



Materials Engineering Concepts

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Human Equivalence of Material

- What are the characteristics of a human?
 - For a particular task, one may be more efficient than others.
- How would a human respond to external stimuli (e.g., environment, emotion, etc.)?
- How can we model the human behavior under a particular condition?



Application of Materials

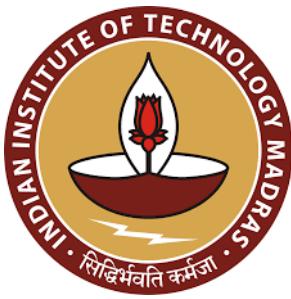
- Selection
- Specifications
- Quality control



Criteria for Selecting a Material

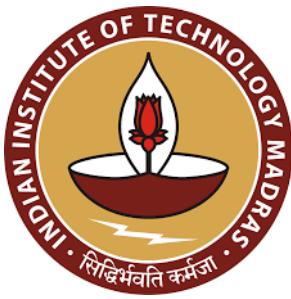
- Economic factors
- Mechanical properties
- Non-mechanical properties
- Construction/production aspects
- Aesthetic properties
- Sustainability





Economic Factors

- Availability and cost of raw materials
- Manufacturing costs
- Transportation
- Placing
- Maintenance



Mechanical Properties

- Loading
- Stress-strain relations
- Elastic behavior
- Elastoplastic behavior
- Viscoelastic behavior
- Temperature and time effects
- Work and energy

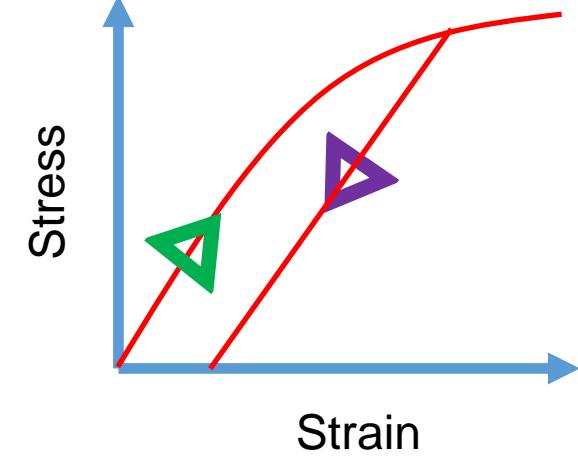
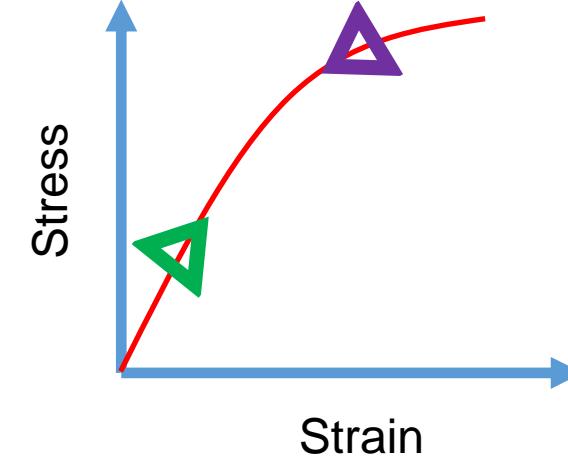
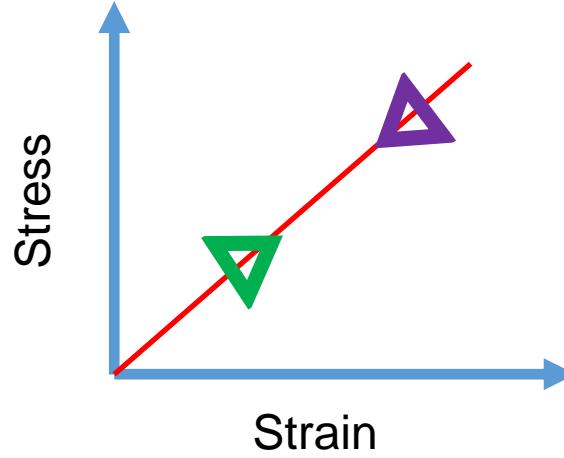


Nonmechanical Properties

- Density
- Thermal expansion
- Surface characteristics
 - Corrosion and degradation
 - Abrasion and wear resistance

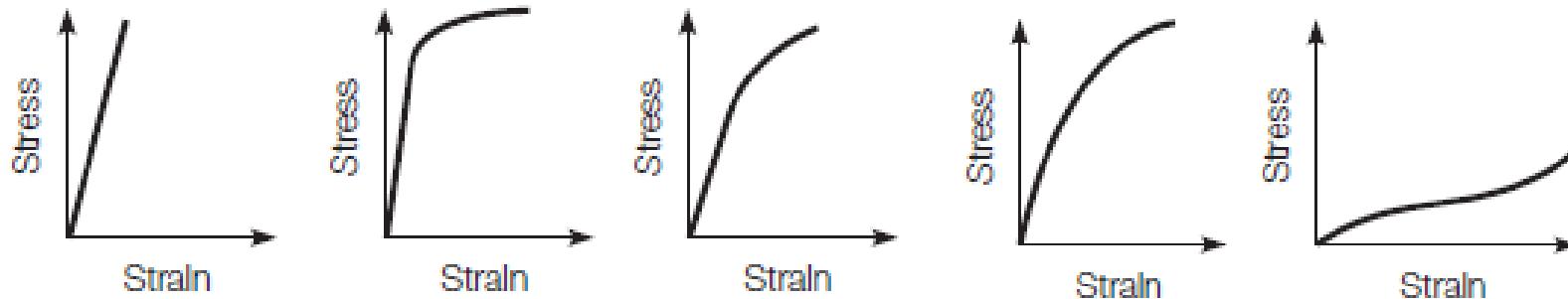


Stress-Strain Relations





Elastic Behavior



Young's Modulus or Modulus of Elasticity

Poisson's Ratio

Generalized Hooke's Law



Elastic Behavior

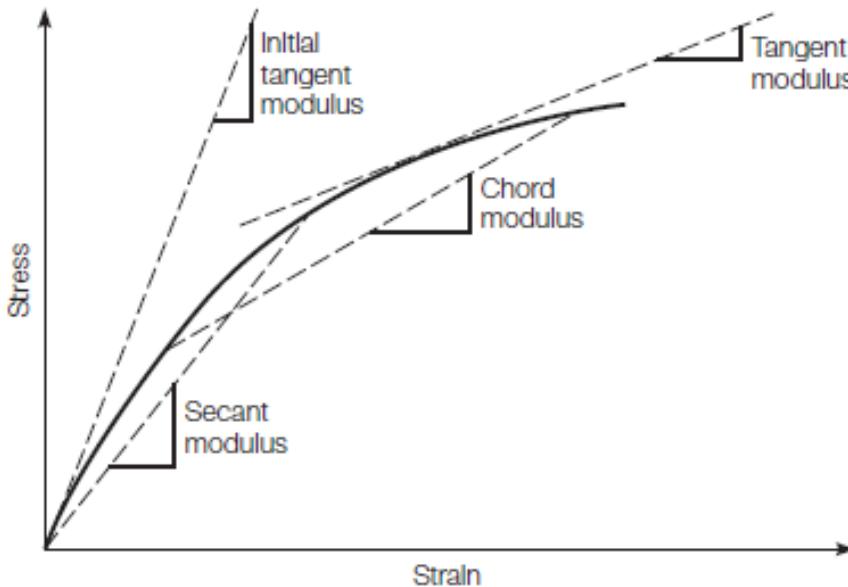
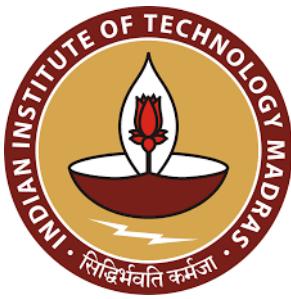
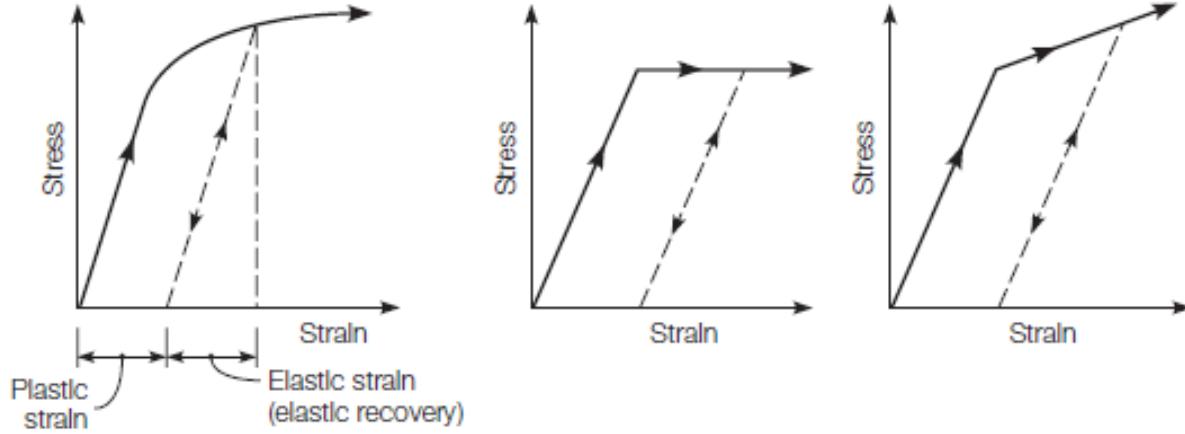


TABLE 1.1 Typical Modulus and Poisson's Ratio Values (Room Temperature)

Material	Modulus GPa	Poisson's Ratio
Aluminum	69–75	0.33
Brick	10–17	0.23–0.40
Cast iron	75–169	0.17
Concrete	14–40	0.11–0.21
Copper	110	0.35
Epoxy	3–140	0.35–0.43
Glass	62–70	0.25
Limestone	58	0.2–0.3
Rubber (soft)	0.001–0.014	0.49
Steel	200	0.27
Tungsten	407	0.28
Wood	6–15	0.29–0.45



Elastoplastic Behavior

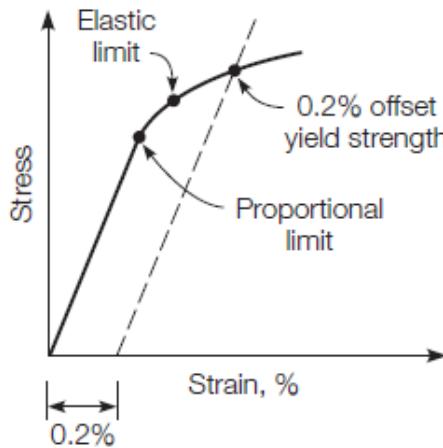


An elastoplastic material with strain hardening has the stress–strain relationship shown in the rightmost figure. The modulus of elasticity is 175 GPa, yield strength is 480 MPa, and the slope of the strain-hardening portion of the stress–strain diagram is 20.7 GPa.

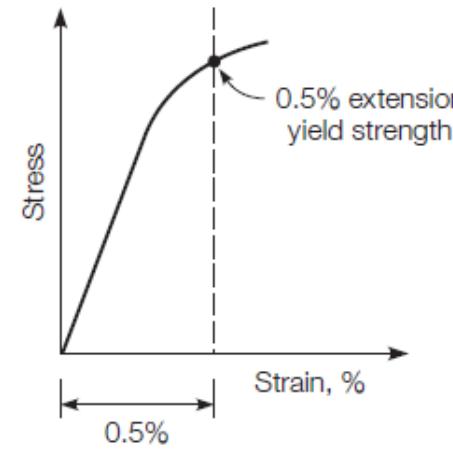
- Calculate the strain that corresponds to a stress of 550 MPa.
- If the 550 MPa stress is removed, calculate the permanent strain.



Defining Yield Stress



Offset Method



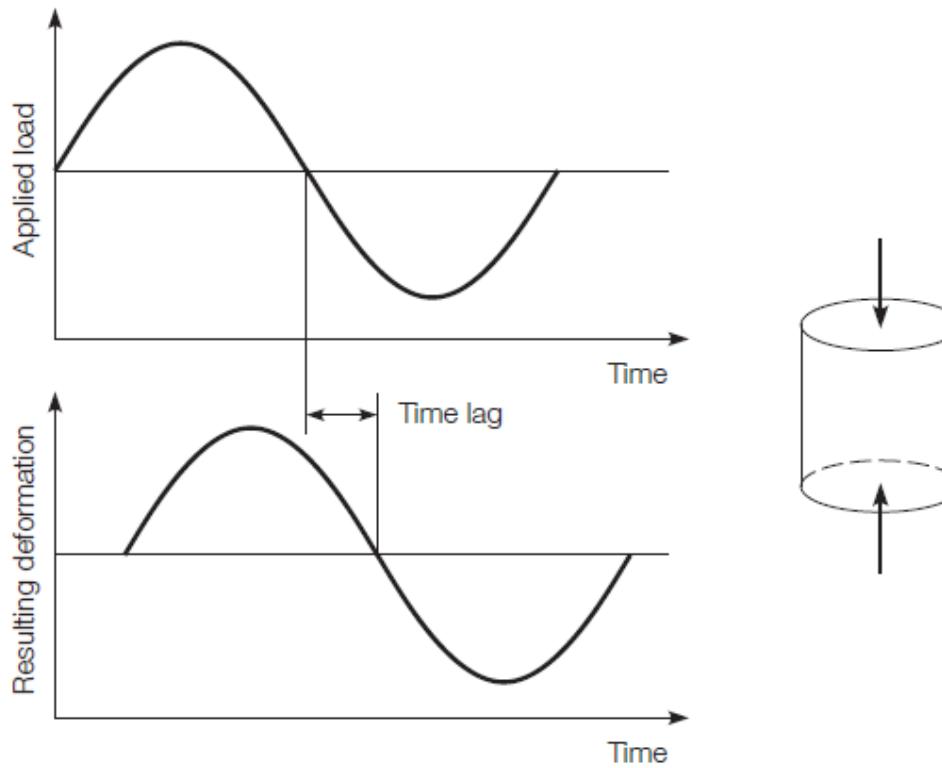
Extension Method

A rod made of aluminum alloy, with a gauge length of 100 mm, diameter of 10 mm, and yield strength of 150 MPa, was subjected to a tensile load of 5.85 kN. If the gauge length was changed to 100.1 mm and the diameter was changed to 9.9967 mm, calculate the modulus of elasticity and Poisson's ratio.

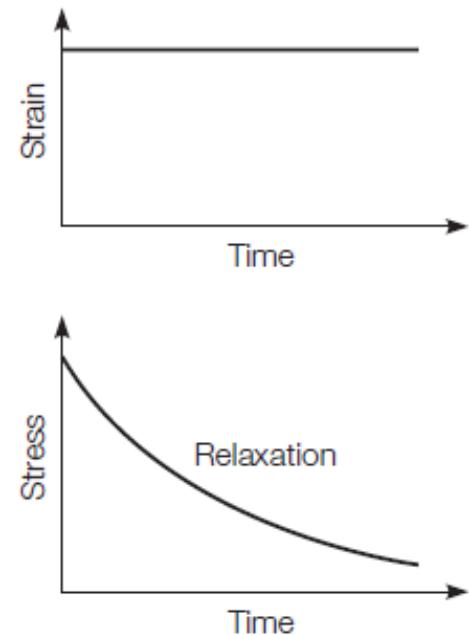
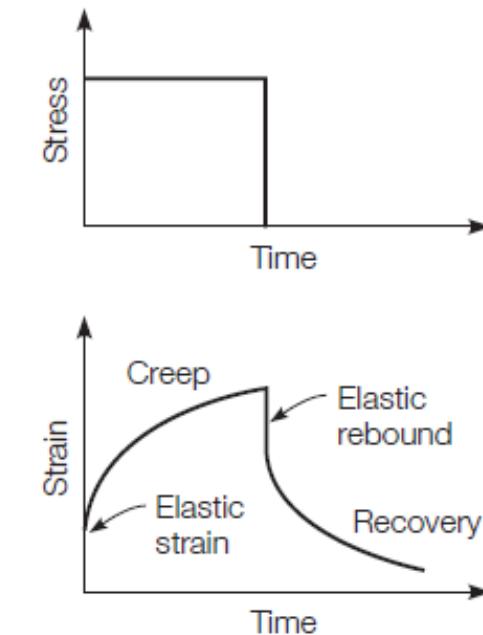


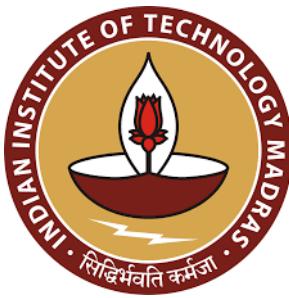
Viscoelastic Behavior

Load-deformation response of a viscoelastic material



Behavior of time-dependent materials

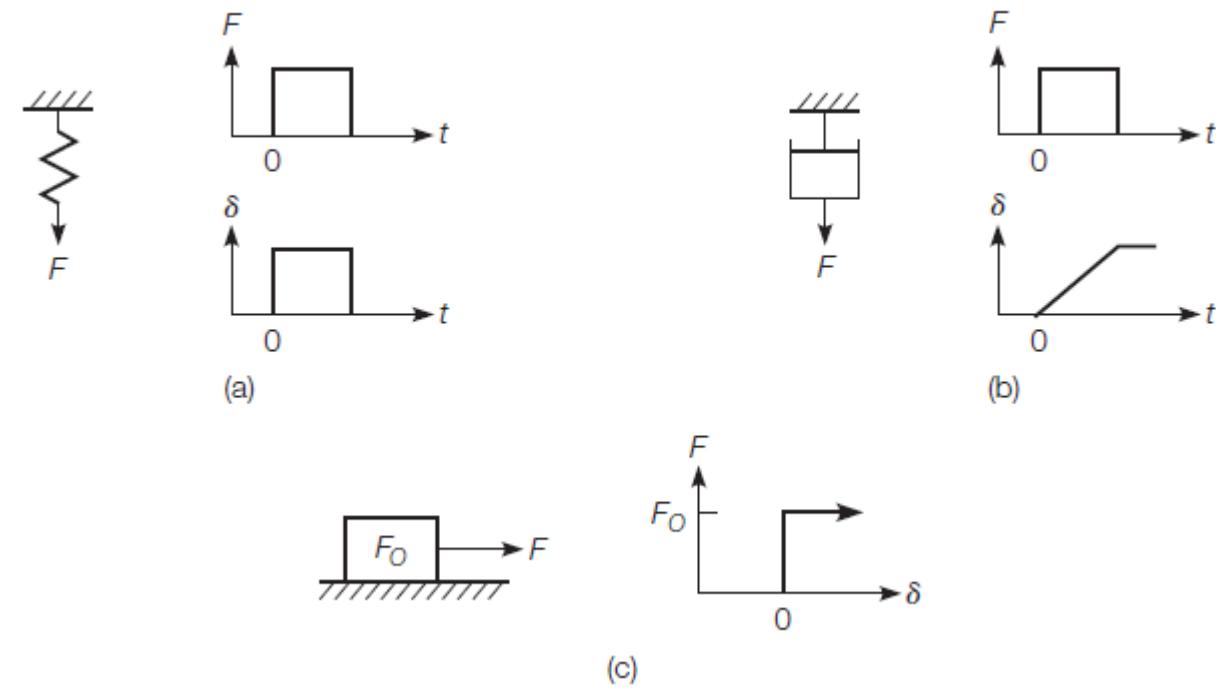




Rheological Models

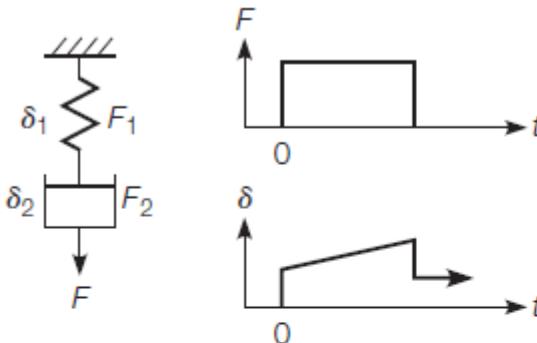
- Used to model time-dependent behavior

- Hookean element
- Newtonian element
- St. Venant element

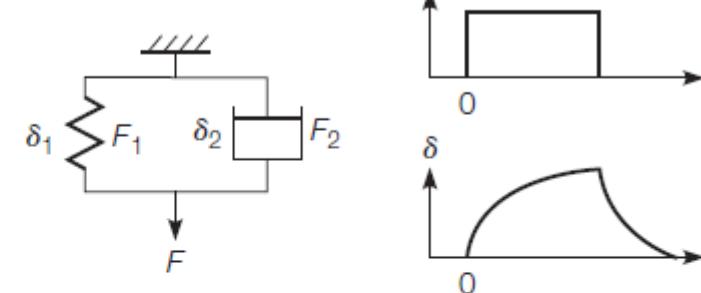




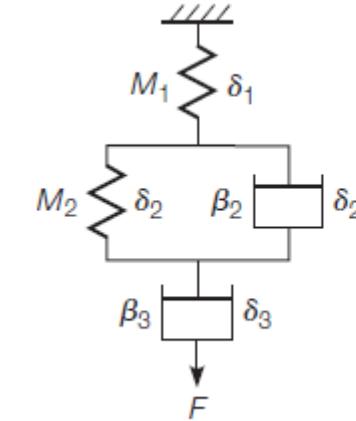
Rheological Models Cont'd...



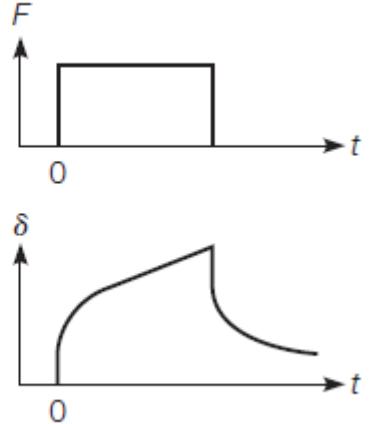
Maxwell Model



Kelvin Model



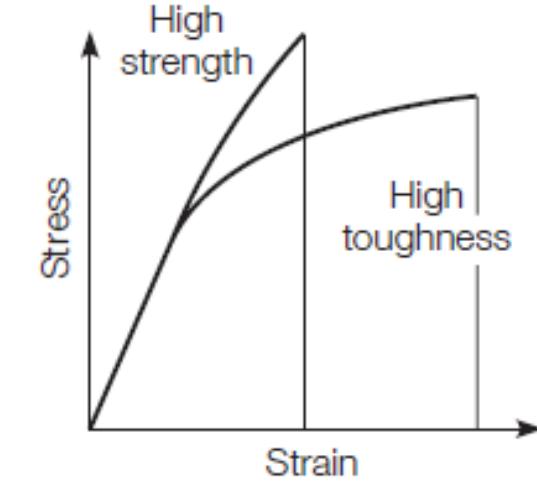
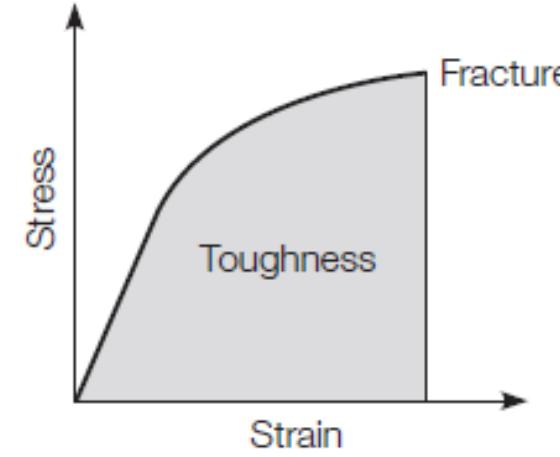
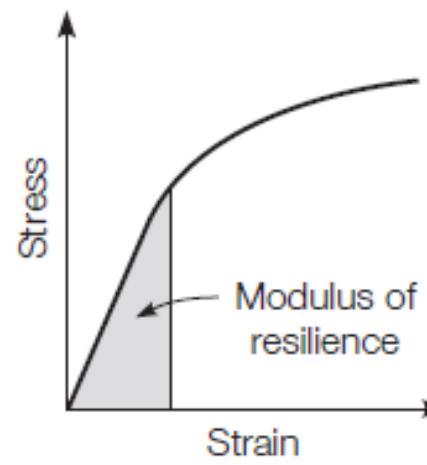
Kelvin Model with dashpot and spring in series



Example: Asphalt concrete



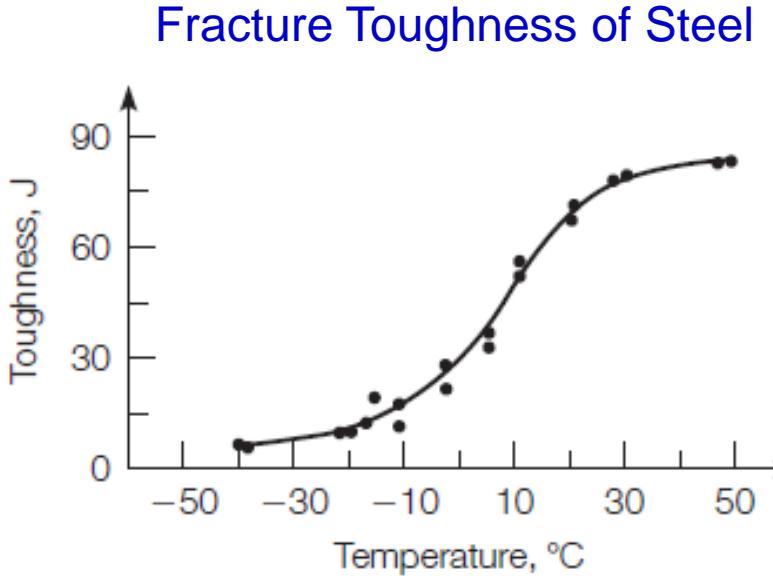
Work and Energy



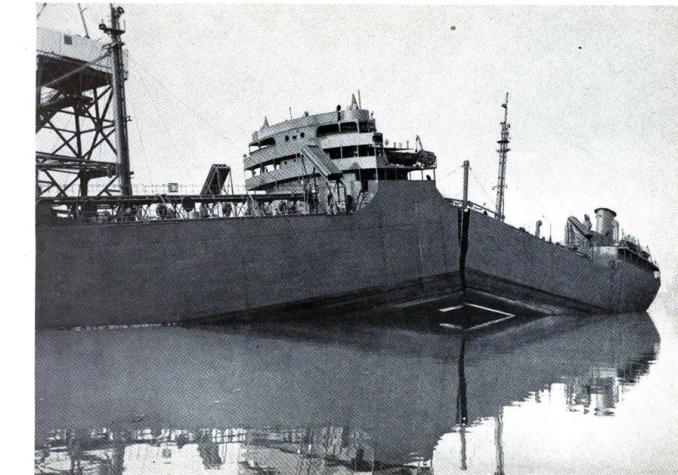
A high-strength material is not necessarily a tough material!



Temperature and Time Effects

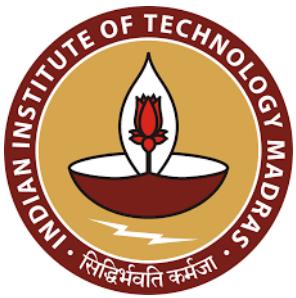


- Mechanical behavior of all materials is affected by temperature. Some are more susceptible to temperature changes.
- Effect of loading duration and loading rate



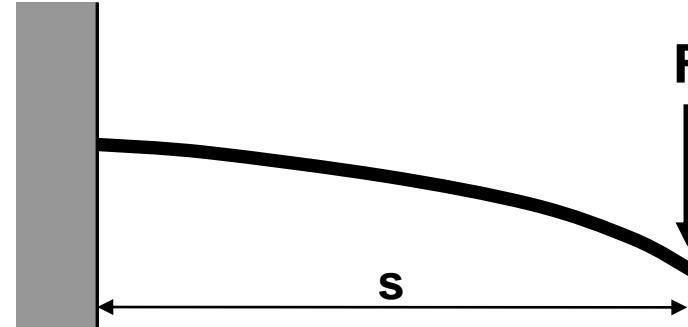
During World War II, many Liberty ships sank because the steel used in the ships met specifications at ambient temperature, but became brittle in the cold waters of the North Atlantic.

https://www.tf.uni-kiel.de/matwis/amat/iss/kap_9/backbone/r9_1_2.html#_7



Example: Material for Beam

Simple example: Cantilever beam



Consider an application with a given load, span and beam width.

Free end deflection is given by:

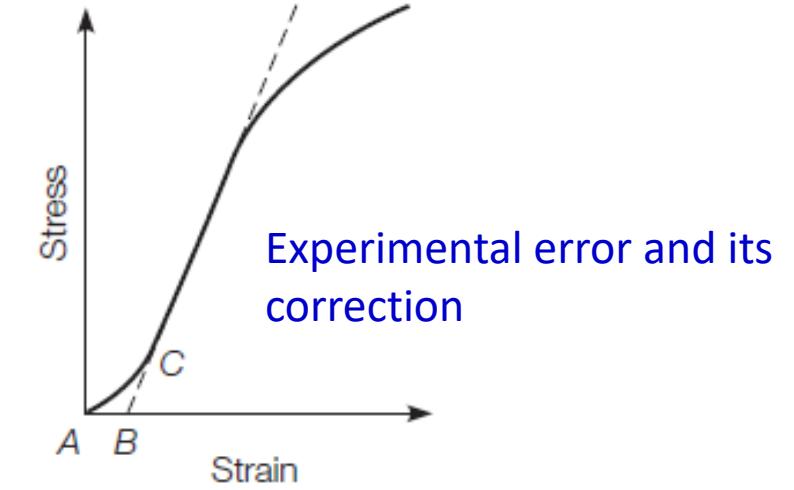
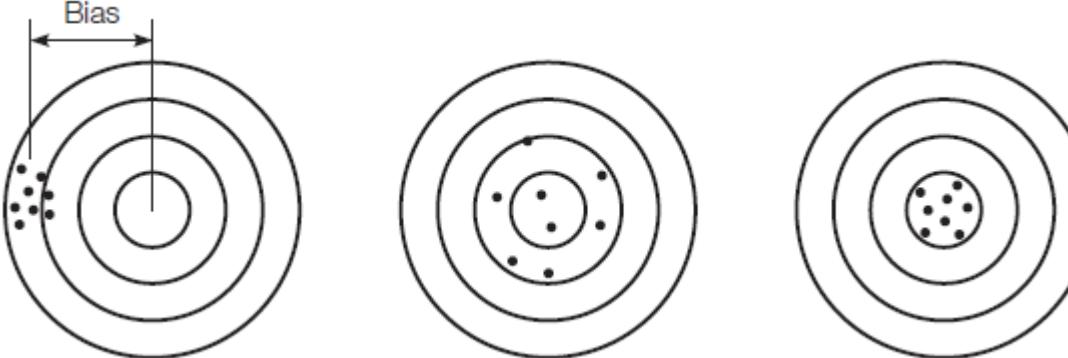
where E is the modulus of elasticity, and I is the moment of inertia.



Example Cont'd...



Material Variability



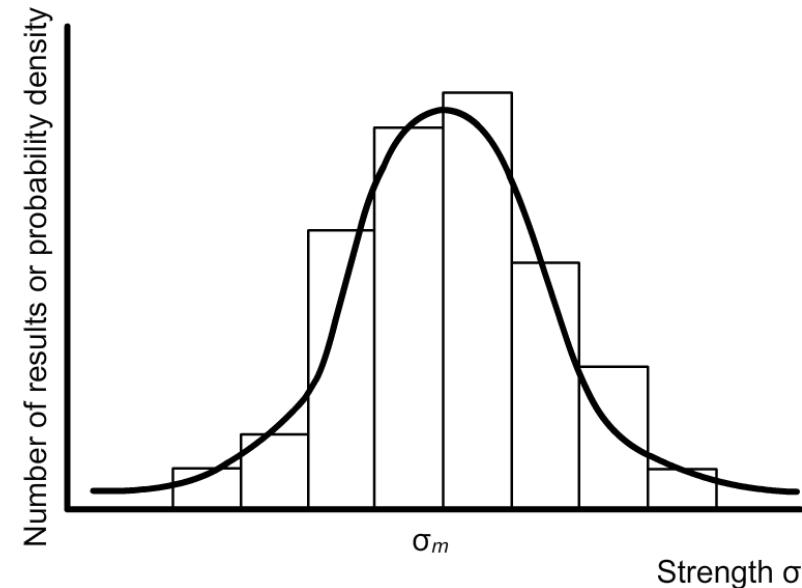
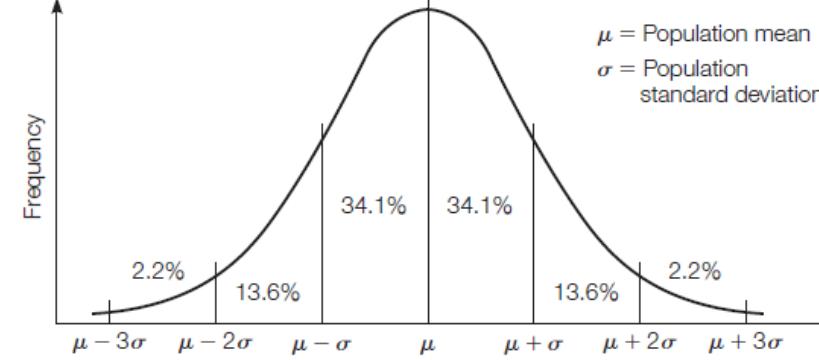
Precision refers to the variability of repeat measurements under carefully controlled conditions.

Accuracy is the conformity of results to the true value or the absence of bias.

Bias is a tendency of an estimate to deviate in one direction from the true value.



Variability of Material Parameters



Typical bell-shaped (normal or Gaussian) distribution of strength within a series of samples of the same material:

$$y = \frac{1}{s\sqrt{2\pi}} \exp \left[-\frac{(\sigma - \sigma_m)^2}{2s^2} \right]$$

where y is the probability density, σ is the strength, σ_m is the mean, s is the standard deviation, and c_v is the coefficient of variation.

For n results:

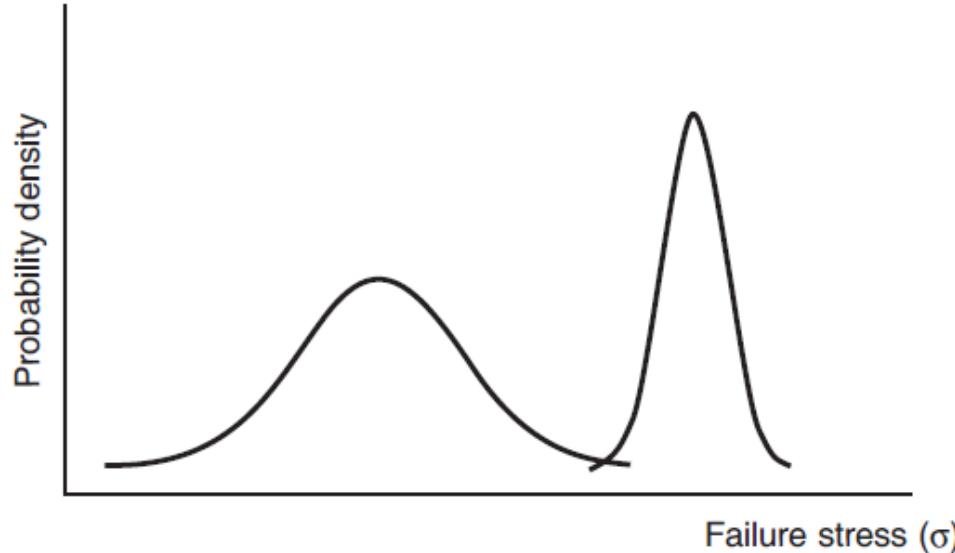
$$\sigma_m = \sum \sigma / n$$

$$s^2 = \sum [(\sigma - \sigma_m)^2 / (n-1)]$$

$$c_v = s / \sigma_m$$



Variability of Material Parameters



What is the key difference between two curves?



Laboratory Measuring Devices

- Dial gauge
- Linear variable differential transformer (LVDT)
- Strain gauge
- Load cell



References

- Michael S. Mamlouk and John P. Zaniewski, "Materials for Civil and Construction Engineers," Addison Wesley Longman Inc., USA, 1999.



Nature of Materials

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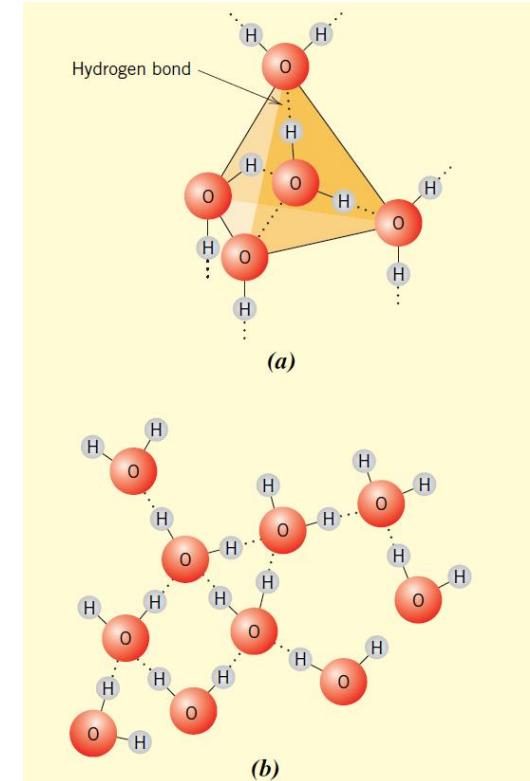
Different Types of Bonding

Why geckos are so comfortable in navigating through vertical planes?



Source: Callister and Rethwisch

Ice vs. Water



Graphite



Diamond

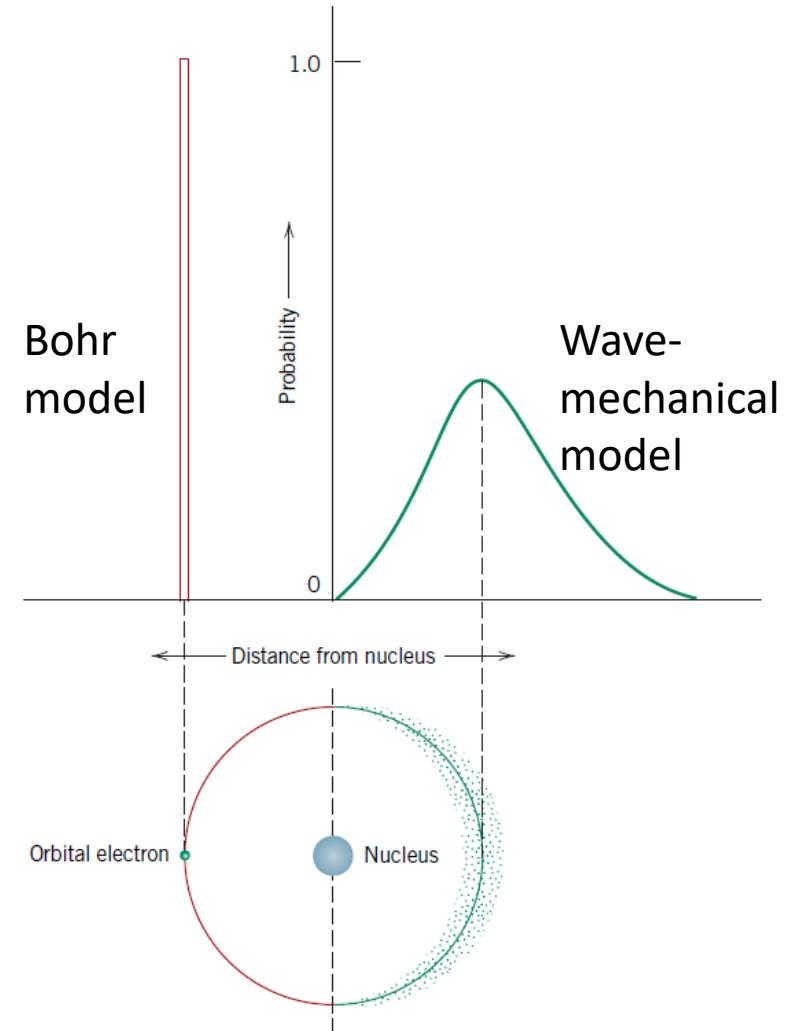


Source: Wikipedia



Atomic Structure

- Each atom consists of a very small nucleus composed of protons and neutrons and is encircled by electrons.
- Bohr's model was updated with a wave-mechanical model (right figure).

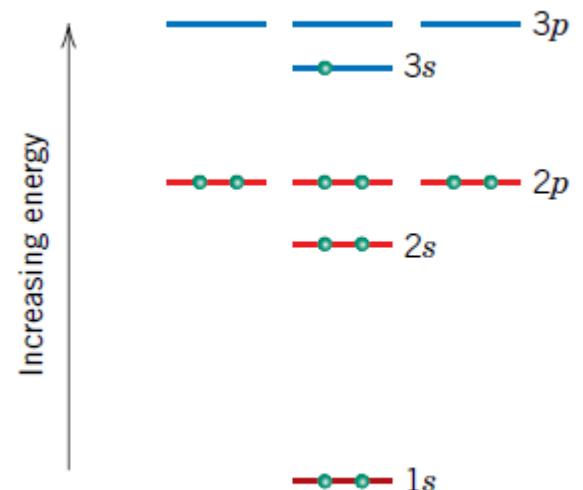


Callister and Rethwisch



Electron Configuration

- For example, the electron configurations for hydrogen, helium, and sodium are, respectively,
 $1s^1$, $1s^2$, and $1s^2 2s^2 2p^6 3s^1$.
- The energy structure for a sodium atom is represented schematically in Figure (right).
- The **valence electrons** are those that occupy the outermost shell. These electrons are extremely important in the bonding.



Callister and Rethwisch



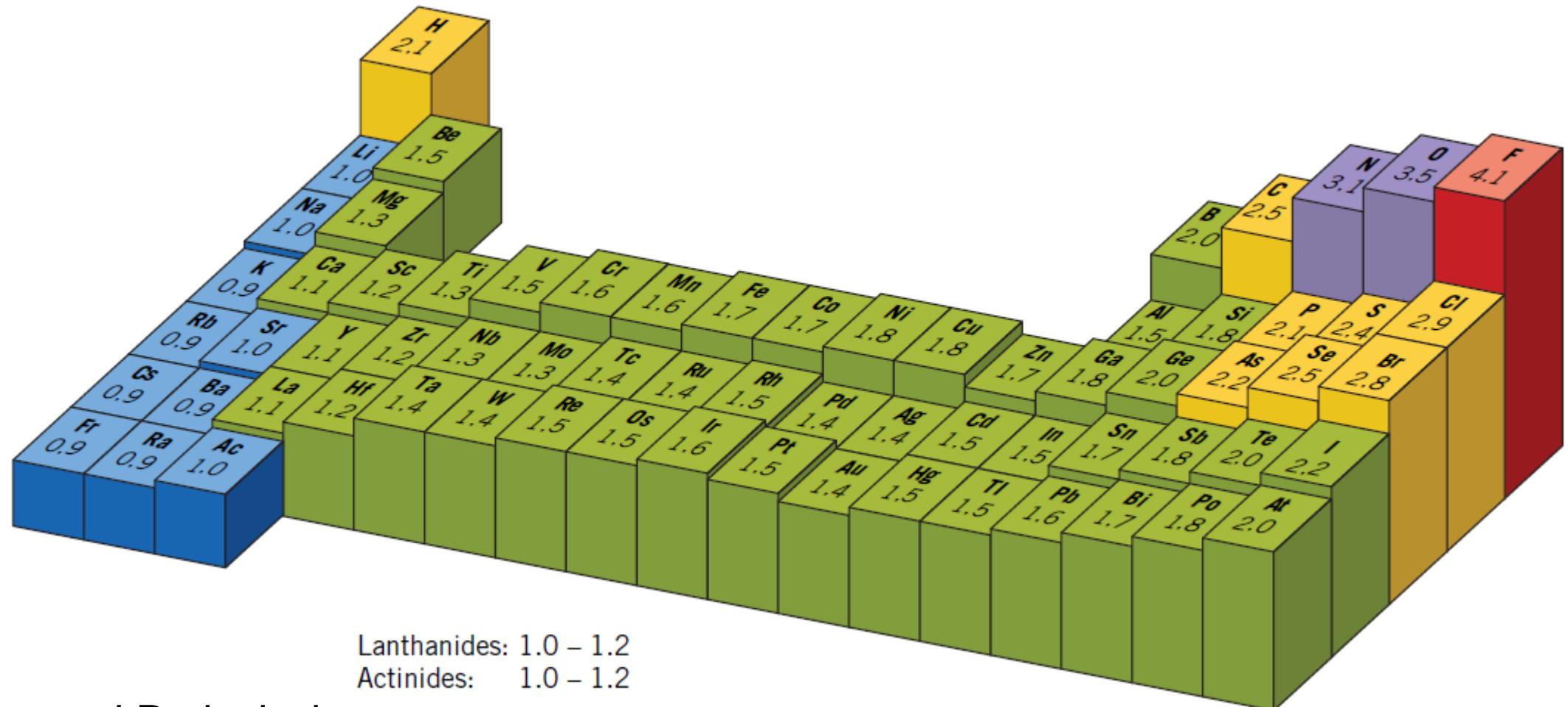
Periodic Table

Key																		
IA		IIA		IIIB		IVB		VB		VIB		VIIB		VIII		IB		
1 H 1.0080		3 Li 6.941	4 Be 9.0122															
11 Na 22.990	12 Mg 24.305																	
19 K 39.098	20 Ca 40.08	21 Sc 44.956	22 Ti 47.87	23 V 50.942	24 Cr 51.996	25 Mn 54.938	26 Fe 55.845	27 Co 58.933	28 Ni 58.69	29 Cu 63.55	30 Zn 65.41	31 Ga 69.72	32 Ge 72.64	33 As 74.922	34 Se 78.96	35 Br 79.904	36 Kr 83.80	
37 Rb 85.47	38 Sr 87.62	39 Y 88.91	40 Zr 91.22	41 Nb 92.91	42 Mo 95.94	43 Tc (98)	44 Ru 101.07	45 Rh 102.91	46 Pd 106.4	47 Ag 107.87	48 Cd 112.41	49 In 114.82	50 Sn 118.71	51 Sb 121.76	52 Te 127.60	53 I 126.90	54 Xe 131.30	
55 Cs 132.91	56 Ba 137.33	Rare earth series series	72 Hf 178.49	73 Ta 180.95	74 W 183.84	75 Re 186.2	76 Os 190.23	77 Ir 192.2	78 Pt 195.08	79 Au 196.97	80 Hg 200.59	81 Tl 204.38	82 Pb 207.19	83 Bi 208.98	84 Po (209)	85 At (210)	86 Rn (222)	
87 Fr (223)	88 Ra (226)	Actinide series series	104 Rf (261)	105 Db (262)	106 Sg (266)	107 Bh (264)	108 Hs (277)	109 Mt (268)	110 Ds (281)									
Rare earth series			57 La 138.91	58 Ce 140.12	59 Pr 140.91	60 Nd 144.24	61 Pm (145)	62 Sm 150.35	63 Eu 151.96	64 Gd 157.25	65 Tb 158.92	66 Dy 162.50	67 Ho 164.93	68 Er 167.26	69 Tm 168.93	70 Yb 173.04	71 Lu 174.97	
			89 Ac (227)	90 Th 232.04	91 Pa 231.04	92 U 238.03	93 Np (237)	94 Pu (244)	95 Am (243)	96 Cm (247)	97 Bk (247)	98 Cf (251)	99 Es (252)	100 Fm (257)	101 Md (258)	102 No (259)	103 Lr (262)	

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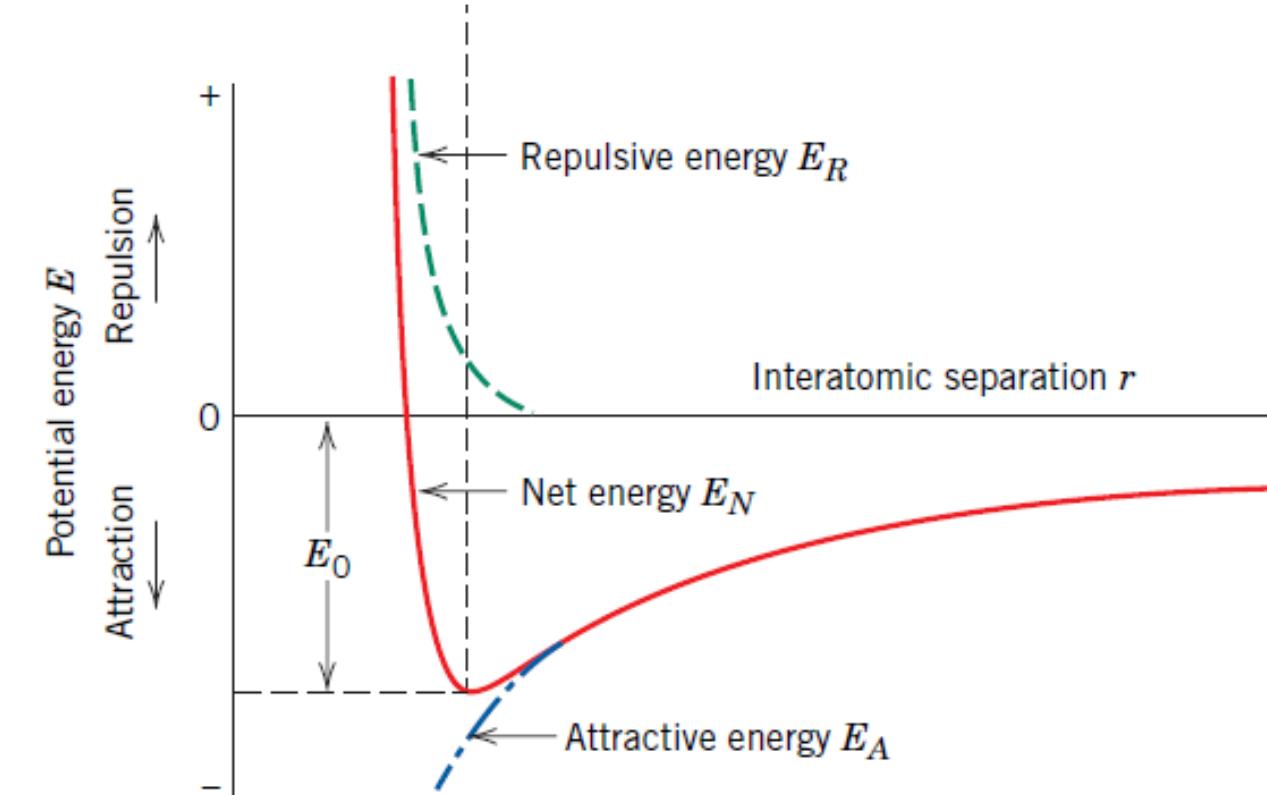
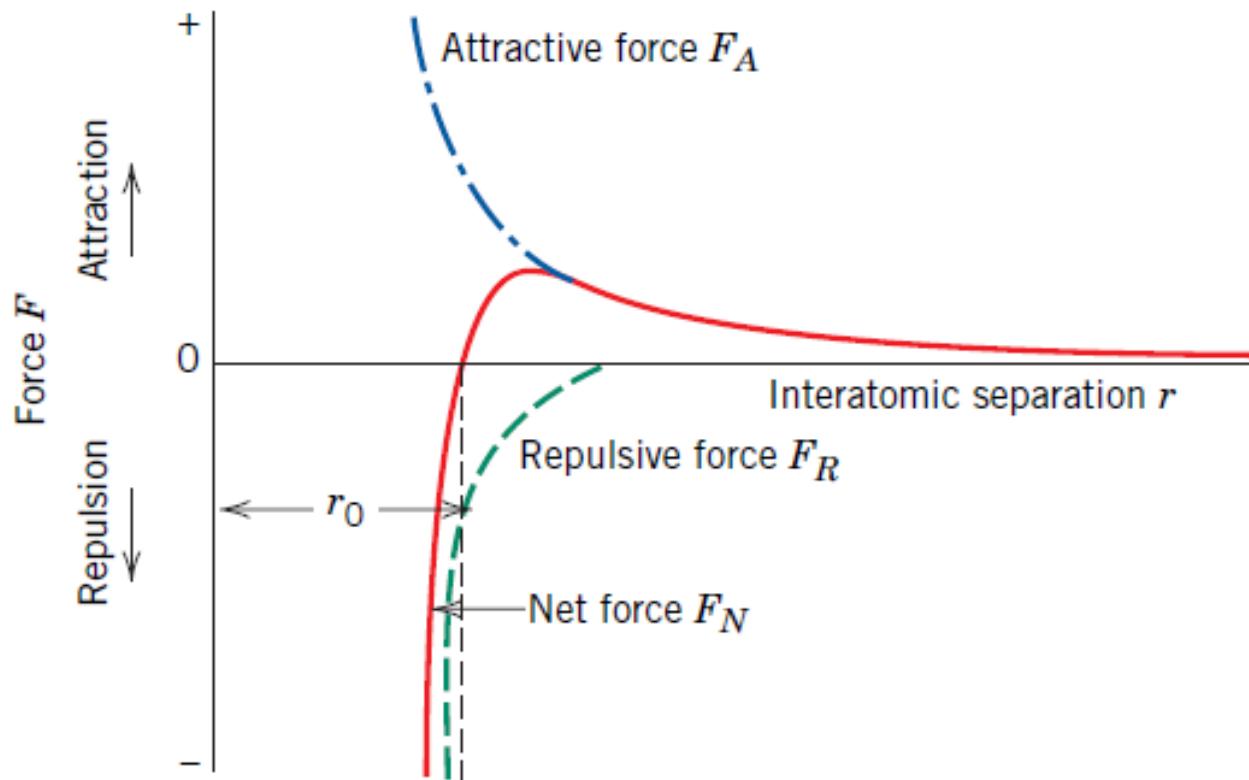
Electronegativity of Elements



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Bonding Forces and Energies

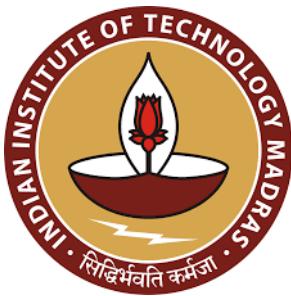


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Interatomic Bonding

- Primary Bonding Forces
 - Ionic
 - Covalent
 - Metallic
- Secondary Bonding Forces
 - Van der Waals
 - Hydrogen bonding

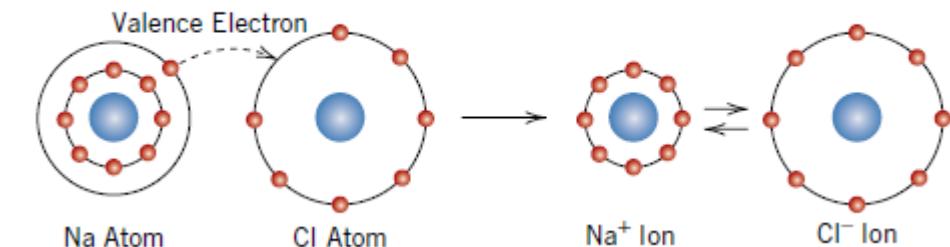


Ionic Bonding

- Atoms of a metallic element easily give up their valence electrons to the nonmetallic atoms.
- In the process, all the atoms acquire stable or inert gas configurations and, in addition, an electrical charge—that is, they become ions. Sodium chloride (NaCl) is the classic ionic material.
- The attractive bonding forces are coulombic. **Non-directional** in nature!

$$E_A = -\frac{A}{r} \quad (\text{attractive energy})$$

$$A = \frac{1}{4\pi\epsilon_0} (|Z_1|e)(|Z_2|e)$$

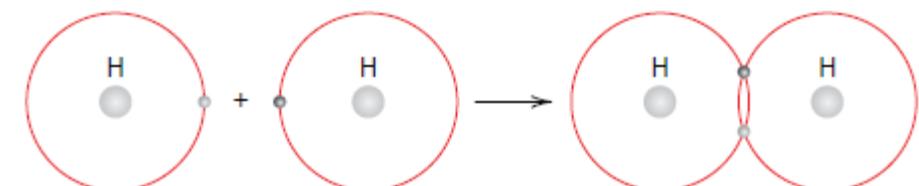


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Covalent Bonding

- Covalent bonding is found in materials whose atoms have smaller differences in electronegativity.
- For these materials, stable electron configurations are assumed by the sharing of electrons between adjacent atoms.
- Covalent bond is directional.
- Examples: Cl_2 , F_2 , CH_4 , etc.



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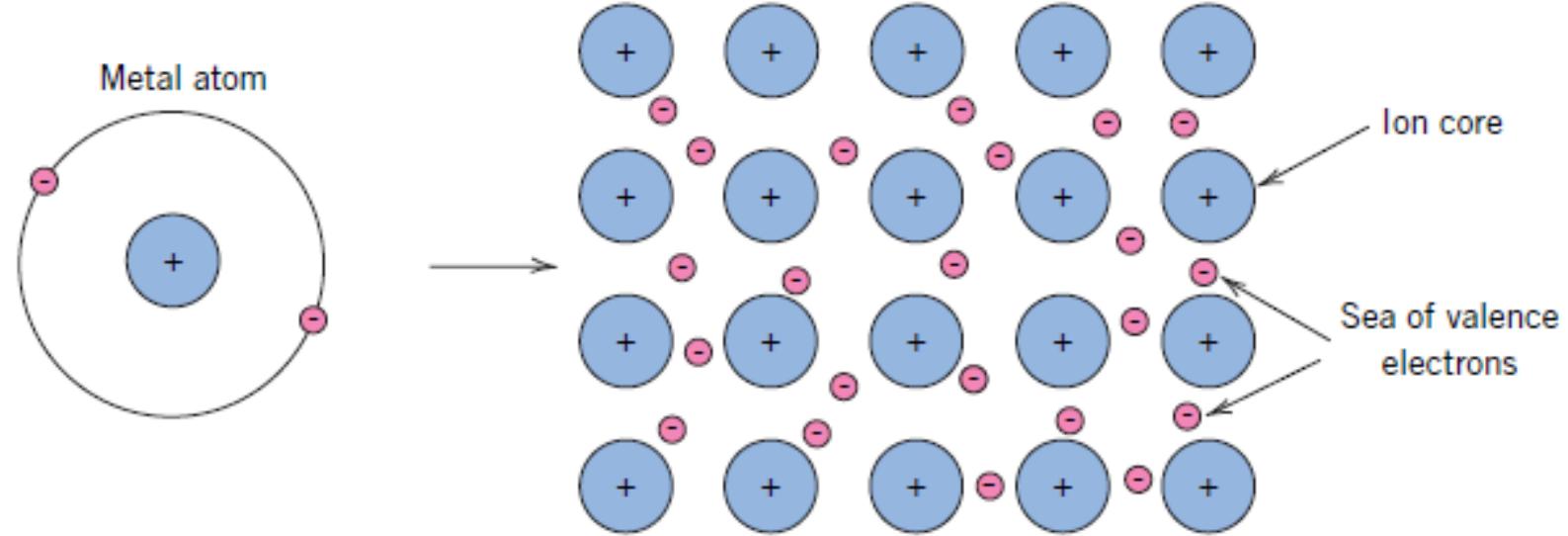
Metallic Bonding

- Metallic bonding is found in metals and their alloys.
- The valence electrons are not bound to any particular atom in the solid and are more or less free to drift throughout the entire metal.
- Valence electrons can be thought of “sea of electrons” and the remaining non valence electrons and atomic nuclei form “ion cores”

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Metallic Bonding



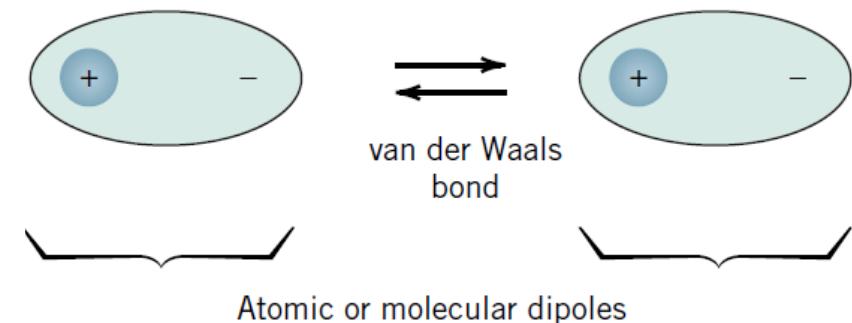
Metals are good conductors of both electricity and heat as consequence of their free electrons.

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Van der Waals Bonding

- Van der Waals (physical) bonds, are weak in comparison to the primary or chemical bonds; bonding energies range between about **4** and **30 kJ/mol**.
- Secondary bonding exists between virtually all atoms or molecules, but its presence may be obscured if any of the three primary bonding types is present.
- Secondary bonding forces arise from atomic or molecular dipoles.
- Van der Waals bonding is responsible for the **viscosity** and **surface tension** of liquids.

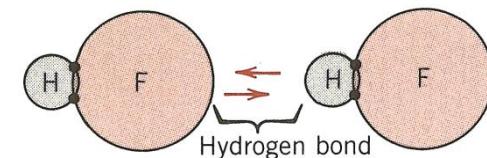
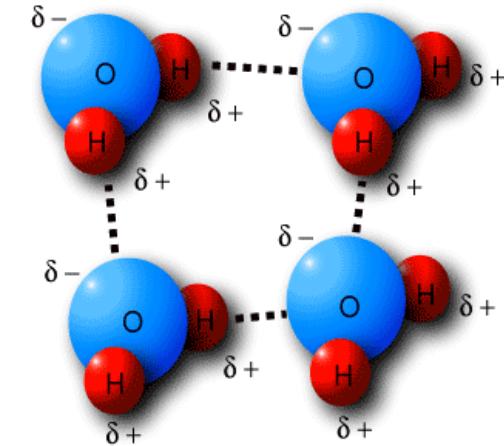


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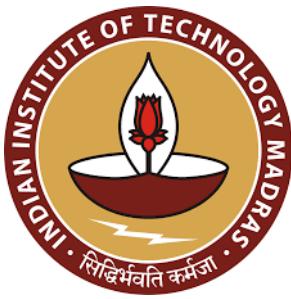


Hydrogen Bonding

- The strongest of dipole interactions occurs when the hydrogen atom is involved. This is called the hydrogen bond.
- This is responsible for the high melting point of ice and boiling point of water.
- Hydrogen bonding contributes to high mechanical performance and heat resistance of some modern polymers (e.g., nylon, Kevlar).



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Hydrogen Bonding: Examples

- Common properties
 - *Solubility of one substance in another*
 - *Surface tension*
 - *Vapor pressure*
 - *Volatility*
 - *Viscosity*
- Common applications
 - *Adhesives*,
 - *Surfactants*
 - *Emulsifiers*
 - *Desiccants*



Comparison of Bond Energies

Substance	Bonding Energy (kJ/mol)	Melting Temperature (°C)
Ionic		
NaCl	640	801
LiF	850	848
MgO	1000	2800
CaF ₂	1548	1418
Covalent		
Cl ₂	121	-102
Si	450	1410
InSb	523	942
C (diamond)	713	>3550
SiC	1230	2830
Metallic		
Hg	62	-39
Al	330	660
Ag	285	962
W	850	3414
van der Waals^a		
Ar	7.7	-189 (@ 69 kPa)
Kr	11.7	-158 (@ 73.2 kPa)
CH ₄	18	-182
Cl ₂	31	-101
Hydrogen^a		
HF	29	-83
NH ₃	35	-78
H ₂ O	51	0

^aValues for van der Waals and hydrogen bonds are energies *between* molecules or atoms (*intermolecular*), not between atoms within a molecule (*intramolecular*).

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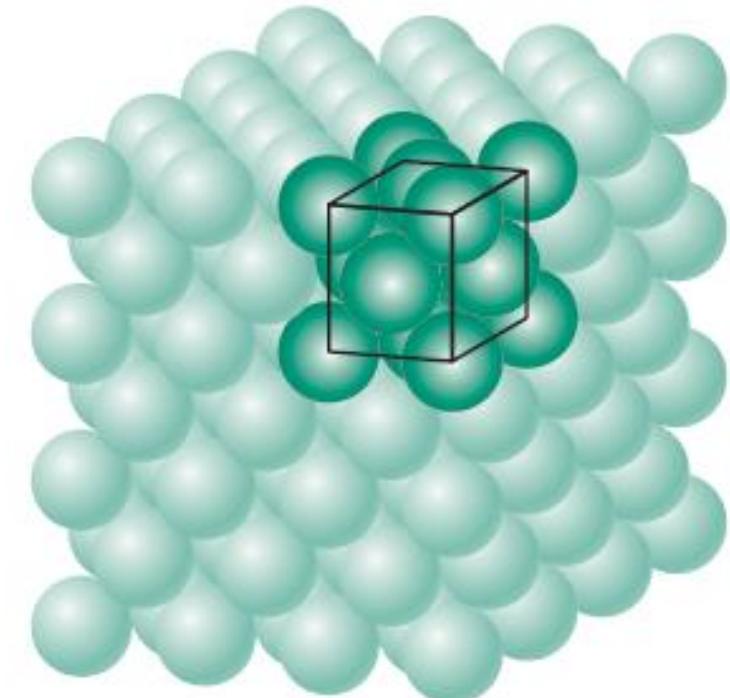
Bonding Type-Material Classification

- Polymers – covalent
- Metals – metallic
- Ceramics – ionic/mixed ionic – covalent
- Molecular solids – van der Waals
- Semi-metals – mixed covalent-metallic

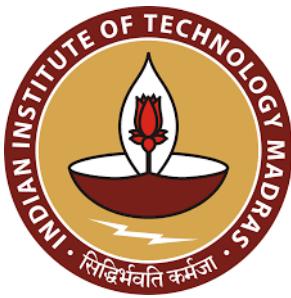


Crystalline Materials

- Crystalline material: A solid with atoms arranged in a repeating or periodic array over large atomic distances
- Long range order exists
- Repetitive 3-D pattern
- Each atom is bonded to its nearest-neighbor atoms
- Simple arrangement for metals, extremely complex for polymers and ceramics
- Properties depend on the spatial atomic arrangement



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Metallic Crystal Structures

- Face-Centered Cubic Crystal Structure

- Atoms located at each of the corners and the centers of all the cube faces
- Examples: Copper, Aluminum, Silver, Gold, etc.
- Derive the relationship $a = 2R\sqrt{2}$ where a is the cube edge length and R the atomic radius
- The number of atoms per unit cell, N , can be computed using

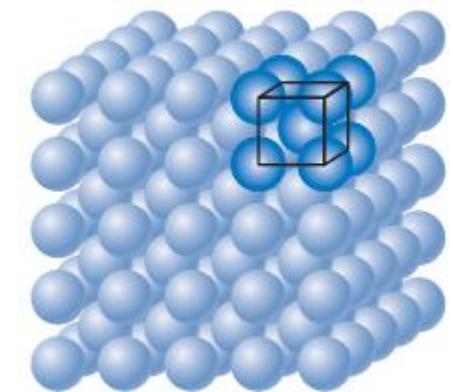
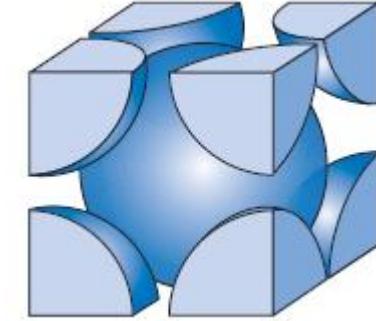
$$N = N_i + N_f/2 + N_c/8$$

Interior atoms Face atoms corner atoms

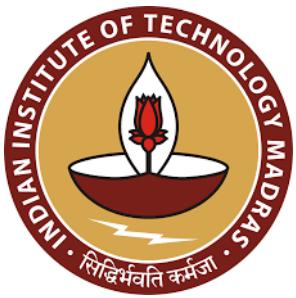


Body-Centered Cubic Structure

- **BCC structure:** Another common metallic crystal structure also has a cubic unit cell with atoms are located at all eight corners and a single atom at the cube center.
- **Examples:** Chromium, Molybdenum, Tungsten, etc.
- $a = 4R/\sqrt{3}$ (derive)
- The number of atoms per BCC unit cell, $N = 2$
- APF for BCC – 0.68 (lower than FCC)
- Coordination number – 8



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Density Computations

$$\rho = \frac{n A}{V_c N_A}$$

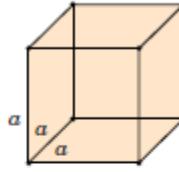
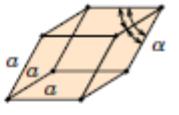
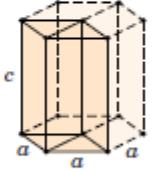
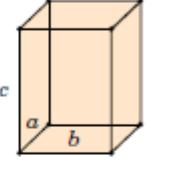
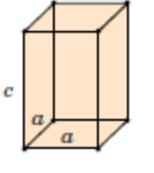
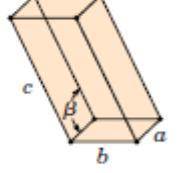
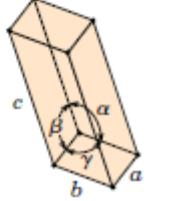
atoms/unit cell → n → Atomic weight (g/mol)

Volume/unit cell
($\text{cm}^3/\text{unit cell}$) → V_c → Avogadro's number
 $(6.023 \times 10^{23} \text{ atoms/mol})$

Exercise: Copper has an atomic radius of 0.128 nm, an FCC crystal structure, and atomic weight of 63.5 g/mol. Compute its theoretical density and compare it with measured density.



