Polymers: Concepts, Properties, Uses and Sustainability

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Lecture – 50
Damping Applications

Hello welcome to this exploration of polymers and in this particular lecture we will focus on the polymer applications in damping and what is meant by damping. So, our focus will remain on users while we try to get an understanding about damping applications of polymer.

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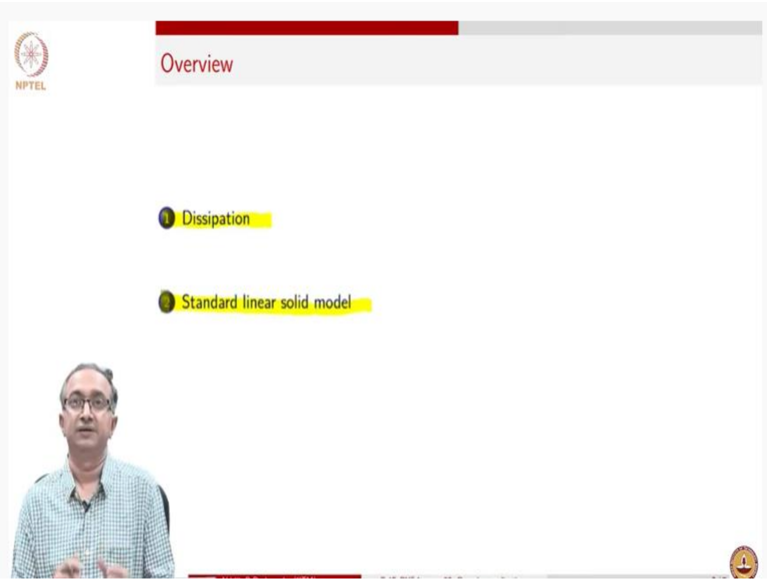

And this will be done by first looking at energy dissipation which is central to damping behaviour. We will see that all damping materials will lead to energy dissipation and especially energy dissipation with respect to energy storage capacity. So, it is the ratio of these two energies which gives us an idea about whether a material is damping material or it is not a good damping material. And we will end the lecture by looking at a simple model which is useful to describe the rubber response and rubber are very good damping materials. So, through this lecture we hope to understand the damping behaviour and application of rubbers in such damping applications.

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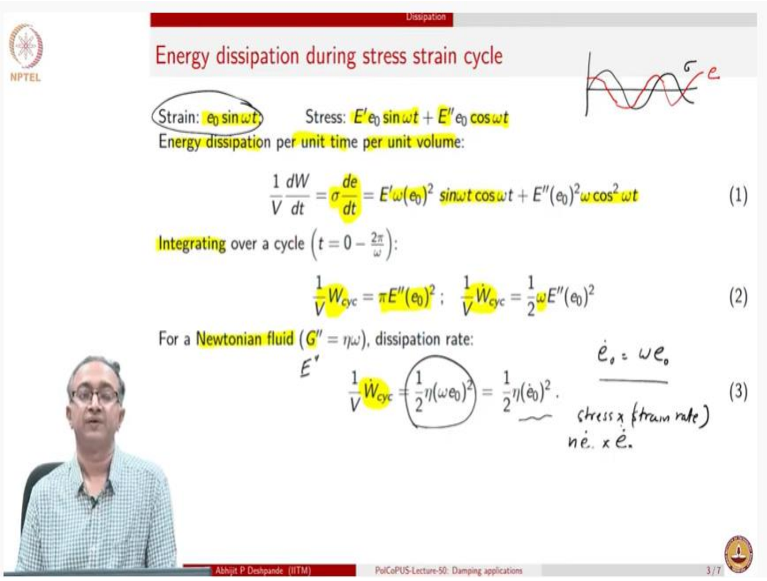

So, let us start by first thinking about energy dissipation. Since a lot of dynamic testing involves an oscillatory test. So, we will consider energy dissipation during a cycle of test. So, as we have seen several time that what we do during a cyclic test is maybe apply a let us say sinusoidal stress or we could apply sinusoidal strain and then we basically measure what happens to the strain as a function of time.

