Modern Construction Materials

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Module - 3
Lecture - 11
Thermal Properties

Welcome to lecture eleven of Modern Construction Material. We have been until now discussing the response of materials to stress; we looked at failure theory, we looked at how materials fracture, and also we looked at the geological behavior of materials. Now we completes this module of material properties by discussing properties related to thermal behavior. And here to start with I have a picture, so of Thikse Monastery in Ladakh.

Generally in India, when we talk about thermal behavior, we always think our very hot climate, we look at how materials were respond to high temperatures and how we have to establish comfort to handle a hot and humid environment. And exception is in Ladakh, which is in the north of India, close to Tibet and this is Monastery which is very beautiful, very impressive in close to Leh which called the Thikse Gompa – the Thikse Monastery. And you see here, at the top the Monastery; and at the bottom, you see that stupas and these are all the different buildings comprising the Monastery.

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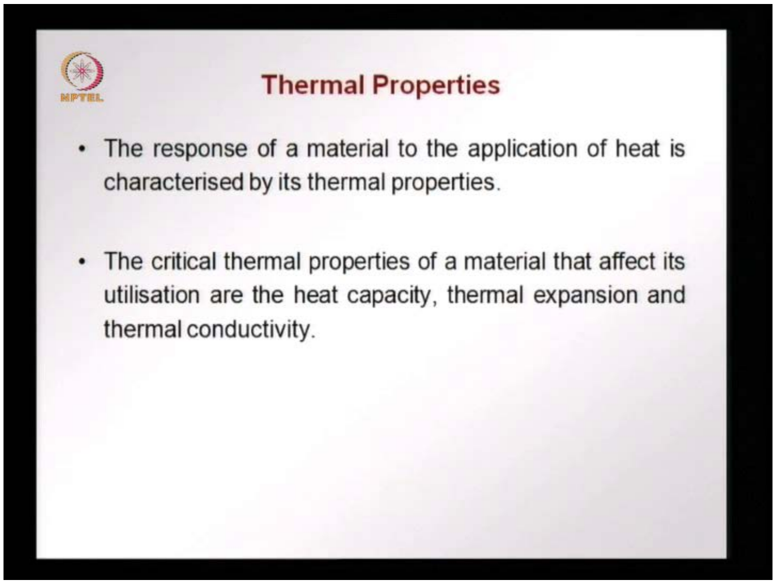

Thermal Properties

- The response of a material to the application of heat is characterised by its thermal properties.
- The critical thermal properties of a material that affect its utilisation are the heat capacity, thermal expansion and thermal conductivity.

So we will get back to business, we will talk about the thermal properties of the different materials. The response of a material to the application of heat is governed by what are called its thermal properties. And there are three critical thermal properties that we are interested in for any materials, because they affect the utilization in civil engineering applications. One is the heat capacity, then thermal expansion and thermal conductivity. Now we will look at each one of these in detail and see what are typical properties and compare the properties of the different material that we have introduced up to now.

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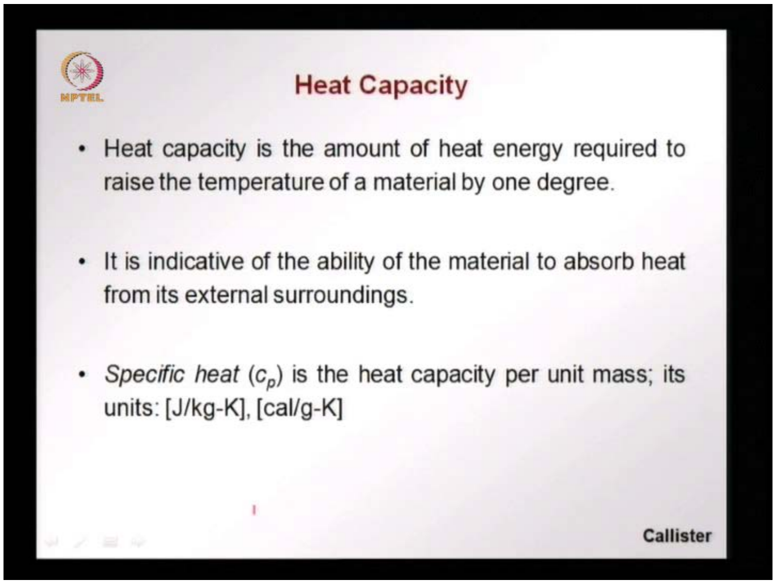

Heat Capacity

- Heat capacity is the amount of heat energy required to raise the temperature of a material by one degree.
- It is indicative of the ability of the material to absorb heat from its external surroundings.
- *Specific heat* (c_p) is the heat capacity per unit mass; its units: [J/kg-K], [cal/g-K]

Callister

Heat capacity or specific heat is related to the amount of heat energy required to raise the temperature of a material. Heat capacity is that heat energy required to raise the temperature of a material by one degree that is what is called the heat capacity. So this indicates the ability of the material to absorb heat from its surroundings. How much heat the material can absorb as its temperature goes up. The specific heat is the heat capacity of the material per unit mass; and its units are given as joules per kilogram Kelvin or calories per gram Kelvin.

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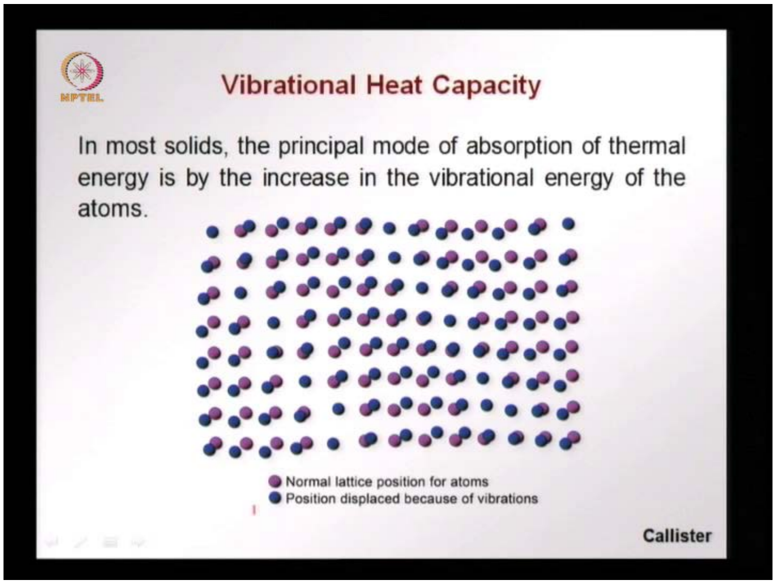

Vibrational Heat Capacity

In most solids, the principal mode of absorption of thermal energy is by the increase in the vibrational energy of the atoms.