Crystal Systems

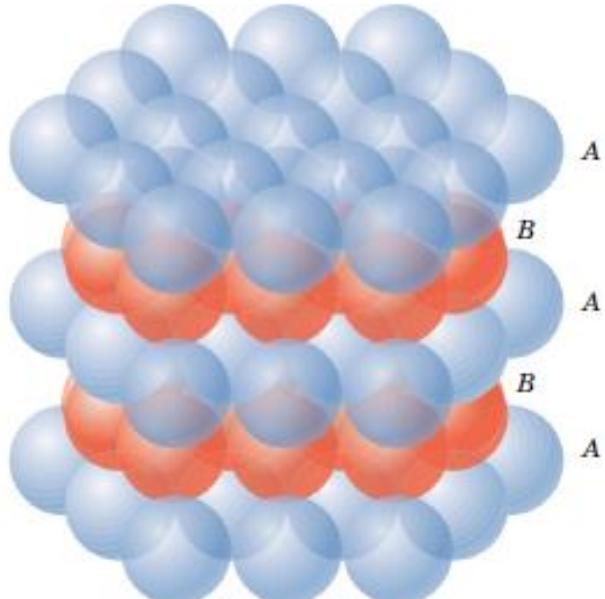
Crystal System	Axial Relationships	Interaxial Angles	Unit Cell Geometry	Crystal System	Axial Relationships	Interaxial Angles	Unit Cell Geometry
Cubic	$a = b = c$	$\alpha = \beta = \gamma = 90^\circ$		Rhombohedral (Trigonal)	$a = b = c$	$\alpha = \beta = \gamma \neq 90^\circ$	
Hexagonal	$a = b \neq c$	$\alpha = \beta = 90^\circ, \gamma = 120^\circ$		Orthorhombic	$a \neq b \neq c$	$\alpha = \beta = \gamma = 90^\circ$	
Tetragonal	$a = b \neq c$	$\alpha = \beta = \gamma = 90^\circ$		Monoclinic	$a \neq b \neq c$	$\alpha = \gamma = 90^\circ \neq \beta$	
				Triclinic	$a \neq b \neq c$	$\alpha \neq \beta \neq \gamma \neq 90^\circ$	

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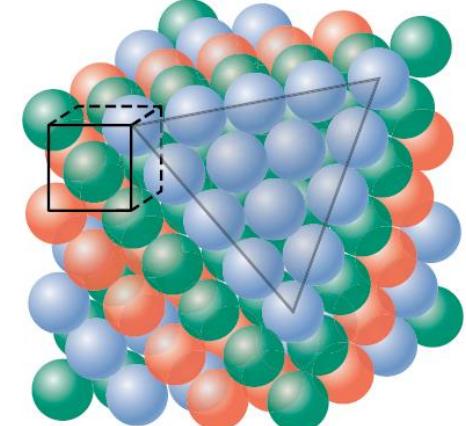
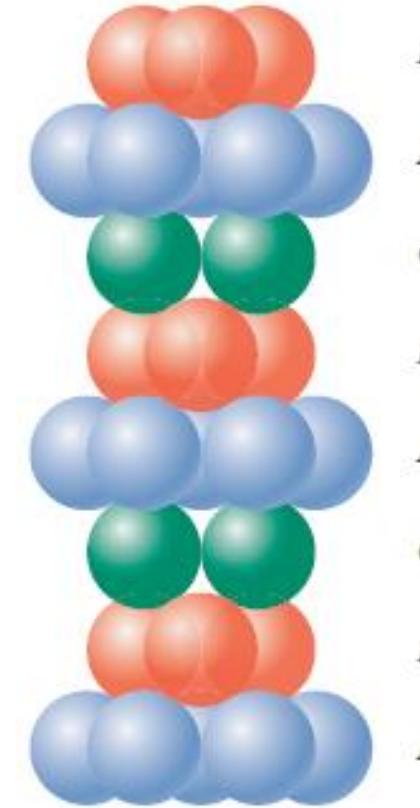


Close-Packed Crystal Structures

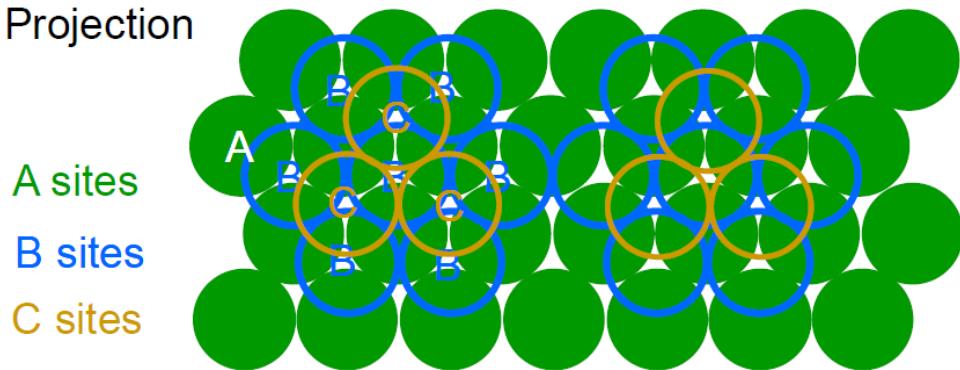
ABABAB (HCP)



ABCABC (FCC)



- 2D Projection



A sites

B sites

C sites

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Classification of Solid Structures

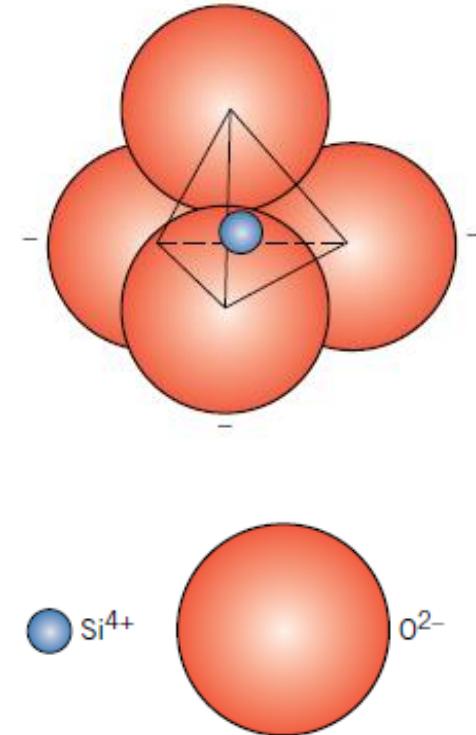
Type	Description	Examples
Ionic crystals	Close-packed array of ions (alternate M^{n+} and X^{n-})	E.g., crystalline salts, common salt (NaCl), fluorite (CaF_2)
Metallic crystals	Close-packed array of metal cations	Iron, copper
Covalent crystals	Packing of atoms to satisfy directional covalent bonds	Diamond, silica, clay minerals
Molecular crystals	Packing of specific molecules held together by van der Waals bonds	Crystalline polyethylene, ice
Amorphous materials	Irregular packings of ions, covalently bonded atoms, or distinct molecules	Metglas, soda glass, amorphous polymers
Composite materials	Particles or fibers dispersed in a continuous matrix	Fiber-reinforced plastics, portland cement concrete

Young et al.



Silicate Ceramics

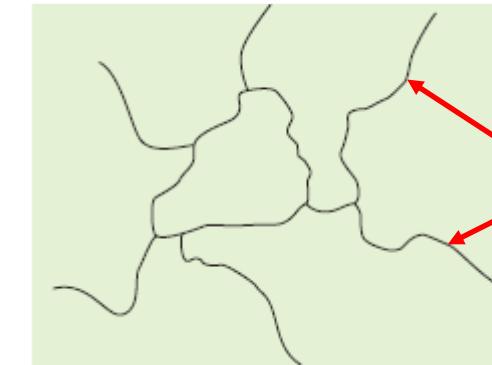
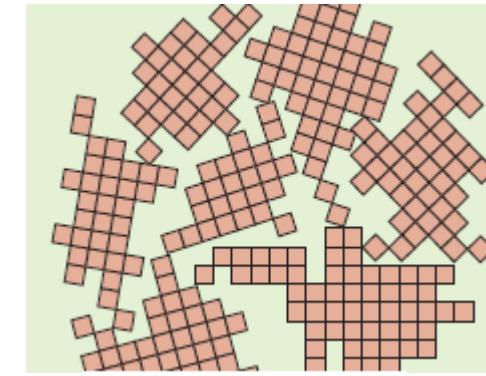
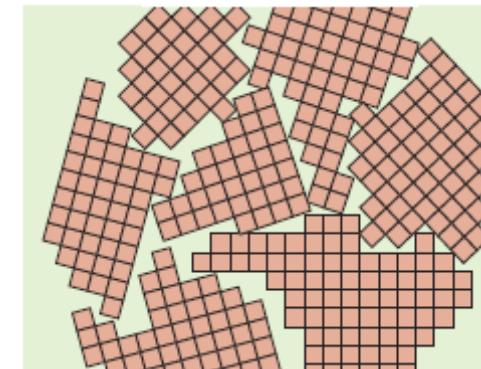
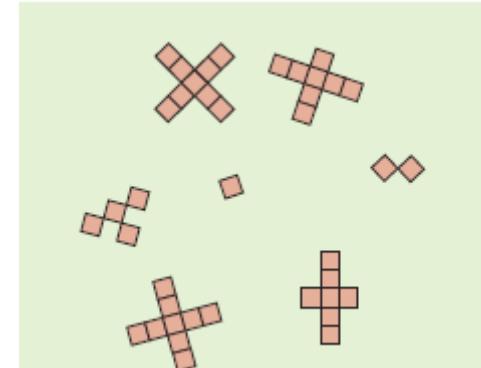
- **Silicates** are materials composed primarily of silicon and oxygen, the two most abundant elements in Earth's crust.
- The bulk of soils, rocks, clays, and sand come under the silicate classification.
- Rather than characterizing the crystal structures of these materials in terms of unit cells, it is more convenient to use various arrangements of an SiO_4^{-4} tetrahedron





Polycrystalline Materials

- Most crystalline solids are composed of many small crystals or grains



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Defects in Crystals

- Imperfections have profound influence on the properties of some materials.
- Brass (70% Cu and 30% Zn) is much harder and stronger than pure copper.
- Point, line, surface and volume defects



Classification of Defects

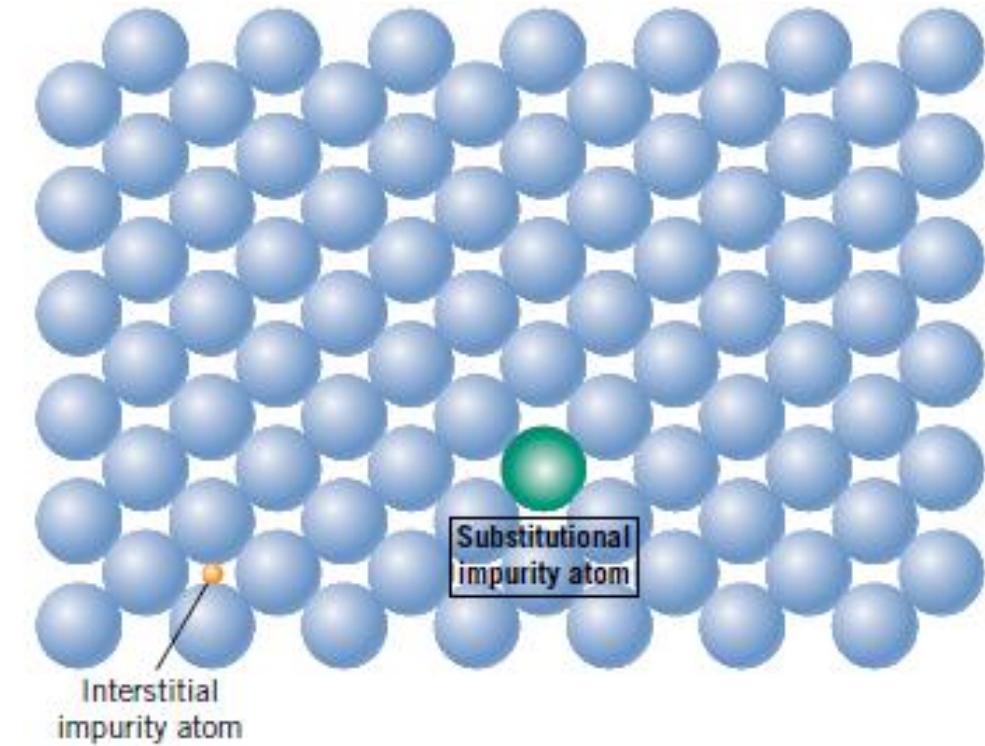
Type	Specific Examples	Influence on Material Properties
Point	Interstitial, substitutional	Solid solution strengthening, swelling of clays
Line	Dislocations	Ductility in metals, work hardening
Surface	Grain boundaries	Grain size strengthening
Volume	Pores	Sites of stress concentrations and crack initiation

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Point Defects in Crystals

- Solid solutions
- Impurity point defects are found in solid solutions
 - Substitutional
 - Interstitial

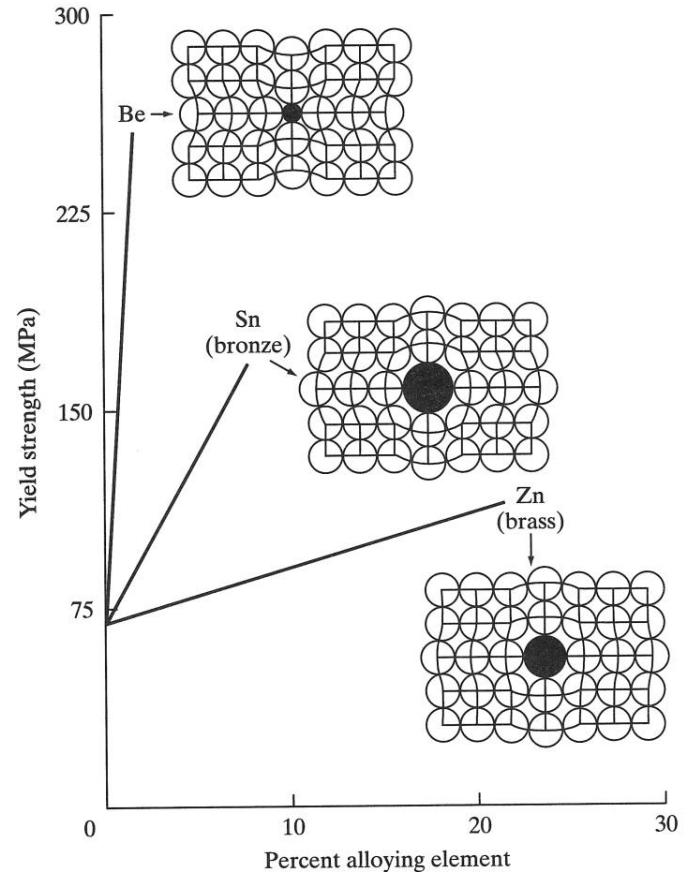


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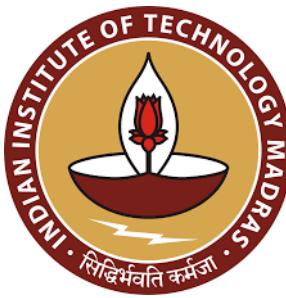
Points Defects in Crystals

- These defects distort the surrounding lattice.
- The additional strain increases the energy of the crystal.
- Point defects lead to strengthening of alloys.



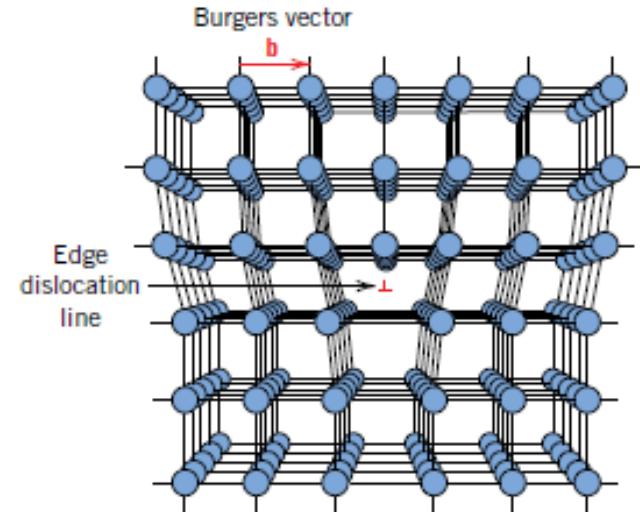
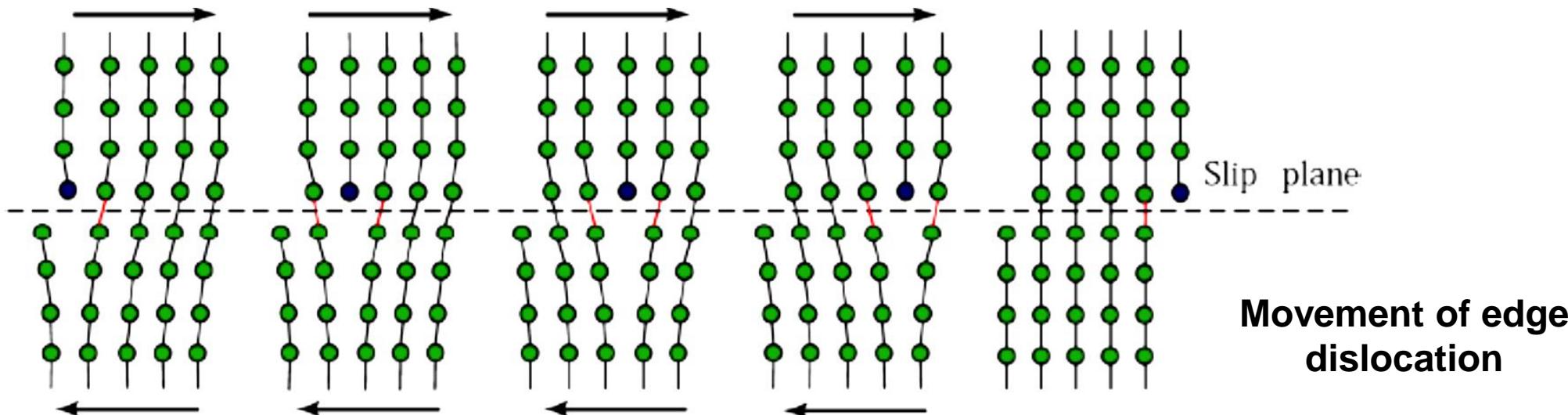
Strengthening of Copper

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Line Defects

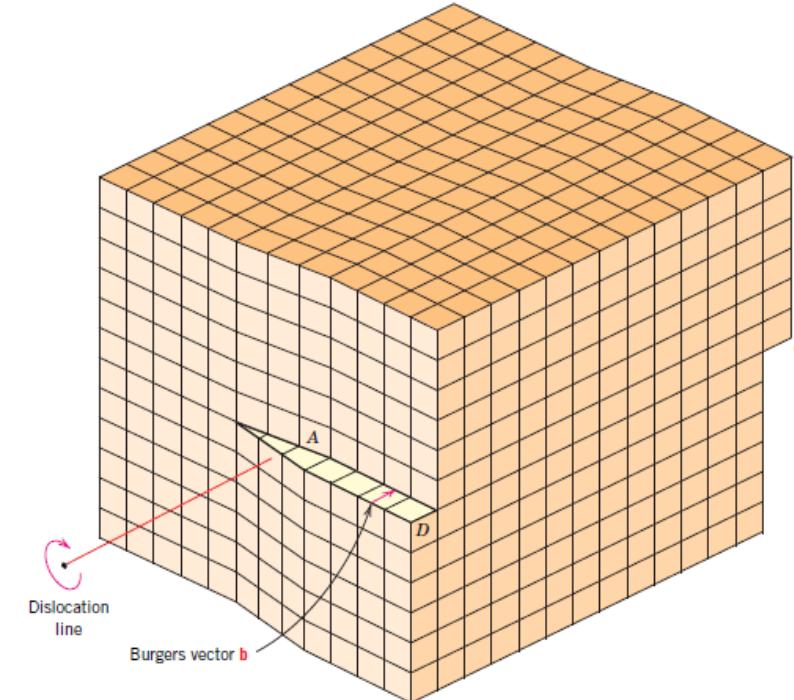
- These are imperfections in a crystal lattice where a line of atoms becomes mismatched with their surroundings.
- Line defects are called dislocations. (Edge and Screw)





Line Defects

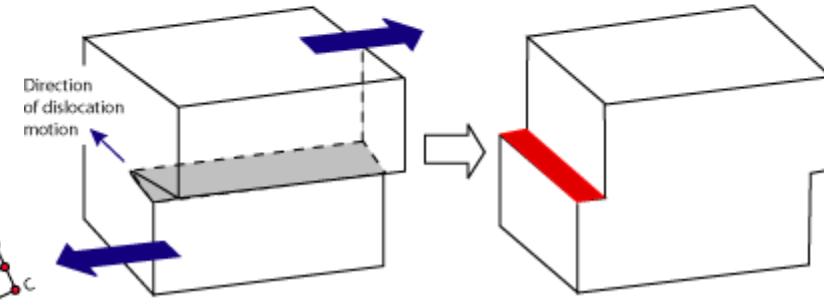
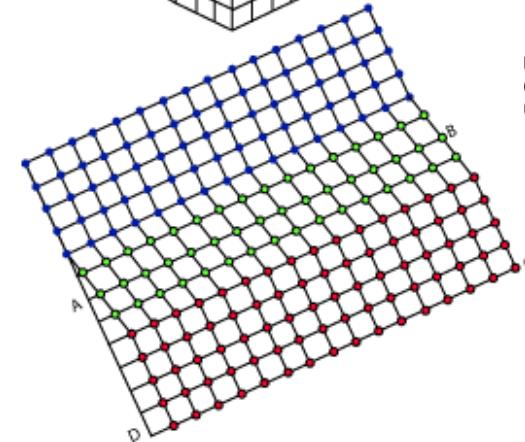
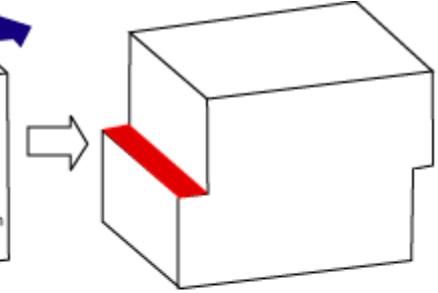
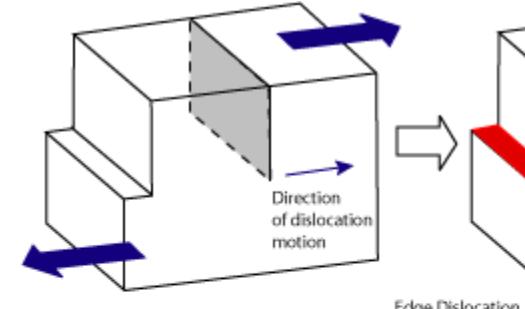
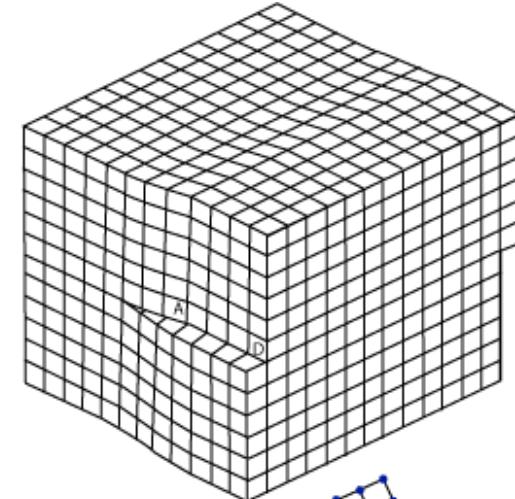
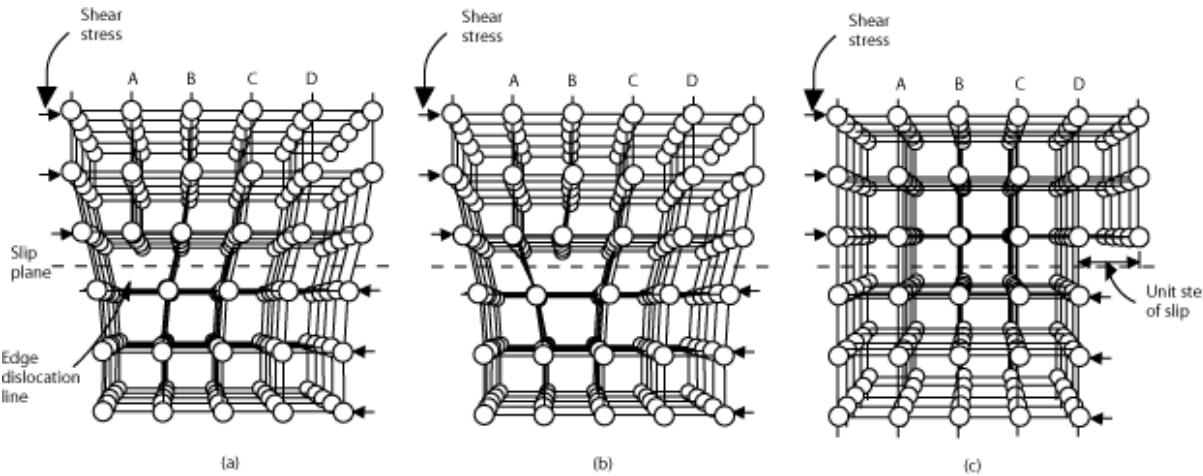
- **Screw dislocation:** formed by a shear stress that is applied to produce the distortion



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Edge vs. Screw Dislocation

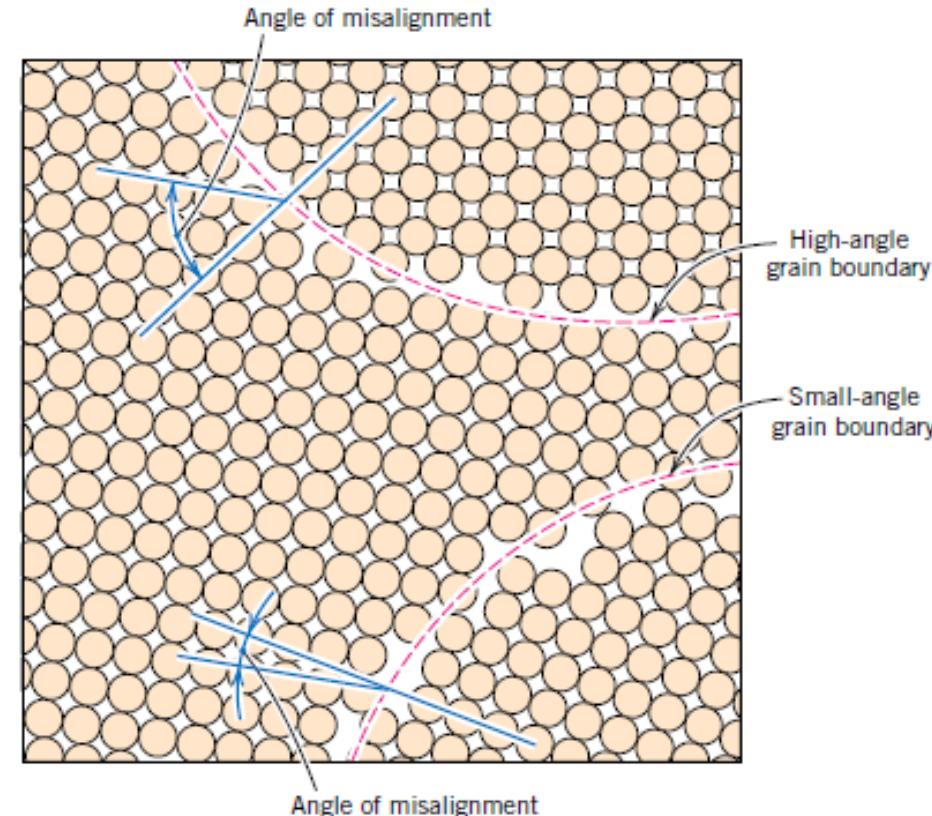


https://www.nde-ed.org/EducationResources/CommunityCollege/Materials/Structure/linear_defects.htm

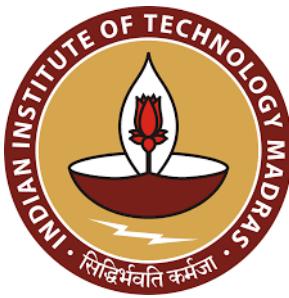


Plane Defects: Grain Boundaries

- A boundary separating two small grains or crystals having different orientations in polycrystalline materials
- Various degrees of crystallographic misalignments are evident from the Figure (right).
- Due to the interfacial energy, the atoms at the grain boundary are chemically more active than those within grain. Also, impurity atoms tend to segregate along the interfaces.

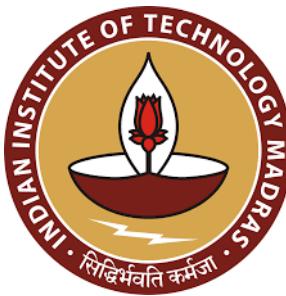


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Volume Defects

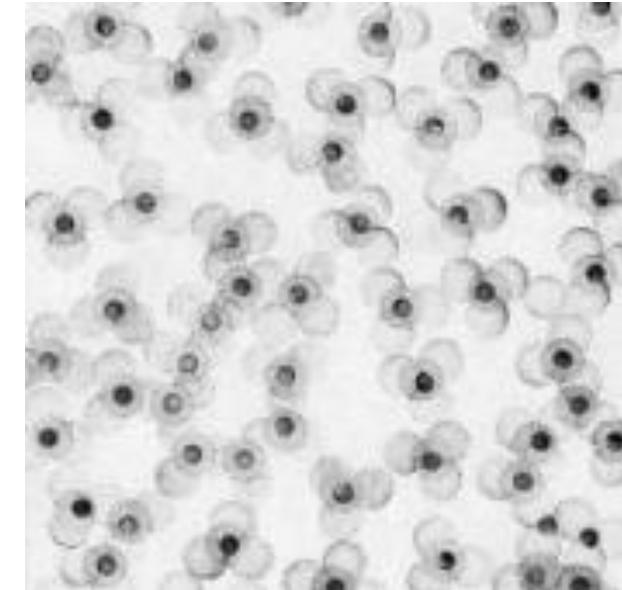
- Three-dimensional regions of defects, called volume defects, are voids and inclusions.
- Voids are small pores left by incomplete filling of the available space.
- Inclusions are regions of a second phase contained wholly within a single grain.



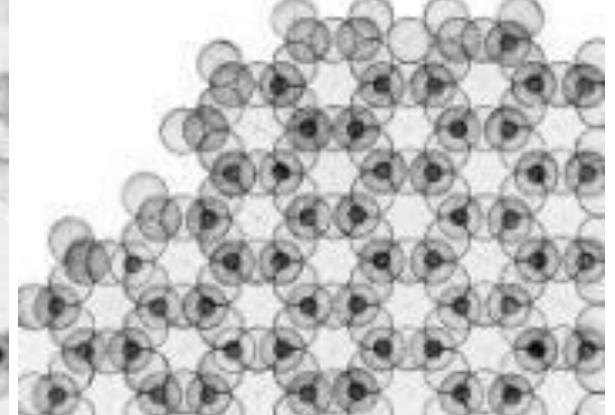
The Amorphous State

- When the regularity of atomic packing is completely absent, a solid is said to be non-crystalline or amorphous.
- The most familiar kind of amorphous solids are glasses.
- Glasses form from melts when the rate of cooling is too fast.

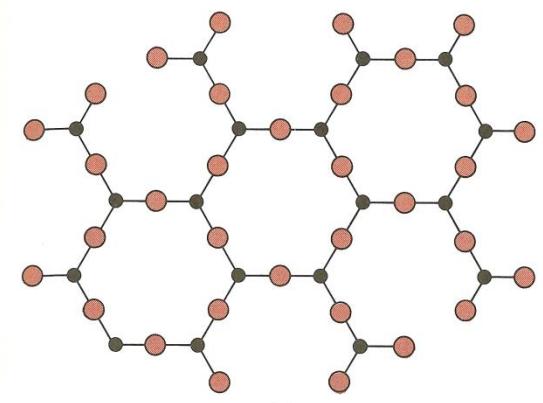
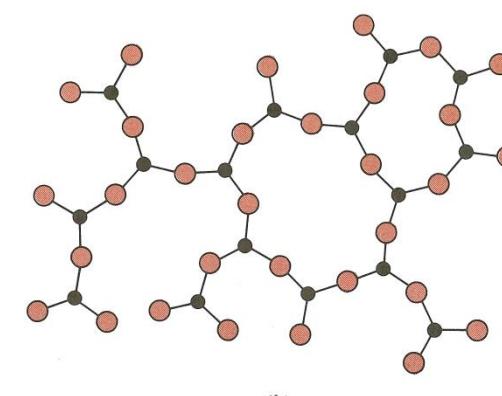
Amorphous Silica



Crystalline Silica



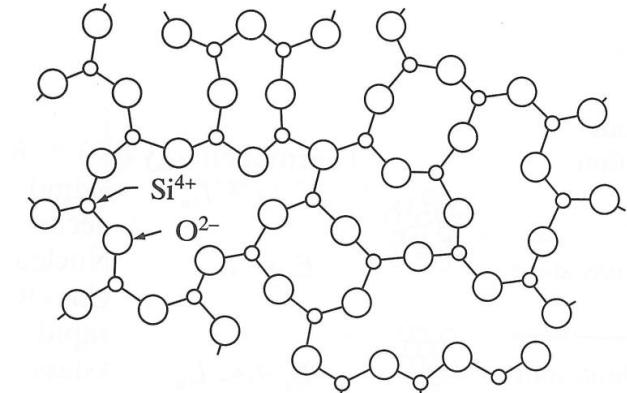
● Silicon atom
● Oxygen atom



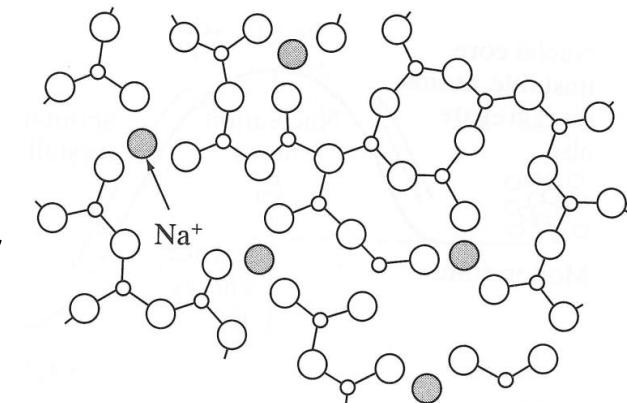


The Amorphous State: Glasses

- Although they have random packings, glasses can be considered in terms of ideal, defect-free structures.
- Fused silica has a random arrangement of silica tetrahedra.
- In soda glass, this arrangement is disrupted by the presence of sodium ions: some Si-O-Si bonds are replaced by Si-O-Na⁺ bonds.
- Soda glass has a lower binding energy and melts at a lower temperature than fused silica (~600°C vs. 1200°C).



SiO₂ glass



Na₂O modified glass



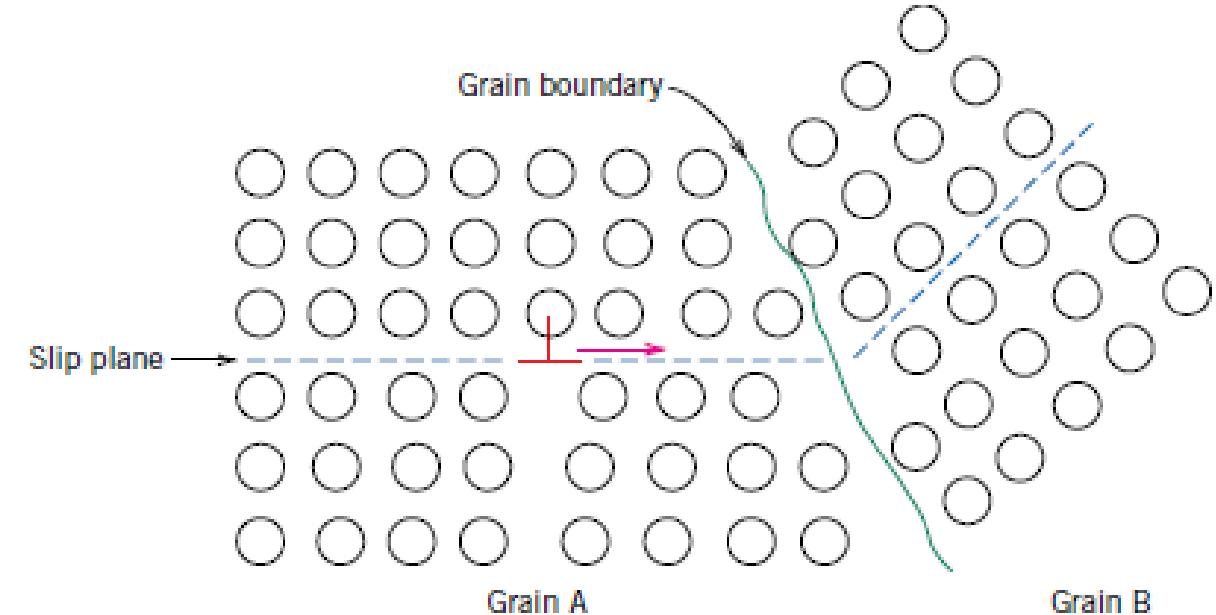
Mechanisms of Strengthening in Metals

- Strengthening by Grain size reduction
- Solid-solution strengthening
- Strain hardening



Strengthening by Grain Size Reduction

- A fine-grained material (one that has small grains) is harder and stronger than one that is coarse grained because the former has a greater total grain boundary area to impede dislocation motion.
- Grain size reduction also improves toughness of many alloys.

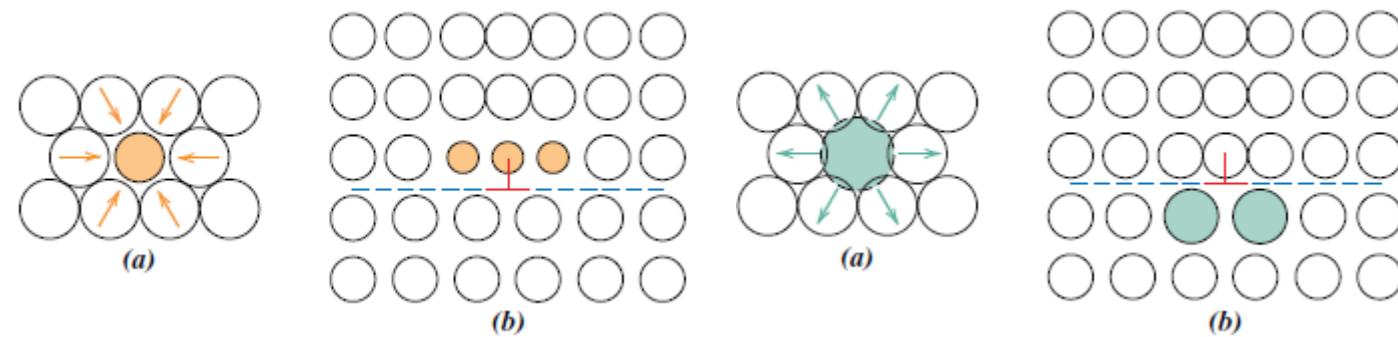
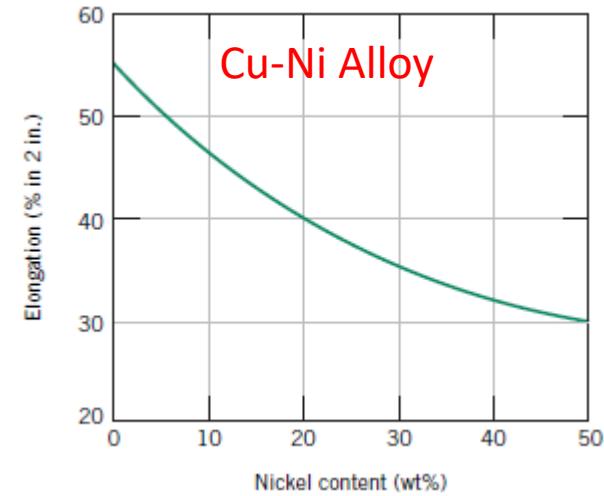
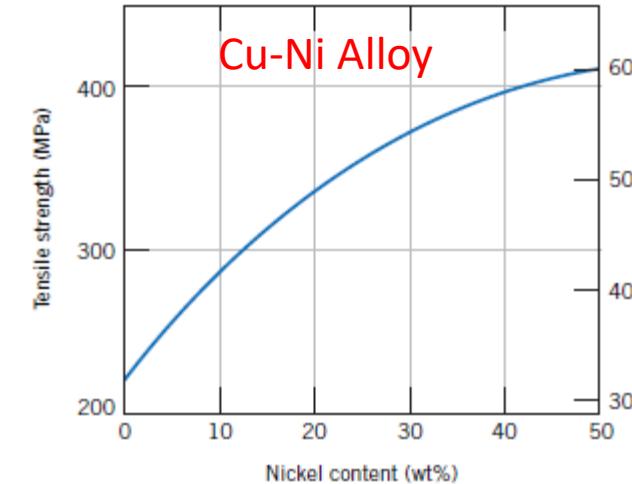


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Solid-Solution Strengthening

- Alloying with impurity atoms that go into either substitutional or interstitial solid solution.
- High-purity metals are almost always softer and weaker than alloys composed of the same base metal.

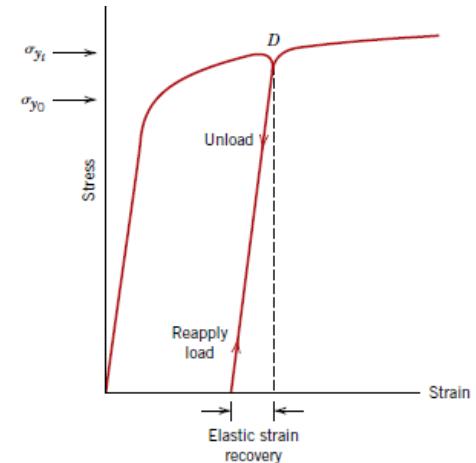
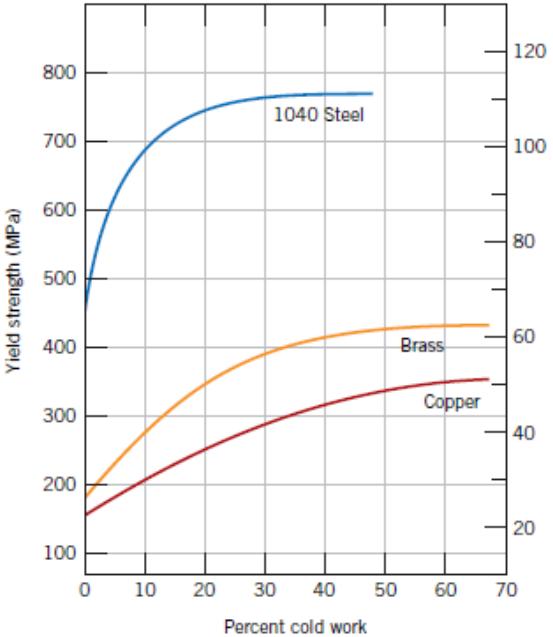


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Strain Hardening

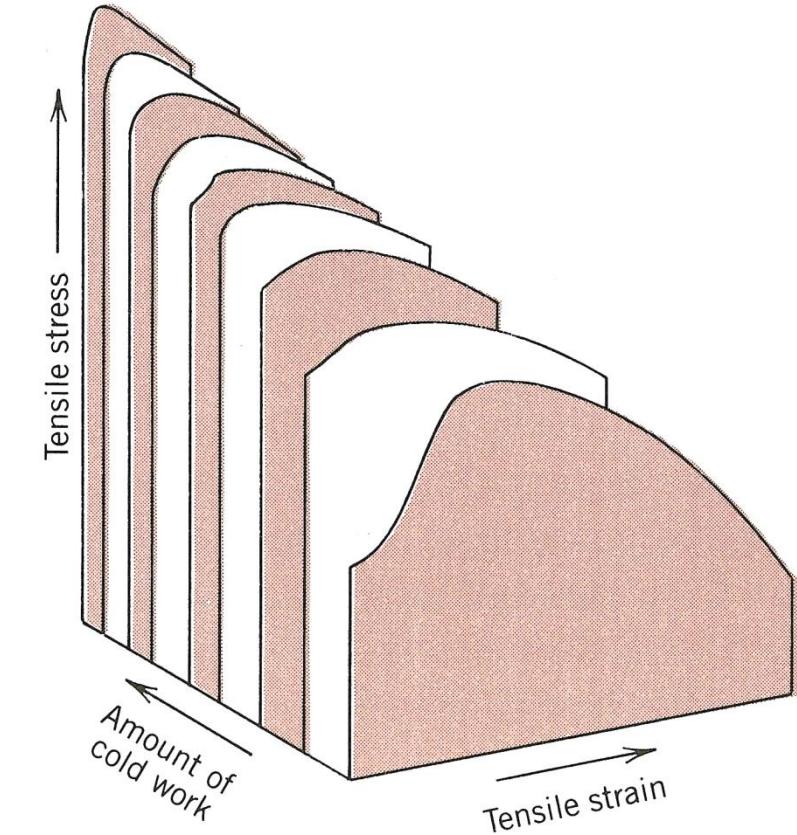
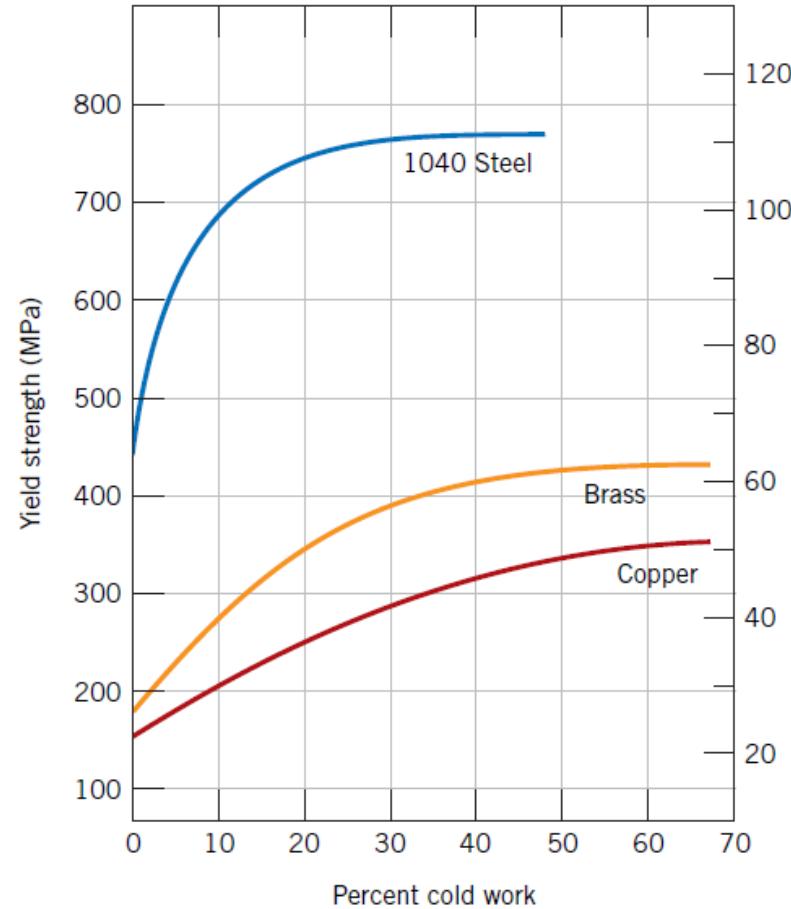
- The phenomenon by which a **ductile metal** becomes **harder and stronger** as it is plastically deformed.
- Also called, **work hardening**, or **cold working** (because the temp. at which deformation takes place is “cold” relative to the absolute melting temperature of the metal).
- **Dislocation-dislocation interaction** responsible for strain hardening.



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Strain-Hardening in Metals



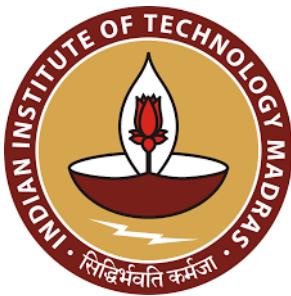
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Strain-Hardening of Metals

- The dislocation density in a metal increases with deformation or cold work. Consequently, the separation between dislocations decreases.
- Since the motion of dislocations is hindered by the presence of other dislocations, the resistance to dislocation motion increases with an increase in the dislocation density. As a result, the stress necessary to deform a metal increases with increasing cold work.
- The effect of **strain hardening** may be removed by an *annealing* heat treatment.

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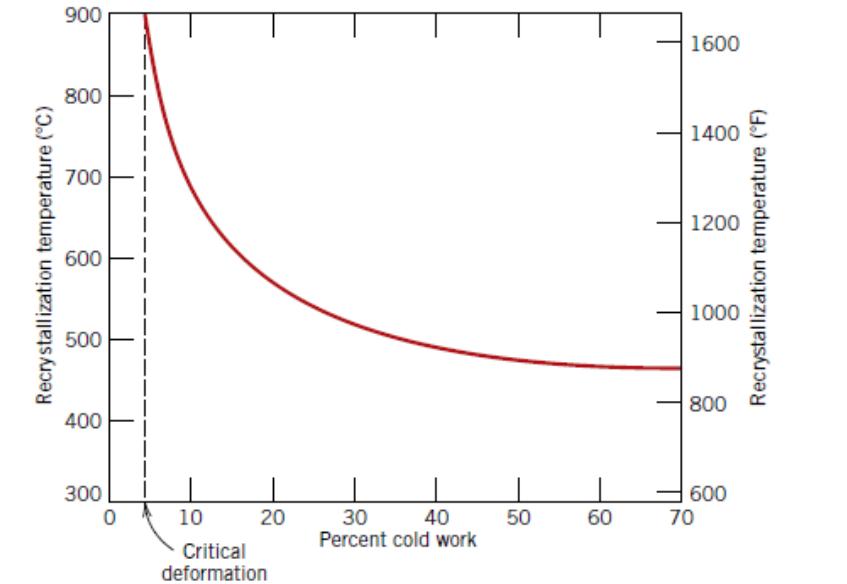
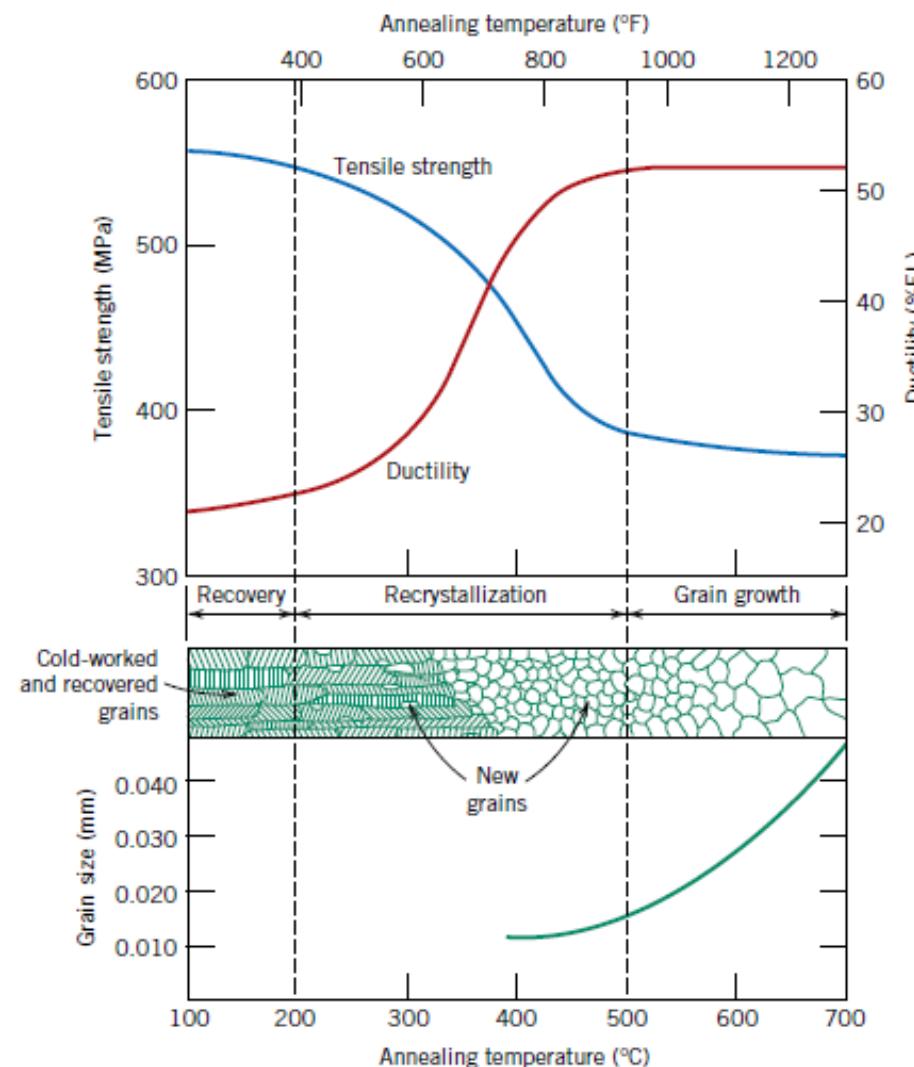
Annealing

- The properties and structure of cold worked metal can return to the **pre-cold worked states by appropriate heat treatment.**
- Such heat treatment, called annealing, consists of three stages: **recovery, recrystallisation and grain growth.**
 - **Recovery** - A low-temperature heat treatment designed to eliminate residual stresses introduced during deformation without reducing the strength of the cold-worked material.
 - **Recrystallization** - A medium-temperature heat treatment designed to eliminate all of the effects of the strain hardening produced during cold working.
 - **Grain growth** - Movement of grain boundaries by diffusion in order to reduce the amount of grain boundary area.

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Annealing



Metal	Recrystallization Temperature		Melting Temperature	
	$^{\circ}\text{C}$	$^{\circ}\text{F}$	$^{\circ}\text{C}$	$^{\circ}\text{F}$
Lead	-4	25	327	620
Tin	-4	25	232	450
Zinc	10	50	420	788
Aluminum (99.999 wt%)	80	176	660	1220
Copper (99.999 wt%)	120	250	1085	1985
Brass (60 Cu-40 Zn)	475	887	900	1652
Nickel (99.99 wt%)	370	700	1455	2651
Iron	450	840	1538	2800
Tungsten	1200	2200	3410	6170

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Diffusion



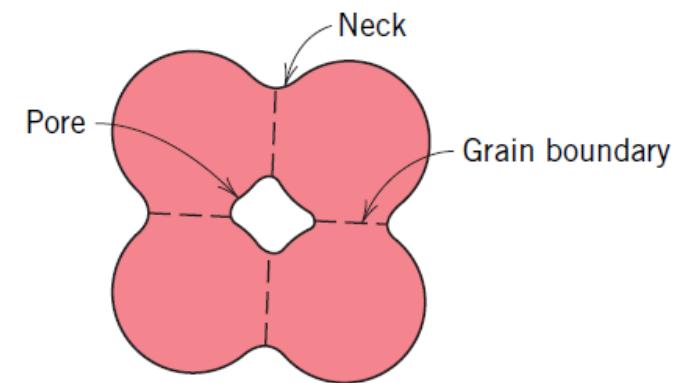
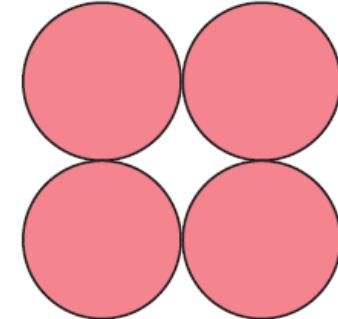
- A steel gear that has been *case hardened*—that is, its outer surface layer was selectively hardened by a high-temperature heat treatment during which carbon from the surrounding atmosphere *diffused* into the surface.
- This increase in the carbon content raises the surface hardness, which in turn leads to an *improvement of wear resistance* of the gear.

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Atomic Diffusion

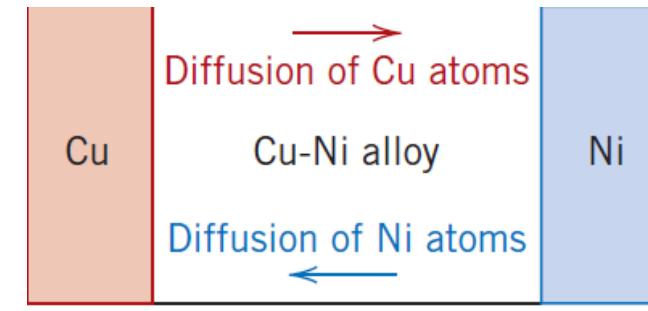
- Many reactions and processes rely on the transfer of mass either within a specific solid or from a liquid, a gas or another solid phase.
- This is accomplished by diffusion, the phenomenon of material transport by atomic motion.



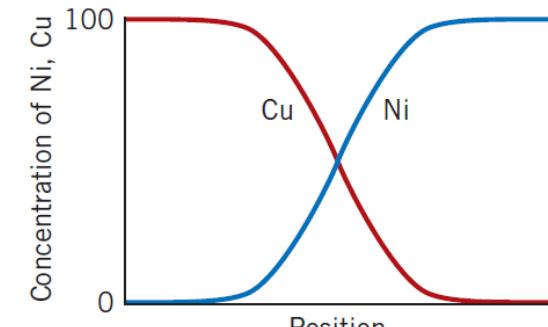
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Atomic Diffusion



After High Temperature



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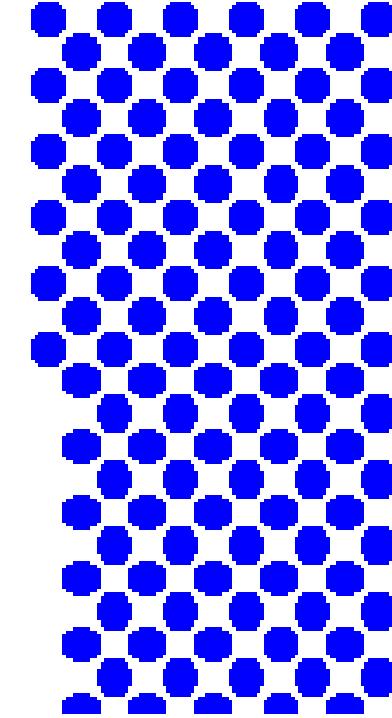
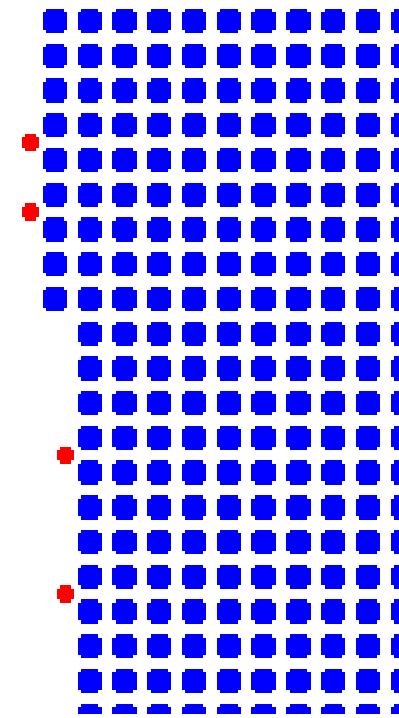
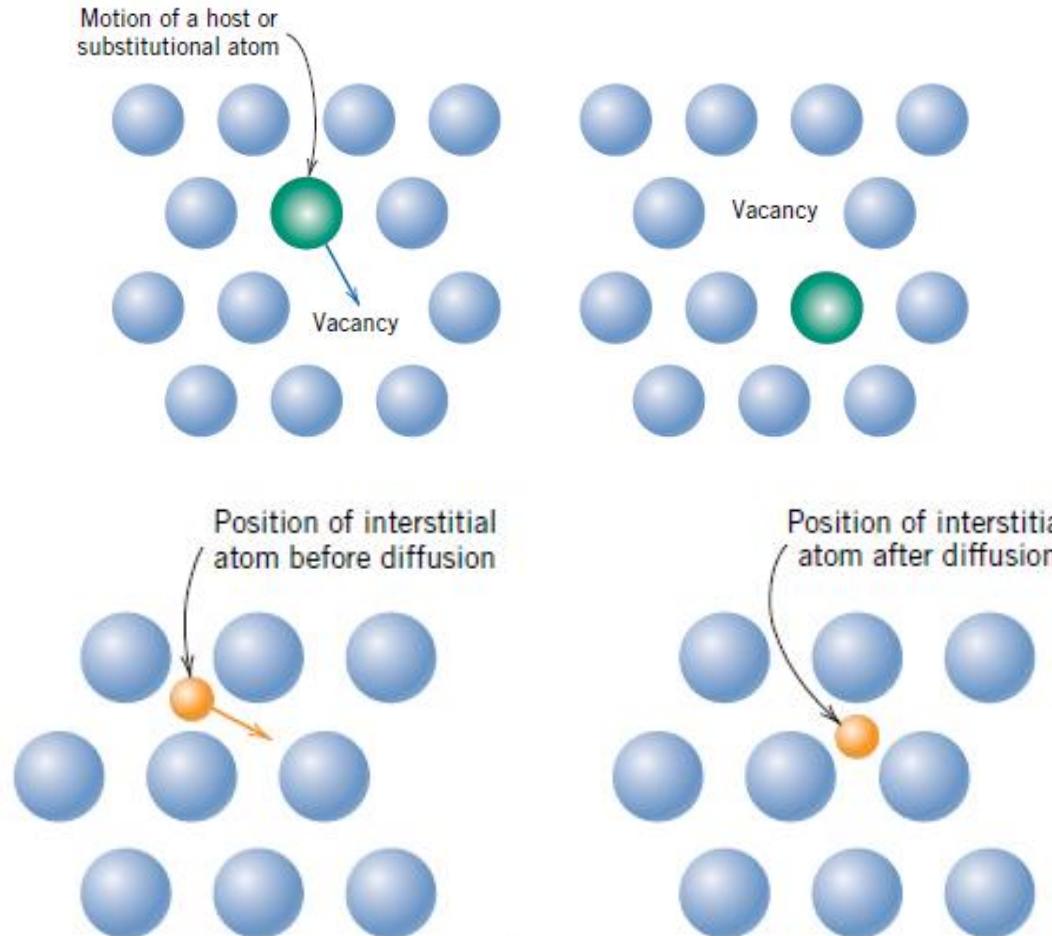
Atomic Diffusion: Mechanism

- Atomic diffusion is just the stepwise migration of atoms from lattice site to lattice site.
- For atomic diffusion, two conditions must be met:
 - availability of an empty adjacent site
 - sufficient energy to break bonds with its neighbor atoms

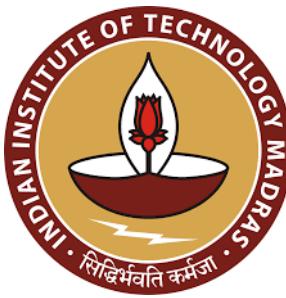
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Vacancy vs. Interstitial Diffusion



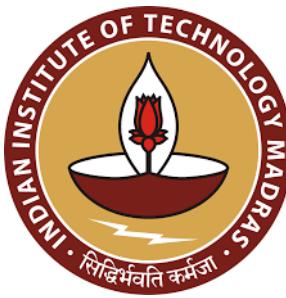
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Formation of Microstructure

Conditions	Material	Remarks
Crystallization from melts	Metals; Igneous rocks	
Precipitation or crystallization from solution	Hardened cement paste; Clays	Amorphous and crystalline components
Solidification without crystallization	Silicate glass; Thermoplastics	Limited crystallization for some plastics
Solidification from gas phase	Silica fume; Carbon black	Amorphous powders
Sintering of inorganic powders	Ceramics bricks	May involve reaction between two kinds of powders

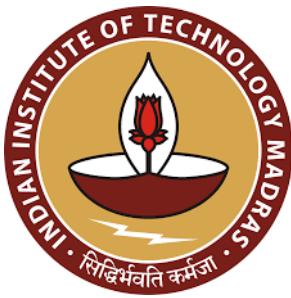
Young et al.



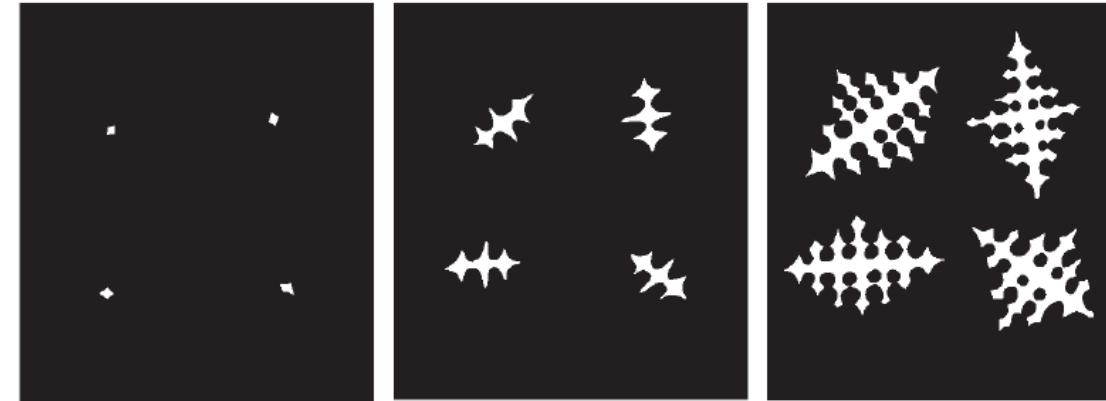
Microstructure

- Metals, polymers and glasses are generally formed by solidification from melts.
- Solidification does not always involve crystallization.
- Cementitious materials develop microstructures by solidification from solutions.

Young et al.



Dendritic Solidification of a Metal



① Nuclei form.

② Dendrites begin to grow from these nuclei.

③ Secondary arms form, and meet others growing in the opposite direction.



④ Dendrites grow until their outer arms touch. Existing arms thicken and –



⑤ – When the metal is completely solid, only the grain boundaries are visible.

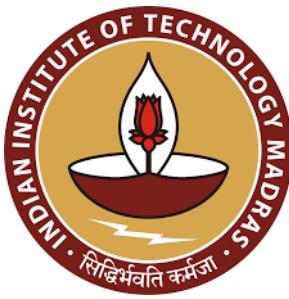
Higgins



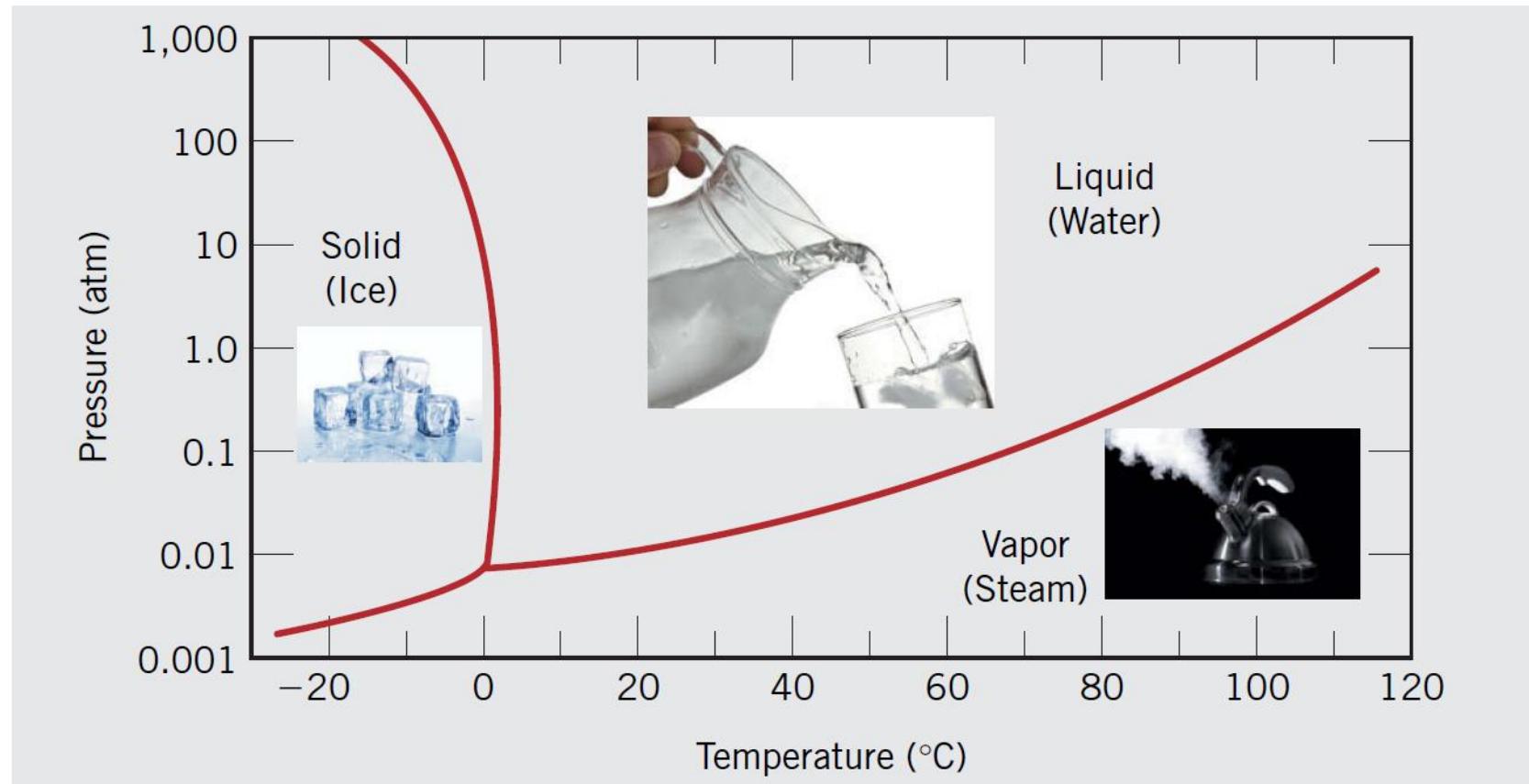
Crystallization from Solution

- Crystallization can also occur from solutions. Here, nucleation and growth are governed by the degree of *supersaturation*.
- Saturation occurs when the crystal is in equilibrium with its solution, so the rate of dissolution is equal to the rate of crystallization.
- Temperature plays an important role by changing the level of saturation.
- Once crystals have formed, their rate of growth depends on the diffusion of ions to the growing faces.

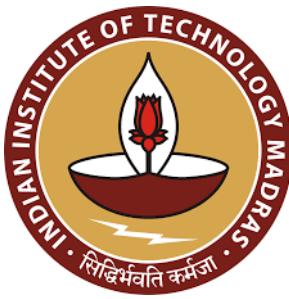
Young et al.



