Structural Geology
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Lecture No 10.3
Rheology – 1 (Basics of Rheology)

Hello Everyone! We already learned elastic rheology and now we will switch to viscous rheology. For elastic rheology we have seen that the strain is recoverable if you remove the stress and interestingly there are many materials, many natural materials that we see every day. These process do not happen that if you deform something the formation remains.

At the same time you have seen the flow of water or flow of water with some sediments and then magma flows and things like that. These things are not likely to be elastic, so you need a different kind of rheology or another rheology which is not similar to elastic rheology and therefore we will now introduce this viscous rheology in detail.

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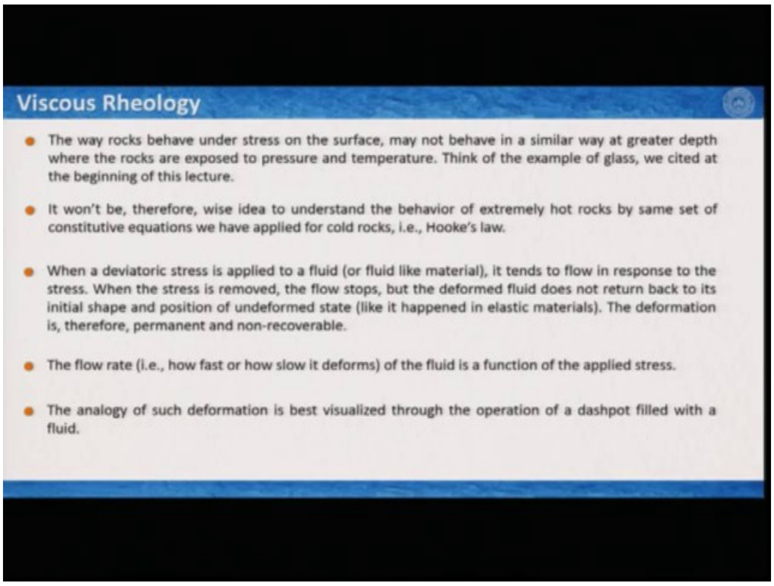

Already I was talking about the way the rocks behave under stress on the surface may not behave in a similar way at greater depth where you have much higher pressure and temperature and rocks are not really a solid material there, so you can think of the example of a glass that we have cited in the very beginning that at surface temperature it is extremely brittle, it produces fracture but when we heat it up it flows like honey, so in a very similar behaviour we can observe in rocks at greater depth.

Thus we need different kind of rheology which we actually can apply for hot rocks and in these case when you apply a deviatoric stress to this hot rocks or we can consider this now as a fluid or a fluid like material, the first instance it reacts the way that it has a resistance to respond to the stress you have applied but it tends to flow in response to the stress.

When the stress is removed the flow stops certainly but this material or the deform fluid does not come back to its original position, so their shape and their geometry et cetera remains permanently to their deform state, so therefore the deformation under this kind of rheology is permanent and non-recoverable and we will also see that the flow rate or the way we explain flow rate is how fast or how slow it flows or it deforms.

Say for example if you just put water along a slope it flows very fast but if you put honey under the same slope under the same gravity load it does not flow as fast as water flows, so water has a higher flow rate and honey has a lower flow rate, so this flow rate in general of this fluid is also a function of applied stress and we will see that as well. Now how to visualise this viscous rheology, the best way to visualise it like we saw for elastic rheology it was a spring and this time it is a dash pot filled with fluid, what is dash pot?

Dash pot is something that we use in our door stopper like you open the door and then you do not want the door to close very-very quickly, so you want the door to close very-very slowly and then there you have a device at the top of the door with a little barrel and this barrel actually is a dash pot. So what is inside the dash pot?

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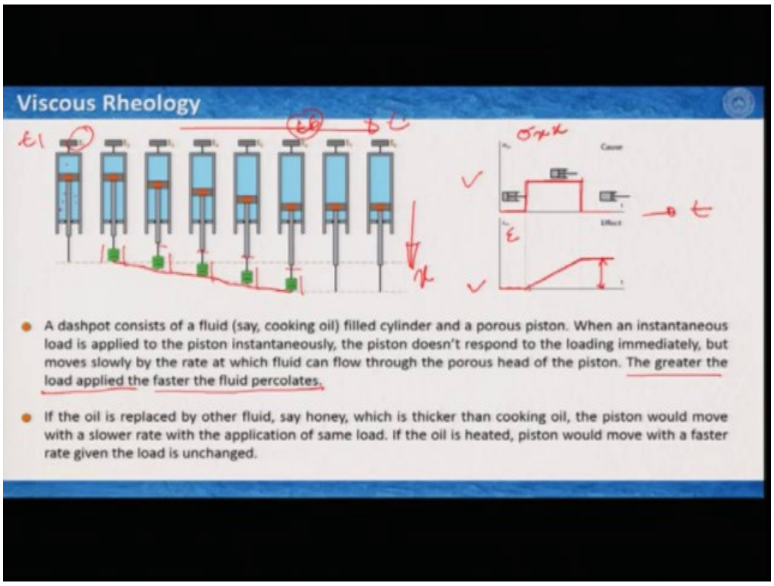

Let us have a look at the 1st diagram what we see here, it is a barrel or a cylinder where it is filled by a fluid and then you have a piston inside, so this is the cylinder... Now you look at a cross-section, this is the cylinder and then we have a piston, piston is like a T-shaped material and the top part of the T or the piston is porous so that means this fluid filled cylinder, in this case the fluid is the blue color you see here, they can flow through this piston and the flow must happen if there is any differential stress or pressure.

