Medical Biomaterials
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Lecture – 06
Properties (Mechanical)

Hello. Welcome to the course on Medical Biomaterials.

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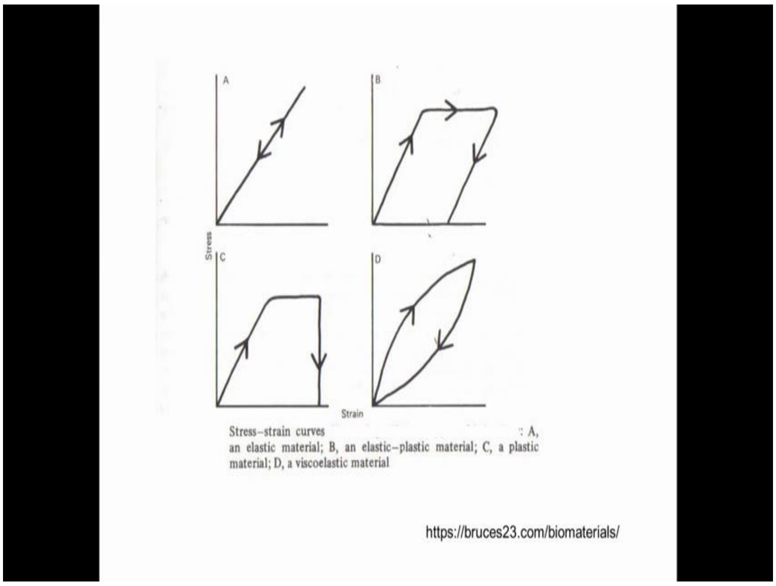

We will continue on the topic of mechanical properties biomaterial should have. Previous class I did talk about different types of material. This is called a elastic material. If you remember I apply a force. So, it is gets stretched. I means the when I remove the force or the stress comes back. This is called the elastic material. And materials behave in this particular fashion actually you apply a force. So, there is a stress and there is a strain developed we remove the force it comes back in the same order. And there is a linear relationship which is called the Young's modulus.

Now, if you look at elastic plastic material, it does exhibit this elastic property, when you apply the force. And when you remove the force it comes back parallel, but in a different path way. So, you have the elastic region and you have the plastic region and then the elastic comes down, but in a different. Now there is a plastic, it does exhibit little bit of elasticity, but it completely you can see completely becomes plastic. It loses it is entire stretch ability the 4th type of material is called viscoelastic material. So, it goes up as you apply the stress, and then it comes down as you remove the force, but it exhibits something called a hysteresis. This is called a viscoelastic material. And many of the human body systems exhibit this type of viscoelastic property. So, all biological tissues are viscoelastic in nature. So, it is sort of shows in hysteresis type of behavior when you draw the stress strain diagram.

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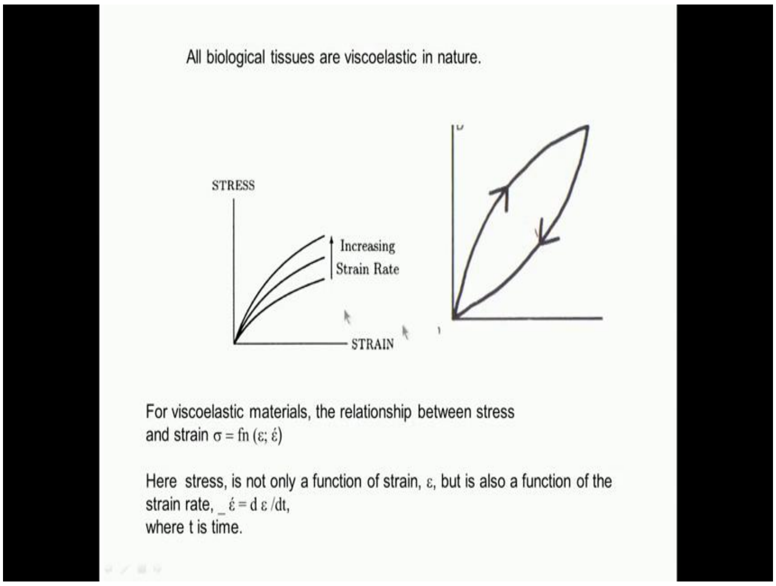

So the stress not only depends on the strain, but it also depends on the strained rate; that means, the stress is to call it sigma, if you remember strain is called epsilon. So, sigma is not only a function of epsilon, but also a function of epsilon dot. Epsilon dot is given by d epsilon by d t t is your time. So, the rate of strain also determined as stress. So, that is why you can have increasing strain rate you can have different types of stress strain graphs. W will talk about this viscoelastic later also, because many of the biological systems exhibit this.

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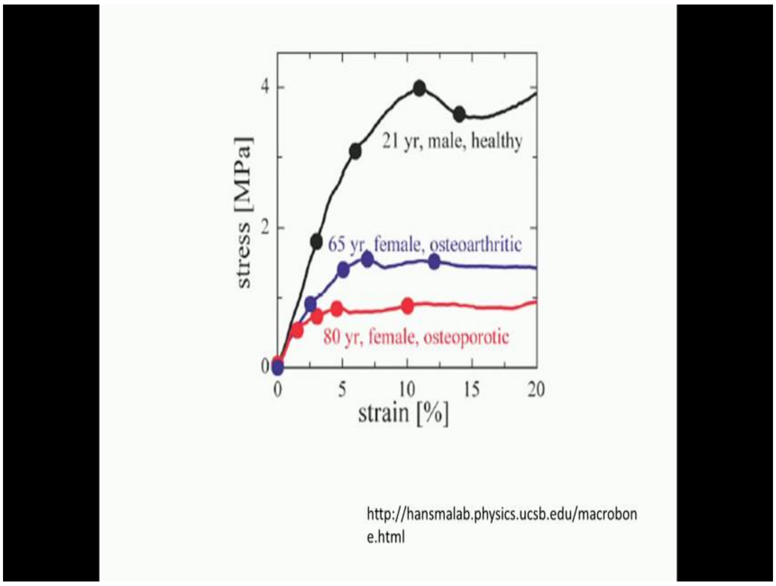

For example, if you look at the stress strain diagram, of the bone. This is a 21 year male healthy person. So, this modulus of elasticity or the Young's modulus; so it goes up and then goes up then there is a yield and a person a 65 year old female having an osteoarthritic. So, as you can see the stress strain diagram is really short because osteoarthritic problem leads to the bone getting very weaken actually. It loses lot of these modulus of elasticity or Young's modulus, but look at it 8 year old female osteoporotic. It still comes down further.

