Modern Construction Materials
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Module - 3
Lecture - 10
Rheology of Liquids and Solids

Welcome to lecture ten of modern construction materials until now we've been looking at the mechanical behaviour and the responsible materials to stress and we saw that some of the responses and some of the properties were time dependant today we look further into the time dependence of the mechanical behaviour when we talk about rheology and i open with this slide of a glacier this is the perrito moreno glacier in argentina and a glacier is a river of eyes and it slowly moves. So, rheology is not only associated with liquids that flow, but also solids move and in this case the glacier move slowly may be a few millimeters every year or even less and then pieces of a break and fall of. So, ice is a rheological material as many other solids even rock masses concrete wood and so on change their deformation and move with time.

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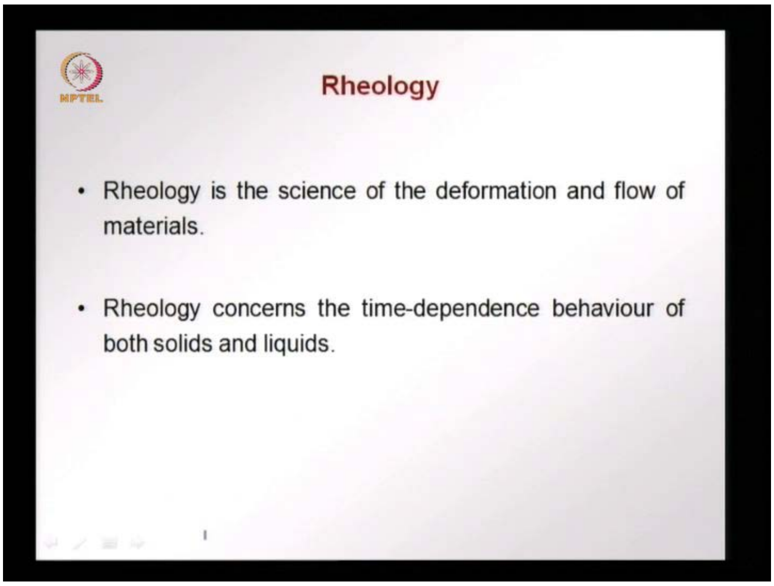

Rheology is therefore, the science of the deformation and flow of materials it is related to the time dependence of the behaviour of both solids and liquids.

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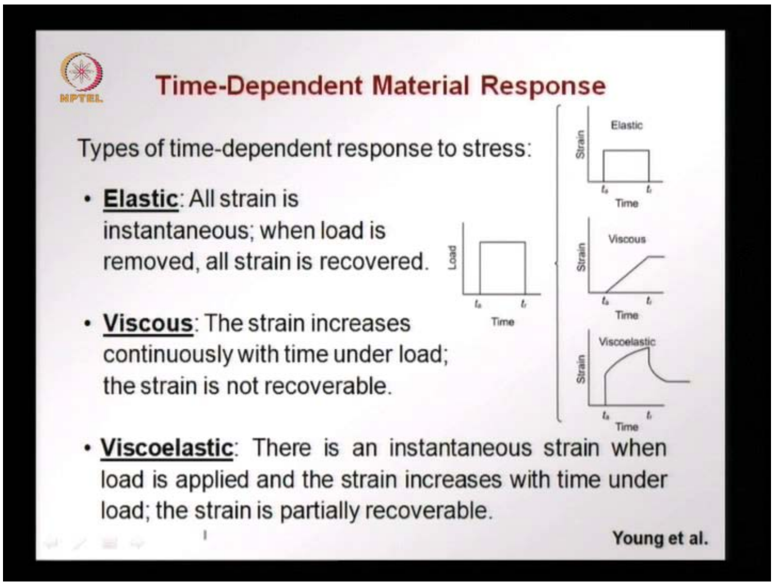

When we talk about time-dependent material response there are basically three types of responses to stress first is the elastic response where all strain is instantaneous that is it occurs instantaneously and when the load is removed all the strain is recovered. So, if we where to look at and application of load very fast that is instantaneously we apply a loader stress keep it constant and then release it remove the load in the elastic case we will have a response like this we will have all the strain instantaneously occurring during the period the stresses constant the strain would also be constant and then we when we releases stress a load all the strain is recovered and we go back to the initial state.

So, that is elastic response or instantaneous response the whatever strain has occurred creates strain energy in the material and when the load is removed this strain energy causes the material to return to its original state in a viscous material on the other hand we find that strain increases continuously with time under the load and the strain is not recoverable when the stress is remove. So, under the same loading case the strain response would be like this where we have initially strain not jumping like in the elastic case, but slowly starting to increase and as long as the stress is there the material deforms in a linear manner than afterwards when we remove the stress a load there is no recovery this strain does not go to zero, but it remains at the state that we left this stress or we remove this stress this is called viscous behaviour viscoelastic response is a combination of the two.

There is some instantaneous strain when the load is applied and the strain continues to increase with time under the load and the strain is partially recoverable. So, we have under the same loading case we have strain having an instantaneous component there is a sudden jump and then under load the strain slowly increases when we release the load there is an instantaneous recovery there is a vertical drop and then there is the slope recovery partial recovery we do not go back to zero like in the elastic case not do we stay at the same point as in the viscous case. So, the viscoelastic case is in between or a combination of the two phenomena and we will discuss now little bit further the the viscoelastic response because models are needed for this and lot of materials like a mentioned ice concrete wood polymers even metals undergo viscoelastic responses.

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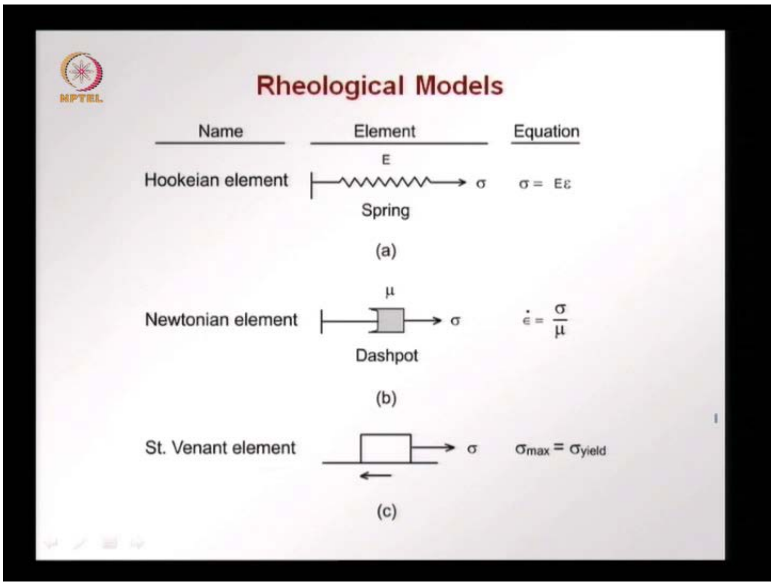

