Characterization of Construction Materials
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Lecture 6
Structure of Construction Materials an Overview Part4

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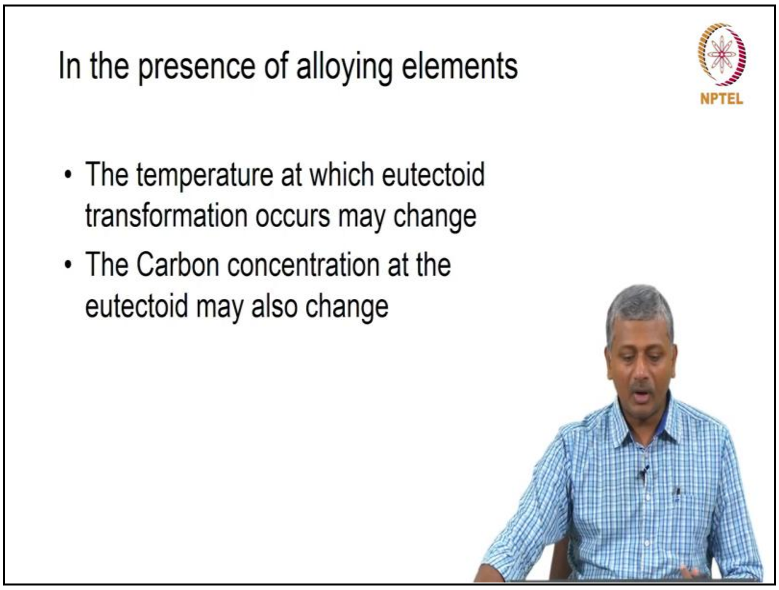

In the presence of alloying elements

- The temperature at which eutectoid transformation occurs may change
- The Carbon concentration at the eutectoid may also change

So when alloying elements are used in steel, (Nickel, chromium, sometimes copper are used to increase the corrosion resistance of the Steel),what happens is these may shift the temperature at which eutectoid transformation occurs, and the carbon concentration also may shift a little bit, when some alloying elements are built into this system.

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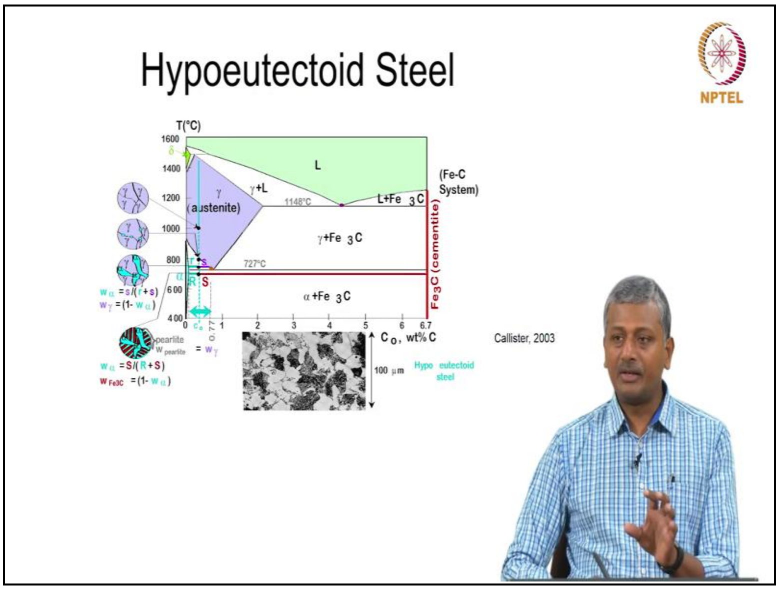

Hypoeutectoid Steel

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So we want to look at the phases that form at low percentages of carbon so we need to look at hypoeutectoid Steel, that means less than eutectoid. So we are looking at carbon contents in this range between 0 and 0.77% and what happens here is Gamma phase now will convert not only to the pearlite phase, it will also convert to the ferrite phase. So, if you take any composition in between 0 and 0.77, and if you come down this temperature axis, you have now the possibility of forming either a completely eutectoid transformation of gamma to Alpha + Fe3C or you can form something called direct Alpha phase or Pro-eutectoid Alpha phase.

Basically this Alpha that is marked in blue, is the Alpha phase that is formed, even before the temperature of 727 degree is reached. What happens after 727 is that whatever remaining gamma is there gets converted to Pearlite - Eutectoid phase of pearlite, eutectoid transformation of Gamma will take place at 727. But even before temperatures of 727, you also have the Alpha phase crystallizing forming out. So, the resultant steel that you have at low carbon contents has more of what phase ? Alpha or cementite?

If you are somewhere here and you are coming down the temperature axis, that means the proportion of this phase is lot more than this phase. If you are here, coming down the axis, the proportion of this phase is a lot more than other phase. So if we are to the left, the proportion of the Alpha phase is more and cementite phase is less. So, your pro-eutectoid or hypoeutectoid steel will have a large characteristic of Alpha that means the primary characteristic in this material will be – Ductility as Alpha phase is more ductile. So there will be a lot of ductility in the steel. Whereas if you move away from the hypo-eutectoid phase, towards the hyper eutectoid phases which is on the other side, you will start forming more of cementite phase, and because of that you will get more strength, but less ductility. But anyway we are not concerned with hypo eutectoid transformation.

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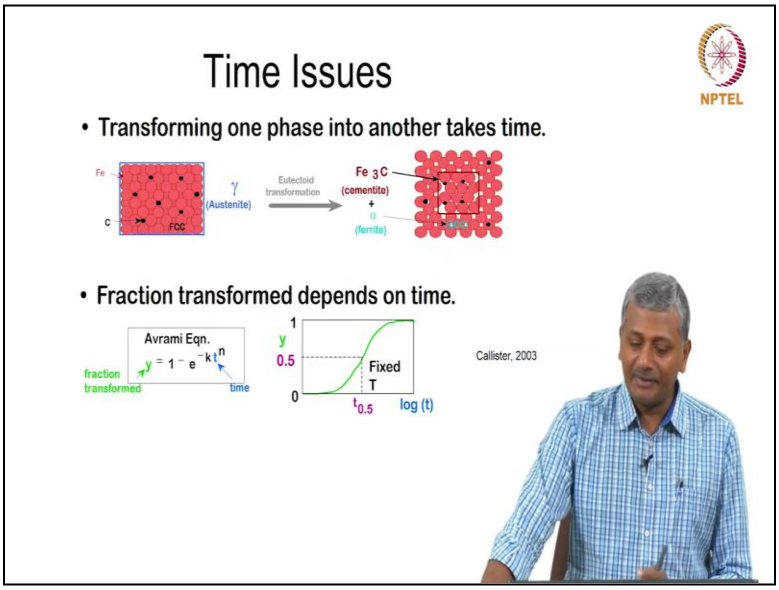

Time Issues

- Transforming one phase into another takes time.

- Fraction transformed depends on time.

Callister, 2003

Now it does not end with that. We know that steel is formed in molten state and then cooled to the solid. The time over which this transformation takes place determines actually what the microstructure which is forming, but earlier we saw that there is a eutectoid transformations that assumes one important thing that - there is equilibrium during this transition. That means you have infinite time over which this transformation is happening from above 727 to below 727.

But in reality, time plays a major role in the kind of microstructure that we actually get with steel.

