Medical Biomaterials
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Lecture – 07
Properties

Hello. Welcome to the course on Medical Biomaterials. We will continue on the topic of mechanical properties of some of the body parts such as a tissues tendons and bones.

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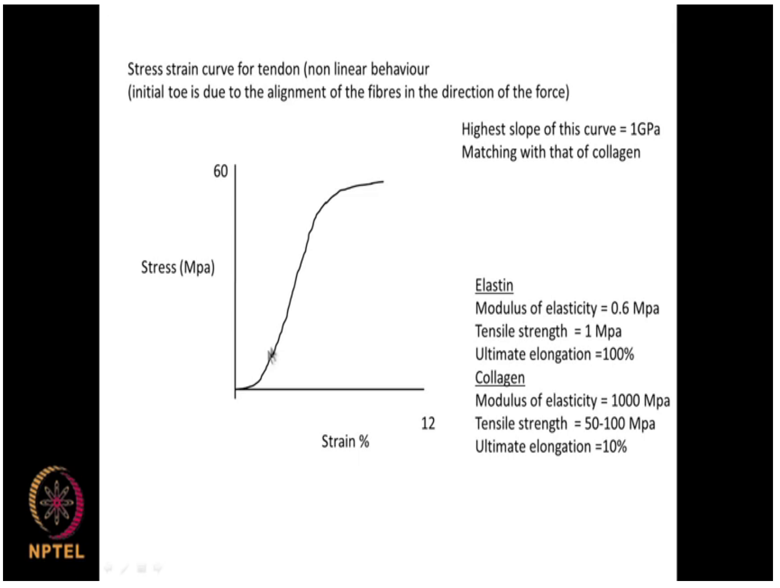

If you look at the stress strain curve for a tendon, it exhibit is a non-linear behavior. So, you can see initially, this is called a toe portion; that means, initially this stress does not increase with strain, but after certain strain it is starts increasing. And then it behaves in the normal elastic and then the plastic. So, why does this happen. This happens because the fibers get aligned, when you apply a force in the direction of force. So, that is why we do not see much tension here, but beyond a certain strain you see the normal behavior of the elastic.

So, this highest slope is about 1 Giga Pascal this matches with that of collagen. That is why collagen is used to quite a lot and in many biomaterials, especially if you want to mimic the tendon and other muscles. Elastin has a modulus of elasticity of.6 mega Pascal tensile strength of 1 mega Pascal ultimate elongation hundred percent. Collagen modulus of elasticity is 100 mega Pascal tensile strength or a 1 Giga Pascal. Tensile strength is 50 to 100 mega Pascal ultimate elongation is about 10 percent. So, collagen has much lower ultimate elongation when compared to elastin.

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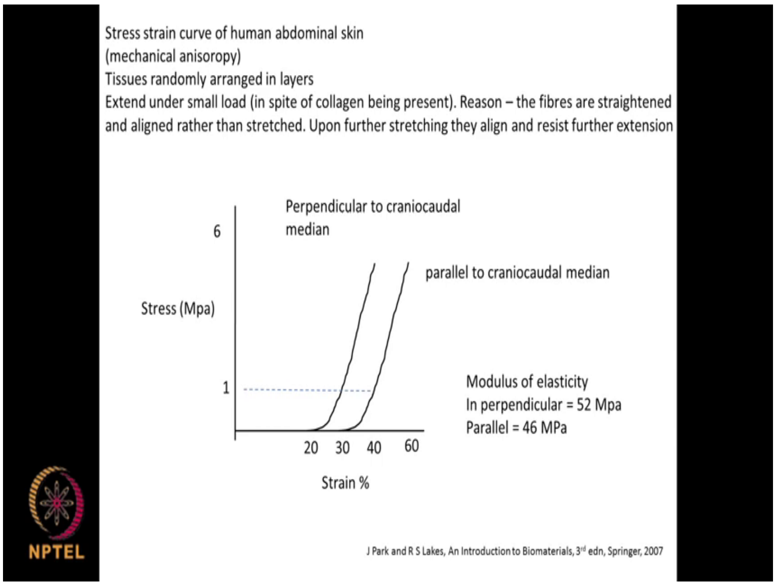

If you look at the human abdominal skin, if you look at the stress strain curve, if a force is applied perpendicular to the craniocaudal median means if you consider an x ray entering the head. And then if it is leaving the tail that is called the craniocaudal median. So, it is perpendicular to that. And if it is parallel to that we have 2 different stress strain diagrams. As you can see here that stress strain diagrams are 2 different; so if you apply a stress of 1 mega Pascal, it may have around 25 or 26 percent strain perpendicular to the craniocaudal.

