Nature and Properties of Materials
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Lecture 28
Materials Selection in Engineering Design

So far we have talked about various types of materials, but in this last series we will enter into the application of this knowledge domain. That means now we are going to talk about how all this knowledge that you have acquired so far, on the basis of that knowledge how you can basically select a particular material for some engineering design application. So there will be various case studies that we will carry out and this will be really the test of how much knowledge to have acquired towards the material properties.

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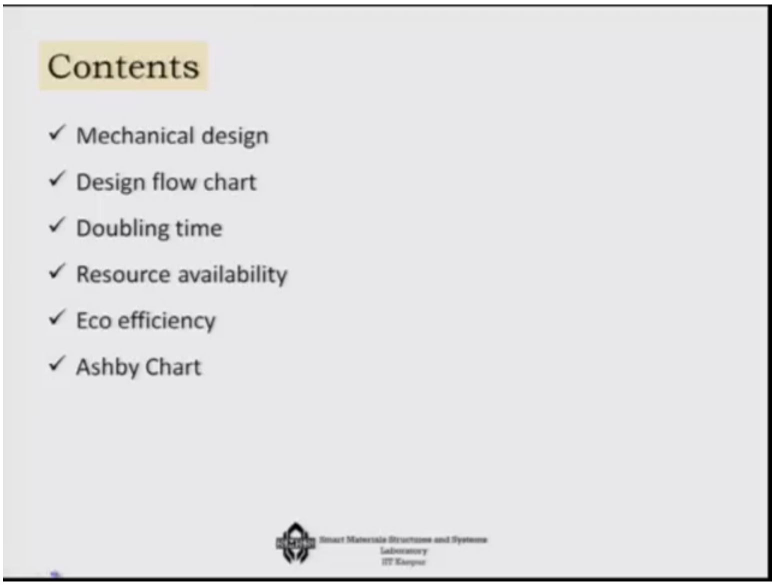

So what we are going to talk about one example is the general, today we will discuss all these things in principle and from the next class we will talk about that how to apply it. So today we are going to talk about the general aspects of the mechanical design, design flowchart and the doubling time issues, resource availability, eco-efficiency and finally the Ashby chart. The knowledge of Ashby chart which is the culmination of today’s lecture is very very important for us to apply from the next lecture onwards.

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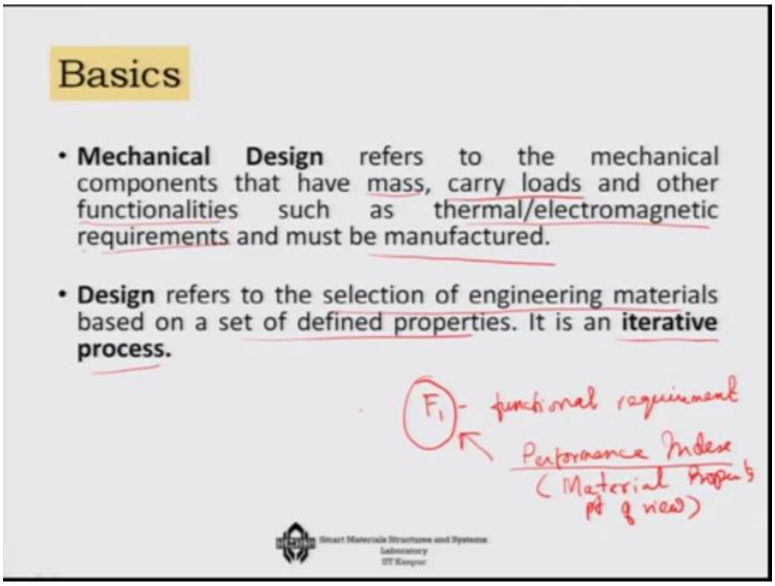

So let us 1st talk about that what do we mean by mechanical design, because I said that we are going to talk about material selection for mechanical design. Now, mechanical design refers to the mechanical component design which has definitely some mass and which will carry some load that is functional and also it may have other functionalities such as thermal or electromagnetic requirements and then it must be manufactured. So that is the way this kind of design would qualify.

And the design for say would refer to the selection of engineering material based on a set of defined properties, so it will be naturally an iterative process. What we will try to do is that, corresponding to some functional requirements let us say you have functional requirement A, so you have a particular personal requirement let us say then corresponding to this requirement, we will you say F1 is the functional requirement we will try to find out that what is the performance index that we should look for and this performance index we should look for from the material property point of view.