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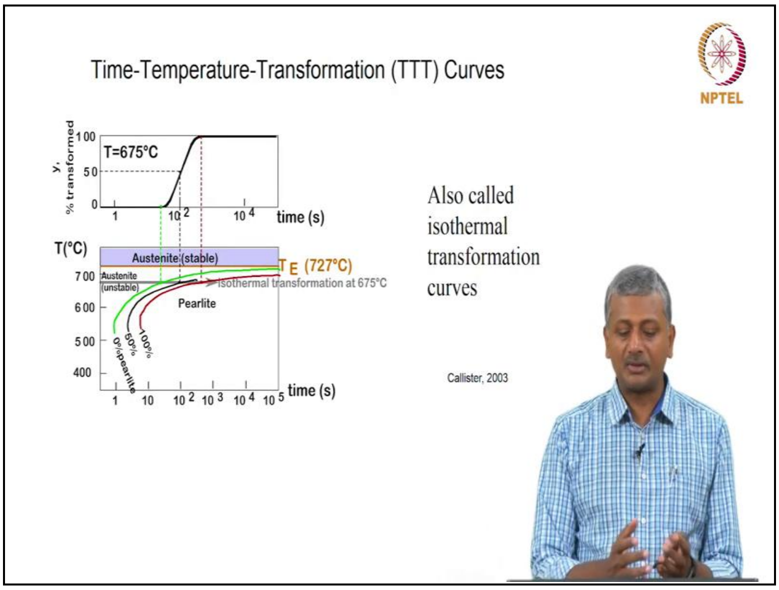


Time-Temperature-Transformation (TTT) Curves

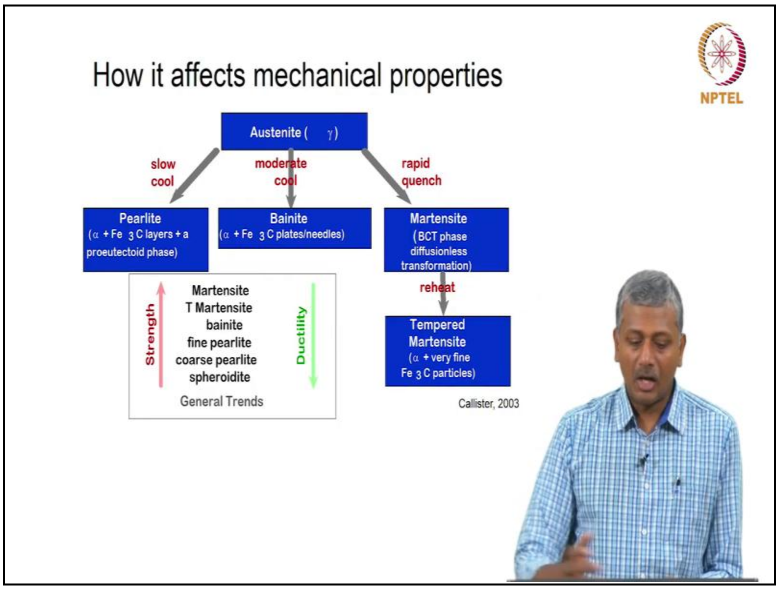
Also called isothermal transformation curves

Callister, 2003

So, without getting too much into the details what happens with stages of time, is that you can start forming different types of phases. If the time is very large (if you have a lot of time over which this transformation occurs), obviously all the austenite will get converted to pearlite. But in reality that does not happen, so you need to study the isothermal transformation curve or Time-Temperature-Transformation curves to realise what is going to happen to this steel when we actually cool it down from the molten state or from the gamma state.

In reality, you can have several different phases forming, you have Pearlite. We can have Bainite phase forming. You can get Martensitic phase and Spheroidite phase. In our case most concerned with Pearlite and Martensite. Now martensite is very interesting, because it is formed when you suddenly cool the Steel from austenite to room temperature. How do you suddenly cool something? Just quench the material, throw water on it, it becomes cool immediately.

So this immediate cooling transforms steel into martensitic phase which is a very hard and strong phase, whereas if you have a very slow cooling, you will start forming the other phases pearlite, bainite and so on. So, but mainly we are concerned with pearlite and martensitic phases, because it will come later when we deal with the structure of your Quenched Self Tempered Steel or QST, which we otherwise wrongly call as TMT steel. **(Refer Slide Time: 05:42)**



How it affects mechanical properties

Austenite (γ)

slow cool

moderate cool

rapid quench

Pearlite (α + Fe_3C layers + a proeutectoid phase)

Bainite (α + Fe_3C plates/needles)

Martensite (BCT phase diffusionless transformation)

reheat

Tempered Martensite (α + very fine Fe_3C particles)

Strength

Martensite
T Martensite
bainite
fine pearlite
coarse pearlite
spheroidite

Ductility

General Trends

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So how the composition affects mechanical properties, austenite on slow cooling can form pearlite, in moderate cooling it forms bainite and rapid quenching it forms martensite. So, if you go from pearlite towards martensite, your ductility reduces but strength increases. But what you can do is take the martensite and reheat it and then cool it slowly, you do not reheat to above austenitic temperature because then that will convert to austenite again.

So you heat it to below austenitic temperature, and this heating what it does is it gets rid of the internal strains. So, when you cool it back again, the material will still be strong, but it would have lost some of its brittleness; it will become a lot more ductile. So, that is called tempering - it is a heat treatment process. Tempering - where you heat the martensite to lower temperature than the austenite transformation temperature and then cool it back slowly.

But one thing which is very clear is that the type of microstructure has a major effect on the properties.

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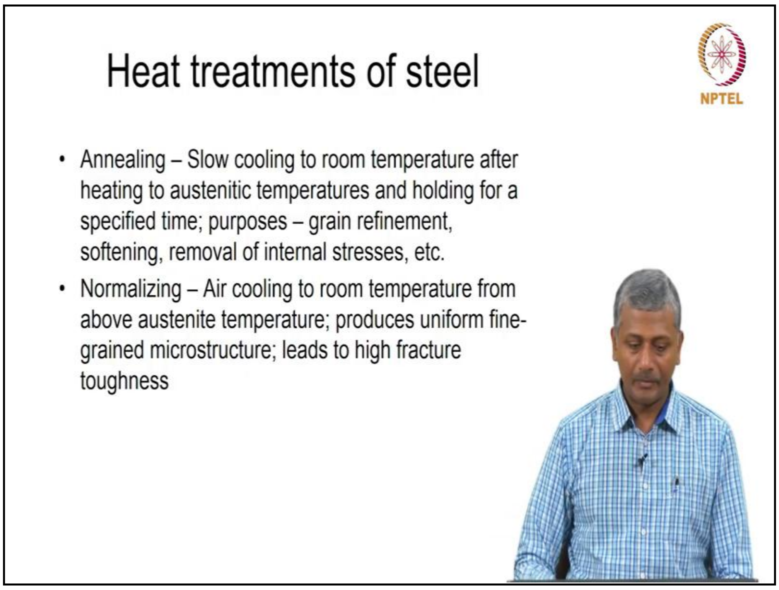

Heat treatments of steel

- Annealing – Slow cooling to room temperature after heating to austenitic temperatures and holding for a specified time; purposes – grain refinement, softening, removal of internal stresses, etc.
- Normalizing – Air cooling to room temperature from above austenite temperature; produces uniform fine-grained microstructure; leads to high fracture toughness

So again, there are different types of heat treatments for Steel. You have annealing, normalising.