And then we know that depending on the relative variations of stress and strain we can get the loss modulus storage modulus or viscosity which is η' and η''. So, several in phase and out of phase quantities can be defined which give an idea about energy dissipation and energy storage in the material. So, let us look at a case where we are applying let us say a sinusoidal strain input with an amplitude e_o and as we know the stress will be therefore characterized by two material response functions E' which is the storage modulus and E'' which is the loss modulus. And we call these moduli iso because one of them is out of phase with the input strain and the other one which is in phase. So, in phase tells us about the elasticity in the material and therefore E' is storage modulus and now the energy dissipation is based on the amount of stress that is being applied that the material is subjected to and the rate of change of strain. So, this you can think of in terms of basically the work being done and work being done is forced into distance and the rate of work being done will be forced into distance into time.

So, basically what we have instead of force into distance into time we have stress into strain rate and I leave it to you to do small units' rationalization and see that when we talk about stress into strain rate, we are talking about energy per unit volume per unit time. So, basically, we are saying power per unit volume remember power is energy per unit time. So, basically what we have is energy dissipation per unit time per unit volume and that is given by stress into strain rate.

And given that we know about stress and strain for this sinusoidal variation in terms of response functions E' and E''. So, just to highlight the fact that what we are writing here is for a general linear viscoelastic material because only thing we have assumed so far is a stress of a form where frequency is omega because input frequency is also omega and so we have assumed only linear viscoelasticity otherwise it could be a material of any different kind because we have not specified what is E' and what is E''.

So, in general then the overall power per unit volume is going to be given by basically some functions of sin and cos and we could do this by in terms of per cycle what happens because this is as a function of time. So, let us look at because material is being subjected to several cycles, we will look at what happens during one cycle and that can be done by just integrating this from 0 to $2\pi/\omega$ because 1 cycle is $2\pi/\omega$.

ω is the frequency and if you do that again with some algebra you will be able to see that E' in fact does not contribute to energy dissipation and that should not be surprising to you at all because E' signifies elastic storage and its E'' which signifies viscous or loss properties of the material and therefore that contributes directly to the dissipation in the material.

You could also look at the power itself or the energy and they are related to each other through basically ω and so what this says is E'' is a very good determinant of what is the energy dissipation in the material quantitatively also because we can look at what is the amount of energy dissipated in a cycle and that gives us a capability of material to dissipate energy and in turn we will see that is what a damping material should do it should dissipate energy. And so now let us look at the overall the dissipation rate for let us say Newtonian fluid and Newtonian fluid is where G' or E''. As I have mentioned E is usually indicated whenever we do a tensile loading and G is whenever we do shear loading and so but depending on what material is being tested in which mode you can either have G'' or E'' and so for a Newtonian fluid you can show that E' , E'' and G'' are nothing but η times ω.

So if you substitute it here we get the expression for dissipation rate in Newtonian fluids and since we know that è is nothing but ω times e_o stress strain and strain rate are related to each other through omega you can just take a derivative of this with respect to time and omega will come out and you will get basically this relationship and so we what we get is the magnitude of amplitude in terms of $\dot{e}_o^2$

So, this is nothing but stress x strain rate because η x è is the stress and e_o is the strain rate so that is the amount of dissipating energy in a material.

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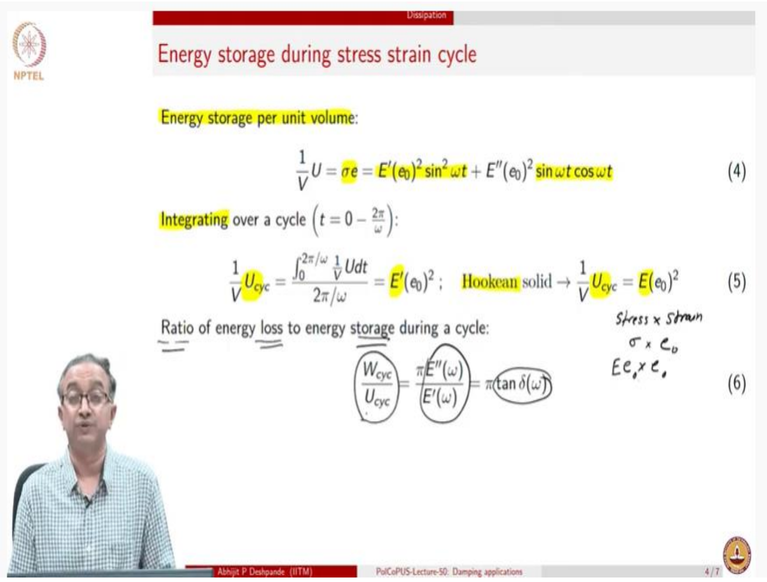

We could do the other side of it which is the energy storage and so the energy storage per unit volume is basically given by stress into strain. So, this is again the work being done load into distance but per unit volume and therefore stress into strain and strain remember is distance per unit distance and so again it is a function of sin and cosine and again we if we do integration, we can show that these energy during one cycle is directly related to the storage modulus.