So, the stress strain diagram changes as a function of even time here, can you see this. So, the healthy male and then for a person with a osteoarthritic, and person higher age older person it seems osteoporotic. So, the Young's modulus comes down still further down.

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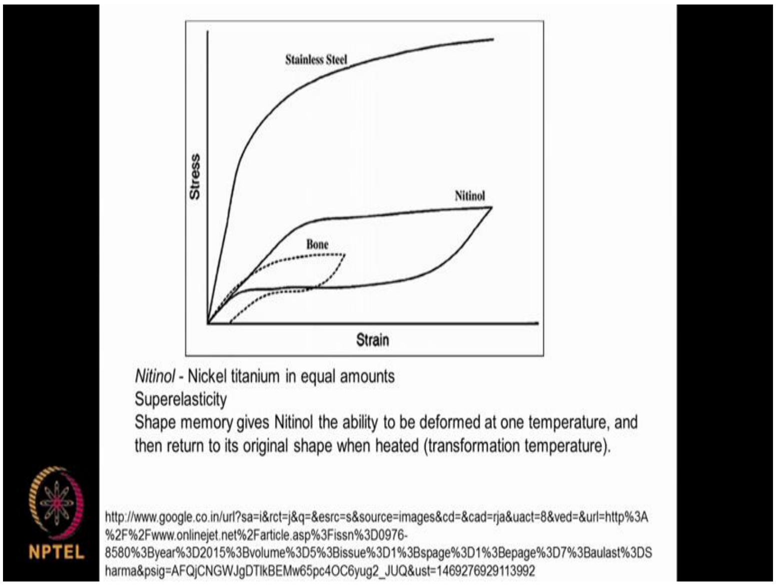

So, if you look at stress strain diagram, you have again seen stainless steel going nicely. So, it is exhibiting a very good elastic region. And then it goes into the plastic and you have here the strength bone as I said is a viscoelastic. So, may have graphs like this with hysteresis type. There is a material made up nickel titanium almost 45 percent weight percent. It exhibit is also a viscoelastic behavior like this you know. So, when the strain is increased stress goes up, then the strain is removed stress comes down, but it follows a different pathway. So, this material is called a shape memory. The beauty is when it is deformed at one temperature, then when I increase the temperature heat it up regains it is old shape it remembers. It is old shape, that why it is called shape memory material that temperature is called transformation temperature.

There is lot of interest in using shape memory material in biological medical applications. Imagine I can have a very small stent or a sensor. I put it inside the body. Because it is very small it can be easily inserted. Then once it goes inside it may regain it is old shape may be configure like your umbrella it opens and then becomes smaller; so exactly that sort of behavior. It has remembered it is original shape, but it can be compressed to a very small shape of our interest or we can handle it, but then at that higher temperature it will regain it is old shape. So, shape memory alloys shape memory materials even shape memory polymers, there is lot interest especially in the area of medical biomaterials.

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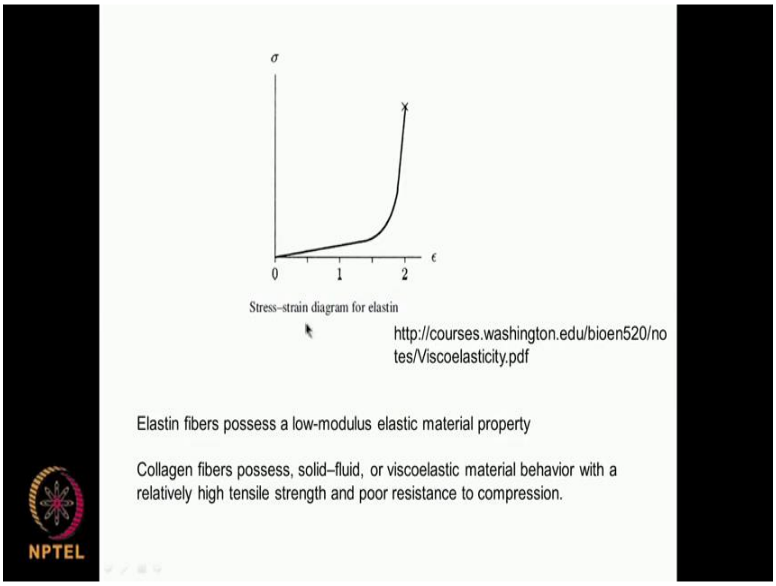

If you look at stress strain diagram for elastin, it goes like this. It is got a low modulus elastic property. And then there is no plastic at all. If you look at collagen fibers it is like a viscoelastic material behavior with a very high tensile strength and poor resistance to compression. So, biological materials behave very differently and like a synthetic material like stainless steel titanium or polyethylene and so on actually.