For this we look at three basic elements to model the behaviour such as what we have discussed the first basic element is the hookeian element or a spring element basically here we have element that behaves according to hooks law and the the fundamental equation is stress is equal to young's modulus time strain. So, this takes care of the elastic response then we have the newtonian element with basic unit that follows newtons law in terms of fluid behaviour we have now a dashpot instead of a spring with.

a coefficient of viscosity mu. So, when we pull there is a gradual response or a gradual increase in strain and the governing equation is given by this epsilon dot that is the strain rate is equal to stress divided by mu the coefficient of viscous a third basic element is the saint venant element where we have no movement up to a certain stress until the friction is overcome say in this block and when a certain amount of stress is put in then there is movement that is sigma max is equal to sigma yield until sigma max there is no strain and after that when yielding occurs then you have a movement. So, this is the saint venant element these three elements are combined have been combine in many many models to represent the rheological behaviour of materials.

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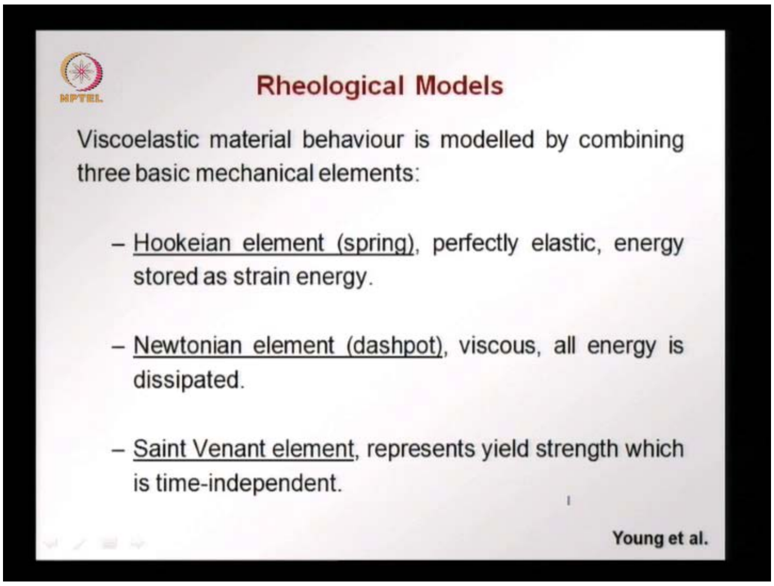

So, we have look at three basic elements and with this we can model the viscoelastic material behaviour the hookeian element or the spring element is perfectly elastic energy stored as strain energy when we release the load this strain energy springs the material back to the initial state in the newtonian element or the dashpot we have viscous behaviour all the energy is dissipated as the strain is occurring or as under the stress and there is no recovery in the saint venant element we represents the yield strength as time independent as only when a limits stress is applied movement will occur.

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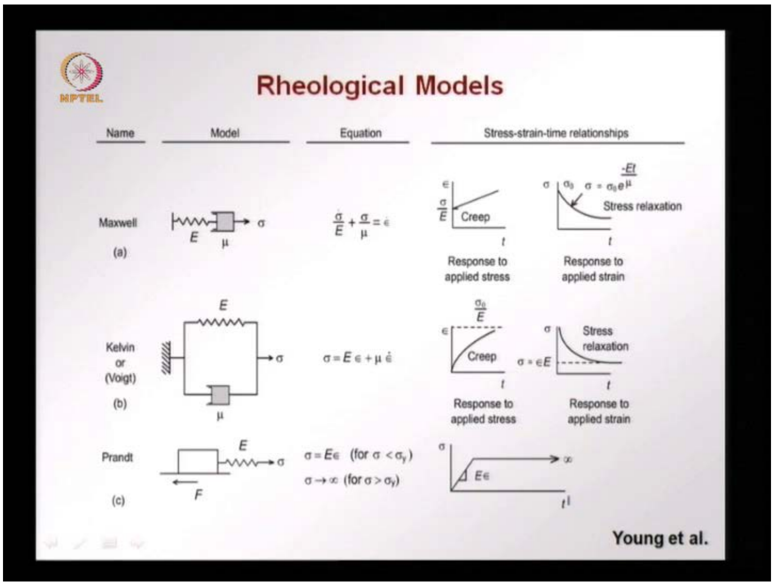

So, some simple combinations of these elements to give rheological models are given here on the top we have the maxwell model which is a combination of this spring and the dashpot elements in series and certain stress is applied which is taken both by the dashpot and this spring and now the governing equation is given by this its sigma dot by e that is stress rate divided by the young's modulus plus sigma the stress divided by the coefficient of viscosity is equal to strain rate all the values with dots on the top or rates with respect to time.

So, this is the governing equation of the maxwell model below we have the kelvin or the voigt model which has the same two elements now combined in parallel. So, this stress is distributed between the spring element and the dashpot element and now the governing equation of the kelvin model is given by sigma the stress is equal to e the young's modulus time strain plus mu the coefficient of viscosity times the strain rate epsilon dot in the prandt model we have a combination of the saint venant block plus a spring and we find that until a certain limit stress sigma max equal to the yield strength we have elastic behaviour we have sigma equal to e epsilon. So, that is the elastic behaviour beyond that as stress the stress keeps changing whenever we have sigma greater than.

Sigma y the stress can keep on increasing until this we have elastic behaviour an after this we have an increasing behaviour with time rather for the prandt model we have a combination of the saint venant block and the hookeian model of the spring element in this case we have elastic behaviour until a certain limits stress is reach that is sigma is equal to e epsilon when as long as the stress is below the yield strength and after that the stress remains constant that is what is shown here we have sigma the stress and t the time here until a certain limit we have elastic behaviour sigma is equal to e epsilon then after that we have yielding and sigma being constant up to infinite time now here what we have done is looked at these models and how they behave under creep and stress relaxation creep is when we have a constant applied stress the stress is instantaneously applied and then we keep it constant that is the stress rate becomes zero after the initial application of stress. So, in this case we have an instantaneous strain and then we have a constantly increasing strain. So, in this case to reiterate stress is kept constant over time and we are looking at how the strain changes with respect to time this is y axis we have epsilon the strain and x-axis we have time. So, as i said creep response of the maxwell model would be like this we have an instantaneous strain and the strain keeps on increasing.