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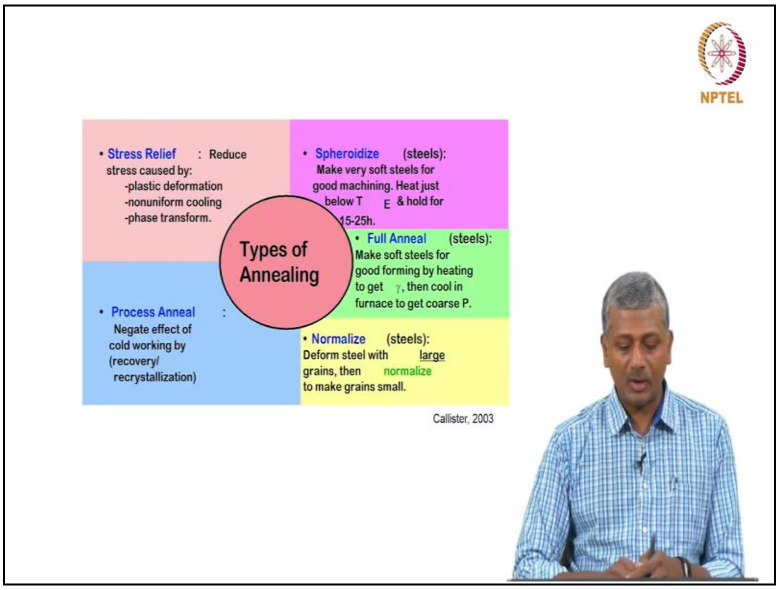

Types of Annealing

- Stress Relief : Reduce stress caused by:
  - -plastic deformation
  - -nonuniform cooling
  - -phase transform.
- Spheroidize (steels): Make very soft steels for good machining. Heat just below T_E & hold for 15-25h.
- Full Anneal (steels): Make soft steels for good forming by heating to get γ, then cool in furnace to get coarse P.
- Process Anneal : Negate effect of cold working by (recovery/ recrystallization)
- Normalize (steels): Deform steel with large grains, then normalize to make grains small.

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And in case of martensite you have this tempering process, which we just saw. Again within annealing itself we got different types of processes which need to be studied in detail to really figure out what ultimately we get in the steel.

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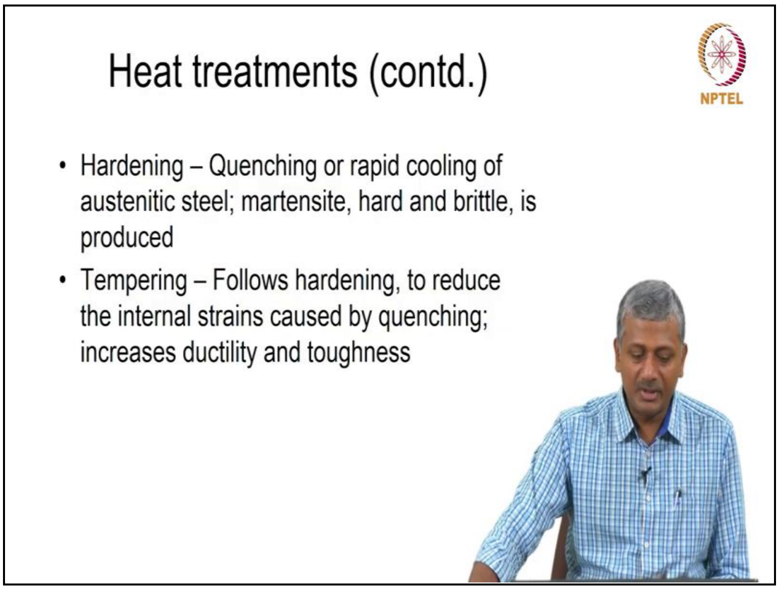

Heat treatments (contd.)

- Hardening – Quenching or rapid cooling of austenitic steel; martensite, hard and brittle, is produced
- Tempering – Follows hardening, to reduce the internal strains caused by quenching; increases ductility and toughness

But as civil engineers, most of the time we really do not look at the process of manufacturing steel. We deal with the material as it is obtained from the factory which is manufacturing the steel. With cement concrete and asphalt concrete, till the last step of the process we are involved. But as far as steel is concerned, civil engineers have very little understanding of what this material is? But then, when you start dealing with issues of service, when we deal with premature failures of structures, we need to really get into the processing of Steel, to understand what could have happened that lead to this behaviour during the performance.

Especially when we deal with things like corrosion, a lot of interesting aspects actually come about because of that.

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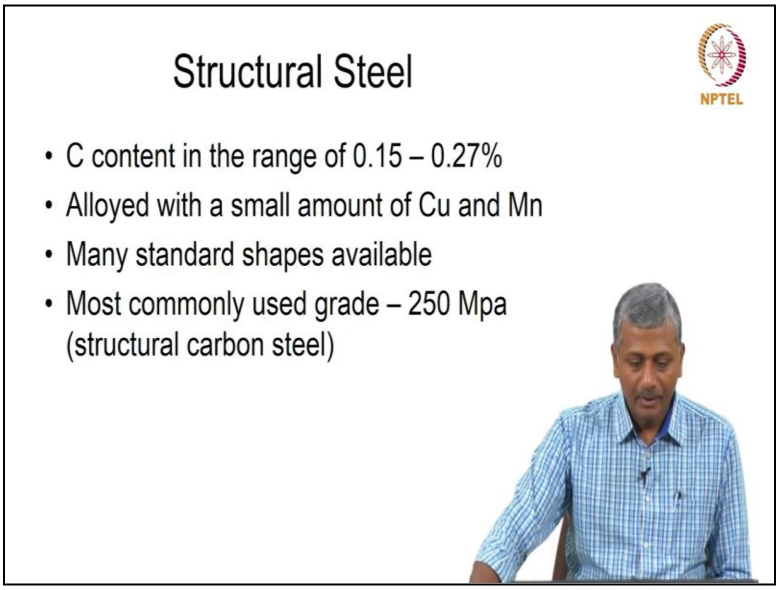

Structural Steel

- C content in the range of 0.15 – 0.27%
- Alloyed with a small amount of Cu and Mn
- Many standard shapes available
- Most commonly used grade – 250 Mpa (structural carbon steel)

Structural Steel has very low carbon content typically we are talking about less then 0.2 but range is from 0.5 to 0.27%, we generally alloy it with small amount of copper and manganese, to introduce a little bit higher corrosion resistance. Several standard shapes are used - I shaped, H, channel, Angle and all those are used for different types of Steel frames, and the most commonly used grade is 250 MegaPascals (MPa) which is the Yield strength. 250 MPa which is structural carbon steel or we otherwise know it as mild steel. 250 MPa is the yield strength of mild steel.

Reinforcing steel on the other hand you can either get plain bars, of course we do not get any plain bars these days, mostly you get deformed bars. And you also get bars primarily which have ribs on them. Ribs are there to promote bonding with the concrete. Commonly in India we have three grades - 415, 500 and 550. Now in the past people, were producing Steel with cold twisting which were also known as CTD bars or HYSD bars, which again is put in the next slide.

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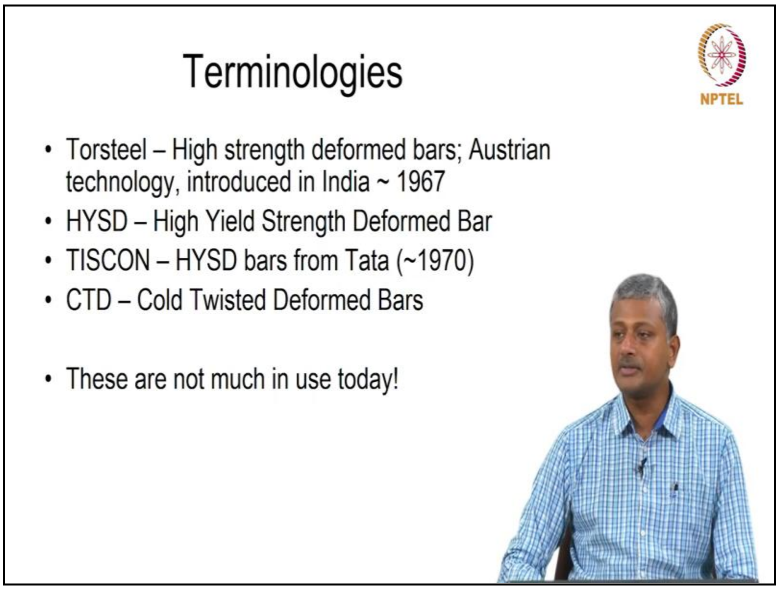
Terminologies

- Torsteel – High strength deformed bars; Austrian technology, introduced in India ~ 1967
- HYSD – High Yield Strength Deformed Bar
- TISCON – HYSD bars from Tata (~1970)
- CTD – Cold Twisted Deformed Bars
- These are not much in use today!