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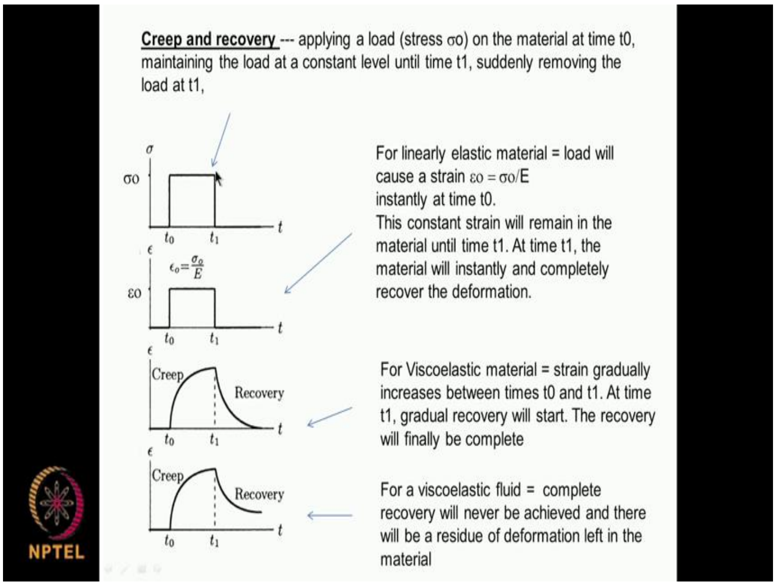

Another important property we need to know that is called creep and the recovery, the creep and the recovery. Suppose, I am applying a load sigma 0 at time equal to t naught.

And maintain that load for a time up to t 1. And then you are removing the load. So, normally any material like your stainless steel or titanium will have the epsilon not varying a sigma 0 by e right, because this is your law where this is epsilon is your Young's modulus, sigma is your stress epsilon is your strain. So, epsilon is equal to sigma 0 by e.

So, at time equal to 0 immediately it gets strained. It remains until the stress is maintained and it falls down. This is the constant strain many materials will be here, but there are materials viscoelastic materials. So, when I apply the stress the strain will not go up sharply reaching a epsilon or it will slowly build up and reach the value. And once I remove the strain sorry once I remove the stress it will not immediately fall to 0. It will slowly come down and this is the called the recovery. So, this is called the creep and this is called the recovery. All the viscoelastic material will have this type of property. So, if you look at materials it will have this type of immediate increase in the strain as soon as stress is applied and immediate fall in the strain as soon as the stress is removed whereas, viscoelastic material will have this type of creep and a recovery.

Whereas, viscoelastic fluid that also will have a creep and a recovery, but there will be some residual deformation left in the material; that means, it will never reach that 0 value of strain that is called a creep and recovery.

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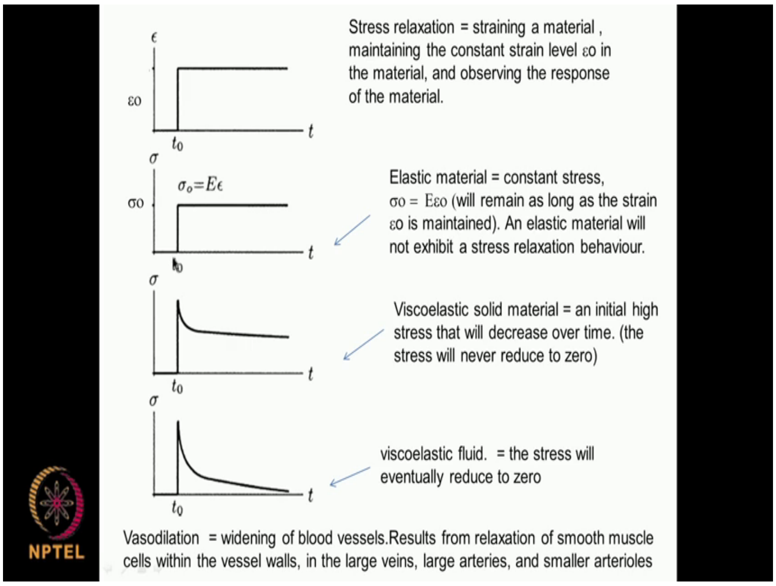

There is another conversely that is called stress relaxation. Suppose I strain material at time equal to t 0; that means, I pull it and then see how the stress looks like. Of course, materials like stainless steel a normal elastic material will follow this law sigma 0 is equal to e multiplied by epsilon e is your young modulus. That is any elastic material immediately it will pick up the stress and then go.

So, that a normal elastic material will not exhibit a stress relaxation behavior whereas, if you look at viscoelastic material it will have a initial high stress and then it will start decreasing with time it will never reach 0, but it will start decreasing with time. That is a called viscoelastic material; if look at viscoelastic fluid the stress will eventually reduce and come down to 0. So, a normal elastic material the stress will remain as long as the strain is kept, and it will follow the law sigma 0 is equal to e multiplied by epsilon. Whereas, viscoelastic material it will reach the maximum and it will start falling down although we still maintain the strain whereas, viscoelastic fluid the stress can reach 0 value.

Now, this is in medical we have a term called vasodilation. It means widening of the blood vessels. This happens because of relaxation of smooth muscle cells within the vessel walls in the large veins in the large arteries and smaller arterioles. So; that means, the vasodilation is this type of viscoelastic behavior, the diameter of these veins or arteries increased. And many other human body parts also undergo this type of behavior; although you apply a strain the stress might not remove remain like an elastic material, but the strain may come down as a function of time.

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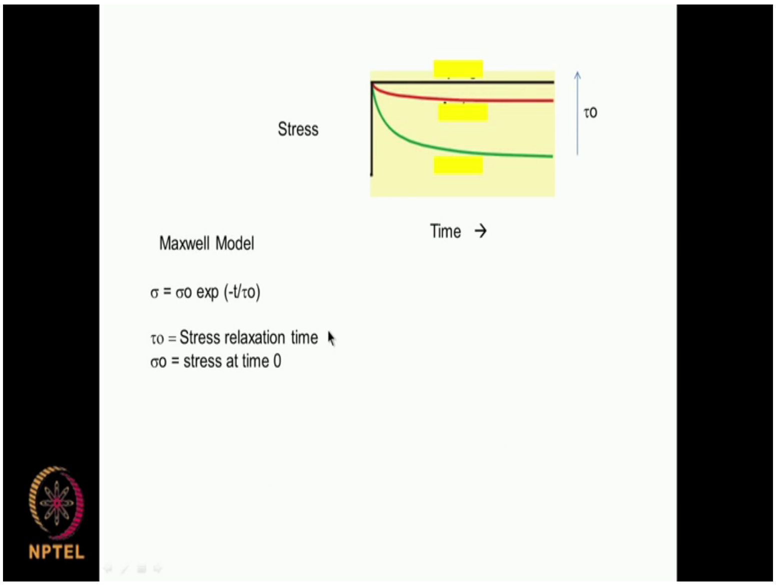

There is a model called Maxwell model. So, when we have the stress was a strain. It will keep coming down for different values of something called tau naught. And this is called a stress relaxation time, sigma that is the stress is equal to sigma naught exponent minus t by tau naught, where sigma naught is the stress at time equal to 0, and tau naught is a stress relaxation time. So, it will fall down exponentially, the stress will fall down exponentially as a function of time, and that falling will depend upon your stress relaxation time. Let us look at spring for example.