Phase Diagram

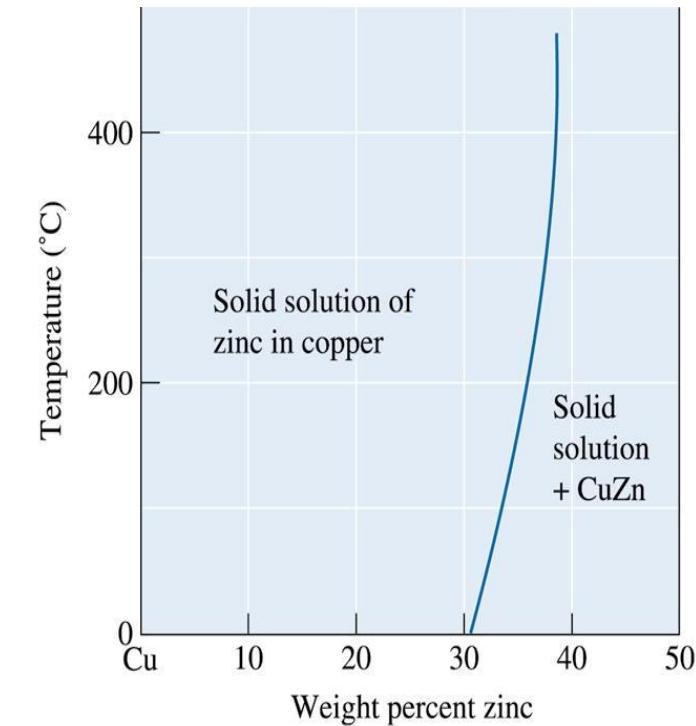
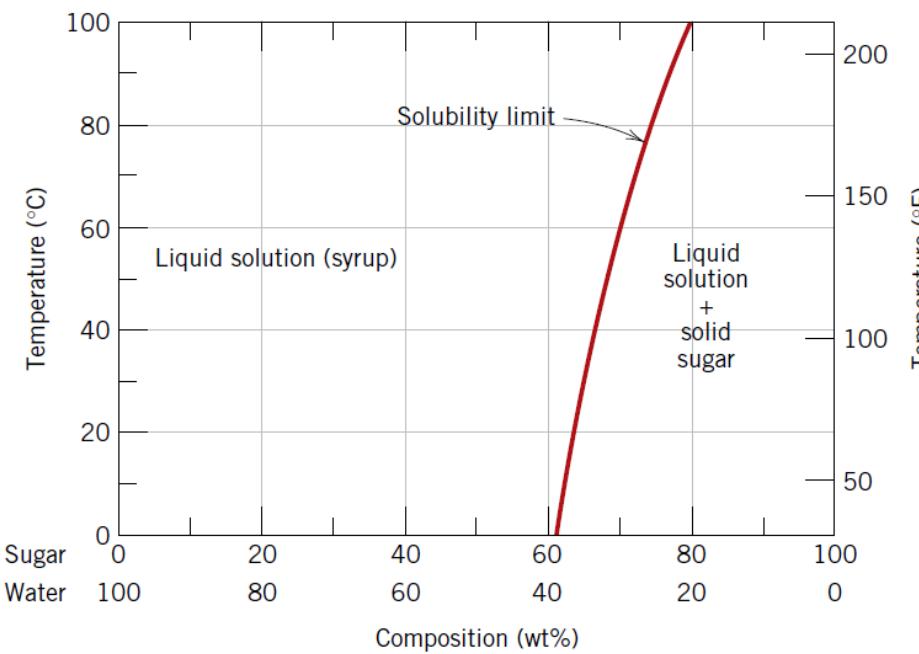


Callister and Rethwisch



Solubility Limit

- Solubility limit is the maximum concentration of solute concentrations that may dissolve in the solvent to form a solid solution



Callister and Rethwisch



Phase Equilibrium

- Free energy
 - A function of the internal energy of the system and also the randomness or disorder of the atoms or molecules
- Equilibrium
 - System is in equilibrium if the free energy is minimum at some combination of pressure, temperature, and Composition
 - Indicates that the system is stable
 - Phase equilibrium applies to systems in which more than one phase exists
- Phase equilibrium is reflected by a **constancy** with time in the phase characteristics of a system



Understanding Phase Diagrams

- Phase (P)
- Component (C)
- Degree of freedom (F)

Gibbs Phase Rule

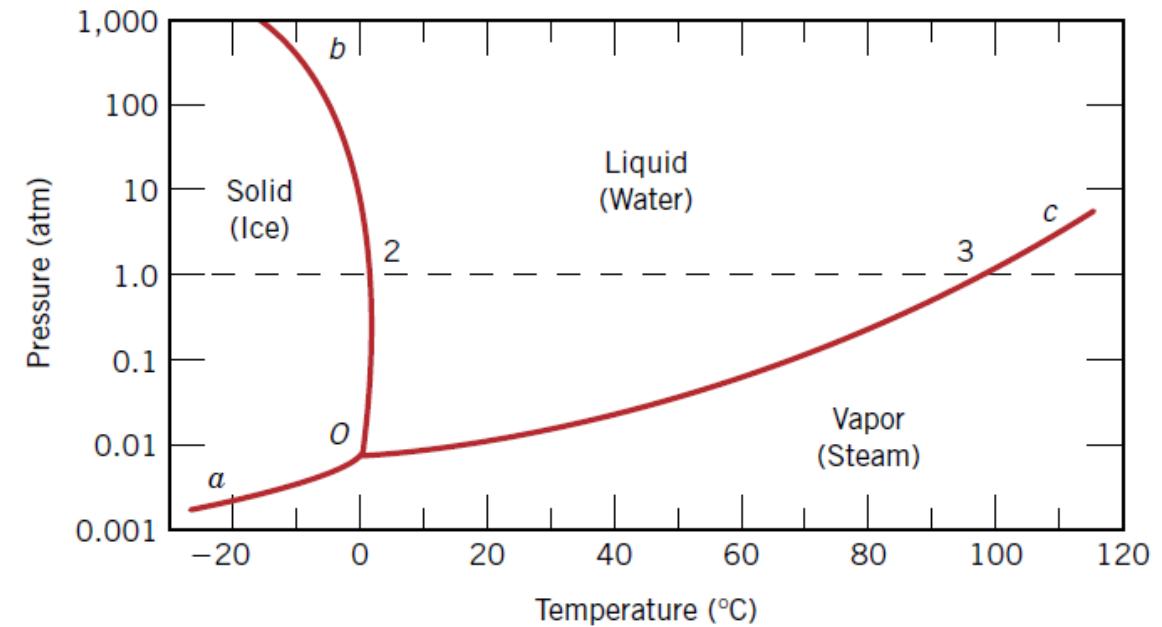
$$F + P = C + 2$$

Temperature and
Pressure



One-Component Phase Diagram

- Within the phase
- On the boundary
- At triple point “O”

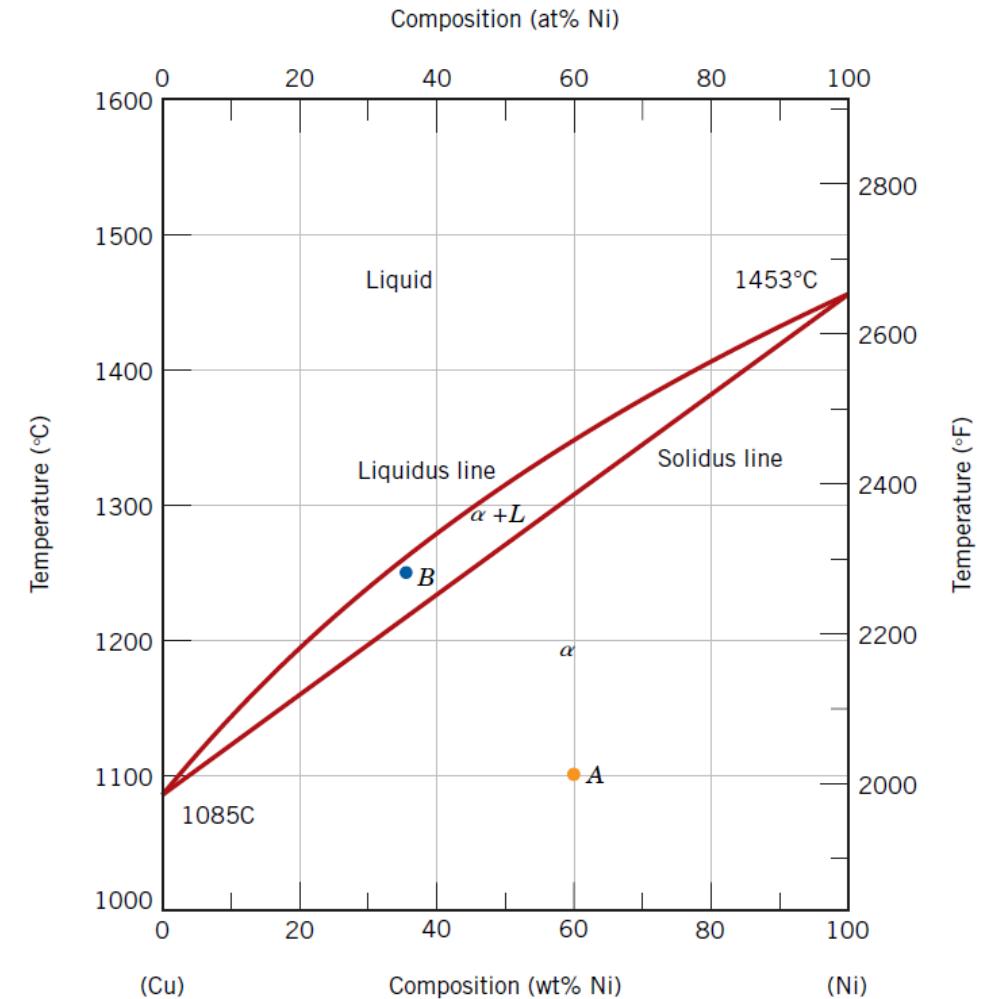


Callister and Rethwisch



Binary Phase Diagram

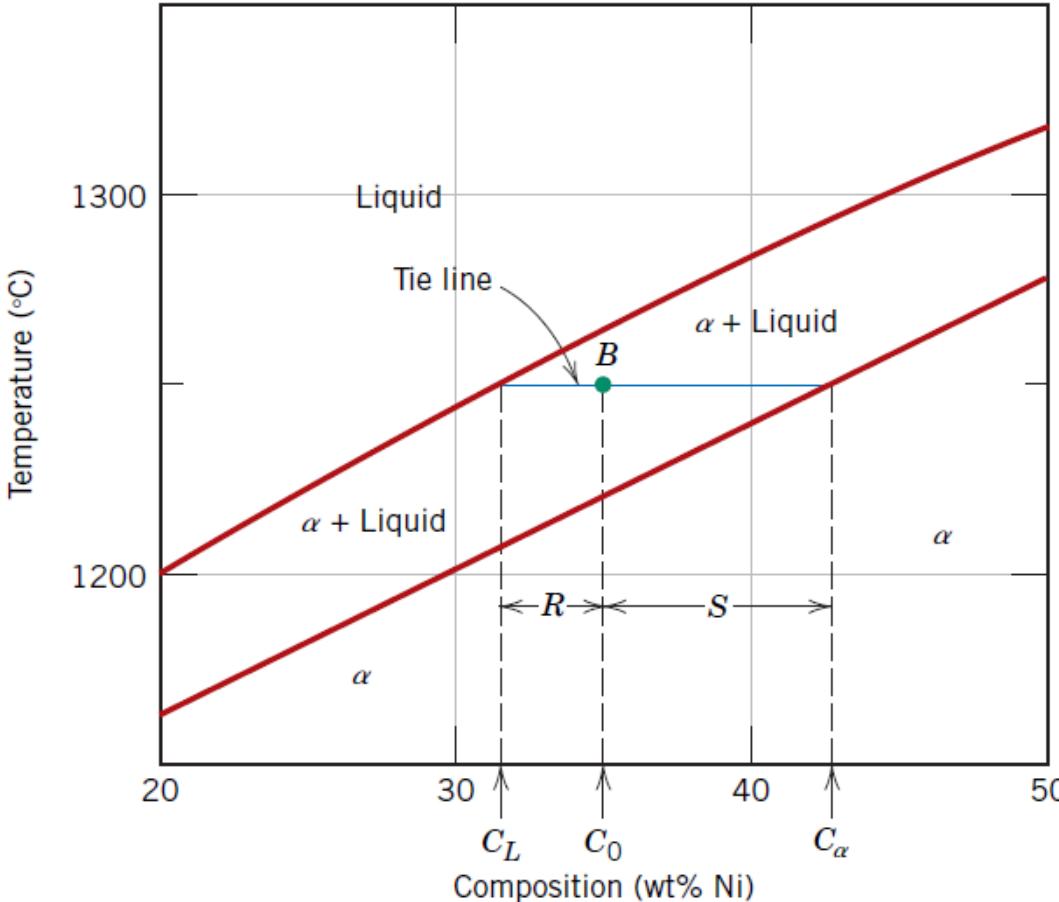
- Two components
- Liquidus line
- Solidus line



Callister and Rethwisch



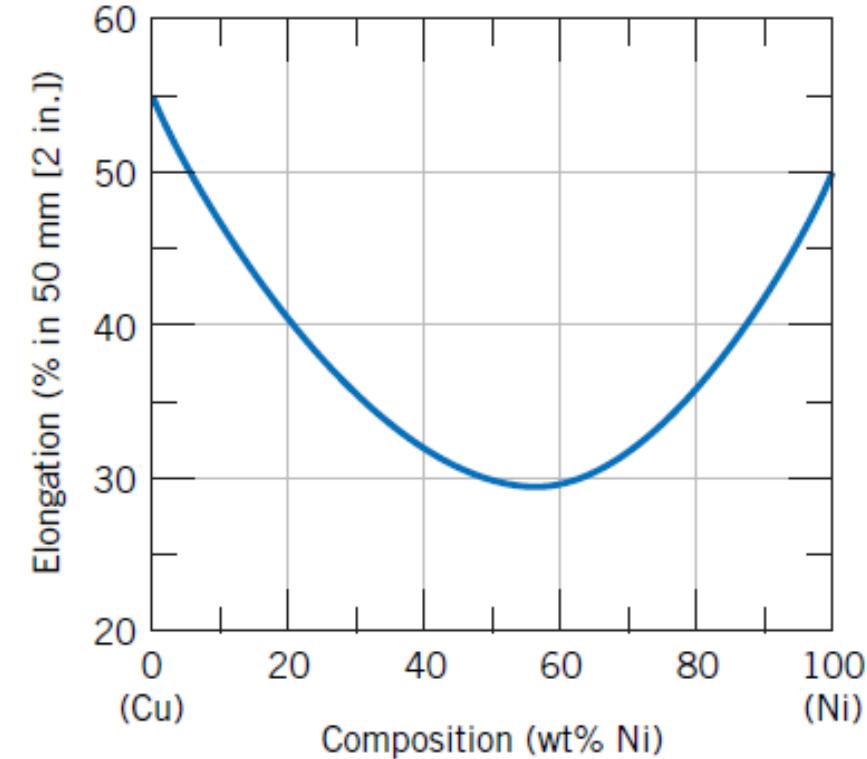
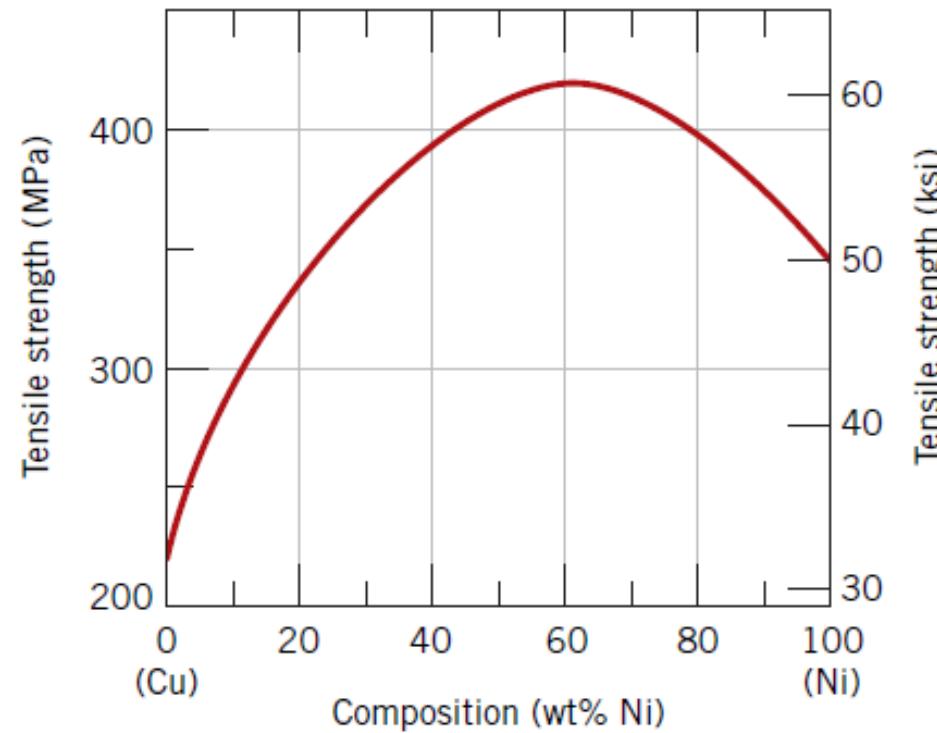
Phase Composition and Amount



Callister and Rethwisch



Mechanical Properties of Isomorphous Alloys



Callister and Rethwisch

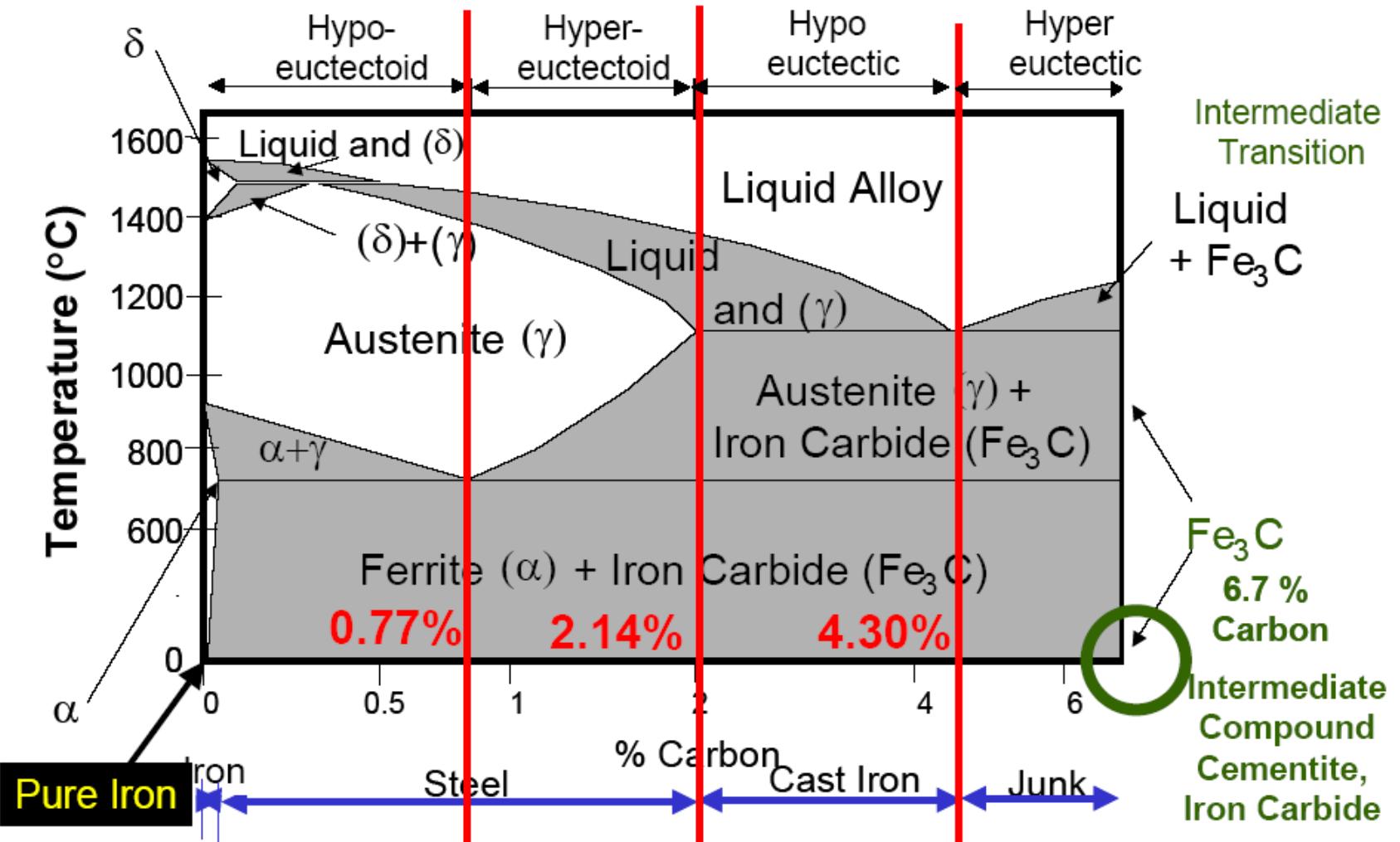


Pure Iron

- Pure Iron, upon heating, experiences two changes in crystal structure before it melts
- At room temperature, the stable form called **Ferrite (α -Iron)** has a **BCC structure**
- At 912°C , Ferrite undergoes polymorphic transformation to **Austenite (γ -Iron)**, which has an **FCC structure**
- At 1394°C , Austenite reverts back to another BCC phase called **δ -Ferrite**, which finally melts at 1538°C



The Role of Carbon Content





References

- Construction Materials – Their Nature and Behavior, *Edited by M Soutsos and P. Damone*, Fifth Edition, CRC Press.
- Materials Science and Engineering, *Callister, William D., and David G. Rethwisch*, John Wiley & Sons, 2011.
- *The Science and Technology of Civil Engineering Materials*, J. F. Young, S. Mindess, R. J. Gray & A. Bentur, Prentice Hall, 1998.

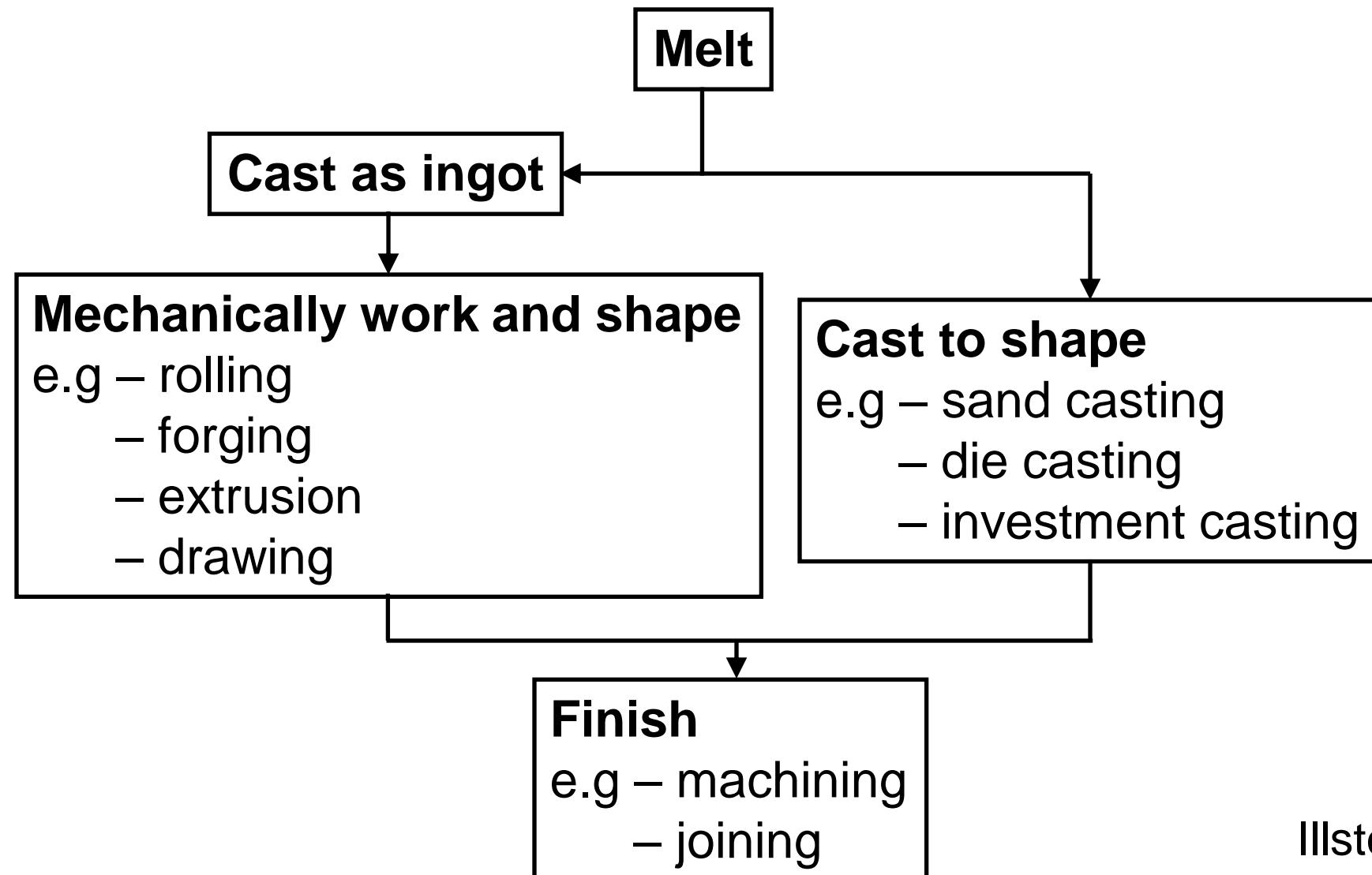


Metals: Steel and Aluminum

Piyush Chaunsali
Department of Civil Engineering
IIT Madras



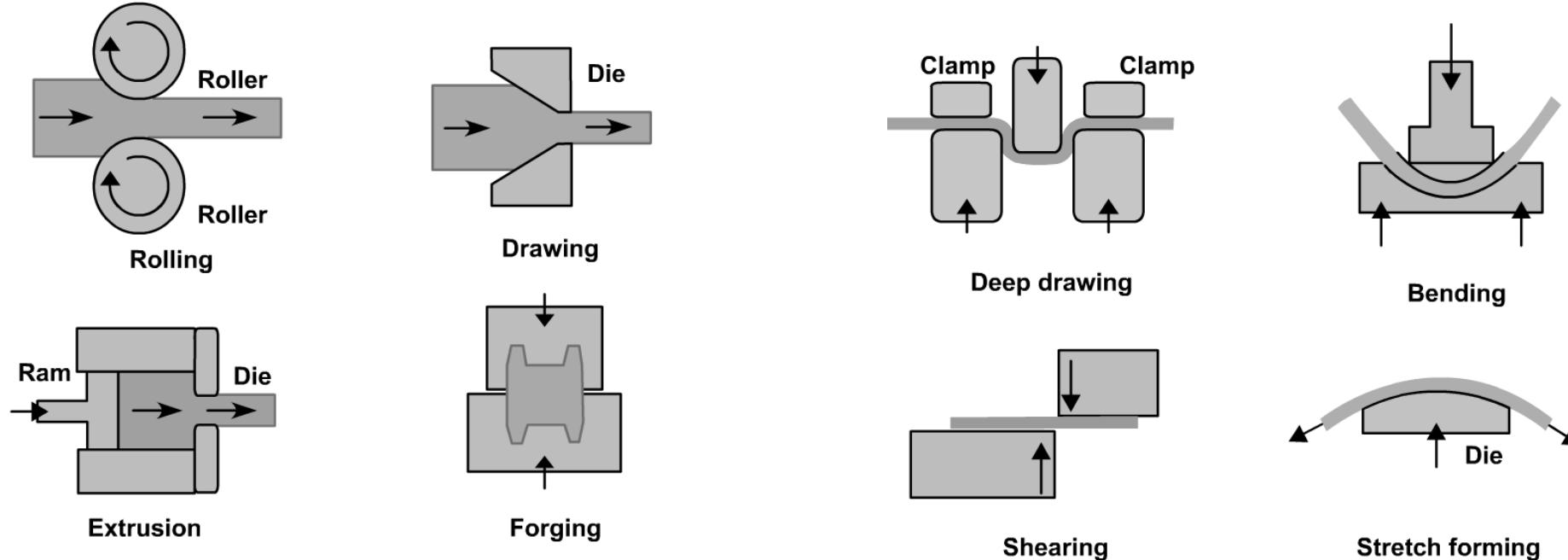
Forming of Metals



Illston & Domone



Forming of Metals: Hot Working



Hot working processes depend on plasticity, which is higher at high temperatures, i.e., above the recrystallisation temperature. This allows common metals to be deformed in compression, without breaking.

Illston & Domone



Forming of Metals: Hot Working

- For steel structural members, the usual method is by *hot rolling*, with cylindrical or shaped rollers at temperatures of 1000 °C or more. The members are later allowed to cool naturally, ending up with an annealed microstructure. The exposure of the hot metal to air causes a heavy film of oxide on the surface.
- One disadvantage of hot forming arises from the contraction of the dimensions on cooling.

Illston & Domone



Forming of Metals: Cold Working

- Many metals and alloys can be cold worked, i.e., shaped at temperatures below that of recrystallisation.
- This creates an immense amount dislocations, and consequently, work hardening. As a result, the yield strength increases.
- There are many cold working processes:
 - Cold rolling – used for producing sheet material
 - Cold drawing – used for making high-strength wires
 - Cold extrusion
- There is a limit to cold working; beyond a certain limit, the ductility is exhausted and the material fractures.

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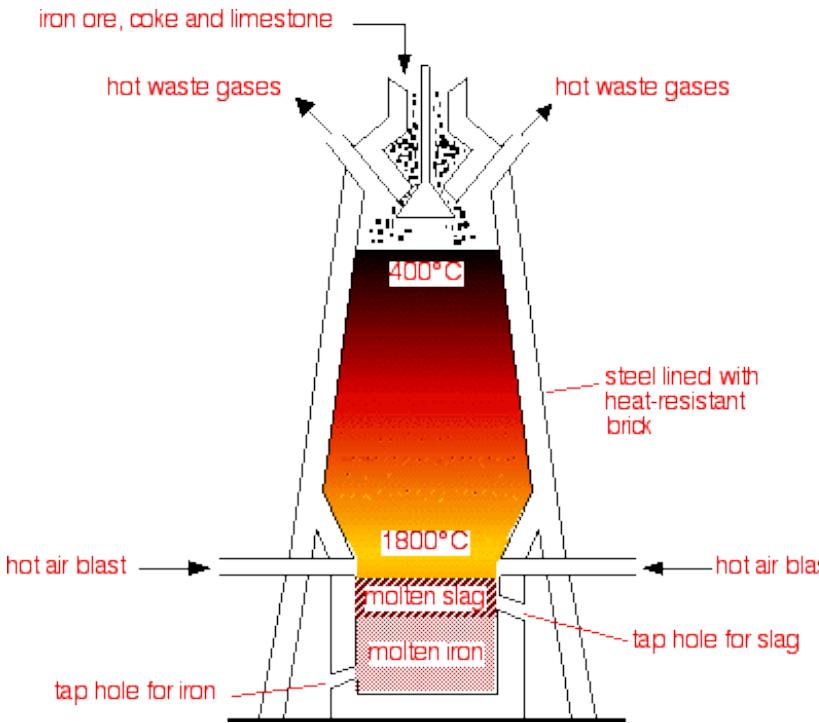


Steel





Steel Production

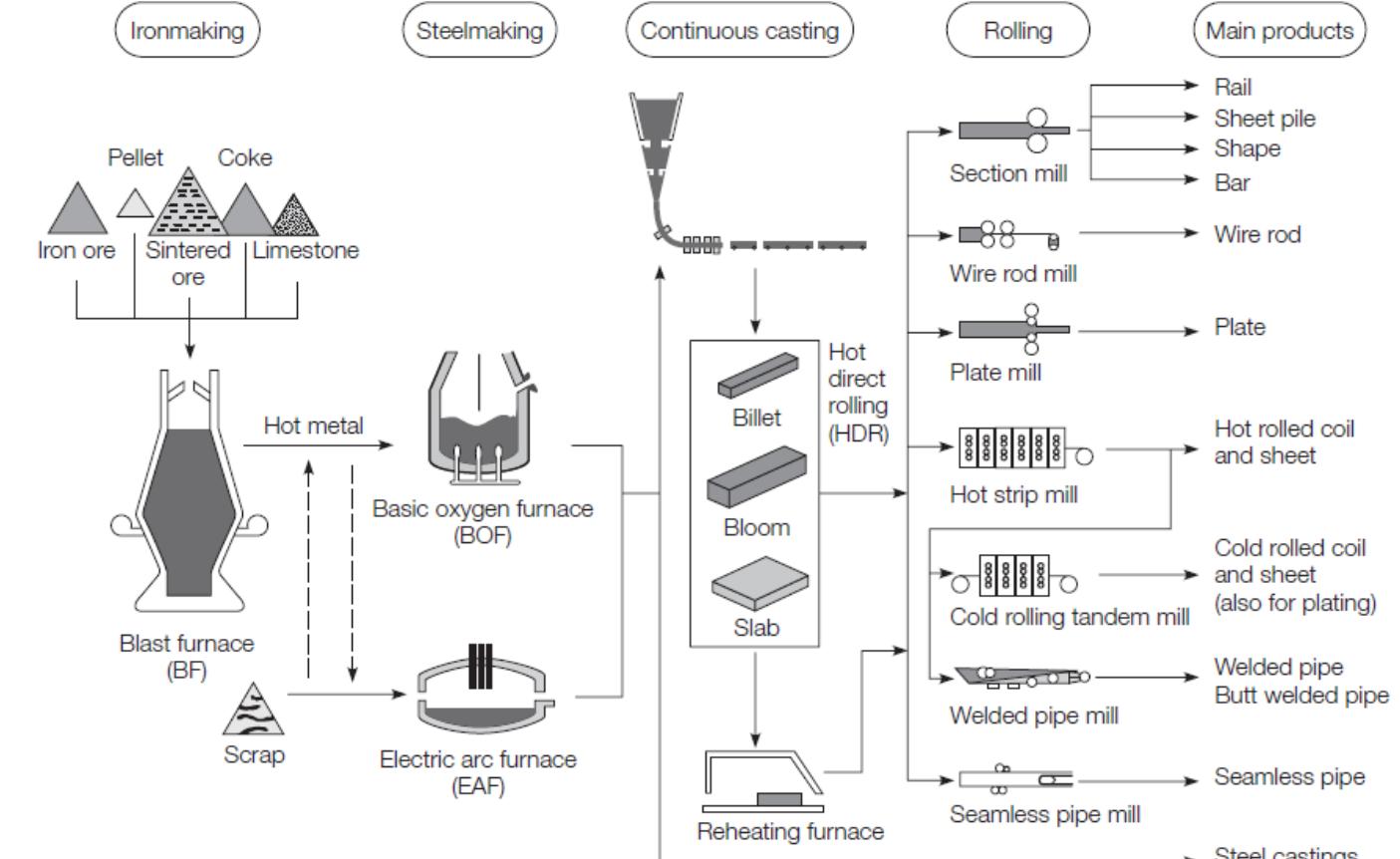


Feed

1. Iron Ore (Iron + Impurities)
2. Limestone (Flux – to clean up impurities in ore)
3. Coke (Fuel)

Output

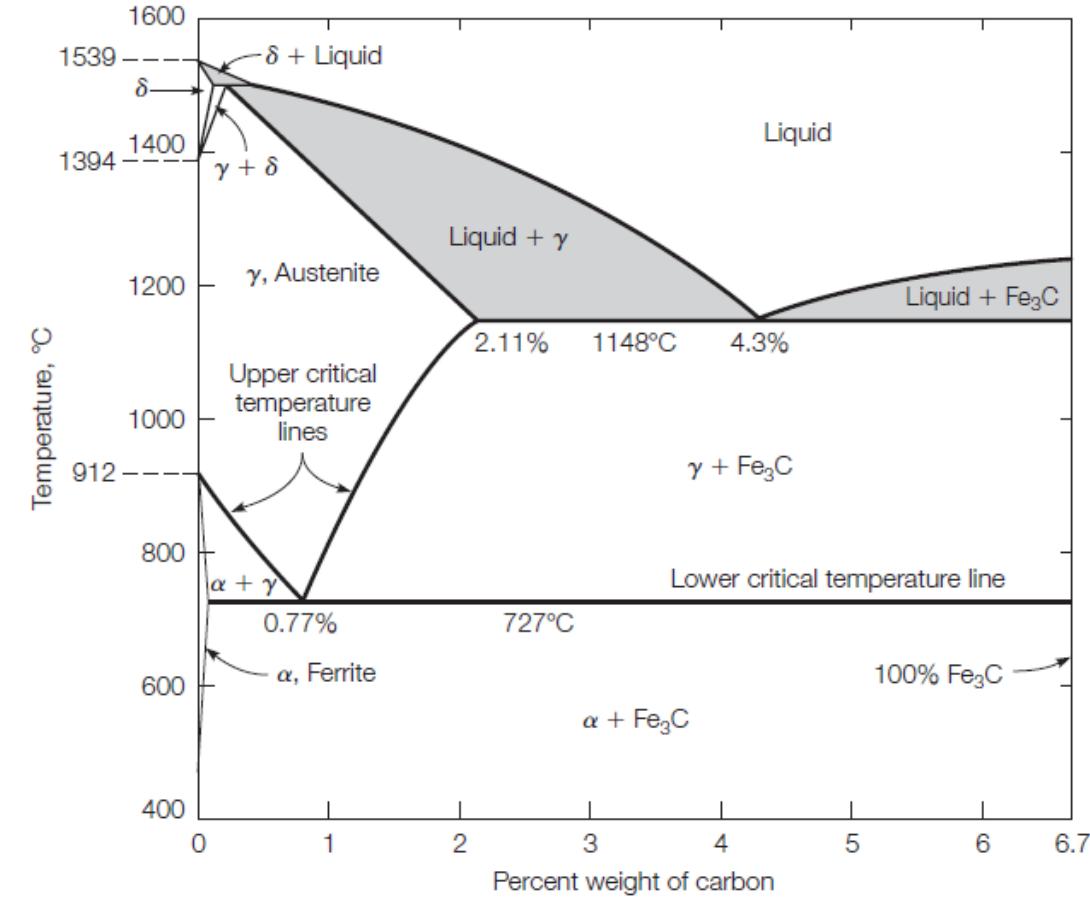
1. Molten Iron (predominantly iron with some carbon)
2. Slag (molten impurities tied up in limestone)



<https://www.chemguide.co.uk/inorganic/extraction/iron.html>



Fe-C Phase Diagram



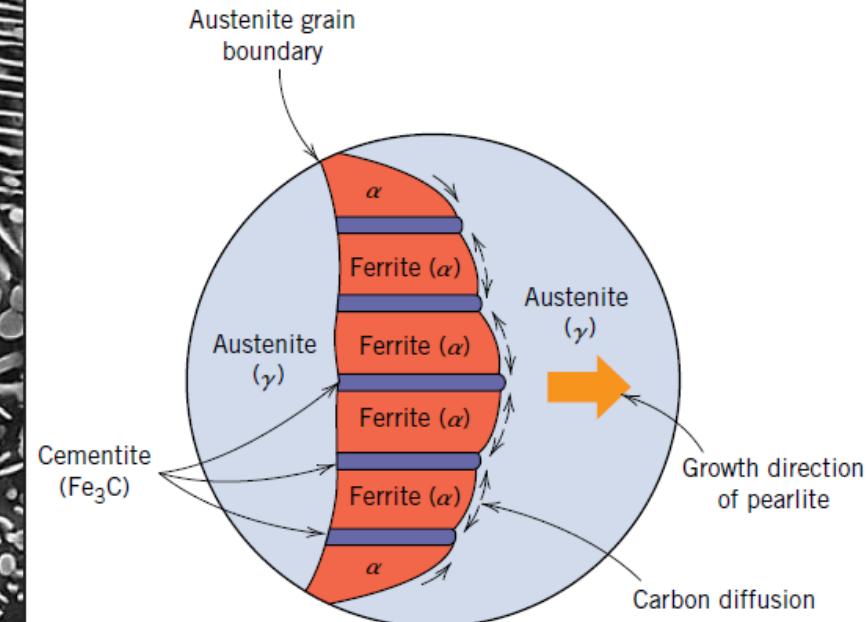


Pearlite Structure

Structure of the eutectoid composition 0.8 wt. % C steel. The eutectoid constituent, called pearlite, has a lamellar (layered) morphology consisting of alternating plates of Fe (light areas) and Fe_3C (dark areas).



Schaffer et al.



Callister and Rethwisch



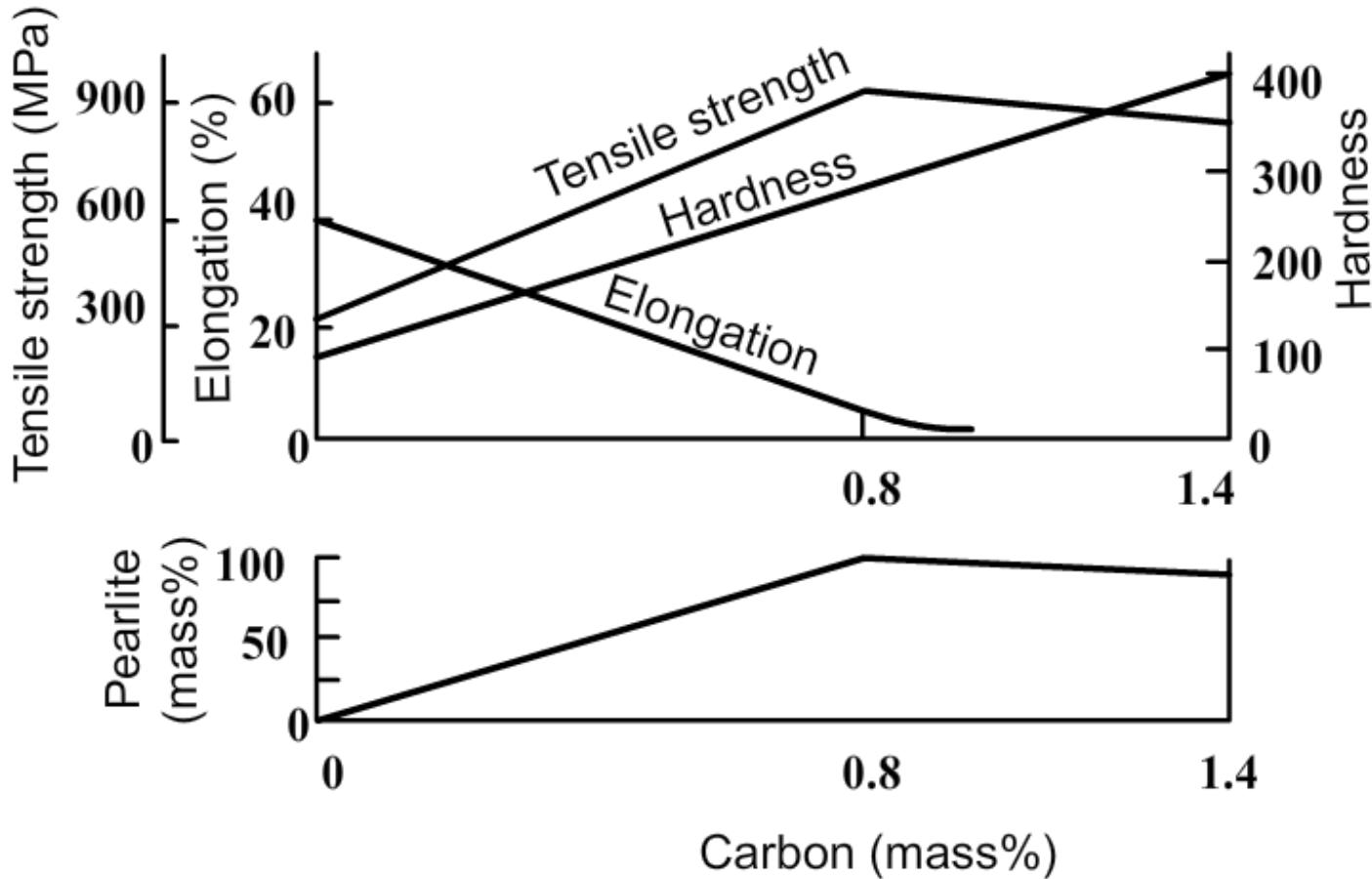
Use of Steel in Construction

- Structural steel
 - Plates, bars, pipes, structural shapes, etc.
- Cold-formed steel
 - Studs, trusts, roofing, cladding
- Fastening products
 - Bolts, nuts, washers
- Reinforcing steel
 - Rebar for concrete
- Miscellaneous
 - Forms, hardware, etc.



Structural Steel

- At **high carbon contents**, the properties are dominated by those of pearlite – **high hardness, high strength, and poor ductility and toughness**.
- At **low carbon contents**, the properties of (metallic) ferrite govern – **depend on grain size, work hardening**; as the grain size decreases, the yield strength increases and the ductile-to-brittle transition temperature decreases.



Illston & Domone



Cold Rolled Steel

- Many lightweight sections are produced from cold rolled steel of very low carbon content.
- Strength is derived from work hardening of the ferrite.
- Applications include angle sections, hollow square sections, etc.
- Welding will locally anneal the material with consequent changes in properties. Therefore, such sections are often joined mechanically.



Source: Wikipedia



Heat-Treated Steel

- When the carbon content is greater than about 0.3%, the properties of steel can be varied through heat treatment; i.e., fast cooling (*quenching*) from a high temperature, followed by reheating to a temperature not exceeding 650°C (*tempering*).
- The fast cooling produces a hard brittle microstructure, called *martensite*, which is of little use except in cutlery or tools.
- However, upon reheating the carbon of martensite is precipitated as tiny particles of carbide throughout the matrix. The material consequently becomes softer and more ductile.

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Classification of Steels

- Mild steel or low carbon steel: Carbon content of up to 0.25%.
- Medium carbon steel or carbon steel: Carbon content of 0.3-0.6%.
- High carbon steels: Carbon content of more than 0.6%.
- When certain elements, such as Cr and Ni are added, it is called stainless steel.

Illston & Domone



IS 1786 - High strength deformed steel bars and wires for concrete reinforcement

**Table 3 Mechanical Properties of High Strength Deformed Bars and Wires
(Clause 8.1)**

SI No.	Property	Fe 415	Fe 415D	Fe 415S	Fe 500	Fe 500D	Fe 500S	Fe 550	Fe 550D	Fe 600
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
i)	0.2 percent proof stress/ yield stress, <i>Min</i> , N/mm ²	415.0	415.0	415.0	500.0	500.0	500.0	550.0	550.0	600.0
ii)	0.2 percent proof stress/ yield stress, <i>Max</i> , N/mm ²	—	—	540.0	—	—	625.0	—	—	—
iii)	TS/YS ratio ¹⁾ , N/mm ²	≥ 1.10, but TS not less than 485.0 N/mm ²	≥ 1.12, but TS not less than 500.0 N/mm ²	1.25	≥ 1.08, but TS not less than 545.0 N/mm ²	≥ 1.10, but TS not less than 565.0 N/mm ²	1.25	≥ 1.06, but TS not less than 585 N/mm ²	≥ 1.08, but TS not less than 600.0 N/mm ²	≥ 1.06, but TS not less than 660 N/mm ²
iv)	Elongation, percent, min. on gauge length $5.65\sqrt{A}$, where A is the cross-sectional area of the test piece	14.5	18.0	20.0	12.0	16.0	18.0	10.0	14.5	10.0
v)	Total elongation at maximum force, percent, <i>Min</i> , on gauge length $5.65\sqrt{A}$, where A is the cross-sectional area of the test piece (see 3.9) ²⁾	—	5	10	—	5	8	—	5	—

¹⁾ TS/YS ratio refers to ratio of tensile strength to the 0.2 percent proof stress or yield stress of the test piece

²⁾ Test, wherever specified by the purchaser.



Stainless Steels

- **Stainless steels** are alloys that contain **at least 12% of chromium**. Other alloying elements such as nickel and molybdenum may also be present.
- There are three basic types:
 - **Martensitic** – contain 13% Cr, very hard, heat treatable
 - **Ferritic** – contain 13% Cr but with very low carbon content, ductile, middle strength, not heat treatable
 - **Austenitic** – 18% Cr and 8% Ni, ductile, good strength, not heat treatable.
- Provide good resistance against corrosion as long as passive film is maintained. All will corrode in solutions low in oxygen.

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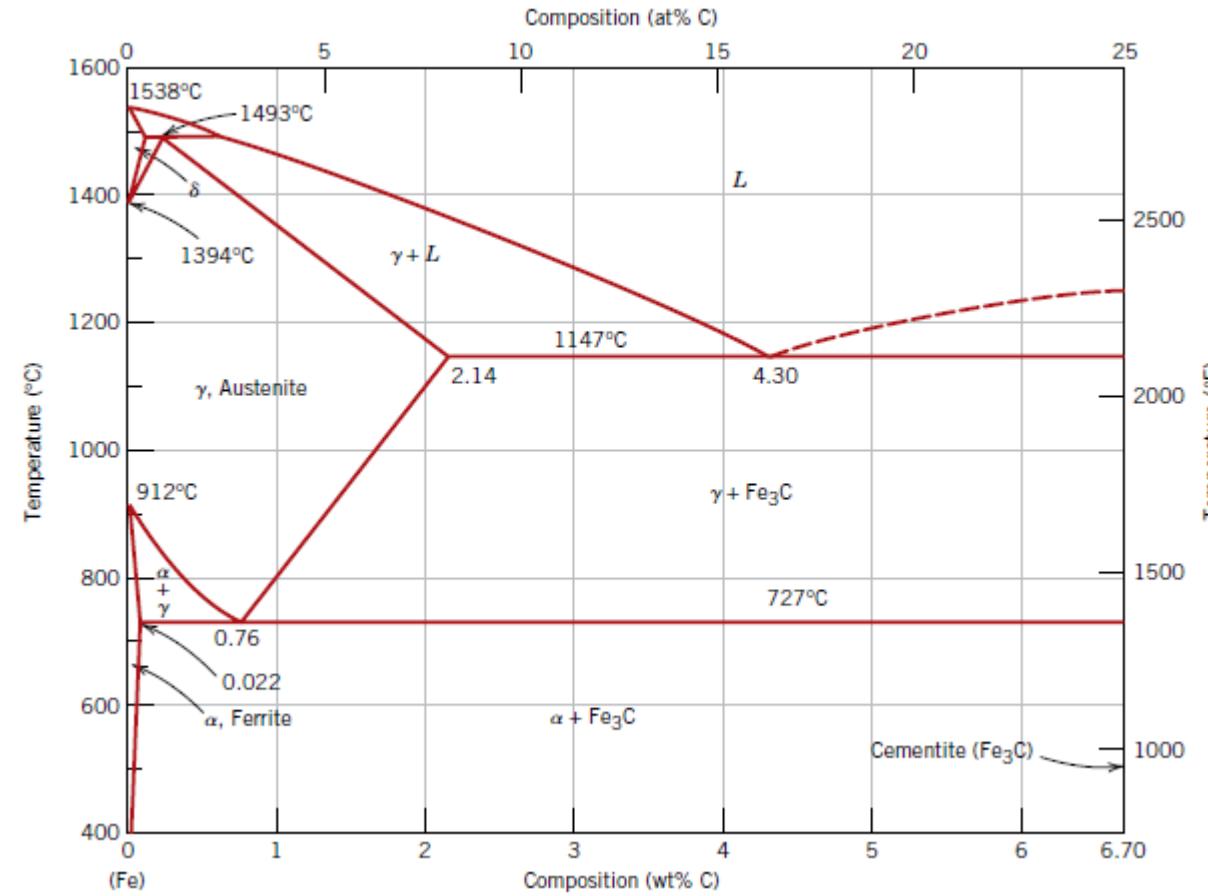


Classification Based on Carbon Content

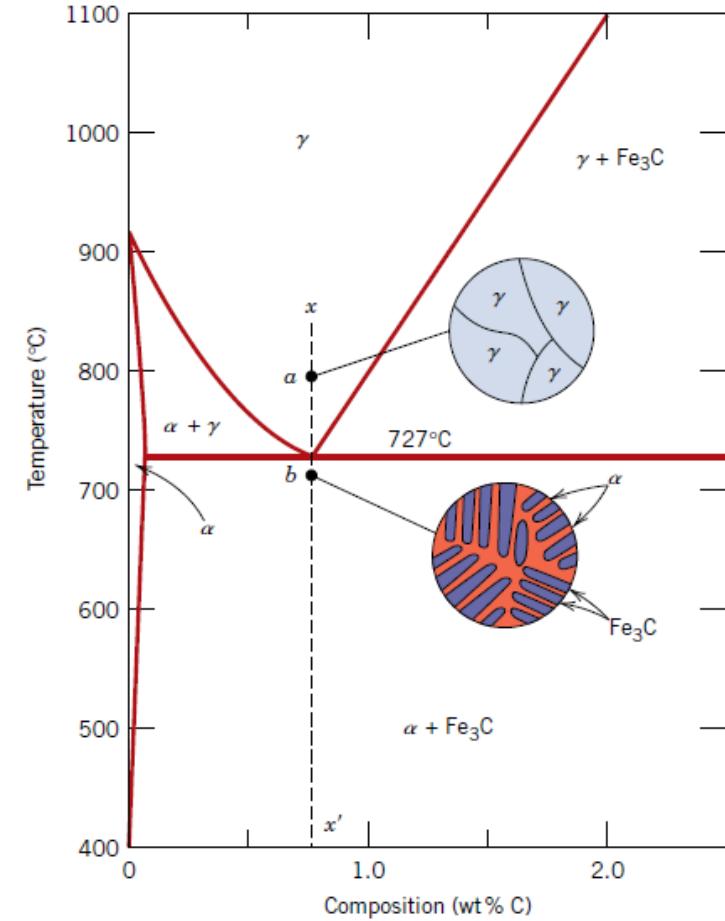
- Pure iron (less than 0.008 wt.% C)
- Steels (0.008 to 2.14 wt.% C)
- Cast iron (2.14 to 6.7 wt.% C)



Fe-C Phase Diagram

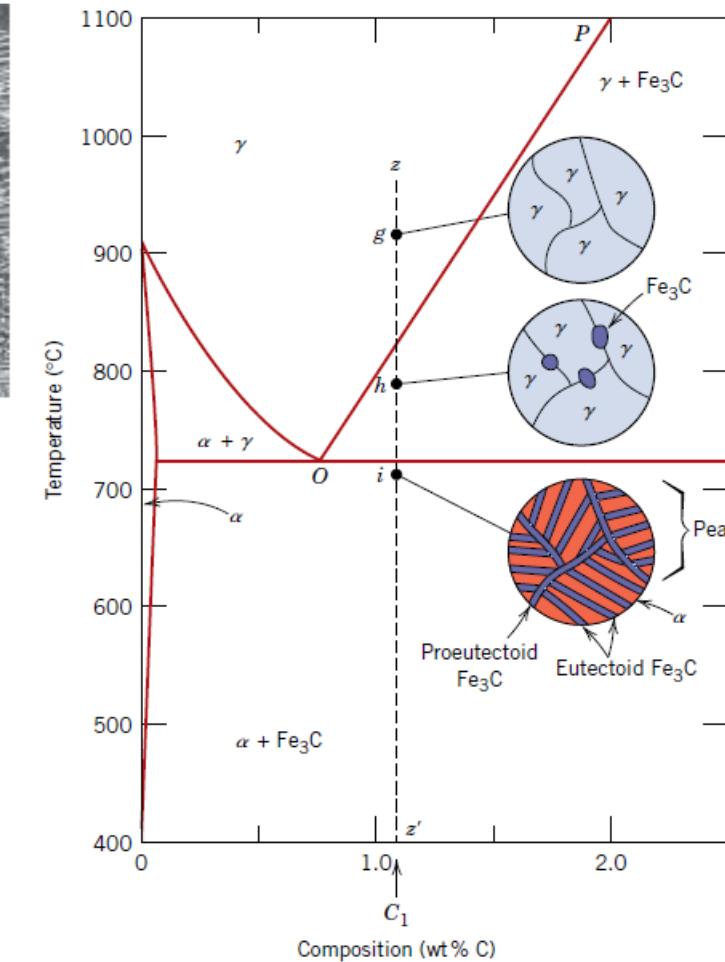
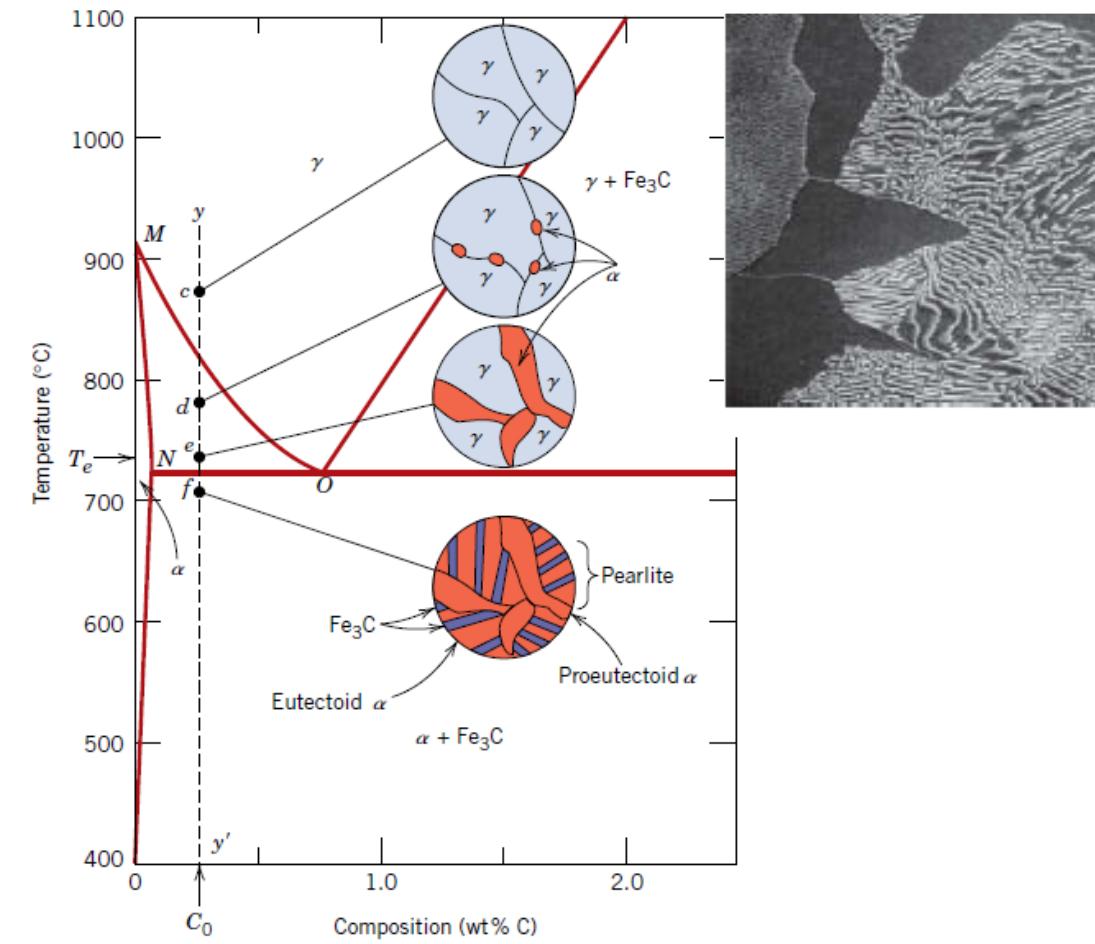


Austenite
Cementite
Ferrite



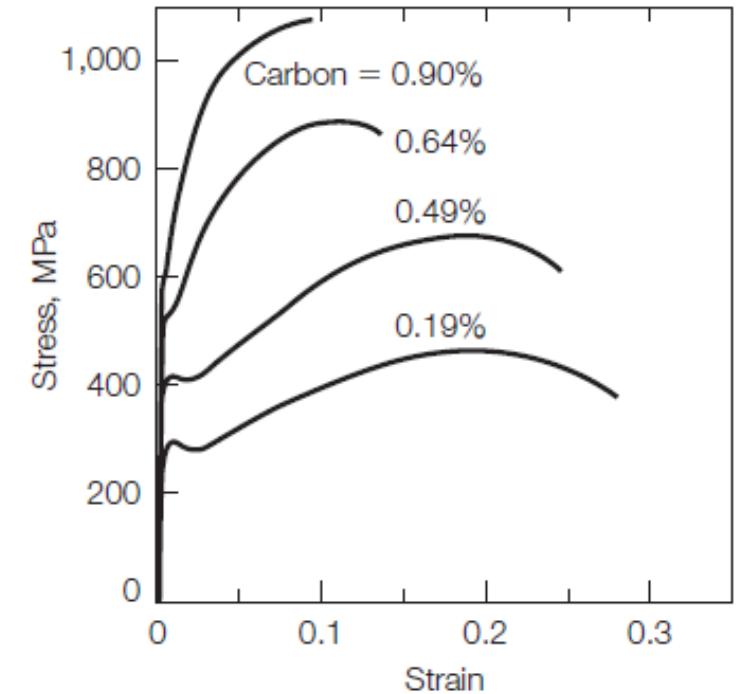
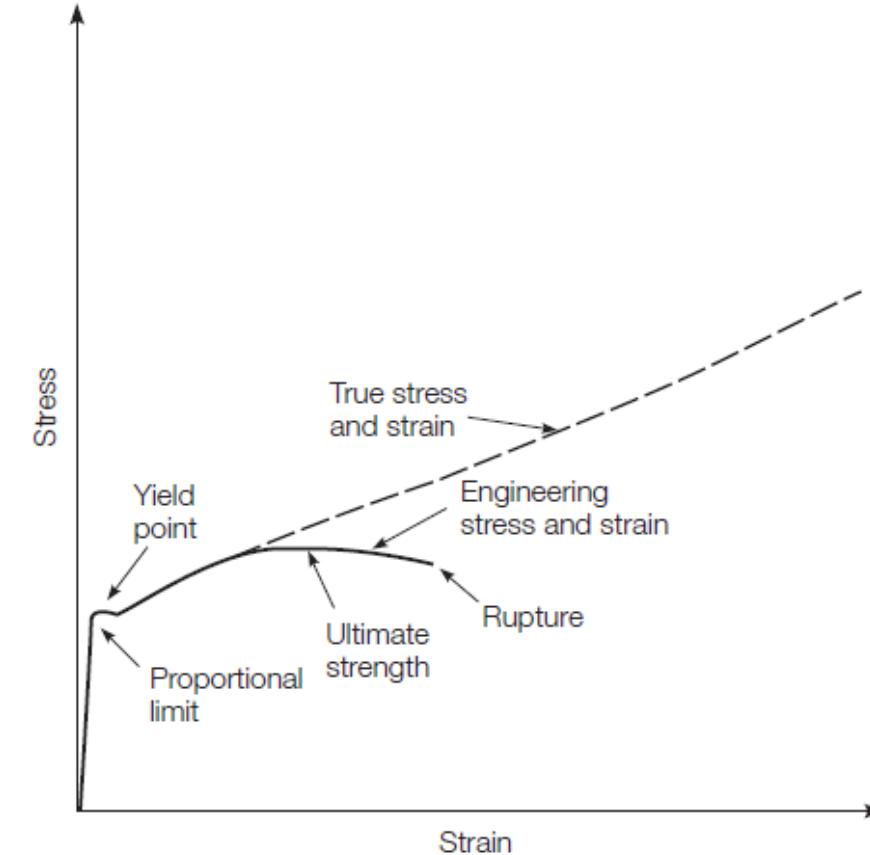


Fe-C Phase Diagram





Tension Test on Steel





Aluminum in Construction

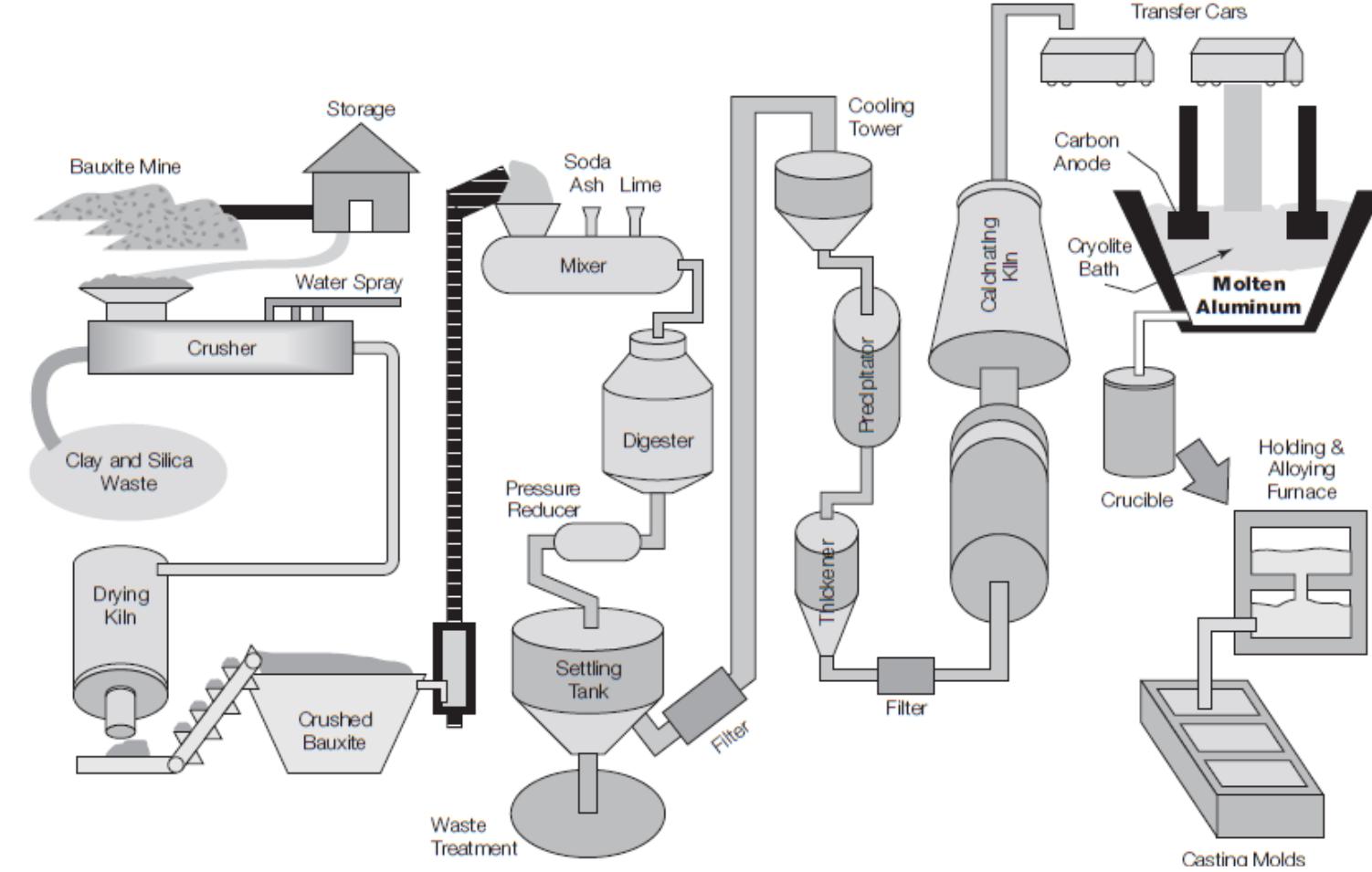
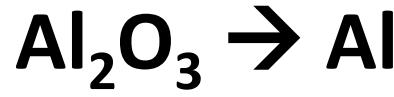
Advantages in Construction

- High strength-weight ratio
- High corrosion resistance
- Not attacked by insects – replacing wood for window and door frames
- Easy maintenance
- High reflectivity – does not absorb radiant heat
- Ease in fabrication and assembly

Varghese



Aluminum Production





Aluminum

- Aluminum and its alloys are widely used in construction.
- Properties:
 - specific gravity = 2.7
 - melting temperature = 658°C
 - ultimate tensile strength = about 200 MPa
 - modulus of elasticity = 68.9 GPa
- Pure aluminum is soft and ductile and has to be alloyed with other metals like copper, magnesium, silicon and manganese for increasing its strength and hardness.

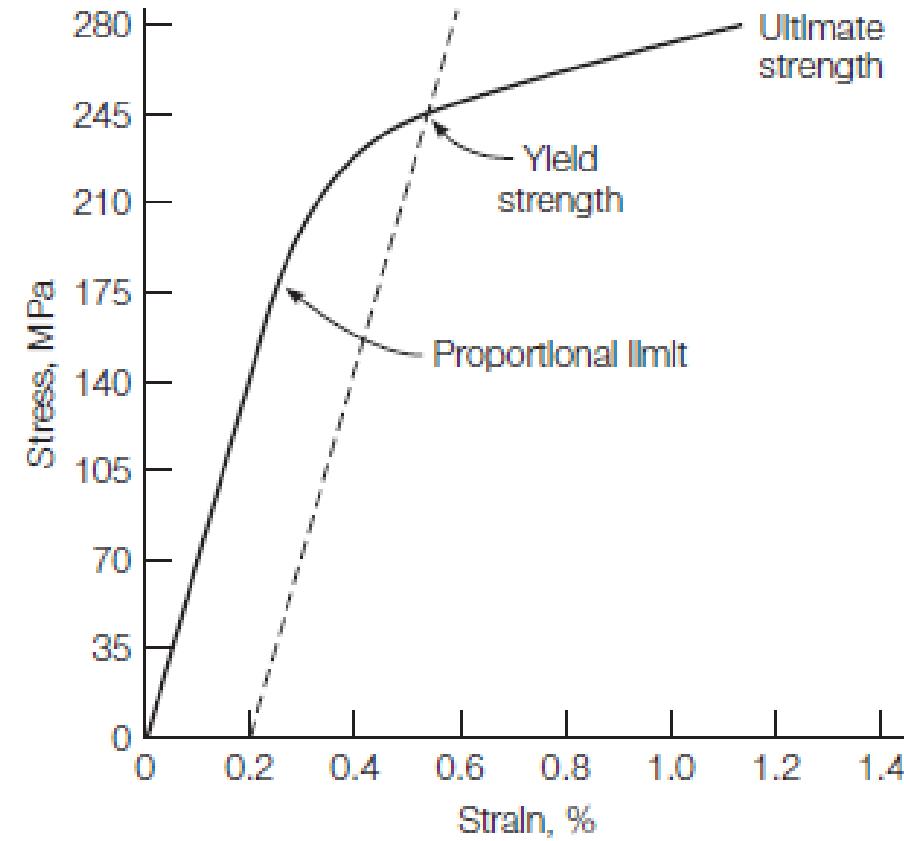
Varghese

<i>Alloy and treatment</i>	<i>Yield strength (MPa)</i>	<i>Tensile strength (MPa)</i>	<i>% elongation to fracture</i>
Pure aluminium:			
annealed	28	70	43
work-hardened	125	130	6
Al-11.5%Si, as-cast, modified	—	190	7
Al-2.5%Mg, non-heat-treatable, work hardened	270	330	10
Al-5.5%Cu, naturally aged	310	405	15
Al-5.5%Zn, 2.5%Mg, 1.6%Cu, artificially aged to best strength	505	570	11

Illston and Domone



Stress-Strain Diagram of Aluminum





Aluminum Foil Insulation

- Reflective insulation systems work by reflecting “radiant energy”.
- Traditional forms of mass insulation, like fiberglass, are effective in preventing heat transfer by conduction and convection, but they have virtually no effect on radiant heat. Radiant heat transfer typically has at least as much impact on the temperature in a building as do conduction and convection, and in many cases, it is the most significant cause of unwanted heat loss or gain.
- Aluminum foil, which can reflect up to 97% of the radiant energy that strikes it, has proven to be an outstanding component of reflective insulation systems. Reflective foil insulation is composed of two outer layers of aluminum foil with an inner layer of some inert material to create the required air gap between them.