So, this is again something that you can check from this equation set the value of stress rate as zero after the instantaneous application of stress and then you will see that you will get this behaviour on the right we have look that stress relaxation that is the strain rate is zero strain is kept constant and if you work out you will get this equation the stress starts of from a value sigma zero where we are keeping the strain constant and then sigma would change as sigma zero e to the power of minus e t divided by exponential minus e times t divided by mu.

So, this gives us the stress relaxation means strain is kept constant will have a relaxation of the stress and this is how the maxwell change maxwell model reflect this in terms of the kelvin model when we look at creep again now creep is vest stress is kept constant over time we have the strain increasing up to a limit of sigma zero divided by e which should be the stress that is applied an kept constant in terms of relaxation we find that in the kelvin model we have an a drop similar in shape to what we saw in the maxwell model with a limit of sigma equal to epsilon e . So, again stress relaxation occurs when strain is kept constant that in the strain rate is zero and creep occurs when stress is kept.

Constant or the stress rate is zero. So, this this behaviour you can check using this governing equations and setting the different values and this could also be used in excises with different para meters given for the different constant like e and mu.

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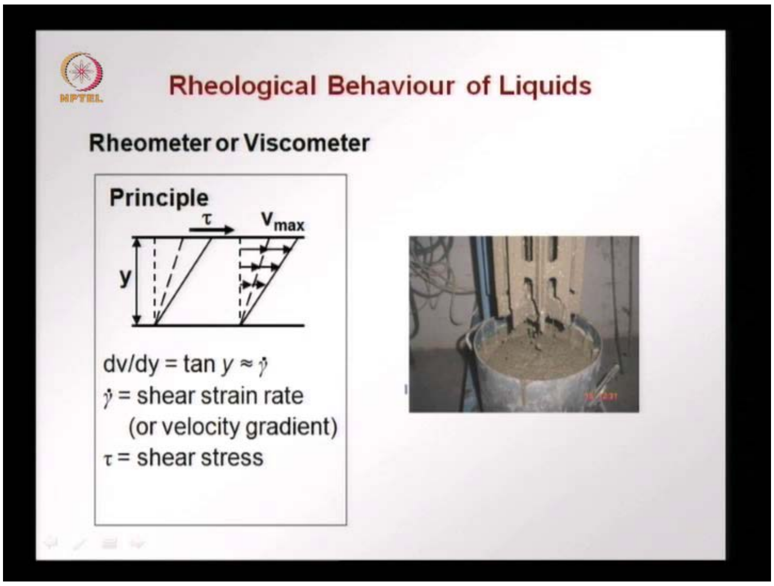

How let us move on to the rheological behaviour of liquids and from fluid mechanics you remember how viscosity is defined and basically we have the case of a layer of liquid that can be sheared and we have the shear strain rate given as the change in voracity by distance this gives as the shear strain rate or the velocity gradient and then we have shear stress which has been apply to cause this behaviour and we find these two are proportional to each other here we have rheometer that can be used for concrete instead of two plates moving with the liquid in between we have here something that is more practical a drum that is rotating and an inner cylinder that is the measuring device for the stress or the shear stress.

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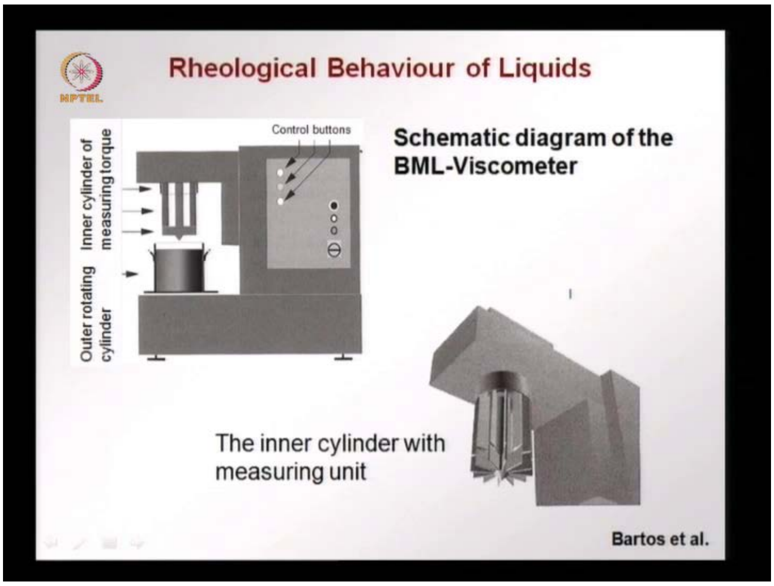

So, this is a schematic diagram of the b m l viscometer this is viscometer used in the case of in the case of concrete cement matter and. So, on where we have and outer cylinder which is filled with concrete and this rotates at a certain velocity for different velocities.

And for each velocity this inner cylinder measures the tark that is cost and this is use to calculate the shear stress the rotation gives us the shear strain inward this is the inner cylinder it is not really a perfect cylinder because the perfect cylinder could cause slip of the liquid against the cylinder liquid in this case concrete which is more of a semisolid instead of that we have cylinder in the form of gains which gives as a good measure of the shear stress or the tark.

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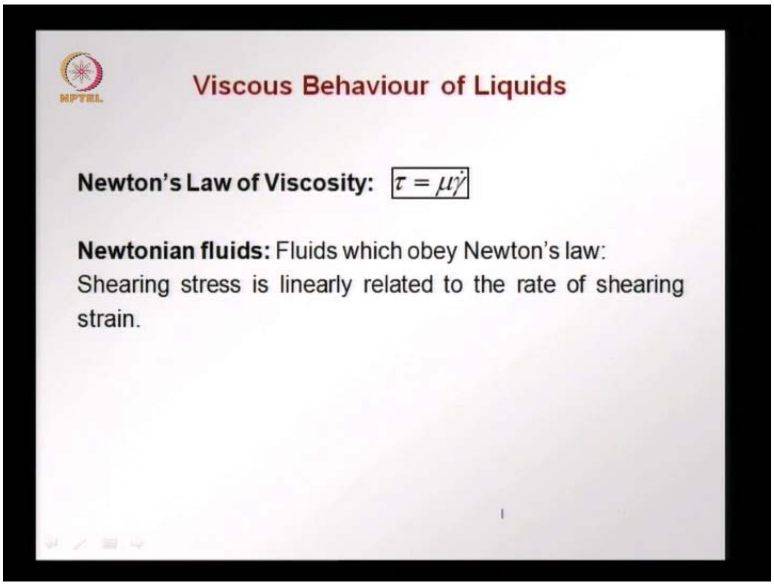

How through experiments such as this we can determine whether a liquid follows newtons law of viscosity or not to remind you newtons law of viscosity says that shear stress is proportional to the shear strain rate and the constant of proportionality is mu the coefficient of viscosity. So, newtonian fluids are those which obey newtons law that is shearing stress is linearly related to the rate of shearing strain.