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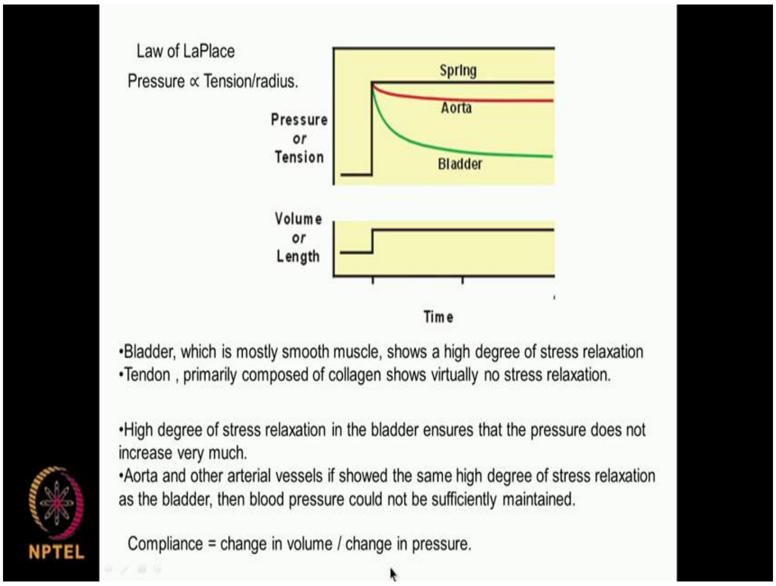

So, when I am applying increase the length, or I if I give a strain and keep it over a long period of time, if you take a spring. So, the tension will remain whereas, if you take up bladder the tension will not remain at that value, but it will slowly fall down with time much larger. If you look at aorta the tension will fall down with time, but it will not be as much as bladder. So, these are viscoelastic material.

So, bladder which is smooth muscle shows a high degree of stress relaxation, when compare to say aorta. And for example, tendon which is made up of collagen will have any stress relaxation; that means if I apply a strain and maintain it for a long period of time, the tension will remain as such the tension will not fall down unlike a bladder. Now this stress relaxation is very useful in body part like bladder, because as the urine keeps flowing in I if the stress relaxation does not happen the pressure inside the bladder can keep increasing and the urine flow into the bladder will not happen because the pressure will be much higher. So, stress relaxation is very important in the human system for the flow of urine into the bladder.

So, high degree of stress relaxation in the bladder ensures that the pressure does not increase very much. So, when the pressure does not increase urine can filling up your bladder. Whereas, aorta in other arterial vessels if they have too much of stress relaxation. That will happen the blood pressure inside those vessels will fall down So, much. The blood pressure will not be maintained. That is why you see they have very little stress relaxation, whereas bladder has very high stress relaxation. Whereas, tendon will not does not have any stress relaxation. There is another term that is called compliance which is change in volume divided by change in pressure.

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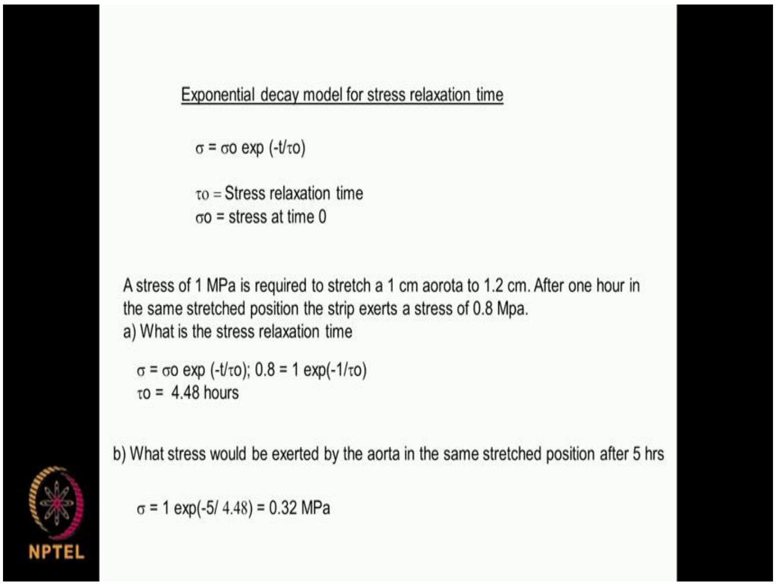

Now, I did mention that there is an exponential decay for stress relaxation. Sigma is equal to sigma naught exponent minus t by t naught. Tau naught is a stress relaxation time t is your time sigma naught is your initial stress. So, stress at any time t is given by this relationship. This is also called Maxwell relation. Let us look at a simple problem a stress of 1 mega Pascal is required to stretch a 1 centimeter aorota at to o1.2 centimeter long.

After 1 hour in the same stretched position the strip exerts 0.8 mega Pascal's. So, the stress is gone down from 1 to 0.8 in 1 hour. Now the question is what is the stress relaxation time. You are supposed to calculate tau naught. You are given sigma naught as 1 sigma as 0.8 time is equal to 1 hour. So, it is very simple tau naught is what? So, we get tau naught as 4.48 hours.