Aluminum Foil Insulation



<https://insul.net/astroshield/>



References

- Construction Materials – Their Nature and Behavior, *Edited by M Soutsos and P. Damone*, Fifth Edition, CRC Press.
- Materials Science and Engineering, *Callister, William D., and David G. Rethwisch*, John Wiley & Sons, 2011.
- Michael S. Mamlouk and John P. Zaniewski, “Materials for Civil and Construction Engineers,” Addison Wesley Longman Inc., USA, 1999.

The Iron–Carbon System

Of all binary alloy systems, the one that is possibly the most important is that for iron and carbon. Both steels and cast irons, primary structural materials in every technologically advanced culture, are essentially iron–carbon alloys. This section is devoted to a study of the phase diagram for this system and the development of several of the possible microstructures. The relationships among heat treatment, microstructure, and mechanical properties are explored in Chapters 10 and 11.

9.18 THE IRON–IRON CARBIDE ($\text{Fe}-\text{Fe}_3\text{C}$) PHASE DIAGRAM

ferrite
austenite

A portion of the iron–carbon phase diagram is presented in Figure 9.24. Pure iron, upon heating, experiences two changes in crystal structure before it melts. At room temperature, the stable form, called **ferrite**, or α -iron, has a BCC crystal structure. Ferrite experiences a polymorphic transformation to FCC **austenite**, or γ -iron, at 912°C (1674°F). This austenite persists to 1394°C (2541°F), at which temperature the FCC austenite reverts back to a BCC phase known as δ -ferrite, which finally melts

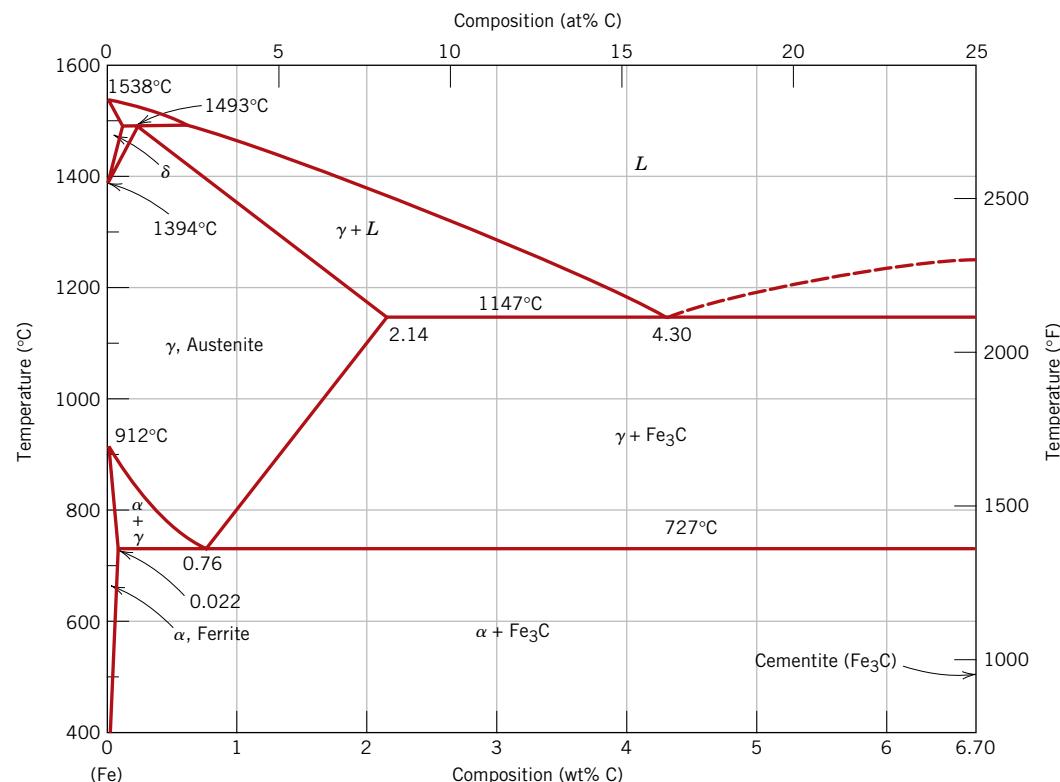
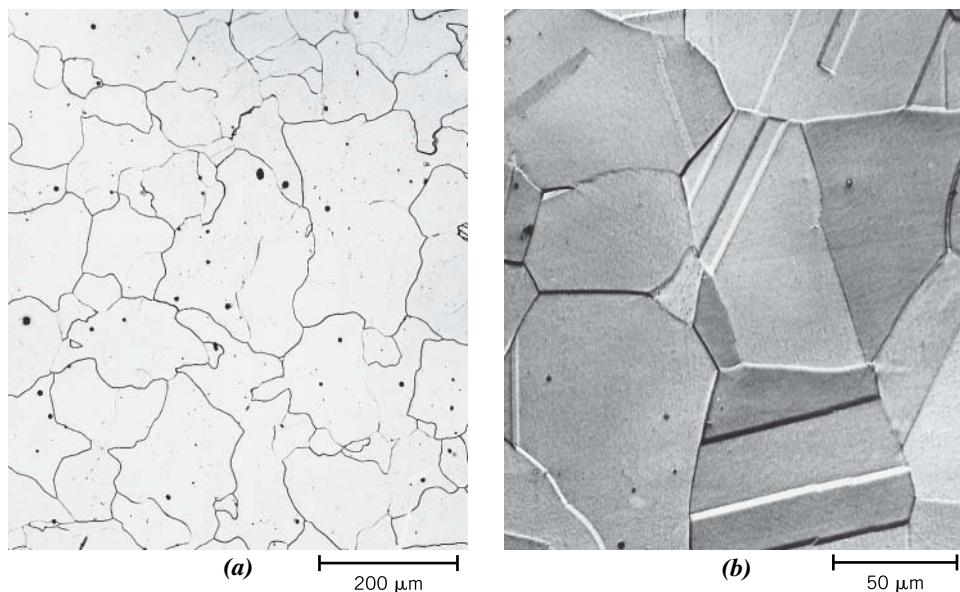


Figure 9.24 The iron–iron carbide phase diagram.

[Adapted from *Binary Alloy Phase Diagrams*, 2nd edition, Vol. 1, T. B. Massalski (Editor-in-Chief), 1990. Reprinted by permission of ASM International, Materials Park, OH.]

Figure 9.25

Photomicrographs of (a) α -ferrite ($90\times$) and (b) austenite ($325\times$). (Copyright 1971 by United States Steel Corporation.)



at 1538°C (2800°F). All these changes are apparent along the left vertical axis of the phase diagram.¹

cementite

The composition axis in Figure 9.24 extends only to 6.70 wt% C; at this concentration the intermediate compound iron carbide, or **cementite** (Fe_3C), is formed, which is represented by a vertical line on the phase diagram. (Schematic representations of the unit cell for cementite from three different perspectives are shown on the front cover of the book. Brown and blue spheres represent iron and carbon atoms, respectively.) Thus, the iron–carbon system may be divided into two parts: an iron-rich portion, as in Figure 9.24, and the other (not shown) for compositions between 6.70 and 100 wt% C (pure graphite). In practice, all steels and cast irons have carbon contents less than 6.70 wt% C; therefore, we consider only the iron–iron carbide system. Figure 9.24 would be more appropriately labeled the $\text{Fe}-\text{Fe}_3\text{C}$ phase diagram because Fe_3C is now considered to be a component. Convention and convenience dictate that composition still be expressed in “wt% C” rather than “wt% Fe_3C ”; 6.70 wt% C corresponds to 100 wt% Fe_3C .

Carbon is an interstitial impurity in iron and forms a solid solution with each of α - and δ -ferrites and also with austenite, as indicated by the α , δ , and γ single-phase fields in Figure 9.24. [Unit cell representations for BCC α -ferrite from three different perspectives are shown on the back cover of the book. Each unit cell contains an interstitial carbon atom (a blue sphere); brown spheres denote iron atoms.] In the BCC α -ferrite, only small concentrations of carbon are soluble; the maximum solubility is 0.022 wt% at 727°C (1341°F). The limited solubility is explained by the shape and size of the BCC interstitial positions, which make it difficult to accommodate the carbon atoms. Even though present in relatively low concentrations, carbon significantly influences the mechanical properties of ferrite. This particular iron–carbon phase is relatively soft, may be made magnetic at temperatures below 768°C (1414°F), and has a density of 7.88 g/cm^3 . Figure 9.25a is a photomicrograph of α -ferrite.

¹The reader may wonder why no β phase is found on the $\text{Fe}-\text{Fe}_3\text{C}$ phase diagram, Figure 9.24 (consistent with the α , β , γ , etc. labeling scheme described previously). Early investigators observed that the ferromagnetic behavior of iron disappears at 768°C and attributed this phenomenon to a phase transformation; the “ β ” label was assigned to the high-temperature phase. Later, it was discovered that this loss of magnetism did not result from a phase transformation (see Section 20.6) and, therefore, the presumed β phase did not exist.

The austenite, or γ phase, of iron, when alloyed with carbon alone, is not stable below 727°C (1341°F), as indicated in Figure 9.24. The maximum solubility of carbon in austenite, 2.14 wt%, occurs at 1147°C (2097°F). This solubility is approximately 100 times greater than the maximum for BCC ferrite because the FCC octahedral sites are larger than the BCC tetrahedral sites (compare the results of Problems 4.8a and 4.9), and, therefore, the strains imposed on the surrounding iron atoms are much lower. As the discussions that follow demonstrate, phase transformations involving austenite are very important in the heat treating of steels. In passing, it should be mentioned that austenite is nonmagnetic. Figure 9.25b shows a photomicrograph of this austenite phase.²

The δ -ferrite is virtually the same as α -ferrite, except for the range of temperatures over which each exists. Because the δ -ferrite is stable only at relatively high temperatures, it is of no technological importance and is not discussed further.

Cementite (Fe₃C) forms when the solubility limit of carbon in α -ferrite is exceeded below 727°C (1341°F) (for compositions within the α + Fe₃C phase region). As indicated in Figure 9.24, Fe₃C also coexists with the γ phase between 727°C and 1147°C (1341°F and 2097°F). Mechanically, cementite is very hard and brittle; the strength of some steels is greatly enhanced by its presence.

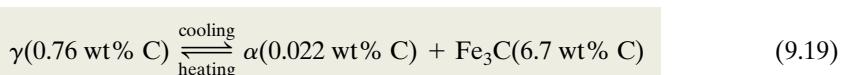
Strictly speaking, cementite is only metastable; that is, it remains as a compound indefinitely at room temperature. However, if heated to between 650°C and 700°C (1200°F and 1300°F) for several years, it gradually changes or transforms into α -iron and carbon, in the form of graphite, which remains upon subsequent cooling to room temperature. Thus, the phase diagram in Figure 9.24 is not a true equilibrium one because cementite is not an equilibrium compound. However, because the decomposition rate of cementite is extremely sluggish, virtually all the carbon in steel is as Fe₃C instead of graphite, and the iron–iron carbide phase diagram is, for all practical purposes, valid. As will be seen in Section 11.2, addition of silicon to cast irons greatly accelerates this cementite decomposition reaction to form graphite.

The two-phase regions are labeled in Figure 9.24. It may be noted that one eutectic exists for the iron–iron carbide system, at 4.30 wt% C and 1147°C (2097°F); for this eutectic reaction,



the liquid solidifies to form austenite and cementite phases. Subsequent cooling to room temperature promotes additional phase changes.

It may be noted that a eutectoid invariant point exists at a composition of 0.76 wt% C and a temperature of 727°C (1341°F). This eutectoid reaction may be represented by



or, upon cooling, the solid γ phase is transformed into α -iron and cementite. (Eutectoid phase transformations were addressed in Section 9.14.) The eutectoid phase changes described by Equation 9.19 are very important, being fundamental to the heat treatment of steels, as explained in subsequent discussions.

Ferrous alloys are those in which iron is the prime component, but carbon as well as other alloying elements may be present. In the classification scheme of ferrous alloys based on carbon content, there are three types: iron, steel, and cast iron. Commercially pure iron contains less than 0.008 wt% C and, from the phase diagram, is composed almost exclusively of the ferrite phase at room temperature. The iron–carbon alloys

WileyPLUS
Tutorial Video:
Eutectic Reaction
Vocabulary and Microstructures
Eutectoid
Reaction Terms

Eutectic reaction for the iron–iron carbide system

Eutectoid reaction for the iron–iron carbide system

²Annealing twins, found in alloys having the FCC crystal structure (Section 4.6), may be observed in this photomicrograph for austenite. They do not occur in BCC alloys, which explains their absence in the ferrite micrograph of Figure 9.25a.

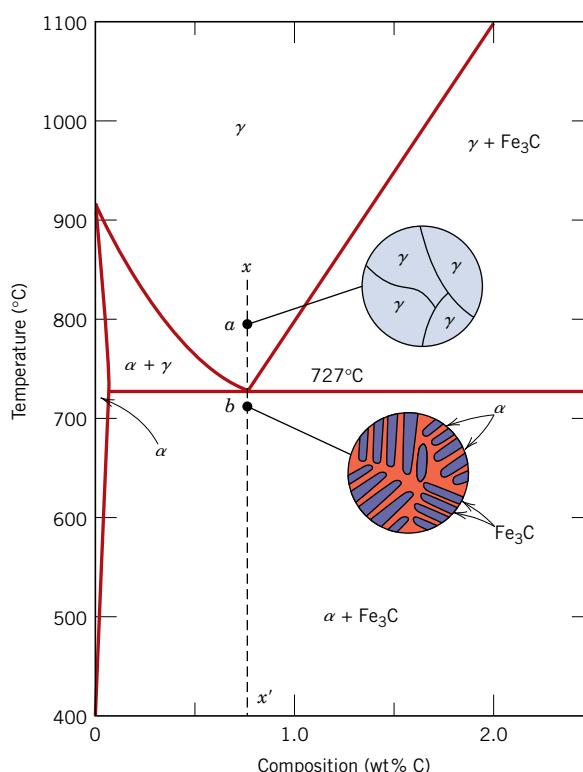
that contain between 0.008 and 2.14 wt% C are classified as steels. In most steels, the microstructure consists of both α and Fe_3C phases. Upon cooling to room temperature, an alloy within this composition range must pass through at least a portion of the γ -phase field; distinctive microstructures are subsequently produced, as discussed shortly. Although a steel alloy may contain as much as 2.14 wt% C, in practice, carbon concentrations rarely exceed 1.0 wt%. The properties and various classifications of steels are treated in Section 11.2. Cast irons are classified as ferrous alloys that contain between 2.14 and 6.70 wt% C. However, commercial cast irons normally contain less than 4.5 wt% C. These alloys are discussed further in Section 11.2.

9.19 DEVELOPMENT OF MICROSTRUCTURE IN IRON-CARBON ALLOYS

Several of the various microstructures that may be produced in steel alloys and their relationships to the iron–iron carbon phase diagram are now discussed, and it is shown that the microstructure that develops depends on both the carbon content and heat treatment. This discussion is confined to very slow cooling of steel alloys, in which equilibrium is continuously maintained. A more detailed exploration of the influence of heat treatment on microstructure, and ultimately on the mechanical properties of steels, is contained in Chapter 10.

Phase changes that occur upon passing from the γ region into the $\alpha + \text{Fe}_3\text{C}$ phase field (Figure 9.24) are relatively complex and similar to those described for the eutectic systems in Section 9.12. Consider, for example, an alloy of eutectoid composition (0.76 wt% C) as it is cooled from a temperature within the γ -phase region, say, 800°C—that is, beginning at point *a* in Figure 9.26 and moving down the vertical line

Figure 9.26 Schematic representations of the microstructures for an iron–carbon alloy of eutectoid composition (0.76 wt% C) above and below the eutectoid temperature.



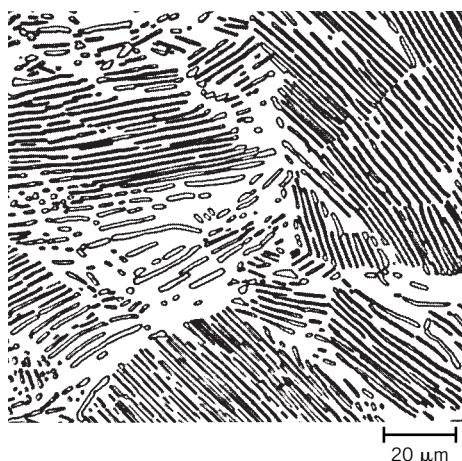


Figure 9.27 Photomicrograph of a eutectoid steel showing the pearlite microstructure consisting of alternating layers of α -ferrite (the light phase) and Fe_3C (thin layers most of which appear dark). 470 \times . (From *Metals Handbook*, Vol. 9, 9th edition, *Metallography and Microstructures*, 1985. Reproduced by permission of ASM International, Materials Park, OH.)

xx' . Initially, the alloy is composed entirely of the austenite phase having a composition of 0.76 wt% C and corresponding microstructure, also indicated in Figure 9.26. As the alloy is cooled, no changes occur until the eutectoid temperature (727°C) is reached. Upon crossing this temperature to point *b*, the austenite transforms according to Equation 9.19.

The microstructure for this eutectoid steel that is slowly cooled through the eutectoid temperature consists of alternating layers or lamellae of the two phases (α and Fe_3C) that form simultaneously during the transformation. In this case, the relative layer thickness is approximately 8 to 1. This microstructure, represented schematically in Figure 9.26, point *b*, is called **pearlite** because it has the appearance of mother-of-pearl when viewed under the microscope at low magnifications. Figure 9.27 is a photomicrograph of a eutectoid steel showing the pearlite. The pearlite exists as grains, often termed colonies; within each colony the layers are oriented in essentially the same direction, which varies from one colony to another. The thick light layers are the ferrite phase, and the cementite phase appears as thin lamellae, most of which appear dark. Many cementite layers are so thin that adjacent phase boundaries are so close together that they are indistinguishable at this magnification and, therefore, appear dark. Mechanically, pearlite has properties intermediate between those of the soft, ductile ferrite and the hard, brittle cementite.

The alternating α and Fe_3C layers in pearlite form for the same reason that the eutectic structure (Figures 9.13 and 9.14) forms—because the composition of the parent phase [in this case, austenite (0.76 wt% C)] is different from that of either of the product phases [ferrite (0.022 wt% C) and cementite (6.70 wt% C)], and the phase transformation requires that there be a redistribution of the carbon by diffusion. Figure 9.28 illustrates microstructural changes that accompany this eutectoid reaction; here, the directions of carbon diffusion are indicated by arrows. Carbon atoms diffuse away from the 0.022-wt% ferrite regions and to the 6.70-wt% cementite layers, as the pearlite extends from the grain boundary into the unreacted austenite grain. The layered pearlite forms because carbon atoms need diffuse only minimal distances with the formation of this structure.

Subsequent cooling of the pearlite from point *b* in Figure 9.26 produces relatively insignificant microstructural changes.

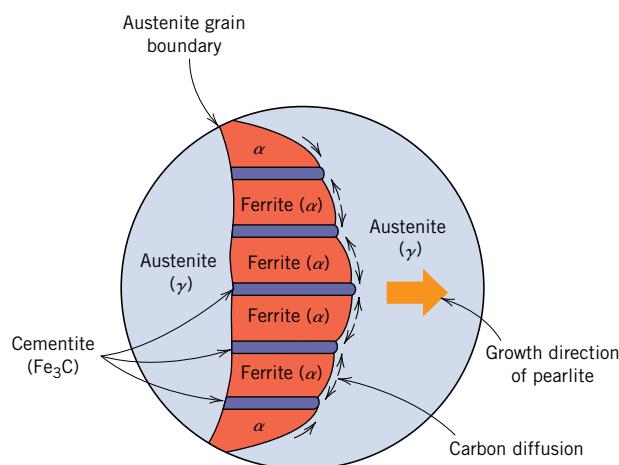
pearlite

Figure 9.28 Schematic representation of the formation of pearlite from austenite; direction of carbon diffusion indicated by arrows.

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Tutorial Video:
Eutectoid
Reaction
Vocabulary and
Microstructures

How do the Eutectoid
Microstructures Form?

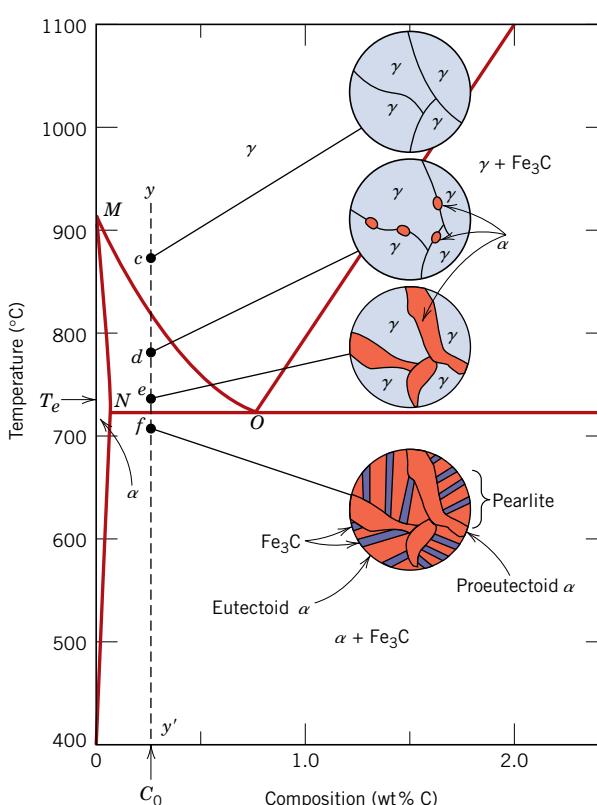


Hypoeutectoid Alloys

Microstructures for iron–iron carbide alloys having other than the eutectoid composition are now explored; these are analogous to the fourth case described in Section 9.12 and illustrated in Figure 9.16 for the eutectic system. Consider a composition C_0 to the left of the eutectoid, between 0.022 and 0.76 wt% C; this is termed a **hypoeutectoid** (“less than eutectoid”) **alloy**. Cooling an alloy of this composition is represented by moving down the vertical line yy' in Figure 9.29. At about 875°C, point c , the microstructure consists

hypoeutectoid alloy

Figure 9.29 Schematic representations of the microstructures for an iron–carbon alloy of hypoeutectoid composition C_0 (containing less than 0.76 wt% C) as it is cooled from within the austenite phase region to below the eutectoid temperature.





Scanning electron micrograph showing the microstructure of a steel that contains 0.44 wt% C. The large dark areas are proeutectoid ferrite. Regions having the alternating light and dark lamellar structure are pearlite; the dark and light layers in the pearlite correspond, respectively, to ferrite and cementite phases. 700 \times . (Micrograph courtesy of Republic Steel Corporation.)

proeutectoid ferrite

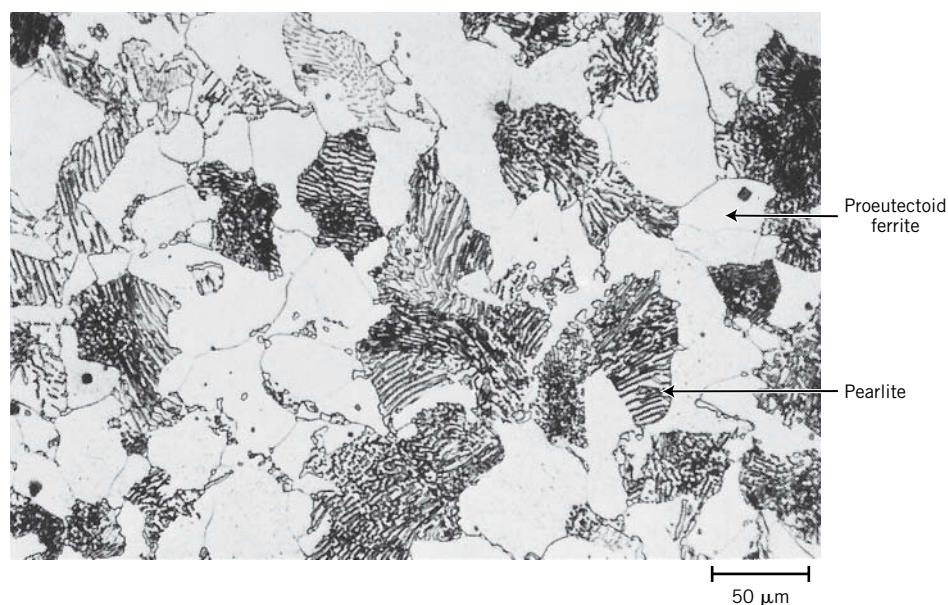
entirely of grains of the γ phase, as shown schematically in the figure. In cooling to point *d*, about 775°C, which is within the $\alpha + \gamma$ phase region, both these phases coexist as in the schematic microstructure. Most of the small α particles form along the original γ grain boundaries. The compositions of both α and γ phases may be determined using the appropriate tie line; these compositions correspond, respectively, to about 0.020 and 0.40 wt% C.

While cooling an alloy through the $\alpha + \gamma$ phase region, the composition of the ferrite phase changes with temperature along the $\alpha - (\alpha + \gamma)$ phase boundary, line *MN*, becoming slightly richer in carbon. However, the change in composition of the austenite is more dramatic, proceeding along the $(\alpha + \gamma) - \gamma$ boundary, line *MO*, as the temperature is reduced.

Cooling from point *d* to *e*, just above the eutectoid but still in the $\alpha + \gamma$ region, produces an increased fraction of the α phase and a microstructure similar to that also shown: the α particles will have grown larger. At this point, the compositions of the α and γ phases are determined by constructing a tie line at the temperature T_e ; the α phase contains 0.022 wt% C, whereas the γ phase is of the eutectoid composition, 0.76 wt% C.

As the temperature is lowered just below the eutectoid, to point *f*, all of the γ phase that was present at temperature T_e (and having the eutectoid composition) transforms into pearlite, according to the reaction in Equation 9.19. There is virtually no change in the α phase that existed at point *e* in crossing the eutectoid temperature—it is normally present as a continuous matrix phase surrounding the isolated pearlite colonies. The microstructure at point *f* appears as the corresponding schematic inset of Figure 9.29. Thus the ferrite phase is present both in the pearlite and as the phase that formed while cooling through the $\alpha + \gamma$ phase region. The ferrite present in the pearlite is called **eutectoid ferrite**, whereas the other, which formed above T_e , is termed **proeutectoid ferrite** (meaning “pre- or before eutectoid”) **ferrite**, as labeled in Figure 9.29. Figure 9.30 is a photomicrograph of a 0.38-wt% C steel; large, white regions correspond to the proeutectoid ferrite. For pearlite, the spacing between the α and Fe_3C layers varies from grain to grain; some

Figure 9.30
Photomicrograph of a 0.38 wt% C steel having a microstructure consisting of pearlite and proeutectoid ferrite. 635 \times . (Photomicrograph courtesy of Republic Steel Corporation.)



of the pearlite appears dark because the many close-spaced layers are unresolved at the magnification of the photomicrograph. Note that two microconstituents are present in this micrograph—proeutectoid ferrite and pearlite—which appear in all hypoeutectoid iron–carbon alloys that are slowly cooled to a temperature below the eutectoid.

The relative amounts of the proeutectoid α and pearlite may be determined in a manner similar to that described in Section 9.12 for primary and eutectic microconstituents. We use the lever rule in conjunction with a tie line that extends from the α –(α + Fe₃C) phase boundary (0.022-wt% C) to the eutectoid composition (0.76-wt% C) inasmuch as pearlite is the transformation product of austenite having this composition. For example, let us consider an alloy of composition C'_0 in Figure 9.31. The fraction of pearlite, W_p , may be determined according to

Lever rule expression for computation of pearlite mass fraction (composition C'_0 , Figure 9.31)

$$\begin{aligned} W_p &= \frac{T}{T + U} \\ &= \frac{C'_0 - 0.022}{0.76 - 0.022} = \frac{C'_0 - 0.022}{0.74} \end{aligned} \quad (9.20)$$

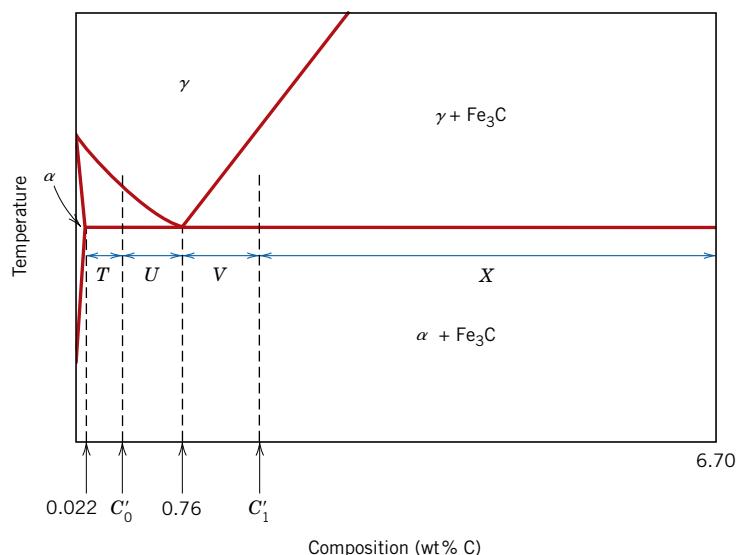
The fraction of proeutectoid α , W_α , is computed as follows:

Lever rule expression for computation of proeutectoid ferrite mass fraction

$$\begin{aligned} W_{\alpha'} &= \frac{U}{T + U} \\ &= \frac{0.76 - C'_0}{0.76 - 0.022} = \frac{0.76 - C'_0}{0.74} \end{aligned} \quad (9.21)$$

Fractions of both total α (eutectoid and proeutectoid) and cementite are determined using the lever rule and a tie line that extends across the entirety of the α + Fe₃C phase region, from 0.022 to 6.70 wt% C.

Figure 9.31 A portion of the Fe–Fe₃C phase diagram used in computing the relative amounts of proeutectoid and pearlite microconstituents for hypoeutectoid C'_0 and hypereutectoid C'_1 compositions.



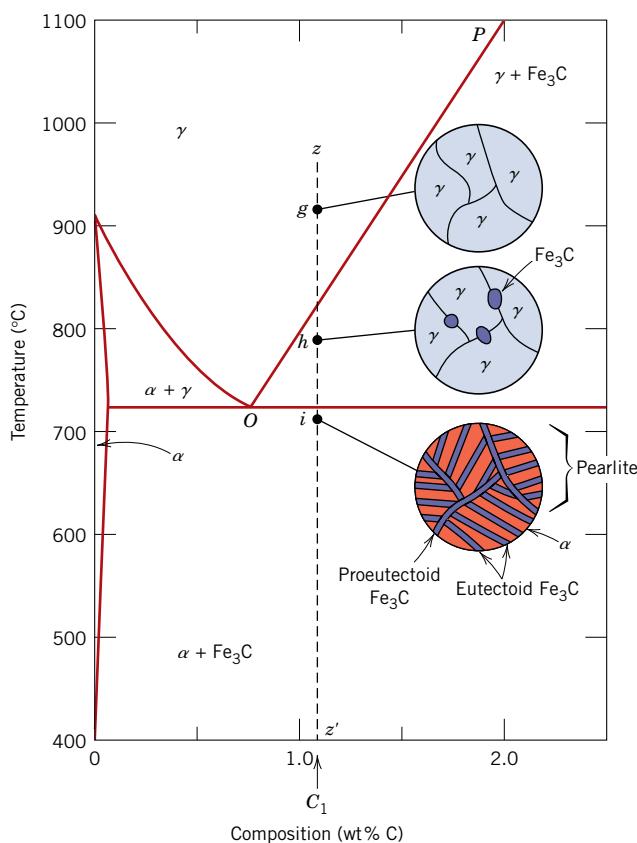


Figure 9.32 Schematic representations of the microstructures for an iron–carbon alloy of hypereutectoid composition C_1 (containing between 0.76 and 2.14 wt% C) as it is cooled from within the austenite-phase region to below the eutectoid temperature.

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Tutorial Video:
Eutectoid Reaction Vocabulary and Microstructures

Which Eutectoid Microstructures go with Which Regions on a Eutectoid Phase Diagram?

Hypereutectoid Alloys

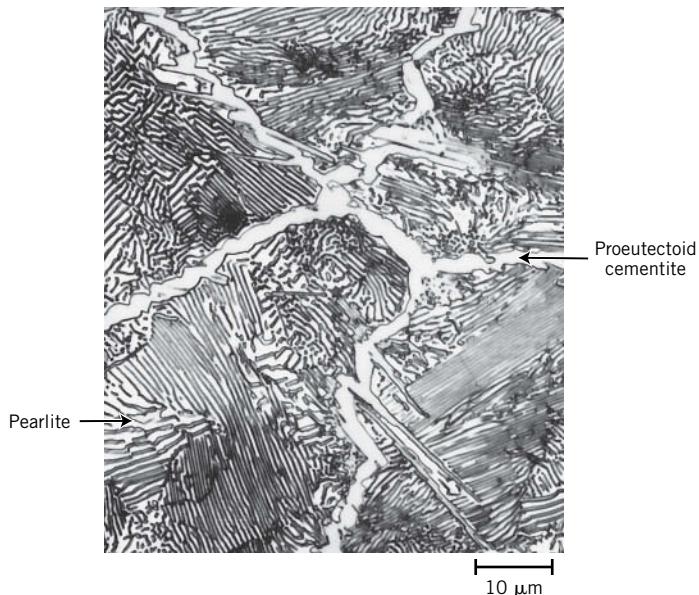
hypereutectoid alloy

Analogous transformations and microstructures result for **hypereutectoid alloys**—those containing between 0.76 and 2.14 wt% C—that are cooled from temperatures within the γ -phase field. Consider an alloy of composition C_1 in Figure 9.32 that, upon cooling, moves down the line zz' . At point g , only the γ phase is present with a composition of C_1 ; the microstructure appears as shown, having only γ grains. Upon cooling into the $\gamma + \text{Fe}_3\text{C}$ phase field—say, to point h —the cementite phase begins to form along the initial γ grain boundaries, similar to the α phase in Figure 9.29, point d . This cementite is called **proeutectoid cementite**—that which forms before the eutectoid reaction. The cementite composition remains constant (6.70 wt% C) as the temperature changes. However, the composition of the austenite phase moves along line PO toward the eutectoid. As the temperature is lowered through the eutectoid to point i , all remaining austenite of eutectoid composition is converted into pearlite; thus, the resulting microstructure consists of pearlite and proeutectoid cementite as microconstituents (Figure 9.32). In the photomicrograph of a 1.4-wt% C steel (Figure 9.33), note that the proeutectoid cementite appears light. Because it has much the same appearance as proeutectoid ferrite (Figure 9.30), there is some difficulty in distinguishing between hypoeutectoid and hypereutectoid steels on the basis of microstructure.

Relative amounts of both pearlite and proeutectoid Fe_3C microconstituents may be computed for hypereutectoid steel alloys in a manner analogous to that for hypoeutectoid materials; the appropriate tie line extends between 0.76 and 6.70

proeutectoid cementite

Figure 9.33 Photomicrograph of a 1.4 wt% C steel having a microstructure consisting of a white proeutectoid cementite network surrounding the pearlite colonies. 1000 \times . (Copyright 1971 by United States Steel Corporation.)



wt% C. Thus, for an alloy having composition C'_1 in Figure 9.31, fractions of pearlite W_p and proeutectoid cementite $W_{\text{Fe}_3\text{C}'}$ are determined from the following lever rule expressions:

$$W_p = \frac{X}{V + X} = \frac{6.70 - C'_1}{6.70 - 0.76} = \frac{6.70 - C'_1}{5.94} \quad (9.22)$$

and

$$W_{\text{Fe}_3\text{C}'} = \frac{V}{V + X} = \frac{C'_1 - 0.76}{6.70 - 0.76} = \frac{C'_1 - 0.76}{5.94} \quad (9.23)$$



Concept Check 9.9 Briefly explain why a proeutectoid phase (ferrite or cementite) forms along austenite grain boundaries. *Hint: Consult Section 4.6.*

[The answer may be found at www.wiley.com/college/callister (Student Companion Site).]

EXAMPLE PROBLEM 9.4

Determination of Relative Amounts of Ferrite, Cementite, and Pearlite Microconstituents

For a 99.65 wt% Fe–0.35 wt% C alloy at a temperature just below the eutectoid, determine the following:

- (a) The fractions of total ferrite and cementite phases
- (b) The fractions of the proeutectoid ferrite and pearlite
- (c) The fraction of eutectoid ferrite

Solution

- (a) This part of the problem is solved by applying the lever rule expressions using a tie line that extends all the way across the $\alpha + \text{Fe}_3\text{C}$ phase field. Thus, C'_0 is 0.35 wt% C, and

$$W_\alpha = \frac{6.70 - 0.35}{6.70 - 0.022} = 0.95$$

and

$$W_{\text{Fe}_3\text{C}} = \frac{0.35 - 0.022}{6.70 - 0.022} = 0.05$$

- (b) The fractions of proeutectoid ferrite and pearlite are determined by using the lever rule and a tie line that extends only to the eutectoid composition (i.e., Equations 9.20 and 9.21). We have

$$W_p = \frac{0.35 - 0.022}{0.76 - 0.022} = 0.44$$

and

$$W_{\alpha'} = \frac{0.76 - 0.35}{0.76 - 0.022} = 0.56$$

- (c) All ferrite is either as proeutectoid or eutectoid (in the pearlite). Therefore, the sum of these two ferrite fractions equals the fraction of total ferrite; that is,

$$W_{\alpha'} + W_{\alpha e} = W_\alpha$$

where $W_{\alpha e}$ denotes the fraction of the total alloy that is eutectoid ferrite. Values for W_α and $W_{\alpha'}$ were determined in parts (a) and (b) as 0.95 and 0.56, respectively. Therefore,

$$W_{\alpha e} = W_\alpha - W_{\alpha'} = 0.95 - 0.56 = 0.39$$

Nonequilibrium Cooling

In this discussion of the microstructural development of iron-carbon alloys, it has been assumed that, upon cooling, conditions of metastable equilibrium³ have been continuously maintained; that is, sufficient time has been allowed at each new temperature for any necessary adjustment in phase compositions and relative amounts as predicted from the Fe–Fe₃C phase diagram. In most situations these cooling rates are impractically slow and unnecessary; in fact, on many occasions nonequilibrium conditions are desirable. Two nonequilibrium effects of practical importance are (1) the occurrence of phase changes or transformations at temperatures other than those predicted by phase boundary lines on the phase diagram, and (2) the existence at room temperature of nonequilibrium phases that do not appear on the phase diagram. Both are discussed in Chapter 10.

³The term *metastable equilibrium* is used in this discussion because Fe₃C is only a metastable compound.



Aggregates

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Applications of Aggregates

- Foundations and pavements
- Riprap for erosion protection
- Ingredients in Portland cement and asphalt concrete





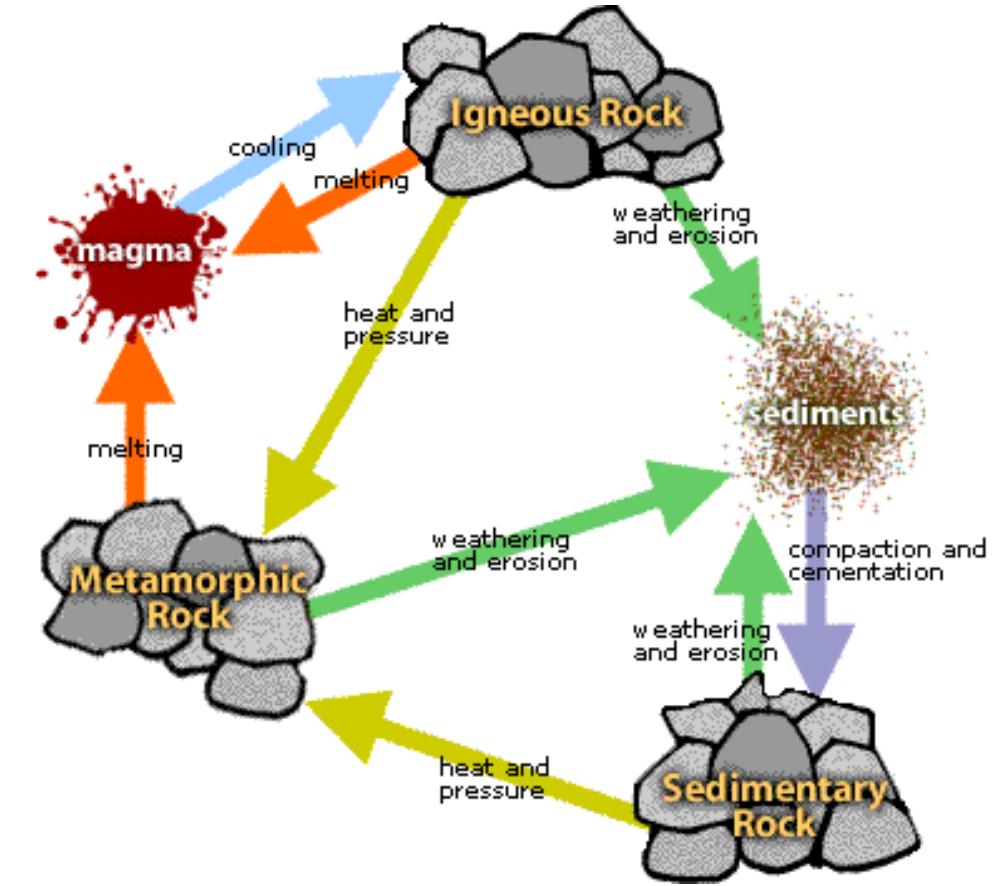
Types of Aggregates

- Coarse aggregates: aggregate particles that are retained on a 4.75 mm sieve
- Fine aggregates: aggregate particles that pass a 4.75 mm sieve

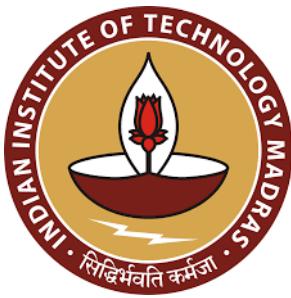


Sources of Aggregates

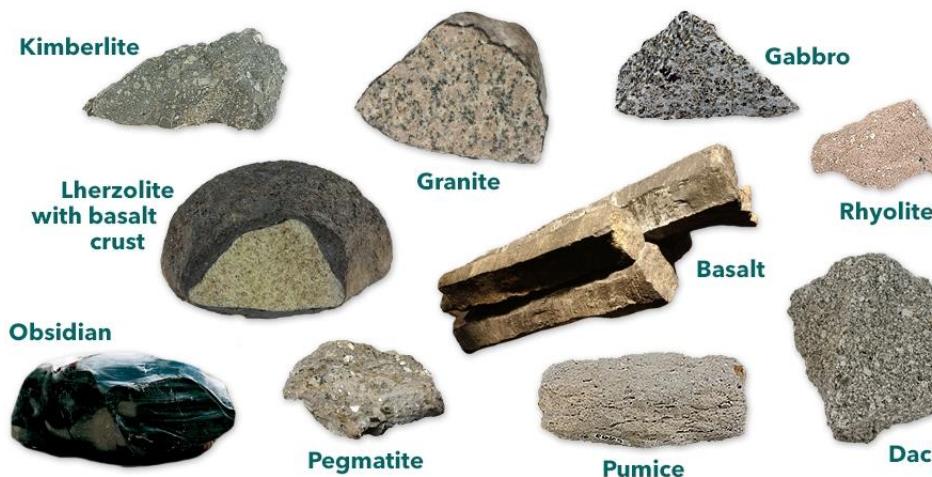
- Igneous rocks
- Sedimentary rocks
- Metamorphic rocks



<http://www.cotf.edu/ete/modules/msese/earthsystlr/rock.html>



Igneous Rocks



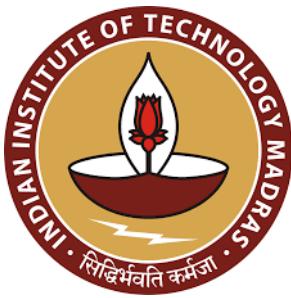
Sedimentary Rocks



Metamorphic Rocks



<https://www.amnh.org/explore/ology/earth/if-rocks-could-talk2/three-types-of-rock>



Aggregate Properties

- Physical
 - Shape
 - Size
 - Surface texture
 - Pore structure
 - Specific gravity
 - Soundness
 - Unit weight
 - Volumetric stability – thermal; wet/dry; freeze/thaw
 - Deleterious constituents
- Chemical
 - Solubility
 - Surface charge
 - Volume stability - chemical
- Mechanical
 - Compressive strength
 - Toughness
 - Abrasion resistance

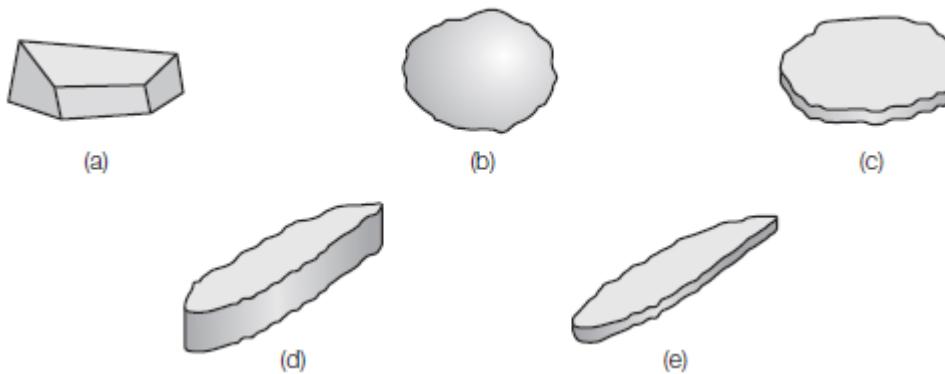


Property	Relative Importance for End Use*		
	Portland Cement Concrete	Asphalt Concrete	Base
PHYSICAL			
Particle shape (angularity)	M	V	V
Particle shape (flakiness, elongation)	M	M	M
Particle size—maximum	M	M	M
Particle size—distribution	M	M	M
Particle surface texture	M	V	V
Pore structure, porosity	V	M	U
Specific gravity, absorption	V	M	M
Soundness—weatherability	V	M	M
Unit weight, voids—loose, compacted	V	M	M
Volumetric stability—thermal	M	U	U
Volumetric stability—wet/dry	M	U	M
Volumetric stability—freeze/thaw	V	M	M
Integrity during heating	U	M	U
Deleterious constituents	V	M	M
CHEMICAL			
Solubility	M	U	U
Surface charge	U	V	U
Asphalt affinity	U	V	M
Reactivity to chemicals	V	U	U
Volume stability—chemical	V	M	M
Coatings	M	M	U
MECHANICAL			
Compressive strength	M	U	U
Toughness (impact resistance)	M	M	U
Abrasion resistance	M	M	M
Character of products of abrasion	M	M	U
Mass stability (stiffness, resilience)	U	V	V
Polishability	M	M	U

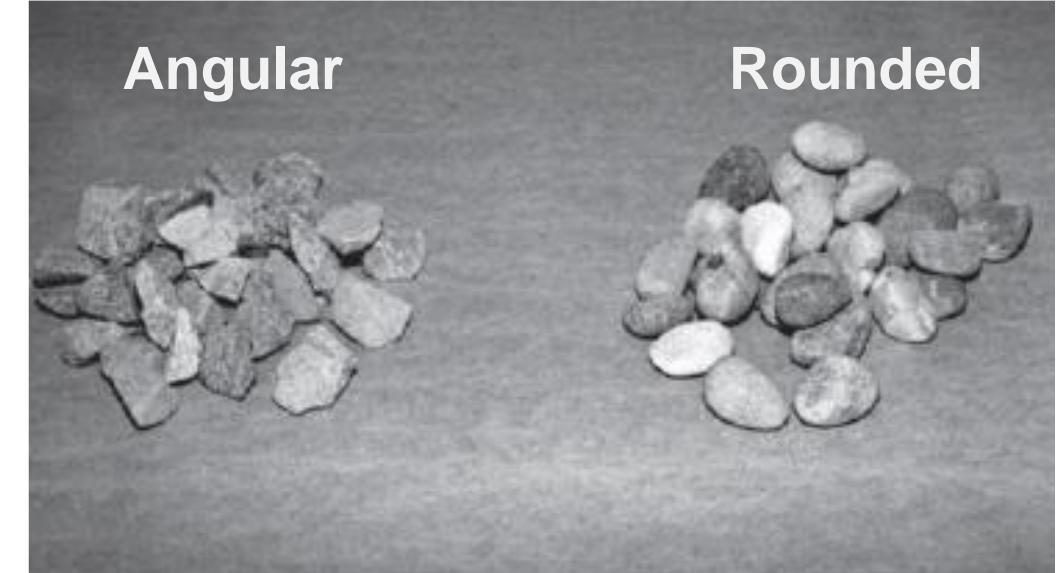
* V = Very important; M = Moderately important; U = Unimportant or importance unknown



Particle Shape and Texture



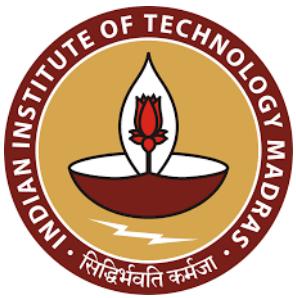
- a) Angular
- b) Rounded
- c) Flaky
- d) Elongated
- e) Flaky and elongated





Soundness and Durability

- The ability of aggregate to withstand *weathering* is defined as *soundness* or *durability*.
- Aggregates used in various civil engineering applications must be sound and durable, particularly if the structure is subjected to severe climatic conditions.
- Water freezing in the voids of aggregates generates stresses that can fracture the stones.
- Weight loss due to multiple cycles of soaking in aggressive solution



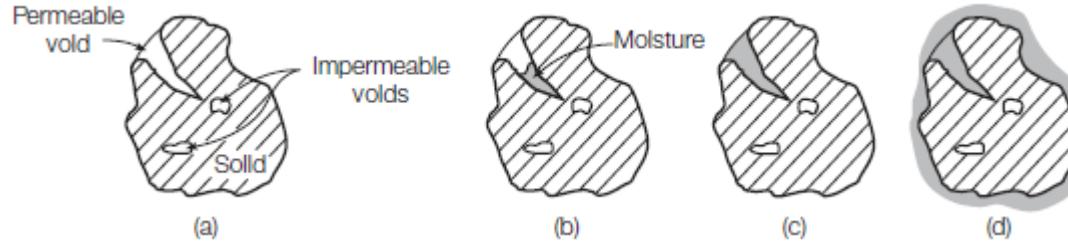
Toughness, Hardness and Abrasion Resistance

- The ability of aggregates to resist the damaging *effect of loads* is related to the hardness of the aggregate particles and is described as the *toughness* or *abrasion resistance*.
- The aggregate must resist crushing, degradation, and disintegration when stockpiled, mixed as either portland cement or asphalt concrete, placed and compacted, and exposed to loads.
- Los Angeles abrasion test





Absorption



- a) Bone dry
- b) Air dry
- c) Saturated surface dry (SSD)
- d) Moist

$$MC = \frac{W_{\text{moist}} - W_{\text{dry}}}{W_{\text{dry}}} \times 100$$

where

W_{moist} = weight of moist aggregate
 W_{dry} = weight of dry aggregate

A sample of sand has the following properties:

Moist mass = 625.2 g
Dry mass = 589.9 g
Absorption = 1.6%

Determine (a) total moisture content and (b) free moisture content.



Specific Gravity

- **Specific gravity:** the mass of a material divided by the mass of an equal volume of distilled water

For coarse aggregate

$$\text{Bulk Dry Sp. Gr.} = \frac{\text{Dry Weight}}{(\text{Total Particle Volume})\gamma_w} = \frac{W_s}{(V_s + V_i + V_p)\gamma_w}$$

$$\text{Bulk SSD Sp. Gr.} = \frac{\text{SSD Weight}}{(\text{Total Particle Volume})\gamma_w} = \frac{W_s + W_p}{(V_s + V_i + V_p)\gamma_w}$$

$$\text{Apparent Sp. Gr.} = \frac{\text{Dry Weight}}{(\text{Volume Not Accessible to Water})\gamma_w} = \frac{W_s}{(V_s + V_i)\gamma_w}$$

$$\text{Bulk Dry Sp. Gr.} = \frac{A}{B - C}$$

$$\text{Bulk SSD Sp. Gr.} = \frac{B}{B - C}$$

$$\text{Apparent Sp. Gr.} = \frac{A}{A - C}$$

$$\text{Absorption (\%)} = \frac{B - A}{A} (100)$$

W_s = weight of solids

V_s = volume of solids

V_i = volume of water impermeable voids

V_p = volume of water permeable voids

W_p = weight of water in the permeable voids when the aggregate is in the SSD condition

γ_w = unit weight of water

where

A = dry weight

B = SSD weight

C = submerged weight



Gradation

- Maximum density gradation: In 1907, Fuller established the relationship for determining the distribution of aggregates that provides the maximum density or minimum amount of voids as

$$P_i = 100 \left(\frac{d_i}{D} \right)^n$$

where

P_i = percent passing a sieve of size d_i

d_i = the sieve size in question

D = maximum size of the aggregate

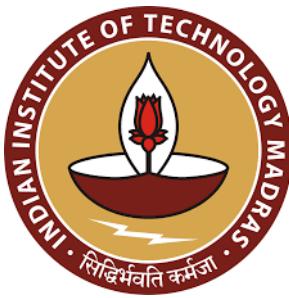


Fineness Modulus

- The *fineness modulus* is a measure of the fine aggregates' gradation and is used primarily for portland cement concrete mix design. It can also be used as a daily quality control check in the production of concrete.
- The fineness modulus is one-hundredth of the sum of the cumulative percentage weight retained on the 0.15-, 0.3-, 0.6-, 1.18-, 2.36-, 4.75-, 9.5-, 19.0-, 37.5-, 75-, and 150-mm sieves.
- The fineness modulus for fine aggregates should be in the range of 2.3 to 3.1, with a higher number being a coarser aggregate.

Sieve Size, mm	Percentage of Individual Fraction Retained, by Weight
9.5	0
4.75	2
2.36	13
1.18	25
0.60	15
0.30	22
0.15	20
Pan	3
Total	100

Calculate fineness modulus



Cleanness and Deleterious Materials

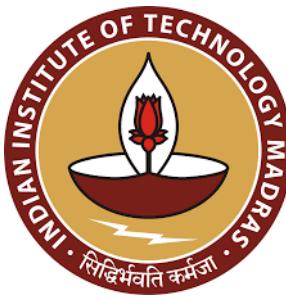
Main Deleterious Substances and Their Effects on Portland Cement Concrete

Substance	Harmful Effect
Organic impurities	Delay settling and hardening, may reduce strength gain, may cause deterioration
Minus 0.075 mm	Weaken bond, may increase water materials requirements
Coal, lignite or other low-density materials	Reduce durability, may cause popouts or stains
Clay lumps and friable particles	Popouts, reduce durability and wear resistance
Soft particles	Reduce durability and wear resistance, popouts



Alkali Aggregate Reaction

- The reaction between the active silica constituents of an aggregate and the alkalis in cement (sodium oxide, Na_2O , and potassium oxide, K_2O).
- The alkali–silica reaction results in excessive expansion, cracking, or popouts in concrete.
- If alkali-reactive aggregate must be used, the reactivity can be minimized by limiting the alkali content of the cement.



References

- Michael S. Mamlouk and John P. Zaniewski, "Materials for Civil and Construction Engineers," Addison Wesley Longman Inc., USA, 1999.



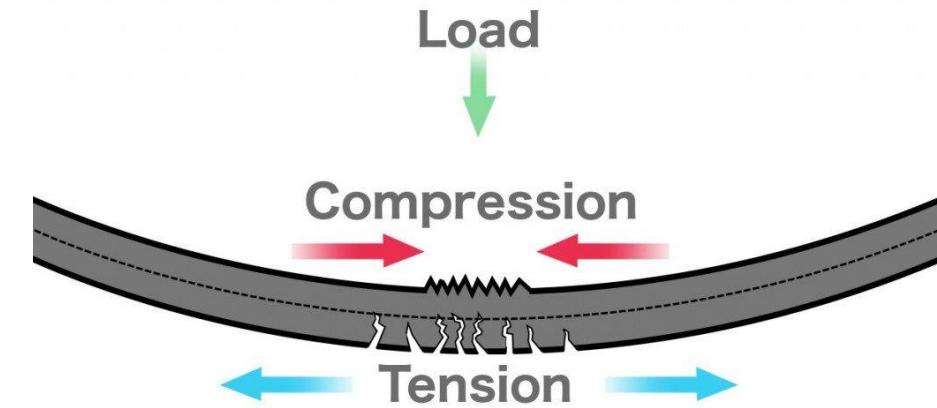
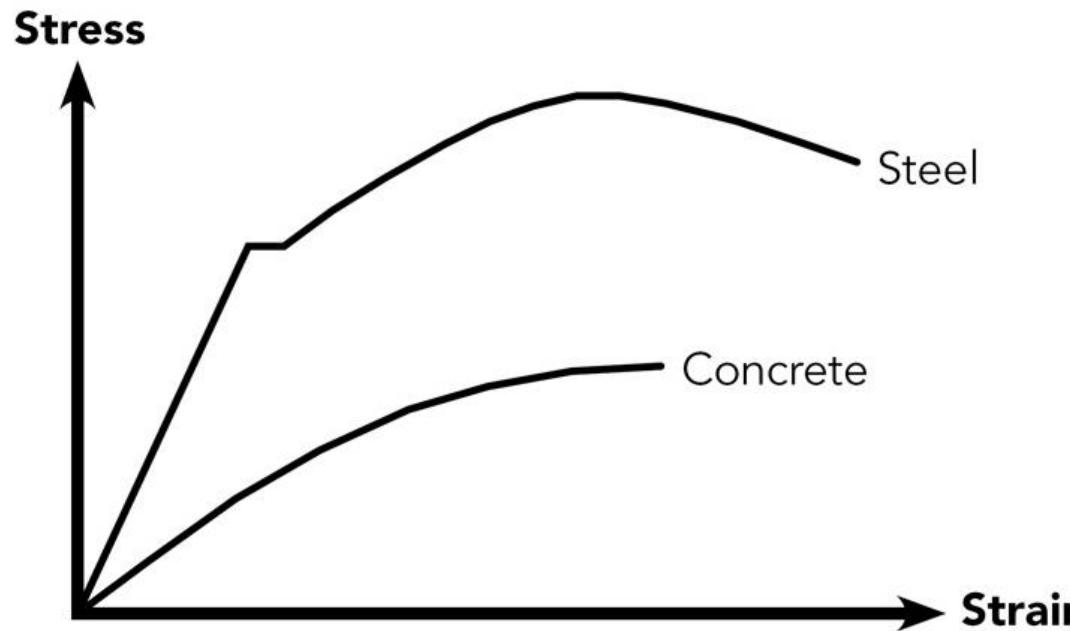
Concrete

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Concrete vs. Steel

Stress-Strain Curve for Steel and Concrete



- Concrete is weak in tension.
- Tensile strength is ~10% of its compressive strength.
- Reinforced concrete uses steel for resisting tensile stresses.



Interesting Facts about Concrete

- Current consumption of concrete is more than **30 billion tons** every year.
- No material is consumed in such tremendous quantities except **water**.
- Why concrete?
 - Can be molded into any shape and size
 - Water resistant
 - Cheap and most readily available material



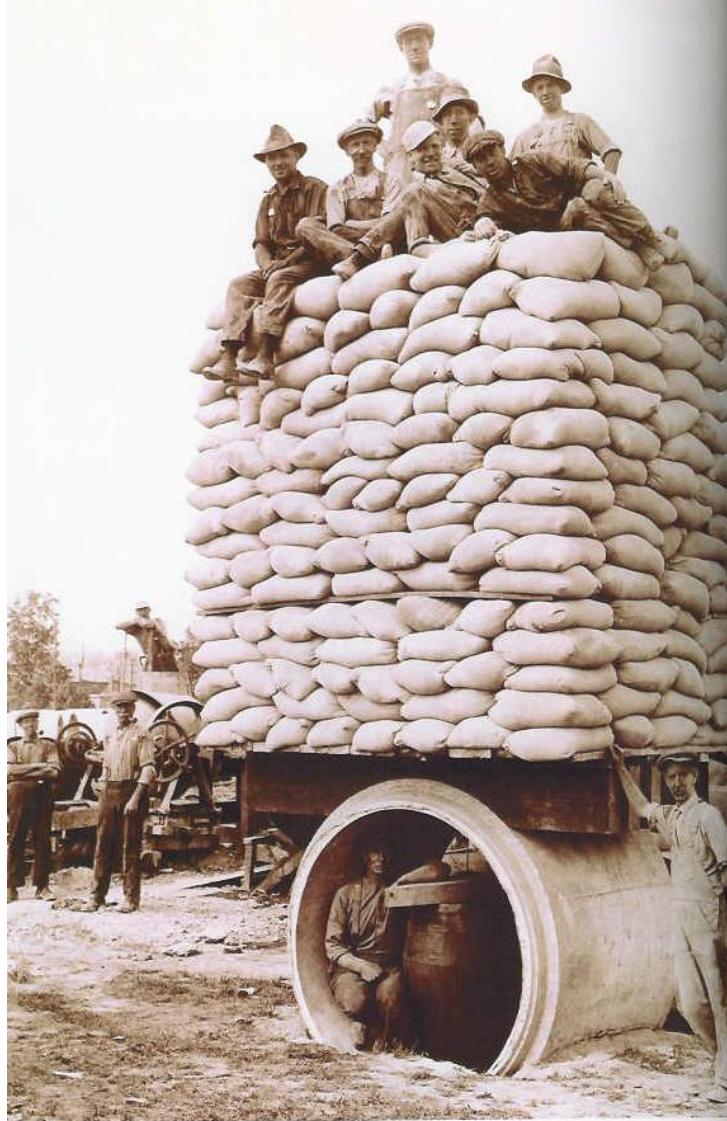
Glenfinnan Viaduct Scotland 1897

380 m long & has 21 spans.

Constructed with mass concrete.

“Concrete is strong in compression.”

“Structures can be cast monolithically.”



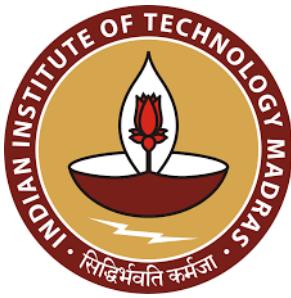
Concrete pipes Ontario, Canada 1920s

Pipe withstood load of 21,300 kg.

(Traditional load tests were performed by weights – sand bags.)

“Concrete is essential in water supply.”

“Concrete inspires confidence.”



Concrete as a Material

Concrete consists of:

- Cement
- Aggregates (fine and coarse)
- Water

And may incorporate:

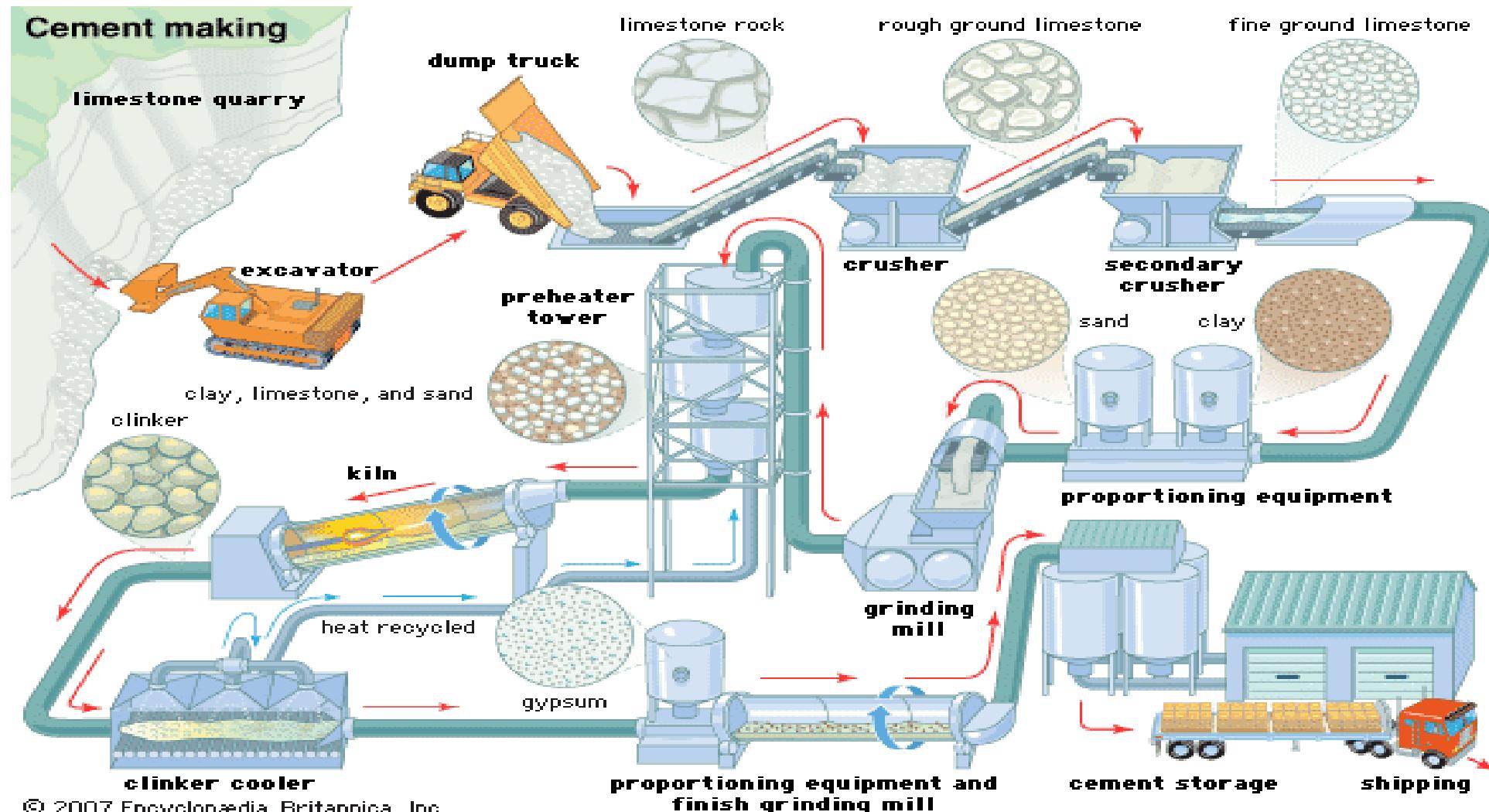
- Chemical admixtures
- Mineral admixtures
- Fibers



Portland Cement Manufacturing



Cement Production

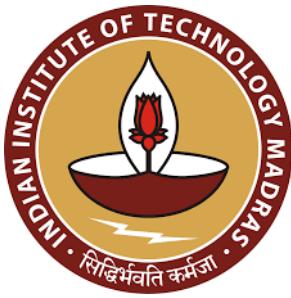


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Pulverization

- Raw material feedstock should be pulverized to the right size
- Reduces overall power consumption
- Better blending and burning possible with reduced size of material
- Desired size: Residue of 1% on 200 micron sieve and 12% on 90 micron sieve



Blending of Raw Materials

- Choice of blending process
 - Wet or dry
- Wet process – more uniform mixing
- Dry process – higher output, lower power consumption (3000 kJ/kg as opposed to 5500 kJ/kg for wet process)
- Dry process with precalciners are the order of the day

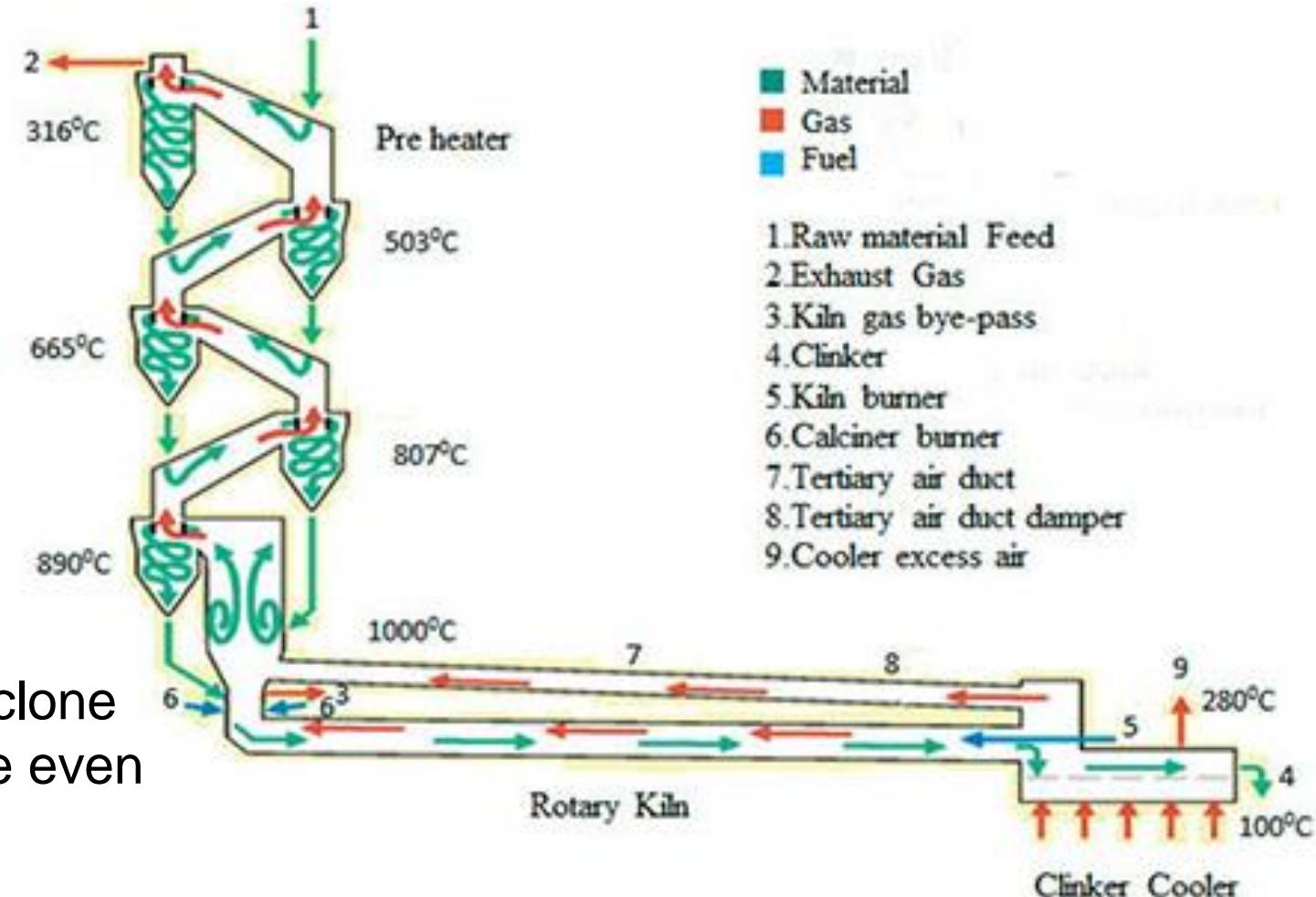


Preheaters / Precalciners

Counter-current heating mechanism

Stack of cyclonic separators – ensures uniform heating

Precalcirer – fuel introduced into the cyclone
→ causes reactions to partially complete even before kiln

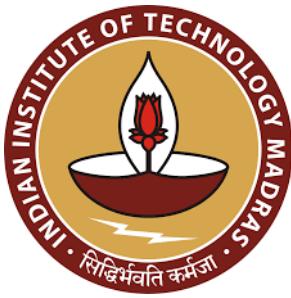


FLSmidth Pvt. Ltd



Burning in Kiln

- Only rotary kilns used nowadays
- Typical kilns are long ~ 30–70 m (5–6 m diameter)
- Length of kiln also depends on blending process
- Temperature inside kiln varies from 850°C (inlet) to 1450°C (outlet)
- Reactions are not completed inside kiln; some require cooling to occur
- What comes out of kiln is called ‘clinker’



Intergrinding with Gypsum

- Final step in cement manufacture
- Gypsum added as a set regulator (absence → flash set)
- Strict control on temperature required
- Done in ball mills; vertical roller presses are now used for better efficiency
- All other blending materials are typically introduced at this stage (e.g. fly ash for PPC)
- Cement of required fineness produced



Portland Cement Composition



Oxide Composition of Cement

• CaO (C):	60-67%
• SiO ₂ (S):	17-25%
• Al ₂ O ₃ (A):	3-8%
• Fe ₂ O ₃ (F):	0.5-6%
• MgO (M):	0.1-4%
• Alkalies (eq. Na ₂ O):	0.2-1.3%
• SO ₃ (S):	1-3%

Oxide composition of cement is determined using X-ray fluorescence (XRF).