So this will be from the material property point of view. And then we will go through all our knowledge of the material and we will see that which group of materials can give you the best performance index that means that satisfies this function in the very best manner, so that is what is the sense of the whole direction.

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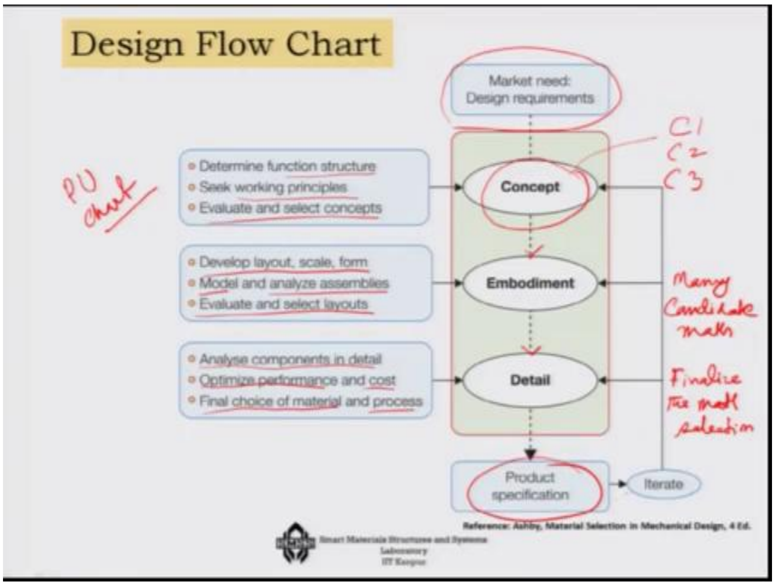

Now in any particular design when we do what exactly we actually carry out in this design process. So we 1st start with the market need, what are the design requirements in a market? Let us say tomorrow I want to develop I find out that there is a energy crisis, so there is a market need of developing a micro scale energy solution. Then we have to find out what is the design requirement, do I need to actually design a system which is which can extract energy from say wind energy or from water or maybe from both or from vibration, so you have to find out what are the design requirements, based on that we have to go for a conceptual solution.

So at this stage, we have to determine what is the function structure that means how many functions this particular concept has to certify and then we have to see what are the work principles corresponding to this function structure and we have to evaluate and select the concept, because you can have multiple concepts right, so one can give many design concepts C1, C2, C3. So each concept you have to find out that in a something called PU chart okay, you have to find out that which concept is good for a particular work and which concept is not so good.

So once we rank these concepts then we choose one concept from that and then we go ahead with the next part which is known as the embodiment design. In the embodiment design part, we actually develop the layout, scale, forms, etc and then we also work on the system model, we analyze the system and then we evaluate and select the layout. So embodiment design is something like a detailed analysis that you have to carry out in order to know that what sort of materials system you will need in terms of materializing the concept.

Then you have to come to the detail, and in the detail part we are going to talk about each of the some assemblies, look into it in details, then optimize the performance, minimize the cost and then choose the final set of material and the process. So, when we are at the conceptual stage generally we do not select the material, but at the embodiment stage we have many candidate materials, so at this stage we have many candidate materials.

And when we are doing the detailed design, here we finalize the material selection and then we see that how the products specifications are satisfied and we can iterate that process okay. Suppose we are not happy with it, we may go back to the concepts; we may look into the other concepts like we can then work with concept 2 or concept 3 and then carry out the same process again and again until and unless we are satisfied with the solution of the system.

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Now, when we will be selecting a particular material for a particular function, what are the points that you have to keep in your mind? The 1^{st} important point you have to keep in your mind is the money that is the price and availability of the material, so that is the 1^{st} important part we have to keep in our mind. Then the 2^{nd} is we have to look into the group of mechanical properties and in this group of mechanical properties we have to think of things like density of the material because many times your system is to be of lightweight, then you have to think of the modulus because modulus is related to stiffness of the system, we will see it through some examples in the next class.

We may have to think of the damping because for dynamic works damping is very important, then the yield strength, the tensile strength, the hardness, fracture toughness, fatigue strength, the thermal fatigue resistance particularly if it is for a high temperature application as well as the creep strength, so these are like certain very important mechanical properties, other than that there could be some other some more properties very specific to the application, but these are definitely some of the very important mechanical properties that we need to look into before we select a particular material.