● Normal lattice position for atoms
● Position displaced because of vibrations

Callister

How this heat is absorbed and stored is of interest to us, when we are looking at development of materials and understanding of materials. In most solids, the principal mode of absorption of heat or thermal energy is by the increase in the vibrational energy of this atoms. Normally, the atoms would be in a certain lattice position that say this purple circles denote the normal lattice position of the atoms. When heat is absorbs these atoms start vibrating and you could have a different position displace position, because of these atoms given by the blue dots which will keep vary due to the vibrations.

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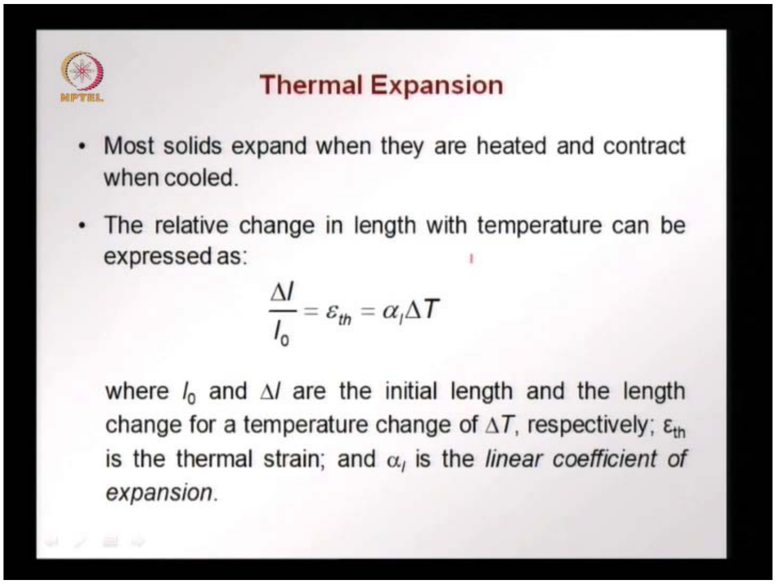

Thermal Expansion

- Most solids expand when they are heated and contract when cooled.
- The relative change in length with temperature can be expressed as:

$$\frac{\Delta l}{l_0} = \varepsilon_{th} = \alpha_l \Delta T$$

where l_0 and Δl are the initial length and the length change for a temperature change of ΔT, respectively; ε_{th} is the thermal strain; and α_l is the *linear coefficient of expansion*.

Another aspect of thermal behavior, which is also important to us is the expansion. Most solids will expand when they are heated and contract when cooled; this is generally the case. The change in length with temperature can be given by this equation delta l or the change in length induced by the change in temperature divided by the original length gives a thermal strain epsilon t h, which is given as alpha l which is the linear coefficient of expansion, this is called linear coefficient of expansion or sometimes simply coefficient of expansion times the change in temperature. So we see that the strain introduced by change in temperature is proportional to the temperature change and the factor of proportionality is called the coefficient of expansion and this varies from material to material.

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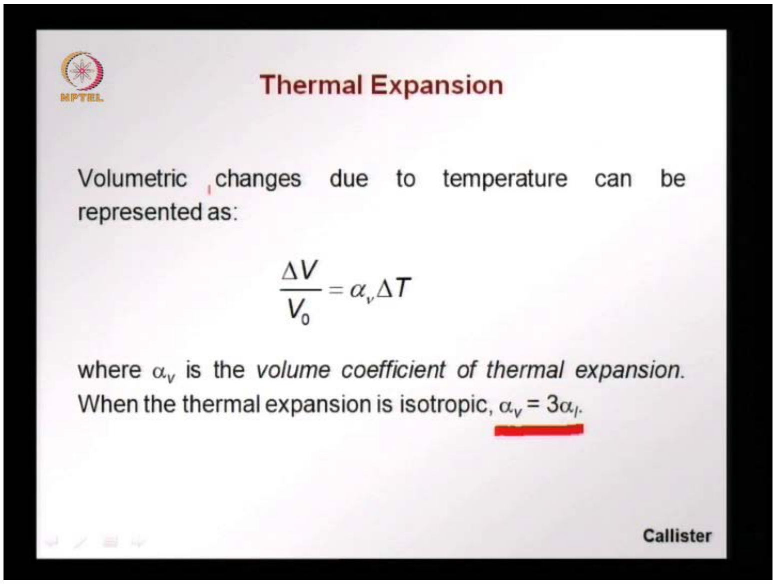

Thermal Expansion

Volumetric changes due to temperature can be represented as:

$$\frac{\Delta V}{V_0} = \alpha_v \Delta T$$

where α_v is the *volume coefficient of thermal expansion*. When the thermal expansion is isotropic, $\alpha_v = 3\alpha_l$.

Callister

Volumetric changes in temperature can be represented in this form, where delta V is the change in volume due to the ah temperature increase, the material expands by a certain volume delta V. The ratio between the delta V and the original volume V0 is equal to alpha v times delta T; alpha v is the volumetric coefficient of thermal expansion, and this gives now the proportionality between the volumetric strain and the change in temperature. And we find that for an isotropic material, alpha v is equal to three times alpha l. So knowing the linear coefficient of thermal expansion, we can find out what is the volumetric coefficient of thermal expansion.

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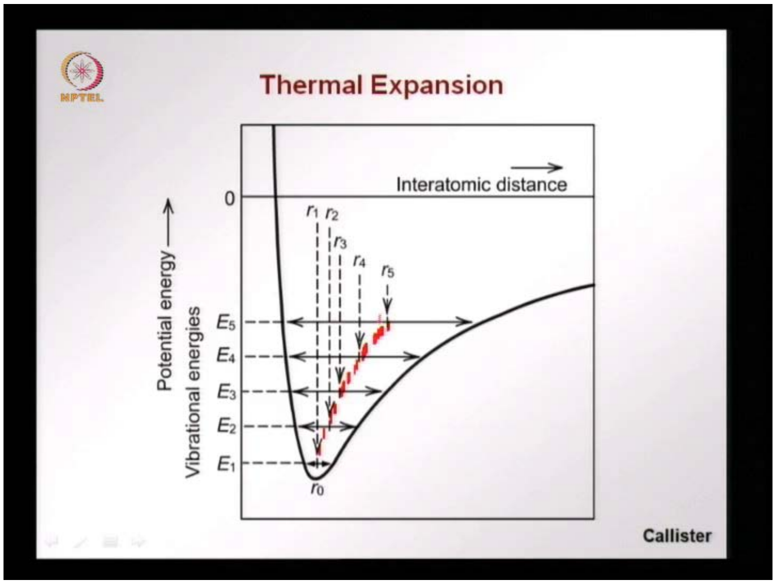
Thermal Expansion

Callister

Now why does thermal expansion occur? So this goes back to our discussion of the diagram. And we saw that in the valley where the material lattice structure is stable. The minimum value of potential energy, now the maximum attractive energy corresponds to a spacing r 0 and this only occurs at 0 Kelvin, the absolute 0 temperature. Above this temperature, that is all normal temperatures, there is a possibility that the spacing can be anything over a certain range. Say instead of the 0 Kelvin, we are at a certain temperature here. At this temperature corresponding to this potential energy or vibrational energy, they can be different atomic position, inter atomic position, which will have the same energy.