And if the stress is applied a parallel then you may have 4percent strain. So, both are very different. This is called mechanical anisotropy. Because if the load is applied in perpendicular and load is applied to the parallel we will get 2 different stress strains diagrams, because the tissues are randomly arranged in layers. So, it extends under small load, because the fibers get straightened and then aligned rather than stretched. And upon further stretching they align and resist further extension.

So, if you look at the modulus of elasticity or the Young's modulus in the perpendicular direction it will be 52 mega Pascal. If it is in the parallel direction it is 46 mega Pascal both are very different. So, it depending upon how the tension is applied whether it is perpendicular or parallel it will be exhibit 2 different graphs as shown here if you look at mechanical properties of human tissues.

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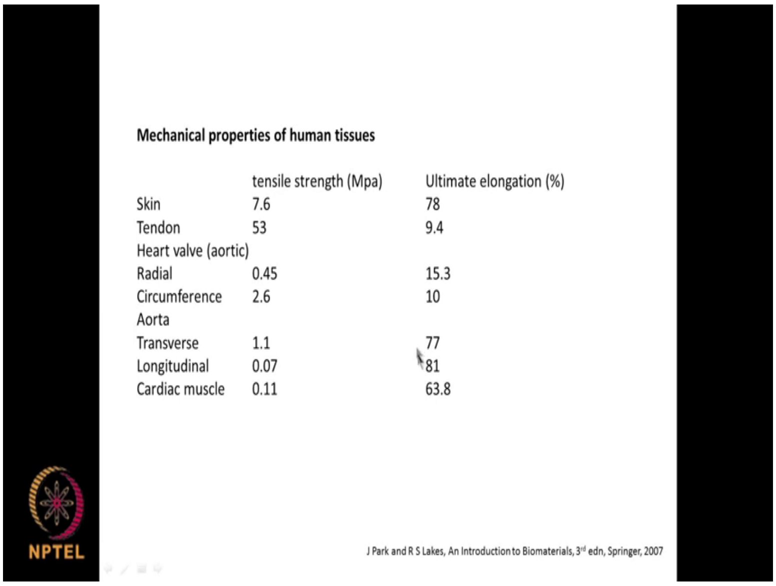

For example, skin tensile strength is very low 7.6 mega Pascal ultimate elongation is 8 percent that is before it breaks it can along almost quite a lot, actually you can see 78 percent.

Look at tendon tensile strength is 53 mega Pascal ultimate elongation is 9.4. Heart valve that is a mistake spelling mistake, heart valve heart valve aortic radial tensile strength is 0.45 mega Pascal if it is circumference it is 2.6 mega Pascal. Aorta transverse is one.1 longitudinal is 0.07 very low. Cardiac muscle tensile strength is 0.11 mega Pascal. So, depending upon the direction in which the stress or load is applied, the tensile strength is different actually. And the ultimate elongation also can vary depending upon how the load is applied actually this is taken from this particular reference.

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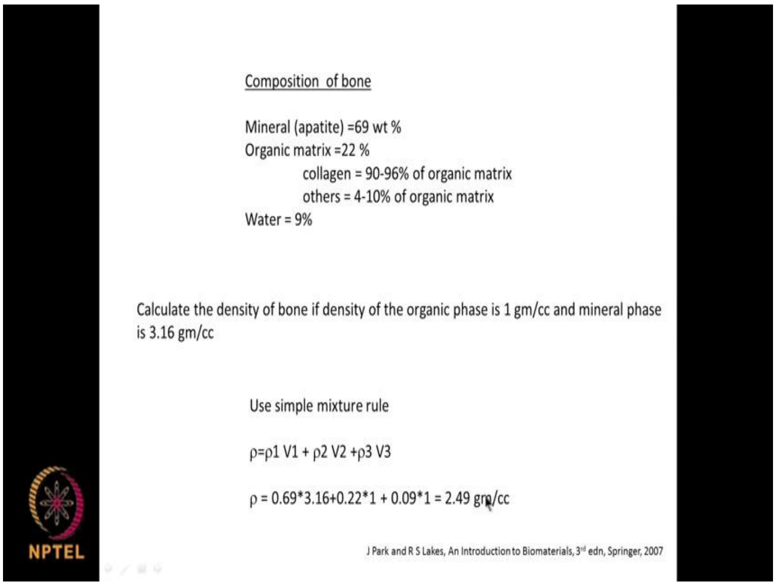