Next, we are going to talk about the other properties like thermal, like optical, magnetic and electrical properties. This comes because a machine for example today is usually multifunctional and it has to interact with a very complex environment, so you need to know about properties which are other than the so called mechanical properties of the system. Thermal property is one of the examples for example, these gas turbine blades, it has to work in a high temperature environment, so you have to look into the conductivity of the material, so thermal property comes in to a very important property.

There are some applications where the for example a kind of a transparent oven say if I have to design, then I have to think of that the optical property should not be sacrificed with respect to temperature, so then that also comes into picture. Or let us say, you have to design a microscope, and then the optical property comes into the picture. Magnetic and electric property comes into picture for example, just a simple example that you have to design a motor housing, now the magnetic and the electrical properties of the motor becomes important for you.

So thus even for mechanical design, all these things actually gets covered and this becomes important for us. Next is there is chemical environment change, the oxidation, corrosion becomes important. There could be things like there could be friction in the system, so the frictional properties are important, there could be abrasion or wear and tear, so the properties becomes important for us. Now, that is the property number set number 4 that we have to look into it.

Then in the property set number 5, we have to look for the ease of the manufacturing and the joining so this is related to the manufacturability of the system, so design for manufacturing. And then finally, we have to think of the appearance, we have to think of the texture, feel, et cetera, so the aesthetics become important, right. So thus this 6 property set becomes important for us. Now, once we know that these are the property sets, then we have to start to look into that what are the specific property level for each of the property set.

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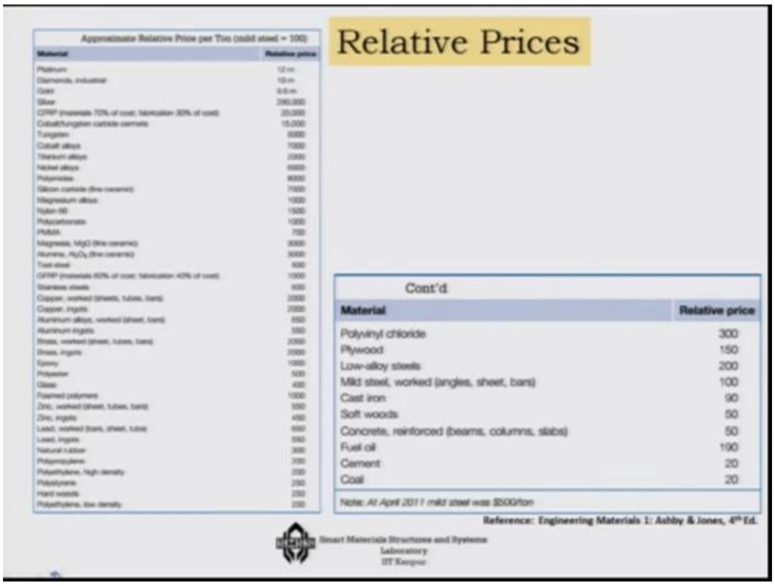

For example, price and availability are the 1st important property set I told you. So if you look into the relative prices of a system, you would see that diamond, platinum, gold, silver, these are all very expensive, right so till this point we are at a very expensive level of the property set. So naturally you cannot use them unless you have a very-very compelling situation of using such materials. So the next interesting material which can be used is actually carbon fibre reinforced plastic, is highly functional I have told you when we have discussed about carbon fibres that is one of the very high performance system are designed using carbon fibres, so this we can use.

And then further for example, tungsten is one of the materials for many space grade applications you will see that the tungsten is used okay, then there will be titanium alloys once again for space grade applications and then polyamides, polyamides are like kevlons if you remember we have talked about Kevlars, right or bullet-proof jackets this is like polyamides. And then once again magnesium alloys, then nylons, polycarbonate, so where we are in terms of for example, steel?

Steel is one of the cheapest materials, so if you look into this list for example, you will see that presence of steel or such material let us say here we have the aluminium alloys in this list okay. Even below the aluminium alloys you can get epoxies, polyester and glasses that mean you can make GFRPs Glass Fibre Reinforced Plastics. And then down this line in fact, somewhere below this because it is not here covered I can see that the steel would come into picture, so this is one of the cheapest material basically it is somewhere here as you can see that this is where is the steel.