And for a Hookean solid since we know that storage modulus is a constant quantity which is nothing but let us say the young's modulus of the material then energy involved in a cycle is just E times e_o^2. And this is again stress into strain so that is going to be sigma into e because sigma itself is e times the modulus. So, e times modulus into e. This is some measure of the storage energy during one cycle.

And so what is important for a damping material is to see the ratio between the loss and the storage and generally given the expressions that we have got what we will get is the this ratio of loss to storage is directly related to tan delta which we have defined earlier which is just a ratio of E''/E' or G''/G' for shear mode and so the tan delta is an important determinant tan delta which is a material property which tells us about the loss in the material and we call it loss factor or loss tangent it directly tells us about the ratio of energy loss to the ratio of energy storage by a material during a cycle.

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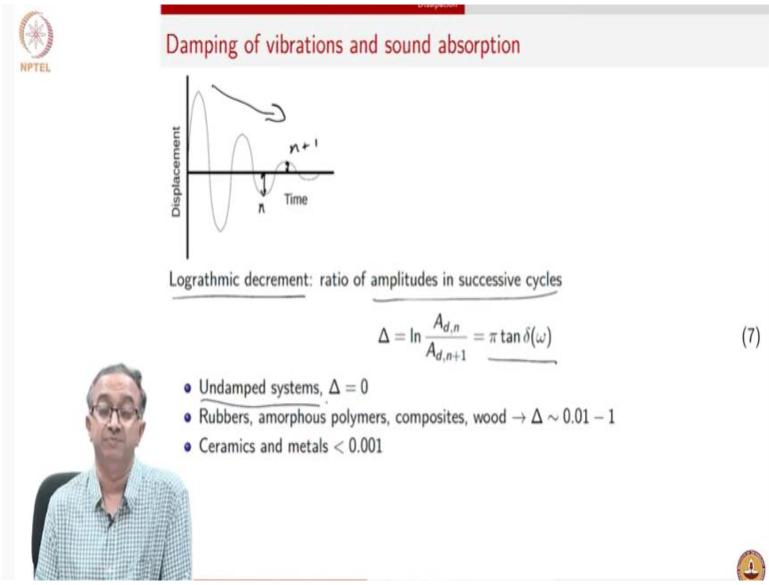

So, let us look at and consider what is the phenomena happening during damping of a material. So, damping is basically where we put the material and let us say one side is vibrating the other side should not feel it. So, for example a machine which is located on a floor we put vibration isolation pads below so that when the machine vibrates, we on the floor should not get feel the vibrations.

The reverse could also be true that if we have a very sensitive instrument and if we walk on the floor our walking should not induce vibration to the instrument. So, therefore again we vibration isolate so what this vibration isolation device does is it takes the mechanical energy which is due to vibration on one side and absorbs it and does not transmit it if you have a perfectly elastic material then what happens is whatever vibration is being felt by this material will get transmitted to the other side and it will not dissipate any energy.

So, generally if you look at displacement a damping material would imply that displacement will die over time. So, whatever vibration are caused if I let say do the vibration at some instant of time, I apply some load and material starts vibrating if I leave it then over time the energy of the vibrations will slowly decay to 0 and that is a characteristic of a damping system. So, displacement as a function of time will keep on decreasing so you can see that the amplitude of displacement keeps on going down and eventually of course it will go to 0. And so, the idea here is to say that you know how does this displacement vary as a function of time and for a damping material of course this displacement has to go down with time and that can be measured by estimating what is the logarithmic decrement and this is basically a ratio of amplitudes in successive cycles.

And so, amplitude in n cycles so let us say this is n cycle and this is n + 1 then we take the ratio of these amplitudes and it can be shown that is directly related to the tan delta that we discussed just now. So, therefore this logarithmic decrement is what is characterized for damping materials and if we have let us say a system which is undamped then delta is going to be 0 and for this case of course the displacement versus time will just look like this so that there is no change at all as a function of time it is an undamped system.