Now, the next question is what would be exerted by the aorota in the same stretched position after 5 hours. So, now, I know the tau naught t is 5 hours, sigma a 0 is 1 mega Pascal. So, what is the sigma simple? So, sigma s is equal to 1 into exponent of that is minus 5 divided by 4.4 hours; so 0.32 mega Pascal. So, stress has come down to .32 mega Pascal. So, originally when I stretched it, when I stretched it we had the stress as 1 mega Pascal. Now it is become a 0.1. Now this is become 0.32 mega Pascal. So, this is the equation. And this is their relationship which we are talking about actually.

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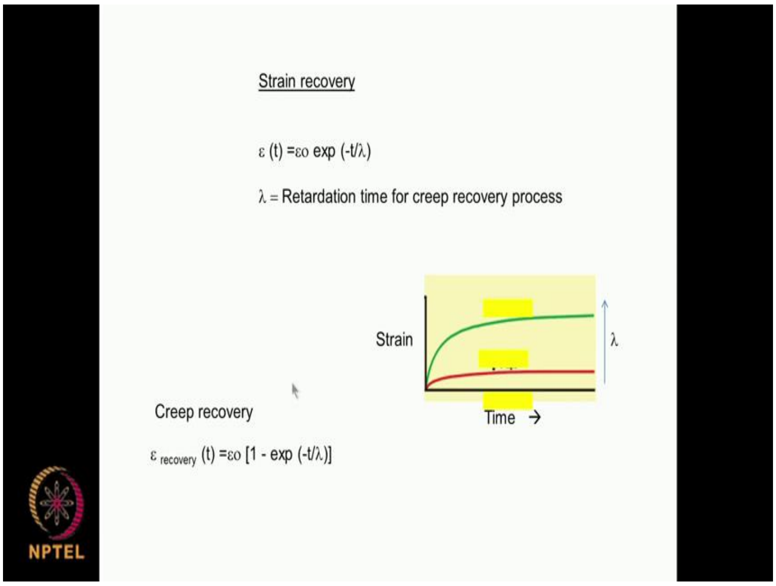

There is something called strain recovery. So, strain recovery is given by this. Another exponential model epsilon t is equal to epsilon 0 exponent minus t by lambda. Lambda is called the creep recovery process or the retardation time. So, strain for different values of lambda as a function of time comes back to it is original value. So, that is called the strain recovery. So, that is given by again another exponential model x epsilon tau is equal to epsilon 0 is your is it is original strain, exponent of minus t by lambda. Lambda is called the retardation time or the creep recovery process.

So, creep recovery is nothing, but 1 minus particular term right. So, original strain and the strain recovered as a function of time. So, recovery t is equal to epsilon into 1 minus exponent t minus lambda.

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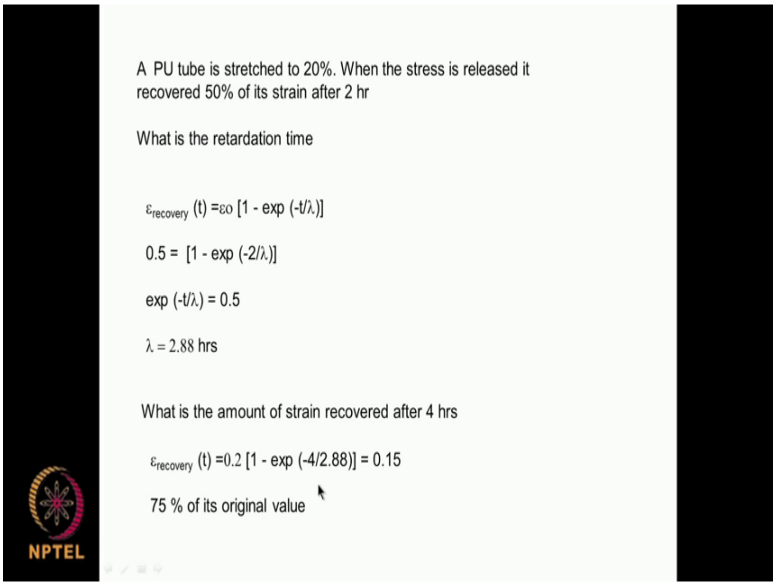

So, another problem let us look at a problem a PU tube polyurethane tube is stretched to 20 percent. When the stretch is released it recovered 50 percent of which strain after 2 hours what is the retardation time. You have to use this equation the recovery is 0.5 and 1 minus e to the power minus t by lambda after 2 hours. So, you put 2 hours here. So, from there we can calculate lambda which is given by 2.88 hours. What is the amount of strain recovered after 4 hours? What is the amount of strain recovered after 4 hours? So, we can put the time as 4 we know lambda. So, we can calculate. So, it recovered 75 percent of the original value.

So, we have 2 different types of equation. One is called the stress relaxation. How the stress gets reduced as a function of time? It follows an exponential relationship. There is a tau naught coming here which is called the stress relaxation time. So how the stress gets reduced from it is initial value of sigma naught? And other one is called strain recovery how the strain gets recovered from its initial value epsilon naught. And here lambda is called the creep recovery process. These stress relaxation and creep recovery are very important especially in biological settings. Because most of them material in biological system or body or viscoelastic.

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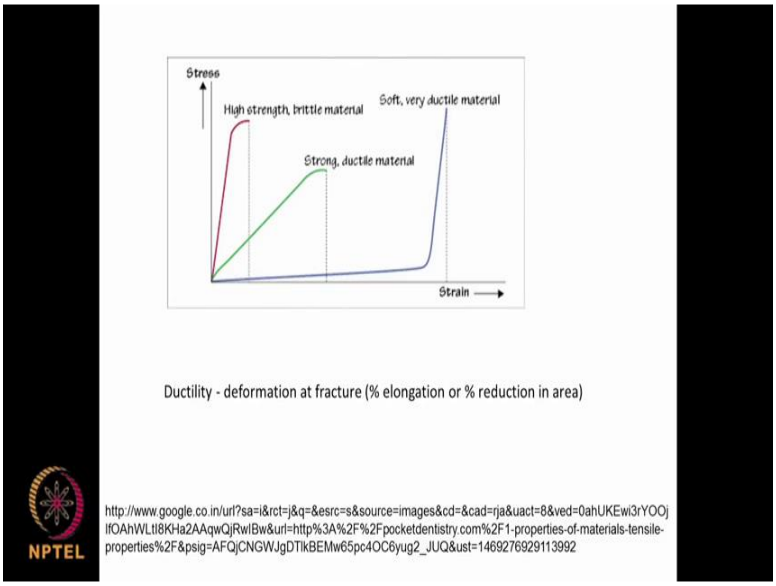