So you can use also that as a baseline of your material selection. Let us say, if steel is 100 units of in any units if this particular set would be in terms of basically pound or dollar so however, if it is 100 units in comparison to that if you look at the aluminium alloys, then this is somewhere around 650 units. So that means it is that many times expensive aluminium as a material. So you have to be cautious of that what is the going to be the cost of the system as you are trying to improve the performances using a better material.

And similarly, from aluminium let us say if you want to jump to something like magnesium alloys this is about thousand units, so this is 10 times more expensive than steel. If you want to go for something like tungsten or super alloys, 5000, so it is like 50 times more expensive. If you want to go for something like CFRPs, then it is 20,000 so that means it is 200 times more expensive than steel. This is very-very important for us because we will indeed save lot of weight by using carbon more expensive than steel, by using carbon fibre reinforced plastic, but have to be ready to spend a 200 times more money for that system.

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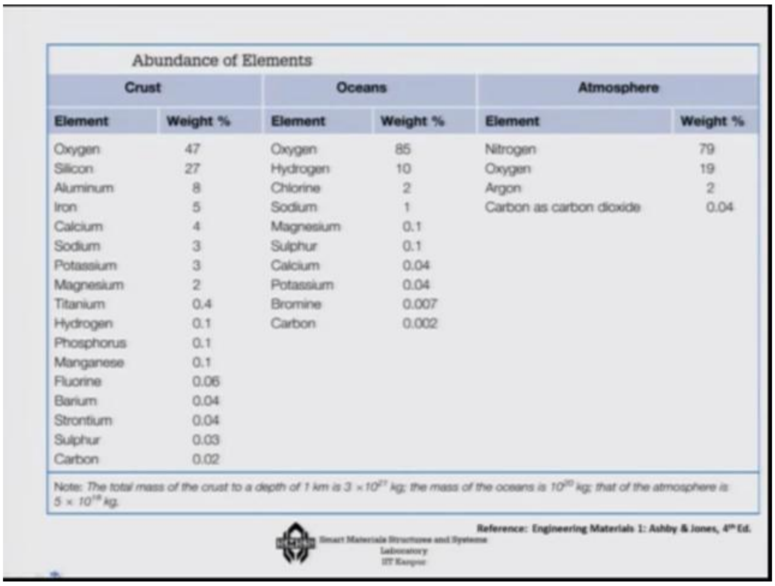

Abundance of Elements

Crust		Oceans		Atmosphere	
Element	Weight %	Element	Weight %	Element	Weight %
Oxygen	47	Oxygen	85	Nitrogen	79
Silicon	27	Hydrogen	10	Oxygen	19
Aluminum	8	Chlorine	2	Argon	2
Iron	5	Sodium	1	Carbon as carbon dioxide	0.04
Calcium	4	Magnesium	0.1		
Sodium	3	Sulphur	0.1		
Potassium	3	Calcium	0.04		
Magnesium	2	Potassium	0.04		
Titanium	0.4	Bromine	0.007		
Hydrogen	0.1	Carbon	0.002		
Phosphorus	0.1				
Manganese	0.1				
Fluorine	0.06				
Barium	0.04				
Strontium	0.04				
Sulphur	0.03				
Carbon	0.02				

Note: *The total mass of the crust to a depth of 1 km is* 3×10^{21} *kg; the mass of the oceans is* 10^{20} *kg; that of the atmosphere is* 5×10^{18} *kg.*

Reference: Engineering Materials 1: Ashby & Jones, 4th Ed.

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Now, let us look into the availability of the materials. There are 2 groups of it that is availability in the earth's crust and availability in ocean and in atmosphere. Of course, atmosphere you get mostly gaseous substances, but in the oceans there are certain things which are very peculiar for example, magnesium good supply from the ocean comes okay, so that is also used as one of the structural materials. However, most of the materials that we use they actually come from the earth's crust itself.

And in terms of abundance you can see that aluminium is about 8%, so aluminium is highly abundant. Next to that is in fact steel, but aluminum's processing cost is more that is why aluminium is actually more expensive than steel, so this actually gives us a broad picture of what is the abundance of different materials. Now, once the abundance there is the particular knowledge which is very important at this stage that is known as the doubling time.