But whenever damping happens the amplitude will go down and rubbers and many of the amorphous polymers and wood have actually the damping factor this logarithmic decrement in the order of 0.01 to 1. So, it is a two orders of magnitude change but if let us say you compare it with ceramic and metals, they have far lower logarithmic decrement and clearly therefore ceramics and metals are not good damping materials well many times rubber and in fact even wood can do a very good job of damping and vibration isolation.

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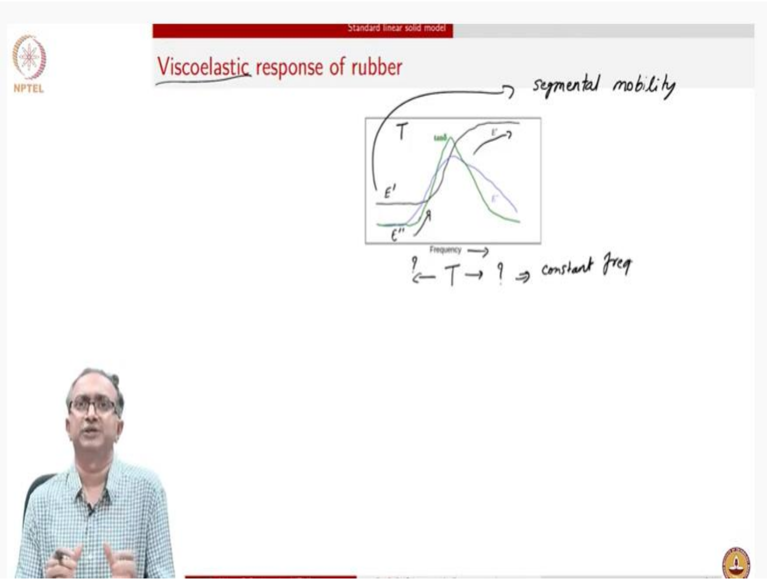
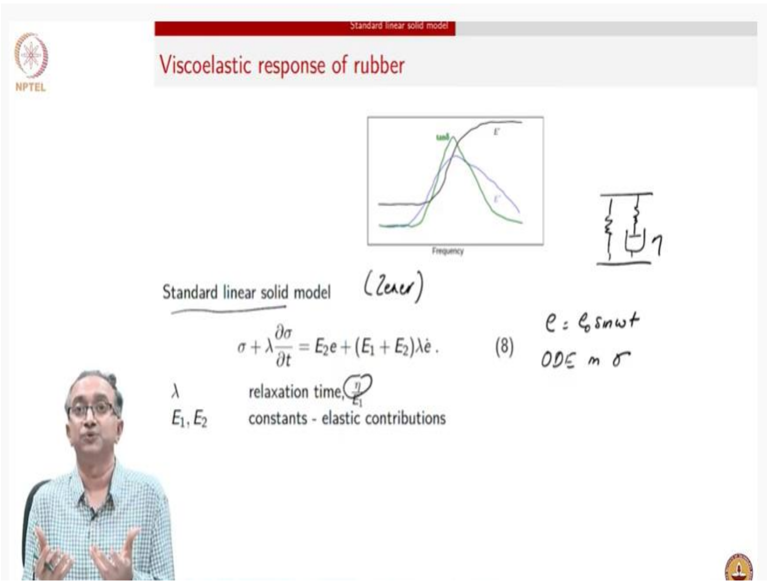


So, in the closing what we will do is look at a generic response of rubber materials given that they are used so much in case of these damping applications and energy dissipation applications. So, viscoelastic response of rubber generically is follows. What we have is if we subject the material to low frequencies since the material is in the rubbery state segmental mobility is there and segments can fluctuate.

So, this is where segmental mobility is present. So, this particular data that qualitatively is being shown is at some temperature T. So, it is an isothermal experiment but frequency is what is being varied so at low frequency given that segments can move around we get E prime is constant and E double prime is lower than E prime which means the material is more elastic then it can dissipate energy and this is where we use rubber bands or many of the other materials. So, where the loading is slow and, in this case, therefore the material is predominantly elastic and that is why we use elastic rubber band or many other rubbers where we are exploiting the fact that when you deform and release it comes back. Now when you start subjecting the same rubber to higher and higher frequencies what happens is the now the frequencies of vibration and frequencies of mechanical loading are similar order of magnitude as the segment’s relaxation time and or the time scales associated with segmental relaxation. And so what happens is the bond rotation and bond fluctuations and the segmental mobility these start absorbing the energy and lot of this starts happening and there is a resonance phenomenon which is what we have already in whether its FTIR, molecular spectroscopy, dielectric loss when its electrical dielectric spectroscopy or now this is mechanical spectroscopy.