So, if you look at materials, there is another property that is called ductility. That is how the material deforms at fracture; that means, when it breaks what is it, how it looks like what is the deformation that is called ductile. So, if you have a material like this you know if you look at the stress strain diagram, high strength material brittle in nature. So, it is got very high modulus of elasticity; that means a slope. So, strain slope is very and steep, but it just breaks high strength, but brittle material strong, but it ductile material. So, you can see this. Soft very ductile material again sees this soft material because it is got a very low elastic region, but it is going up very sharp here. So, it is a soft material and it is very ductile material.

So, we have different types of stress strain relationship that are possible. So, high like if you take your ceramic. So, high strength brittle it immediately breaks. This is a strong material the modulus of elasticity is low. You can see here there is a deformation at when it fractures. It is a ductile material. Look at this type of stress strain behavior it is a soft material because the e or the slope of the regions is very low. It is a very ductile material that can be nicely shaped into. Deformation at fracture it is quite a lot.

So, brittle material like ceramics fails before permanent deformation. It does not deform immediately it breaks, whereas ductile material which deform for a long time then it breaks. Bone is in between these 2. So, bone can be brittle and it little bit of ductility. So, ductile deforms greatly before deformation, before it breaks. Brittle material does not deform it immediately breaks, whereas bone lies between these 2 brittleness versus the ductility. So, you have to keep.

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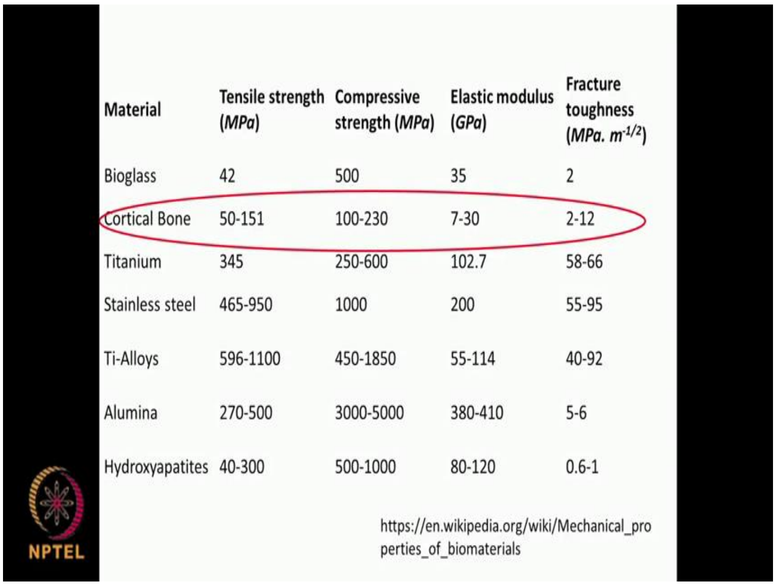

Material	Tensile strength (*MPa*)	Compressive strength (*MPa*)	Elastic modulus (*GPa*)	Fracture toughness (*MPa.* $m^{-1/2}$)
Bioglass	42	500	35	2
Cortical Bone	50-151	100-230	7-30	2-12
Titanium	345	250-600	102.7	58-66
Stainless steel	465-950	1000	200	55-95
Ti-Alloys	596-1100	450-1850	55-114	40-92
Alumina	270-500	3000-5000	380-410	5-6
Hydroxyapatites	40-300	500-1000	80-120	0.6-1

https://en.wikipedia.org/wiki/Mechanical_properties_of_biomaterials

So, if you look at the some of the properties of materials non materials and your bone. Look at that tensile this is taken from this particular reference. The tensile strength is 50 to 150 mega Pascal. Stainless steel is 45900, titanium is 5 and 600 to 1100 very high, titanium is trying to be lower, but still it is high, originally stainless steel was used, but then the tensile strength is absolutely no comparison. So, started using titanium just low and now materials are still coming alloys which still have lower tensile strength.

Look at the inorganic oxide alumina hydroxyapatites; they are quite low, tensile strength look at hydroxyapatites after all your bone is made up of this. So, it is very low. Bio glass around very low. Compresses strength you bone has a compressive strength of 100 to 230. Alumina hydroxyapatites they have very high compressive strength. Stainless steel has also high. Elastic modulus that is a stretch based strain, bone around 7 to 30. Stainless steel titanium they are very high. Your alloy are coming down alumina hydroxyapatites are quite high. Fracture toughness as I said if there is crack how it propagates that is called the fracture toughness. It is low for the bone alumina is reasonable comparable to bone, whereas other materials are very high. Absolutely no comparison with that hydroxyapatites is of course, is again comparable with the bone.

So the challenge in medical biomaterial is to have especially in orthopedic materials, which are comparable if the mechanical properties of the bone. That is very important whether it is tensile strength whether it is a elastic modulus or whether it is fracture toughness. Otherwise if the materials have very high elastic modulus or compressive or tensile strength, then we have something called stress shielding and the bones slowly loses it is part or the strength.