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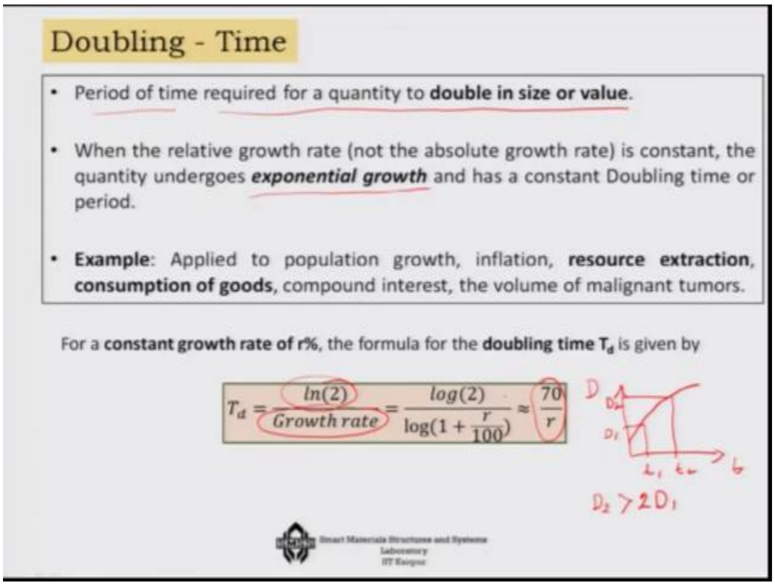

So what is the doubling time? The definition of doubling time is that it is the period of time required for a quantity to double in size or value. That means, if you think of it that this is like X axis is time and Y axis is the demand of a particular material and let us say that the demand is increasing exponentially. So if it is increasing exponentially, than at a particular time T 1 if the demand is D 1, how much of time would it take say T 2 to go to D 2 where D 2 is actually twice of D 1. So that time that is needed between this T 1 to T 2 that is what is the doubling time that is needed.

Now if you assume an exponential growth, in many cases the growth rate will be given to you and hence by knowing the growth rate and logarithmic base of with respect to 2, you can actually approximately find out the doubling time to be about 70 over R, so that means if I know the growth rate, then I can find out that what is the doubling time and if I know the doubling time, then I know that a particular material is of very high demand, which means as I will be designing, I have to be get ready of a situation where its cost may increase because it's doubling time is small.

So material whose doubling time is more, essentially is a either a cheaper material or that material is completely rare, so either of the cases but the doubling time helps you to take a decision on that.

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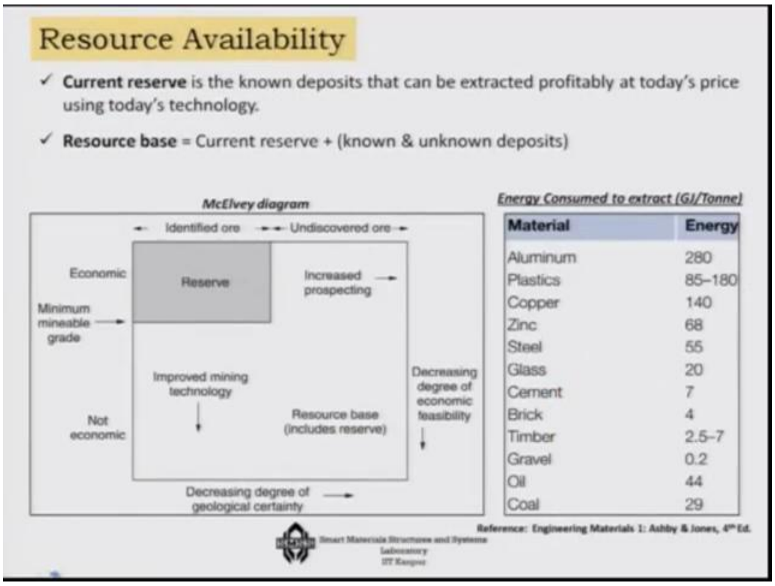

Now this also in terms of the availability, this also brings us to the very famous McElvey diagram okay. So what this diagram tells us is that this is like engineering materials this Ashby and Jones book, you can use it for reference for this particular beautiful diagram that this actually tells us that there are 2 things; one is called reserve and the other one is actually the total resource base. So, you can have actually a very big resource base like this okay.

But a good part of the resource base is maybe actually undiscovered or maybe actually not economic. So it is the economy level and the level of discovered known part actually makes the reserve and the rest of the things are your resource base which includes the reserve of course okay. So for example, if you consider aluminium another point here it is important that why some of the things are not economic? Like if you consider aluminium, it takes about 280 gigajoule per ton, plastics 85 to 180 gigajoules per ton, so these are all high energy consuming, copper 140.