So, HYSD or CTD bars are obtained from cold twisting of the mild steel. So if you remember your mild steel stress-strain diagram you have initial linear portion, and then you have a yielding, and then you have strain hardening, and then you have failure, breaking happening at a stress which is lower than the ultimate stress. You have sigma ultimate (σ_u) here and you have Sigma yielding (σ_y) here and this is what we are looking at as 250. So, how does cold twisting lead to the formation of reinforcing Steel?

We are not changing the material we are only using mild steel and we are cold twisting it to form reinforcing Steel. So, what does cold twisting do? In cold twisting, we are taking it through this initial phase taking this stress up to this location and then unloading. When we unload, the material unloads parallel to the initial linear phase. And when we reload this material what happens now?

It follows this path, that means it is reaching a higher level of stress but it does not have any more well-defined yield point because it's lost this plastic deformation. It now goes directly to the strain hardening region and then we measure the yield stress with the 0.2% offset method. We draw a line parallel and this becomes the new yield stress. So that is called the 0.2% offset method, which is why we call this yield stress strength as Proof stress.

That is why from the same mild steel, which has a yield strength of 250 MPawe are able to obtain grades of 415. But for the higher grade 550 and all we go for TMT technology or QST which is the correct name.

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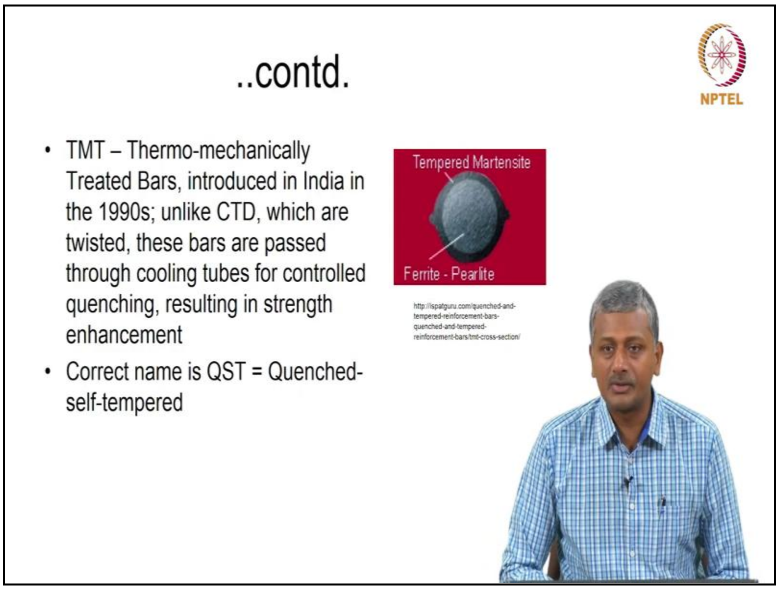

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- TMT – Thermo-mechanically Treated Bars, introduced in India in the 1990s; unlike CTD, which are twisted, these bars are passed through cooling tubes for controlled quenching, resulting in strength enhancement
- Correct name is QST = Quenched-self-tempered

http://ispatguru.com/quenched-and-tempered-reinforcement-bars-quenched-and-tempered-reinforcement-bars/tmt-cross-section/

TMT which is otherwise written as thermo mechanically treated bars were introduced in India in 1990’s. So, here what happens is these bars, actually any bar goes through a thermo mechanical process. So, actually this is not the correct name. The correct name is QST or quenched self tempered bar. Thermo mechanical process means any bar goes through a temperature treatment and some mechanical treatment - that happens for anything.

What is done in this case is that these bars are passed through cooling tubes for controlled quenching. So, as soon as the bars are cooling from the molten state, you cool them very fast, quench them so that you get an outer surface of martensite and then the inner part or the core of the bar, then cools very slowly and when it cools it reheats this martensitic outer part and causes it to get tempered.

So that is an interesting technology because now what we have is, we have inner core of the soft and ductile pearlite material and outer layer of the hard and probably not as brittle because now it is got tempered it is the martensitic exterior. So you get good strength, good ductility and one more very important point of TMT is also get good corrosion resistance. Why is the corrosion resistance better? Because the martensite phase is less prone to corrosion as compared to the pearlite phase. Again now you see the importance of microstructure.

The types of phases that formed because of processing have a direct connotation with the performance of your system. So here we are dealing with strength, ductility, which are imparted to this bar by the inner core which is ductile and the outer layer which is hard and strong, and then you also get good corrosion resistance because the phase in the outer layer is less prone to corrosion problems as compared to the inner phase that is pearlite. So, again the importance of microstructure here can definitely be understood.

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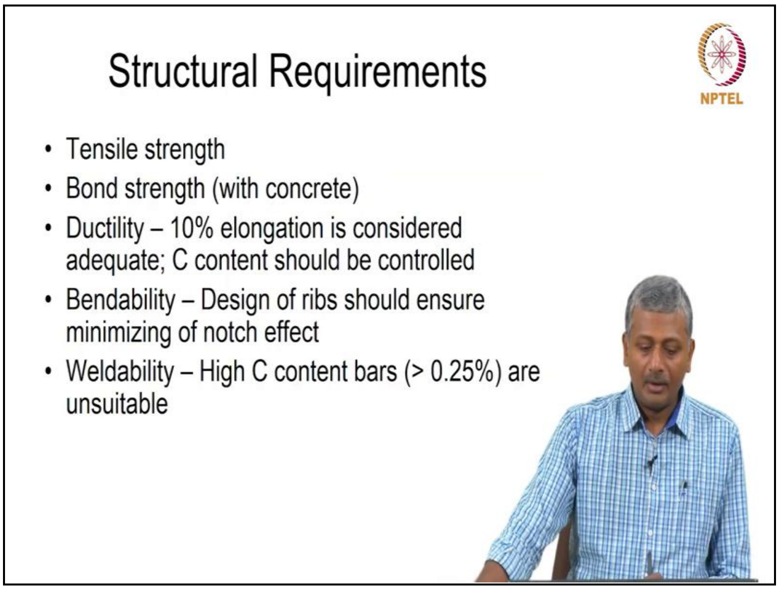

Structural Requirements

- Tensile strength
- Bond strength (with concrete)
- Ductility – 10% elongation is considered adequate; C content should be controlled
- Bendability – Design of ribs should ensure minimizing of notch effect
- Weldability – High C content bars (> 0.25%) are unsuitable

Of course you also have structural requirements for steel, you need obviously the tensile strength, which is the primary characteristic as a reinforcing material. You need to have a good bond with concrete because of which the ribs are introduced into the steel and ductility is important because we need sufficient level of ductility to get the performance of the structure that we desire. 10% elongation is usually considered adequate but typical steels will give you close 20% elongation.

Carbon content has to be controlled because the higher the carbon content, the lesser the elongation. Bendability again is important because when you bend it should not start causing failure at the bends. Weldability also is affected with carbon content when you have high carbon content, they are unsuitable for welding. Why do you need welding? You need to extend the length of the sections, so welding has to be done.