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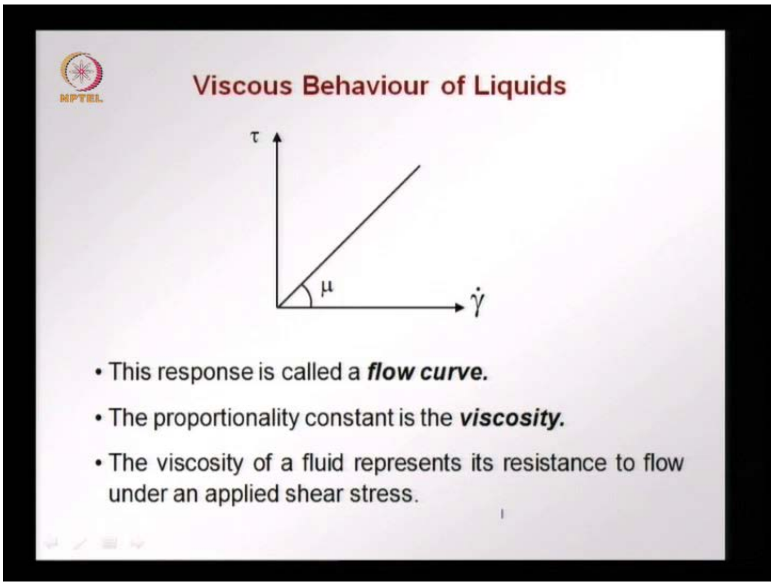

And we have a behaviour like this where we have shear stress on the y-axis and the shear strain rate on the x-axis and the constant of proportionality is the viscosity a curve such as this is called the flow curve and in this case it is a simple flow curve of a newtonian liquid later on we will see that this flow curve can change a lot depending on how the material behaves and viscosity can be taken as a representation of the resistance to flow of a material under and applied shear stress

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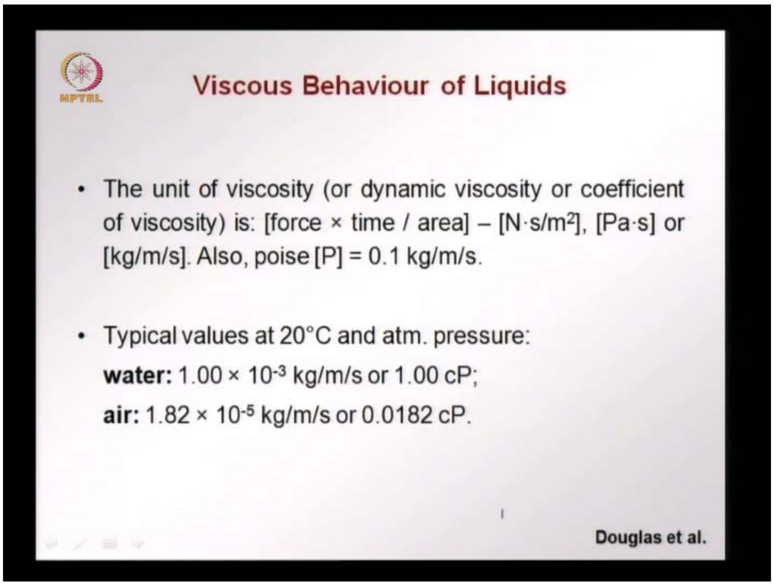

The unit of viscosity sometimes is also called the dynamic viscosity or coefficient of viscosity is newton second per meter square of pascal second or kilogram per meter per second it is basically units of force times stine divided by area and are poised is often used as the unit of viscosity it is equal to mind one kilogram per meter per second some typical values of viscosity at twenty degrees celsius and atmospheric pressure water has a viscosity of one centipoise or one times ten to the power of minus three kilogram per meter per second air; obviously, will have much lower viscosity one point eighty-two times ten to the power minus five kilogram per meter per second or zero point zero one eight centipoise.

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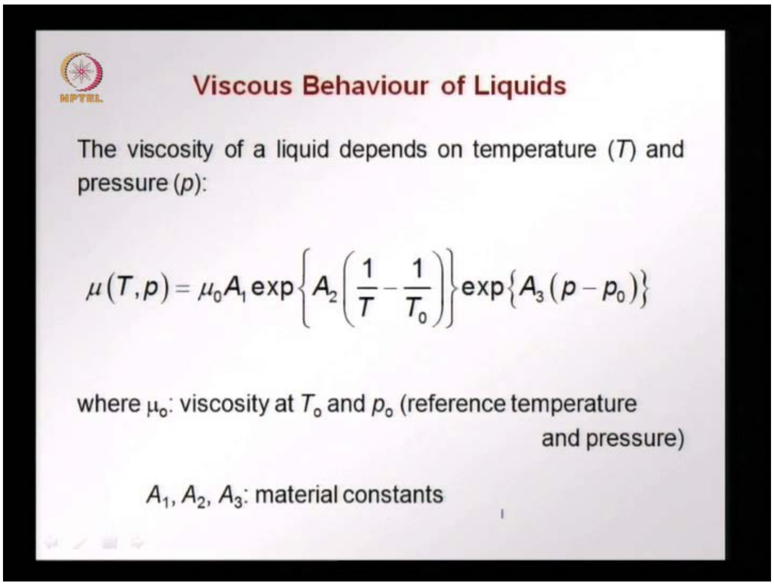

This viscosity is not a constant like in the last slide it was said that those values spear for twenty degrees celsius and atmospheric pressure we find that viscosity of a liquid depends on temperature and pressure. So, this is a general equation that you see here mu as a function of t the temperature p the pressure is equal to mu zero which is measured at reference temperature t zero and pressure p zero times a one a one a two and a three are constants for a certain material times the exponential of a two times the inverse the difference between the inverses of the the temperature where we want to know the viscosity and the reference temperature times the exponential of a three times the difference in pressure p p again is the pressure where we want.

to determine the value of viscosity and p zero is the reference for which we have determine mu zero. So, what we find is there is an inverse relation with temperature and a positive relation with pressure as pressure increases the viscosity increases as temperature increases viscosity decreases. So, at higher temperatures a material will have less resistance to flow at higher pressures the material will have a higher resistance to flow.