This is a simple piston dash pot or some sort of piston cylinder. Now the way the viscous rheology is explained using this dash pot is that at T1 time here is T1 it stays in its stationary mode and then you can apply and instantaneous load to this piston, so which are represented by this 3 green bars or 3 green loads, when you apply this loader to this piston unlike the elastic materials it does not deform the fluid or the piston does not come down immediately, so I keep this load constant and then I see this piston and is slowly going down this is how it comes and you can see that the load is constant in all stages.

So the response is not instantaneous but it happens very slowly and interestingly for this material we see that the response or what is given in this diagram that this increase of the deformation or the elongation is linear. Now at T6 after T6 we remove the load and interestingly unlike the elastic materials this piston does not go back to its original position, it remains there and this entire behaviour of the deformation is known as viscous deformation where in nut shell that the material does not respond immediately after application of the stress but it responds slowly and the response at least in this case is linear and when you remove the stress or remove the load then it does not come back to its original position and this is known as viscous rheology.

Now you can clearly understand that instead of 3 green bars if I would have applied 4 or 5 then probably the movement would be faster therefore the greater the load applied, the faster the fluid percolates through this porous spaces of this piston. Now we can visualise this in terms of plots, so what I have here like we have seen in elastic materials in this area, in this plot I have Sigma XX that means the movement along the X direction.

So this is X and then this side I have time so this is the time and here instead of Sigma I have strain, so how strain is responding with time is shown here and how stress is responding with time is shown here where the time is corresponding to each other, so what is happening at t on time it was… there was no load so stress is 0 strain is 0 which is normal, which is expected and now an instantaneous load has been applied this 4 bars and we see that strain here is not instantaneous but it is increasing slowly.

Accordingly you apply the load and kept it for a while, so here during the application of the load and then we kept the load at constant value the strain increase and when you reduce the load it did not come back but it stayed at a constant position that for this is the permanent deformation of this fluid. Now we can also understand that instead of say whatever fluid you have used say cooking oil, if we use some other fluid like honey then under the application of the same load the flow would be slower and if we heat the cooking oil and put it inside the cylinder then the flow would be faster.

So of course in all cases the load is unchanged, so therefore it has some response or some relations with some sort of ambience like what is the material and at the same time some external parameters influence of temperature and so on as we have seen with the glasses. We will learn about it later that what are the influences of the external parameters to all sorts of rheology but this is in nutshell what is viscous rheology that we can understand very easily and very quickly with the example of a dash pot.

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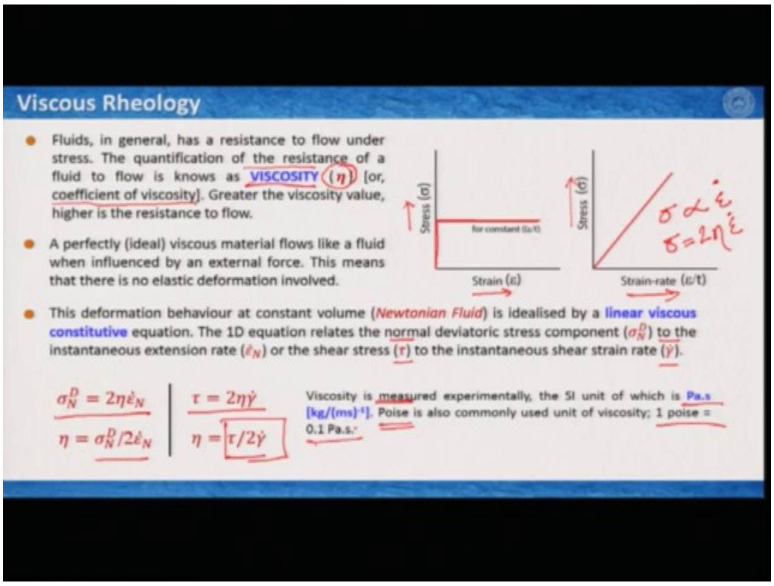

We have already learned that fluids in general has a resistance to flow under stress and this typical term that resistance to flow when you try to quantify this resistance of flow of fluid under the application of stress is known as viscosity and viscosity is generally denoted by the Greek letter Eta or sometimes we call it coefficient of viscosity. Now greater the viscosity value higher is the resistance to flow, so honey is high viscos material compared to water, so you can explain this way.