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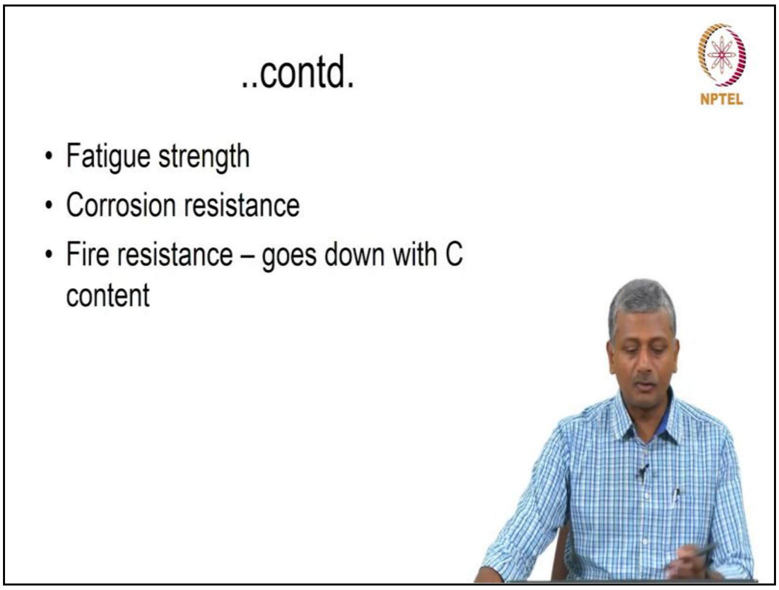

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- Fatigue strength
- Corrosion resistance
- Fire resistance – goes down with C content

Of course other important characteristics include fatigue strength, corrosion resistance and finally fire resistance. Again fire resistance goes down with carbon content, the higher the carbon the lower the fire resistance.

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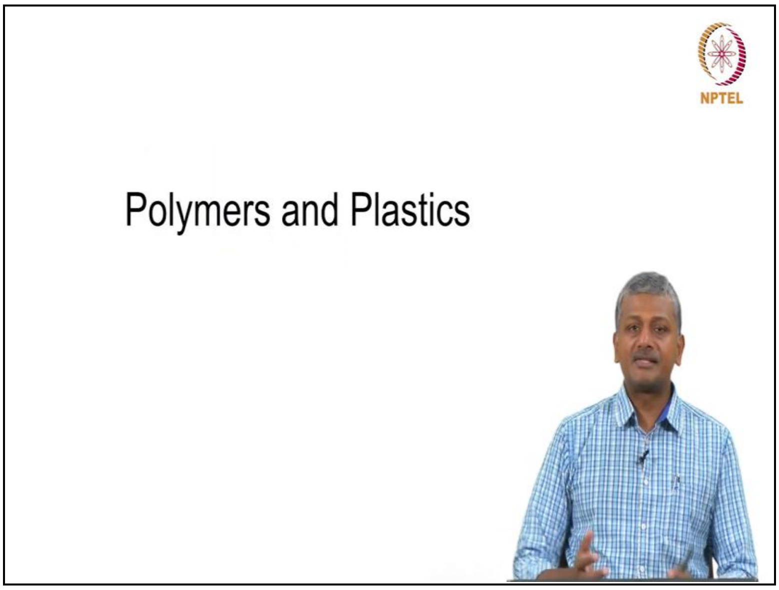

Polymers and Plastics

So, moving on to the final segment of this initial understanding of the structure of materials, just to get you some overview and help you remember the concepts you learned in the past. So we will not learn a lot about Polymers and plastics because primarily our concern is with asphalt, but a lot of the basics of Asphalt are in understanding polymers and plastics.

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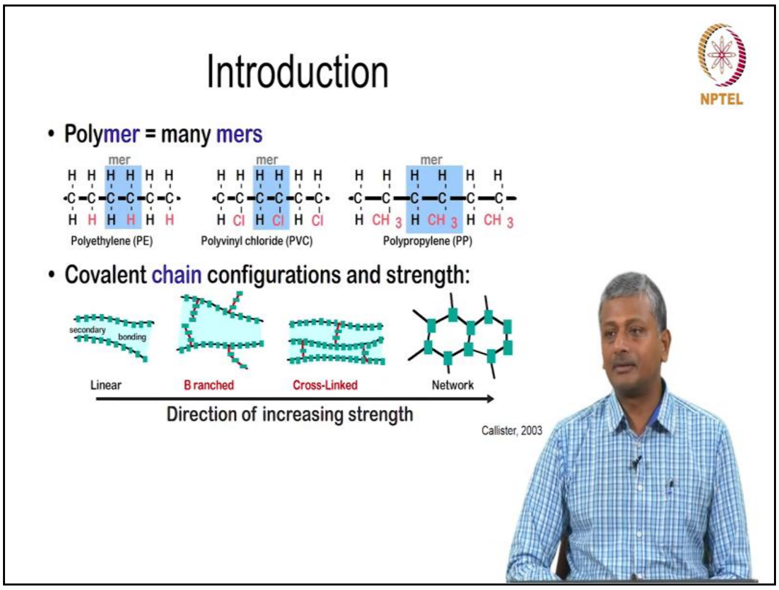

Introduction

- Polymer = many mers
- Covalent chain configurations and strength:

Polymer simply means that, it is a combination of many repeating units called ‘mers’ or monomers. So, many monomers together make a polymer. So, these are some examples of polymer you have come across in standard textbooks - polyethylene, polyvinyl chloride, polypropylene and so on. The structure of the polymer is defined by how these links are connected. In certain Polymers like linear Polymers these links or long Chains of individual monomeric units may not be connected through a strong bond, but only through a secondary Bond.

What are some examples of secondary bonding? Secondary bonding includes Van der Waals forces. You can have hydrogen bonding and so on, that is secondary bonding. It is not a primary bond between the links. But in certain cases, the same linear structure can also have branches but still they are not bonded with primary bonds there only bonded with secondary bonds. If you go to a little bit more organised structure you have these cross links which start appearing between the main links / main chains that is called a crosslink structure.

And in a greater degree of order you have the polymer network which is having a proper repeated orderly arrangement. So now, the direction of increasing strength obviously leads it from this loosely defined structure to a well regulated and created structure. So, when we go from a linear to a network structure your strength is rapidly increasing. What about crystallinity? How do you define crystallinity? Crystalline means it has some ordered arrangement.

So when you go from linear to network, your crystallinity also increases. What about temperature susceptibility of the polymers? The properties of the polymer will change a lot when you have what type of structure? What is going to happen when you increase the temperature which sort of polymer starting to flow a lot more than others, here among these structures?

The linear and branched - these are the polymers that will be expected to get deformed significantly when you change temperatures. These will be affected lot more by temperature and rate of loading as compared to the cross-linked and network structures. Once again, what we want to emphasize here is that the structure of the material controls its characteristics. And how do you understand this structure, you understand it by characterization.

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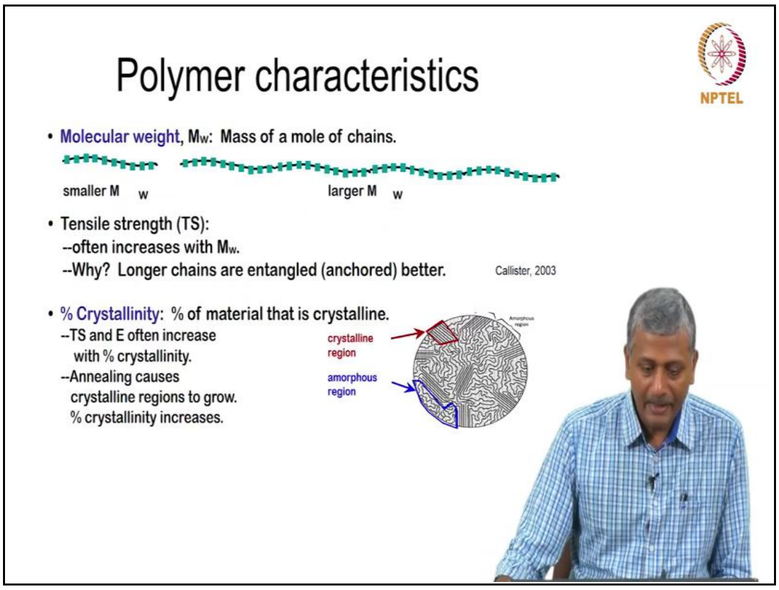

Polymer characteristics

- Molecular weight, M_w: Mass of a mole of chains.