So even if you find it may not be economically feasible to use such a material, so hence your even though you have the resource, you may not be able to consider it as your reserve because it is not profitable at that particular point of time. Now a broad picture I want to tell you.

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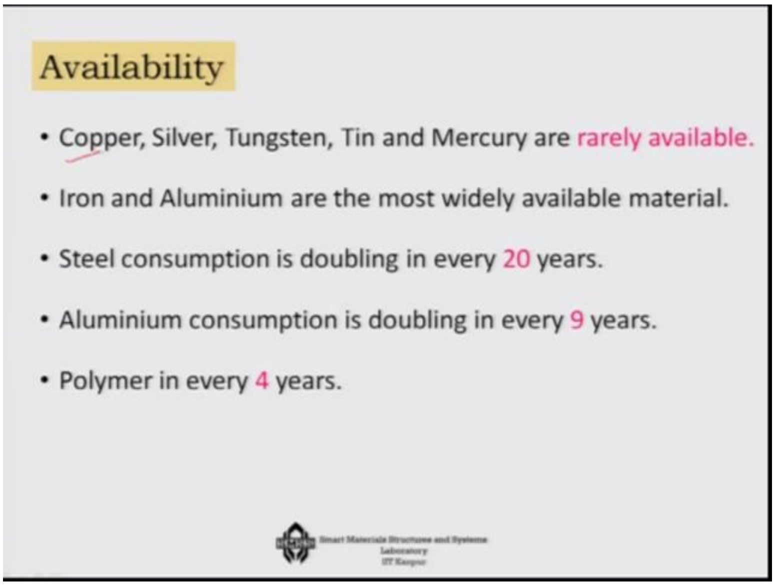

For example, copper, silver, tungsten, tin and Mercury they are rarely available, so you should avoid them by all means from your general design. Iron and aluminium are most widely available materials, so you should try to use them more. Steel consumption is doubling every 20 years, so it is taking time and it is cheaper. Aluminium consumption on the other hand is doubling in every 9 years, so it is doing going at a even faster rate. And polymers in every 4 years, so you have to be cautious of this particular fact that at this point of time polymer is the most popular material is of highest demand, next is aluminium and next is steel, so accordingly you should select the material. How to encounter shortages of material?

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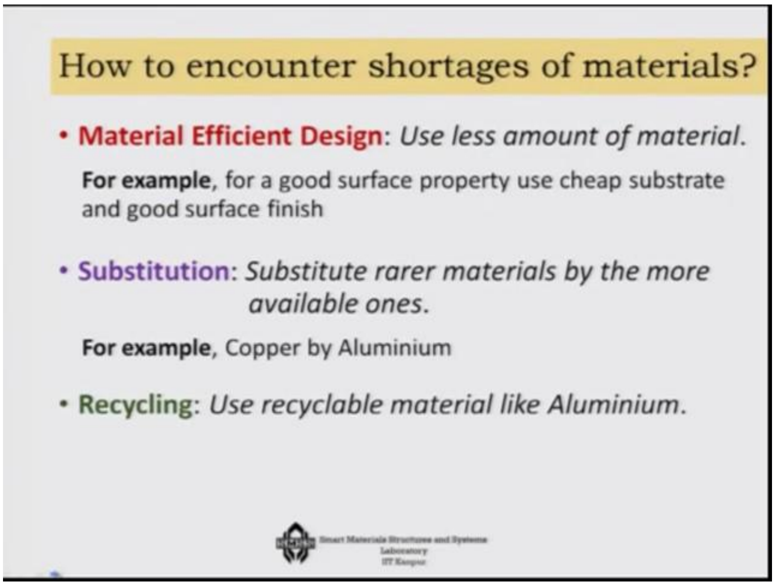

First of all, you have to go for a material efficient design that means use less amount of material for example, for a good surface property use cheap substrate and good surface finish okay, so there are certain tricks of using more material efficient designs. Substitution, substitute rarer materials by the more available ones for example, substitute copper by aluminium in the electrical wires we have seen that this has already taken place. Recycling, use such materials which are recyclable materials like aluminium, this is also being done today, so these are certain strategies that you want to take in order to encounter the shortages of materials.