As a result when you say viscosity is high that means it as higher resistance to flow and if the viscosity or the viscous material that we are considering is a perfect or ideal viscosity material that we hardly see in nature then it flows like a fluid when influence by an external force this we have learned and that means that there was no elastic deformation involved, so if we then plot the stress versus strain of the deformation of this ideal viscous fluid then we do not have any elastic deformation, so in this side in this plot I have a long vertical axis stress and horizontal axis strain and we see that there is no elastic deformation.

In this context you apply the stress and there is no elastic deformation and then you have a permanent strain for a constant strain rate, however because this is rate dependent, the deformation that means it takes some time to respond and it flows with time under the constant loads, so strain rates here with the viscous rheology is very important and then if I plot stress versus strain rate then the plot actually looks like stress versus strain plot of elastic deformation. In elastic deformation stress versus strain was linear and in this case stress versus strain rate is linear, so if I plot stress in the side and strain rate along the horizontal direction then I get a curve like this for an ideal viscous material.

When this deformation of ideal viscous material happens in constant volume then we call it a linear viscous material or sometimes or most of the time we actually are refer it as a Newtonian fluid or Newtonian flow and the constitutive equation in one-dimension actually there for relates because we have to relate the strain rate, so for normal deviatoric stress components if we use the normal stress then it is related to the normal deviatoric stress components which will refer as Sigma DN to the instantaneous extension rate which is Epsilon dot n.

Now Epsilon dot n again this brought always indicate… Epsilon dot means Epsilon by T right where T is the time or you can also relate it with the shear stress there for you can assign shear stress as tau as we have been doing since beginning and the instantaneous shear strength rate, so the equation then takes the form, so you can clearly understand from this equation that stress or Sigma is proportional to the strain rate right, so you need a constant to make this equation, so we simply write a constant which is in this case the viscosity, the coefficient of viscosity and strain rate and this is exactly the same equation in the same form we are looking at… I am sorry it is this one and this one, so we can actually extract viscosity from this equation, so it takes the shape like this and here it takes the shape like this.

Therefore viscosity is a term that we have learned is a constant, coefficient and this is constant for each material when other parameters are constant, pressure temperature and so on. The SI unit as you can see that viscosity is actually… So if I look at here so I have stress, the unit is pascal and then I have strain rate, strain does not have any unit, so strain is unit less or dimensions less but time has unit, second and time comes at the denominator of the denominator, so it would be pascal multiplied by second, so the unit is pascal dot second or you can write it KG per metre second or minus 1 and there is also one unit of viscosity that people use frequently it is poise, so pascal second is the commonly used SI unit but poise is another unit and 1 poise 0.1 pascal second, so that is the conversion of poise to pascal second.

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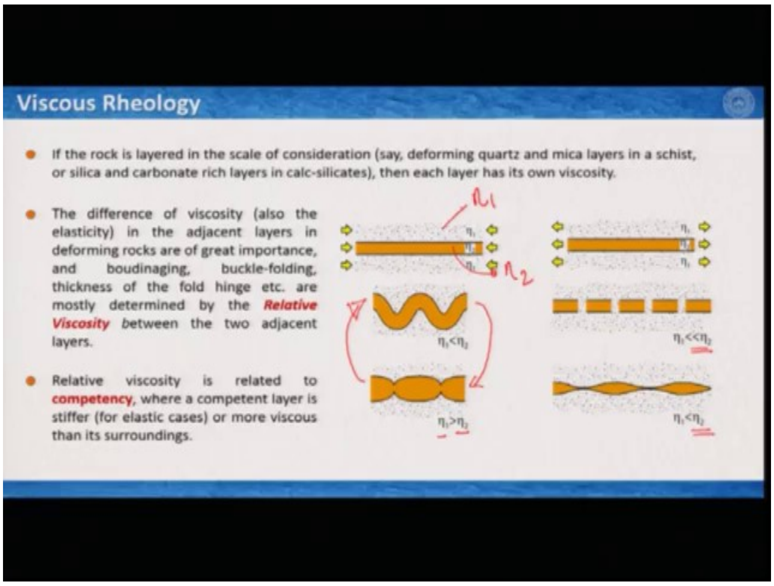

Now you can ask this question that we learned viscosity, dash pot, linear viscosity, Newtonian fluid and the dimensions of viscosity which is pascal second, so what is the implication of viscosity in (())(15:58) sciences or structural geology, the course we are learning.

Now you can clearly visualise the fact, as the Answer of your question that in a very simple we say a rock is layered in the scale you are considering. You can imagine as an example that in very micro scale a layer of quartz and a layer of Mica they are alternated in our Mica schist or in a type of schist where you have mica and quartz as dominant minerals or you can think of in a little larger scale outcrop scale or handspesiment scale that silicate and carbonate rich layers like we see in cal silicate then it is important to visualise the fact that at high pressure temperature when these minerals or these rocks are like fluid then quartz layer because it is quartz it has different viscosity to that of the Mica and similarly a silica rich layer would have different viscosity to that of the carbonate.