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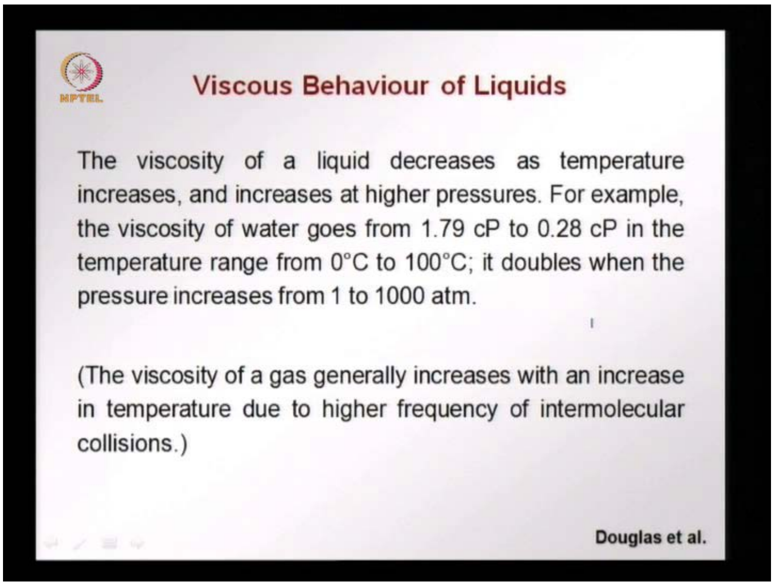

So, in a liquid we find that viscosity decreases as temperature increases and the viscosity increases at higher pressures. So, this generally holes for all liquids we find that viscosity and temperature and pressure have a definite relation for example, in the case of water viscosity goes from one point seven nine centipoise to point two eight to zero point two eight centipoise when the temperature changes from zero degrees to hundred degrees at twenty degrees we saw that it had a value of one centipoise when pressure increases from one to thousand atmosphere the viscosity doubles. So, viscosity goes down when temperature increases viscosity goes up when pressure increases in a gas; however, we have the opposite trend in that case of temperature when temperature increases there is a higher frequency of intermolecular collusions between the particles and therefore, the viscosity increases when temperature increases this is for a gas for a liquid the relation is as i explained earlier.

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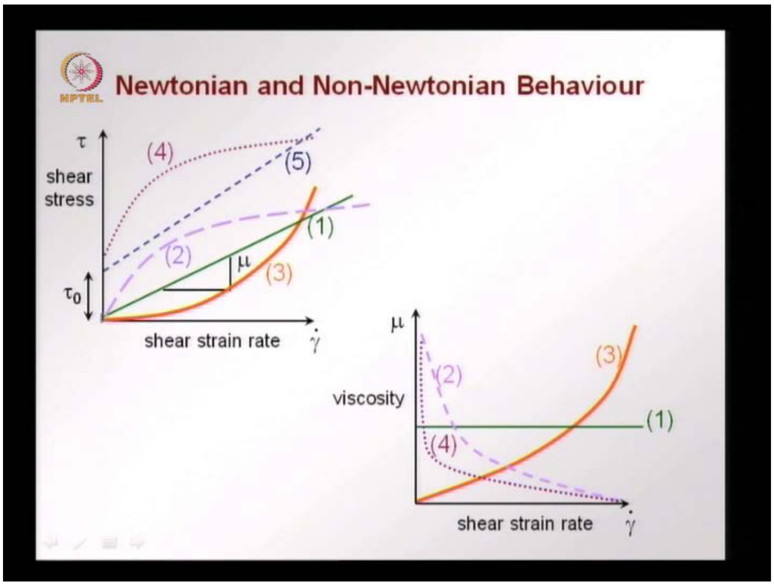

How i said that we have some liquids that follow newtonian behaviour and there are other types of behaviour. So, we look at some different responses that can be newtonian or non-newtonian in all these cases what we are going to is see how the plots of shear stress versus shear strain rate look like and what is the variation of the viscosity as a function of the shear strain rate for a newtonian liquid we saw already actually should get a linear response here and the viscosity should be constant. So, for a newtonian liquid that is how the figures look like we have a constant increase the slope is a coefficient of viscosity and this viscosity is now constant over different strain rates here it is a material property which is constant we can have a material or a liquid behave in a pseudo-plastic manner what is called shear thinning that is has the shear strain rate increases that is the faster the shear the liquid we have a decrease in viscosity there is a gradually decreasing slope. So, we find that initially we have a higher resistance and then the resistance decreases as the shear faster and faster.

So, this is reflected in this graph as a decrease in the value of the coefficient of viscosity coefficient of viscosity gives decreasing and can go down to zero when this curve becomes flat the opposite occurs in shear thickening or dilatant behaviour here we have initially a very low resistance to flow and as we move the liquid faster and faster we have an increase in the viscosity the viscosity increases and this is again what we see here the plot of viscosity versus shear strain rate looks like this initially the viscosity is very low and then it keeps going higher and higher as this curve goes up now we can have shear thinning with a certain amount of yield; that means, that instead of starting from zero the curve initially there is very high resistance the material does not move at all until a certain stress occurs and only after this shear stress or the yield shear stress is reached the material starts to shear tin and you have this behaviour. So, in this case you have very high initial resistance and then we have a drop like in the case of shear thin this behaviour is often representate by what is called the bingham model in the bingham model hence we have a yield shear stress. So, until this there is no movement until the shear stress reaches a value of tau zero which is called the yield shear stress we do not have any movement after that we have a linear behaviour like in the case of a newtonian liquid. So, here we have a case of the viscosity being very high initially and then being constant

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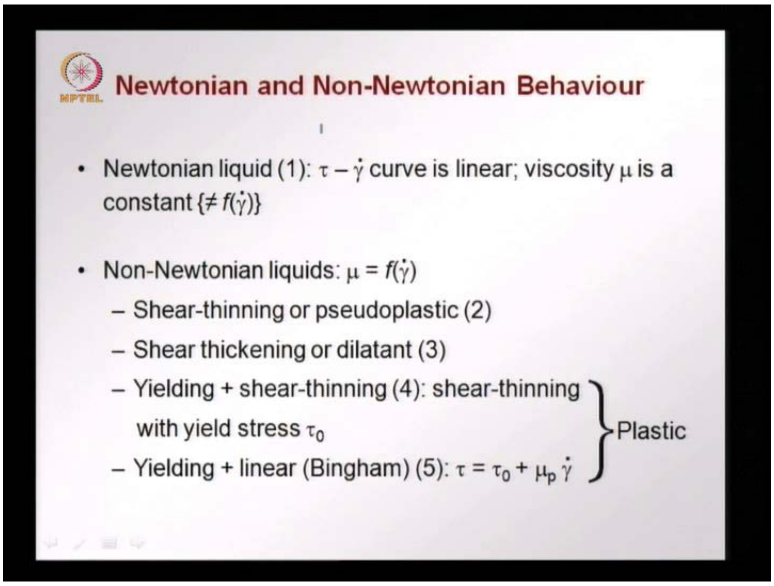