So what the atoms do is vibrate over this energy, vibrate over this range of inter atomic spacing, and the average distance would be the mean of this; same this case, it would be this point r three corresponding to the vibrational energy or potential energy E three. Since this values not symmetric, it is not symmetric, but it’s shape like this; the mean distance at any energy now deviates to the right. So we have a deviation of the mean distances at any energy. As the mean now deviates from r zero, the material experiences the expansion. This is the expansion that we absorb in the material at different temperature, due to the vibration that is occurring in the inter atomic distance.

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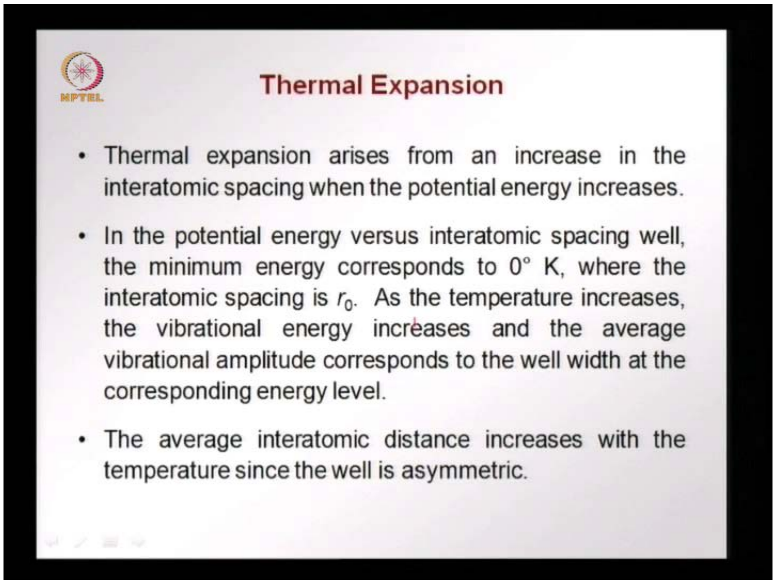

Thermal Expansion

- Thermal expansion arises from an increase in the interatomic spacing when the potential energy increases.
- In the potential energy versus interatomic spacing well, the minimum energy corresponds to 0° K, where the interatomic spacing is r_0. As the temperature increases, the vibrational energy increases and the average vibrational amplitude corresponds to the well width at the corresponding energy level.
- The average interatomic distance increases with the temperature since the well is asymmetric.

So thermal expansion arises due to the increase in the inter atomic spacing as the potential increases. And in the well, in the curve between potential energy and inter atomic space, the minimum energy corresponds to 0 degrees Kelvin, where the inter atomic spacing is r 0. For any other temperature, as the temperature increases, the vibrational energy increases - the potential energy and the average vibrational amplitude corresponds to the well width that is the range the two sides of the well at that corresponding energy level. So, the amplitude of the vibration is this; this is called the amplitude of the vibration. The average inter atomic distance that is the mid-point of the well width increases with the temperature since the well is asymmetric, that is what I showed you before. So as this distance – average distance increases the material experiences expansion.

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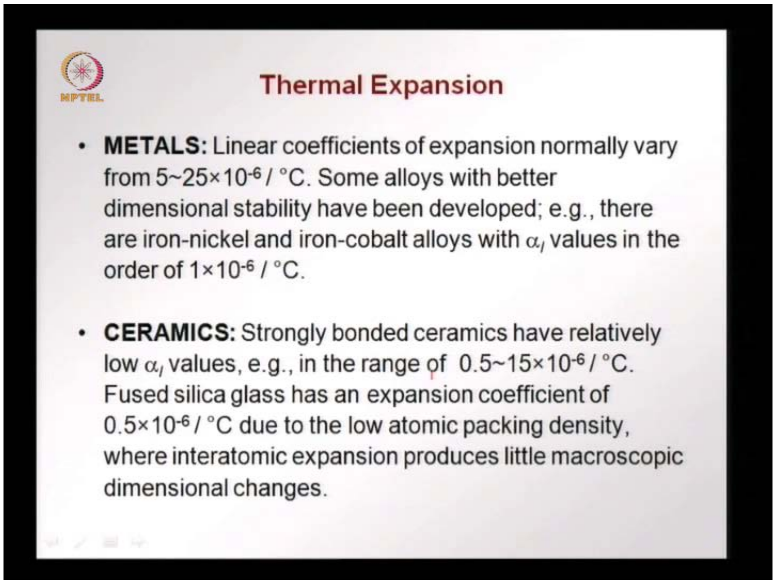

Thermal Expansion

- **METALS:** Linear coefficients of expansion normally vary from $5\sim25\times10^{-6}$ / °C. Some alloys with better dimensional stability have been developed; e.g., there are iron-nickel and iron-cobalt alloys with α_l values in the order of 1×10^{-6} / °C.
- **CERAMICS:** Strongly bonded ceramics have relatively low α_l values, e.g., in the range of $0.5\sim15\times10^{-6}$ / °C. Fused silica glass has an expansion coefficient of 0.5×10^{-6} / °C due to the low atomic packing density, where interatomic expansion produces little macroscopic dimensional changes.

In the case of metals, the alpha l value for the linear coefficient of expansion normally varies from 5 to 25 time 10 the power minus 6 per degree Celsius. There are some alloys which have much lower coefficient of expansion, say iron-nickel, iron-cobalt alloys with alpha l values in the order of one times ten to the power minus 6 per degree Celsius. Ceramics generally seems to have slightly lower thermal expansion coefficient. Strongly bonded ceramics have values in the range of 0.5 to 15 times ten to the power of minus 6 per degree Celsius.

At the lower end, we have a material such as fused silica glass, which has a very low atomic density in its packing; the atomic packing density is very low, so even when the vibration occurs, we do not see any significant increase in the volume. Due to the low atomic packing density, the inter-atomic expansion produces very little macroscopic dimensional changes that is in the material, we do not see a lot of dimensional change even though the temperature is increasing. So we have a low coefficient of expansion.