So, therefore E double prime starts increasing as you increase the frequency of course given that we are now increasing the frequency it becomes more and more difficult for segments to also fluctuate and do their mobility and so they also start storing more energy so E prime also increases. But beyond a certain frequency again the dissipative losses go down because now the segments have become almost frozen and so again, they lose the ability to dissipate energy while ability to storage keeps on increasing and so beyond a certain frequency material becomes glassy.So, in effect in frequency what we do is we are going from a rubber to glass transition and since I said this, I am sure some of you can spot that I can do the same plot pretty much at a constant frequency but as a function of temperature. Now just think about whether if I plot this data which I am doing now as a function of temperature will temperature be increasing this way or will temperature be increasing this way and this data of course same data can be thought of at some other constant frequency. So, I will leave you to think about this and based on our other discussion you should be quickly able to answer this question. **(Refer Slide Time: 16:28)**



So, let us look at a simple model which can actually capture this and it is called standard linear solid model there is an electrical analog also of this model and that is called Zener. So, sometimes when you search the resources you might find Zener as another popular model where the capacitor capacitance and resistances are combined in in a way that you get this response which is a good combination of elastic and viscous and importantly it gives a more solid like response.

If you recall my discussion related to Maxwell model it is more applicable for fluid like response and therefore creep cannot be explained. On the other hand, Voigt model which was again a very simple model could be used for creep but it could not be used for stress relaxation. So, the standard linear model does a good job with both of them when I say good job it does a qualitatively reasonable job that we can see that in creep actually material does not just keep on creeping like a fluid it deforms and then stabilizes the strain becomes constant after some time.

Similarly in stress relaxation stress does not decay immediately your stress does not remain constant like a hooky and solid but it decays over time and so it is a three parameter model and for those of you who are interested in the mechanical analog you can look at and try to justify in terms of the spring and dashpot this is how the standard linear solid model looks like and I want you to think about which one of these spring is E and which one of spring is E_2 and why?

The eta the is basically the damping response which is the Newtonian like response or the viscous response so if you look at response of this particular model and again how you get the response of the model is in this particular equation you just substitute let us say a sinusoidal strain. So, let us say if you apply $e = e_o \sin \omega t$, we are saying that we are subjecting the material to a sinusoidal strain. So, when you substitute this here you will get an ODE in sigma and then you can start with an initial condition that stress is a particular value in the beginning and then just solve initial value problem and then get the solution and based on the solution again you will get a sin component and a cos component when you split it in the two you can get E’ and E’’.

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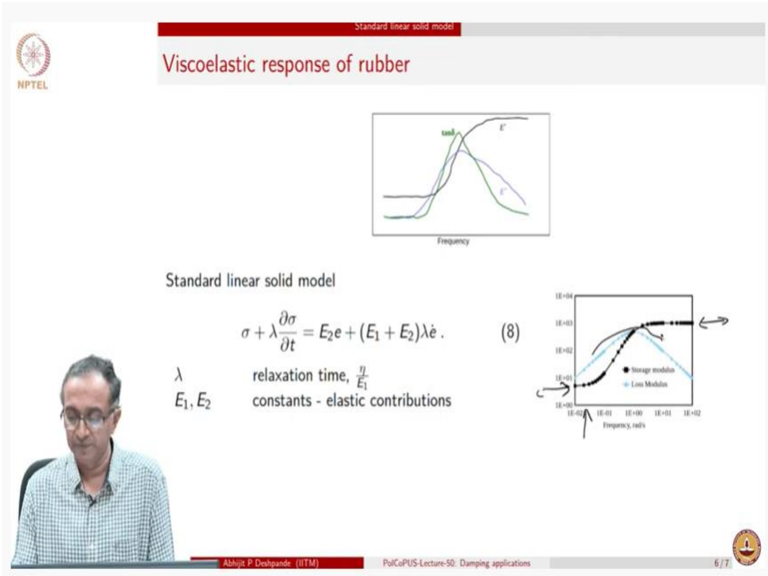

And if you do such a calculation also there are analytical expressions available. So, if you just do some search you can find out the analytical expressions for E’ and E’’ for standard linear solid model and if you plot those you can see the qualitative features that E’ is constant at low frequency then E’ is again glassy state higher modulus at high frequency and then the G’’ or tan delta also will go through a peak.