Phase Composition of Cement

Name	Formula	Shorthand	Weight %
Tricalcium silicate (Alite)	$3 \text{CaO} \cdot \text{SiO}_2$	C_3S	~ 55-60
Dicalcium silicate (Belite)	$2 \text{CaO} \cdot \text{SiO}_2$	C_2S	~ 15-20
Tricalcium aluminate	$3 \text{CaO} \cdot \text{Al}_2\text{O}_3$	C_3A	~ 5-10
Tetracalcium aluminoferrite	$4 \text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot \text{Fe}_2\text{O}_3$	C_4AF	~ 5-8
Gypsum	$\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$	$\overline{\text{CSH}}_2$	~ 2-6

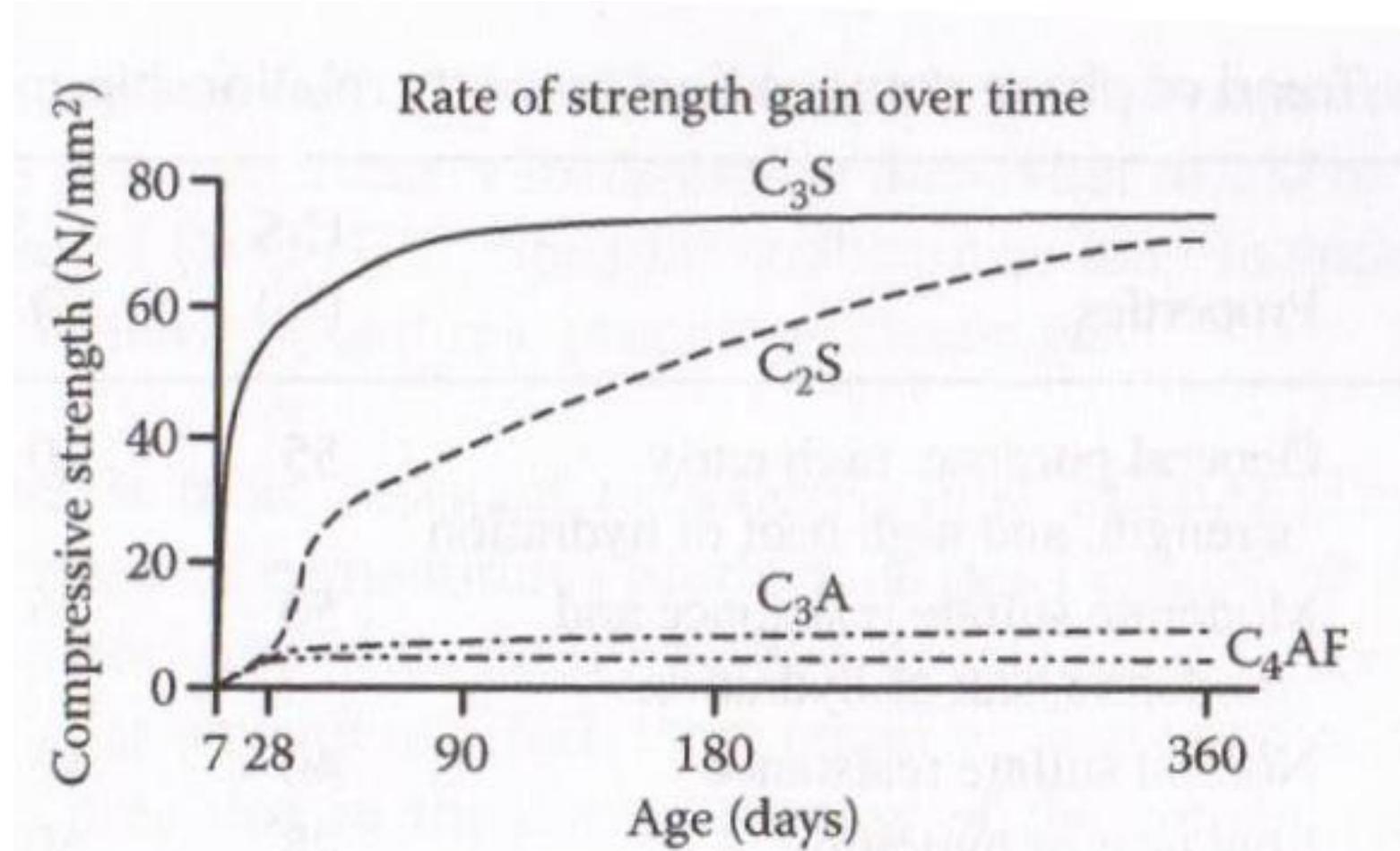


Contributions of Phases to Strength

- C_3S contributes to high early strength – to make high early strength concrete, higher C_3S proportions needed
- C_2S contributes to later age strength – defines the long term strength
- C_3A reacts immediately with water – defines flash set
- In the presence of gypsum, flash set is prevented.



Strength Development of Cement Phases



A. K. Chatterjee, 2018

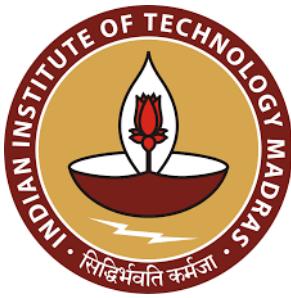


BIS Classification

- Ordinary Portland Cement – IS:269-1989 (further classified into 33, 43, and 53 grade; the grade implies the strength achieved by the cement mortar at 28 days)
- Portland Cement, Low Heat – IS:12600-1989
- Rapid Hardening Portland Cement – IS:8041-1978
- Portland-Pozzolana Cement – IS:1489-1976
- Portland-Slag Cement – IS 455-1976



Portland Cement Hydration



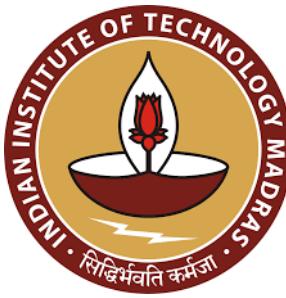
Cement Hydration

- Reaction of cement with water
- Exothermic reaction; heat released is called ‘Heat of Hydration’
- The chemical components react with water to form new compounds
- The “glue” that binds the aggregates together is formed as a result of hydration

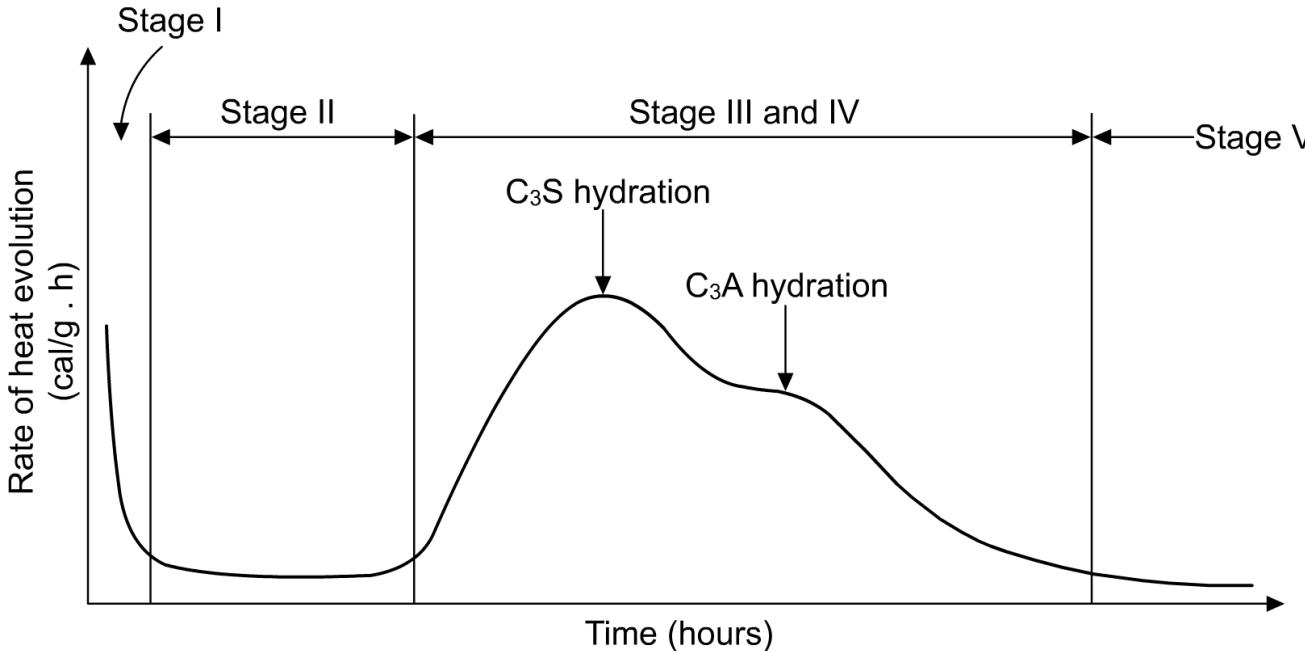


Water-to-Cement (w/c) Ratio

- The ratio of the weight of water to that of cement
- In presence of secondary cementing materials, their weights are also considered
- The single most important “controllable” characteristic that determines the most of concrete properties
- Conflicts from workability and property viewpoints

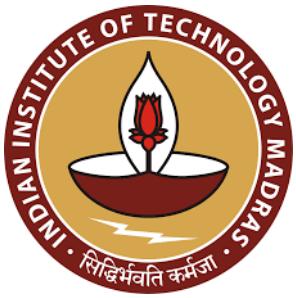


Typical Heat of Hydration Curve



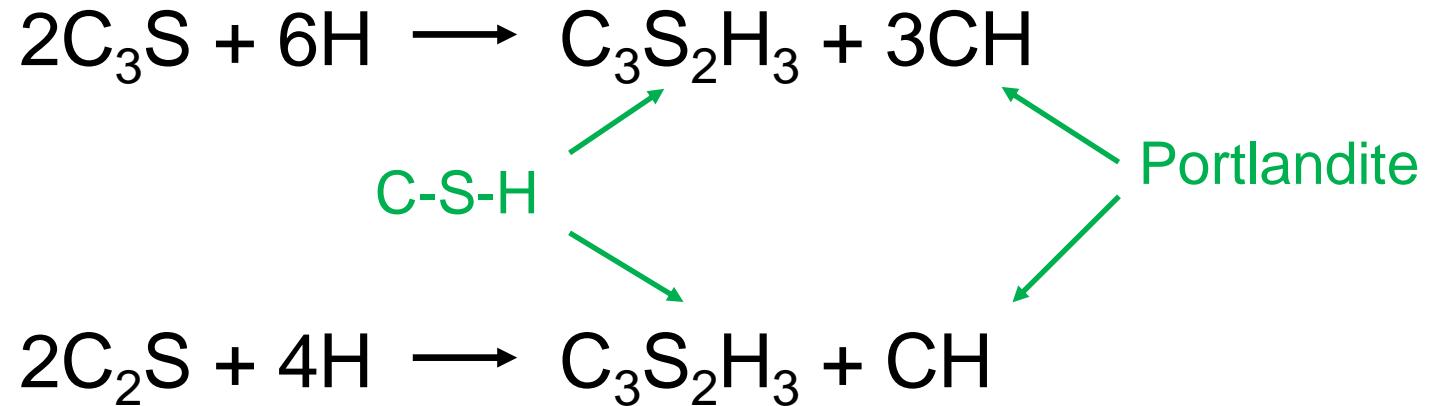
- **(Stage I)** Rapid evolution of heat, lasts about 15 minutes.
- **(Stage II)** Dormant period, lasts until initial set occurs in 2 to 4 hours.
- **(Stage III)** Rapid reaction of C₃S during the acceleration period, with the peak being reached at about 8-10 hours, much after final set at 4-8 hours and hardening has begun.
- **(Stage IV)** Rate of reaction slows down until steady state is reached in 12-24 hours
- **(Stage V)** Steady state

Mindess and Young



Hydration of Calcium Silicates

Calcium Silicates (C_3S and C_2S)





Hydration of Tricalcium Aluminate

In presence of enough gypsum



After gypsum depletion remaining C_3A reacts with ettringite and forms monosulfate

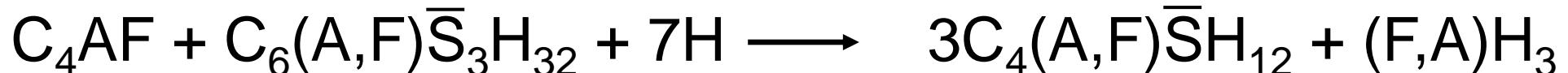


Flash set reaction!



C₄AF Hydration

Similar hydration as C₃A



(A,F) indicates aluminum with variable substitution of iron

(F,A) indicates iron with variable substitution of aluminum

C₄AF is responsible for the gray color of cement.

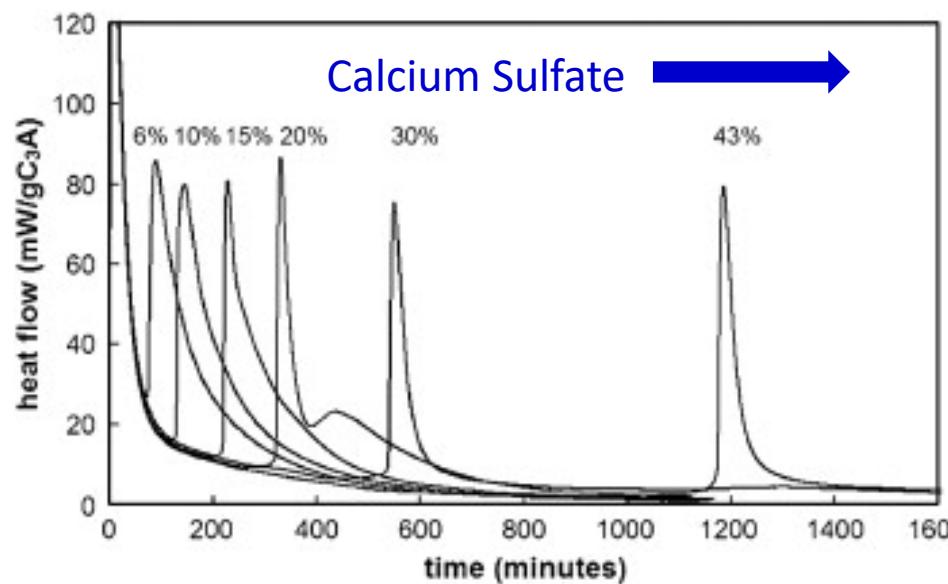


Rates of Reactions

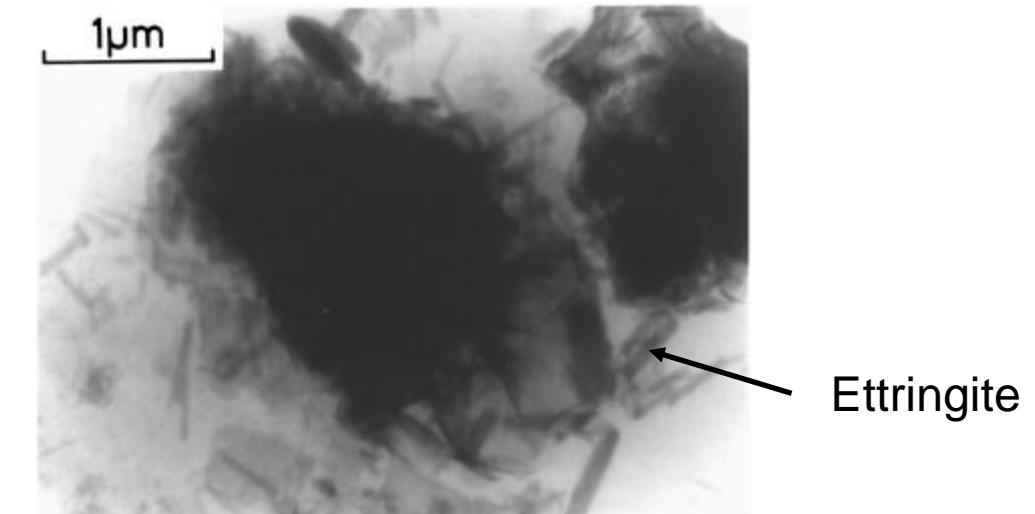
- $C_3A > C_3S > C_4AF > C_2S$
- Reactivity is influenced by the nature of grinding, fineness, and cooling of clinker
- Impurities influence the reactions
- C_3A and C_4AF will compete for sulfates

C₃A Hydration

- Retardation of C₃A reaction in presence of gypsum



Minard et al., 2007

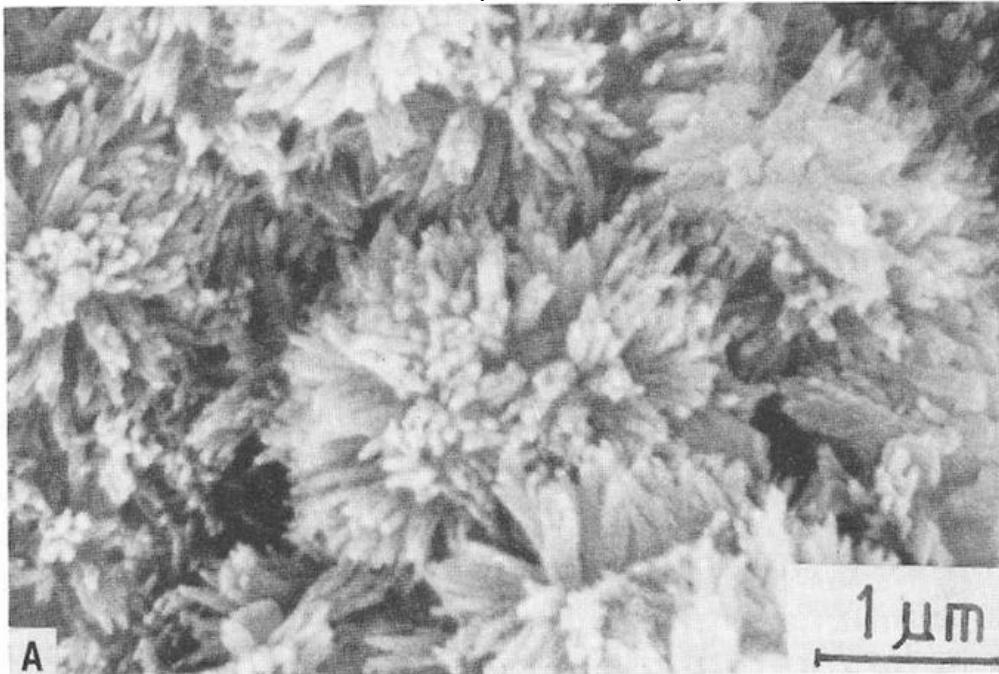


Scrivener, 1984



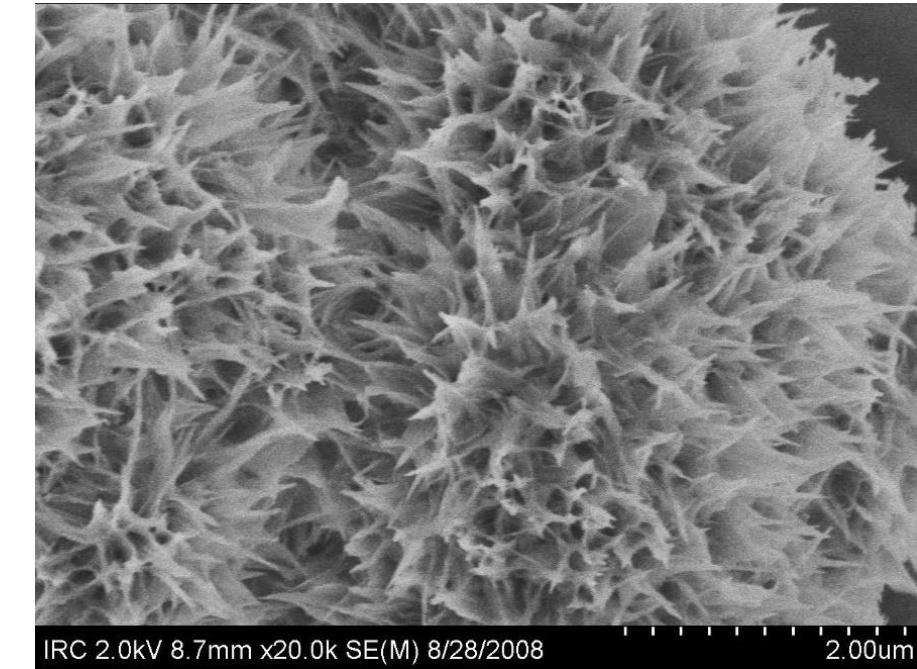
Calcium Silicate Hydrate (C-S-H)

Hydrated ordinary Portland cement paste at 10 hrs (W/C=0.5)



Courtesy: Prof. Karen Scrivener

The flaky C-S-H crystals grown after 2 weeks of hydration of C_3S (W/C=0.8)



<http://cementlab.com/cement-art.htm>

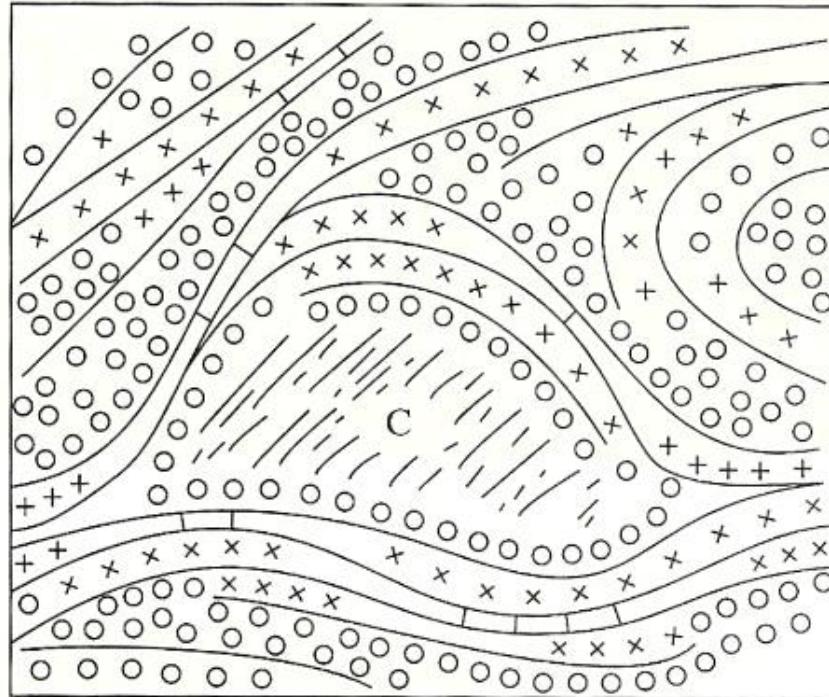


C-S-H

- 50-65% of solids volume
- C/S ranges from 1.5 to 2
- Morphology – poorly crystalline to a reticular network
- The structure of C-S-H is compared to the crystal structure of Jennite and Tobermorite. A combination of the two minerals is supposed to be the closest to C-S-H.



C-S-H Structure: Feldman-Sereda Model

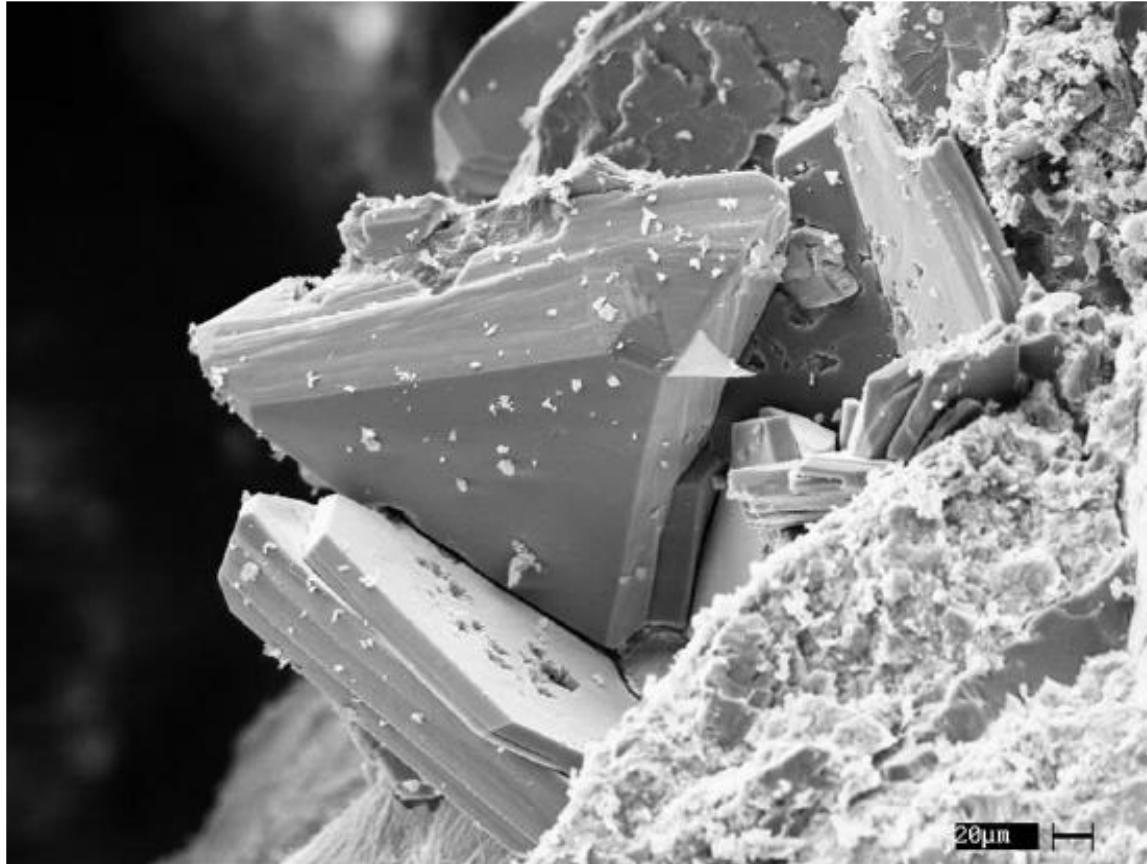


Bonding	Porosity
— C –S layers	// Bulk water in capillary pores (C)
— Adjacent layers covalently bonded	○○○○ Water molecules in micropores, or physically adsorbed on external surfaces.
— Adjacent layers bonded by van der Wall forces	Under surfaces forces, but mobile
— Adjacent layers bound by oriented water molecules between the layers	×××× Water in very small micro-pores between C–S layers. (Interlayer) Water molecules are located at special sites on the “internal” surfaces between the layers. Not very mobile
○○○○ Adjacent layers held together by a restricted water film	

The structure of C-S-H is best described by the Feldman-Sereda model. It consists of randomly oriented sheets of C-S-H, with water adsorbed on the surface of the sheets (adsorbed water), as well as in between the layers (interlayer water), and in the spaces inside (capillary water).



Calcium Hydroxide (CH)



- Occupies 20 – 25% of the paste's solid volume
- Hexagonal crystals, generally oriented tangentially to pore spaces and aggregates along the longitudinal axis
- Low surface area ($0.5 \text{ m}^2/\text{g}$)
- Low van der Waals forces

Mehta and Monteiro

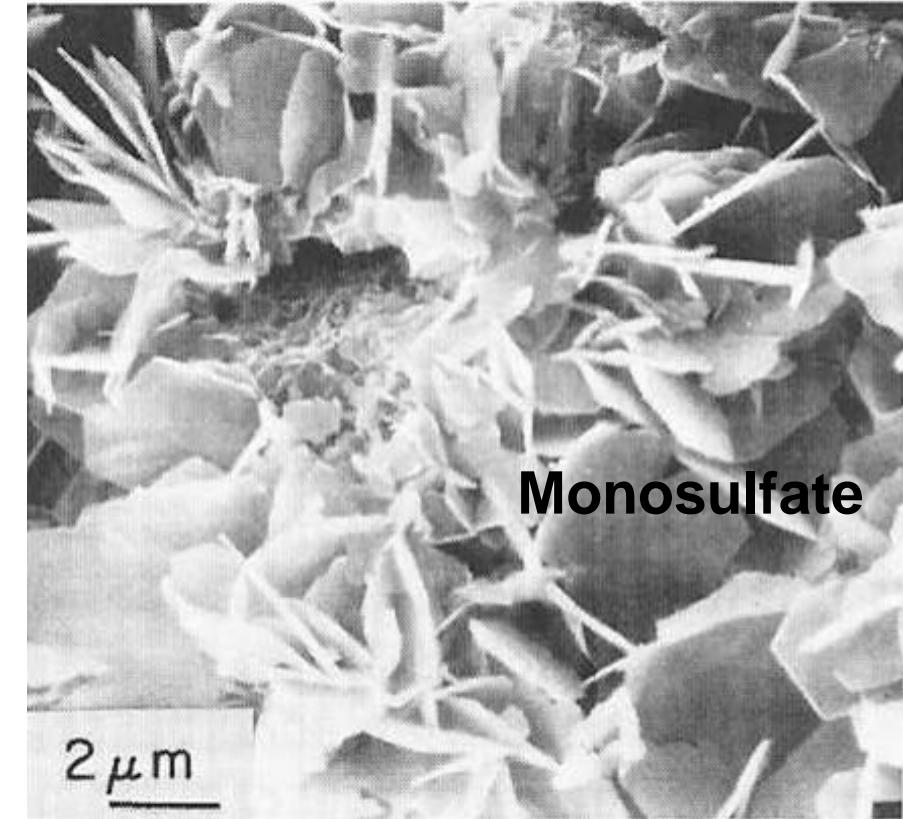
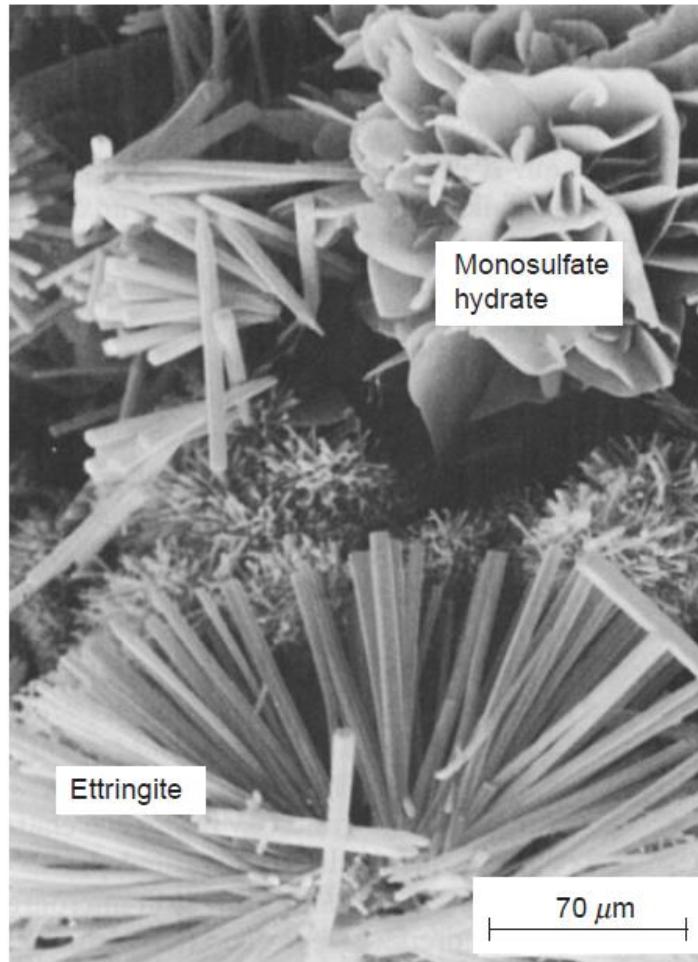


Calcium Sulfoaluminates

- Ettringite – Acicular, columnar, hexagonal crystals (seen as prismatic needles)
- Monosulphate – plain hexagonal
- Volume occupied is 15 – 20%



Ettringite and Monosulfate

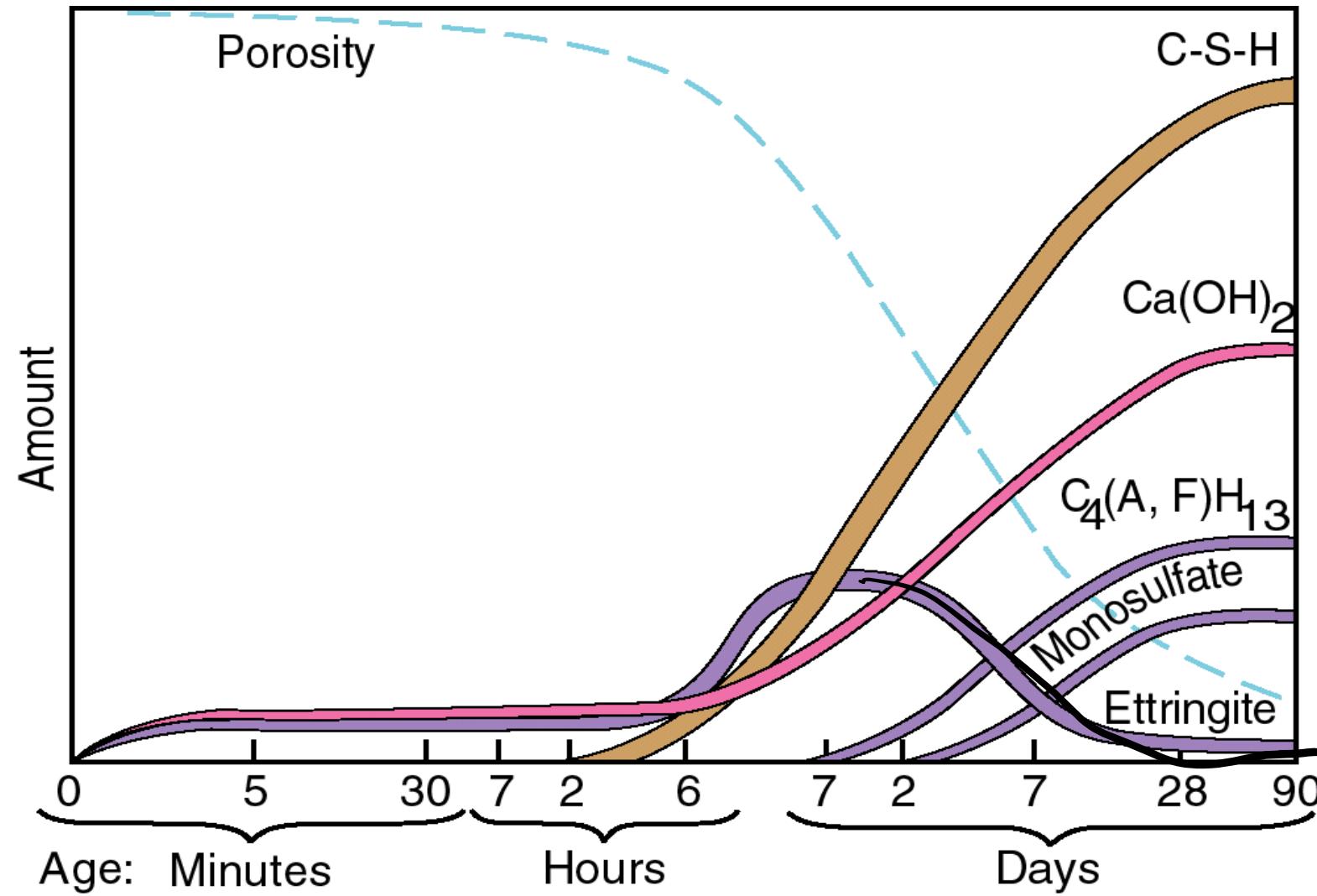


Mehta and Monteiro

Mindess and Young



Evolution of Hydration Products



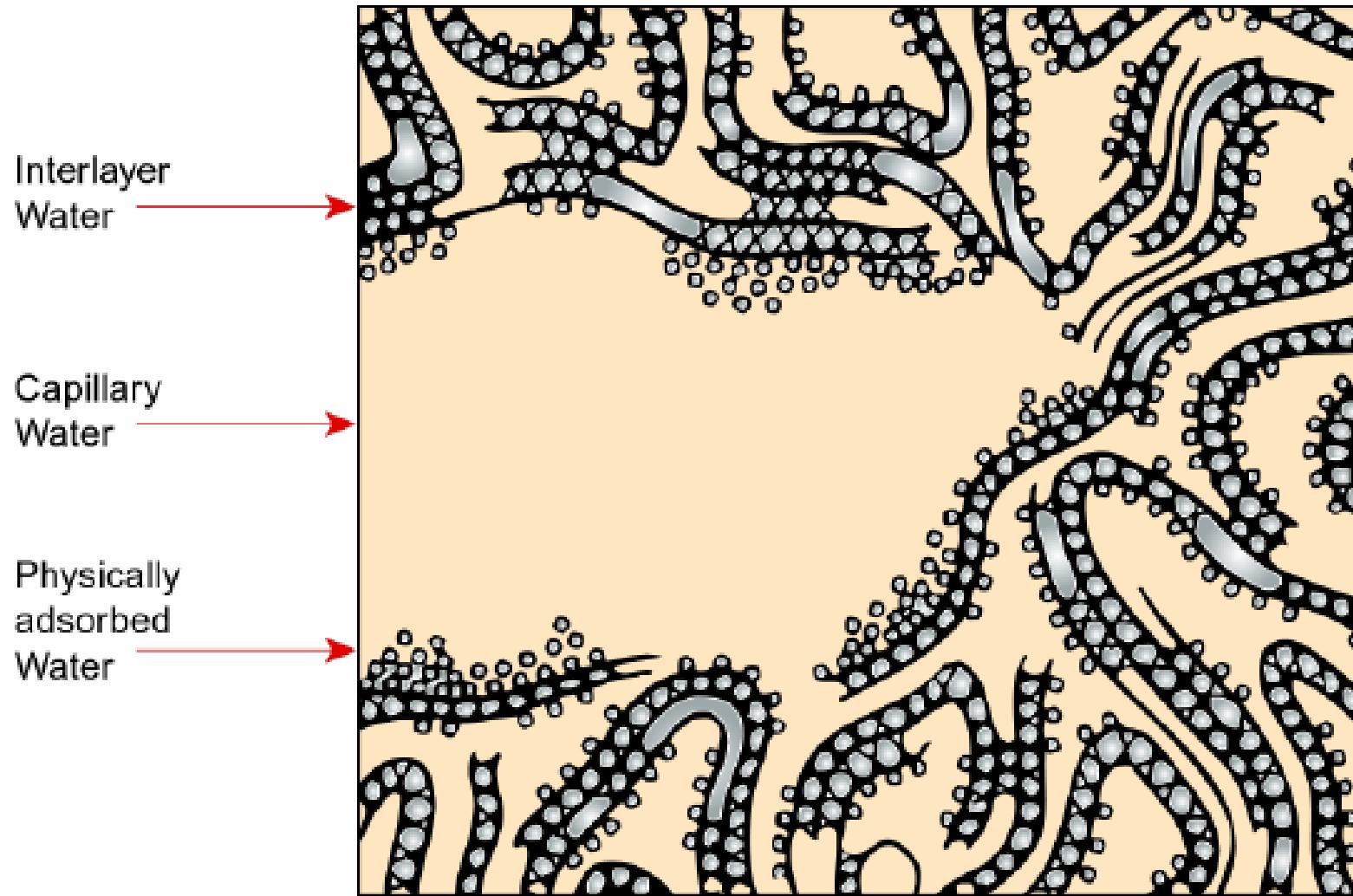


Role of Water

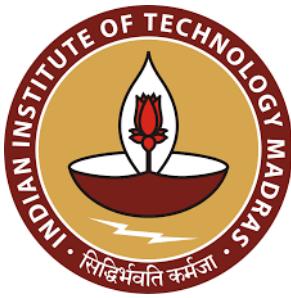
- Mixing water reacts with cement to form hydration products
- Part of water (gel water) is included in hydration products
- Remaining water is held in capillary pores



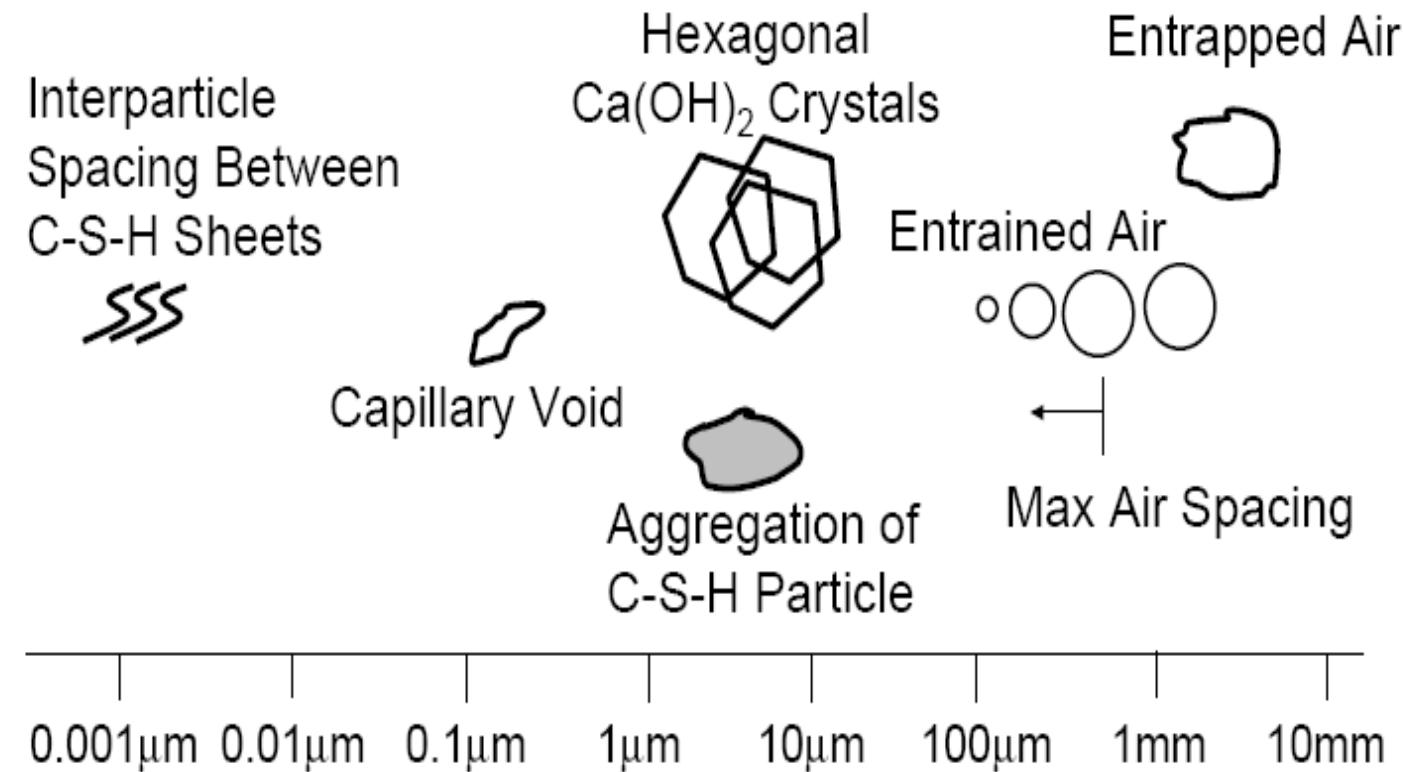
Water Inside Pores



Mehta and Monteiro



Pores and Air Voids

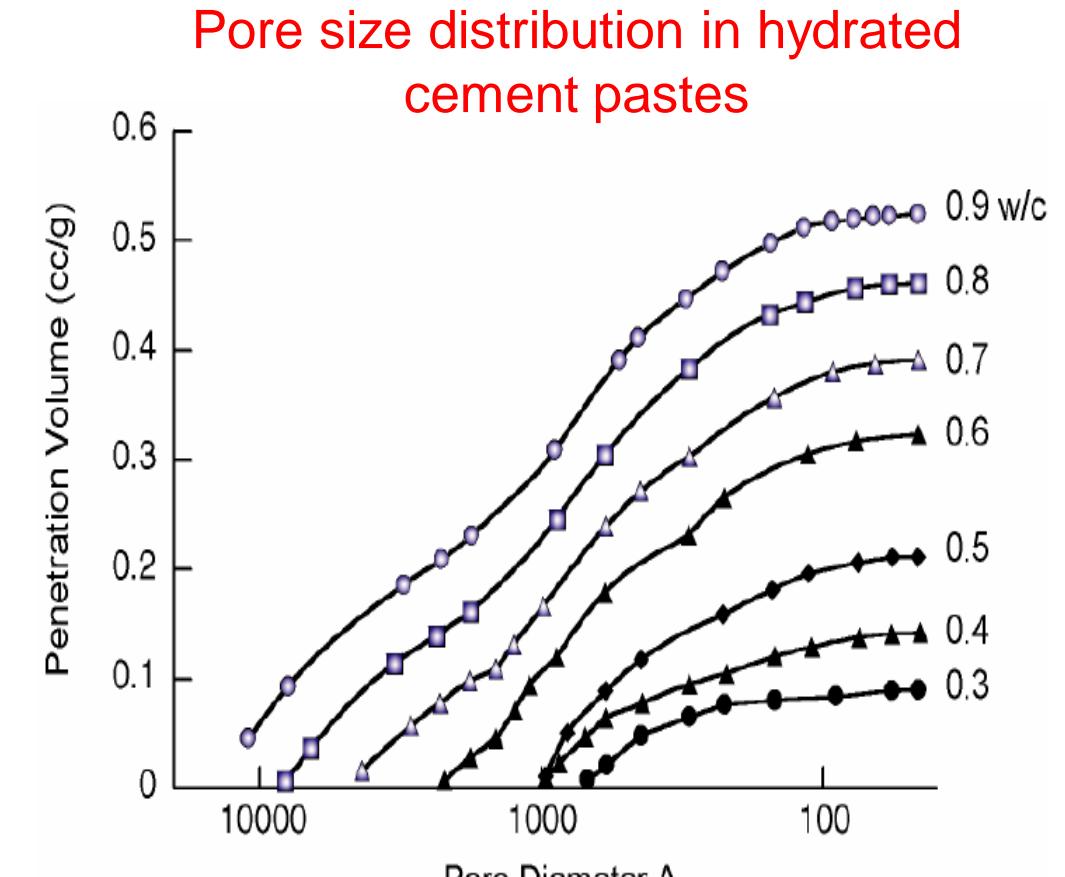


Mehta and Monteiro



Controlling Porosity is the Key

- Can control porosity primarily by w/c
- Higher w/c – higher pore diameter
- It is the pore size and their connectivity that is more important than total pore volume



Mehta and Monteiro



Supplementary Cementitious Materials (SCMs)



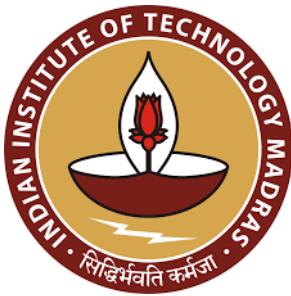
High Volume Fly Ash Concrete



Image: Wikipedia

<https://himalayanacademy.com/monastery/temples/iraivan/mehta-speaks-on-fly-ash-concrete>

- Iraivan Temple, Kauai Island, Hawaii
- Prof. P K Mehta designed high volume fly ash concrete for the temple to last 1000 years.
- Around 57% of Portland cement was replaced with fly ash.

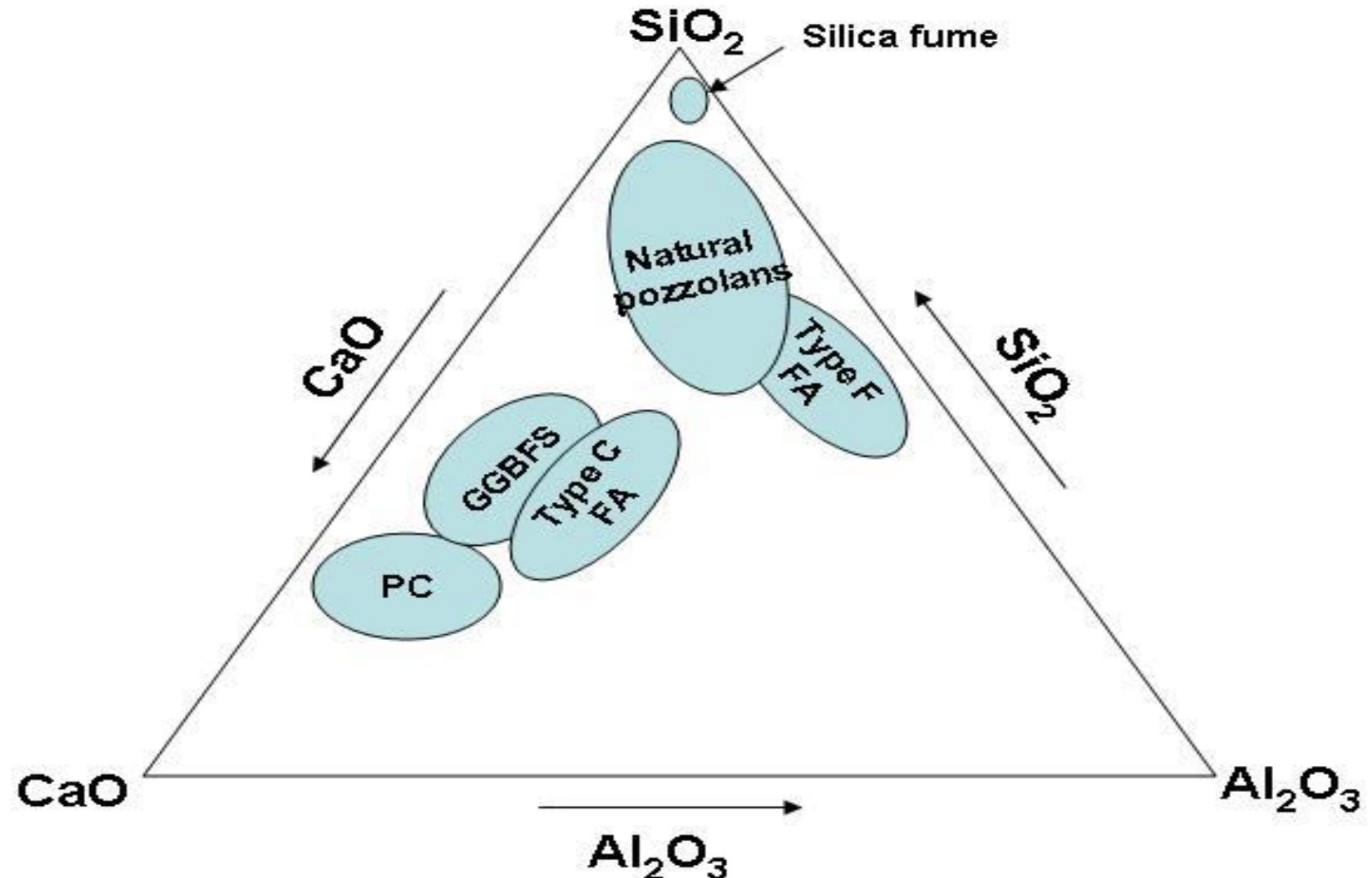


Why SCMs?

- To reduce the carbon footprint of concrete
- To increase the compressive strength, other mechanical properties, and durability
- To improve fresh properties of concrete
- To decrease the heat of hydration



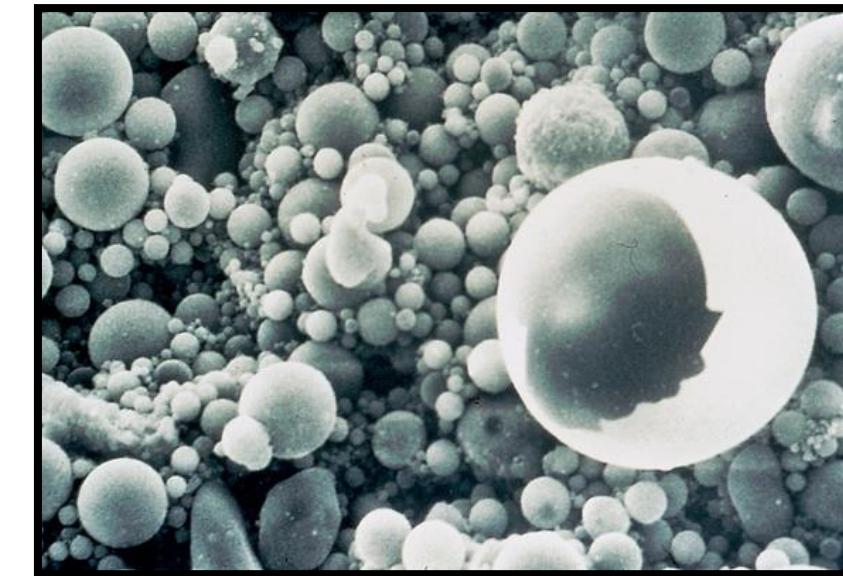
Types of SCMs





Fly Ash

- Derived from burning coal
- Spherical glassy particles are formed due to rapid cooling of the molten ash in the furnace.



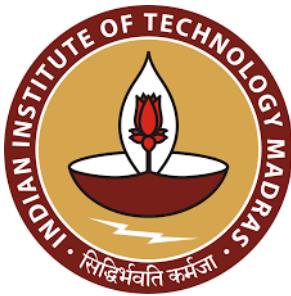
Portland Cement Association



Ground Granulated Blast-Furnace Slag

- GGBS is a by-product of steel manufacturing
- GGBS is obtained by quenching molten iron slag (a by-product of iron and steel-making) from a blast furnace in water or steam, to produce a glassy, granular product that is then dried and ground into a fine powder.





Silica Fume

- Silica fume is a byproduct of producing silicon metal or ferrosilicon alloys.
- Silica fume consists primarily of amorphous (non-crystalline) silicon dioxide (SiO_2).
- Silica fume for use in concrete is available in wet or dry forms.



<https://www.silicafume.org/general-silicafume.html>



Influence of SCMs on Concrete Properties

Fresh Properties

Quality Measure	Effect
Water requirements	Fly ash reduces water requirements. Silica fume increases water requirements.
Air content	Fly ash and silica fume reduce air content, compensate by increasing air entrainer.
Workability	Fly ash, ground slag, and inert minerals generally increase workability. Silica fume reduces workability; use superplasticizer to compensate.
Hydration	Fly ash reduces heat of hydration. Silica fume may not affect heat, but superplasticizer used with silica fume can increase heat.
Set time	Fly ash, natural pozzolans and blast furnace slag increase set time. Can use accelerator to compensate.

Hardened Properties

Quality Measure	Effect
Strength	Fly ash increases ultimate strength but reduces rate of strength gain. Silica fume has less effect on rate of strength gain than pozzolans.
Drying shrinkage and creep	Low concentrations usually have little effect. High concentrations of ground slag or fly ash may increase shrinkage. Silica fume may reduce shrinkage.
Permeability and absorption	Generally reduce permeability and absorption. Silica fume is especially effective.
Alkali-aggregate reactivity	Generally reduced reactivity. Extent of improvement depends on type of admixture.
Sulfate resistance	Improved due to reduced permeability.



Chemical Admixtures



What is a Chemical Admixture?

- Any chemical additive to the concrete mixture that enhances the properties of concrete in the fresh or hardened state
- Does not typically include paints and protective coatings (for steel or concrete)
- ASTM C 125 defines the term admixture as “a material other than water, aggregates, hydraulic cement, and fiber reinforcement, used as an ingredient of concrete or mortar, and added to the batch immediately before or during its mixing”.



Requirements of Concrete in a Fresh State

- Ease of mixing and transportation
- Uniformity within a batch and between batches
- Ability to fill the form completely
- Ability to be placed and compacted fully without a high energy requirement
- Absence of segregation during placing and consolidation
- Capable of being finished properly



Chemical Admixtures

- Water reducers and superplasticizers
- Retarders and accelerators
- Viscosity modifying admixtures
- Shrinkage reducing admixtures
- Air-entraining agents
- Corrosion inhibitors



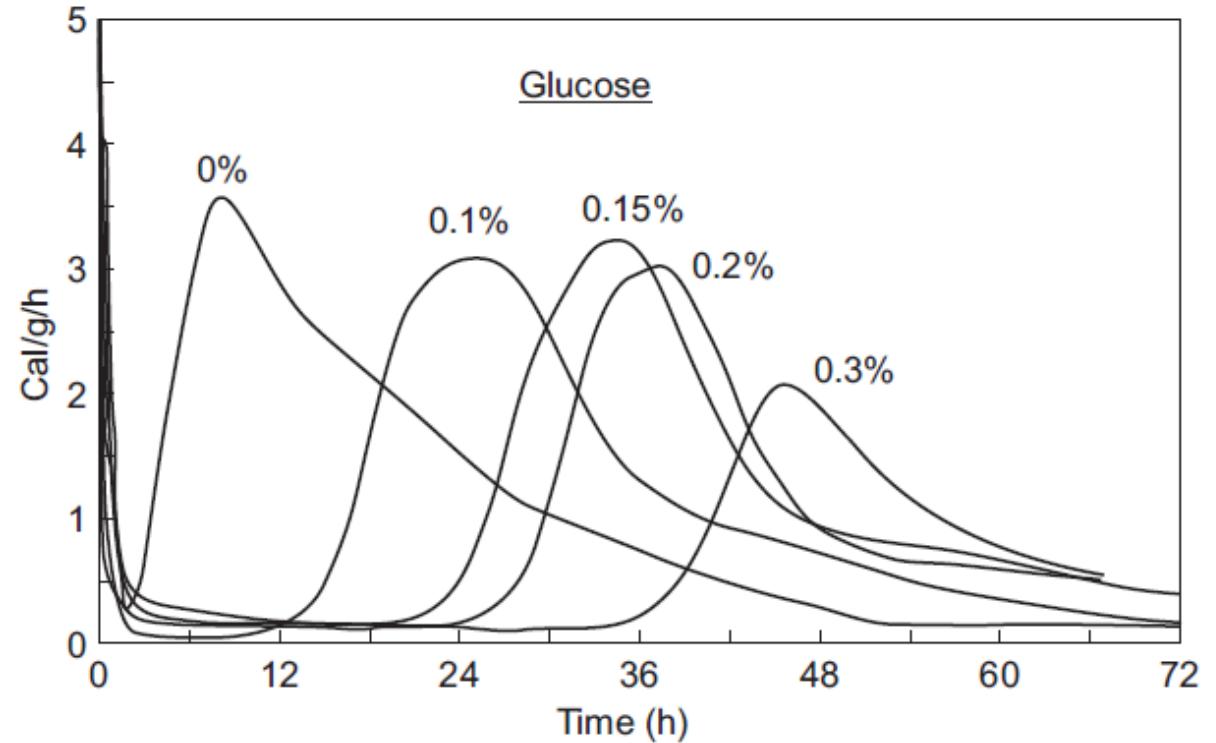
Water-Reducing Admixtures

- Normal range water reducers (plasticizers)
- High range water reducers (superplasticizers)
- For a given workability, the water demand is reduced, thus resulting in higher strength and durability.
- For a given w/c and strength, workability can be increased.
- For a given w/c, strength and workability, the quantity of cement can be reduced



Set-Controlling Admixtures

- Accelerators
 - Earlier finishing of slabs
 - Increase early age strength
 - Early removal of forms
 - Cold-weather concreting
- Retarders
 - Hot-weather concreting
 - Workable for longer time

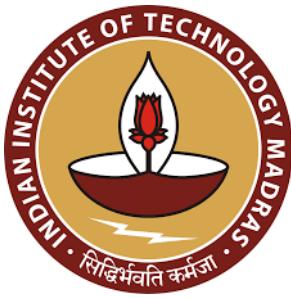


Science and Technology of Concrete Admixtures, 2016



Viscosity Modifying Admixtures

- VMAs are essential to control the stability and cohesion of concrete with very specific rheological requirements, such as **self compacting concrete, underwater concrete, or shotcrete**
- Polymeric VMAs enhance the stability of the mix by increasing one or several rheological parameters at the same time, such as **plastic viscosity, yield stress, shear thinning, and thixotropy**



Air-Entraining Admixtures

- Protect against damage due to **freezing and thawing cycles**
- Side effects:
 - Improve workability
 - Reduce segregation and bleeding
 - Reduce strength due to increased porosity



Design of Concrete and its Fresh Properties



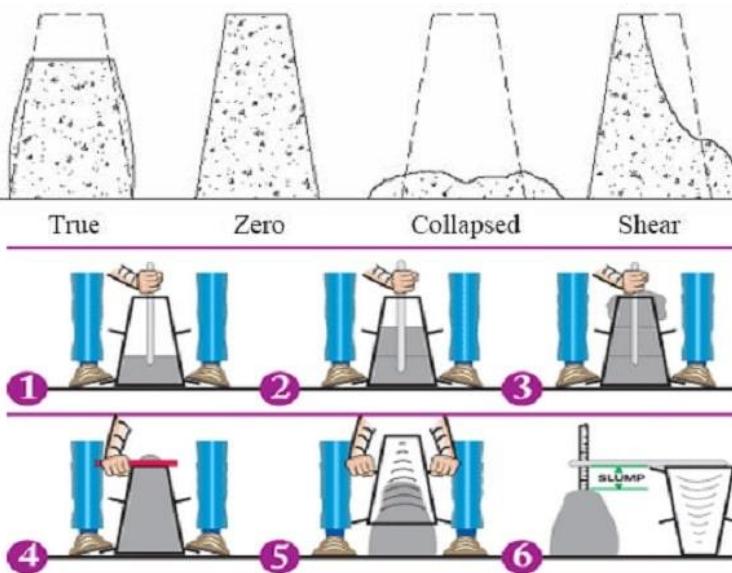
Desired Characteristics of Concrete

- Acceptable workability of freshly mixed concrete
- Durability, strength, and uniform appearance of hardened concrete
- Economy



Factors Affecting Workability

- Water content
- Cement content
- Aggregate size and shape
- Mineral admixtures
- Chemical admixture



<i>Placing Conditions</i>	<i>Degree of Workability</i>	<i>Slump (mm)</i>
(1) Blinding concrete; Shallow sections; Pavements using pavers Mass concrete; Lightly reinforced sections in slabs, beams, walls, columns; Floors; Hand placed pavements; Canal lining; Strip footings	Very low	See 7.1.1
(2) Heavily reinforced sections in slabs, beams, walls, columns; Slipform work; Pumped concrete Trench fill; <i>In-situ</i> piling Tremie concrete	Low	25-75
(3) Medium	50-100	75-100
(4) High	100-150	
(5) Very high	See 7.1.2	

NOTE—For most of the placing conditions, internal vibrators (needle vibrators) are suitable. The diameter of the needle shall be determined based on the density and spacing of reinforcement bars and thickness of sections. For tremie concrete, vibrators are not required to be used (see also 13.3).

<https://theconstructor.org/concrete/concrete-slump-test/1558/>

IS 456- 2000



Concrete Mix Design

- Evaluate strength requirements
- Determine the water–cement (water–cementitious materials) ratio required
- Evaluate coarse aggregate requirements.
 - maximum aggregate size of the coarse aggregate
 - quantity of the coarse aggregate
- Determine air entrainment requirements
- Evaluate workability requirements of the plastic concrete
- Estimate the water content requirements of the mix
- Determine cementing materials content and type needed
- Evaluate the need and application rate of admixtures
- Evaluate fine aggregate requirements
- Determine moisture corrections
- Make and test trial mixes

Table 2 Grades of Concrete
(Clause 6.1, 9.2.2, 15.1.1 and 36.1)

Group	Grade Designation	Specified Characteristic
		Compressive Strength of 150 mm Cube at 28 Days in N/mm ²
Ordinary Concrete	(1)	(2)
	M 10	10
	M 15	15
Standard Concrete	M 20	20
	M 25	25
	M 30	30
	M 35	35
	M 40	40
	M 45	45
	M 50	50
High Strength Concrete	M 55	55
	M 60	60
	M 65	65
	M 70	70
	M 75	75
	M 80	80

NOTES

1 In the designation of concrete mix M refers to the mix and the number to the specified compressive strength of 150 mm size cube at 28 days, expressed in N/mm².

2 For concrete of compressive strength greater than M 55, design parameters given in the standard may not be applicable and the values may be obtained from specialized literatures and experimental results.