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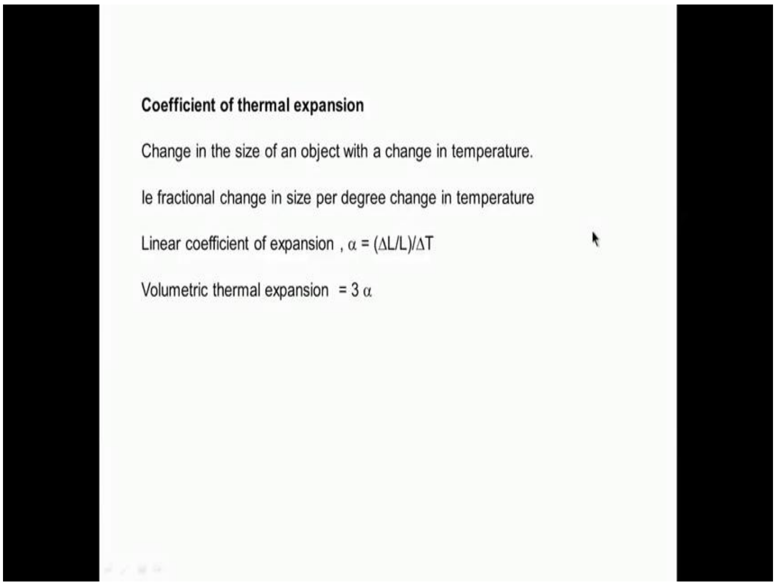

Next important property we need to keep in mind is coefficient of thermal expansion. There is a change in the size of an object the change in temperature. We have a something called the coefficient of thermal expansion, which is given by this relationship delta l by l that is change in length and to the original length divided by change in temperature if you look at volume at thermal expansion 3 times this alpha approximately. So, fractional change in size per degree change in temperature coefficient of thermal expansion is very important. Especially, if we are sterilizing material and using steam or if you are a looking at dental implants where we are applying polymerization type of reactions like pmma undergoes sorry methyl acrylate or methyl acrylic acid or they all undergo polymerization. And that polymerization leads to very high temperature rise. So, there could be changes in the expansion thermal due to thermal expansion volumetric expansion.

We take hot food or even cold beverages. So, there could be changes in the temperature inside and the dentin teeth the various implants that are placed. So, when you do that, there is going to be changes in their relative expansion, both linear as well as volume. So, there could be lot of issues. So, one needs to look at designing material especially in the oral region so that the volumetric expansion or linear expansion coefficients are comparable to that of a dentin and other parts inside the oral cavity.

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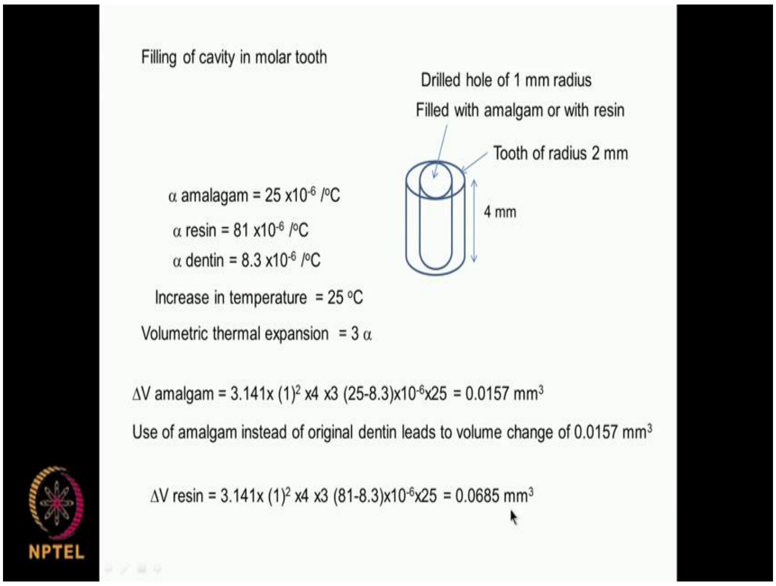

Let us look at a simple problem. Imagine we are filling a cavity in a molar tooth. So, there is a whole drilled which is a 1 millimeter radius, filled with amalgam or resin, but the teeth have a radius 2 mm. So, this radius is 1 mm. So, this is 2 mm. Then you have 1 mm here. The height is 4 mm. If you look at the coefficient of thermal expansion amalgam is 25, for resin is 81, and the dentin is 8.3 you see there is lot of difference here. So, imagine there is increase in temperature of 25 degrees and volumetric thermal expansion we will take it as 3 times this linear thermal expansion.

So, do we calculate? We calculate a volume. Suppose I want to see volume what is the thermal expansion volumetric expansion of this amalgam rod, which has got a one millimeter radius and 4 millimeter height. And which is got a linear expansion coefficient of 25 into 10 to the power 6 degree centigrade. So, I calculate the volume of this portion. Then I will multiply with this then u multiply with this 25 and I will multiply with this 3 to get a delta v. That means, change in the volumetric I could do that

that will give you an idea about the change in the volume because of increase of 25 degrees.

So, let us see amalgam the 3.14 pi r square radius is 1. So, r square height is 4 3 4 here 3 times alpha. Suppose if I have the dentil it will be 8.3 as my alpha and there is coefficient of thermal linear expansion whereas, if have amalgam 25. So, the difference I put it as 25 minus 8.3 into 10 to the power of minus 6 this 25 corresponds to the temperature. So, this will give me millimeter cube. That is a change in the volume because instead of dentin I have an amalgam. So, you use a amalgam instead of the original dentin leads to a volume change in this particular molar teeth of the order of 0.0157 millimeter cube. So, that is not good there is a change in the volume.

Now, let us look at what happens if I put instead of amalgam a resin here which has got very high coefficient of thermal expansion. So, instead of 25 I will be putting 81. So, when I put that my delta v resin comes to be 0.068 millimeter cube. So, the coefficient of volumetric expansion is quite high when I use a resin and like an amalgam. That is why amalgam is quite popular amalgam is made up of mercury and metal and. So, it is still popular u because the coefficient of volume expansion is 0.01. Whereas, resin looks like a resin are made up of say acrylate acrylic acid. So, the color exactly matches with that of the dentin and the tooth unlike a amalgam which may look like a silver.

So, people prefer resin, but look at this volumetric expansion is much higher almost 5 to 6 times higher. There could be problems will let us look at the slight modification into this problem then you will see.