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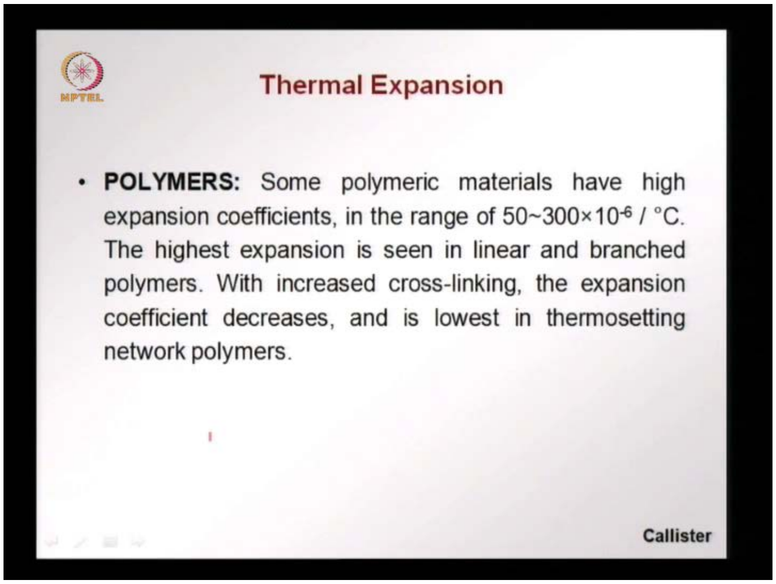

Thermal Expansion

- **POLYMERS:** Some polymeric materials have high expansion coefficients, in the range of $50 \sim 300 \times 10^{-6}$ / °C. The highest expansion is seen in linear and branched polymers. With increased cross-linking, the expansion coefficient decreases, and is lowest in thermosetting network polymers.

Callister

On the other hand, in polymers, we generally have high expansion coefficients, in the range of fifty to three hundred times ten to the power minus 6, sometimes one order higher than what we saw in ceramics and metals. And the highest expansion is seen in linear and branch polymers. If you remember, these are the polymers, which have Van der Walls bonds between the chains; these are weak bonds and we do not have covalent bond between the chains.

There we have higher expansion whereas in cross-link polymers with increasing cross-linking, the expansion coefficient decreases, that is less thermal expansion when the cross link is stronger. And in thermoset network polymers, we have the least thermal expansion occurring, that is where you have strong covalent bond between the different molecules and you have a set network structure.

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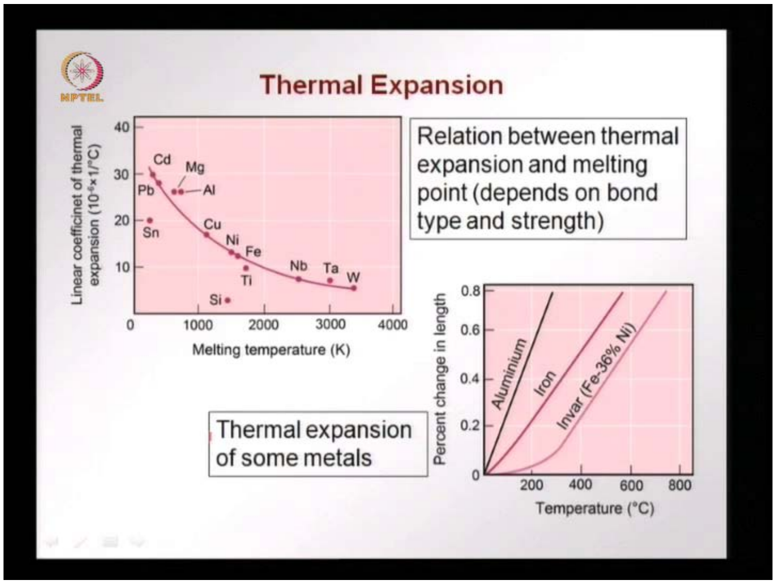

Thermal Expansion

Relation between thermal expansion and melting point (depends on bond type and strength)

Thermal expansion of some metals

Now when we discuss the ((Refer Time: 12:59)) diagram, if you remember we said that when the bond strength is larger, the melting point is also higher, because the energy needed to break the bond is higher and this increases with the strength of the bond. We also saw that when the diagram was such that, the well was narrower and deeper that is for a stronger bond. The width of the well being narrower made less variation give raise to less variation of the average inter-atomic spacing at different temperature that is the thermal expansion was also less.

So when we have strong bonds, we have a higher melting point and we also have a lower thermal expansion and this what do we see here on the curve on the left we have different metals, and on the x-axis we have the melting temperature. So higher melting temperature indicates a higher bond strength. On the y-axis, we have the coefficient of thermal expansion and again a higher bond strength would mean that the coefficient of expansion is lower. And you see a range of materials which fall, range of materials which fall on this line. So clearly, we see that as the melting temperature increases due to the higher bond strength, we have a lower thermal expansion.

On the right, we have compared three metals as a function of temperature; on the x-axis, we have a range of temperatures going to from 0 to about eight hundred degree Celsius; and on the y-axis, we have a percent change in length. For aluminum and iron, we have a linear increase; the coefficient of this is alpha l that is the coefficient of thermal expansion, the linear coefficient of thermal expansion. We find that aluminum for the same temperature change expands more than iron. And what is interesting is this alloy invar which is iron is 36 percent nickel. Which has a final slope that is parallel to that of the iron, but initially we see very little or almost 0 thermal expansion until about hundred degrees and then slowly increasing and then finally the behavior is parallel to that of the iron.

But what is interesting to us is this region. We find that over a range of temperature invar does not expand at all that is the thermal coefficient of expansion is 0 up to a range of say hundred degrees. So this means that this material will not vary in its dimensions up to a temperature about hundred degree C, that is why we use invar as a reference in calibration, when we want in the lab to measure change of strains or deformations over a period of time.

From one day to the other, we can have a different ambient temperature, but we always want to have the same reference. So in this case, calibration is done with reference to an invar bar which we know that over normal temperatures, even though the temperature is changing will not change its length, so that is the application of invar and this is one of the few alloy which do not have any significant thermal expansion over a wide range of temperatures.

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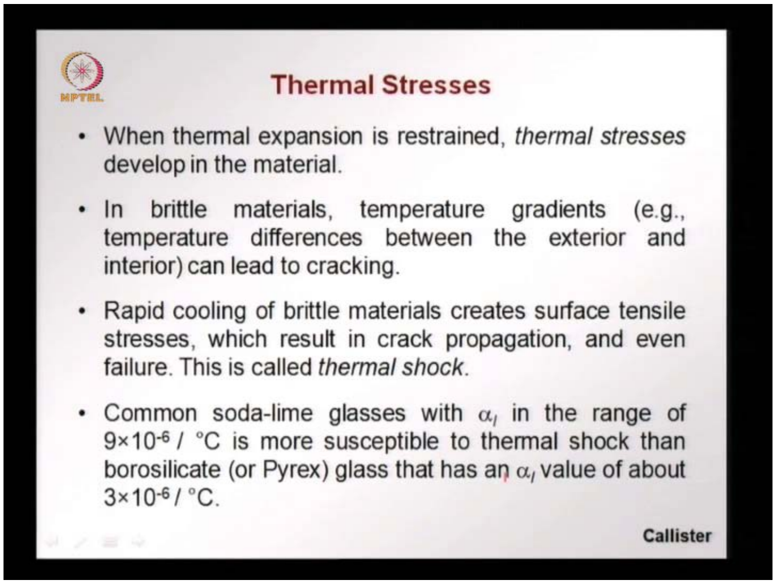

Thermal Stresses

- When thermal expansion is restrained, *thermal stresses* develop in the material.
- In brittle materials, temperature gradients (e.g., temperature differences between the exterior and interior) can lead to cracking.
- Rapid cooling of brittle materials creates surface tensile stresses, which result in crack propagation, and even failure. This is called *thermal shock*.
- Common soda-lime glasses with α_l in the range of 9×10^{-6} / °C is more susceptible to thermal shock than borosilicate (or Pyrex) glass that has an α_l value of about 3×10^{-6} / °C.