Now under that condition if I deform this rock by compression or by extension, what are the different kind of structures we can produce and this is a subject of research since years and people still are continuing researching on this. Say, for example, whether you would have a boudinage with sharp fractures or we would have a pinch and soil structure under the same dynamic conditions is governed by what is a viscosity of the boudinaging layers and the surrounding materials.

I have some examples here we can also think of the fact that the thickness of the fold if you go to the field we will learn it later that in few folds the thickness of the hinge zone the top part of this fold is thicker related to its lean and vice a versa that hinge is very thin compared to its lean and sometimes we see that throughout the fold the thicknesses constant these are known as parallel folds, so why these kind of differences we see when we know that buckle folding is just you need a layer parallel compression but these are all functions of viscosity between the layer we are considering which is being folded and its surrounding rock which must have a different viscosity to produce fold, so here is one example.

For example this orange layer is embedded in another layer in the matrix and if this matrix has viscosity Eta 1 and the orange layer has viscosity Eta 2 then to produce a buckle fold the Eta 1 that means the viscosity of the matrix must be pretty less than the viscosity of the buckling layer and if that reverses, that is the viscosity of the buckling layer is lower than the viscosity of the surrounding rocks then which produces structure something like that and you can clearly understand that a switch from here to here is only possible not buy any dynamic… change of any dynamic parameters that means you are deforming it slowly or you are deforming it very fast does not matter you can switch to this only and only if you have viscosity difference between these 2 in a different way.

Very similar way if the same layer stays in an extension regime then we can see that we can form sharp fracture boudinage when the viscosity of this boudinaging layer is very-very high compared to the viscosity of the surrounding matrix if it is almost similar or slightly higher then we can produce some sort of structures that we know as pinch and swell structures, so what you are dealing here is some sort of the relative viscosity that we are comparing viscosity from one layer to another layer and this relative viscosity sometimes is referred as competency in structural geology and we will refer it later as competence contrast and this is also referred not only for viscous rheology.

It is also used for elastic rheology that elastically competent layer, elastically incompetent layer, viscously competent layer and viscously incompetent layers and so on. So we will see later many more applications of viscous rheology along with some other rheology but to give you a very brief idea that why we need to study rheology to better understand the structures that we see in the field. In structural geology it is very important that we have a solid background of rheology.

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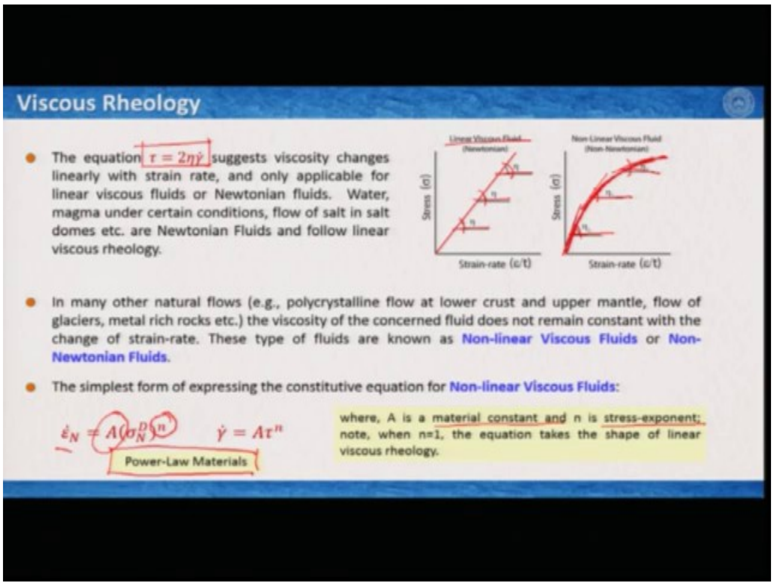

Now we have talked about linear viscosity and this is evident from this equation where shear stress is equal or proportional to the shear strain rate with a constant, so this suggests that viscosity changes linearly with strain rate and it is only applicable for linear viscous fluids or Newtonian fluids. As an example you can consider water, magma under certain condition flow of salt, in salt domes etcetera, are fantastic examples of Newtonian fluids but there are any other flows where the flow do not happen linearly, what I mean by linearly is explained here.

So we have seen this plot stress versus strain rate where the relationship is a straight line that means at any point of time of the deformation if I look I go back to this plot I always can get viscosity and in this case when it is linear viscos fluid or Newtonian fluid the viscosity is constant and if that does not happen then this line is not straight anymore it can be curved and if the line is curved then the relationship is not linear and this is known as non-Newtonian viscosity or non-Newtonian flow or non-Newtonian fluid, so what does it imply?

That with deformation if I take any point draw a tangent and then try to figure out what is the viscosity, you can see the viscosity is constantly changing, so this changing viscosity or the transient viscosity during the formation while all parameter pressure temperature and others remain constant.