If you look at the bone it is made up of many different things like the mineral which is the apatite. Then we have the organic matrix the collagen which is predominantly may of the organic matrix and little bit of the other matrix is also there. So, the mineral will be about 69 percent that is the apatite organic matrix is 22 percent, out of which 90 to 96 percent is collagen then it contains 9 percent water. So, this is the composition of the bine bone before it gets dried. Of course, dried the all the water will go away then you will have some of these 2 actually.

Calculate the density of the bone, if the density of the organic material is 1 gram per cc and the mineral is 3 that is 3.16 gram per cc. How do we do it we can use the mixture of rules. So, we will assume there is a density of the entire bone is mixture of these 2 that is 0.69 into 3.16 plus 1 into 0.2. And then water is also there; so 0.09 into 1. So, the simple mixture rule is density is equal to rho 1 V 1 that could be mineral rho 2 V 2 that could be organic matrix rho 3 V 3 that could be water. So, 0.69 is a mineral into 3.16 plus 0.22 into 1 0.09 into 1 that comes to 2.49 grams per cc. So, density of the bone is this. So, depending upon the changes in the ratio of different parts of or different bones of different animals you could the density could be varying.

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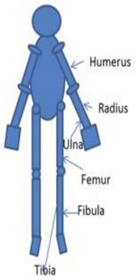
Mechanical properties of bone

	Modulus of elasticity (Gpa)	Tensile strength (Mpa)	Compressive strength (Mpa)
Leg bone			
Femur	17.2	121	167
Tibia	18.1	140	159
Fibula	18.6	146	123
Arm			
Humerus	17.2	130	132
Radius	18.6	149	114
Ulna	18.0	148	117
Vertebra			
Cervical	0.23	3.1	10
Lumbar	0.16	3.7	5
Sponge bone	0.09	1.2	1.9



Let us look at the mechanical properties of the bone. Again these change quite a lot depending upon the type of bone. Suppose I take the leg bone. We have the femur that is here we call it thigh bone. Then here the leg portion fibula and tibia the modulus of elasticity this is in modulus elasticity. And you can see the difference in the compressive strength. The femur has a very high compressive strength, whereas a fibula has the low compressive strength. Similarly arm; the arm you have the 4 arms. So, you have humorous and then outside is radius inside is ulna. Again they have some difference in the modulus of elasticity and then again there is quite significant difference in their compressive strength as well. The ulan has the lowest compressive strength, whereas the humerus has the highest compressive strength.

If you look at the vertebra cervical modulus of elasticity is quite small 0.23 lumbar has 0.6 0.16, and the sponge bone that is the bone which connect with the with the socket that is got a very low modulus of elasticity 0.09, the compressive strength also is much lower when compared to rest of the bones that is why the cervical is a very vertebra is a very important region where one does not like to put in too much tension or compression because of these as you can see from this data actually. So, the values change quite dramatically, if you look at the bones we are taking the tensile strength the range of 120 to 150, whereas, when you come to vertebra it is we are talking in terms of 1 to 3.16. So, almost 100 times less.

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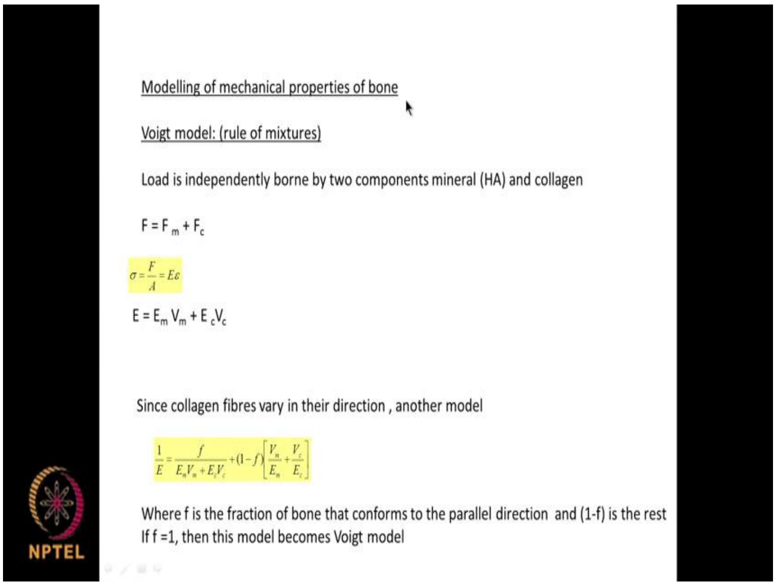