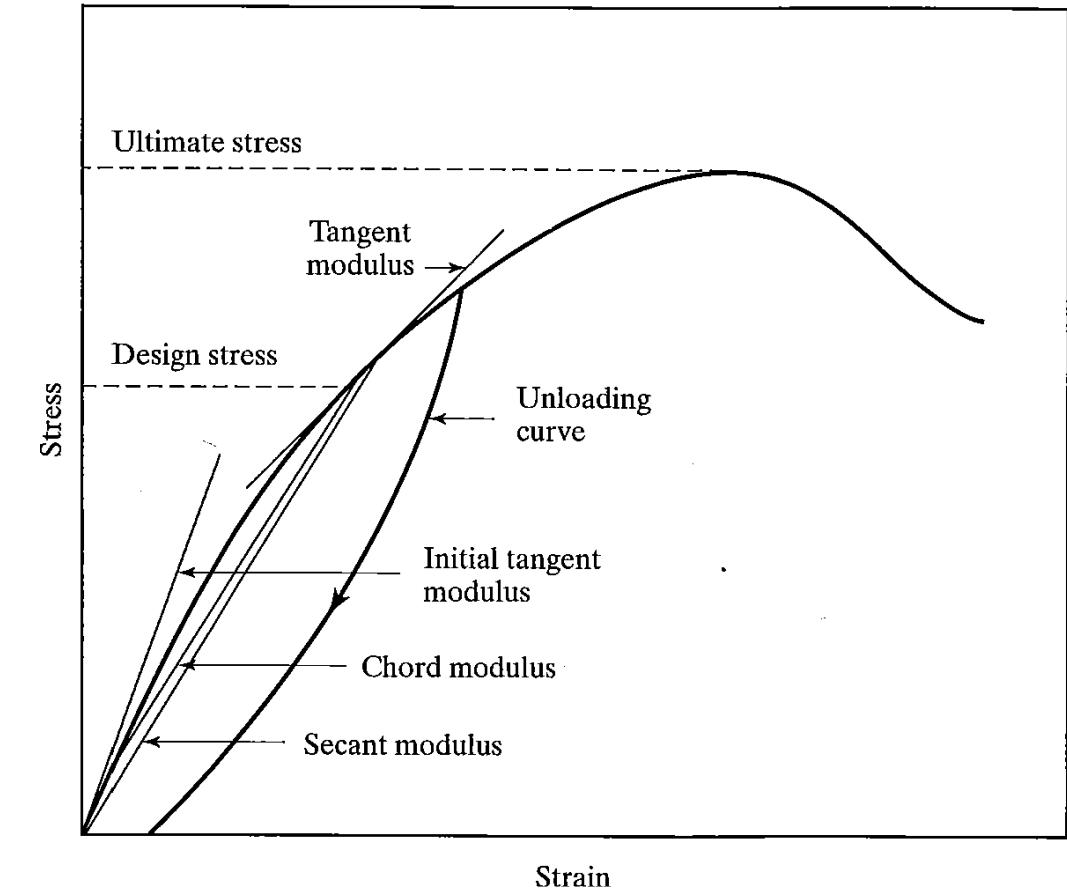
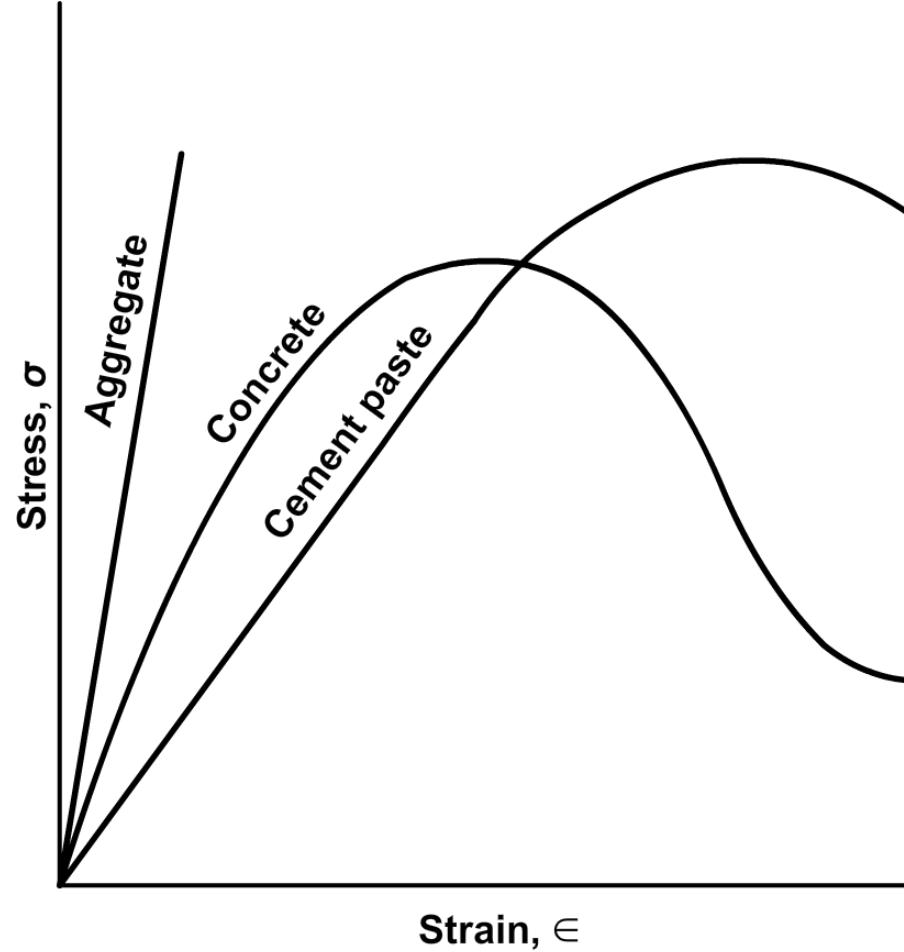
IS 456- 2000



Response of Concrete to Stress



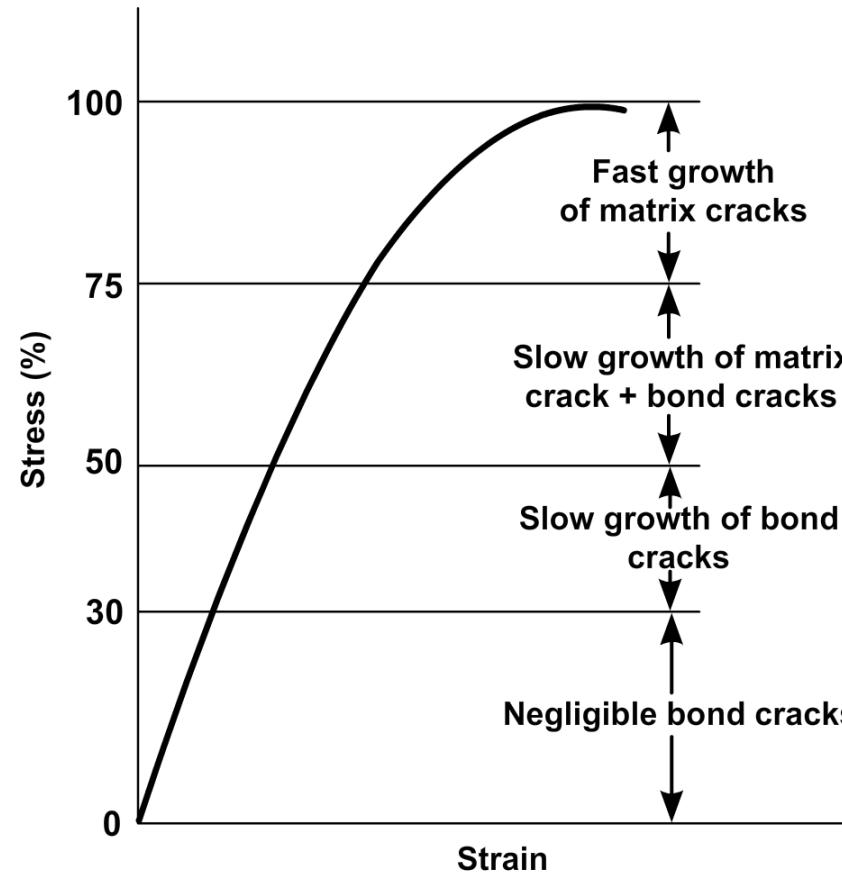
Composite Response of Hardened Concrete



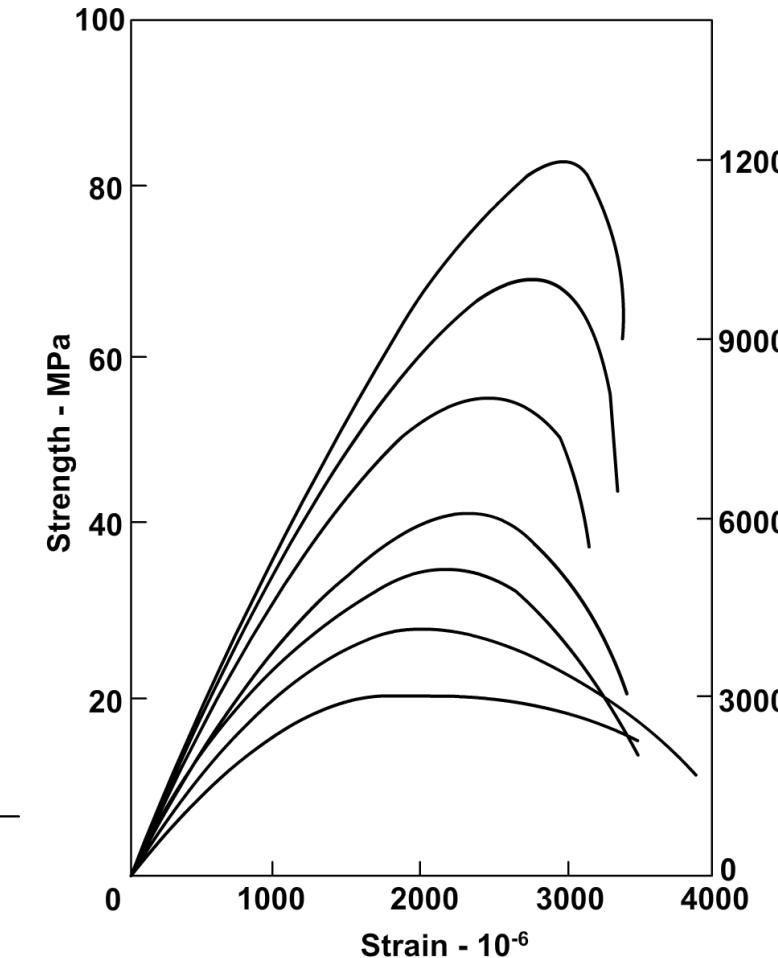
Young et al.; Mindess and Young



Compressive Failure



Young et al.

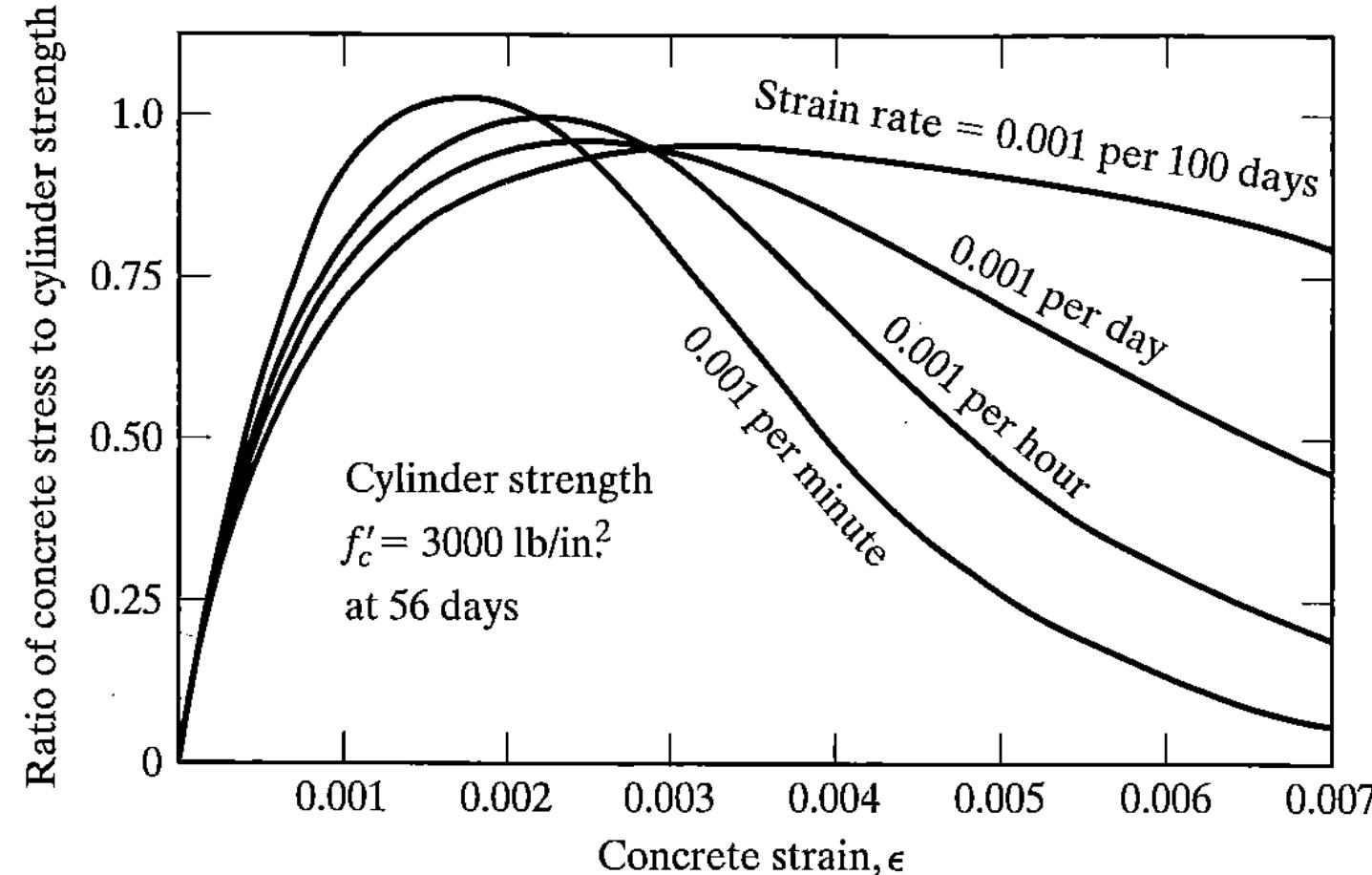


As the strength (or maximum stress) increases, the stress-strain curve under uniaxial compression usually shows a slightly higher elastic modulus, a longer linear response and a sharper post-peak descent.

Neville



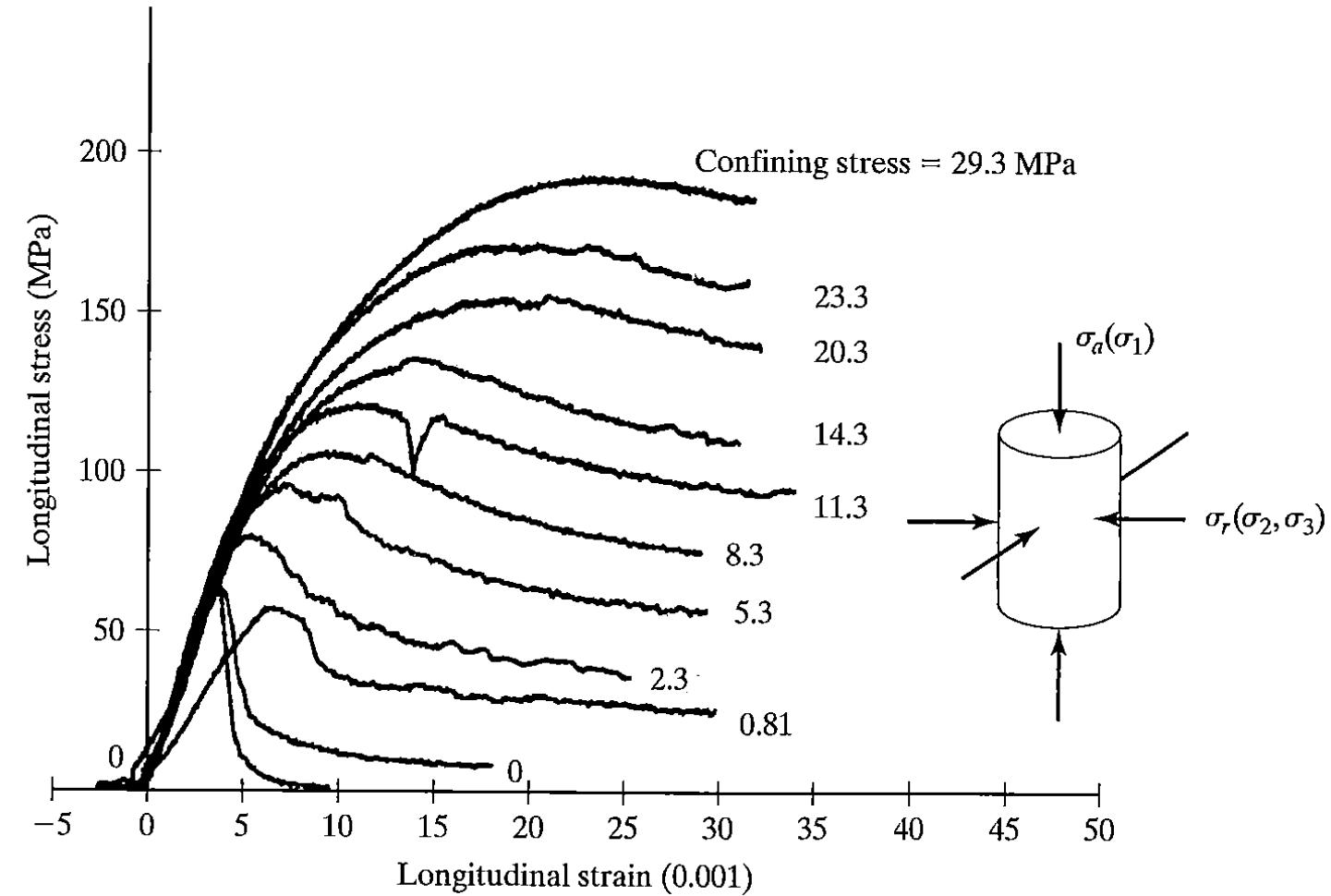
Effect of Strain Rate on Stress-Strain Behavior of Concrete



H Rusch, 1960



Compressive Failure



Mindess & Young



Time-Dependent Deformation of Concrete

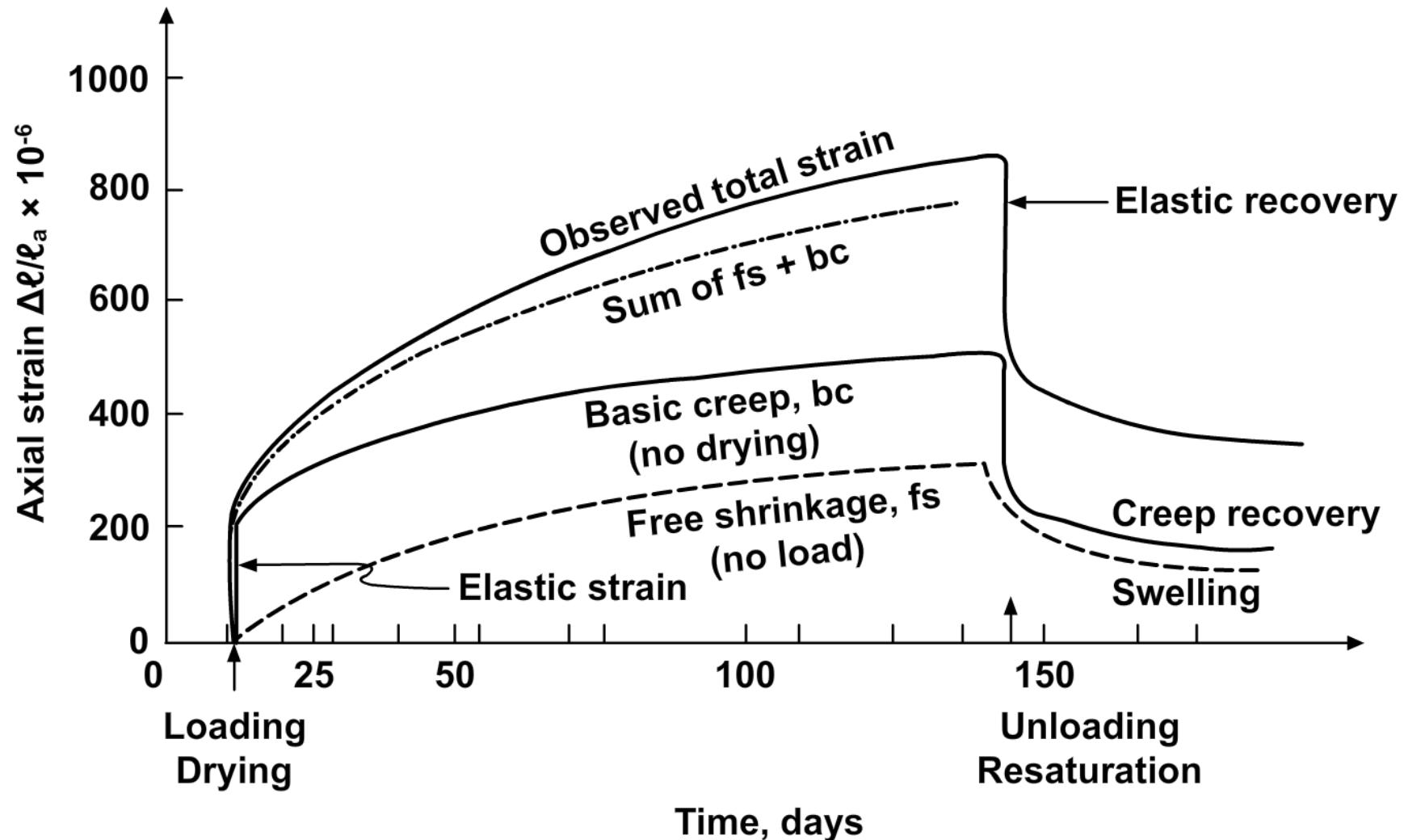


Shrinkage and Creep of Concrete

- Creep and shrinkage are time-dependent strains that involve the movement of water
- Shrinkage strains occur when water is lost
- Creep strains occur when water is forced to move by stress
- These strains are not completely recoverable when the load is removed, or the concrete is re-saturated



Nature of Shrinkage and Creep



Young et al.

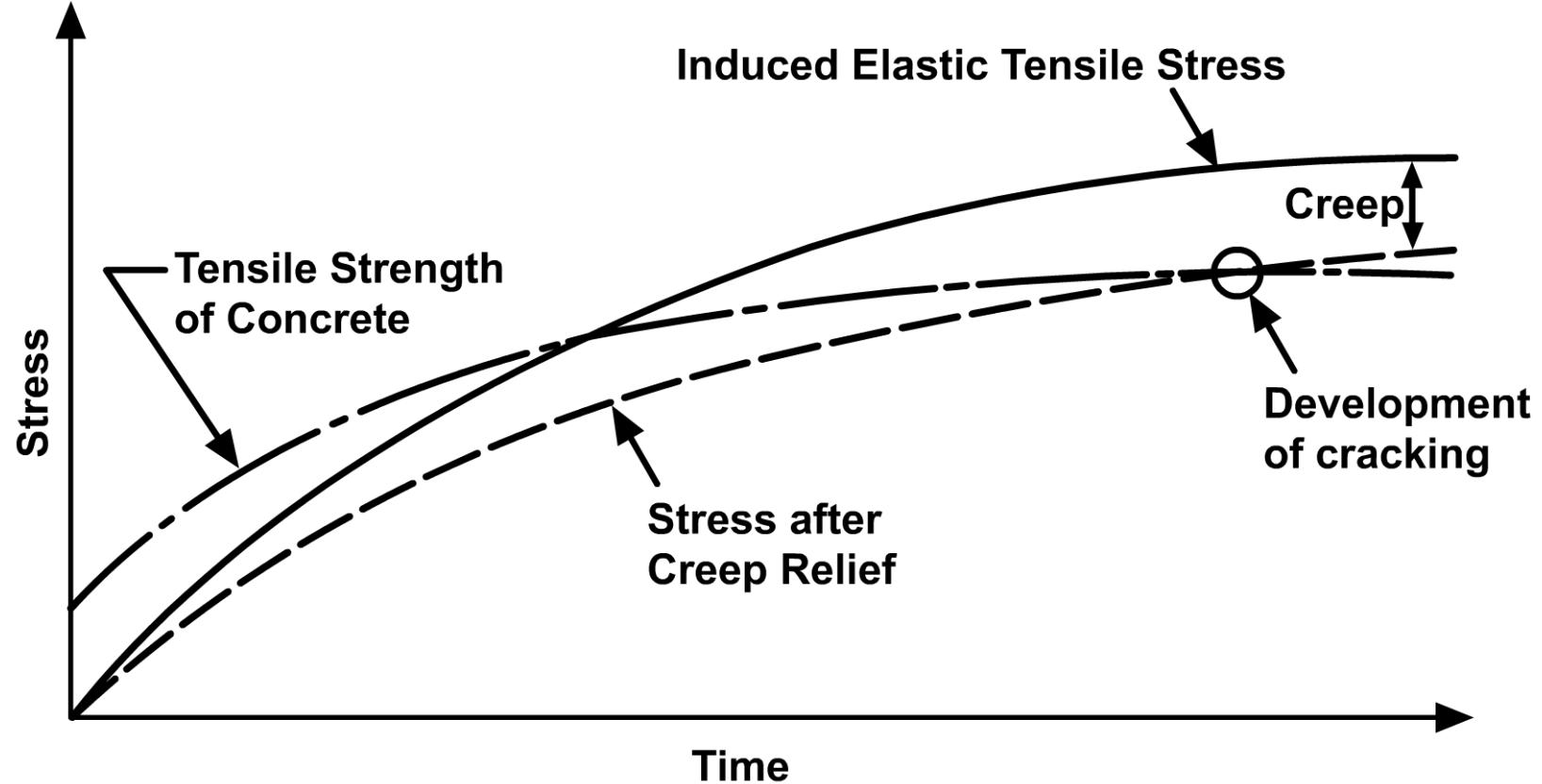


Effects of Shrinkage and Creep

- Axial strains increase with time; e.g., in columns under compressive loads and bridge piers.
- Deflections increase; e.g., beams and girders in flexure.
- Stress relaxation; e.g., the prestressing force decreases with time as the concrete shrinks and creeps.
- Cracks can occur in elements that are restrained and develop tensile stresses; e.g., in pavements and slabs-on-grade.



Combined Effect of Shrinkage and Creep



Neville



Durability of Concrete



Durability of Reinforced Concrete

- **The useful life of a concrete structure can be limited by damage resulting from:**
 - Deterioration of concrete due to chemical reactions or physical phenomena within the material.
 - Corrosion of the steel reinforcement.



Durability of Concrete

Leaching due to exposure to soft (acidic) water

- Calcium hydroxide is dissolved and reacts with carbon dioxide to be deposited as (white) calcium carbonate within the concrete and on the surface.
- Extensive leaching could decrease strength and facilitate ingress of aggressive agents.



Durability of Concrete

Sulphate attack

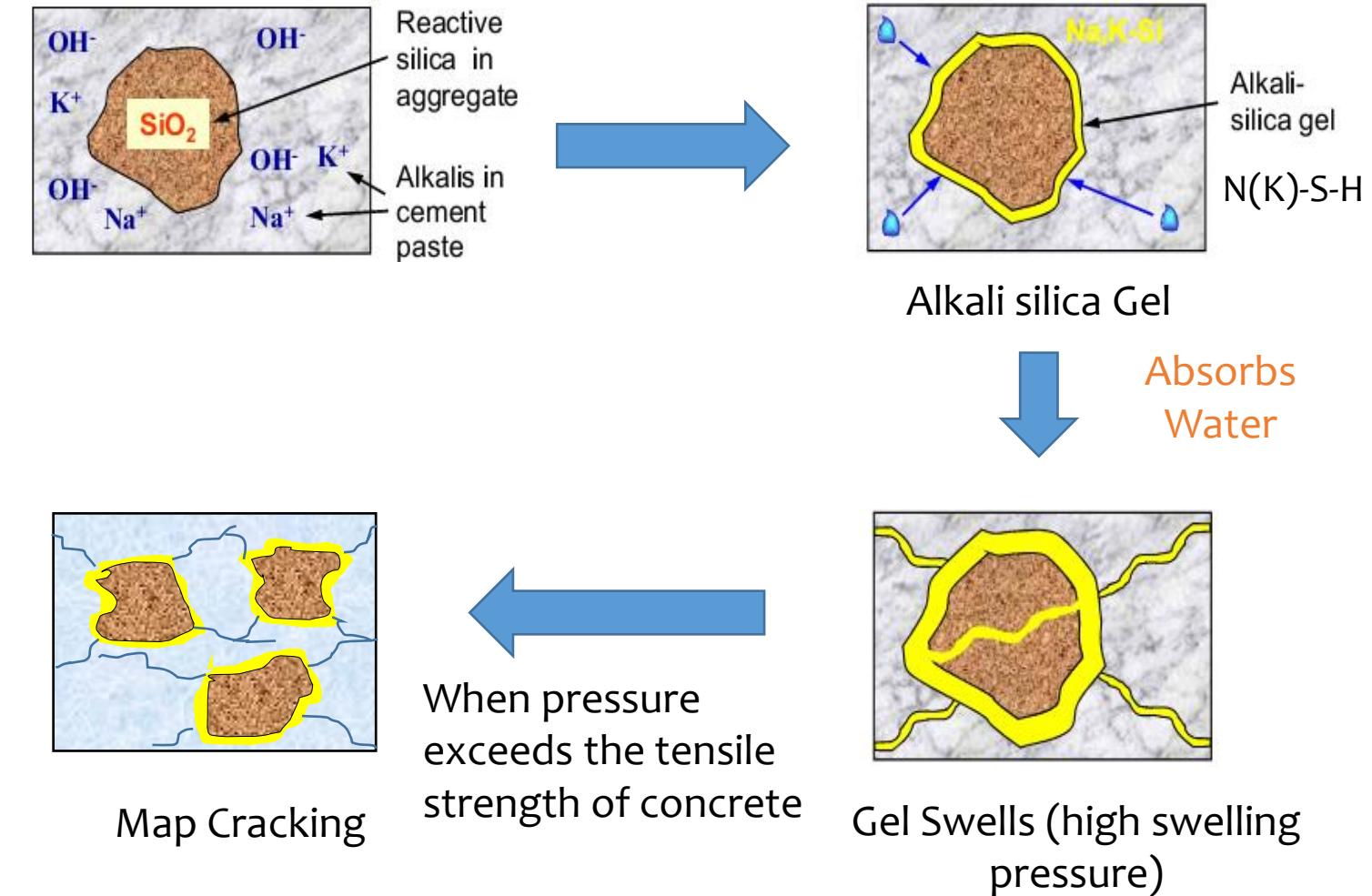
- Sulphates react with the calcium hydroxide to form gypsum. The gypsum reacts with the hydrated compounds to form ettringite. This results in expansion and cracking of the concrete.
- In addition, attack by magnesium sulphate is more damaging since the magnesium hydroxide that is formed in the reaction with the C-S-H replaces the Ca^{2+} ions with Mg^{2+} , which destroys the cementing effect.



Durability of Concrete

Alkali-silica reaction

- Hydroxides of sodium and potassium present in the cement can react with reactive aggregates. The product is a silicate gel that absorbs water and expands. When all the pores are filled, further expansion causes cracking.



Prof. P J M Monteiro



Durability of Concrete

Carbonation

- The surface zone of concrete undergoes carbonation of the hydrated cement paste. The pH of the pore fluid can drop as low as 8 (from ~13.5).
- Carbonation involves the ingress of CO_2 , formation of carbonic acid, dissolution of $\text{Ca}(\text{OH})_2$ and C-S-H, deposition of CaCO_3 and loss of bound water.
- Carbonation-induced shrinkage cracking can be considerable at intermediate relative humidity (50-70% RH).



Durability of Concrete

The entry of aggressive chemicals into concrete depends also on:

- Diffusion of ions and gases through the empty pores and the pore solution in saturated pores
- w/c and curing are again of primary importance

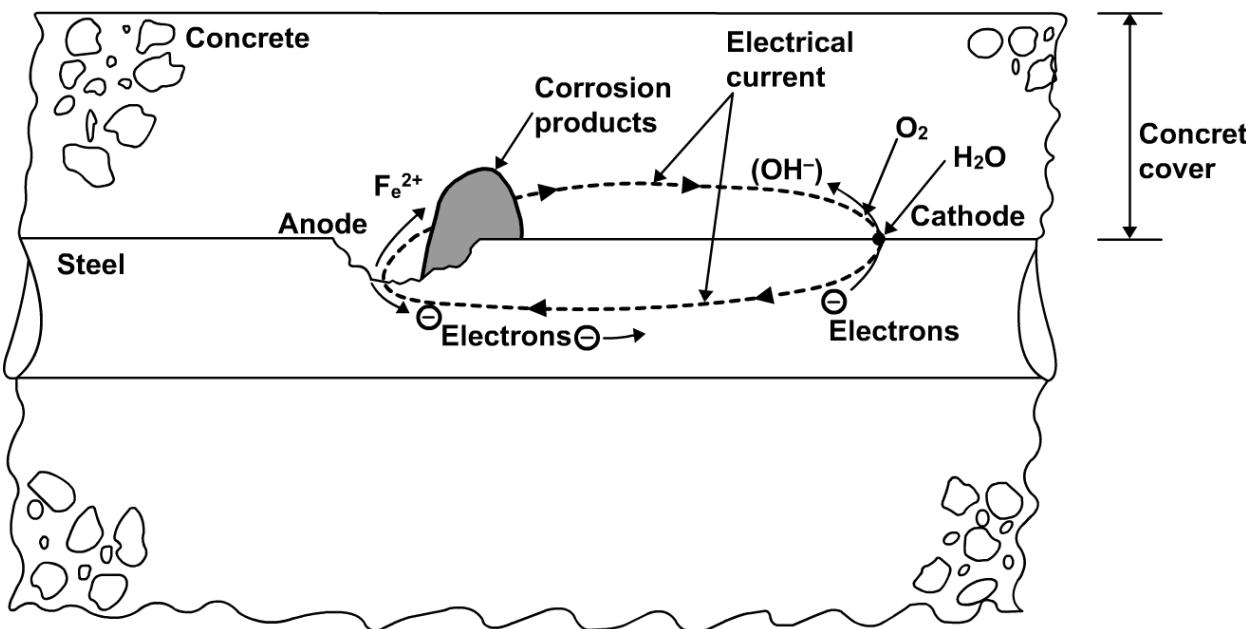
Cracking

- Facilitates the entry of water and other aggressive substances

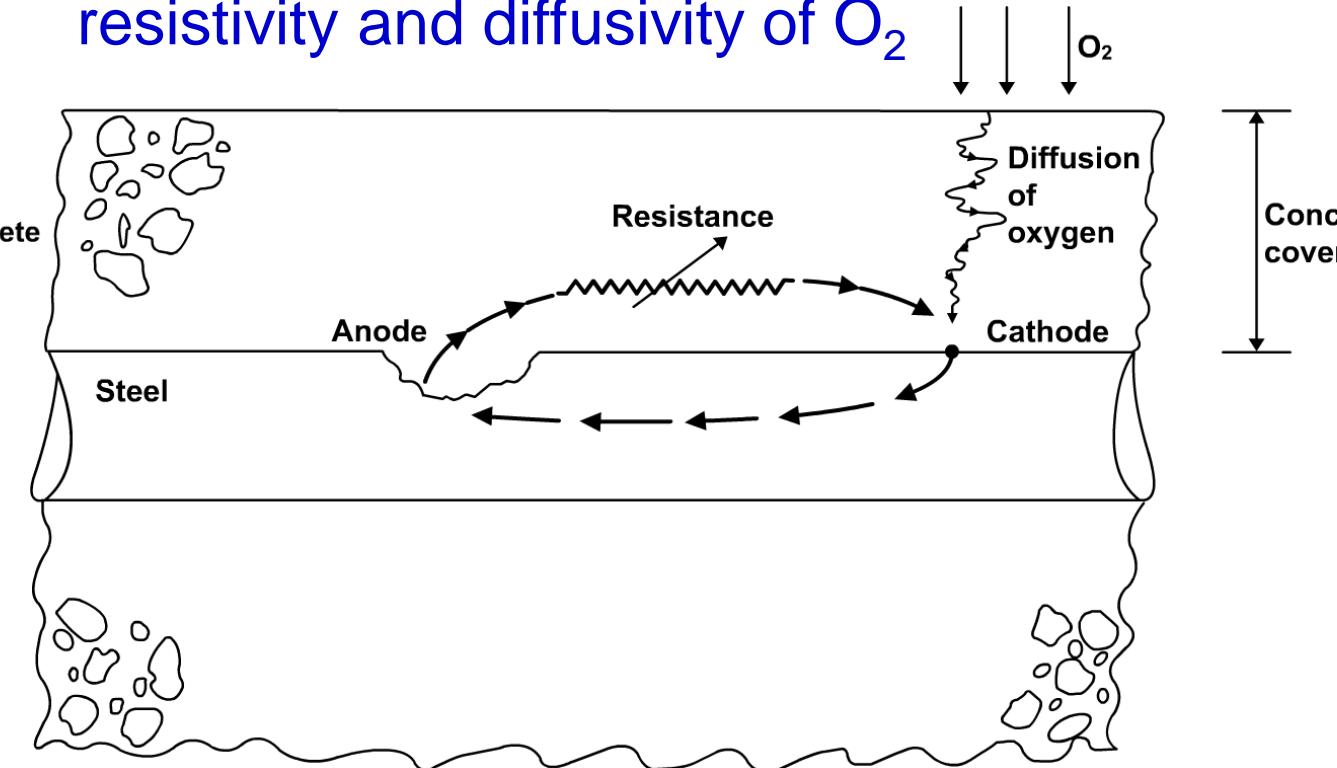


Corrosion of Reinforcement in Concrete

Chemical reactions and charge movements



Parameters controlling the corrosion rate - resistivity and diffusivity of O_2



Young et al.



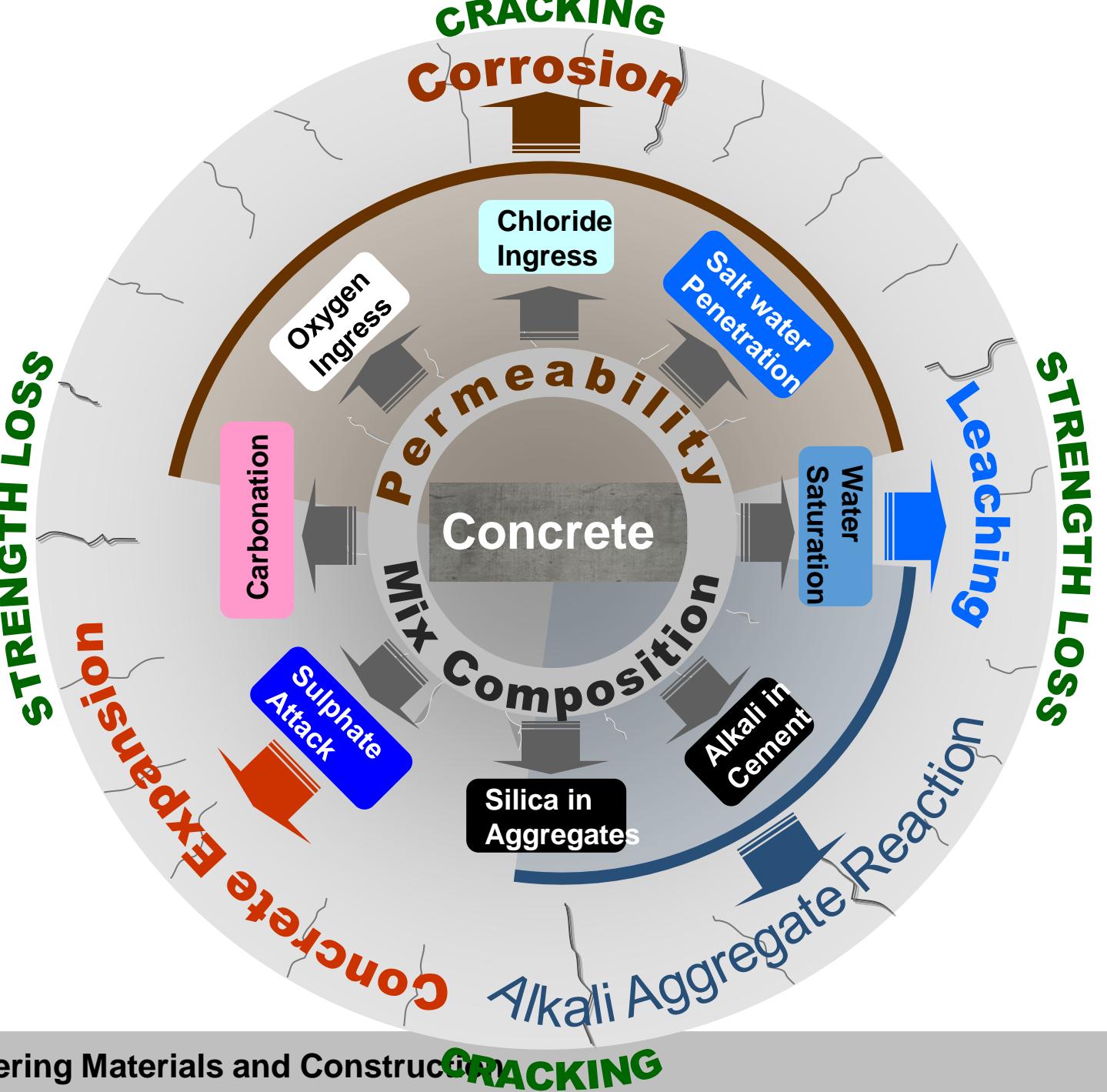
Corrosion Protection

- In general, the high pH of concrete is sufficient to maintain the steel in a passivated state.
- Depassivation of the concrete can occur when:
 - The calcium hydroxide has been carbonated by the penetration of CO_2 into the concrete (and the pH becomes lower than 11).
 - Chloride ions are present in the concrete (more than 0.2-0.4%), even though the pH is high.
- Moisture and oxygen are necessary for corrosion to be sustained. Porous concrete and cracks permit the ingress of water and oxygen and promote corrosion.



Effects of Cracks on Reinforcement Corrosion

- Cracks in cover concrete produce three specific effects:
 - facilitate the onset of corrosion by providing easy access to deteriorating agents (Cl^- ions and CO_2)
 - accelerate the rate of corrosion once begun, by reducing the barrier to diffusion of oxygen
 - produce substantial non-uniformity in the physical and chemical environment around the steel that promotes corrosion



Courtesy: Prof. Mathews



Special Concretes

- Structural Lightweight Concrete
- High Strength Concrete
- High Performance Concrete
- Shrinkage-Compensating Concrete
- Self Compacting Concrete
- Fiber Reinforced Concrete
- Mass Concrete
- Roller Compacted Concrete
- High Resistance Refractory Concrete
- High Density Concrete (density 3360-3840 kg/m³)
- Polymer-Based Concrete



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<http://www.cement.org/cement-concrete-applications/how-cement-is-made>

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<https://cembureau.eu/cement-101/the-manufacturing-process/>

https://www.youtube.com/watch?v=tv71N_NztAw (Cement Manufacturing Process, short video)

<https://www.youtube.com/watch?v=uH6S7WpAsFU> (Cement Manufacturing Process, long video)

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- *Concrete*, Mindess, S., Young, J.F. and Darwin, D., 2003.
- *Concrete Microstructure, Properties and Materials*, Mehta, P.K. and Monteiro, P.J., 2017.
- *Chemical Admixtures for Concrete*, Roger Rixom, R., and N. Mailvaganam, 1999.
- Prof. P. J. M. Monteiro, Online Lecture Notes, UC Berkeley.



Masonry

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Uses/Applications of Masonry

- History

- One of the oldest construction materials
- Pyramids, Great wall of China, Greek and Roman ruins

- Current use

- Bridge piers
- Tunnel linings
- Single & multistory buildings
- Sewer lines





Sewer Lines in London

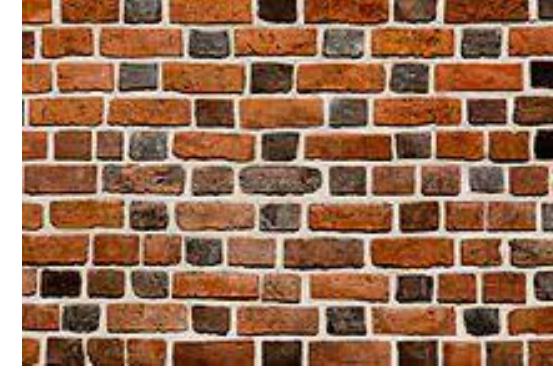
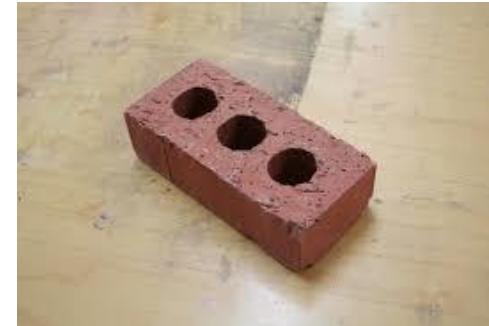


<http://www.sub-urban.com/close-encounters-of-the-turd-kind/>



Types of Masonry Units

- Concrete units
- Clay bricks
- Structural clay tiles
- Glass blocks
- Stone



Wikipedia



Concrete Masonry

- Solid blocks
- Hollow blocks



- Ordinary Portland cement (OPC)
- Portland pozzolana cement (PPC)
- SCMs
- Air entraining agents
 - Freeze-thaw resistance
 - Fresh characteristics
- Casting procedure
 - Relatively dry (zero slump)
 - Molded under pressure
 - Ideally - initial steam curing followed by normal curing



Classification of Concrete Masonry Units

- Normal weight – well-graded sand, gravel, crushed stones
 - Unit weight greater than 2000 kg/m^3
 - Maximum water absorption of 208 kg/m^3
- Lightweight – pumice, expanded shale etc.
 - Unit weight less than 1680 kg/m^3
 - Maximum water absorption of 288 kg/m^3
 - Better fire resistance and sound resistance
- Medium weight – adjusting the mixture proportion
 - Unit weight in range of $1680 - 2000 \text{ kg/m}^3$
 - Maximum water absorption of 240 kg/m^3



Strength Requirement for Concrete Masonry Units

Density Classification	Oven-Dry Density of Concrete, lb/ft ³ (kg/m ³)	Maximum Water Absorption, lb/ft ³ (kg/m ³)		Minimum Net Area Compressive Strength, lb/in ² (MPa)	
		Average of 3 Units	Average of 3 Units Individual Units	Average of 3 Units	Individual Units
Lightweight	Less than 105 (1680)	18 (288)	20 (320)	2000 (13.8)	1800 (12.4)
Medium Weight	105 to less than 125 (1680–2000)	15 (240)	17 (272)	2000 (13.8)	1800 (12.4)
Normal Weight	125 (2000) or more	13 (208)	15 (240)	2000 (13.8)	1800 (12.4)

ASTM C90-21



Clay Bricks

- Clay
 - Silica, alumina, lime, iron, manganese, sulfur, phosphates
- Manufacturing
 - Grind, crush the clay in mills
 - Mix with water to make it plastic
 - Plastic clay is then molded, textured, dried, and fired
 - Firing temperature will determine the color of the brick (varies from 900 to 1200°C);
About 4 to 15% shrinking can also occur.
- Advantages
 - Durable
 - Fire resistant
 - Low maintenance
 - Moderate thermal insulation
 - Non-combustible
 - Poor conductors



Absorption Capacity of Bricks

- ASTM C67-21

$$\text{Absorption by 24-hour submersion (\%)} = \frac{(W_{s24} - W_d)}{W_d} \times 100$$

$$\text{Absorption by 5-hour boiling (\%)} = \frac{(W_{b5} - W_d)}{W_d} \times 100$$

$$\text{Saturation coefficient} = \frac{(W_{s24} - W_d)}{(W_{b5} - W_d)}$$

where

W_d = dry weight of specimen,

W_{s24} = saturated weight after 24-hour submersion in cold water, and

W_{b5} = saturated weight after 5-hour submersion in boiling water.



Specification for Building Bricks

Grade SW (Severe Weathering)—Brick intended for use where high resistance to damage caused by cyclic freezing and thawing is desired.

Grade MW (Moderate Weathering)—Brick intended for use where moderate resistance to cyclic freezing and thawing damage is permissible.

Grade NW (Negligible Weathering)—Brick intended for use where little resistance to cyclic freezing and thawing damage is acceptable.

Designation	Minimum Compressive Strength gross area, psi (MPa)		Maximum Water Absorption by 5-h Boiling, %		Maximum Saturation Coefficient ^A	
	Average of 5 Brick	Individual	Average of 5 Brick	Individual	Average of 5 Brick	Individual
Grade SW	3000 (20.7)	2500 (17.2)	17.0	20.0	0.78	0.80
Grade MW	2500 (17.2)	2200 (15.2)	22.0	25.0	0.88	0.90
Grade NW	1500 (10.3)	1250 (8.6)	no limit	no limit	no limit	no limit

^A The saturation coefficient is the ratio of absorption by 24-h submersion in cold water to that after 5-h submersion in boiling water.

ASTM C62-17



Properties of Fired Clay Bricks (India Specific)

Table 1 Classes of Common Burnt Clay Bricks
(Clause 4.1)

Class Designation	Average Compressive Strength not Less Than N/mm ²	(kgf/cm ²) (approx)
35	35.0	(350)
30	30.0	(300)
25	25.0	(250)
20	20.0	(200)
17.5	17.5	(175)
15	15.0	(150)
12.5	12.5	(125)
10	10.0	(100)
7.5	7.5	(75)
5	5.0	(50)
3.5	3.5	(35)

- After immersion in cold water for 24 hours, water absorption shall not be more than 20 % by weight up to class 12.5 and 15 % by weight for higher classes.

IS 1077 - 1992



Flooring Clay Bricks/Tiles

- Flooring purposes
- High abrasion resistance, smooth, dense
- Paving bricks
 - For roads, sidewalks, patios, driveways, interior floors
 - High abrasion resistance
 - Vitrified (to make it impervious to water)



Mortar for Masonry Construction

- Mortar is a mixture of cementitious material, aggregate, and water. Mortar can be classified as cement-lime mortar, cement mortar, or masonry cement mortar.
- Mortar is used for the following functions:
 - Binding the masonry units together
 - Leveling and seating the masonry units
 - Aesthetics

Mortar



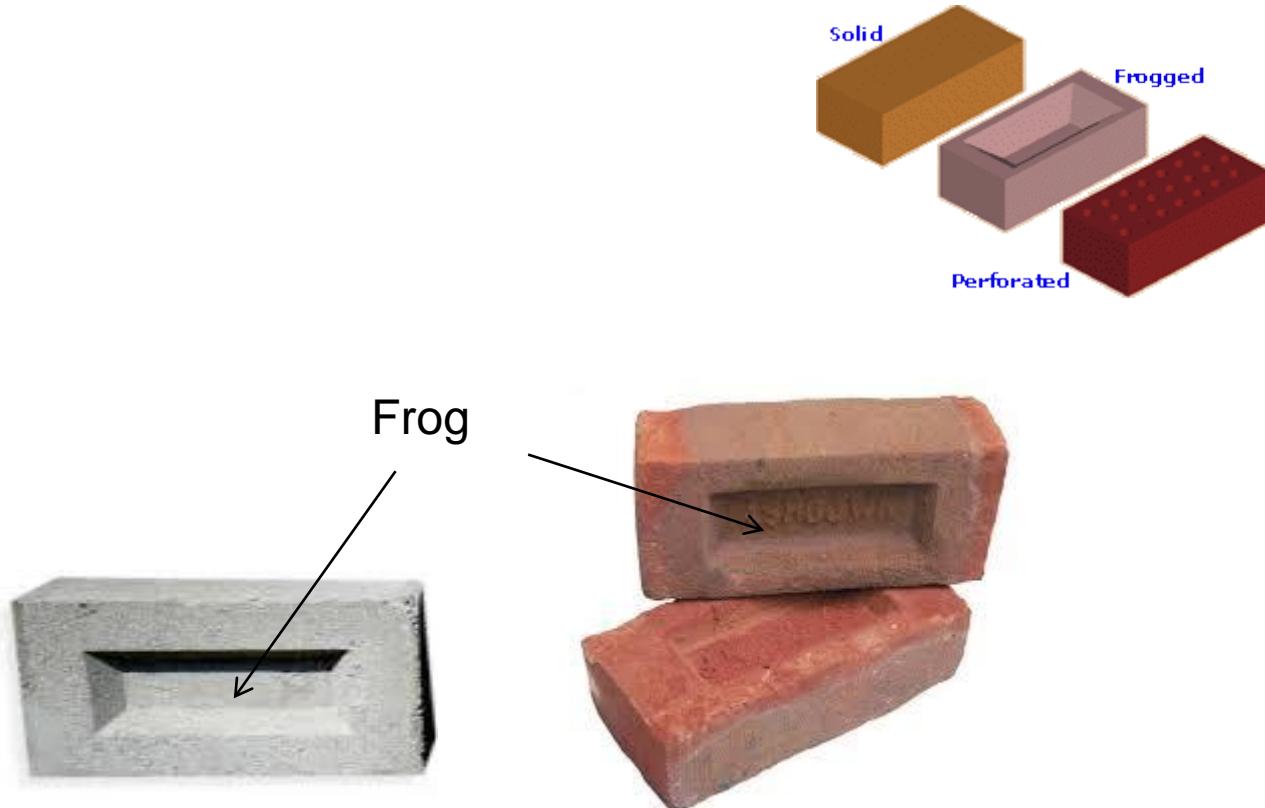


Properties of Mortar

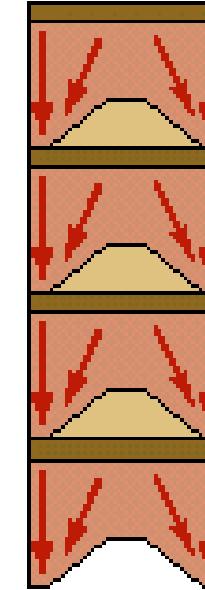
- Compressive strength
 - 50 mm cubes; ASTM C109
- Water retention
 - ASTM C91 defines this as the measure of the rate at which water is lost to the masonry units
- Workability
 - Air content
 - Aggregate ratio
- Tensile bond strength (ASTM C592)
 - Shear strength of masonry walls
 - Flexure strength of masonry



Better Interlocking Through Frogs

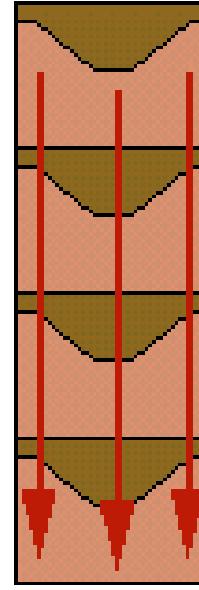


Frog DOWN



Load concentrated onto edges of brick

Frog UP



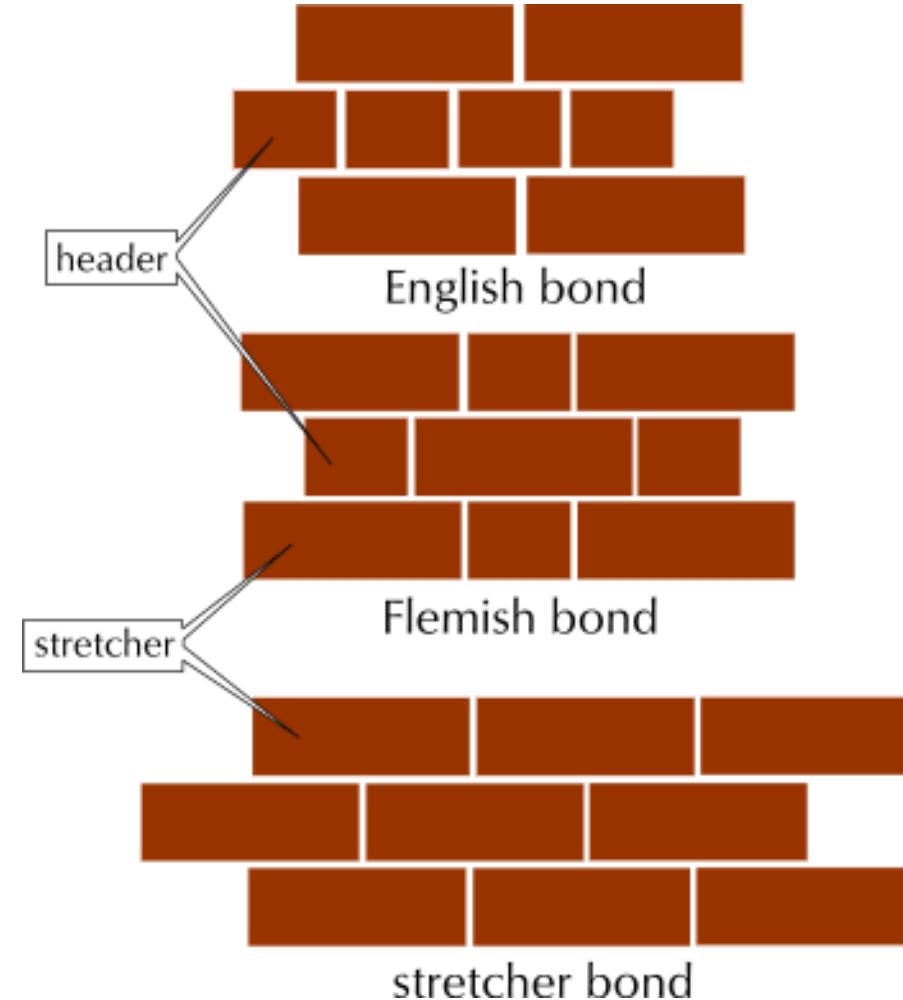
Load evenly spread

<https://www.pavingexpert.com/featur09>



Types of Bonds

- Stretcher
- Flemish
- English



Laying of bricks to avoid a continuous path of weakness!

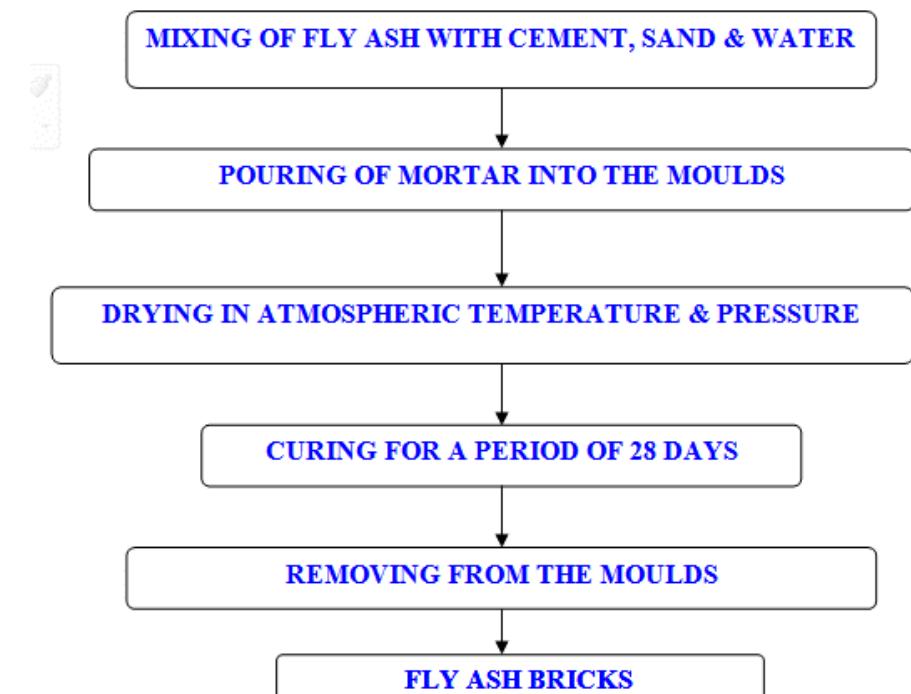
http://www.bricksandbrass.co.uk/design_by_element/external_wall/bricks_and_brickwork_in_period_home.php



Fly Ash Bricks

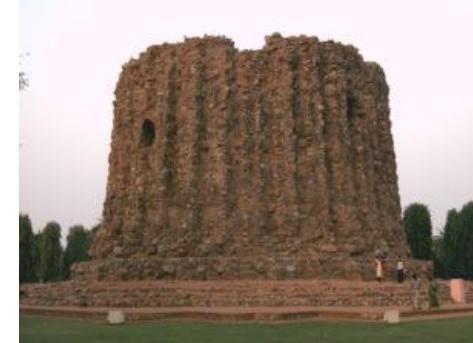
- **Fly ash brick (FAB)** is a building material, specifically masonry units, containing class C or class F fly ash and water.
- Approximate proportions: fly ash (60%), sand /stone dust (30%) and Portland cement (10%)
- The manufacturing method saves energy, reduces mercury pollution in the environment, and often costs 20% less than traditional clay brick manufacturing.
- Compressive strength 7.5-10 MPa
- Lighter and stronger than fired clay bricks

<https://theconstructor.org/building/fly-ash-bricks/5330/>





Stone Masonry: Properties of Stone



Rubble masonry



Ashlar masonry

<http://pittsburgh-masonry.com/blog/what-are-the-different-types-of-natural-stone-masonry/>

Type of stone	Density	Water absorption	Porosity	Compressive strength	Young's modulus
	(kg/m ³)	(% w/w)	(% v/v)	(MPa)	(GPa)
Typical ranges					
Limestone	1800 to 2700	0.1 to 17	0.3 to 30	20 to 240	1 to 8
Sandstone	2000 to 2600	0.4 to 15	1 to 30	20 to 250	0.3 to 8
Marble	2400 to 2800	0.4 to 2	0.4 to 5	40 to 190	–
Slate	2600 to 2900	0.04 to 2	0.1 to 5	50 to 310	–
Granite	2500 to 2700	0.04 to 2	0.1 to 4	80 to 330	2 to 6
Basalt	2700 to 3100	0.03 to 2	0.1 to 5	50 to 290	6 to 10

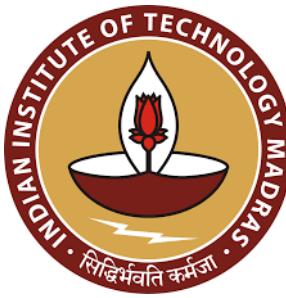
Porosity and pore size distribution influences strength and durability of stones

M Soutsos and P. Damone



Summary

- Brick, Stone and Concrete masonry
- Strength of the masonry construction depends on the strength of mortar and tensile bonding strength of the joint between the mortar and masonry units
- Resistance against environmental factors play a major role in the quality and durability of the masonry construction
 - To attain quality construction, moisture absorption must be minimized



References

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Wood, Timber and Timber Products

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Application of Wood in Construction



<http://www.understandconstruction.com/wood-framed-construction.html>



Wood

- Wood is a naturally occurring, biological material. It is probably the world's oldest structural material.
- Since it is easy to produce and handle, it is a widely used construction material.
- Wood has good structural properties, is aesthetically appealing and relatively cheap. Though it is vulnerable to fire and decay through biological attack, it can last for a long time if properly maintained.

Young et al.



Specific Properties of Structural Materials

Materials	E/ρ	$\sigma_{\text{tensile}}/\rho$	$\sigma_{\text{compressive}}/\rho$	K_I/ρ
Wood	20-30	120-170	60-90	1-12
Mild steel	26	30	-	18
Aluminum alloys	25	180	130	8-16
Concrete	15	3	30	0.08

Young et al.



Wood Species

Trees are divided into two broad classes:

- **Hardwoods:** Tropical, broad-leaved, deciduous (shed leaves annually), porous (contain vessel elements).

Examples: Teak, Sal, Oak.

- **Softwoods:** Conifers, have needle- or scale-like evergreen leaves, non-porous.

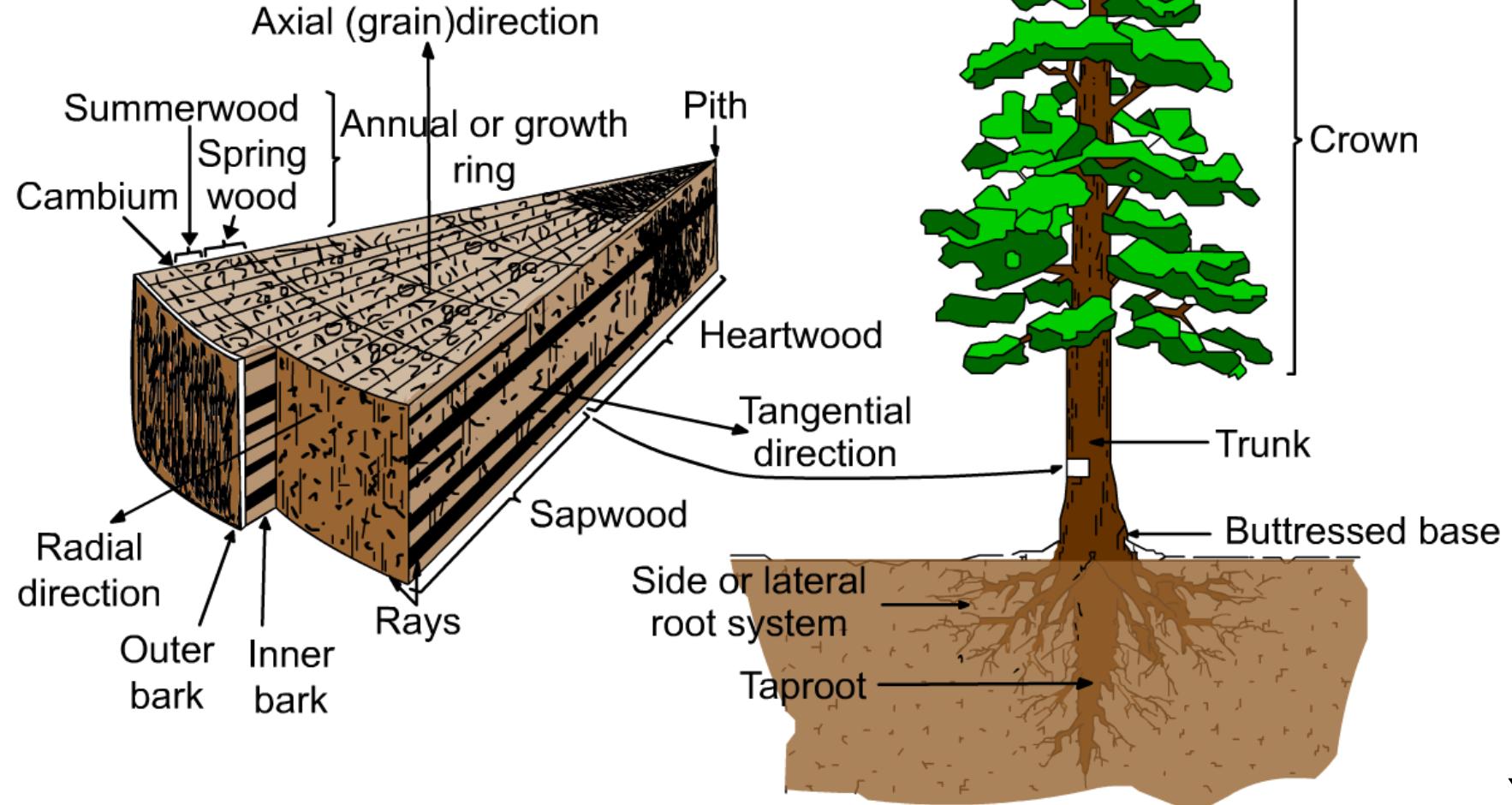
Examples: Fir, Pine, Cedar.

No reference to actual hardness of wood !

Young et al.



Structure of Wood



Young et al.



Structure of Wood

Outer bark: dense rough layer of protection.

Inner bark: transports sap from leaves to growing parts of the tree. Transports sap from leaves to ward off insects.

Cambium: layer of tissue, one to ten cells thick, between bark and wood. Produces sapwood and inner bark.

Sapwood: wood on the outside, conducts moisture and nutrients from roots, stores food.

Heartwood: inner core, nonliving, more resistant to decay, drier and harder. Forms the central supporting pillar for tree.

Young et al.



Structure of Wood

Rays: small amount of cells that grow in the horizontal direction. This allows for transverse movement of sap.

Annual rings are the most distinct feature of a tree trunk. As the cells of the cambium grow and divide during the growing season, they form a ring of cells around the trunk.

Young et al.



Common Indian Wood Species

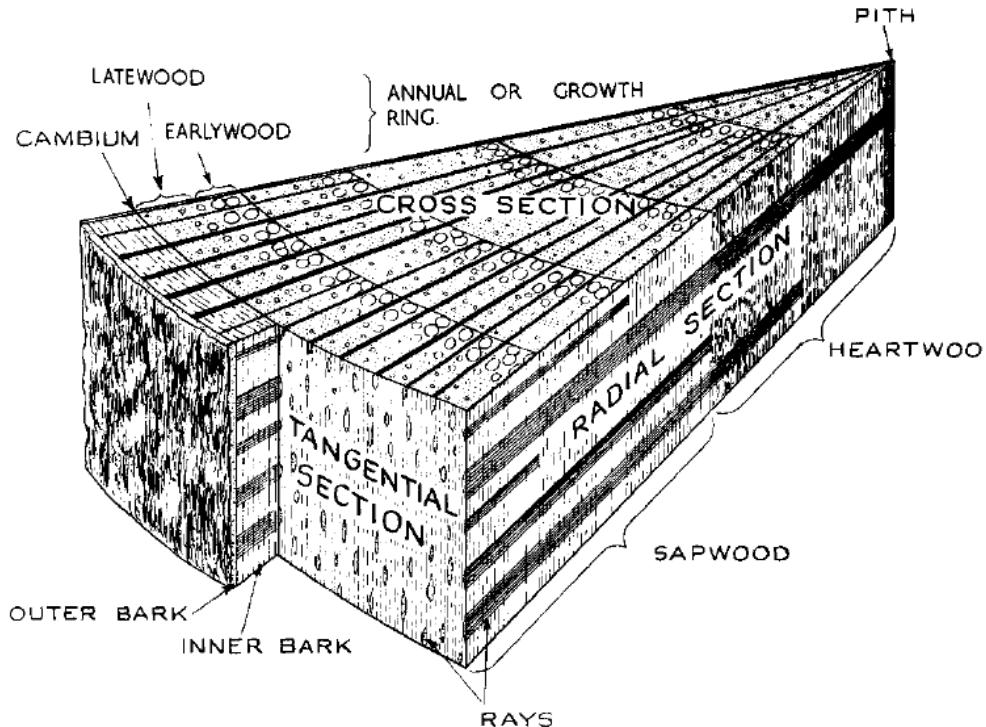
- **Teak:** Good dimensional stability and natural durability. Heartwood varies from yellow-brown to dark golden-brown.
- **Padauk:** Medium density hardwood. Deep red/orange in color.
- **Rubberwood:** Light hardwood. Seasons to light brown.
- **Sal:** Strong and hard wood. Dark brown in color.
- **Deodar:** Light and durable. Light brown in color.
- **Rosewood:** Heavy wood with high strength. Heartwood varies in color from golden brown to dark purplish brown with blackish streaks.

Varghese



Structure of Wood

Macroscopic level



Cross section of tree trunk:

- (A) outer bark (dry dead tissue)
- (B) inner bark (living tissue)
- (C) cambium
- (D) sapwood
- (E) heartwood
- (F) pith, and
- (G) wood rays (transverse cells)



Structure of Wood

The annual rings are the most distinct feature of a tree trunk.

As the cells of the cambium grow and divide during the growing season, they form a ring of cells around the trunk.

In spring, during the period of rapid growth, these cells are larger with thin walls, and are referred to as springwood or earlywood.

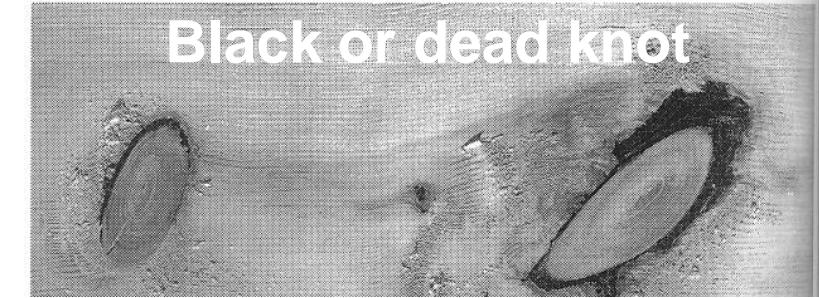
Later in the growing season, the cells are smaller and with thicker walls, and therefore harder and stronger. This is called summerwood or latewood.

Young et al.