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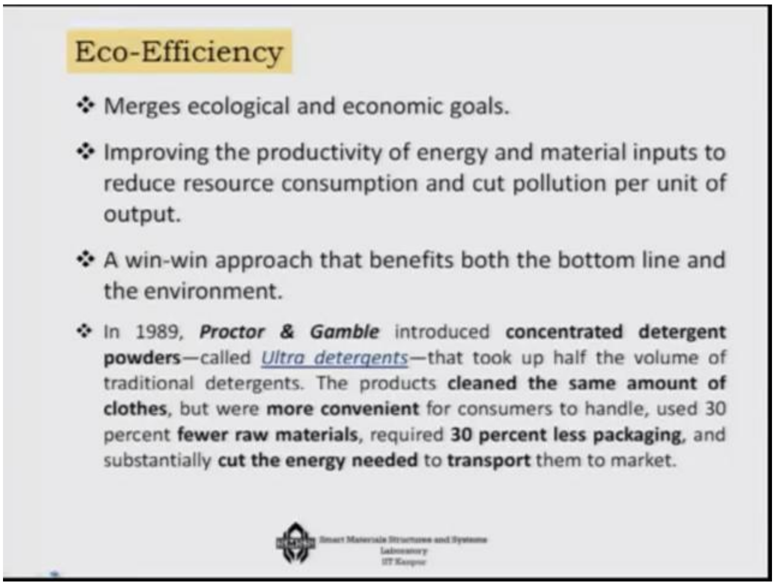

Next is a very important point which is known as eco-efficiency. Today, we are very much conscious about the nature around us okay, so it is the eco-efficiency which means a margin of ecological and economic goals together we have to think before selecting a particular material. So we have to think of improving the productivity of energy and material inputs to reduce the resource consumption, also cut the pollution per unit of output okay. So we have to not only think of reducing my own cost, but also I have to think of it that it should not affect the nature.

So a win-win approach in this direction would benefit both the bottom line design and the environment itself. Just one example in 1989, Procter and Gamble, they introduced a concentrated detergent powder okay, which is also called Ultra detergents. They took up half the volume of traditional detergents, this product cleans the same amount of clothes but were more convenient for consumers to handle, used 30% fewer materials, required 30% less packaging and substantially cut the energy needed to transport them, so as a result this material was actually much more eco-efficient material.

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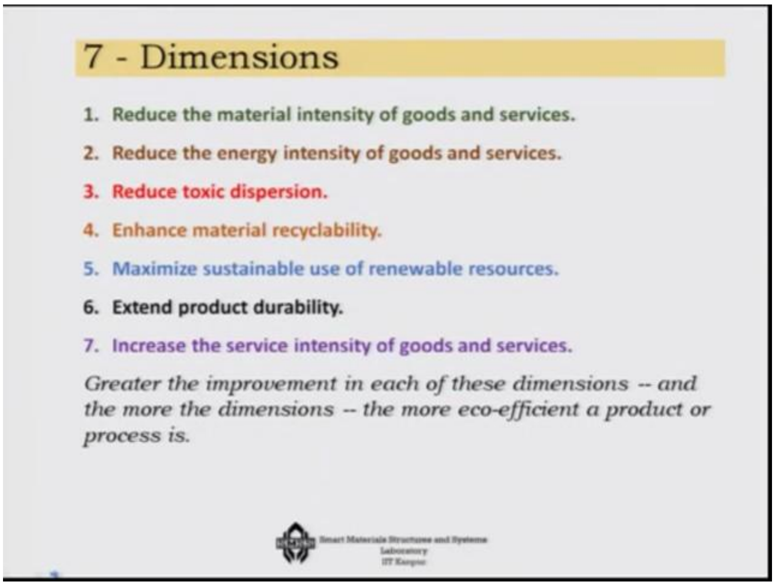

There are 7 dimensions of eco-efficiency, one is to reduce the material intensity of goods and services, then reduce the energy intensity of goods and services, then reduce the toxic dispersion, enhance the material recyclability, and all of them are very simple so I will not explain them. Maximize sustainable use of renewable resources, extend the product durability, increase the service intensity of goods and services that means increase the kind of life of the material.

So greater the improvement in each or any of these dimensions, it is considered that your system is more eco-efficient in terms of a product design. So that means you see you are not only thinking of the material to serve the particular function, but also you are thinking what is the outcome of the use of that material through the environment around us, so that is what forces us to look into the 7 dimensions okay.