This is known as non-linear viscos fluid or non-Newtonian fluid, so to figure out a constitutive equation for non-Newtonian fluids you can clearly understand that this linear equation is of no use, so we introduce a new kind of equation where strain rate is related to stress with some sort of exponent and in this case this exponent is N and it is known as stress exponent.

In structural geology, in tectonics and also in geodynamics this stress exponent is very important term we will learn about it later and then this is related by a constant which is some material constant and we generally denoted by A, so eventually the equation takes the form strain rate equal to a constant multiplied by Sigma to powered by an exponent, so this exponent is known as stress exponent and A is a material constant and because it has a power sometimes we refer it as power law flow or the material which do not have a linear viscosity property we call it also power law materials.

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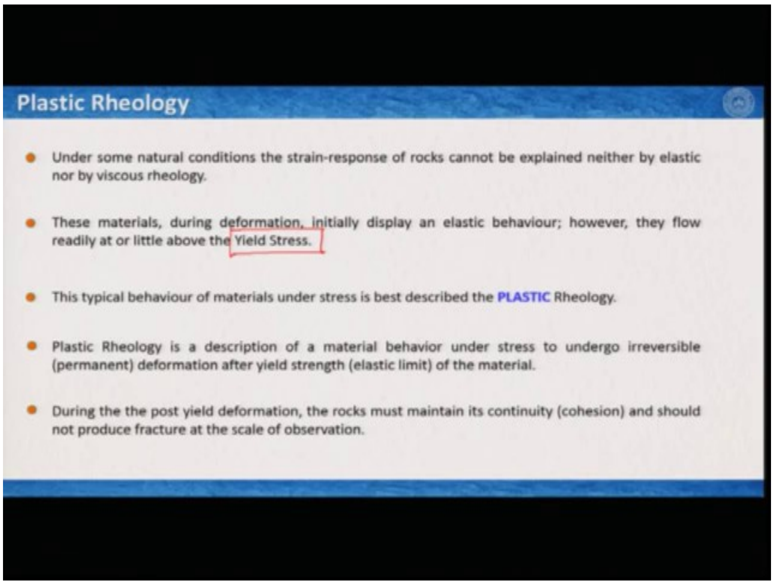

Now we move to plastic rheology, we learnt elastic rheology, we learnt viscous rheology and there are many materials, the behaviour of which under stress it cannot explain neither why a elastic rheology nor by viscous rheology, so we need a 3rd and final end member of the rheology group and this is plastic rheology, so under some natural conditions as I was talking about the strain response of rocks cannot be explained neither by elastic nor by viscous rheology and this materials are extremely typical.

So deposition they initially display an elastic behaviour however after a certain point they flow readily act or little about the yield stress, now this is something a new term we are learning yield stress, so we will talk about it later and we will learn more about it but for the time being you just know yield stress as a kind of a typical value of stress in deforming a material or you can consider it as a threshold stress, so for the time being you just remember that, so in nut shell you need to deform it elastically initially and then once you reach a typical value of this elastic stress which we have referred as yield stress then the materials to flow either at the yield stress or a little above of the yield stress and this typical behaviour of the material under stress is best described by rheology called plastic rheology.

Now plastic rheology is essentially a description of a material behaviour under stress to undergo irreversible or permanent deformation after the yield strength, so yield strength is something that is the limit of your elasticity, so that defines now what is yield stress or yield strength that after you reach the yield stress then you cross your elastic limit and elastic property of the material is gone, it cannot bring it back to its original position, whatever happens after that is elastic deformation.

Accordingly during the postal deformation it is very interesting for elastic material, the rocks to maintain its continuity that means I am stretching a rubber band and I cross the threshold value of the elasticity which is yield stress and immediately after that the rubber band breaks then this is not a typical plastic rheology that we consider the rubber band has to getting stretched and if I release it it should not come back to its original position if it is a plastic material, perfect plastic material but rubber band is not.

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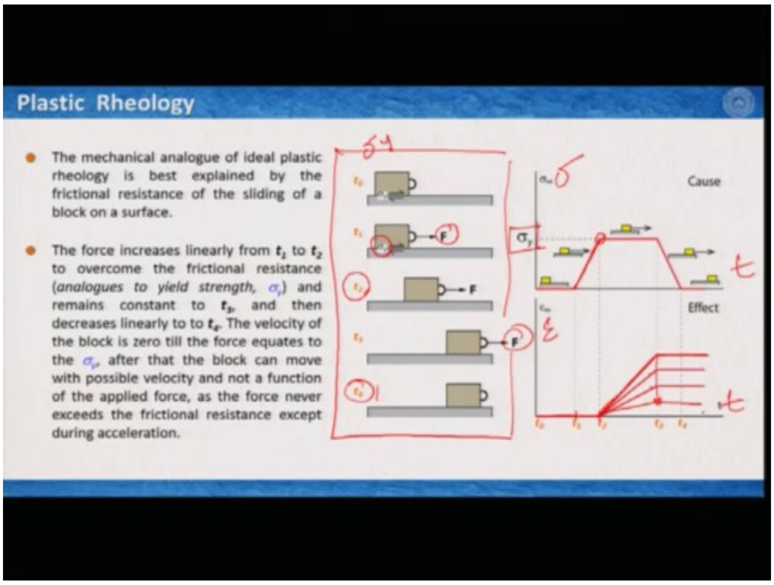

