to the end of the lecture 3. So, what we saw was, we saw, what is the function of a reinforcing, what are the different forms of the reinforcement, then what are the different materials which are used for reinforcement and then how is it influencing the mechanical properties.

So, today we will stop the lecture with a small assignment, the bulk property of glass and the glass fiber properties are entirely different why is it so? I repeat, the bulk whatever you take glass which is used in the glass panel you throw a stone it breaks it shatters into pieces, whereas, when we talk about a glass fiber we talk about E very high properties for example, you look at this E is around about tensile strength is 500 ksi and then Young’s modulus is around about msi it is around about 11. So, it is very high where is this difference though the starting material is the same, but you get different mechanical properties, why is it so.

Thank you very much.