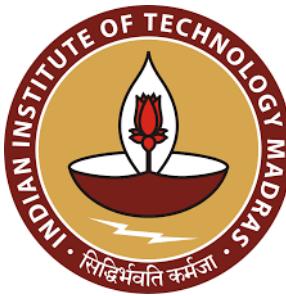
Structure of Wood

Macroscopic level



- Radial growth of the trunk must accommodate existing branches of the tree. This is achieved by the structure known as the *knot*.
- If the cambium of the branch is still alive when it fuses with that of the trunk, there is continuity in growth, and a *green or live knot* is formed.
- If the cambium of the branch is dead, there is absence of continuity, and the trunk grows around the dead branch and even the bark. Here, a *black or dead knot* is formed.

Illston and Domone



Structure of Wood

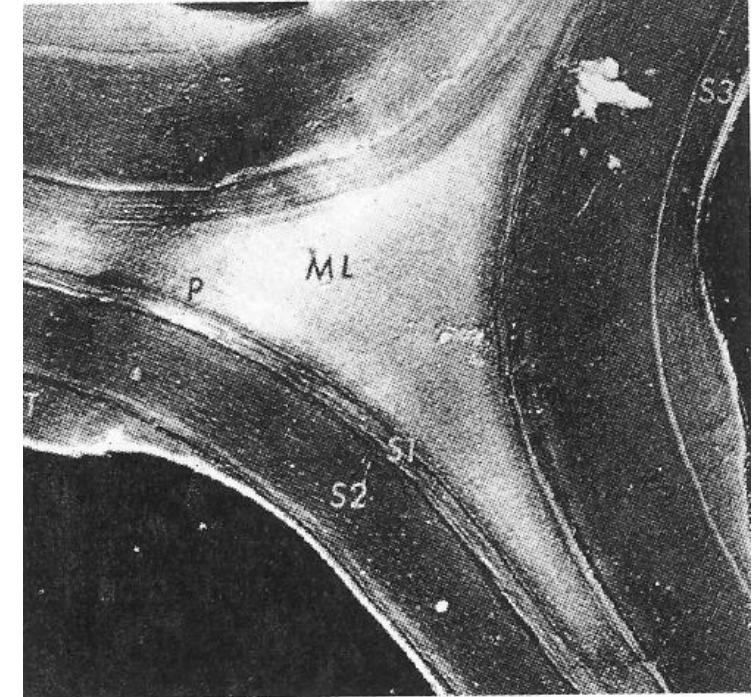
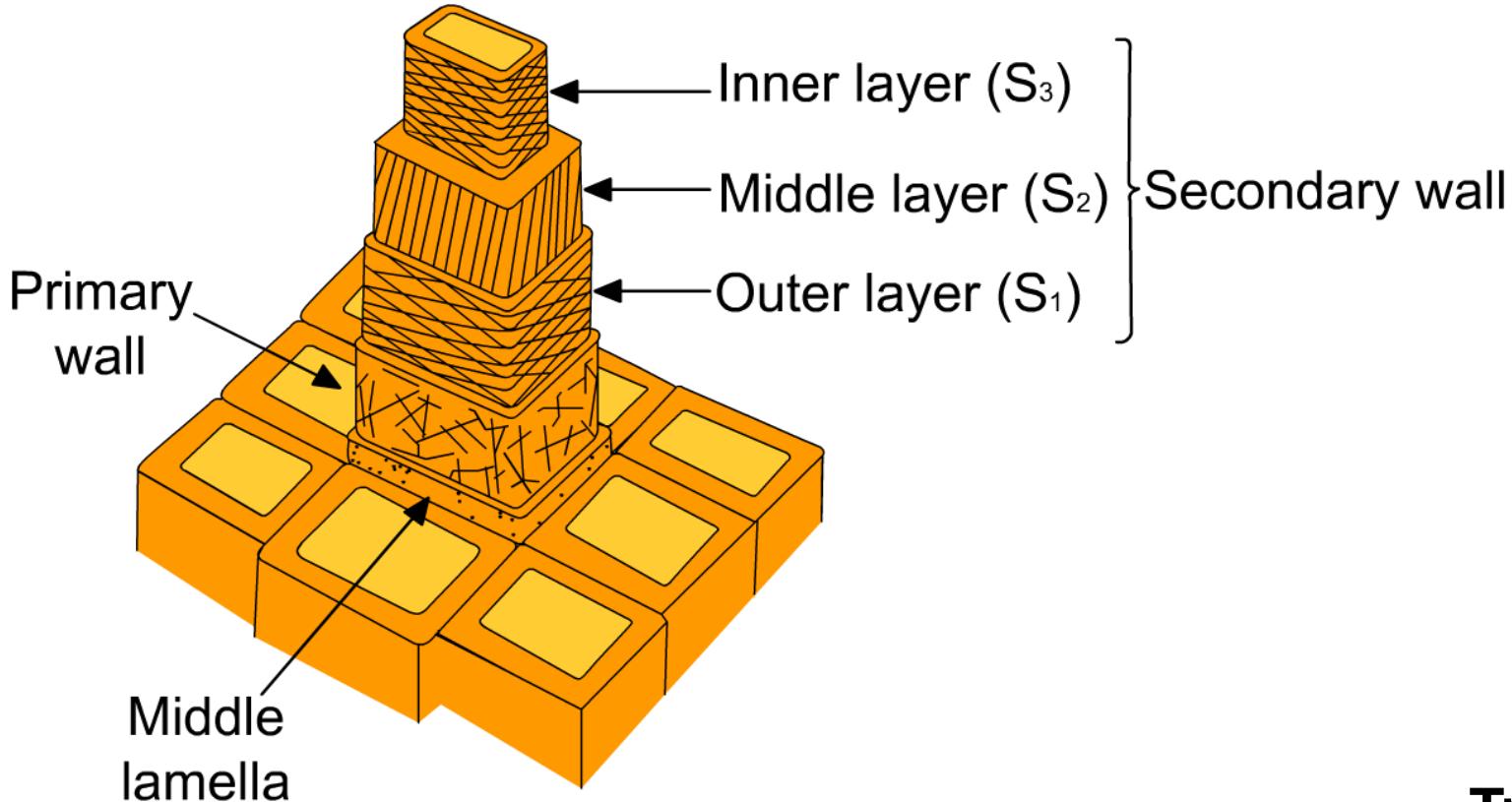
The functions and dimensions of the various types of cells found in softwoods and hardwoods

Cells	Softwood	Hardwood	Function	Wall Thickness	Length	Width
Parenchyma	+	+	Storage		200 µm	30 µm
Tracheids	+	+	Support Conduction		2-5 mm	20-50 µm
Fibers		+	Support		0.7-3 mm	10-20 µm
Vessels(pores)		+	Conduction		0.2-1.2 mm	500 µm

Young et al.



Structure of Wood: Cell



**Transmission electron micrograph
of a cell wall cross-section**

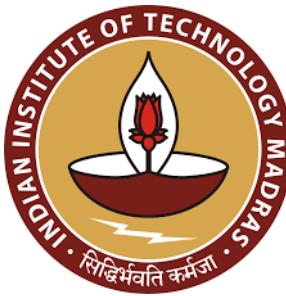
Young et al.



Structure of Wood

Microstructure: Cells

- Wood may be modelled crudely as a bundle of aligned tubular cellulose cells or fibers, glued together.
- The **primary wall (P)** of the cell is thin with randomly oriented microfibrils.
- The **secondary wall** of the cell has a thin outer layer (S_1), a thick middle layer (S_2) and a thin inner layer (S_3). These layers have microfibrils oriented in different directions.
- The **middle lamella (ML)** bonds the neighboring cells.



Structure of Wood

Microstructure: Cells

- In **softwoods**, **90% of the volume** consists of longitudinally oriented cells called **tracheids**; the remaining are transversely oriented cells called **parenchyma**.
- In hardwoods, the microstructure is more complex as they contain, in addition to the tracheids and parenchyma, fibers and pores.



Chemical Composition of Wood

Component	Per cent mass		Polymeric state	Molecular derivatives	Function
	Softwood	Hardwood			
Cellulose	42 ± 2	45 ± 2	Crystalline highly oriented large linear molecule	Glucose	'fibre'
Hemicelluloses	27 ± 2	30 ± 5	Semi-crystalline smaller molecule	Galactose Mannose Xylose	'matrix'
Lignin	28 ± 3	20 ± 4	Amorphous large 3-D molecule	Phenyl-propane	
Extractives	3 ± 2	5 ± 4	Generally compounds soluble in organic solvents	Terpenes Polyphenols Stilbenoids	extraneous

Illston and Domone



Properties of Wood

- Orthotropic in nature

<i>Species</i>	<i>Density (kg/m³)</i>	<i>Moisture content (%)</i>	E_L	E_R	E_T
<i>Hardwoods</i>					
Balsa	200	9	6300	300	106
Khaya	440	11	10200	1130	510
Walnut	590	11	11200	1190	630
Birch	620	9	16300	1110	620
Ash	670	9	15800	1510	800
Beech	750	11	13700	2240	1140
<i>Softwoods</i>					
Norway spruce	390	12	10700	710	430
Sitka spruce	390	12	11600	900	500
Scots pine	550	10	16300	1100	570
Douglas fir*	590	9	16400	1300	900

Illston and Domone



Properties of Wood

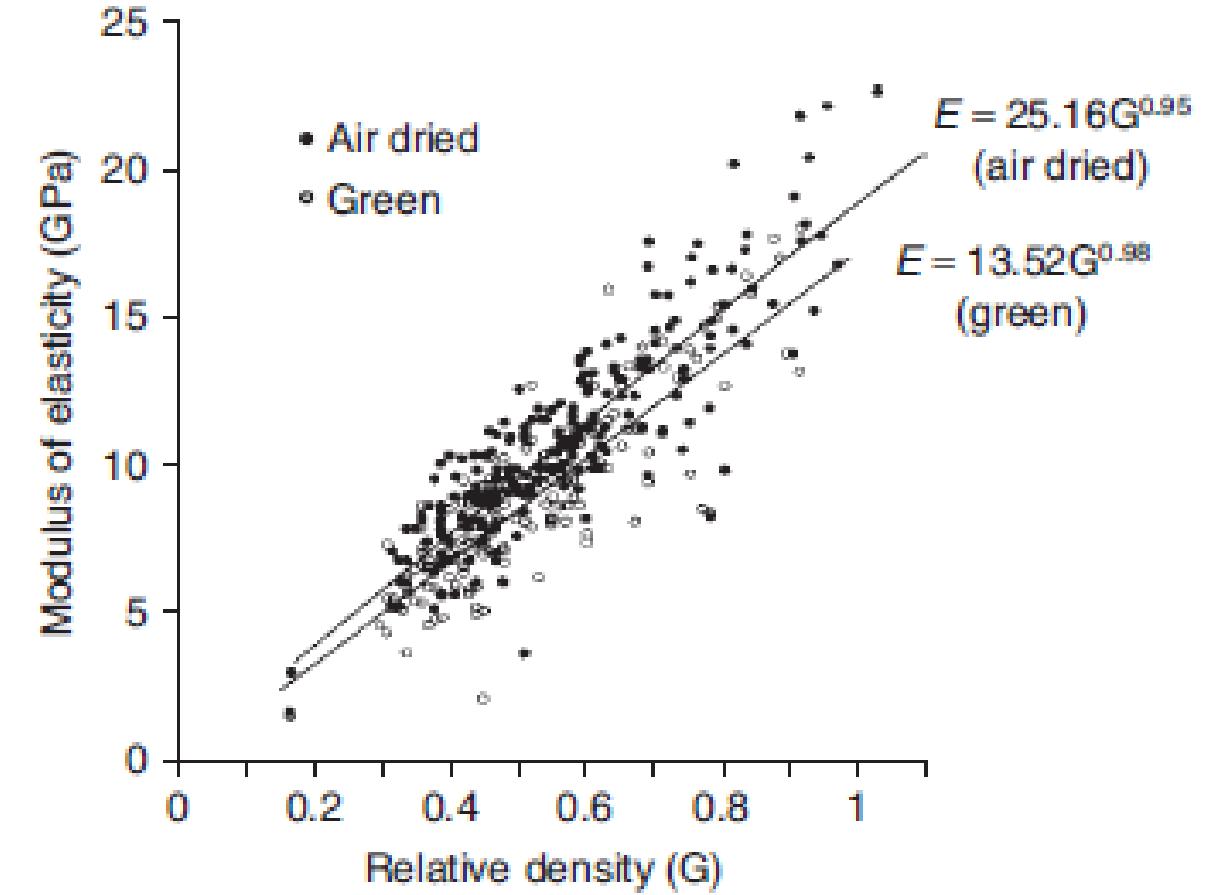
Specific gravity or Relative density

- The differences in the relative densities between species is related to the variations in the void space or porosity associated with the geometry of the wood cells and their grouping.
- Specific gravity is a good indicator of the mechanical properties. Within the same species, the mechanical properties vary linearly with the specific gravity.



Mechanical Properties of Wood

- Strong correlation between relative density and mechanical properties such as modulus of elasticity
- Figure: Effect of specific gravity on the longitudinal modulus of elasticity for over 200 species of timber tested in the green and dry states



Illston and Domone



Properties of Wood: Moisture Content

- The moisture content of green wood is high and can vary from 60-200%.
- Green timber will yield moisture to the environment with consequent changes in its dimensions.
- For every combination of relative humidity and temperature of the environment there is an equilibrium moisture content of the wood.
- **Moist wood is more susceptible to attack by fungi.**
- For all these reasons, it is desirable to dry timber before its use.



Seasoning of Timber

- **Seasoning** is the process of controlled drying to remove sap and reduce moisture without causing cracks and distortion.
- **Natural or air seasoning** – takes about 2 to 6 months. Faster if immersed in water before drying to remove sap.
- **Artificial seasoning** – kiln drying, boiling, chemical seasoning and electrical seasoning.



Effect of Moisture Content

- Moisture in wood exists in two forms:
 - Free water within cell cavities
 - Bound water adsorbed in the cell walls
- As green wood dries, the free water evaporates first. **Fiber saturation point** is reached when all the free water has been removed but the cell walls are still saturated. This generally occurs at moisture contents of 25-30%.
- Further removal of water compacts the molecular structure, leading to additional hydrogen bonding. Therefore, the wood shrinks and becomes stronger. This process is reversible.

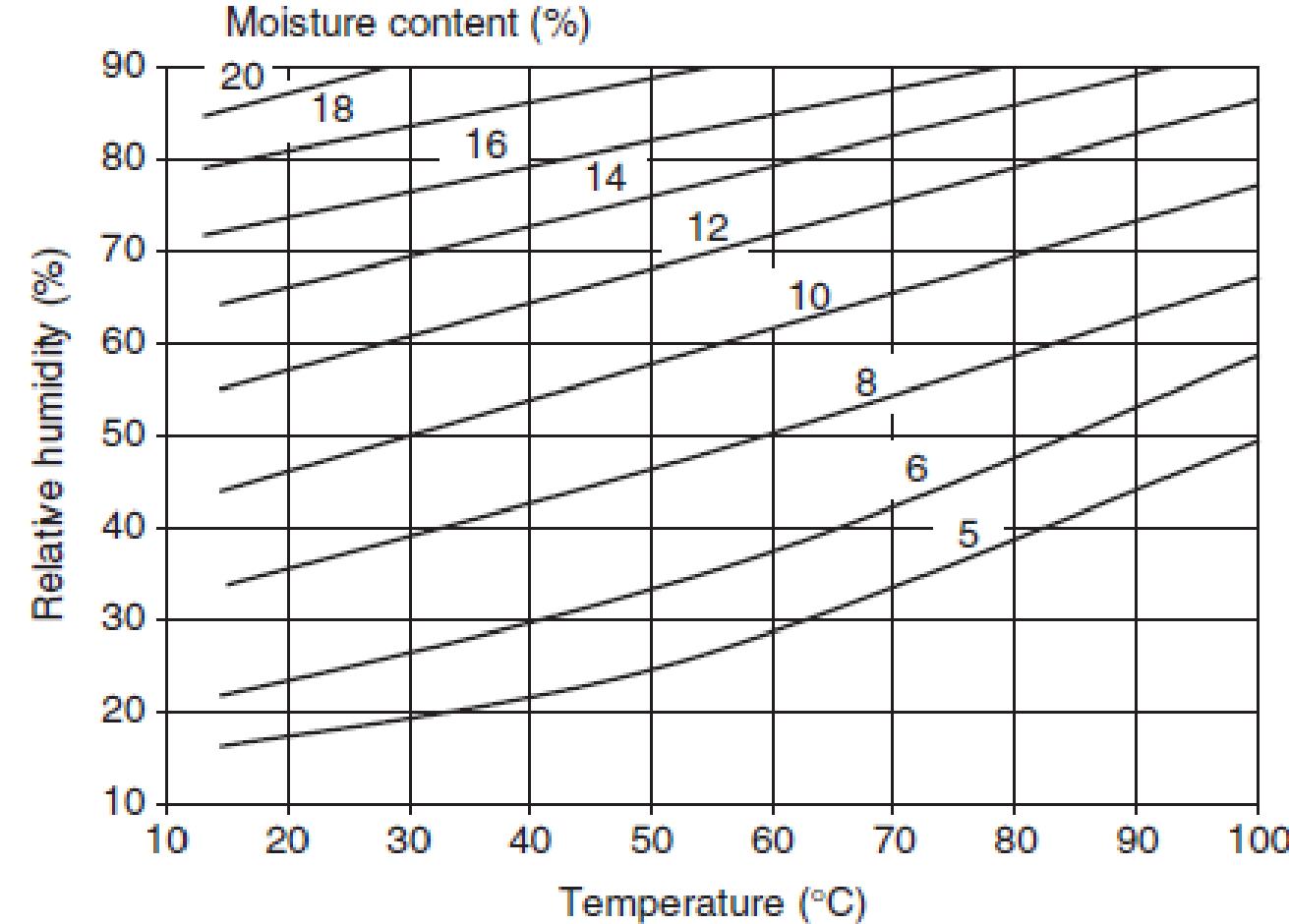


Equilibrium Moisture Content

- When lumber is dried below the fiber saturation point, wood attains equilibrium with atmospheric humidity.
- This level of moisture content is called as the equilibrium moisture content (EMC).
- This point is defined as the moisture content at which wood neither gains, nor loses water to the surroundings. This EMC value ranges from 5 to 17% at 70°C.



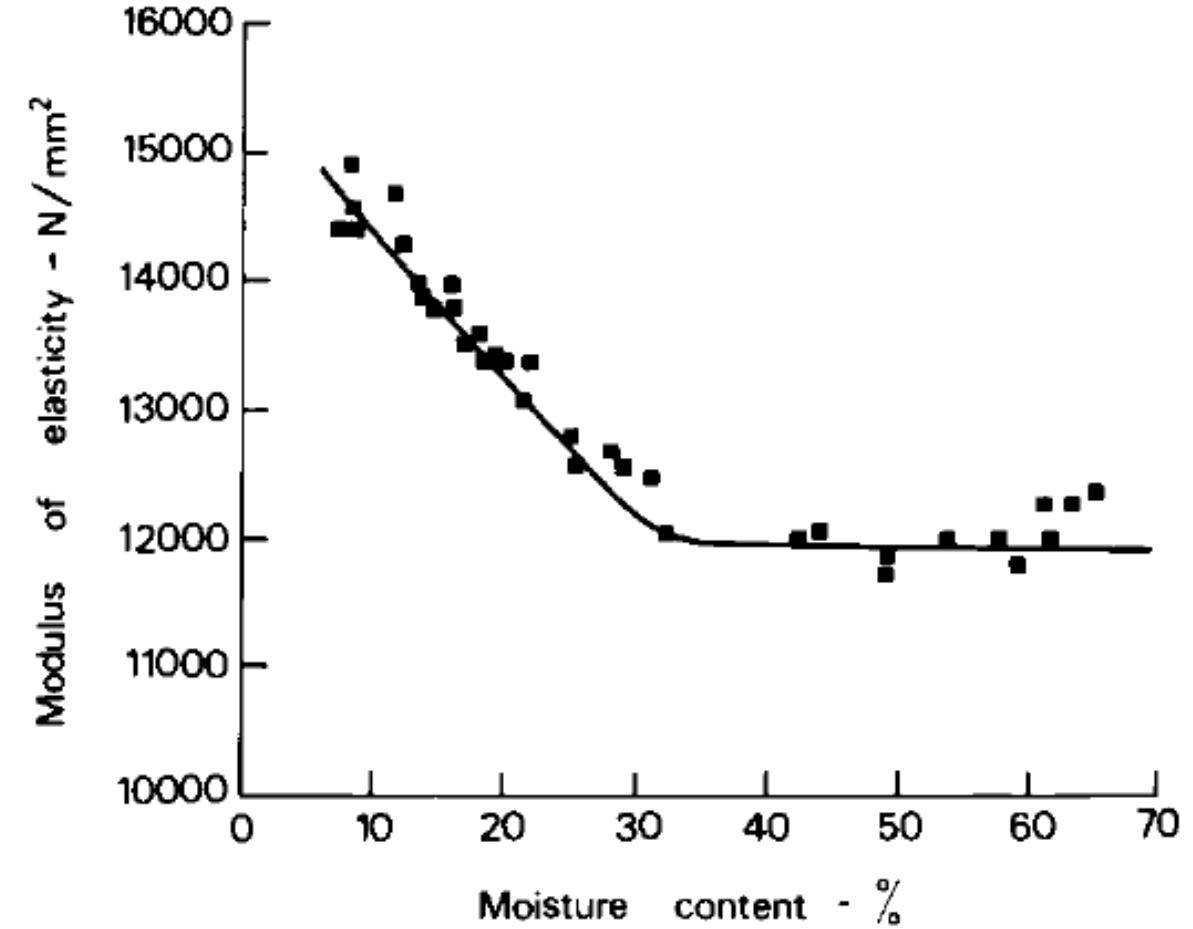
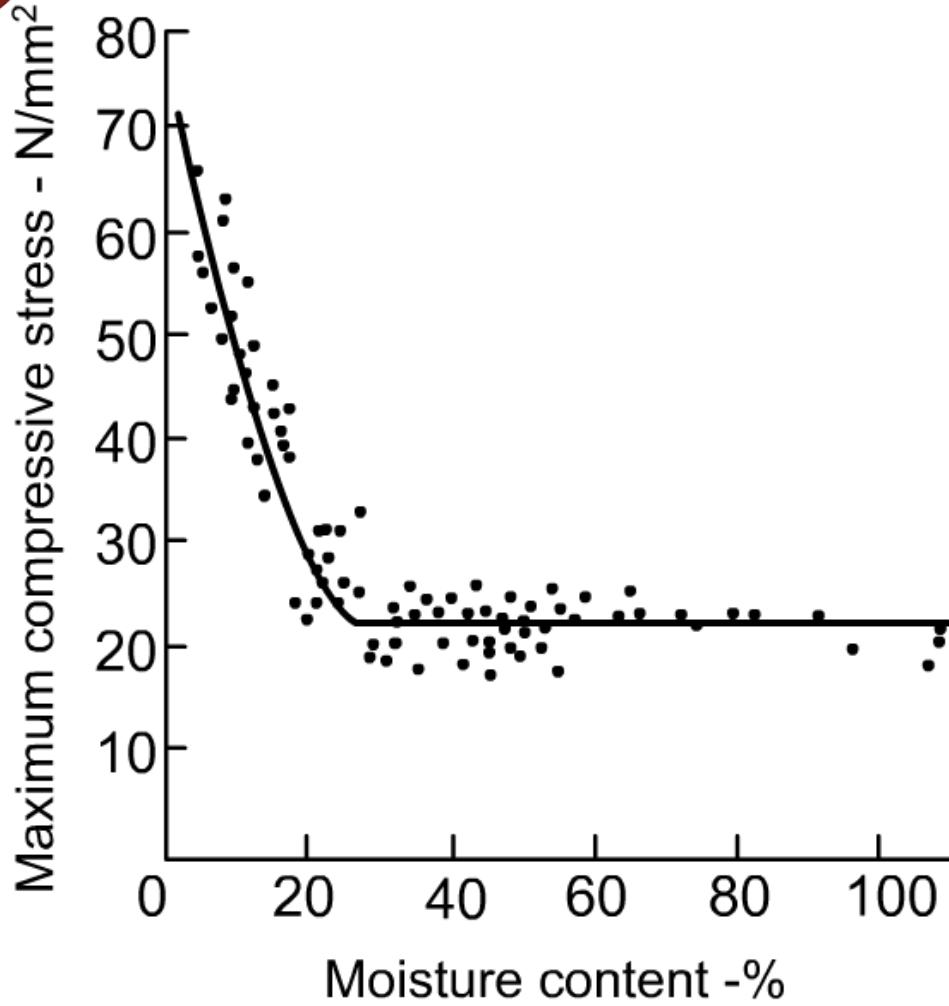
Equilibrium Moisture Content



Illston and Domone



Influence of Moisture on Properties



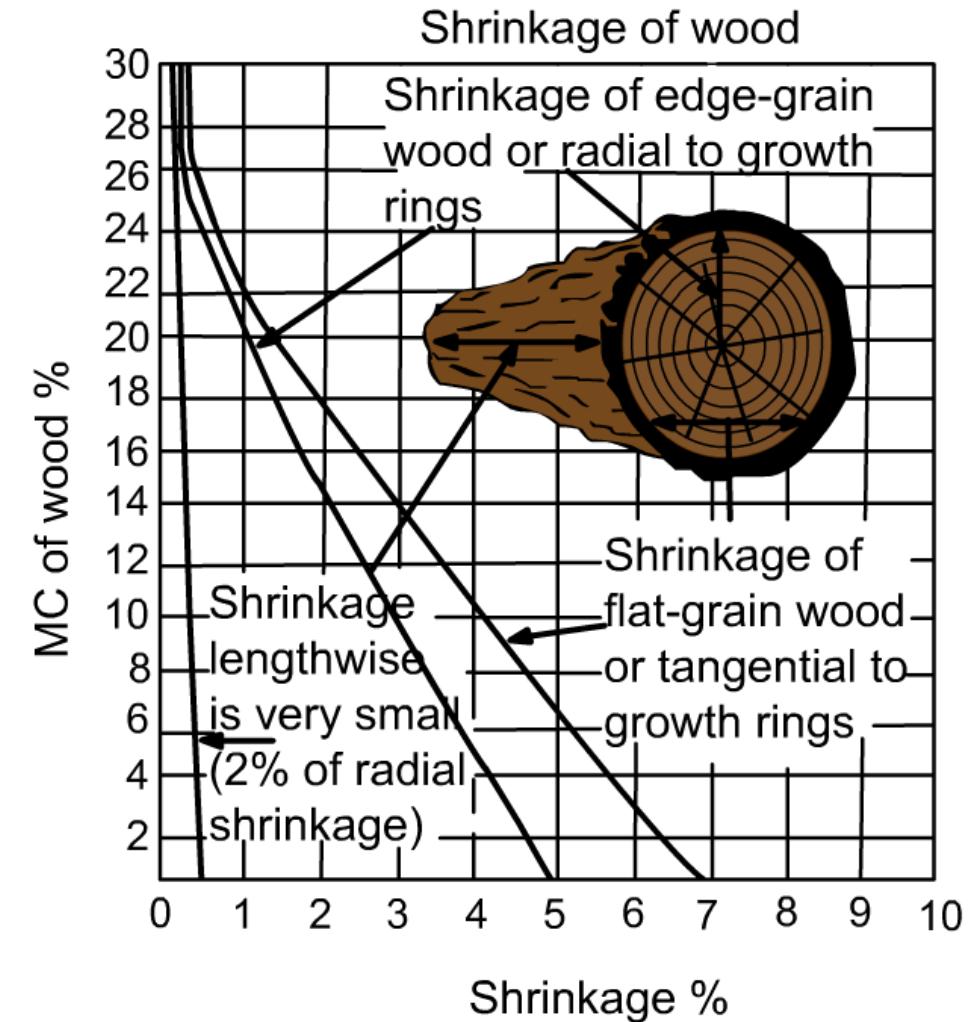
Illston and Domone



Effect of Moisture Content

Shrinkage

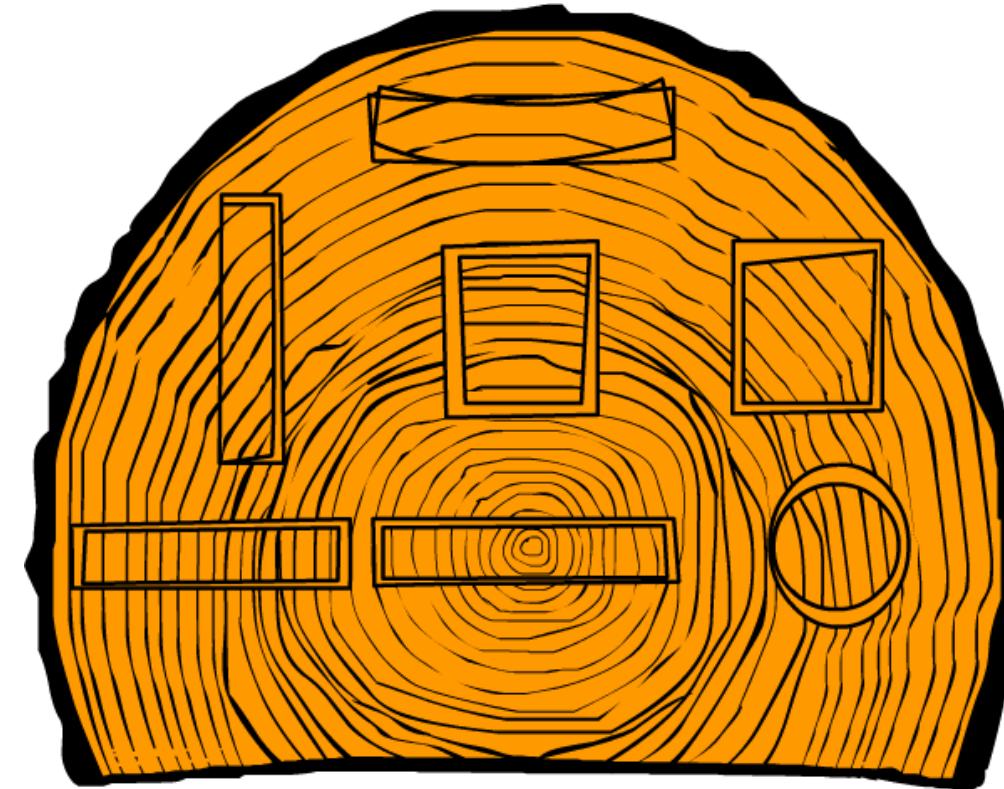
- Shrinkage is not same in all directions. The longitudinal shrinkage is normally negligible.
- However, the values of tangential and radial shrinkage can be in the range of 3-12%. Tangential shrinkage is higher than radial shrinkage.
- For example, teak undergoes radial, tangential and volumetric shrinkage of about 3%, 6% and 7%, respectively.



Young et al.



Shrinkage of Wood



Characteristic shrinkage and distortion of flat, square and round pieces as affected by direction of growth rings. Tangential shrinkage is about twice as great as radial.

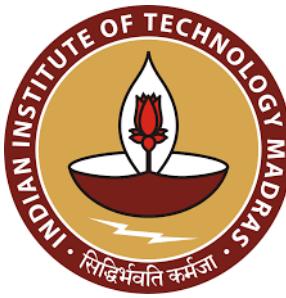
Young et al.



Thermal Properties

Thermal conductivity

- The conductivity of structural softwood timber at 12% moisture content is in the range of **0.1 to 1.4 W/(m-K)**, compared with 216 for aluminum, 45 for steel, 0.9 for concrete, 1 for glass, and 0.036 for mineral wool.
- Conductivity increases with moisture content, temperature or specific gravity.
- Since the **thermal conductivity and heat capacity** of wood are **low**, it does not absorb or release heat quickly. Due to this wood does not feel hot or cold to the touch as some other materials.



Decay Due to Fungi

- Wood that is always dry does not decay.
- When wood is constantly submerged in water, the deterioration is slow since only some bacteria and fungi can attack under water.
- Deterioration is more rapid in hot and wet climates than in cool or dry climates.
- Early stages of decay are difficult to detect before significant weight loss occurs.
- When weight loss reaches 5-10%, the mechanical properties are reduced by 20-80%.



Fire

- Timber is a combustible material. However, the maintenance of strength with temperature and time is better than steel.
- As the surface temperature increases beyond 100 °C, volatile gases are emitted. In excess of 250 °C, there is sufficient build up of these gases for timber to ignite in the presence of a flame. In the absence of a flame, the temperature has to rise beyond 500 °C for self-ignition to occur.

Illston and Domone



Fire

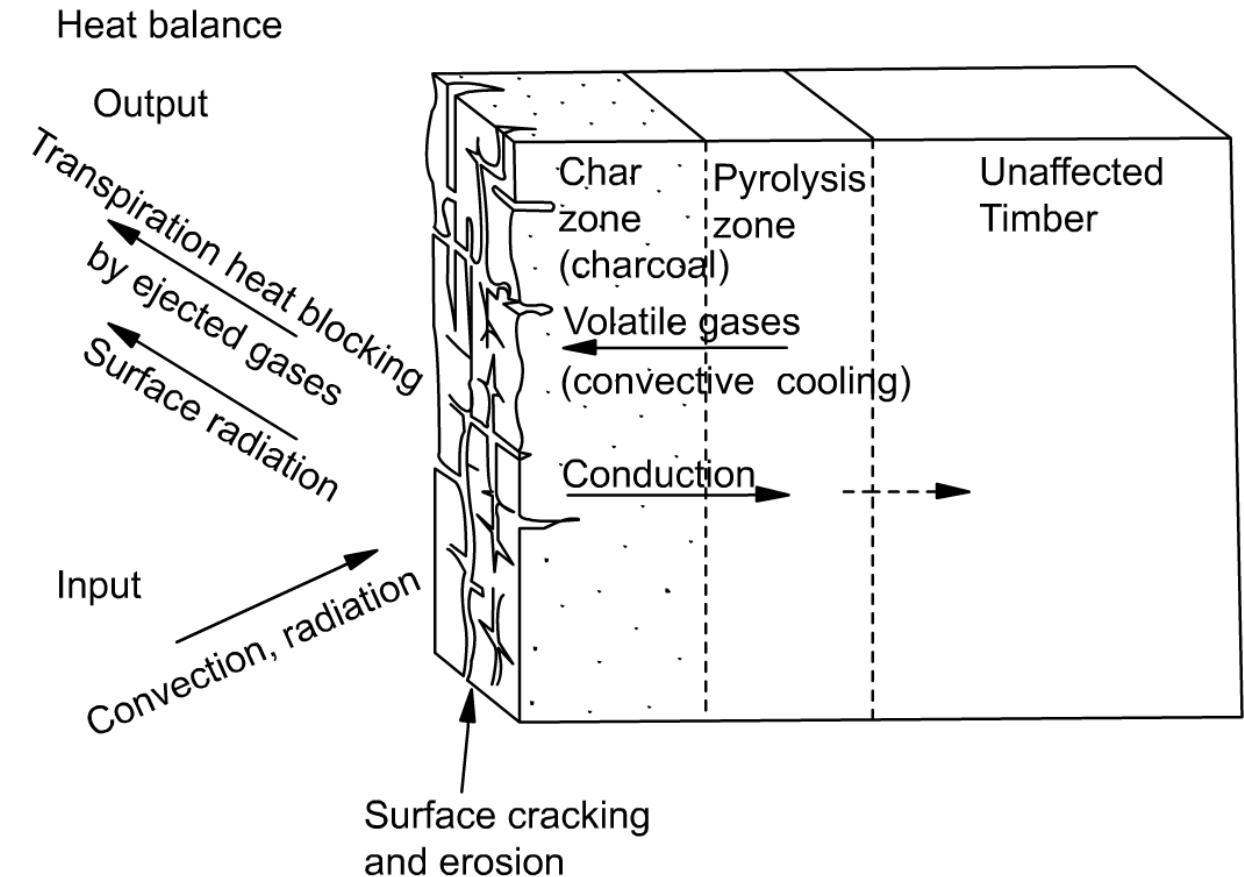
- Chemical bonds break and the microstructure degrades in the temperature range of 175-350 °C. The degradation of cellulose results in the production of volatile gases and a reduction in the degree of polymerization.
- Due to pyrolysis, there is darkening of the timber and emission of volatile gases. Then, the reaction becomes exothermic and charring occurs.
- The volatiles cool the char and block incoming convective heat.
- The surface is cracked, and material is lost gradually.

Illston and Domone



Fire

- Formation of the char protects the unburnt timber.
- Failure occurs only when the unburnt section cannot sustain the applied load.



Illston and Domone



Processing of Timber

- Sawing of logs into suitable pieces of timber is called conversion.
- Conversion losses vary from 30-50%.
- After sawing, the timber is graded depending on type, grain direction, knots, sapwood, worm holes, etc.
- In the USA and other countries, timber for construction is stress-graded based on strength, stiffness and uniformity of size.
- Non-destructive tests may be used to verify the mechanical integrity.

Varghese



Treatment of Wood

- This wood should be chemically treated to:
 - Prevent destruction from fungi and other insects
 - Inhibit combustion
- Treatment often includes a pressurized application of chemicals to inject the preservatives into the fibers.
- Common wood treatment chemicals include:
 - Pentachlorophenol (PCP)
 - Creosote
 - Other chemicals (sodium silicate, potassium silicate, etc.)
- Wood treated with PCP or Creosote is used in exterior structures, such as utility poles, beams, bridges, marine decking, etc.; harmful to skin, under prolonged contact conditions.



Wood Products

- Dimension Lumber
- Heavy Timber
- Round Stock
- Engineered Wood and Panel Products
 - Particle boards
 - Fiber boards
 - Glulam (laminated structural lumber)



Laminated Structural Lumber



Dimension, or framing
Lumber



Heavy Timber



Fiber Board
Or
Oriented Strand Board (OSB)



Round Stock



Particle Board



Need for Wood-Based Composites

- As a material, wood has several deficiencies:
 - It possesses a high degree of variability
 - It's strongly anisotropic in both strength and moisture movement
 - It's dimensionally unstable in presence of changing humidity
 - It's available in only limited widths

Illston and Domone



Wood-Based Composites

Glued-laminated Timber (Glulam)

- Timber manufactured by gluing together a large number of relatively short pieces of timber.
- Glulam timber can be up to 40 m in length and over 2 m deep. They can be straight or curved.
- The pieces are glued together such that the grain directions are generally parallel.

Young et al.



Glued-Laminated Timber

- More expensive than sawn timber
- Advantages:
 - Size capabilities
 - Architectural effects
 - Seasoning advantages (pieces seasoned individually)
 - Varying cross-sections
 - Varying grades

Young et al.



Applications of Glulam



Three-hinge glulam deck arch bridge off Highway 16, near Mount Rushmore, South Dakota, USA. The arch spans 47 m and supports an 8-meter-wide roadway.

<https://www.fhwa.dot.gov/publications/publicroads/97winter/p97wi32.cfm>



Accoya Glulam Bridge in The Netherlands



In Sneek, Netherlands, heavy-traffic bridges have been made entirely of acetylated glued laminated timber (glulam) beams and have been certified for an 80-year life.

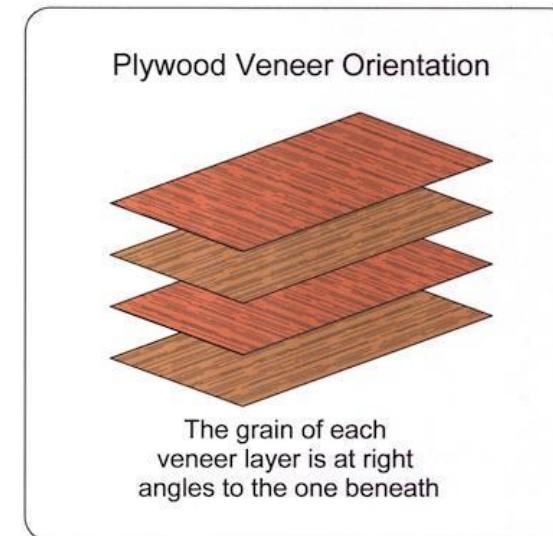
https://en.wikipedia.org/wiki/Glued_laminated_timber



Wood-Based Composites

Plywood

Panels or sheets made from wood by gluing together thin veneers in layers. The layers are placed such that the grains of the successive plies are at right angles to each other.



https://www.lakeexpo.com/boating/boat_projects/underway-the-lowdown-on-marine-plywood/article_f5d1bbfa-c4fd-11e0-9cbc-001cc4c03286.html



Plywood

- Advantages
 - *Can be produced in large sheets*
 - *Split-resistant*
 - *Have same properties in both directions of sheet*
 - *Effect of knots are limited to one ply*
 - *Shrinkage and swelling are minimized*



Plywood in Indian Market

- Normal (MR grade) plywood
- Boiling water resistant (BWR grade) plywood to resist dampness
- Marine plywood for boats and ocean applications
- Shuttering plywood for repeated use (without and with film facing)
- Flexible plywood for curves (bending radii: 7-10 cm)
- Plywood with decorative veneer (no need to paint)



www.sharonply.com

www.centuryply.com



Wood-Based Composites

- Particle Board

- Chips are soaked in water, dried, mixed with resin and pressed together to form boards.
- Typical particle boards have three layers: the faces consist of fine particles and the inner layer consists of coarser material.



- Medium Density Fiberboard (MDF)

- Wood fibers are obtained after debarking, chipping, pulping and blowline processes.
- The fibers are mixed with resin, formed into mats, pressed, laminated and cut to size.



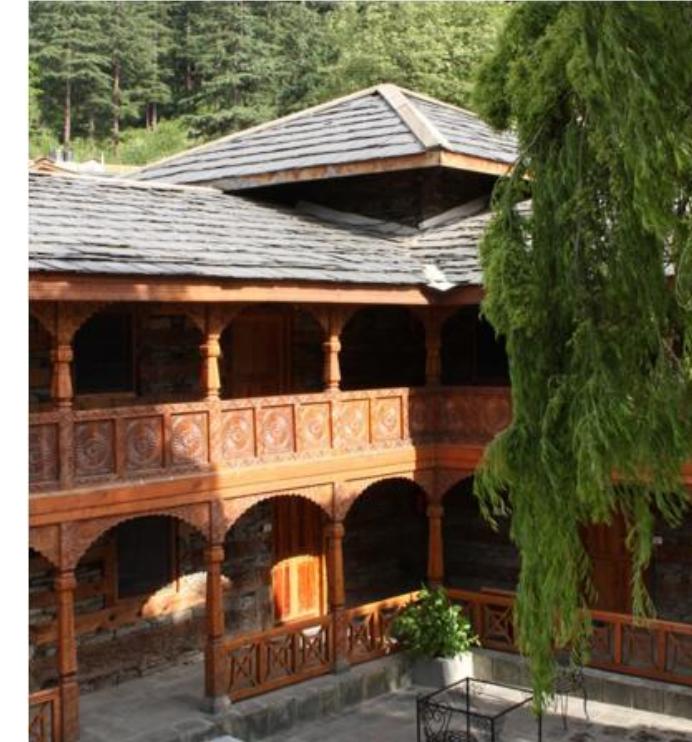
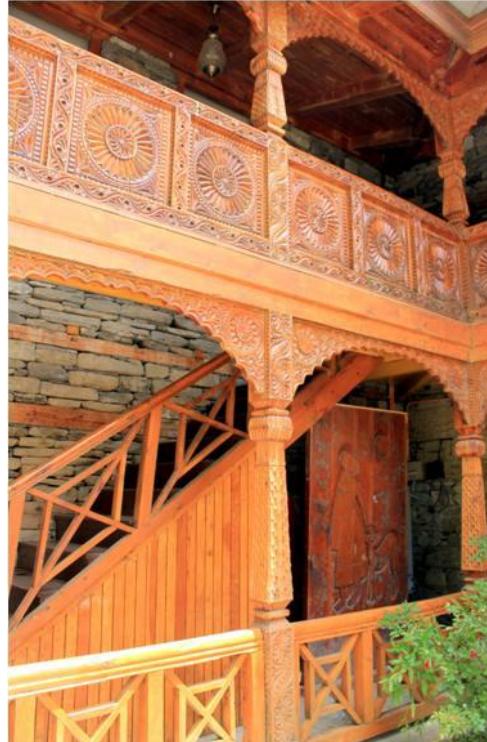
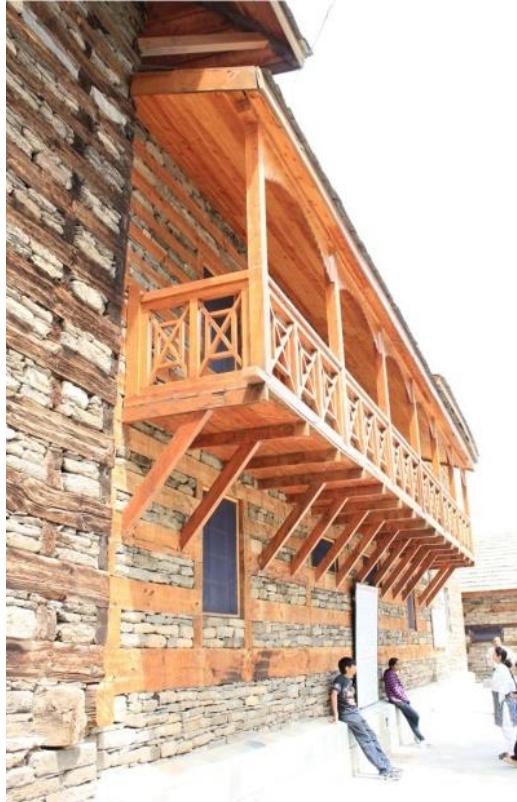
- Blockboard

- They are manufactured by placing softwood strips edge to edge and sandwiched between veneers and then this sandwich is glued together with high pressure.





Wooden Castle in India



Naggar Castle,
Himachal Pradesh, early
17th century



References

- *The Science and Technology of Civil Engineering Materials*, J.F. Young, S. Mindess, R.J. Gray & A. Bentur, Prentice Hall, 1998.
- *Construction Materials: Their nature and behaviour*, J.M. Illston and P.L.J. Domone, Spon Press, 2001.
- *Building Materials*, P.C. Varghese, Prentice-Hall India, 2005.



Polymers and Composites

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Introduction

- Naturally occurring polymers – derived from animals and plants – have been used for many centuries. Examples: wood, rubber, cotton, wool, leather, and silk.
- Many of our useful plastics, rubbers, and fiber materials are synthetic polymers.
- Since the conclusion of World War II, the advent of synthetic polymers have revolutionized the world of materials.

Callister and Rethwisch



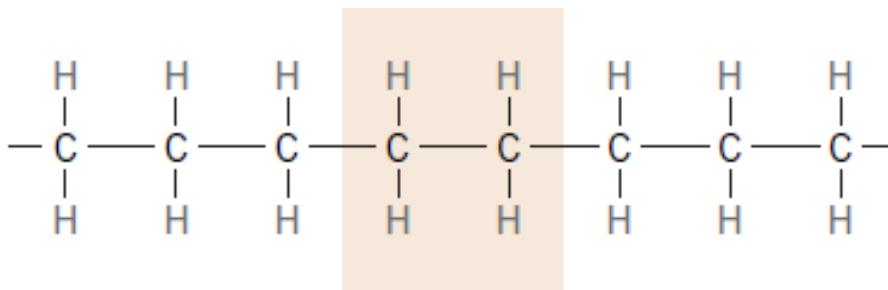
Use of Polymers in Construction

- Polymeric materials are used extensively in construction, in some structural and many non-structural applications, such as roofing, partitions, cladding panels, door/window shutters and frames, pipes/ducts, sealants, adhesives, admixtures, paints, repair systems, signage and floor finishing.
- Most of the development and exploitation of polymers is due to the growth in the oil industry. The by-products of the distillation of petroleum supply the building blocks from which plastics are made.

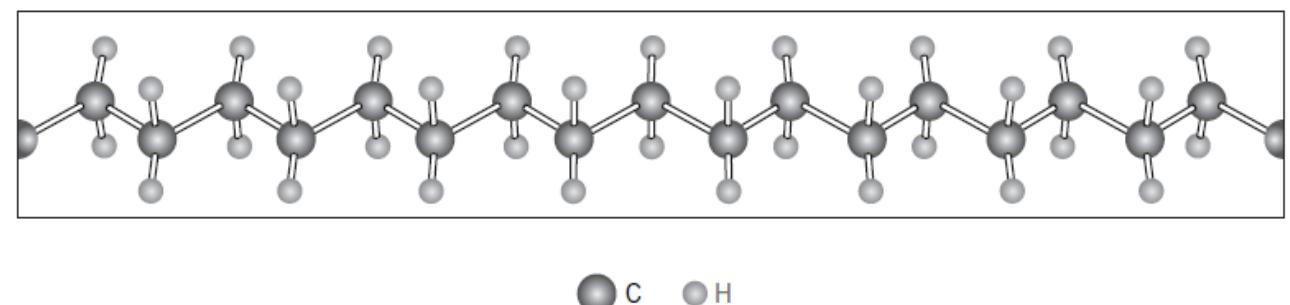


Polymer Molecules

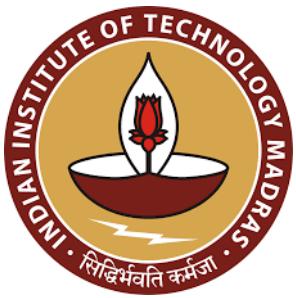
- The molecules in polymers are gigantic in comparison to the hydrocarbon molecules; because of their size they are often referred to as macromolecules. Within each molecule, the atoms are bound together by covalent interatomic bonds.



Repeating unit

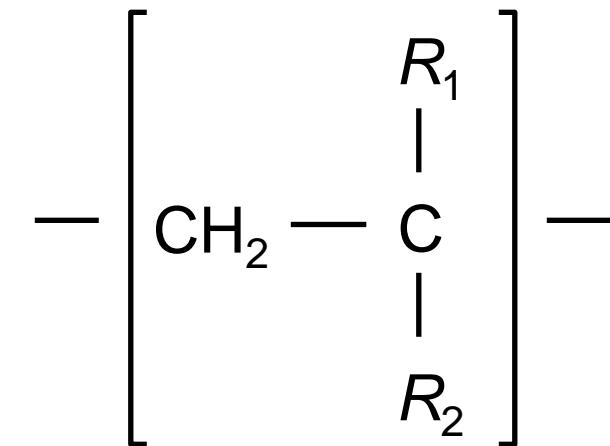


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Common Polymer Materials

- Thermoplastic polymers are generally named after the monomer that makes up its backbone.
- The most common are based on vinyl-type monomers:



where R_1 and R_2 are substitutional groups.

Young et al.



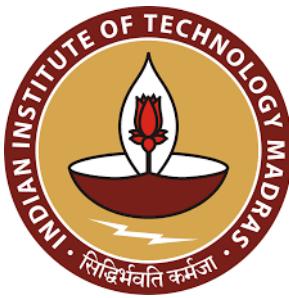
Common Polymers

Thermoplastic polymers with carbon backbone

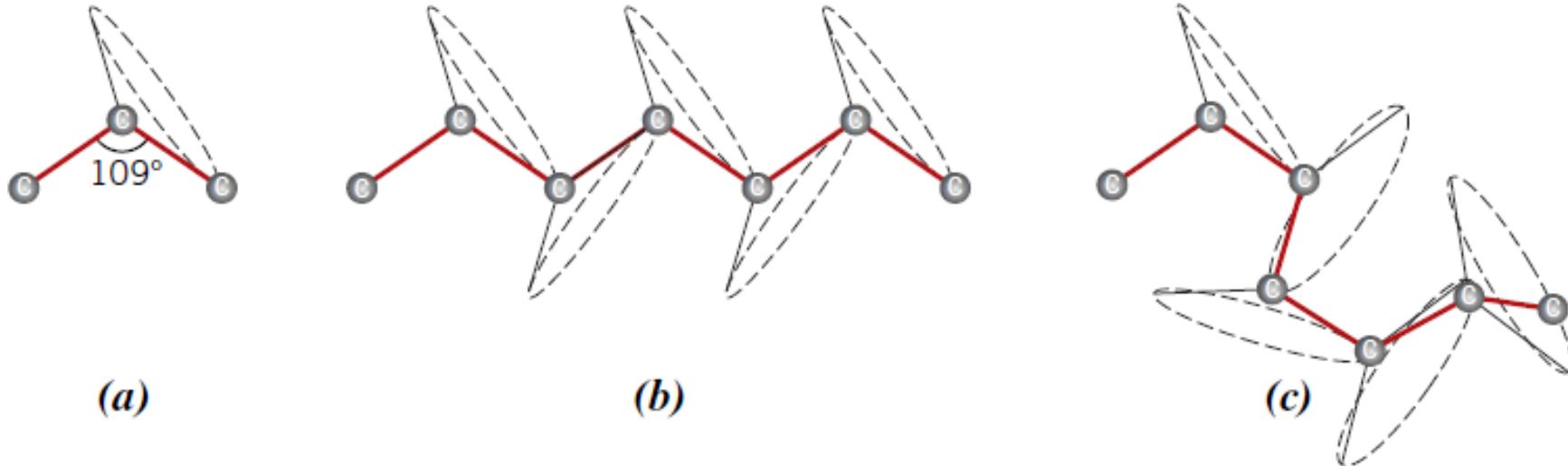
Name of Polymer	Composition of R_1	Composition of R_2
Polyethylene	H	H
Polypropylene	H	CH_3
Polyvinyl chloride (PVC)	H	Cl
Polystyrene	H	C_6H_5
Polymethylmethacrylate (PMMA)	CH_3	COOCH_3

Polymers having the same composition may differ in properties due to differences in the characteristics of the structure of the chain, such as chain length and branching.

Young et al.



Molecular Shape



- Some of the mechanical and thermal characteristics of polymers are a function of rotational flexibility, which is dependent on repeat unit structure and chemistry.
- For example, the region of a chain segment that has a double bond ($C=C$) is rotationally rigid. Also, introduction of a bulky or large side group of atoms restricts rotational movement.

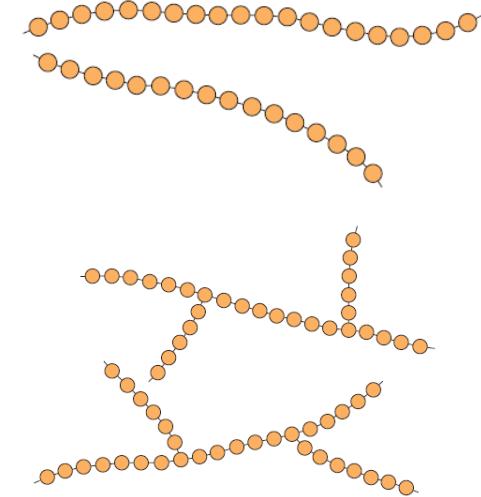
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Molecular Structure

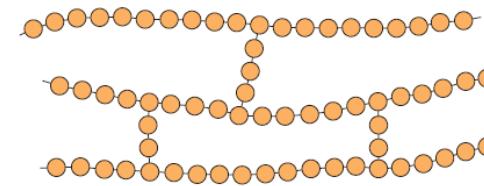
- Linear polymers

- Polyethylene, poly(vinyl chloride), polystyrene, poly(methyl methacrylate), nylon, and the fluorocarbons
- Hydrogen or van der Waals bonding may exist between the chains



- Branched polymers

- LDPE

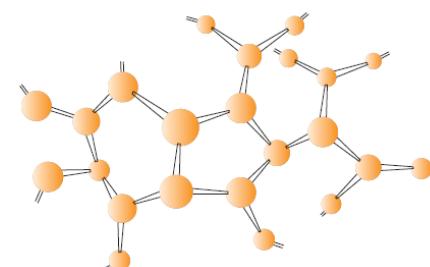


- Cross-linked polymers

- Rubber

- Network polymers

- Polyurethane, epoxy

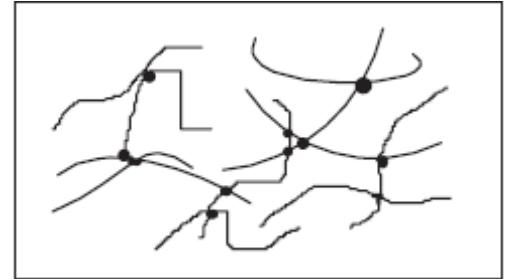
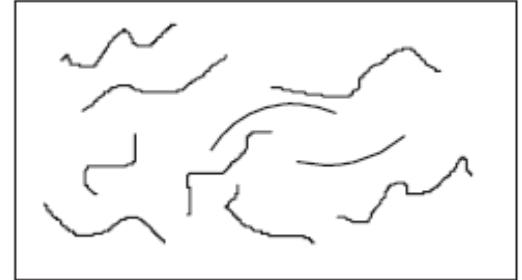


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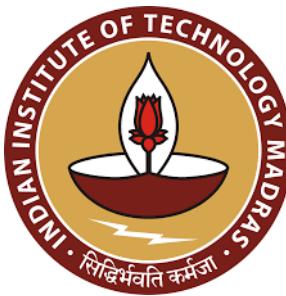


Classification

- **Thermoplastic polymers:** Thermoplastics soften when heated (and eventually liquefy) and harden when cooled—processes that are totally reversible and may be repeated. Examples: polyethylene, polystyrene, poly(ethylene terephthalate), and poly(vinyl chloride)
- **Thermosetting polymers:** These are network polymers. They become permanently hard during their formation, and do not soften upon heating. Network polymers have **covalent crosslinks** between adjacent molecular chains. Examples: vulcanized rubbers, epoxies, and some polyester resins.



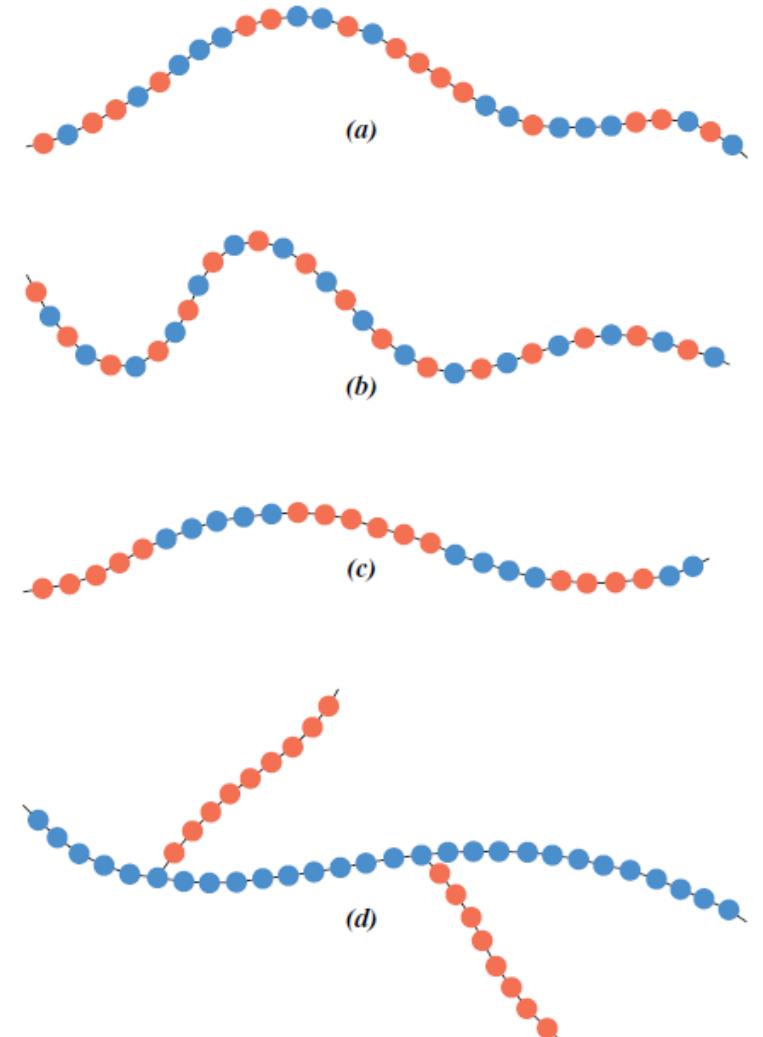
Callister and Rethwisch
Illston and Domone



Copolymers

- Copolymers are easily and economically synthesized and fabricated with improved properties or better property combinations than are offered by the homopolymers.

Schematic representations of (a) random, (b) alternating, (c) block, and (d) graft copolymers. The two different repeat unit types are designated by blue and red circles.



Callister and Rethwisch



Examples of Copolymer

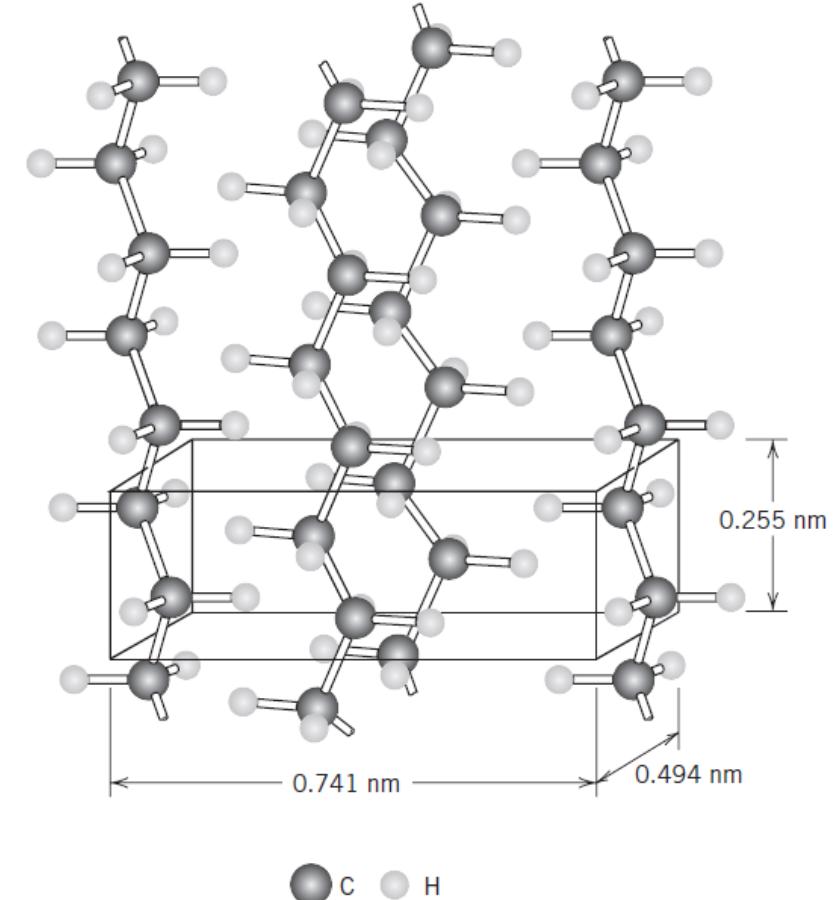
- **Styrene–butadiene rubber (SBR)** is a common random copolymer from which automobile tires are made.
- **Nitrile rubber (NBR)** is another random copolymer composed of acrylonitrile and butadiene. It is also highly elastic and, in addition, resistant to swelling in organic solvents; gasoline hoses are made of NBR.
- **Impact-modified polystyrene** is a block copolymer that consists of alternating blocks of styrene and butadiene. The rubbery isoprene blocks act to slow cracks propagating through the material.



Polymer Crystallinity

- Polymer chains may be in linear or branched form.
- A linear material has a higher tendency for crystallization, higher transition temperature and strength due its ability to pack more densely, leading to higher intensity of van der Waals bonding.