So plastic rheology is best explained by a mechanical analog we generally call a fictional block, so it is something like a fictional resistance on the sliding of block on a surface which has some sort of frictional resistance. The explanation is given here with this series of illustration, it happens this grey shaded that form is you can consider a table which has rough surface, which has a fraction and then on the top of that we have a block with some hook there. Now once I rest this block on this surface that has… Then this interface of this block and the surface has a friction between these to… immediately the friction develops immediately when I try to pull this, so it has a friction and I can actually consider this friction as the yield stress which is Sigma y.

We have given an example in the beginning that you cannot move anything instantaneously, so at t0 everything is in rest and this fictional interface has the frictional resistance value Sigma y or coefficient of friction which is in this case we are considering it or some sort of making it analogues to the yield strength. Now at t1 time I started pulling this block with a force F and I am not changing the… And I am slowly increasing this force.

At time T2 between T1 and T2 what is happening this F has closely reach or slightly above this Sigma y value and once I cross this Sigma y value this block has to move and as you can see in this image this block has moved and if I continue applying this force, the block would continue to move but at time t4 if I remove the force, the block stays in its original position, it does not come back to where it is, and it is not essentially not at all an elastic deformation.

So if I try to look in a very similar diagram that you have been looking at where you have stress versus time and strain versus time the 1st one is your cause, 2nd one is your effect, what is happening here when you have no stress there is no strength and now you started applying f slowly but you have the frictional resistance, so the material is not moving, so you can see there is no strain even if you have applied a significant amount of stress. Now when immediately you reach the stress value equal to your yield stress or in this case the fictional resistance then the material starts moving.

Now here I have 3 different curves and there can be end number of curves we will talk about it later but let us consider only one, so it can then move or it can get deform because it is changing its position and then if you release the stress it does not come back to its original position, so this is a nutshell what is plastic deformation or plastic rheology using the analogic of friction block. Now why we can have some end number of possibilities of different curves?

It is simply because when the block starts moving then you do not have any control to the displacement right so this is some sort of material property which is independent of the force or stress you are applying, so what is written here the velocity of the block is 0 till the force equals to the Sigma y or yield stress, after that this is very important, the block can move with possible velocity and not a function of the applied force and this is why as the force never exceed the frictional resistance except during acceleration.

So if you have 2 accelerate this block then you can increase the force and then you can have a certain curve but otherwise it can move to any possible values, so now if you would like to express plastic rheology mathematically then we have to consider an ideal plastic material or ideal plastic rheology, so which is also known as rigid plastic material or saint venant material.

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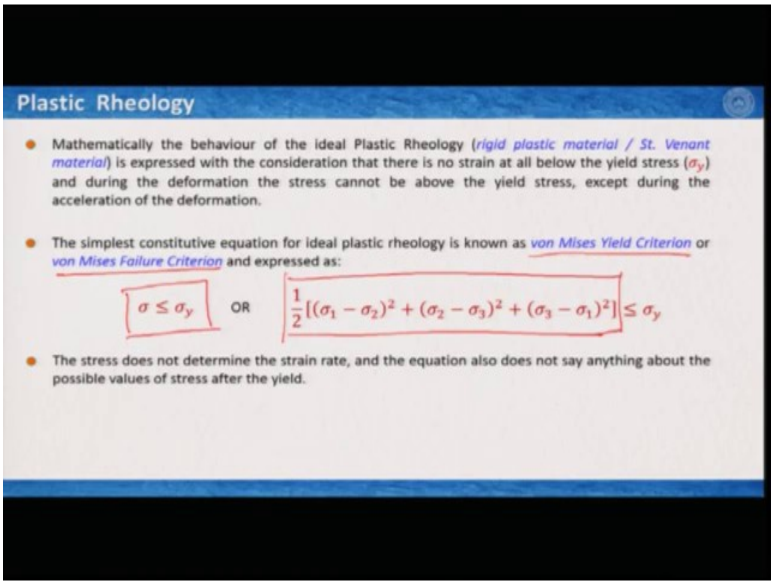

Thus generally the behaviour the constitutive equation of ideal plastic rheology expressed with the consideration that there is no strain at all below the yield stress, so that it is a very primary and basic consideration that material does not deform even elastically till the yield stress is reached and at the same time during the formation of the stress cannot be above the yield stress except you have acceleration.

Now this is little complex in terms of statements but in general you are not accelerating your material while you are deforming it that is the 1st and 2nd at the very beginning before you reach yield stress there is no elastic deformation and these relationships explained by this pic and then Sigma either that is your overall stress is less than or equal to the yield stress and this is known as von mises yield criteria or von mises failure criterion.