Let us look at modeling of mechanical properties of bone, because bone as we saw contains the organic at organic matrix as well as the inorganic material. So, it is a 2 component. So, we have the mineral inorganic hydroxide apatite collagen. So, we can use the rule of mixtures again for calculating the modulus of elasticity. This is called the voigt model. So, force because the force whatever is applied it is distributed on the mineral side as well as on the collagen side. So, as you know sigma the stress is equal to force by area is equal to modulus multiplied by strain. So, when we use this and this equation, we end up as the modulus of the bone is given by the modulus of the mineral volume of the mineral, plus E c into volume of the collagen phase. This is called the mixture.

But then the collagen fibers or not in distributed in the same direction. They vary in their direction. So, there is another model which is taken where f is the fraction of the bone that confirms to the parallel direction. And 1 minus f is the rest. So, if f is equal to 1 then this will become the voigt model actually. So, we can say a fraction which confirms a in in a parallel direction. So, that follows voigt model whereas the remaining portion does not follow the voigt model. So, we can get the modulus using these equations or we can get the modulus using this equation. This is the simple rules mixture whereas, this considers part of the fraction is in the parallel direction. Rest of it is not in the parallel direction. These types of equations are very useful if we want to calculate the modulus of blends or modulus of bone which is a mixture of many different materials.

Let us look at one problem this is bone it contains 20 weight percent organic 70 weight percent water sorry 70 weight percent mineral and 10 weight percent water. The density of organic is 1 gram per cc mineral is 3.2 per cc water is 1 gram per cc. Modulus is 10 Giga Pascal for organic 100 Giga Pascal for mineral and we say mineral it is a apatite.

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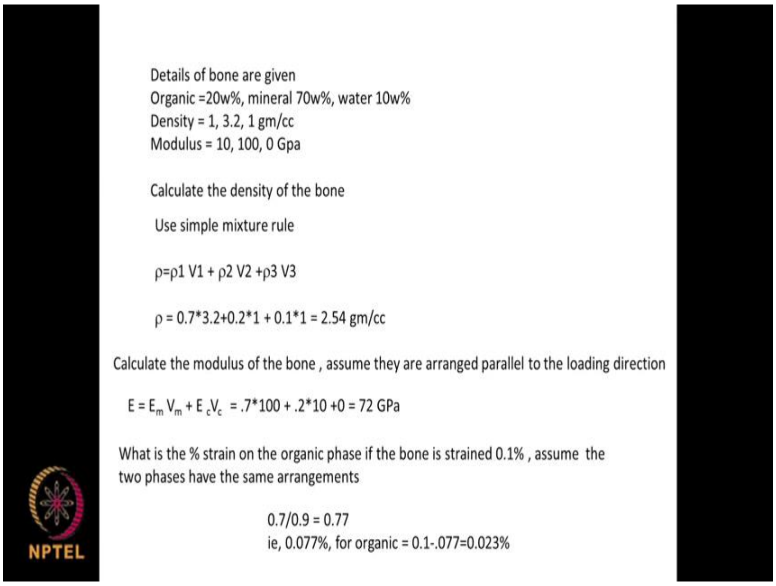

And when you see organic it is collagen and 0 modulus for water; what is the density of the bone we can use the mixture rule we did the problem before. So, we take those ratios multiplied by the corresponding densities and add up, quite simple. So, rho is equal to rho 1 V 1 plus rho 2 V 2 plus rho 3 V 3.16; so 0.7 into 3.2 plus 0.2 into 1 into 0.1 into 1. So, the density is 2.54 gram per cc.

Now, what is the strain percentage strain on the organic phase, if the bone is strained.1 percent assume that the 2 phases have the same arrangement? So, what is the strain? So, the strain will get distributed according to their wait. Before let us do that calculate that modulus of the bone assume that they are arranged parallel to the loading direction. So; obviously, we can use the voigt model. So, 0.2 into 10 plus 0.7 into 100 plus 0 so that comes to; so 0.7 into 100 for the mineral 0.2 into 10 for the organic and 0 that gives you 72 Giga Pascal. So, the modulus of the bone is 72 Giga Pascal. So, mineral of course, contributes to maximum that is because it is 70 weight percent organic and water of course, not have contributed any way any number towards the modulus.