- Tensile strength (TS):
  --often increases with M_w.
  --Why? Longer chains are entangled (anchored) better.

Callister, 2003

- % Crystallinity: % of material that is crystalline.
  --TS and E often increase with % crystallinity.
  --Annealing causes crystalline regions to grow. % crystallinity increases.

So, again, there are several indicators of the performance of the polymer, you have molecular weight, which indicates how many links are connected together. Tensile strength increases with the molecular weight and again percentage of crystallinity is defining the material that is crystalline. So if you look at the polymer under the microscope and recognise how many of the regions are actually looking ordered, that is basically your degree of crystalinity in the polymer.

Tensile strength and modulus of elasticity increase with the degree of the crystallinity. Now similar to metals, in plastics also you can do heat treatments like annealing and annealing basically is slow heating and slow cooling. And that slow heating and cooling process in polymers also, will tend to increase the extent of order that you have in the structure. So, annealing will actually lead to an increase in the strength and modulus of the polymer also.

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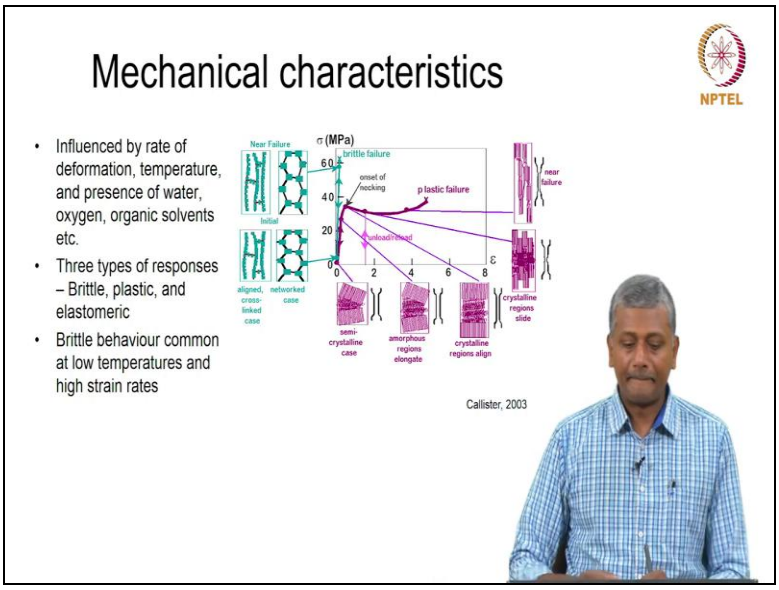

Mechanical characteristics

- Influenced by rate of deformation, temperature, and presence of water, oxygen, organic solvents etc.
- Three types of responses – Brittle, plastic, and elastomeric
- Brittle behaviour common at low temperatures and high strain rates

Callister, 2003

Now important characteristic to understand is, how does the mechanical response change, with different types of structures. So, in the case of reticulated or networked structures, the order is so good that you ultimately end up simply getting a breakage of the bonds and that leads to a brittle failure. But interestingly, when you have secondary bonding or semi crystalline materials you have an interesting load carrying behaviour here, you have an initial increase in the load you have onset of necking which basically is when you start aligning these irregularly ordered chains and they start straightening up.

And then ultimately these bunches of chains start slipping past each other. So, it is almost akin to what you see in the yielding of metals, it is almost like the yielding of metals process. And here you can think of this as something similar to that of a very high strength metal which undergoes a brittle transformation. But here you are dealing with ductile metals so there is arrangement and then rearrangement then finally slippage of the material past each other.

Of course you do not get to see an increase in the order in metals. In plastics and polymers that is an interesting part, that you actually see an increase in the extent of order with more loading in the process. In the beginning there is lot of jumbling up of the amorphous or semi-crystalline regions. But when you increase the load these start becoming straightened up, and that increases the level of order in the Polymers.

Now there some polymers tend to disobey the entropy law. When we say that we do work on the system the entropy always increases. Here in the case of polymers a reverse is happening.

Some work in the system is actually decreasing the level of entropy, increasing the order in the system.

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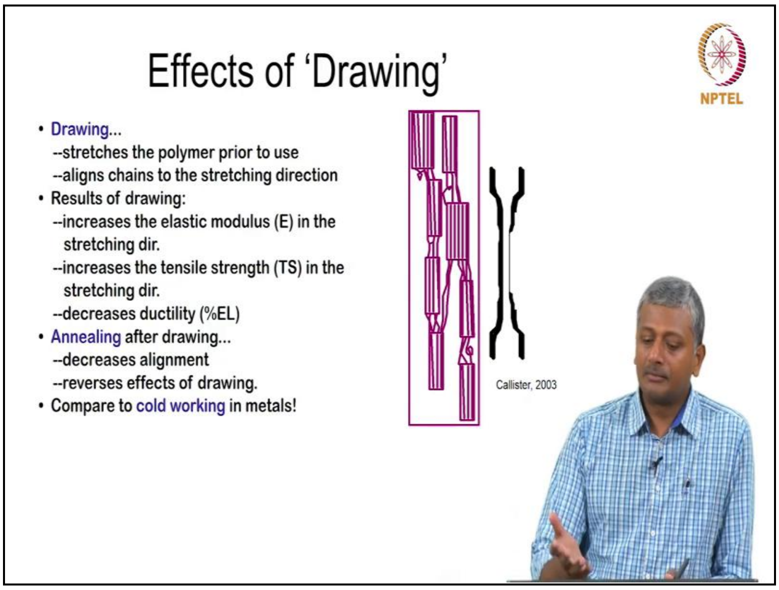

Effects of 'Drawing'

- Drawing...
  - --stretches the polymer prior to use
  - --aligns chains to the stretching direction
- Results of drawing:
  - --increases the elastic modulus (E) in the stretching dir.
  - --increases the tensile strength (TS) in the stretching dir.
  - --decreases ductility (%EL)
- Annealing after drawing...
  - --decreases alignment
  - --reverses effects of drawing.
- Compare to cold working in metals!

Callister, 2003

Similar to cold working in metals you also have something called drawing. So just like in metals, if you do this process even before the loading starts, so you take the polymer and stretch it, what will happen all these amorphous regions straighten up and then your loading will again directly go into this later phase. So, your ultimate failure may actually be at a higher load as opposed to your initial system.

It is just like your cold working of steel, reworking of the plastic by drawing can actually lead to a higher strength. Again, then there is a lot of issues that deals with heat treatment followed by drawing or drawing followed by heat treatment that can lead to different bunches of characteristics inside.