And you can expand these parts in this form Sigma involving all sorts of principal axis of stresses and if you can recalculate it to your stress slides that we have seen it is the stress invariant number 2, so you can figure it out and we can also figure out the stress does not determine the strain rate and the equation also does not say anything about the possible values of stress after the yield, so therefore you not know what would be your stress value after the yield and that gives a very interesting phenomena of rock deformation in structural geology of plastic deformation and which we are going to see now.

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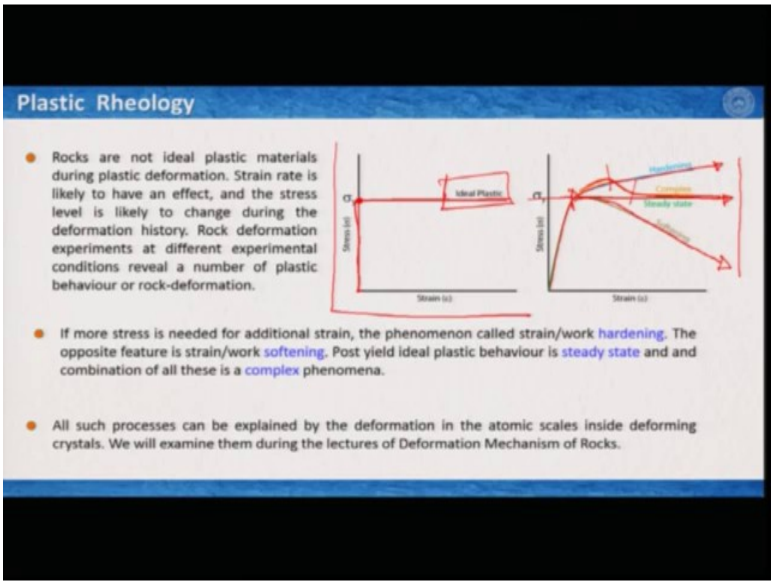

And we know that the rocks are I mean whatever we have considered so far elastic, viscous and plastic we always use the prefix before them is that ideal, an ideal means it is very difficult to figure out, so like in all other materials rocks also are not ideal plastic materials during plastic deformation, so strain rate and others would like to have an effect and the stress level is likely to change during the deformation history and all so you may not have no elastic deformation before the yield stress, so you may have elastic deformation before the yield stress while you are deforming the rock (())(36:50).

So this is mostly visualised by different rock deformation experiment with variable materials at variable conditions and these experiments reveals the fact that at different experimental conditions there are number of possibilities of plastic behaviour after the yield stress. Now this plot shows that behaviour of an ideal plastic material where you do not have any elastic deformation, you straightaway reach to the yield stress, when you reach yield stress your strain remains 0, so there is no deformation you straightaway go to your yield stress.

Once you reach yield stress then you increase the strain keeping your stress at more or less on your yield stress value and if you stay really on yield stress value then you are dealing with one ideal plastic rheology but as I said rocks are not ideal plastic material, so you generally would expect some sort of linear behaviour at the beginning between stress and strain and therefore this is your elastic domain and then you reach your yield stress.

Now post yield deformation there are several possibilities and we can categorise it in 4 different ways, now if after the yield is the material deforms at a constant stress, what we see here with the green curve is known as steady straight flow, if you need some more stress to flow the rock or to deform the rock then this is called strain hardening. If we do not need stress even that much of the yield stress, much lower stress to flow the rock, this is known as softening. We observe all sort of curves in rock deformation experiments and together with this we saw curves that involve both hardening, steady-straight and softening which is an orange curves here that goes like this.

So you see after the yield you have hardening, and then you have softening and then steady straight, so this is known as complex flow or complex plastic rheology. Now all such processes can be explained by the deformation in atomic scales that why I should have hardening? Why I should have steady straight flow? Why I should have softening type of flow, strength softening type of flow? Now these are essentially very micro scale processes and we will learn it in one of our next lectures where we will be dealing with deformation mechanisms of rocks. So with this we finished the 3 basic end members of rheology which is linear, elastic, ideal linear elastic, ideal linear viscous and ideal plastic.

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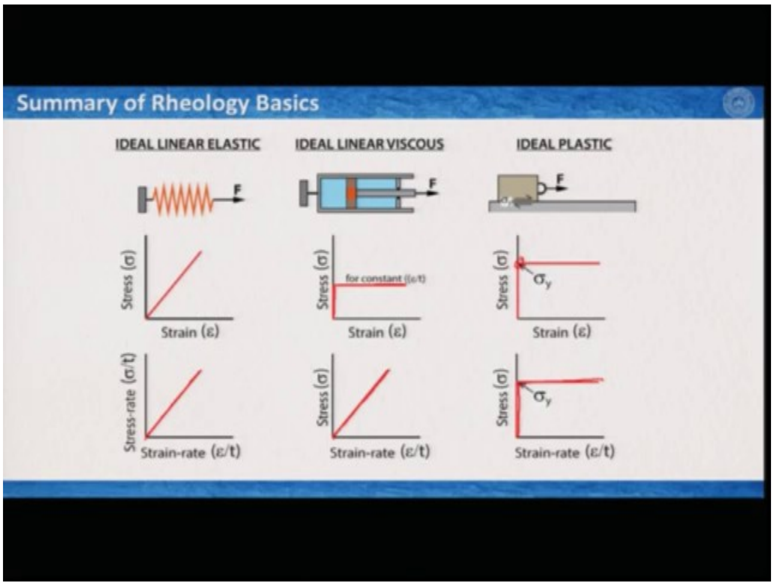