Now, what is the percentage strain, and the organic phase if the bone is strained.1 percent. So, total we have a 0.9 we have the organic is 0.2 mineral is 0.7. So, this gives you 0.0 0.077 percent for the mineral phase, because we have taken mineral 0.7. So, for the organic it will be the other way. So, we put it as 0.2 divided by 0.9, that will come to 0.023 0.16. So, the percentage strain for the organic will be 0.023 0.16. So, for the organic it will be 0.1 minus .077 does not give 0.023 percent.

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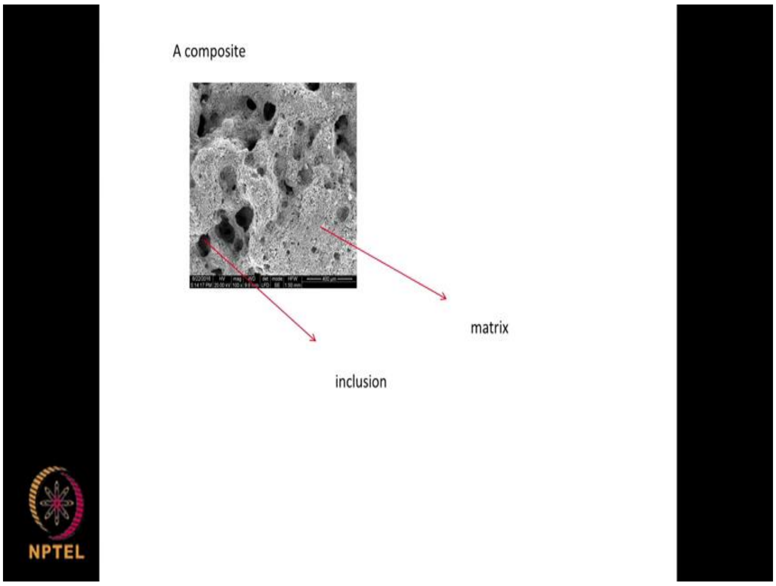

Now let us go to composite: composites for almost like blanks. So, composites we can make composites of 2 polymers, composites of polymer and inorganic material like glass like, we have the glass rain forced polymer, or we can have fibers rain forced polymer, or carbon rain forced polymer. We can have a 2 metal combined or we can have an ceramic and a metal combined together to form a composite. So, we can have different material. Even in your composite because we have the hydroxide apatite and the organic phase the collagen.

So, typically you can have see the matrix and the inclusion. Inclusion could be sometimes they use glass beads. Sometimes they use fibers sometimes they use carbon sometimes you can use another polymer in different shape and size. So, these composites also can exhibit modulus of a elasticity, but there are slight challenges here. Because the way these the inclusion material is aligning towards the load will have an effect on the tension as well as the modulus actually. Like we talked about for the skin here also or we talked about for the previous example if they are aligned parallel or if they are not aligned parallel you can have 2 different situations right. So, same thing can happen on the composites also we will look at that.

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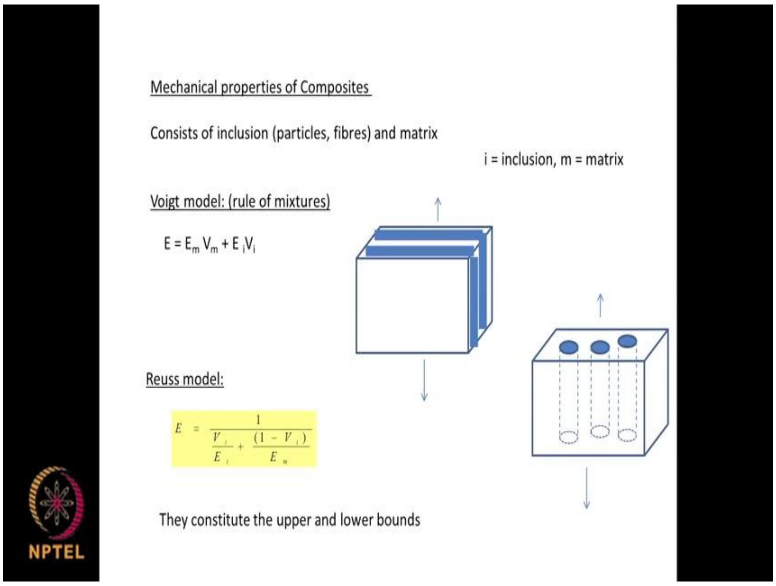