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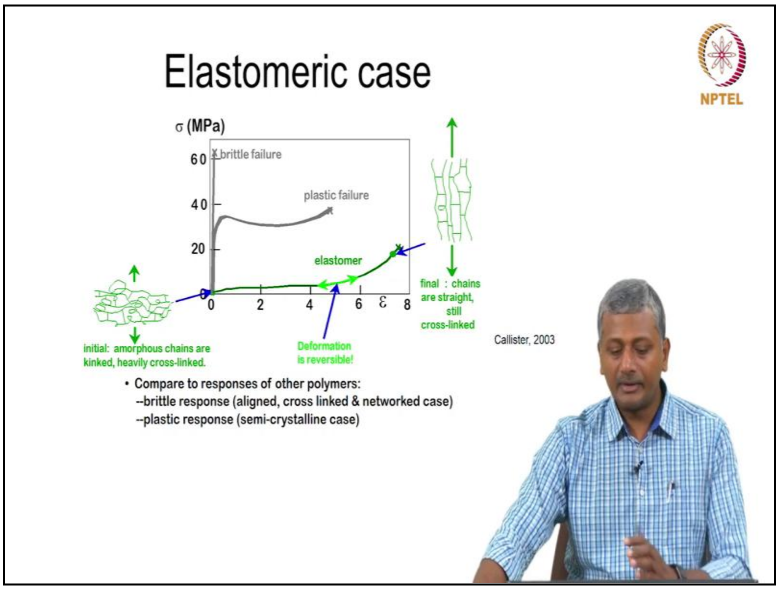

Elastomeric case

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- Compare to responses of other polymers:
  --brittle response (aligned, cross linked & networked case)
  --plastic response (semi-crystalline case)

And there can also be another case called elastomeric case that is just like what we see in rubber. In rubber what happens is at very small level of stress, there is a very large recoverable strain and mostly the stress-strain relationship is non-linear. You see the stress strain relationship of rubber, at very low levels of stress and of extremely high strains which can be recovered but then it is non-linear; the stress strain behaviour is essentially non-linear.

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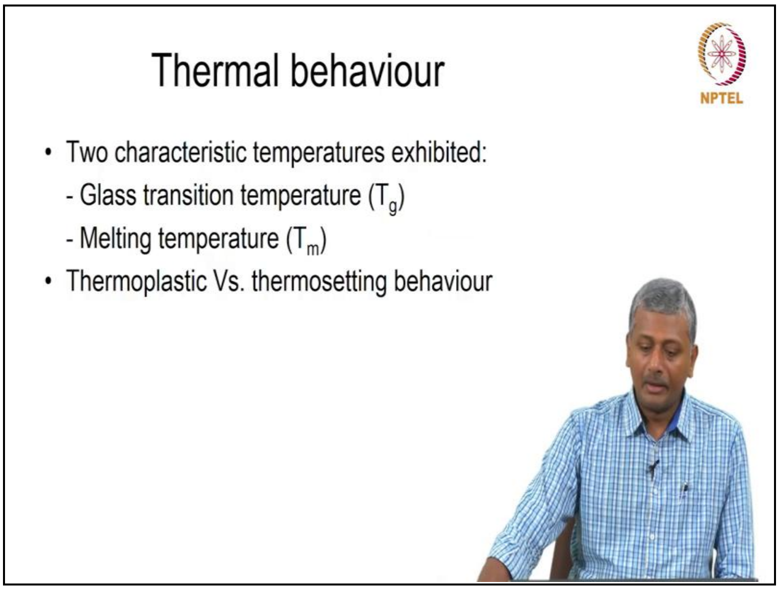

Thermal behaviour

- Two characteristic temperatures exhibited:
  - Glass transition temperature (T_g)
  - Melting temperature (T_m)
- Thermoplastic Vs. thermosetting behaviour

The other important characteristic is obviously the temperature behaviour. Polymers exhibit 2 typical temperatures one is called a glass transition temperature (T_g) and other is the melting temperature (T_m). And because of this we also classify polymers into different types; we call them thermosetting or thermoplastic polymers. Now a purely amorphous polymer will only exhibit glass transition temperature. A purely crystalline polymer will only exhibit melting temperature. Those polymers that have a mixture of crystalline and amorphous phases will exhibit both these temperatures.

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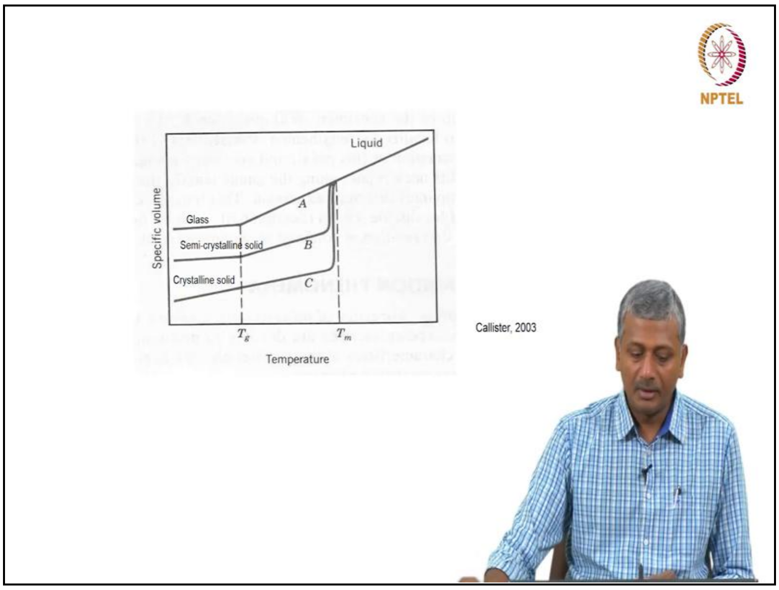

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So again if you look at what happens to the specific volume? What is specific volume? It is just the inverse of density. Density is mass by volume; specific volume is volume by mass. As a variation of temperature, if you see for a glass or an amorphous material you have this transformation occurring at the glass transition temperature. And beyond that the material becomes completely liquid. For semi crystalline solid you have a transition occurring at Glass transition.

You also have a transition occurring at the melting temperature. For a crystalline solid there is no Glass transition temperature, there is only a melting temperature for the crystalline material. Now why is this important? We need to understand this because we need to define the range of working with these materials. For a semi crystalline material obviously for a well-defined mechanical characteristic or mechanical response, we would like to be in this region, which is lower than the glass transition temperature because otherwise material will start becoming too viscoelastic for you to handle carefully.

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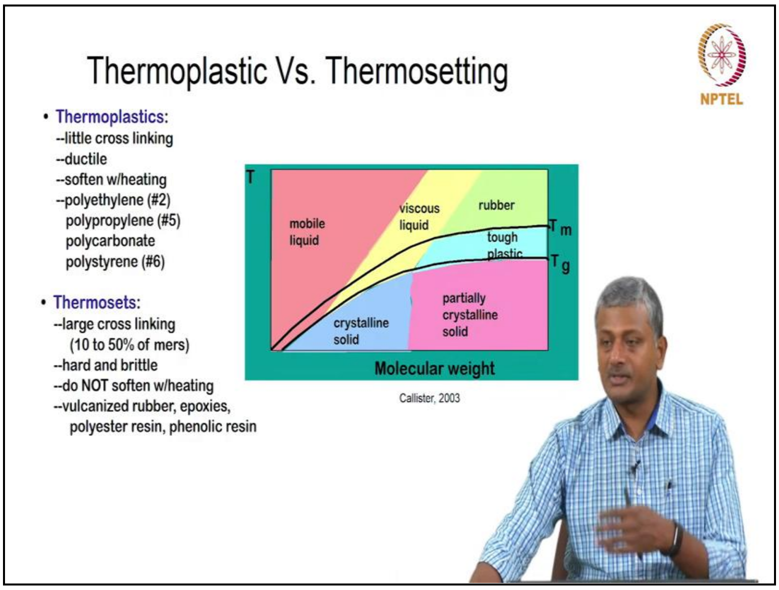

Thermoplastic Vs. Thermosetting

- Thermoplastics:
  - --little cross linking
  - --ductile
  - --soften w/heating
  - --polyethylene (#2)
    polypropylene (#5)
    polycarbonate
    polystyrene (#6)
- Thermosets:
  - --large cross linking
    (10 to 50% of mers)
  - --hard and brittle
  - --do NOT soften w/heating
  - --vulcanized rubber, epoxies,
    polyester resin, phenolic resin

Callister, 2003

So because of this, we have different types of performances exhibited. You must have learnt about thermoplastics and thermosetting. Thermo setting is essentially your cross-linked and reticulated Polymers. Thermoplastic means linear and branched, which are easily able to move when temperature is increased.