And here is the summary slide in ideal linear elastic materials we use spring as our analog model, for linear viscous material we use that spot, for ideal plastic rheology we use friction Block. The stress strain curve for ideal linear plastic is stress versus strain is linearly related. For viscous this curve is little difficult not linear it goes like this. For ideal plastic the curve looks very similar to the linear viscous material but here this point has to be your yield stress.

Now stress rate versus strain rate plot for ideal linear elastic material is exactly same the way we have stress versus strain but in linear viscous and linear plastic materials we do not plot stress rate but we plot stress versus strain rate, in this case this is linear and in this case this is not linear but it looks exactly similar of the stress versus strain because it is strain rate independent if your material is ideally plastic.

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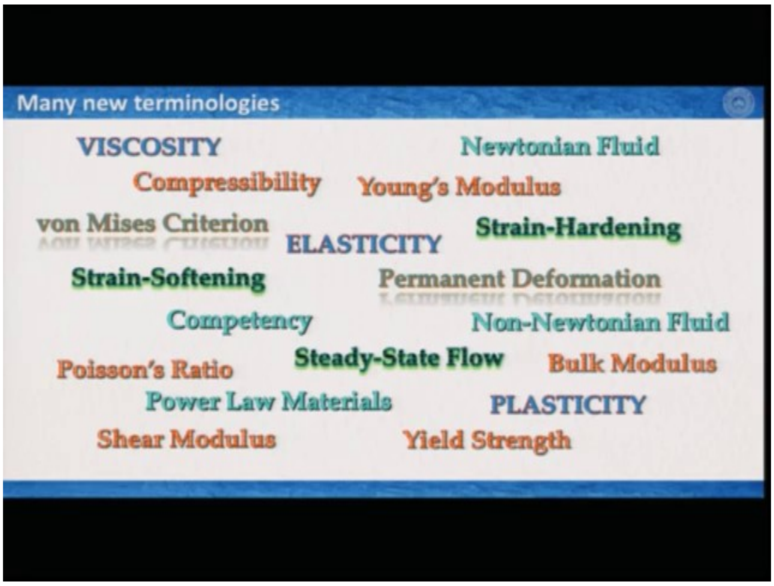

We also have learned a lot of terminologies right viscosity, Newtonian fluid, compressibility, Young's modulus, von mises criteria then elasticity, strain hardening and so on. Now you can see that all these words or phrases that we have learned in this basics of rheology lecture, I have sort of jumbled up, so what you can do that you can pick any of these terminology and can think of what is this, so if you just talk about Poisson's ratio okay what is poisson's ratio?

Let us think about it, if you do not get it go back and look at what is poisson's ratio, this is how you will be very familiar with these sort of terminologies which are extremely important to understand the deformation of rocks at different conditions, so with this we finish this lecture.

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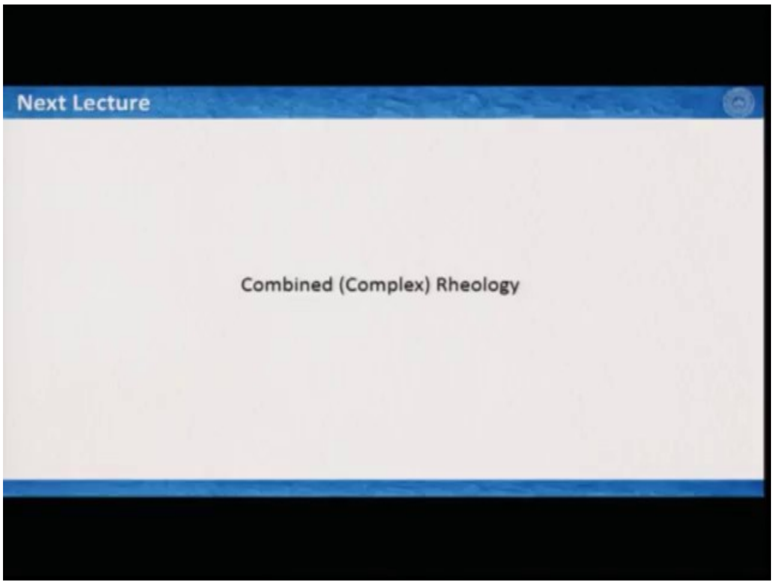

In the next lecture we will learn the combined or complex rheology where we will add one basic rheology to another basic rheology and we will see what kind of responses we get out of it, till then good bye.