How we have looked at newtonian liquids where tau and gamma dot have a linear relationship viscosity mu is a constant it is not a function of the shear strain rate non-newtonian liquid we saw different types of behaviour where we have mu the coefficient of viscosity as a function of gamma dot that is the shear strain rate we have look that shear thinning shear thickening and plastic tie behaviour where there was a yield stress until the yield stress tau zero was reached there was no movement and after that we can have shear thinning or a linear behaviour in the case of the bingham model and this is the equation of the bingham model tau equal to tau zero plus mu p gamma dot mu p is called the plastic viscosity of the plastic or the coefficient of plastic viscosity this and this other parameters of the bingham model.

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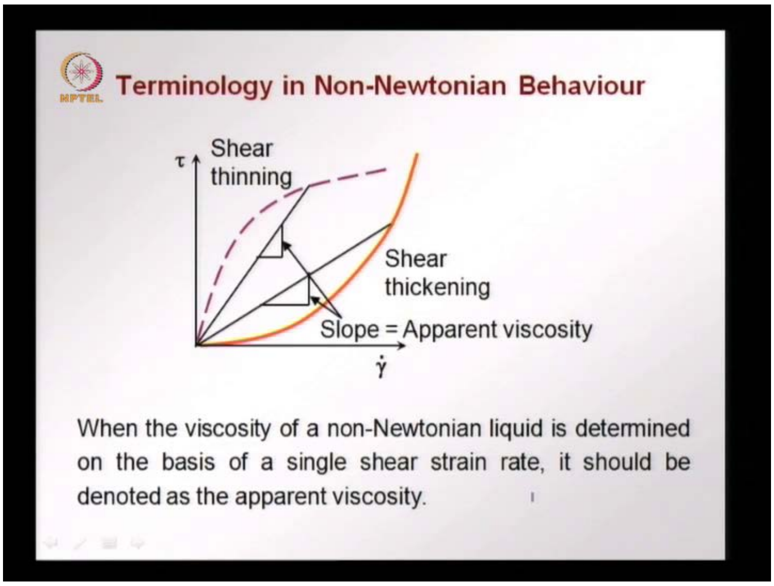

In the case of shear thinning and shear thickening we saw that the viscosity changes with the shear strain rate gamma dot. So, there we cannot have a clear definition of viscosity at any particular point in time. So, when we take the slope such as what we see here at any strain rate what we can get is an apparent viscosity. So, if you at just to get information about one point in the shear stress shear strain rate diagram this will not be the true viscosity, but it will only give the apparent viscosity and we need to determine this curve to know exactly. How this behaviour is changing instead of just looking at discrete points on this curve this is true for both shear thinning and shear thickening and when we use only a single shear strain rate to determine the viscosity we denoted as apparent viscosity as you can very clearly see in.

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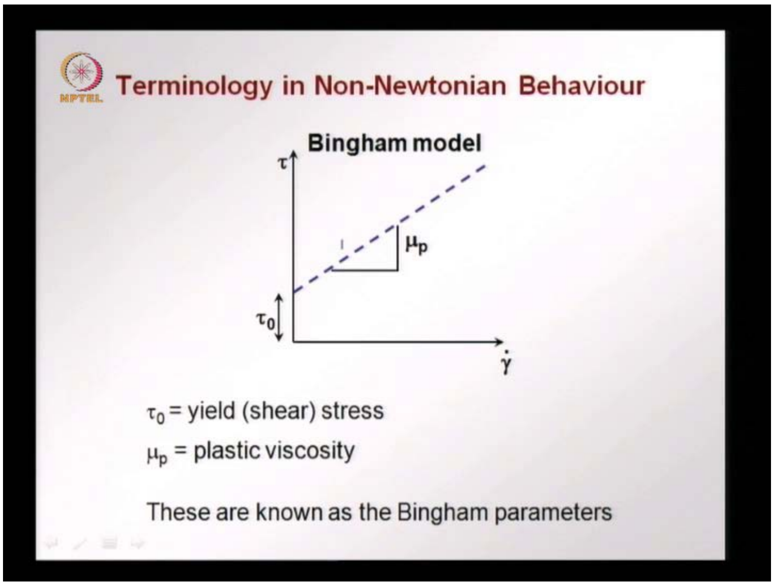

This diagram going back to bingham mode the bingham model which we use a lot in in the representation of concrete asphalted and. So, on we can see again how this model looks we have a yielding response initially there is no movement than afterwards we see that we get a linear behaviour like in the newtonian model and the para meters of the bingham model or the yield shear stress and the plastic viscosity.

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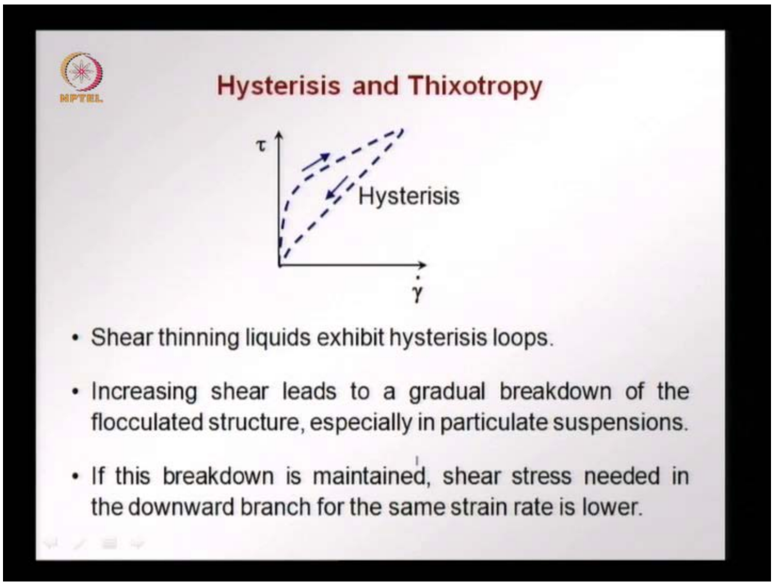

Shear thinning liquids exhibit what is called hysteresis that is there is the difference between the loading and the unloading curve. So, we increase the shear strain rate we have a certain resistance given by the evolution of the shear stress now when we decrease the shear strain rate or we are unloading we find that the paths do not coincide there is less resistance to flow when we unload then when we are load this gives rise to this hysterisis the increasing shear leads to a breakdown of the flocculated structure especially when we have a suspensions a particulate suspensions and if this breakdown is maintained in a material that at this point the breakdown as occurred and the breakdown is maintained then the shear stress needed in the downward branch is lower when we go down. The shear stress requirement is less you see that for a same strain rate we have a less less shear in the downward path then in the upper path.