And so, this rubber like response is qualitatively described by a standard linear solid model which is the simplest of a model which can give this rubber like response.

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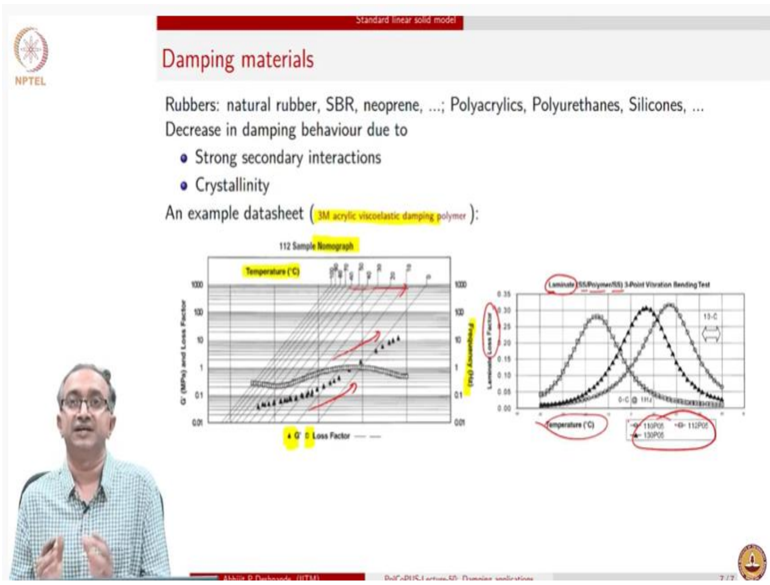

So, the damping materials that we have talked about are rubbers and whether it is natural rubber or whether its styrene butadiene rubber, neoprene or even other families of acrylics for example or urethanes and silicones are common examples of damping materials and generally if damping has to be achieved then we should minimize the secondary interactions and there should be no crystal entity. So, therefore in general if damping behaviour gets affected it decreases due to strong secondary interactions and presence of crystallinity. Can you think why this would be the case why would secondary interactions lead to less damping and you can think also probably in terms of whether in wood whether cellulose is going to contribute to damping or whether lignin is going to lead to damping you can try reading about it.

But what does secondary strong interactions imply in terms of segmental flexibility or crystallinity of course always implies loss of segmental mobility. So, that answer is probably a little more easy. So just think about it and it should be relatively easy answer in terms of trying to justify why should segmental mobility decrease with secondary interactions and therefore it will lead to less damping. Now look at the data for an example material in this case it is from a commercial literature of a 3M acrylic material and the way the nomograph gives is basically for temperature and frequency and G' and the loss factor. Because for damping applications loss factor tells us about the energy dissipation capability quite often, we will have this also material subjected to loads and it has to withstand load.

So, therefore E' or storage modulus is also important and so these kind of data are given in this case G' because again it is a shear based testing and you can see that for a frequency as frequency increases the E' and G' increases or as temperature decreases the E' also increases the tan delta on the other hand goes through a maximum and then so that is again understandable because tan delta is related much more closely to segmental flexibility.

Now how these materials can be tested is we can make a sandwich structure of twos different surfaces from which they are supposed to absorb the vibration. So, in this case for example a laminate is made which is stainless steel and polymer and stainless steel and then it is subjected to vibration and then you can try to look at what happens to loss factor of the laminate as a function of let us say temperature and you can see that if you use three different types of acrylic materials you get maximum in loss at different conditions.

So, therefore if you want to design a particular polymer for a given application you can then look at this loss factor and see where is it maximum which frequencies is it maximum which temperature is it maximum and then choose a material appropriately so that it maximizes the energy dissipation in the given frequency range and in the given temperature range of interest.

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So, with this we close this discussion related to damping behaviour of polymers mainly rubber materials and now in coming lectures we will look at some of the aspects related to superposition and some properties of blends and impact behaviour of materials and so on. So, with this we close the lecture. Thank you. Goodbye.