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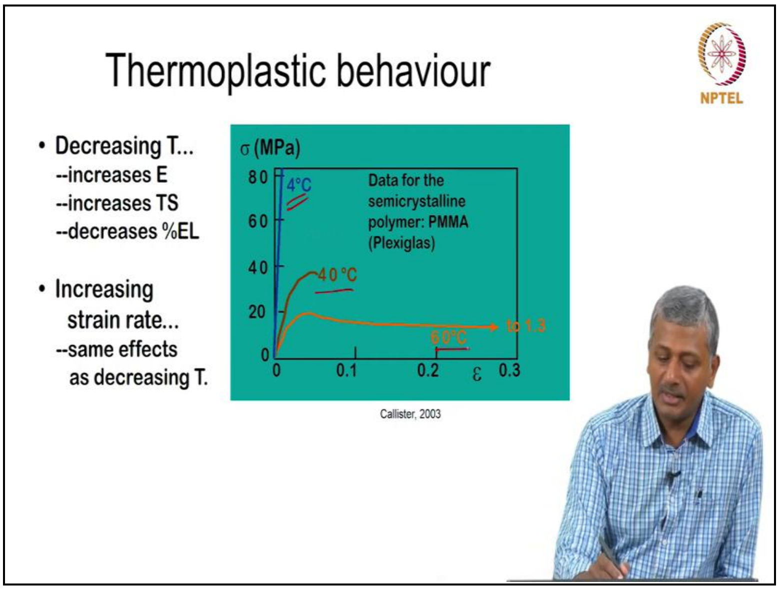

Thermoplastic behaviour

- Decreasing T...
  - --increases E
  - --increases TS
  - --decreases %EL
- Increasing strain rate...
  - --same effects as decreasing T.

Callister, 2003

And what happens to thermoplastic materials when you have change in temperature and you test the mechanical response at 4ºC degrees you get something like this and at 40°C, it is here at 60ºC is here. You can see that there is a major drop in the ultimate stress levels when you increase the temperature. So, thermoplastic materials are extremely dependent on the temperature.

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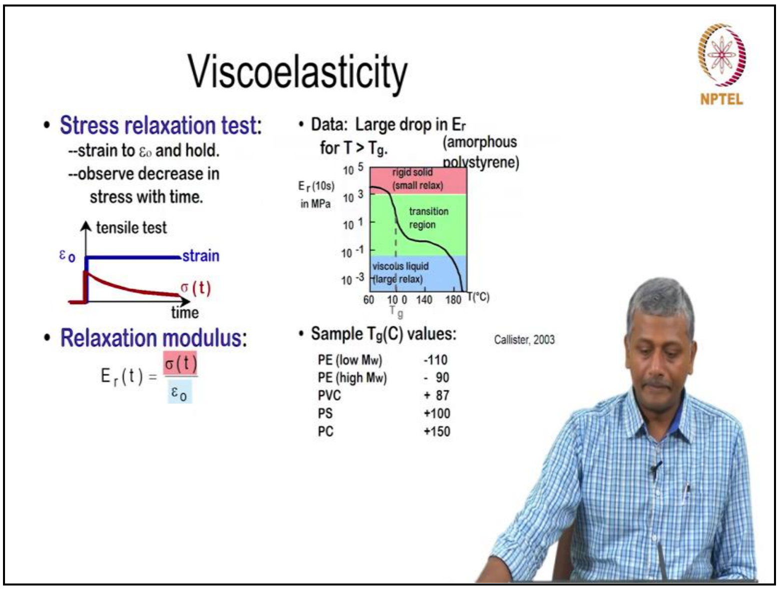

Viscoelasticity

- **Stress relaxation test:**
  --strain to ε_o and hold.
  --observe decrease in stress with time.

- **Relaxation modulus:**

$$E_r(t) = \frac{\sigma(t)}{\varepsilon_o}$$

- Data: Large drop in E_r for $T > T_g$. (amorphous polystyrene)

- Sample T_g(C) values:

PE (low Mw)	-110
PE (high Mw)	- 90
PVC	+ 87
PS	+100
PC	+150

Callister, 2003

And again why I wanted to say that you need to consider these characteristics is the extent of temperature is different for these different polymers. For example if we consider PVC - polyvinyl chloride, what is a common application of PVC; pipes carrying water. So it has a glass transition temperature of 87 °C. What is the relevance of that? What is the significance of that? So when we have extremely hot water, we do not want to use polyvinyl chloride.

So we do not want to use plastic pipes to carry extremely hot water. If you go to Western countries the water pipe systems are essentially lead systems for hot water whereas they can still use plastic for normal water, in India we only use plastic, we do not get piped hot water. So, again we need to consider those things when we do a design of components with these kinds of materials. And again Viscoelasticity is a primary characteristic as far as polymers are concerned.

The rate of loading and temperature can have major effects on the performance of the material. With viscoelasticity you need to look at creep and relaxation and these two aspects also are very important from point of view of testing polymers.

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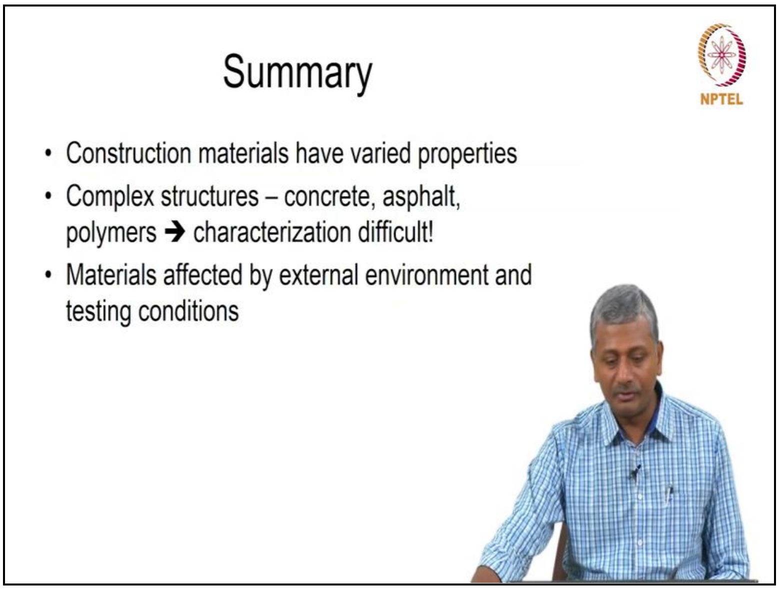

Summary

- Construction materials have varied properties
- Complex structures – concrete, asphalt, polymers ➔ characterization difficult!
- Materials affected by external environment and testing conditions

Without going into the details, I think that level of emphasis is enough for the purpose of this course. The primary idea was to understand that the internal structure of the material can have a major impact on how the processing is done and how the performance actually is obtained from these materials. So, overall you have seen that there are different types of materials used in construction, they have varied properties.

Their structures are complex and that makes characterization interesting but difficult. And the properties of materials are affected to a large extent by the external environment and the testing conditions, so again, when you do characterization of these materials, you need to define the environment and testing conditions properly. So just for example when you read a research paper, trying to figure out what has been done in the experiments, one of the main features that you need to pay particular attention to is what have been the conditions of testing, and that obviously have a net impact on the result that is obtained in the investigation.

So, that is very important to understand the actual methodology of testing, because if you want to replicate the same test you need to ensure that you are capturing the same conditions, otherwise you will get completely different results. Very often we may make that mistake of only looking at problem and the result, the means is very important. In fact in characterization you will see that the means is more important in the end or in some cases means will actually describe the end.

You’ll see that in many of the examples that we look into in this course. So thank you all the session and ends here. In the next session, the Professor Piyush will start the discussion on calorimetric techniques for cement hydration evaluation. Thank You.