Callister

One aspect of interest to us is that there are thermal stresses which can develop due to thermal expansion. Whenever thermal expansion is restrained, there is thermal stress developed. So you can imagine that we have a bar of steel that is increasing in temperature, it will tend to be come longer. But if we had the ends fixed, suppose the bars ends were fixed and not allowed to move, this thermal expansion now will create a stress in the material because the strain, the free strain is stopped. The material cannot lengthen due to its end resistant, and this resistance to deformation causes a stress in the material. Sometimes the stress is so high that the material breaks or fails, or it can cause failure in the material that is supporting it or fixing it.

So many cases, we have to worry about this thermal stresses that can be built up in a structure. And in some cases also when we combine material for the example, in the case of reinforced concrete when we combining steel and concrete, we choose combination that have the same thermal expansion, so that the restrained or the differential thermal expansion does not give raise to thermal stresses or we have we should not induce very high thermal stresses in any structural element that can cause failure. These thermal stresses can also occurred due to temperature gradients. Suppose, you have the exterior of a body, being much cooler or much hotter than the inside, the temperature gradient is setup and this can also lead to cracking.

Thirdly, we can have something called thermal shock, which can also create problems. Suppose, we have a brittle material say glass that is very rapidly cooled then you have very rapid contraction of the surface whereas the inside is still hotter, this creates tension on the surface. Because you can imagine the surface is trying to contract, the inside is not allowing it to contract and the only way the material can contract is by cracking. So this creates crack propagation through the material and can even cause failure and this is called thermal shock. And this is something that might you occur to you when you have say a glass recipient which was in hot conditions and suddenly you pour cold water into it the material the glass can crack; not something that you should try out, but this is something that could occur. And the phenomena that causes this failures is called failure thermal shock.

Different types of glass react differently to thermal shock; say when we have common glasses soda-lime glasses with ah linear coefficient of expansion in the range 9 into 9 times ten to power minus 6 per degree Celsius. This is more susceptible to thermal shock, so this is the type of glass that I just mentioned. If you have it on the stow heating up say any anything that’s been put in it, and then you transfers it to very cold environment you pour ice water into it then it could crack in break suddenly. On the other hand, we can have glass with lower alpha l values, coefficient of thermal expansion could be lower like in the case of borosilicate or Pyrex glass that is used for heating materials even for cooking in the stoves and so on, we used for borosilicate or Pyrex glass. This has a coefficient of thermal expansion that's about one-third that we see in common glasses. So, this is less susceptible to rapid changes in temperature and less susceptible therefore to thermal shock.

So we saw three effects of thermal expansion one is that thermal stresses could develop, when temperature induced expansion is restrained. This thermal stress could cause failure in the material itself or in the surroundings of the material, if it is restrained from expansion. Secondly, we saw that gradients could develop, say in a structure you have temperature outside lower than what is inside, you will have contraction in the outside, cracks developing from the outside to the interior. This happen for example in a massive concrete element, just after setting stars hydration is just becomes the temperature is inside goes up, because of the exothermic reaction; whereas the outside, in contact with the ambient temperature have can encounter cooling then undergo cooling this leads to contraction and you have now cracks developing from the outside to the interior. And these cracks could change the structure and harm the structure later. So temperature differences between the exterior and interior can lead to cracking in brittle materials. Thirdly, we looked at the phenomena of thermal shock that sudden cooling of brittle material can cause crack propagation and failure.

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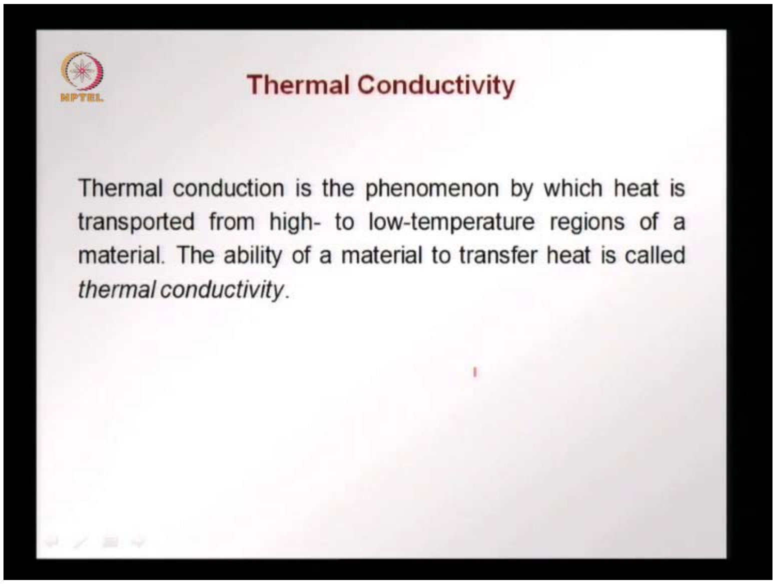

Thermal Conductivity

Thermal conduction is the phenomenon by which heat is transported from high- to low-temperature regions of a material. The ability of a material to transfer heat is called *thermal conductivity*.

The third thermal property, which is of interest to us is thermal conductivity. Thermal conductivity is due to the phenomena by which heat moves from high- to – low- temperature regions through a material, that is a material transfer heat and this ability is called thermal conductivity.