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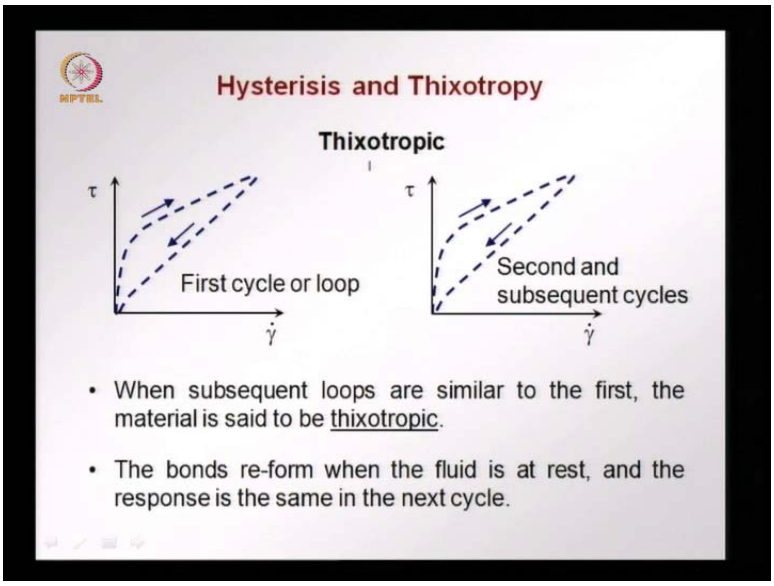

In the case of thixotropy this continues in subsequent cycles also the first cycle we had this hysteresis now in second and subsequent cycles also if you are the same thing that is when you come back the structure rewards to the original state and the same behaviour continues this materials is supposed to be thixotropic where the bonds within the liquid reform when is when it is addressed and the responses the same in the next side the breakdown reversers when we reach a state of the fluid addressed.

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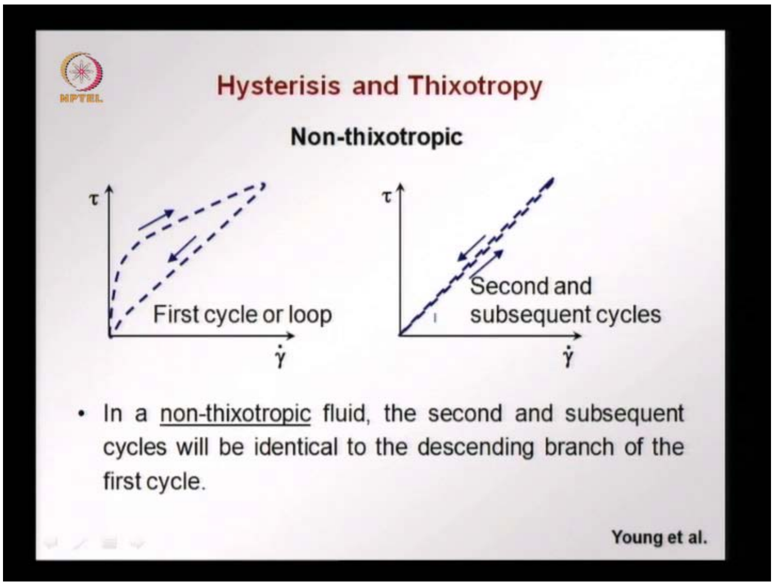

If it is non-thixotropic, but still shear thinning you will have the in the second and subsequent cycles we will have a linear behaviour we will not have hysteresis anymore in second and subsequent cycles it will be the same as the descending brands that we saw in the first cycle this would be non-thixotropic behaviour.

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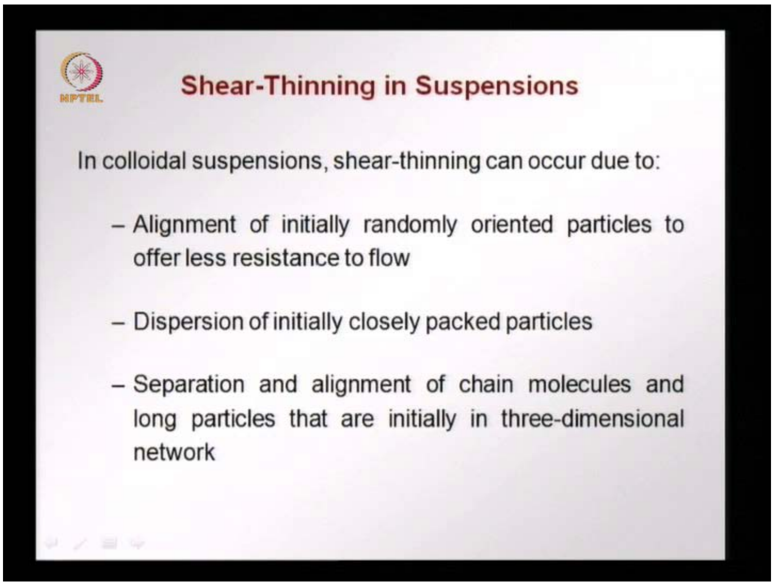

How how does shear thinning occurred when we have say a colloidal suspensions we can have the alignment of the initially randomly oriented particles getting less resistance to flow that is initially we have the particles oriented randomly which could offer more resistance and as the material flows there is an alignment of these particles along the direction of flow such that the resistance to flow decreases you can also have the case of a very.

Close pack system very dense system which is difficult to flow which as difficulty to flow and this packing could be removed or they could be dispersion of the particles leading again to shear thinning then we could have the case of particles like chains fibers that are in the fluid that are initially more entangle in a three-dimensional matrix which offers the idea resistance to flow and with flow they could be separation and alignment of these molecules leading to less flow.