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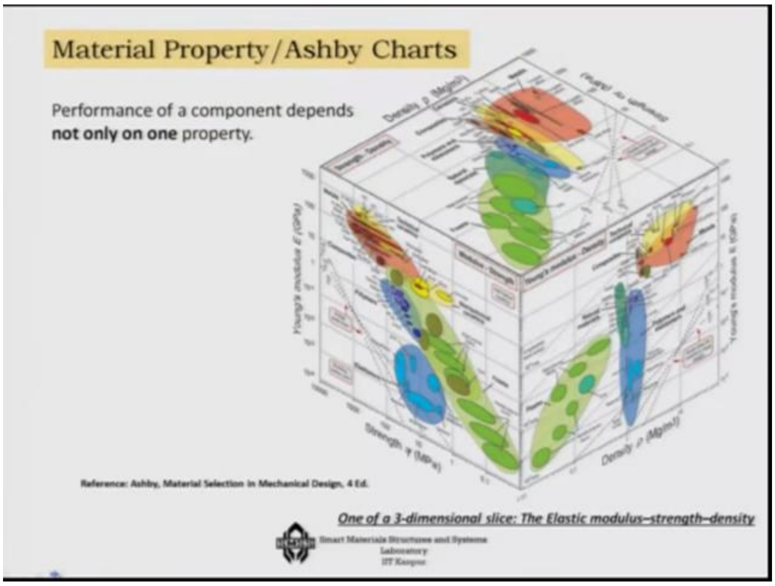

Now, we have talked about the 7 dimensions. Finally, you have to select the material property, to do that a fantastic chart I will introduce you tomorrow is called Ashby chart. So in this chart, what you will get is that you will get this is like you can develop a N dimensional picture out of it, but in each one of the dimension you will get a comparison between supposed 2 properties; Young’s modulus and strength or suppose density and something like Young’s modulus okay, Young’s modulus versus density. Or say density versus some other property of the system like strength of the system, strength-density.

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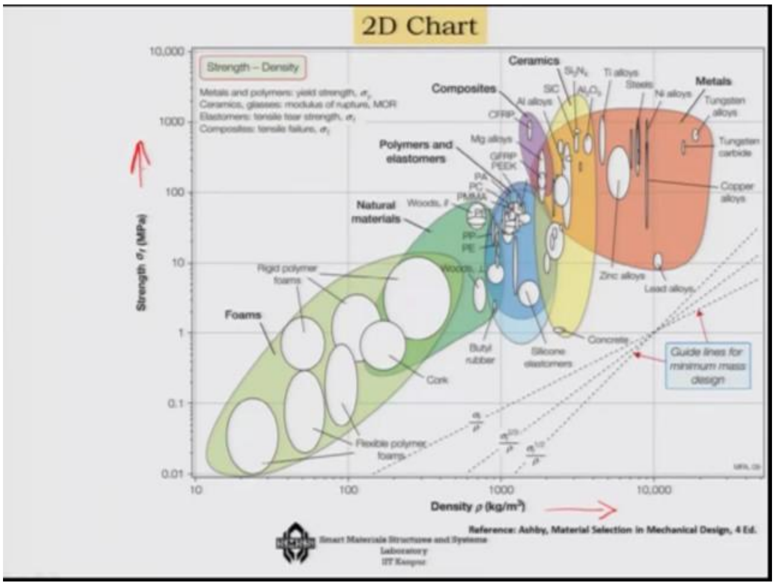

So buy looking at this comparison chart, let us say if I consider one of the slice of this chart here like this is strength versus density, so this is density and this is the strength. So if I look at it, then I will see that the very low-density materials are like foams, then from there we are going to natural materials, then from there we are going to polymers, composites, so gradually as I am increasing the density, the strength is also increasing okay and then the ceramics.

However, the problem is that if I have to go for too much of high-density, then the structure may be very heavy in weight. So if I want to go for low-density relatively, but I strength then we choose something like CFRPs because the metals are so this is where it is, but the metals at the same strength level if you look at it that they are actually an order of magnitude higher at the same strength level. So that is why this 2D charts actually help a lot in terms of selecting the material from a particular function point of view.

This function also you can plot on the Ashby chart like somewhere supposed if it is Sigma F by Rho that is what your point is. Then any material if it is here, it is discarded because that is what your functional chart level is okay; you are searching for properties on that line beyond this level, not below this level. So thus it helps us in terms of the choice of the material, so this we are going to discuss in the next class. I am going to talk about how to use Ashby chart and I am going to talk about the numerical problems on material selection, thank you.