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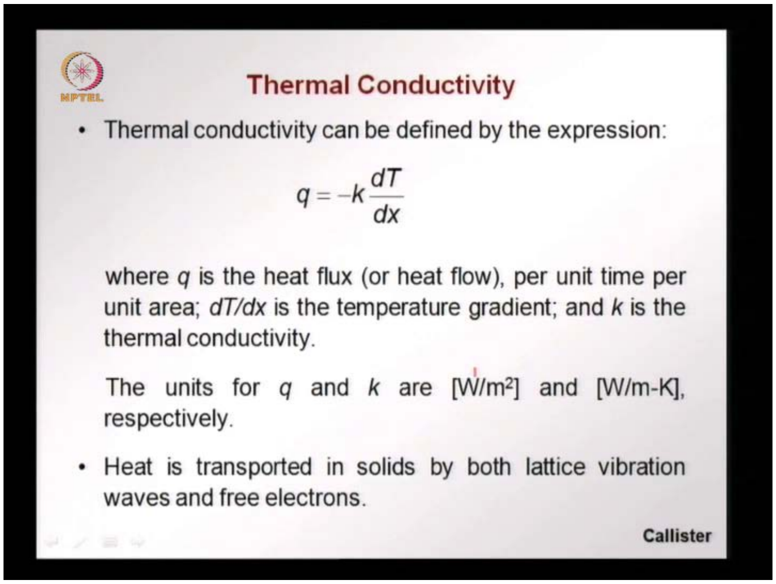

Thermal Conductivity

- Thermal conductivity can be defined by the expression:

$$q = -k\frac{dT}{dx}$$

where q is the heat flux (or heat flow), per unit time per unit area; dT/dx is the temperature gradient; and k is the thermal conductivity.

The units for q and k are [W/m^2] and [W/m-K], respectively.

- Heat is transported in solids by both lattice vibration waves and free electrons.

Callister

Thermal conductivity can be defined by this expression, where q is the heat flux or heat flow. This is equal to minus k – k is the thermal conductivity, it is a material property times the temperature gradient - dT by dx is the rate of change of temperature. The units for q and k are watt per meter square and watt per meter Kelvin. So these are the units of k and q. Now this heat is conducted by the lattice vibration that we looked at when we look at absorption of heat also. The same mechanism also transports heat through a material, lattice vibration and the free electron say in the case of a metal bond facilitate the transfer of heat through the solid. So the heat moves through the solid due to the vibration of the lattice and the free electrons that are present in the lattice structure.

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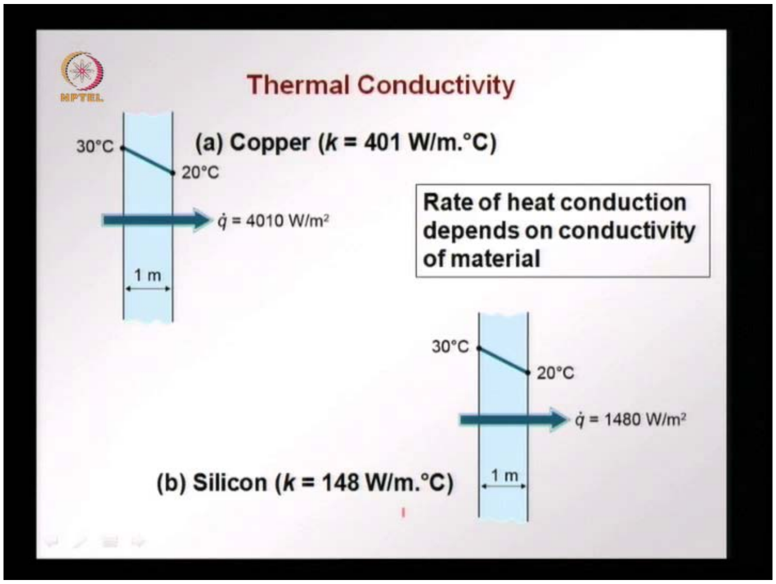

Thermal Conductivity

(a) Copper (k = 401 W/m.°C)

Rate of heat conduction depends on conductivity of material

(b) Silicon (k = 148 W/m.°C)

Thermal conductivity varies significantly between materials say in the case of copper with the conductivity of four hundred and one watt per meter degree Celsius. We can have a case that we have say a panel ah on side temperature is thirty degrees, the other side temperature is twenty degrees and the thickness is about one meter. This would be the rate of thermal conductivity or heat transfer. In the case of silicon, a similar element, silicon has a much lower thermal conductivity, we see that the heat ((Refer Time: 25:34)).

Most of us civil engineering application say in building, we want lower thermal conductivity in are walls and the shell and the envelope that makes up the building, because we don't want to be a influence to much by the temperature changes outside a building or the structure that we living. So we want something that insulates which behaves in man closer to silicon rather than in copper with less heat coming in, in the case where you have a very hot climate outside or let heat going out if you have a very cold temperature outside. This rate of heat conduction depends on conductivity of the material and this influences the thermal comfort in the area that we are living in or working in.

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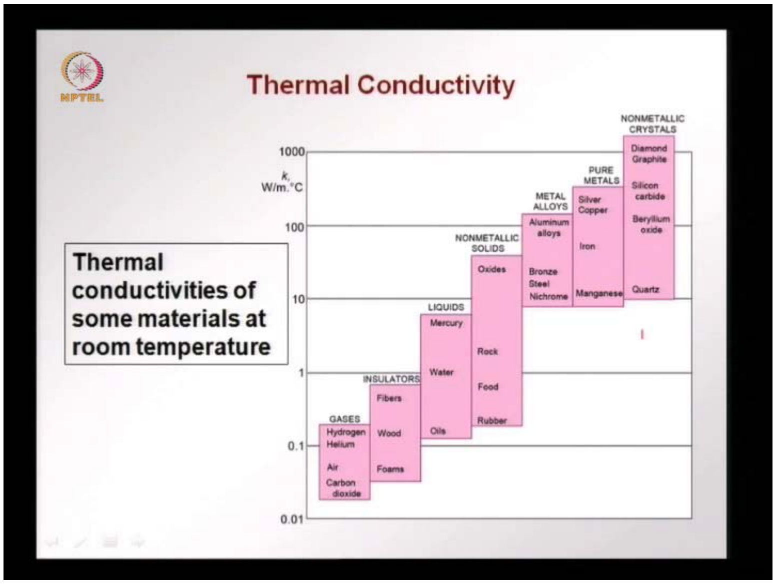

Thermal Conductivity

Thermal conductivities of some materials at room temperature

There are ranges of thermal conductivities for materials. So these are at room temperature, and on the y axis, we have the value of k and you see the range of values. And at the bottom, material like gases, which are good insulator and solids which are good insulators like fibrous material which have a lot of air packets and voids in them. Foams polyurethane foam is a very good insulator that is often used in the filling of walls, so that heat does not go through. Then come the metals, then in other solids, we have lower thermal conductivity in non-metallic solids. And in metals, where if your crystals, we have higher thermal conductivity. These are good conductors; whereas, these are good insulators.