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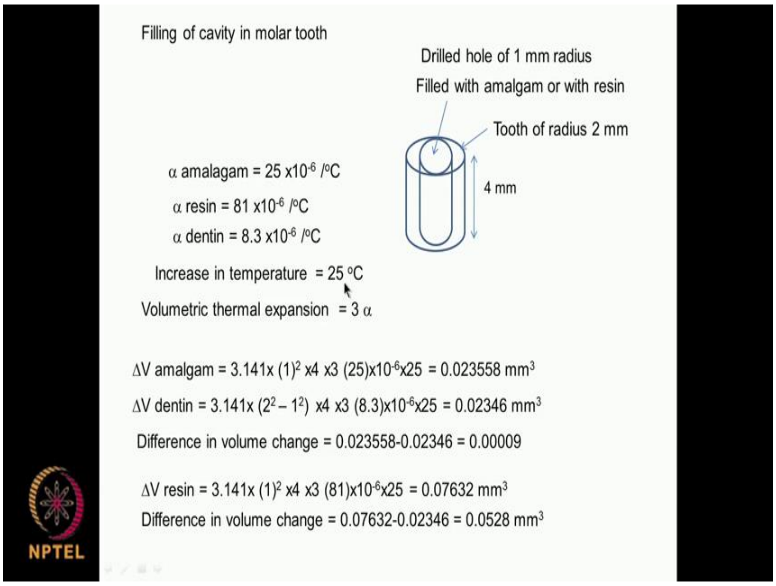

Imagine same problem I have a whole drilled and I fill it up with see amalgam or resin. So, let us take I fill it with amalgam. So, here I amalgam of 1 mm diameter with 4 mm height and then the remaining portion is dentin. Dentin is like your circular ring he outer will be 2 mm inner will be 1 mm. So, it will be like a circular ring made up of dentin and I have a solid portion of amalgam which is 1 mm radius now when there is a temperature raise of 25 degrees centigrade both of them will have different coefficient of volumetric expansion because amalgam has a 25 into 10 to the power of minus 6 degree per c per degree c whereas, your dentin has 8.3. So, I will calculate the volumetric expansion of amalgam alone I will calculate the volumetric expansion of dentin alone for a temperature raise of 25 and I subtract these 2 and see what is the relative change in the volumes.

So for the amalgam it is rod of mm dia and a 4 mm height. So, 3.41 into 1 square into 4 3 times alpha that is 25 into 10 to the power minus 6 into 25 centigrade. So, this is a change in the volume of the amalgam rod when I raise the temperature by 25 degrees centigrade. What will be the change in this dentin which has got an outer radius of 2 mm and an inner radius of 1 mm? This is like a ring long ring. So, that will be 3.42 square minus 1 square that will be the area of this portion height 4 into 3 8.3 that will be 0.02346. So, the amalgam change in the volume of amalgam is 0.235 mm cube because of raise in 25 degrees change in the volume of the dentin will be 0.0234. So, the relative change in the volume this is 1 minus this other that will give you 0.00009 millimeter cube is not very high.

But when you take instead of amalgam a resin; that means, I have filled this whole with resin. So, I will be using 81 as the coefficient of linear expansion. Then when I do the calculation I will get 0.076 millimeter cube. For the dentin it is 0.234. So, the difference the radioactive change in the volume will be 0.07 0.02. So, this is 0.05 millimeter cube, that could be quite high; that means, if I have here a cavity filled up with a resin, which has got a le coefficient of linear expansion 81 into 10 to the power minus 6 divided per degree centigrade and my dentin is 1-10th of that.

So, there will be a difference in the volumetric expansion when you raise by 25 degrees. While you may have a 25 degrees raise especially if you are having hot food or very cold beverages. So, there could be a gap create, there could be gaps created here between the resin and your tooth which may allow the fluids to enter leakage of fluids from your mouth cavity there could be bacterial colonization.

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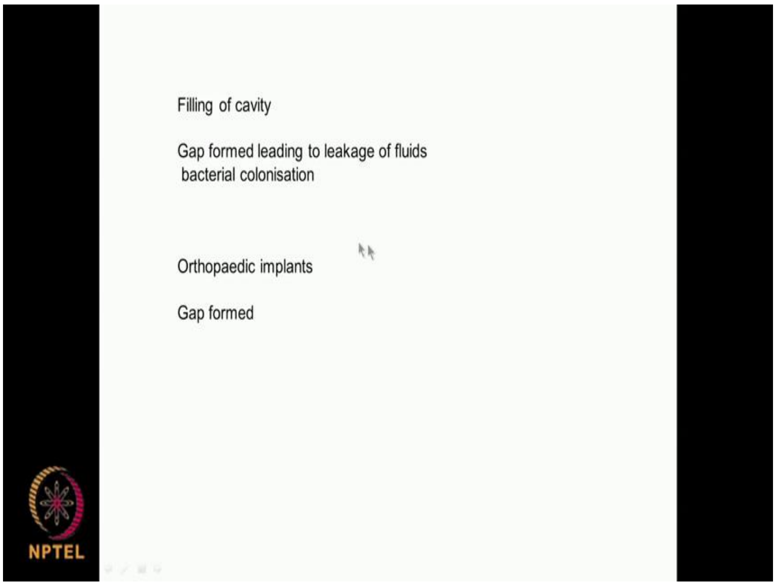

So, when we have a cavity and there is a differential between the co volumetric expansion between the dentin and the material you are using there could be problems over a long period of time; similarly, if you have orthopedic implants.

And there are differences in the volumetric expansion of various materials used. Then there could be gaps formed, which could lead to bacterial colonization. Of course, in orthopedic implants we will not see much difference in temperature as over a period of time, but it can happen quite a lot especially in overall oral region where we taken hot food or cold beverages and So, on actually. This could lead in lead to small gaps formed leading to leakage of fluids and saliva and bacterial colonization and so, on actually.

So, we will continue further on other properties that are required for a medical biomaterial to possess.

Thank you very much.