So, mechanical properties of composites; so it is consisting of say like particles or fibers like fiber rain forced plastic or a glass beads rain forced plastic or your bone like yes it is a composite and we have the continuous material that is called the matrix. So, I could be the inclusion material m could be a matrix. So, we can use the voigt model E is equal to E m V m plus E i V i that is V m and V i or the volumetric properties volume at volume of the matrix and volume of the inclusion complex.

Generally, inclusion complex may be 5 percent 10 percent 2percent and so on. So, this is the voigt model it is applicable when the load is like this, you know it is parallel. Whereas, if the inclusion material is perpendicular, then we are in trouble actually like this, inclusion material is perpendicular. Then there is something called the reuse, model reuse model where you say E is equal to one by V i divided by the E i that is for the inclusion material plus 1 by 1 minus V i divided by E m that is for the matrix material and V i is the volume of the inclusion material 1 by V 1 minus V i is the volume of the it is volume fraction sorry it is volume fraction of the matrix material.

So, here these Vs are volume fractions. So, these are the upper and lower bounds for E values. So, if you are not very sure what to calculate the E for ab blend the best thing is to use both the models and you will get 2 values. And you answer real life answer will be between those 2. So, that is a good way. So, voigt model you use it if the load that is applied is parallel whereas, you use the reuse model if they are perpendicular.

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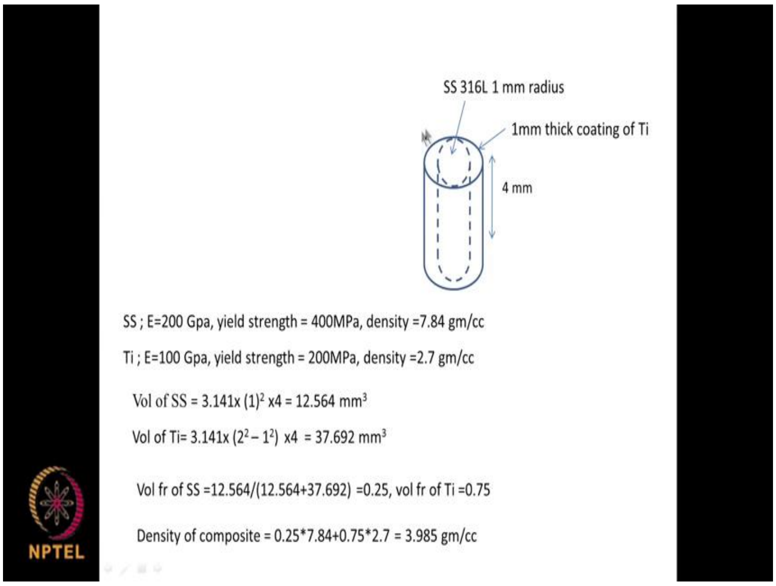

So, let us look at a problem here imagine we have a stainless steel a circular cross section 316 l with 1 mm radius and length of 4 mm. So, it is rod stainless steel rod which quite normally used especially in orthopedic implant, and it is coated with 1 mm thick coating titanium, titanium is very bio compatible and bio inert. So, titanium is very good for such purposes. So, it is coated with titanium. If you look at the stainless steel the modulus is very high 2 Giga Pascal titanium. It is 100 Giga Pascal yields strength of stainless steel is 400 megapascal strength of titanium is 200 density is 7. 84 grams per cc density is 2.7 grams per cc. Now I want to calculate properties of this particular composite material. So, volume of stainless steel it is circular rod. So, 3.14 in pi r square height right it is 1 mm radius; so one square into 4 that is the height. So, it comes to 12.564 millimeter cube.

Volume of titanium now this is like a cube here the inner radius is 1, the outer radius is 2 cube. Outer radius of 2 mm inner radius is 1 mm. So, pi into r square minus r square 2 square minus 1 square into 4. So, this is 3 12, so these 37 millimeter cube. So, the volume of the stainless steel rod is 12.5 millimeter cube. The volume of the titanium cube like this is 37 millimeter cube.