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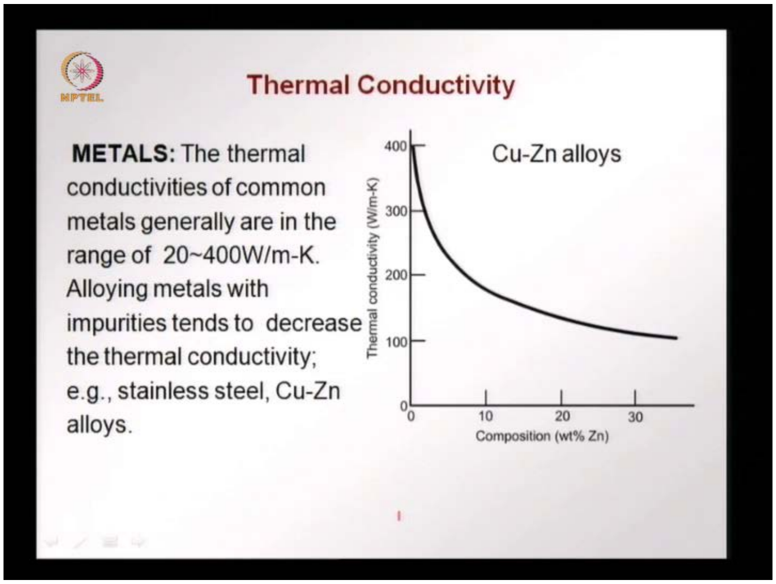

Thermal Conductivity

METALS: The thermal conductivities of common metals generally are in the range of 20~400W/m-K. Alloying metals with impurities tends to decrease the thermal conductivity; e.g., stainless steel, Cu-Zn alloys.

What are the ranges of thermal conductivities? In metals, we have range of 20 to 400 watt per meter Kelvin. We also see that as the composition of the material changes, the thermal conductivity changes on the right hand side we have this graph showing a copper-zinc alloys composition varying as shown in the x-axis, and the thermal conductivity varying with the composition like this. So we find that as more zinc is introduced into the copper the thermal conductivity drops that is the lattice as less possibility of transferring the heat as more impurities in the form of zinc are put in. Generally, we find that alloying materials, alloying metals with impurities tends to decrease the thermal conductivity as we see in this case the copper-zinc alloy, and also in stainless steel.

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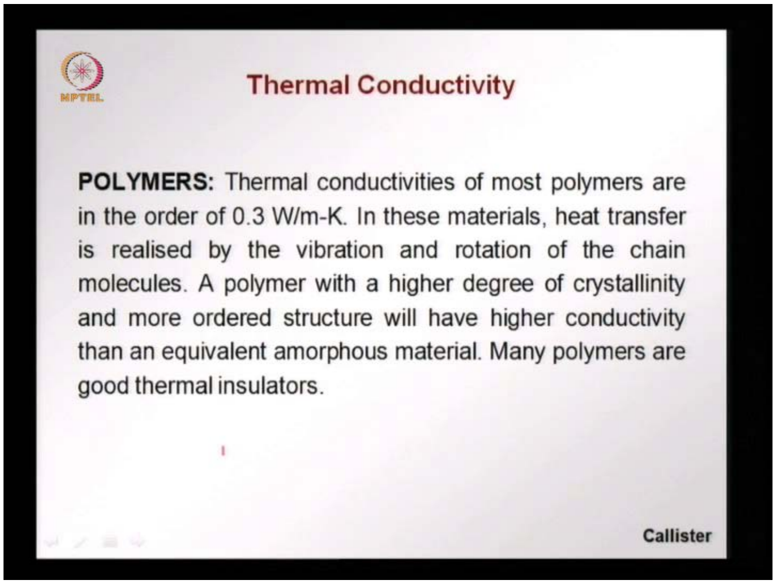

Thermal Conductivity

POLYMERS: Thermal conductivities of most polymers are in the order of 0.3 W/m-K. In these materials, heat transfer is realised by the vibration and rotation of the chain molecules. A polymer with a higher degree of crystallinity and more ordered structure will have higher conductivity than an equivalent amorphous material. Many polymers are good thermal insulators.

Callister

In polymers, the thermal conductivities are in the order of point three watt per meter Kelvin. And here, the heat transfer is realized by again the vibration of the molecules and the rotation of the chain molecules. You remember in polymer, we said that the polymer chain have a high degree of rotation movement without the chain is being broken and this ability to rotate and vibrate facilitate the heat transfer. A polymer with higher degree of crystallinity that is more ordered structure, more arranged structure will have higher conductivity than an equivalent amorphous material, which has a lot of space between the chains. In the case of higher degree of crystallinity, we have a better packing, and therefore the conductivity is better. Many polymers are also good thermal insulators, again because of the amorphous nature and the lack of packing.

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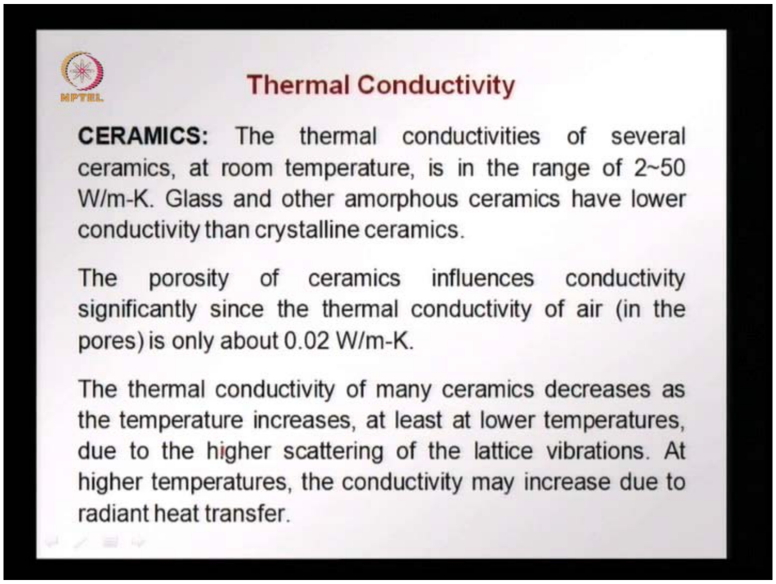

Thermal Conductivity

CERAMICS: The thermal conductivities of several ceramics, at room temperature, is in the range of 2~50 W/m-K. Glass and other amorphous ceramics have lower conductivity than crystalline ceramics.

The porosity of ceramics influences conductivity significantly since the thermal conductivity of air (in the pores) is only about 0.02 W/m-K.

The thermal conductivity of many ceramics decreases as the temperature increases, at least at lower temperatures, due to the higher scattering of the lattice vibrations. At higher temperatures, the conductivity may increase due to radiant heat transfer.

In ceramics, we find that thermal conductivity has a wide range say in the range of 2 to 50 watt per meter Kelvin. Glasses and some amorphous ceramics have lower conductivity than crystalline ceramics, again as the packing increases conductivity becomes better. The porosity also influences the conductivity significantly since the thermal conductivity of gases is very low like the thermal conductivity of air is only about 0.02 watt per meter Kelvin.