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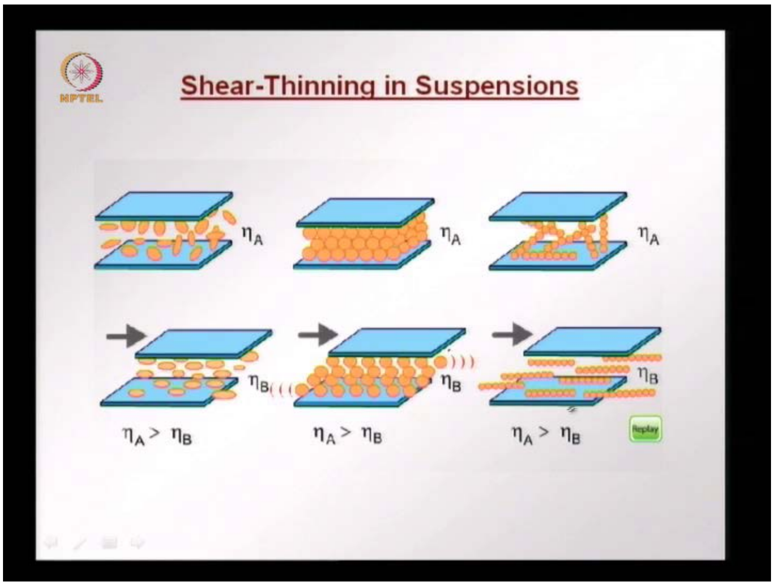

So, that is what we see here we could have randomly oriented particles and you can imagine that when this material has to flow some of these particles will offer more resistance to the others due to their orientation in the other case you can have very densely packed suspension and here again there will be a lot of friction between the particles and the particles may not flow or you could have a case wet you have a lot of chains or fibrous type of microstructures and again this would offer higher resistance to flow because of these particles will be against the direction of the flow now what will happen in shear thinning in this case what we could have if these particles.

Now, all becoming flat in the direction of the flow instead of random orientation the orientation could be along the flow and you can now see that here the flow will be easier and therefore, the viscosity will be less than before. So, this can gives rise to shear thin let us happen let us see what happens here instead now of a close packing we can have the dispersion of the particles the particles now or more separate do not offer. So, much of frictional resistance internally and flow is easier and therefore, the viscosity again decreases in this case of a fibrous nature again we can have the chains the molecules all aligning themselves in the direction of flow all the fibrous microstructures aligning in the direction of flow and you find now there is less resistance and the viscosity now is lower.

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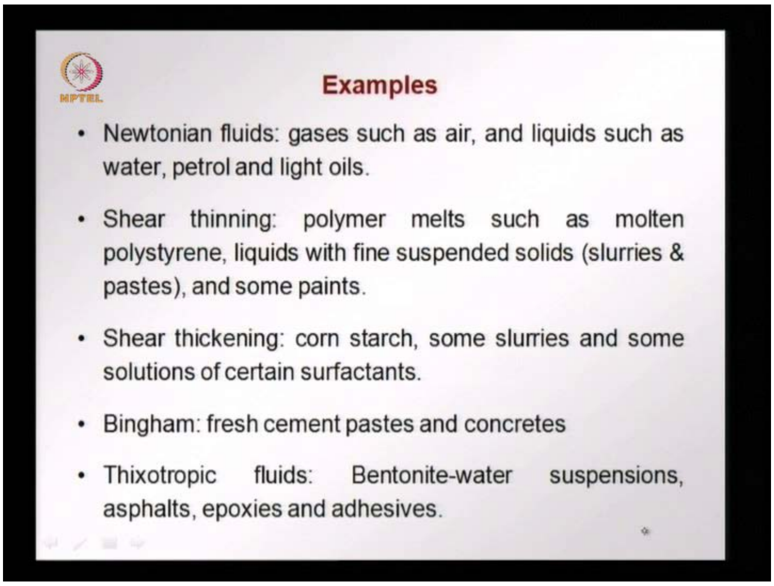

So, to conclude let us look at examples of these different types of newtonian and non-newtonian fluids for a newtonian fluid we have many examples gases such as air liquid such as waters patrol light oils all these are newtonian shear thinning which could be of more interest us occurs in a lot of the materials that we use in civil engineering polymer melts such as polystyrene molten state is shear thinning liquids in very fine suspension likes slurries cement paste all these have shear thinning behaviour paints are also shear thinning and its very important that paints have a shear thinning behaviour because then you want to apply paint say with the brush with more strain rate that is with the brushing we want the paint to spread very easily without offering a lot of resistance, but when the brushing is stop we want the paint to stay there and say a vertical wall and not come off should not flow of, but stay there and it is.

Good that we have the shear thinning behaviour because that the very slow strain rates are zero strain rates where the brushing as stop the viscosity. So, high that the material sticks to the surface and does not flow off otherwise we will have all the paints flowing off after brushing shear thickening we cannot think of many examples some slurries cornstarch and solutions of some surfactants can call shear thickening when you move the liquid faster you have a higher resistance bingham fluids are a particular case of shear thinning we can apply this behaviour to cement paste concretes in the flesh state thixotropic fluids we can of the examples of bentonite used in grouting asphalts epoxies adhesives these are again special case of shear thinning we saw that shear thinning liquids can be either thixotropic or non-thixotropic and these are examples for thixotropic fluids.

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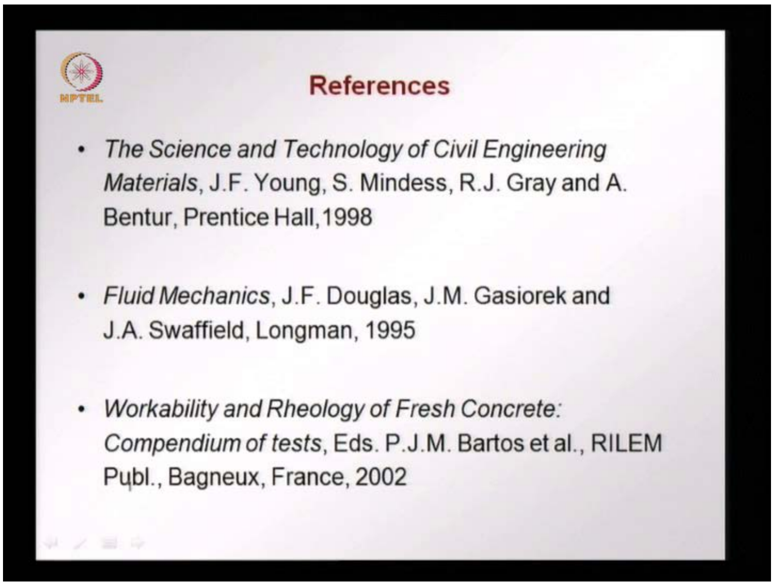

So, to conclude we have look at the time-dependent behaviour of materials we look at how liquids and solids can flow under the application of stress and with time and this gives us a good idea of how we can go about starting the modeling of materials to take into account this time-dependent behavior.

Thank you.