Now, fraction of a stainless steel; so what you do you takes 12.56 divided by this plus this. So, this is 0.25. So, volume fraction of titanium is 0.75; so density of the composite .25 into 7.84 plus 0.75 into 2.7 3.984 grams per cc that is the density of the material. So, as you can see it is more like titanium. Because of the volume of the titanium is very high. And you are using volume fraction in this model.

What is the Young's model of the composite? So, we know the Young's modulus of a stainless is 200 for titanium. So, we use the normal equation if you remember.

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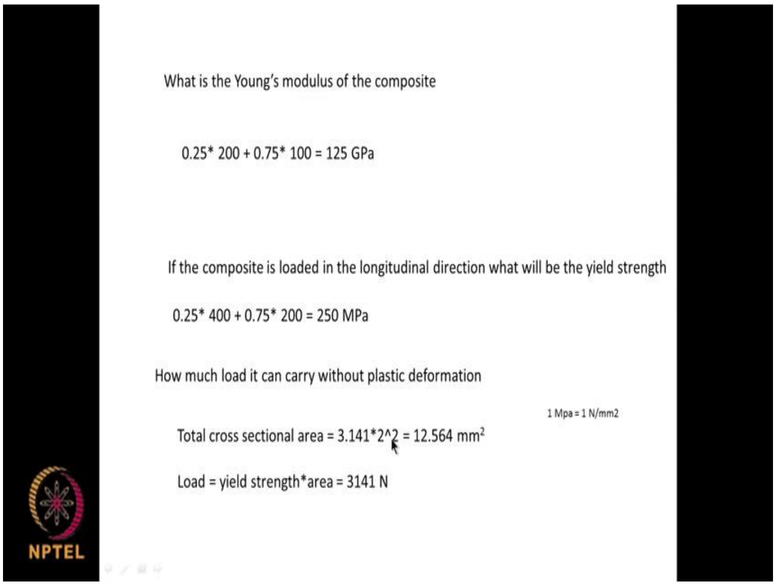

Voigt model is equal to E m V m plus E i V i. So, we use that and.2 5 into 200 plus 0.75 into hundred we get 125 Giga Pascal. This is the Young's modulus of the composite if the composite is loaded in the longitudinal direction what will be the yield strength. Again we know the yield strength yield strength is 400 and 200. We can use the same voigt type of mixture rules 0.25 into 400 plus 0.75 into 200 250.

Now, how much load it can carry without plastic deformation. So, we are to be careful because load is applied. So, we have the titanium we have the stainless steel. So, the total cross sectional are is 3.14 multiplied by 2 raise to the power 2. How did you get this? So, we have a 1 mm here another 1 mm here. So, the radius of the total thing is 2 2 raise to the power 2 that is 12.56. Now load is yield strength into area. Yield strength is what is the yield strength 250 250 into area is 12. So, that comes with 3141 newton. That comes to 3141 newton. So, from there that is the load it can carry without it undergoing plastic deformation.

So, we saw a lot of interesting problems and lot of systems today. Basically we were focusing on blends we were looking at composites, because your bone is made up of a composite situation, we have the mineral and we have the organic collagen and some in implants many time we use composites or blend type of material polymer blends sometimes. We use polymer inorganic material composites sometimes metal combinations are used. So, we looked at how to calculate the density of the blend or the composite how to calculate the modulus. We can use the rule of mixtures or we have different type of model available. Especially this situation comes if the inclusion material whether it is parallel to the load that supplied or whether there it is not parallel fraction of it may be parallel. So, they for that fraction we may be able to use the mixture rule, but remaining portion we will not be able to use the mixture rule. So, we have a slightly models coming into focus.

So, the blends always will have this type of problems. So, if you have 2 different materials having 2 different properties with respect to density tensile strength and modulus of elasticity. The properties of the overall material are going to drastically change. So, when you design biomaterials we need to keep that in mind. This happens in our bone which is a composite of both a hydroxyapatite and a collagen, that is the one is the mineral that is the apatite and collagen is the organic phase. So, both of them have different modulus of elasticity. So, the bone properties also change quite a lot.

And I also showed you very interesting a data on the modulus of different types of bones. We saw that vertebra bones have very low modulus almost by 100. Another interesting we saw is the way the load is applied if we have the skin of the stomach, the way the load is applied in whether it is longitudinal or whether it is in the parallel direction the stress strain diagram can be very different and if the for a given stress the percentage elongation can also vary.

So, we will continue in the next class on some more properties related to biomaterials.

Thank you so much for your time.