And the pores of these ceramics, we have air which is not facilitating the conductivity. Thermal conductivity of ceramics also decreases can decrease as the temperature increases, at least at lower temperatures, due to the scattering of the lattice vibrations. At higher temperatures, conductivity may increase due to radiant heat transfer. Instead of conductivity, the conductivity through lattice vibration heat could be transferred by radiation.

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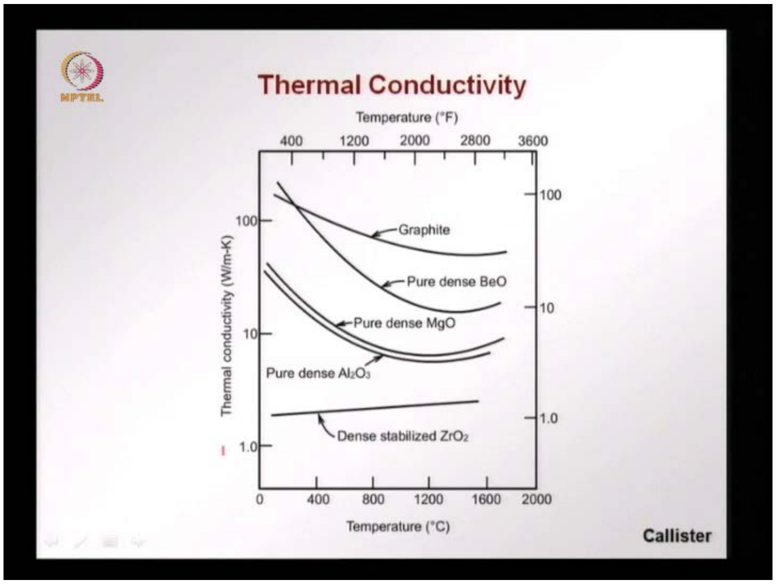

Thermal Conductivity

Callister

So here you see how thermal conductivity changes in some materials as the function of the temperature. You can see in the case of a dense stabilized zirconia, you have an increase in the thermal conductivity as the temperature increases. In other cases, you have a drop and then the effect of radiation coming in and there is an increase in the thermal conductivity.

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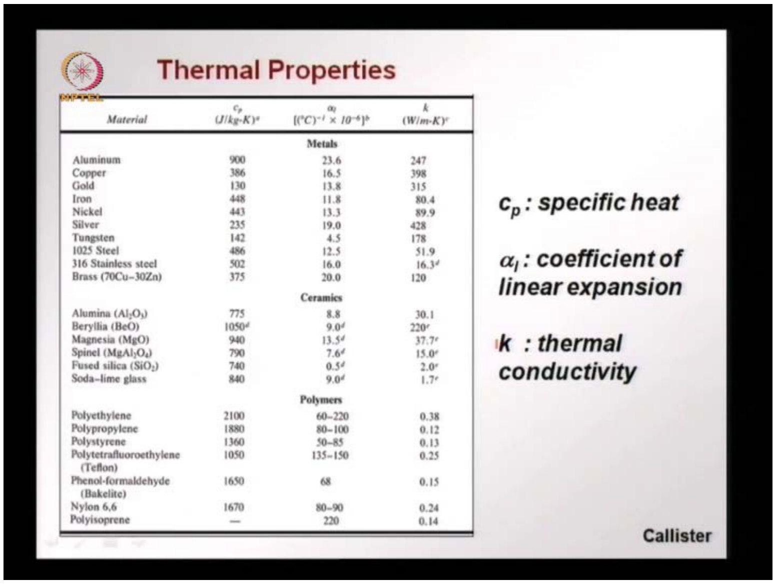

Thermal Properties

Material	c_p (J/kg-K)[a]	α_l [(°C)$^{-1}$ × 10^{-6}][b]	k (W/m-K)[c]
		Metals	
Aluminum	900	23.6	247
Copper	386	16.5	398
Gold	130	13.8	315
Iron	448	11.8	80.4
Nickel	443	13.3	89.9
Silver	235	19.0	428
Tungsten	142	4.5	178
1025 Steel	486	12.5	51.9
316 Stainless steel	502	16.0	16.3[d]
Brass (70Cu–30Zn)	375	20.0	120
		Ceramics	
Alumina (Al_2O_3)	775	8.8	30.1
Beryllia (BeO)	1050[d]	9.0[d]	220[e]
Magnesia (MgO)	940	13.5[d]	37.7[e]
Spinel ($MgAl_2O_4$)	790	7.6[d]	15.0[e]
Fused silica (SiO_2)	740	0.5[d]	2.0[e]
Soda–lime glass	840	9.0[d]	1.7[e]
		Polymers	
Polyethylene	2100	60–220	0.38
Polypropylene	1880	80–100	0.12
Polystyrene	1360	50–85	0.13
Polytetrafluoroethylene (Teflon)	1050	135–150	0.25
Phenol-formaldehyde (Bakelite)	1650	68	0.15
Nylon 6,6	1670	80–90	0.24
Polyisoprene	—	220	0.14

c_p : specific heat

α_l : coefficient of linear expansion

k : thermal conductivity

Callister

This is the table from Callister showing you the three properties that we have discussed - specific heat, coefficient of linear expansion and thermal conductivity. In the first column, we have the different values of specific heat. The second column, we have the coefficient of thermal expansion; and in the third column, we have thermal conductivity. This is the group of metals then we have ceramics like glass, alumina and so on and then we have polymers. We find that the specific heat of metals ranges from about hundred to about thousand joules per kilogram Kelvin. Ceramics are slightly in the higher end of the same range going from about 700 to about 1050 joules per kilogram Kelvin. Polymers much higher almost double the values that we seen in the ceramics and aluminum are more, so more heat is absorbed for a unit change in temperature.

Coefficient of thermal expansion, again we see a wide range with metals been having values in the range of 5 to about 25 times ten to the power of minus 6 per degree Celsius. Ceramics ranging from 0.5 to about 15, and polymers having much higher value more expansion in most of the polymers. Thermal conductivity this give obviously that metals are much better thermal conductors; whereas, we see polymers are poor conductors and probably good insulators. Ceramics have a variation; you have glass with very low thermal conductivity whereas something like Beryllia which has a very high thermal conductivity. So these are the different properties and I explained to you how we use them of what, how they effect as in civil engineering applications.

So to conclude, we have looked at the thermal properties that are important to us in civil engineering application of different materials. And this conclude this module on properties, we have looked at mechanical properties, we have looked at rheological properties, and now we looked at thermal properties. We went to properties after looking at the microstructure, how the material develops and we looked at range of structures that form in materials on the basis of the bonds that form in the molecular scale and then that lead on for us to understand why materials behave in a certain way when stresses applied and when temperature is applied. Now after this, we will go on to look at individual materials and we will try to review these properties as we go through these materials and we look at where the different materials are used and in what application.

Thank you.