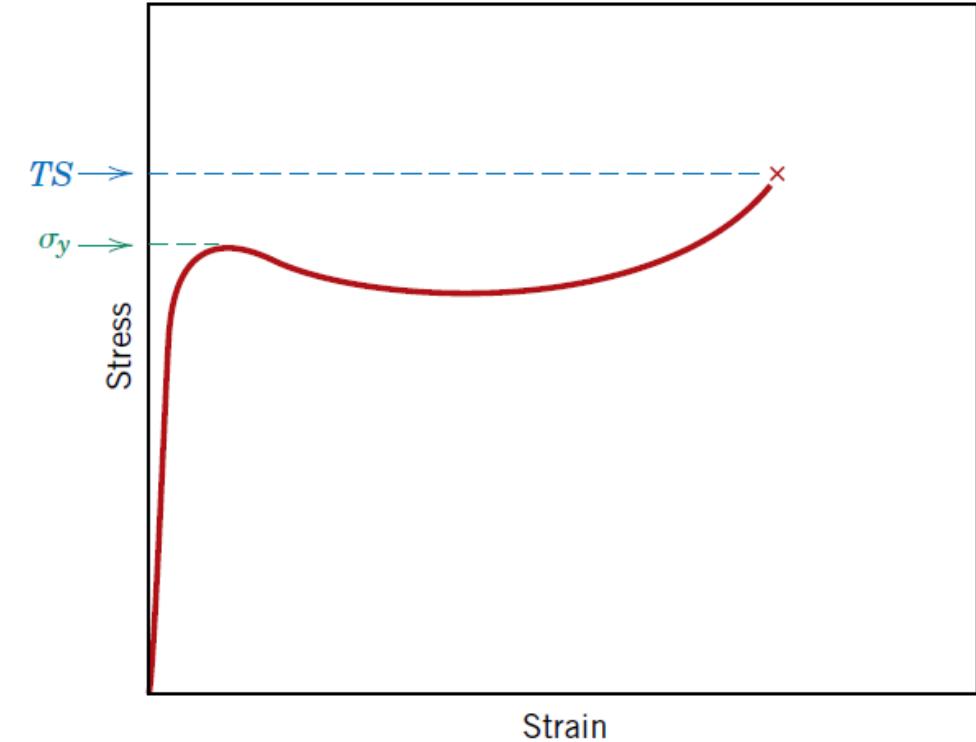
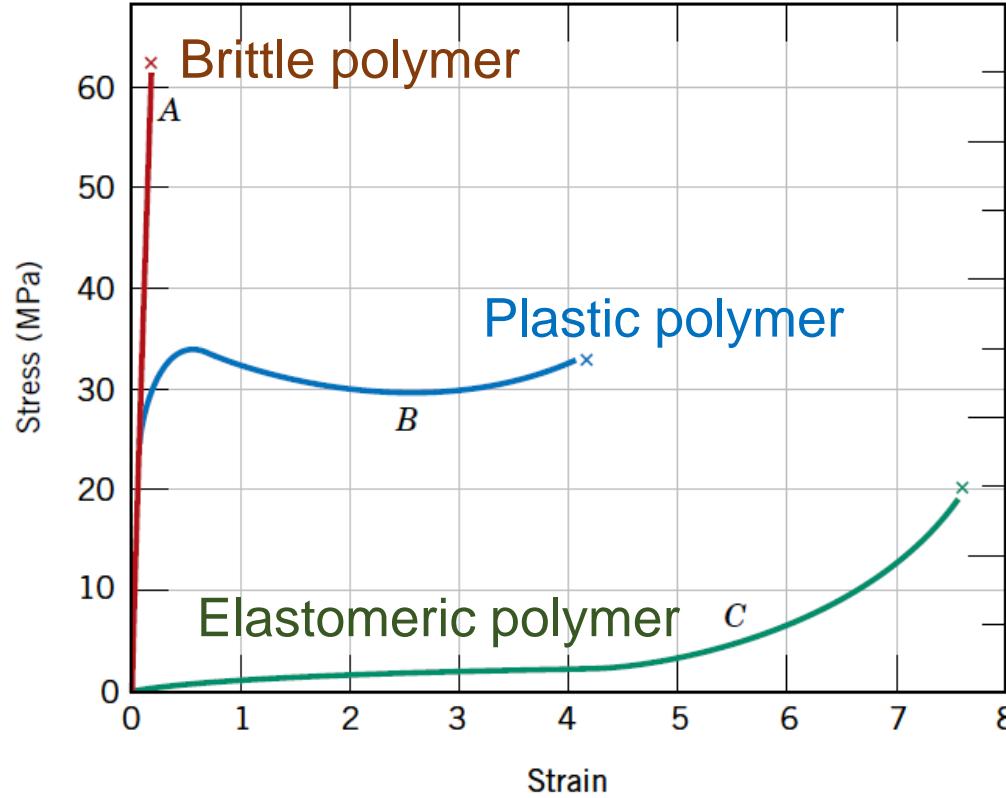
Polyethylene molecule



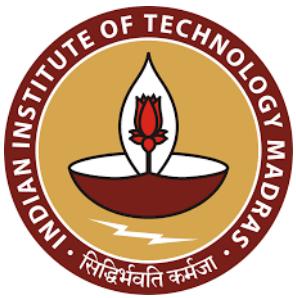
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Mechanical Behavior of Polymers

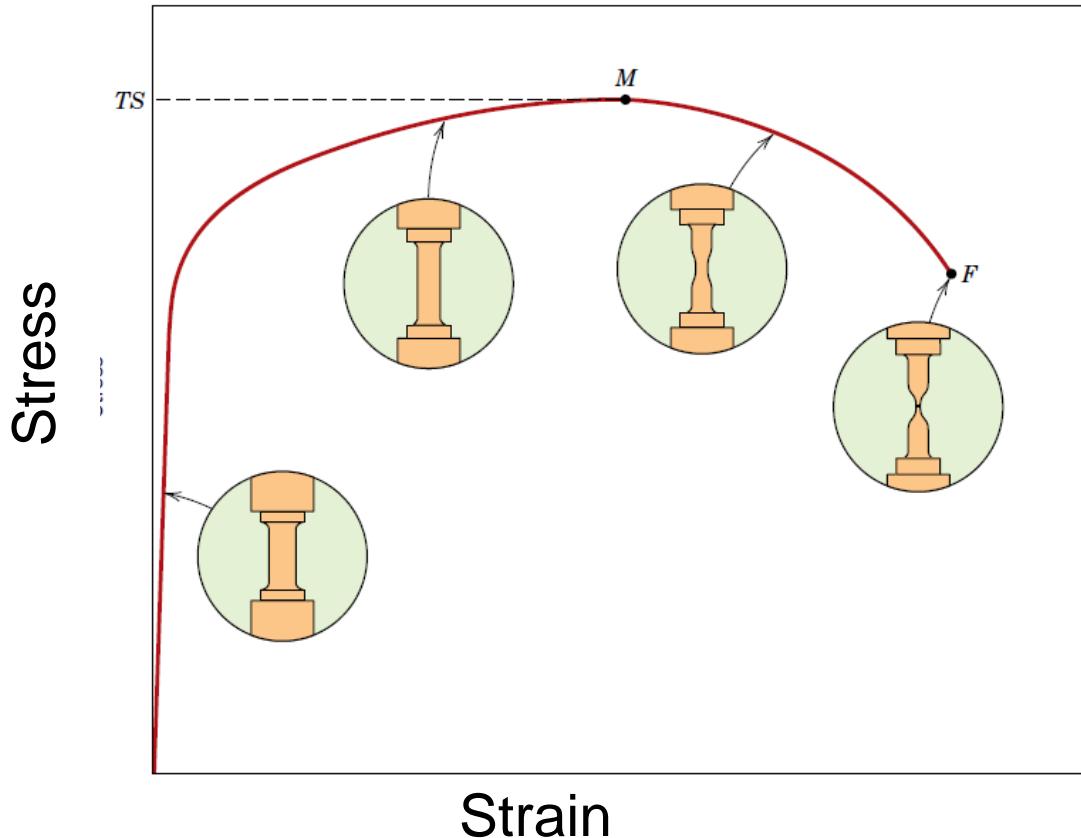


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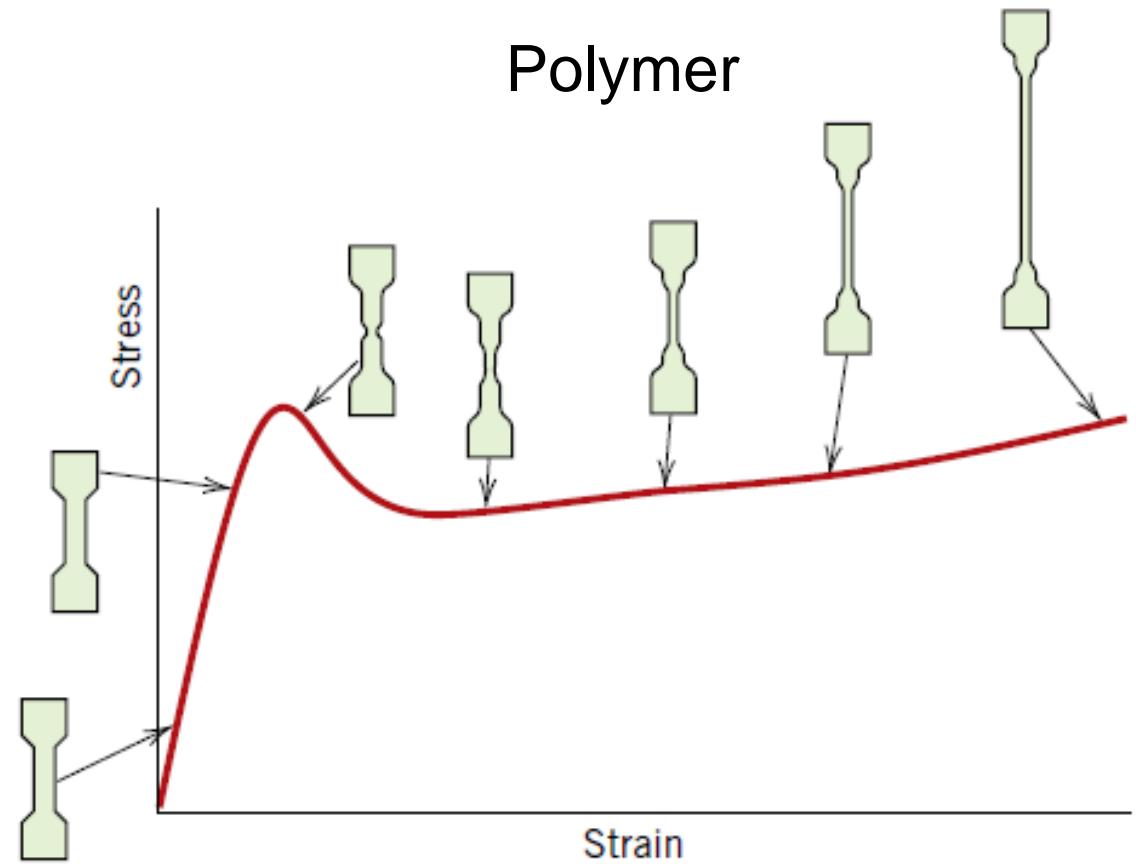


Failure in Polymers: Propagation of Neck Region

Ductile Metal



Polymer



Callister and Rethwisch



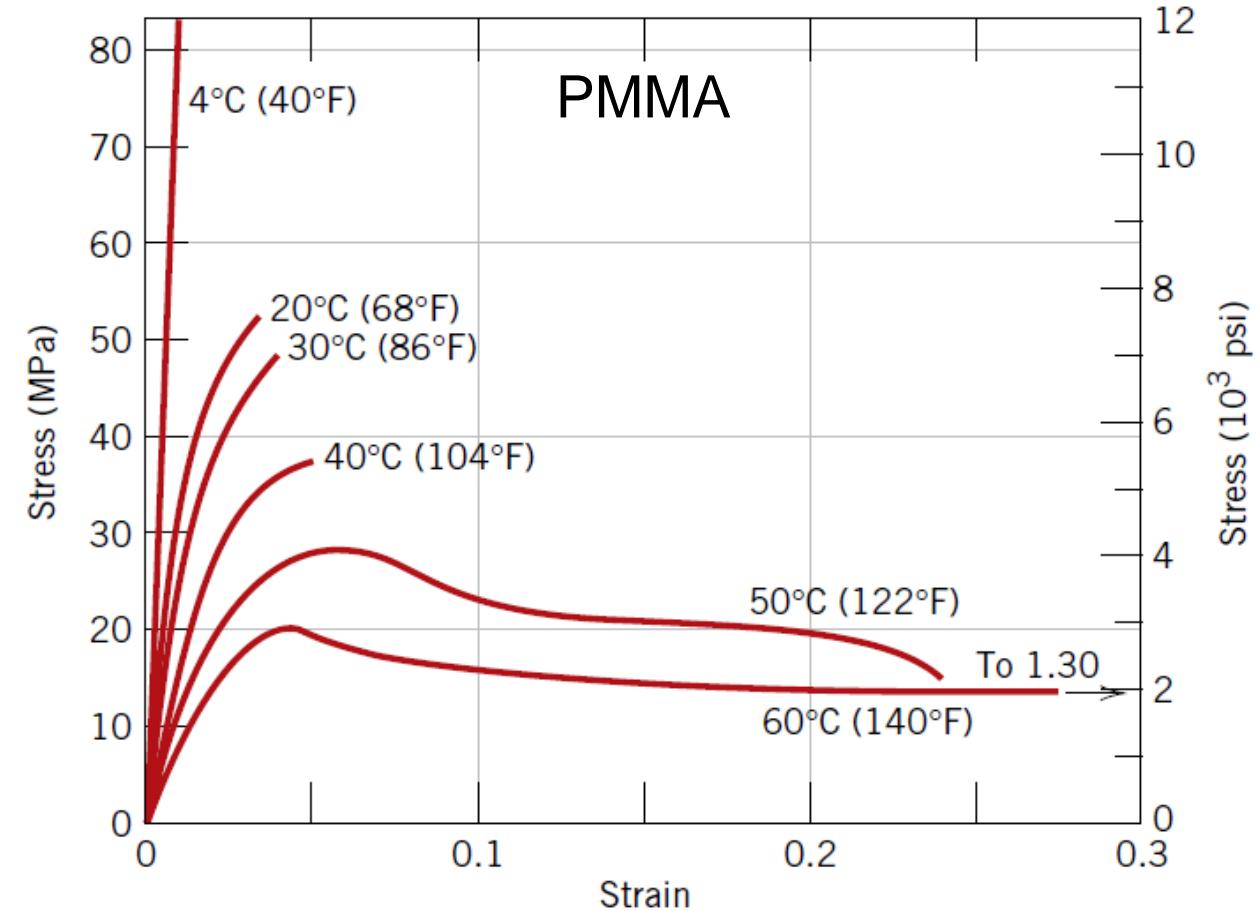
Room-Temperature Characteristics of Common Polymers

Material	Specific Gravity	Tensile Modulus [GPa (ksi)]	Tensile Strength [MPa (ksi)]	Yield Strength [MPa (ksi)]	Elongation at Break (%)
Polyethylene (low density)	0.917–0.932	0.17–0.28 (25–41)	8.3–31.4 (1.2–4.55)	9.0–14.5 (1.3–2.1)	100–650
Polyethylene (high density)	0.952–0.965	1.06–1.09 (155–158)	22.1–31.0 (3.2–4.5)	26.2–33.1 (3.8–4.8)	10–1200
Poly(vinyl chloride)	1.30–1.58	2.4–4.1 (350–600)	40.7–51.7 (5.9–7.5)	40.7–44.8 (5.9–6.5)	40–80
Polytetrafluoroethylene	2.14–2.20	0.40–0.55 (58–80)	20.7–34.5 (3.0–5.0)	13.8–15.2 (2.0–2.2)	200–400
Polypropylene	0.90–0.91	1.14–1.55 (165–225)	31–41.4 (4.5–6.0)	31.0–37.2 (4.5–5.4)	100–600
Polystyrene	1.04–1.05	2.28–3.28 (330–475)	35.9–51.7 (5.2–7.5)	25.0–69.0 (3.63–10.0)	1.2–2.5

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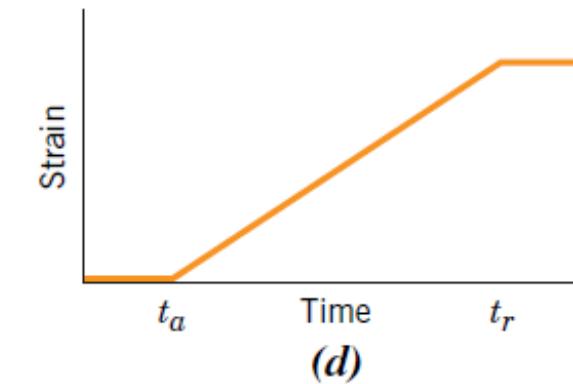
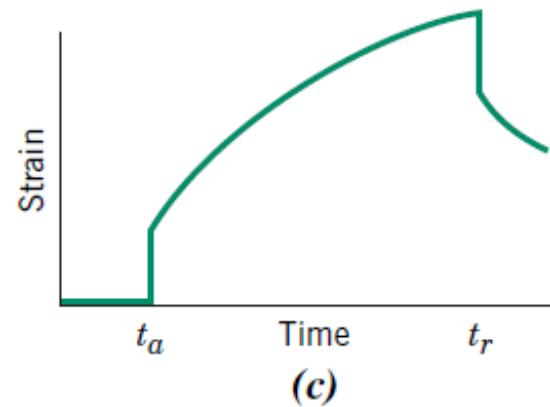
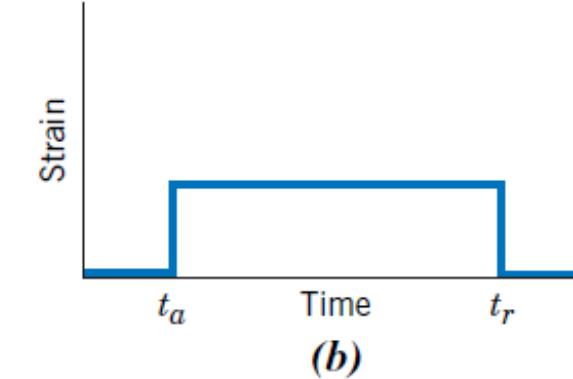
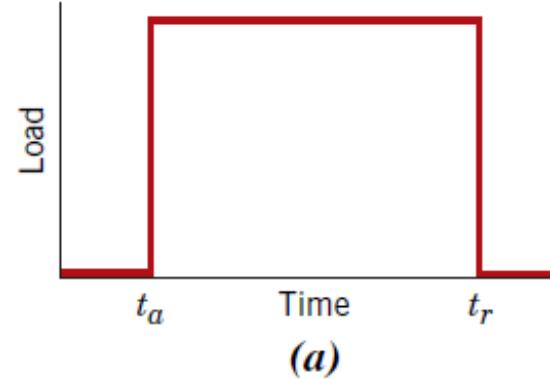
Influence of Temperature



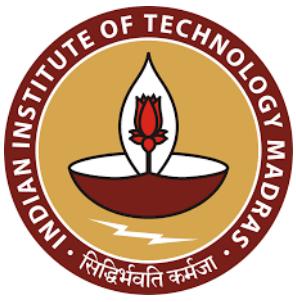
Callister and Rethwisch



Viscoelastic Behavior of Amorphous Polymers

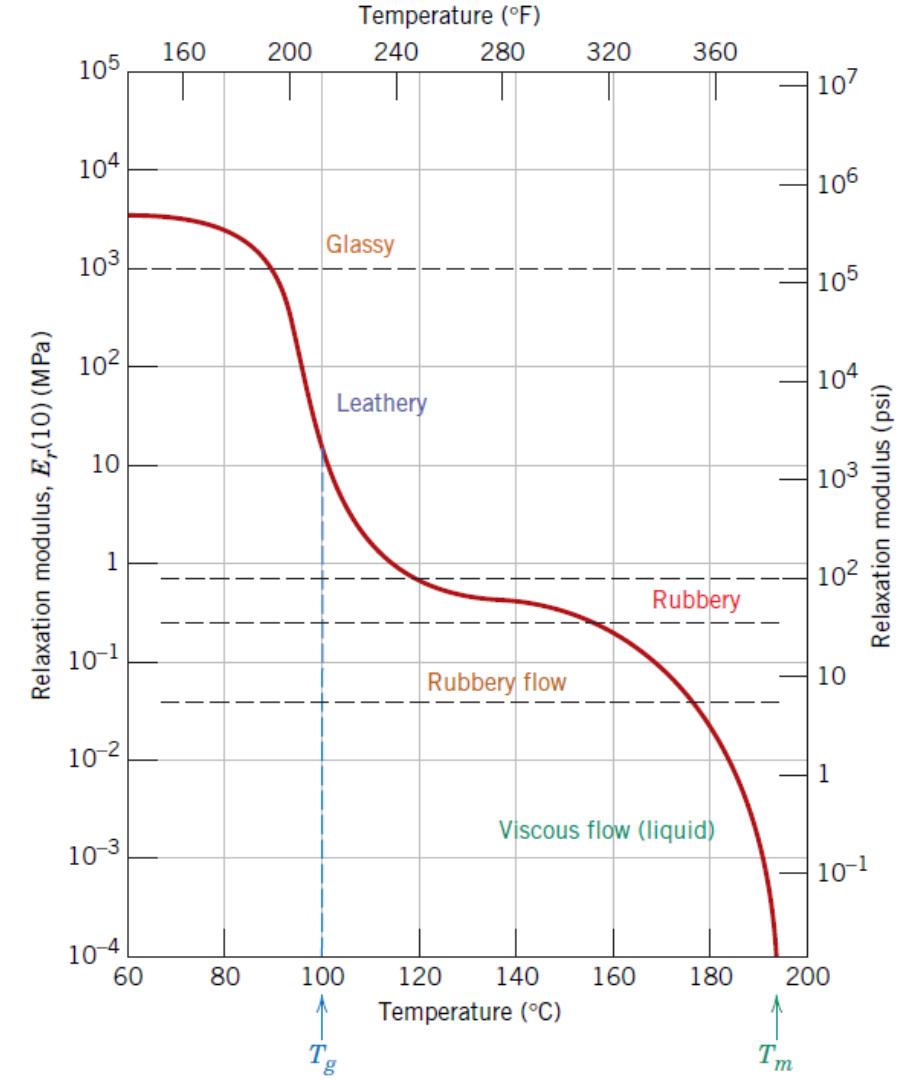
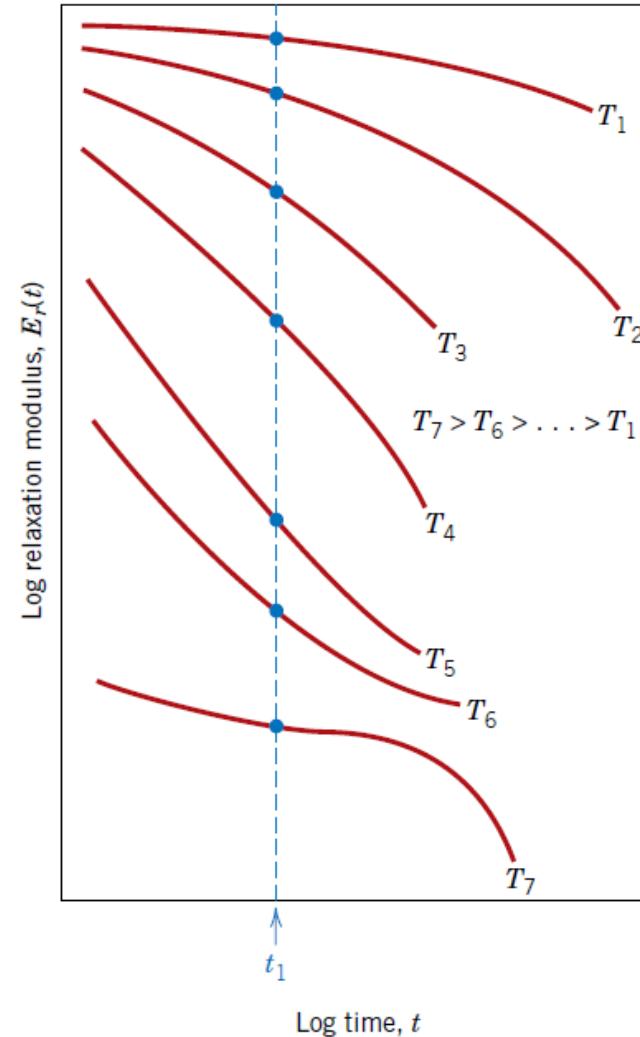


Callister and Rethwisch



Viscoelastic Relaxation Modulus

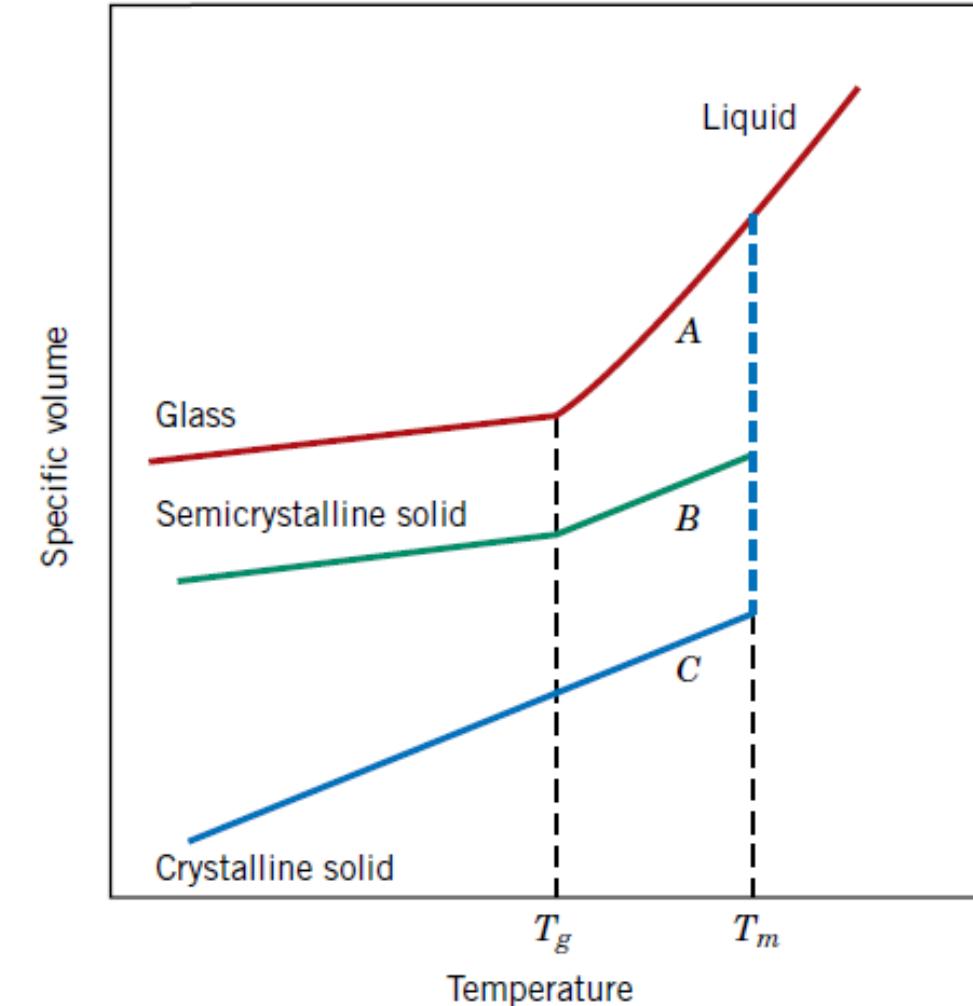
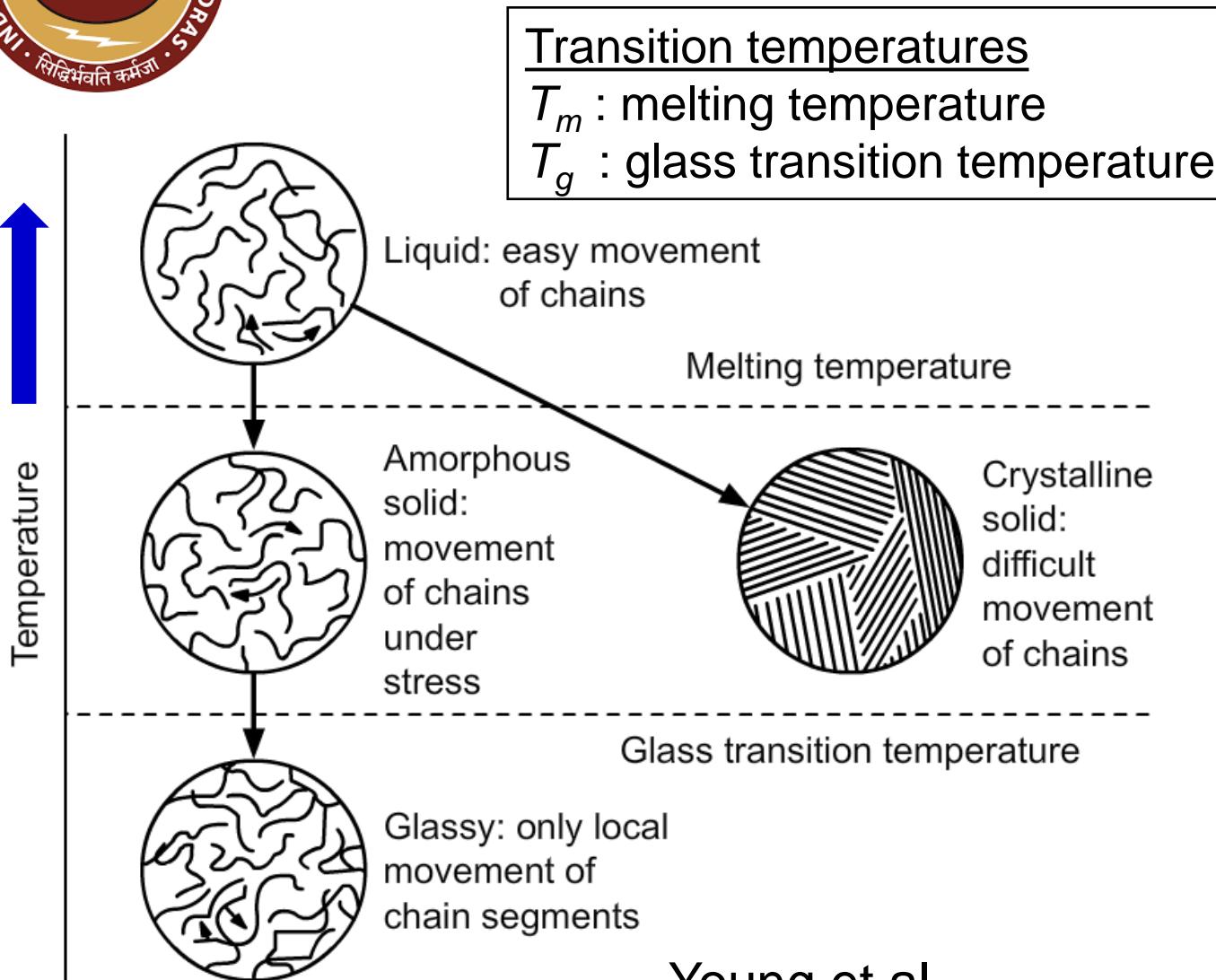
$$E_r(t) = \frac{\sigma(t)}{\epsilon_0}$$



Callister and Rethwisch



Effect of Temperature



Callister and Rethwisch



Transition Temperatures

- Above T_m the polymer behaves as a viscous liquid.
- As the temperature is reduced, the van der Waals forces hinder coiling of the chains and mobility leading to crystallinity in linear polymers where orderly packing can be achieved. Then, the intermolecular bonding is maximized, and a rigid solid is obtained.
- When the chains are irregular in shape and cannot be packed into an orderly structure, the structure does not change much and remains amorphous. The polymer becomes stiffer but not a rigid solid.



Transition Temperatures

- Below T_g , the chain segments loose all mobility, and the structure becomes amorphous, relatively brittle and rigid.
- The presence of bulky and electrically charged substituents will result in higher T_g .
- The preservation of an amorphous structure involves a smaller change in volume than crystallization, where there is a marked decrease in volume.



Polymer Types

- Plastics
- Elastomers
- Fibers
- Coatings
- Adhesives
- Films
- Foams

Material Type	Major Application Characteristics	Typical Applications
Fluorocarbons (PTFE or TFE)	Chemically inert; excellent electrical properties; low coefficient of friction	Anticorrosive seals, chemical pipes and valves, bearings, wire and cable insulation, high-temperature electronic parts
Polyamides (nylons)	Good mechanical strength, abrasion resistance and toughness	Bearings, gears, cams, handles, fibers for carpet, hose
Epoxy	Excellent combination of mechanical properties and corrosion resistance; good adhesion	Electrical moldings, sinks, adhesives, protective coating
Polyesters	Excellent electrical properties and low cost; can be formulated for room- or high-temp use	Helmets, fiberglass boats, auto body components, fans

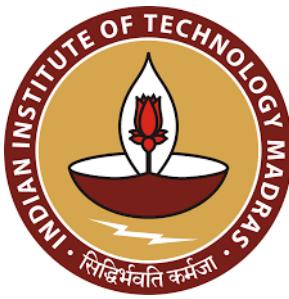


Polymer Additives

Polymers are often combined with additives and fillers to obtain the properties needed for many practical applications:

- **Plasticizers:** Low-molecular-weight molecules that reduce the bonding between polymer chains. This lowers the glass transition temperature.
- **Lubricants:** Reduce external friction during processing and improve flow.
- **Stabilizers:** Improve the durability against heat, oxidation and radiation.
- **Fire retarders:** Inhibit burning.
- **Fillers:** Inert substances that enhance mechanical properties such as hardness, abrasion resistance and strengths. Common fillers are **carbon black** and **calcium carbonate**.
- **Reinforcement:** Fibers that improve the ductility. Fiber reinforced polymer composites.

Young et al.



Durability of Polymers

- Polymeric materials are not usually attacked by chemicals. Therefore, they are used extensively for coating and resurfacing components exposed to aggressive environments.
- Some polymers are sensitive to organic solvents, which penetrate in between the polymer chains and reduce the van der Waals bonding, causing swelling and softening.

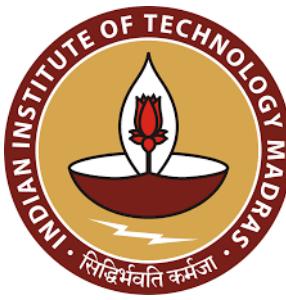
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Durability of Polymers

- Exposure to solar radiation, moisture and heat can cause loss of strength, embrittlement, cracking and changes in appearance. These effects are due to complex processes such as:
 - Photodegradation due to absorbed solar radiation: Ultraviolet light energy leads to the disassociation of bonds.
 - Photooxidation reactions.
 - Leaching of plasticizer.
 - Changes in dimension due to temperature and humidity cycling leading to cracking and crazing. This may enhance the chemical processes.
 - Moisture effects: Swelling and leaching.

Young et al.



Exterior Application of Polymers



Polymer shutters (Perth,
Australia)



Polymer planks and grating
(Penguin Island, WA, Australia)

Prof. Ravindra Gettu



Polymer Gratings

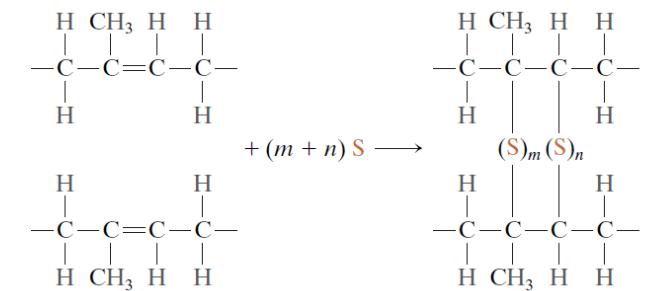
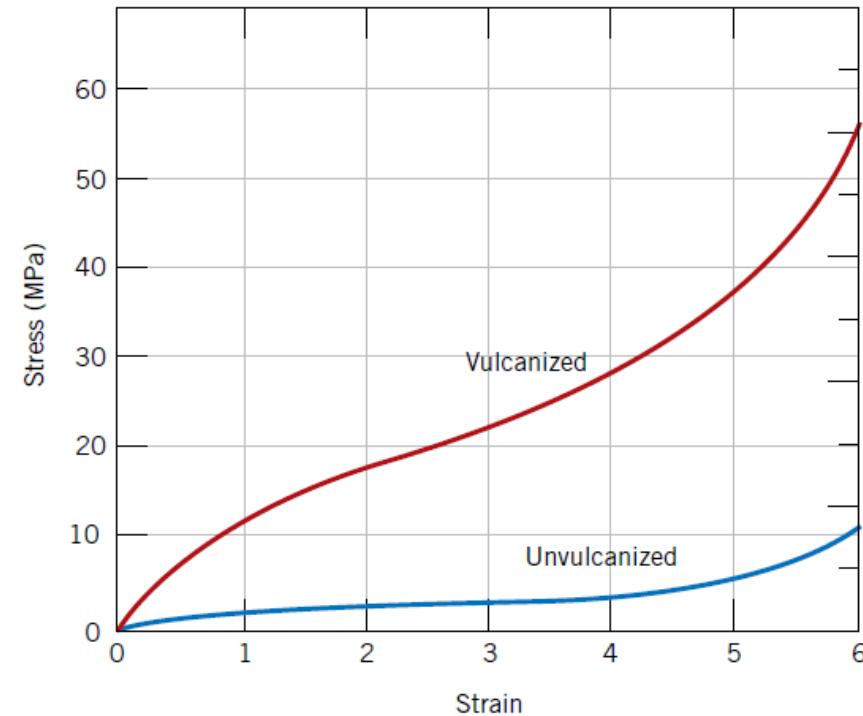
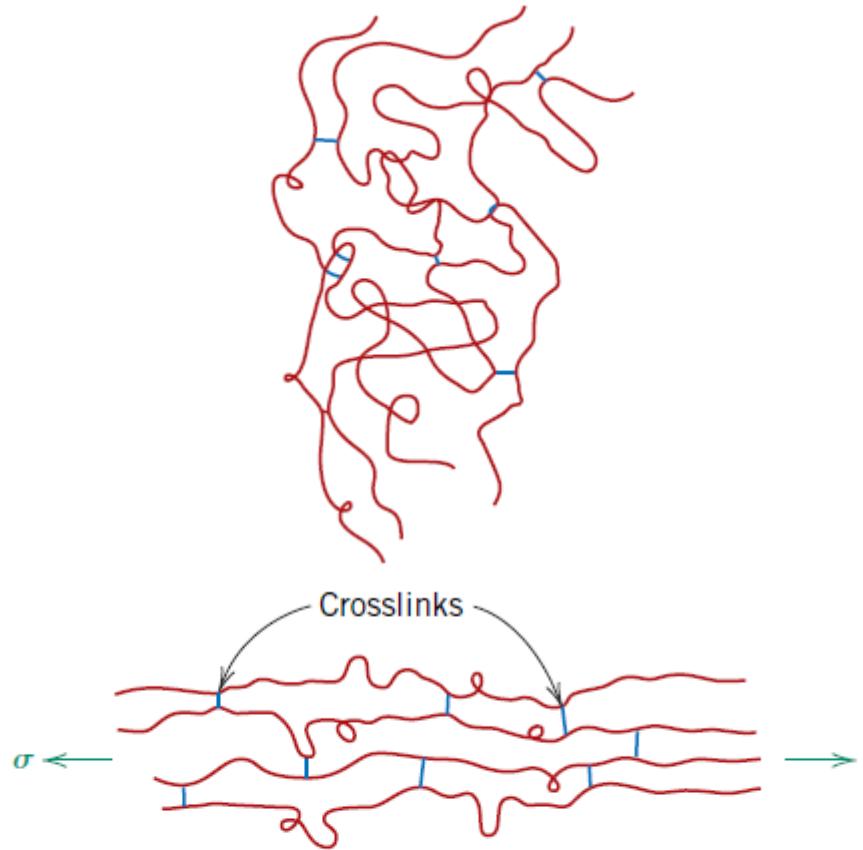


MPCEM Lab, Dept of Civil Engg.,
IIT Madras



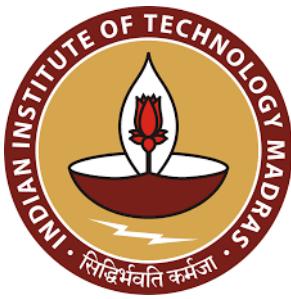
Elastomers

- Elastomers are rubber-like polymers. They have at least 100% elongation in a tensile test and a good ability to recover from elastic deformation.



Sulfur compounds are used for vulcanization.

Callister and Rethwisch



Common Elastomers Used in Construction

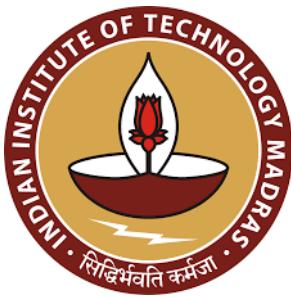
- **Chloroprene rubber (Neoprene):** Carbon chain polymer containing chlorine. Used in supports of bridge girders.
- **Polyurethanes:** Used as sprayed foam insulation in buildings, varnishes and floor coverings.
- **Silicones:** Inorganic polymers with silicon-oxygen chain backbone. Used as caulks, coatings and crack/joint sealants.



Geosynthetics

- **Geotextiles:** Polymeric textile materials used in a soil environment. Essentially permeable to the passage of water. Normally made of synthetic fibers such as polyethylene, polypropylene, polyester and polyamide.
- **Geogrids:** Open, mesh-like polymeric structures. Thermoplastic material that forms a composite system in conjunction with the soil. The grids can be cross-laid strips or punched sheets.
- **Geomembranes:** Polymeric sheets that are impermeable to water. Sheets of thermoplastic polymers or bituminous materials. Can be reinforced by textiles or unreinforced.

Illston and Domone



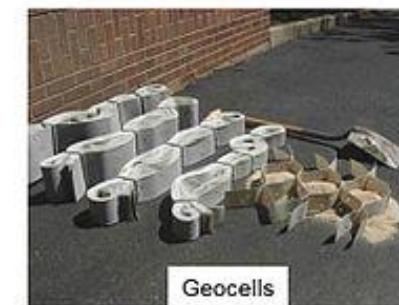
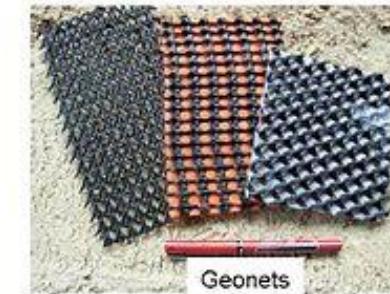
Geosynthetics

- **Geo-linear elements:** Long, slender polymeric materials used as reinforcing tendons in soils and rocks. They have a unidirectional filament fiber core (polyester, aramid or glass) in a polymer sheath of low-density polyethylene or resin.
- **Geocomposites:** Two or more polymer systems combined into a hybrid material. For example, drainage passage with a polymer core as a drainage channel and the geotextile skin as the filter.

Illston and Domone



Geosynthetics



<https://en.wikipedia.org/wiki/Geosynthetics>



Fiber Reinforced Polymer Composites

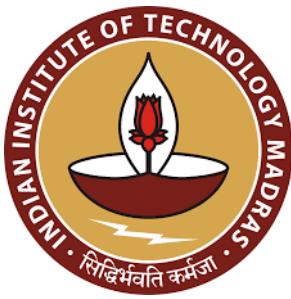


Application for FRP Composite



Carbon fiber reinforced polymer laminates and sheets used to strengthen a concrete slab

Prof. Ravindra Gettu



Composites

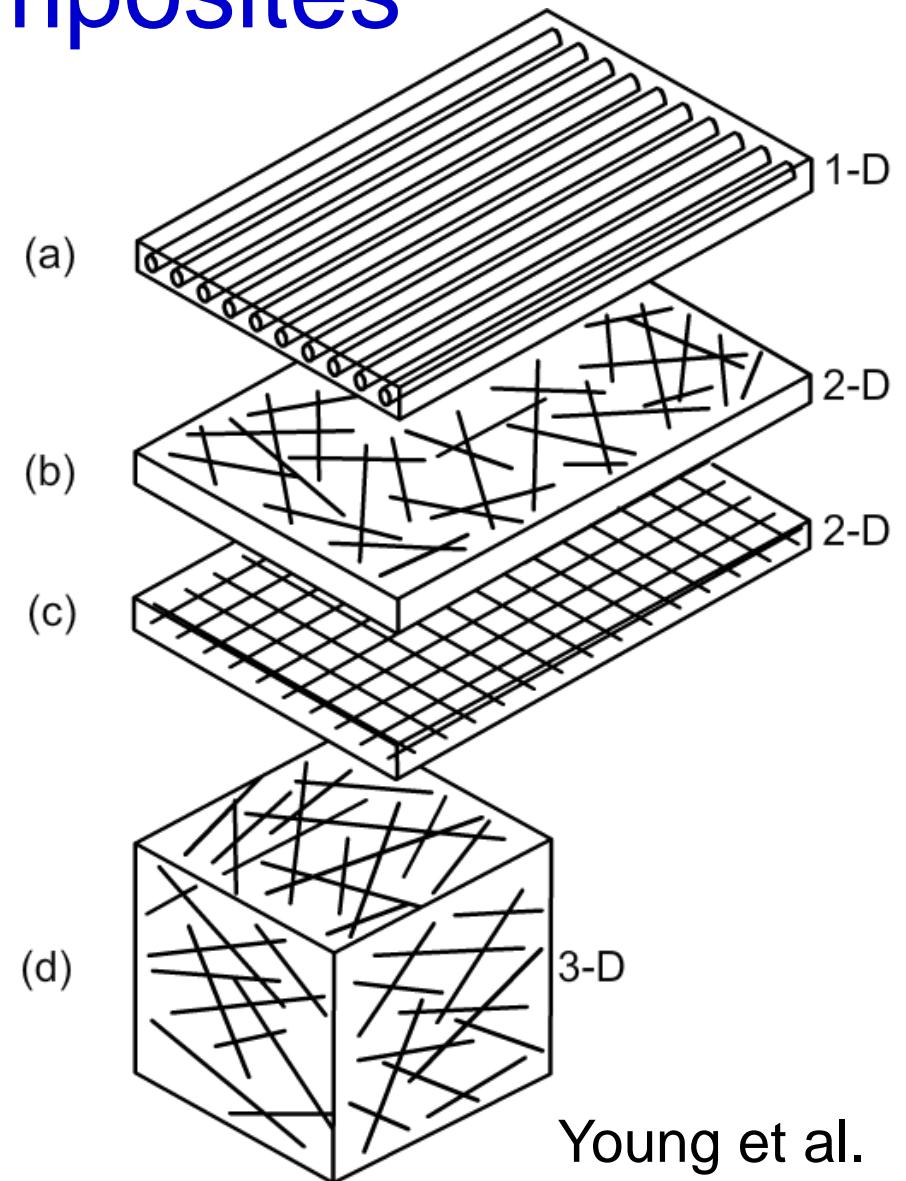
- A *Composite* is a combination of two or more materials, which differ in form or composition on a macroscale. The constituents retain their identities, i.e., they do not dissolve or merge into each other, although they act together.
- *Fiber Reinforced Polymer* (FRP) is a composite that consists of high-performance fibers embedded in a polymer matrix.



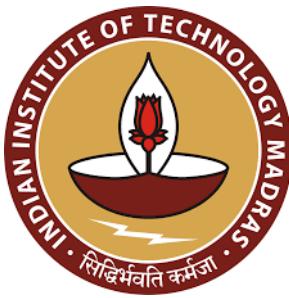
Fiber Reinforced Composites

Geometries:

- a) One-dimensional arrangement
- b) Two-dimensional arrangement, random
- c) Two-dimensional arrangement, oriented
- d) Three-dimensional arrangement, random



Young et al.



Polymers in FRP Composites

Its function in the composite is to transfer stress between reinforcing fibers, and to protect them from mechanical and environmental damage.

Resin Type	Density (kg/m ³)	Tensile Str. (MPa)	Elong. (%)	E-Mod. (GPa)
Polyester	1.2	50-65	2-3	3
Vinyl ester	1.15	70-80	4-6	3.5
Epoxy	1.1-1.4	50-90	2-8	3
Phenolic	1.2	40-50	1-2	3



Properties of Fibers

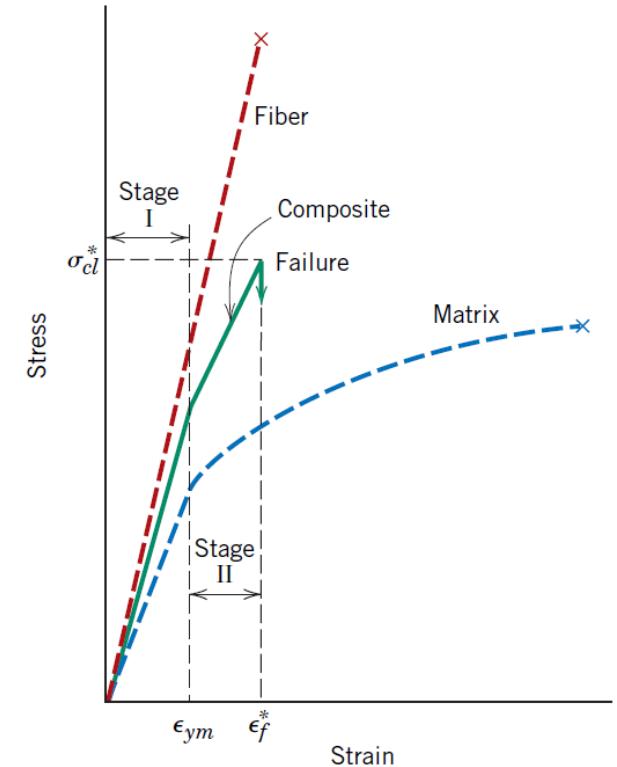
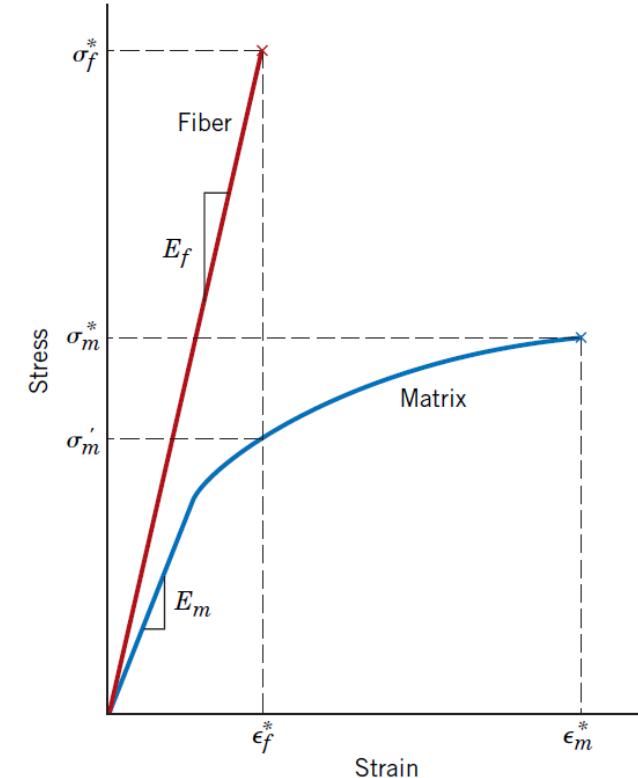
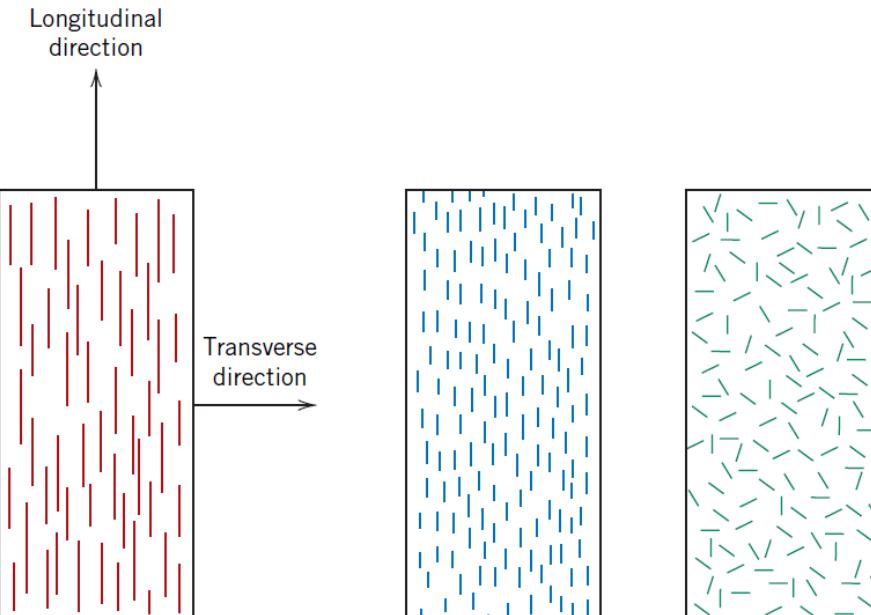
Fiber	Diameter (μm)	Relative Density ^a	Modulus of Elasticity (GPa)	Tensile Strength (GPa)	Elongation at Break (%)
Steel	5-500	7.84	200	0.5-2.0	0.5-3.5
Glass	9-15	2.60	70-80	2-4	2-3.5
Asbestos					
Crocidolite	0.02-0.4	3.4	196	3.5	2.0-3.0
Chrysotile	0.02-0.4	2.6	164	3.1	2.0-3.0
Fibrillated polypropylene	20-200	0.9	5-77	0.5-0.75	8.0
Aramid (Kevlar)	10	1.45	65-133	3.6	2.1-4.0
Carbon (high strength)	9	1.90	230	2.6	1.0
Nylon	—	1.1	4.0	0.9	13.0-15.0
Cellulose	—	1.2	10	0.3-0.5	—
Acrylic	18	1.18	14-19.5	0.4-1.0	3
Polyethylene	—	0.95	0.3	0.7×10^{-3}	10
Wood Fiber	—	1.5	71.0	0.9	—
Sisal	10-50	1.50	—	0.8	3.0

^aFormerly specific gravity.

Young et al.



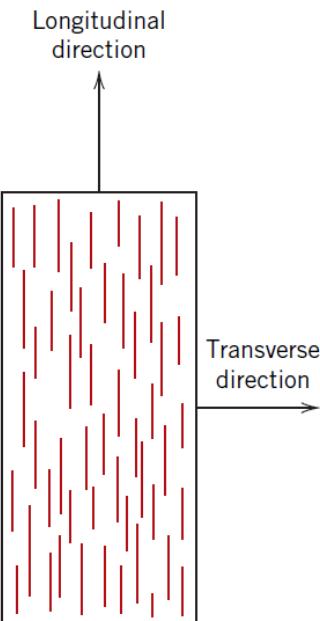
Influence of Fiber Orientation and Concentration



Callister and Rethwisch



Longitudinal vs. Transverse Loading



$$E_{cl} = E_m V_m + E_f V_f$$

$$\frac{1}{E_{ct}} = \frac{V_m}{E_m} + \frac{V_f}{E_f}$$

Material	Longitudinal Tensile Strength (MPa)	Transverse Tensile Strength (MPa)
Glass-polyester	700	20
Carbon (high modulus)-epoxy	1000	35
Kevlar-epoxy	1200	20

Callister and Rethwisch



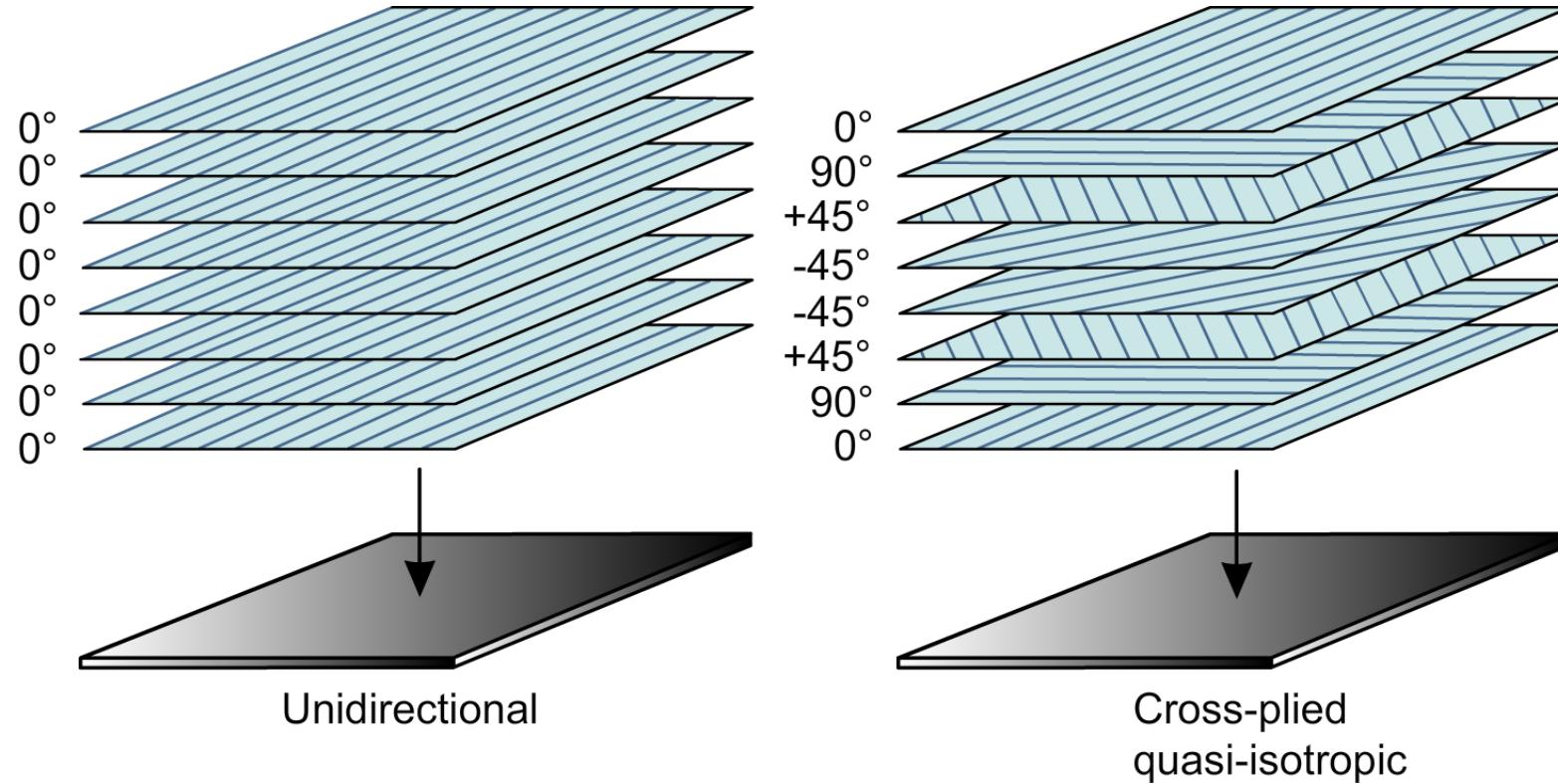
Properties of Common FRP Composites

<i>Property</i>	<i>Glass (E-Glass)</i>	<i>Carbon (High Strength)</i>	<i>Aramid (Kevlar 49)</i>
Specific gravity	2.1	1.6	1.4
Tensile modulus			
Longitudinal [GPa (10^6 psi)]	45 (6.5)	145 (21)	76 (11)
Transverse [GPa (10^6 psi)]	12 (1.8)	10 (1.5)	5.5 (0.8)
Tensile strength			
Longitudinal [MPa (ksi)]	1020 (150)	1240 (180)	1380 (200)
Transverse [MPa (ksi)]	40 (5.8)	41 (6)	30 (4.3)
Ultimate tensile strain			
Longitudinal	2.3	0.9	1.8
Transverse	0.4	0.4	0.5

^aIn all cases, the fiber volume fraction is 0.60.

Callister and Rethwisch

Multi-layer Composites

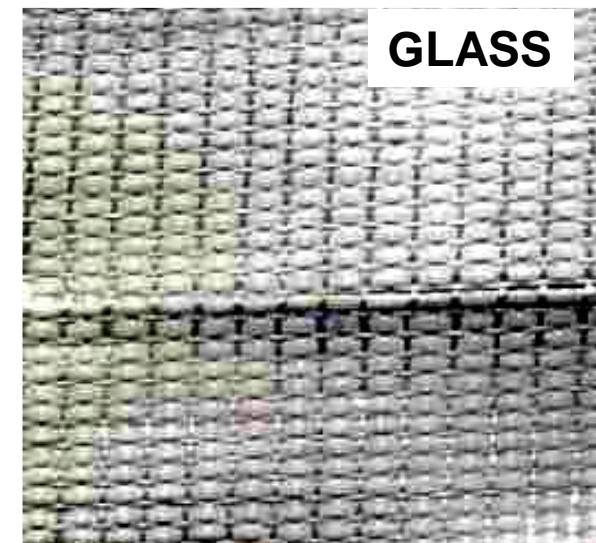


Tapes or laminates containing aligned fibers can be joined to produce a multi-layered composite that is (a) unidirectional or (b) quasi-isotropic, with different fiber orientations.



Fiber Sheets

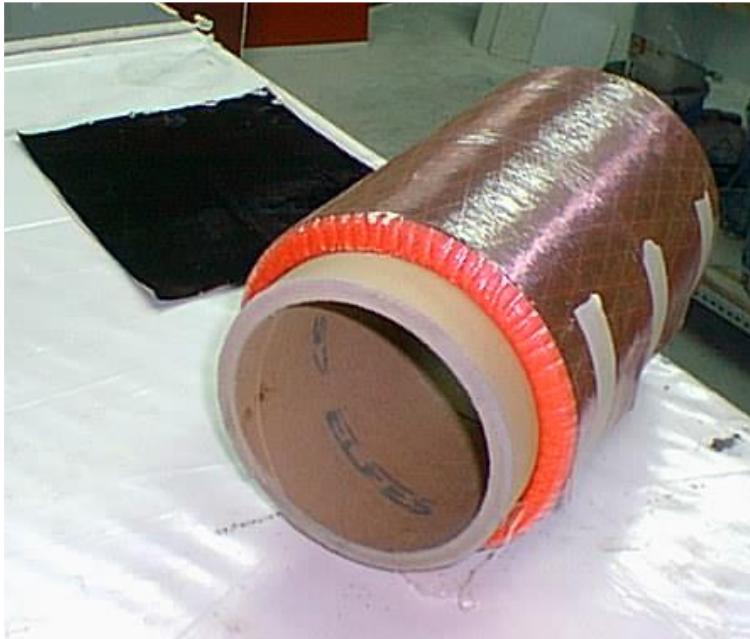
- Fiber sheets or filaments (uni- or bi-directional) are used to obtain a polymer laminate.
- The sheets are available as raw fibers or pre-impregnated (with curing on site).





Fiber Sheets

CARBON FIBRE SHEET: Normally uni-directional. Often layers are superposed for bi-directional strengthening.





FRP Laminates

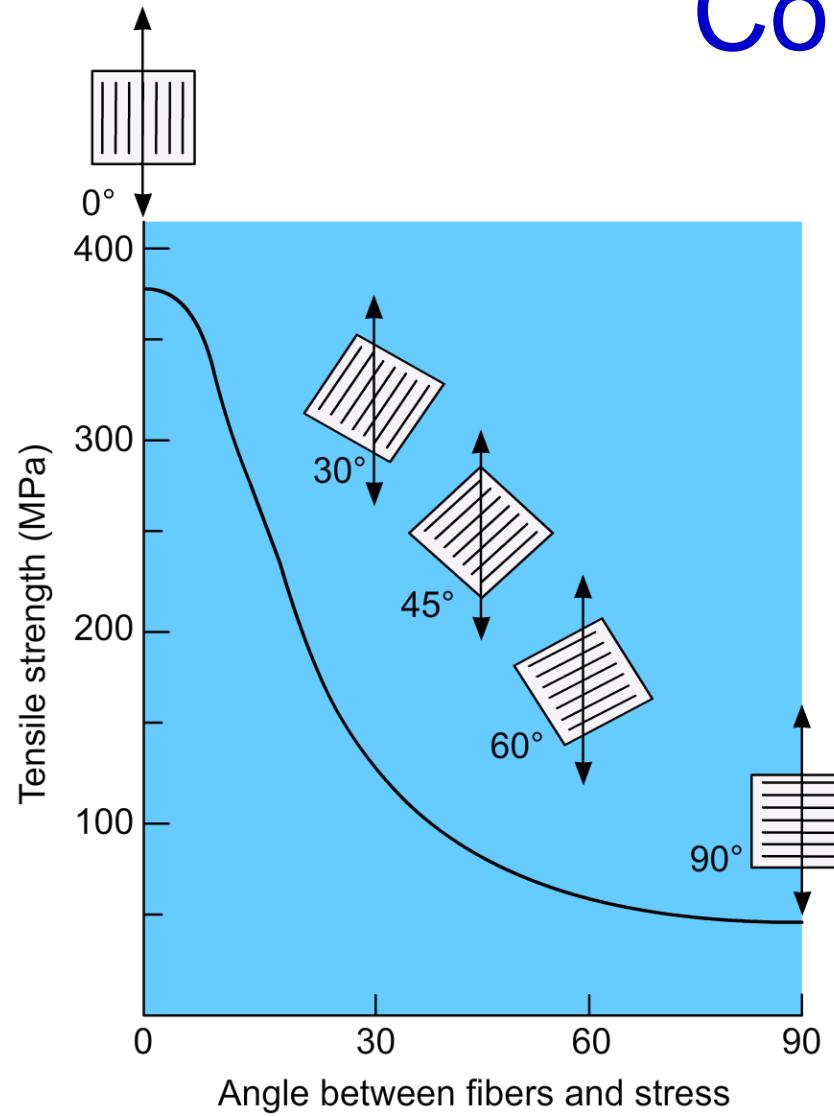
PREFABRICATED LAMINATE: Fabricated by extrusion with continuous unidirectional fibers (of carbon).

- Tensile strength: 2.5 GPa
- Max. elongation: 1.5-1.6%





Effect of Fiber Orientation in Unidirectional Composites



Effect of fiber orientation on the tensile strength of E-glass fiber-reinforced epoxy composites.



FRP Rebars





Fiber Performance in Aggressive Environments

- **CHEMICAL ATTACK:** Carbon and Aramid fibers exhibit good performance. Glass fibers can be damaged in alkaline media.
- **ULTRAVIOLET RAYS:** Carbon and glass fibers are not affected. Aramid fibers lose color and strength.
- **HEAT AND FIRE:** The fibers maintain their mechanical properties until:
Glass - 1000°C; Carbon - 650°C; Aramid - 200°C



Strengthening of Concrete Structures Using FRP Composites

STEPS

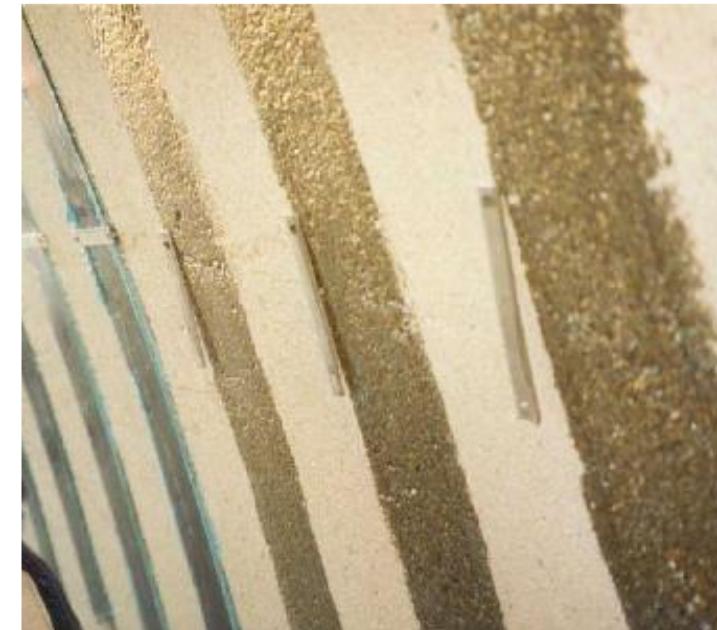
- Structural analysis and design
- Selection of the composite
- Preparation of the base
- Application of the laminate or sheet
- Quality checks



Application



Cleaning with abrasion

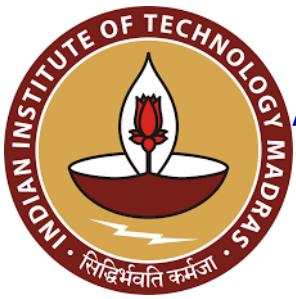


Application of epoxy



FRP Laminate Application

Prof. Ravindra Gettu



Advantages and Disadvantages of FRP in Strengthening

- Advantages
 - Light weight
 - Adaptable to curves surfaces
 - Fast application

- Disadvantages
 - Brittle failure
 - Cost
 - No design code and lack of experience



References

- *The Science and Technology of Civil Engineering Materials*, J.F. Young, S. Mindess, R.J. Gray & A. Bentur, Prentice Hall, 1998.
- *Construction Materials: Their nature and behaviour*, J.M. Illston and P.L.J. Domone, Spon Press, 2001.
- Materials Science and Engineering, *Callister, William D., and David G. Rethwisch*, John Wiley & Sons, 2011.



Khardung La Pass,
Ladakh, at a height of
5359 meters

Bituminous Materials

Dr. Piyush Chaunsali
Department of Civil Engineering
IIT Madras



Bituminous Materials

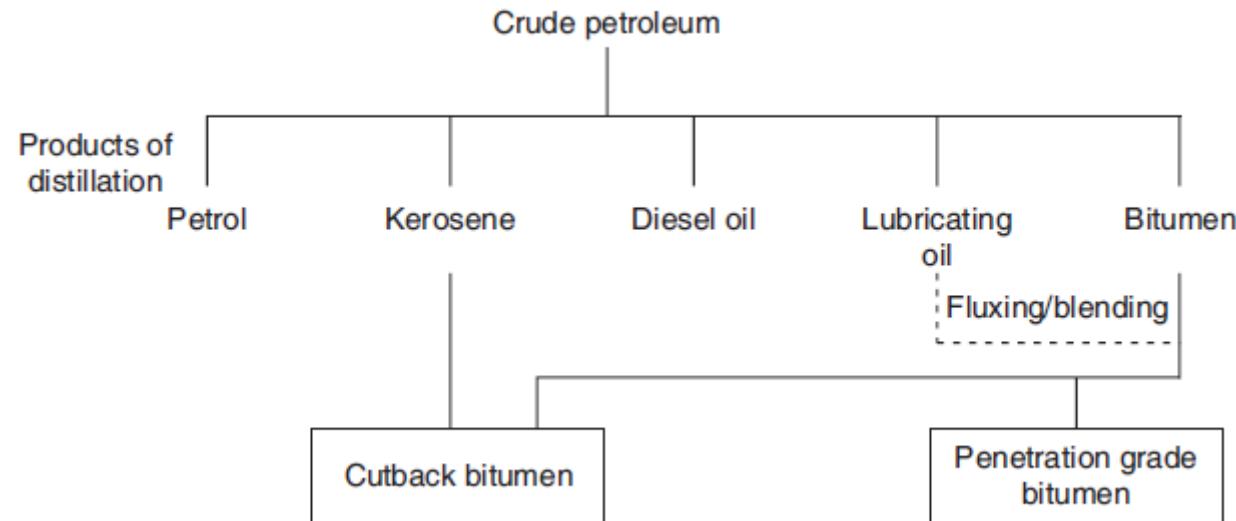
- Bituminous materials consist of graded aggregate bound together with **bitumen**.
- Aggregate is stiff and hard. Bitumen is flexible and soft, particularly susceptible to temperature change.
- In buildings, bitumen is used in:
 - Waterproofing of roofs
 - Damp proofing
 - Flooring material
 - As water barriers in basements

Illston and Domone; Varghese



Sources of Bitumen

- Natural deposits:
 - Formed from petroleum by geological forces
 - Always in intimate association with mineral aggregates
 - Types of deposits range from pure bitumen to bitumen-impregnated rocks and bituminous sands with only few per cent of bitumen
- Refinery bitumen:
 - Residual material left after fractional distillation of crude oil



Illston and Domone



Terminology: Bitumen and Asphalt

- Asphalt and bitumen are the terms used interchangeably except when asphalt term is used for asphalt concrete which is a natural or artificial mixture of bitumen with mineral aggregates.



Composition of Bitumen

- Bitumen has a very complex and variable chemical composition that is dependent on the origin of the crude oil, from which it has been derived.
- They are composed of **high-molecular-weight hydrocarbons**, having the general formula $C_nH_{2n+b}X_d$, where X represents elements such as sulfur, nitrogen, oxygen or trace metals; d is usually small; and b may be negative.
- Carbon 80-87%; Hydrogen 9-11%; Oxygen 2-8%; Nitrogen 0-1%; Sulfur 0.5-7%; Trace metals (Fe, Ni, V, Ca) 0-0.5%

Young et al., Illston and Domone



Composition of Bitumen

- The main fractions of bitumen are *asphaltenes, resins and oils*. Asphaltenes have **higher molecular weights**, and are dark brown to black, brittle solids.

Phase	Component	C/H Ratio ^a	Contribution
Dispersion	Oils	< 0.4	Viscosity and fluidity
Dispersed	Asphaltenes	> 0.8	Strength and stiffness
Interfacial	Resins	~ 0.6	Adhesion and ductility

^a No. of carbon atoms/no. of hydrogen atoms

Young et al., Illston and Domone



Structure of Bitumen

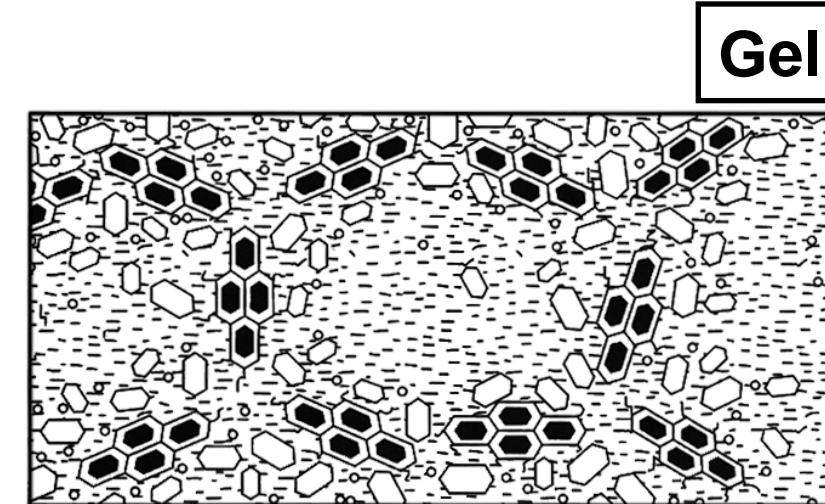
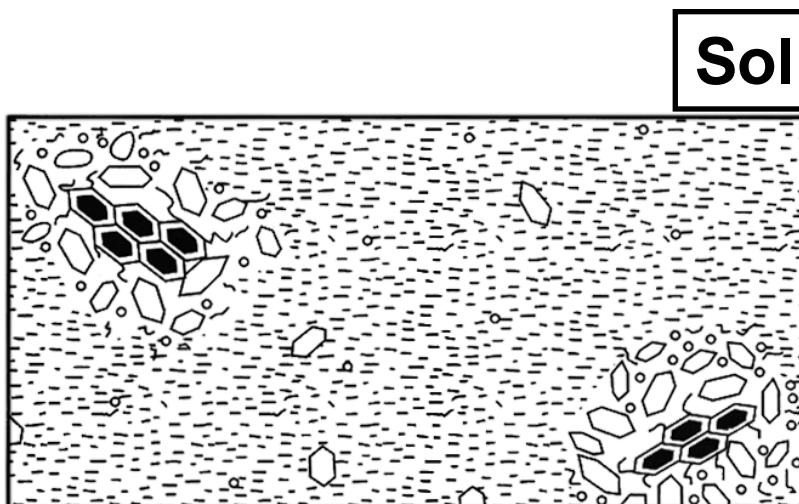
- Bitumen can be described as a **colloidal system**, where the asphaltenes are solid particles in the form of molecule clusters or **micelles dispersed in the oils** with the **resins forming an interfacial phase**.
- The phases act as a continuum with no distinct boundaries between them. The asphaltene micelles, surrounded by a layer of resin, are randomly distributed throughout the oil phase.

Young et al., Illston and Domone



Structure of Bitumen

- ◆ Asphaltenes
- High-molecular weight aromatic hydrocarbon
- Low-molecular weight aromatic hydrocarbon
 - Aromatic/naphthenic hydrocarbons
 - Naphthenic/aliphatic hydrocarbons
 - Saturated hydrocarbons



Young et al.



Structure of Bitumen

Based on their structure, bitumen can be classified as:

- **Sol:** the asphaltene micelles are separated and widely dispersed; the bitumen is essentially viscous (Newtonian) with little or no elasticity.
- **Gel:** the micelles are discrete but are bound in a complex three-dimensional network through molecular attraction; exhibits elastic, inelastic and permanent deformational behavior.
- **Sol-Gel:** intermediate behavior; initially elastic, followed by viscous behavior, hence viscoelastic.

Young et al.



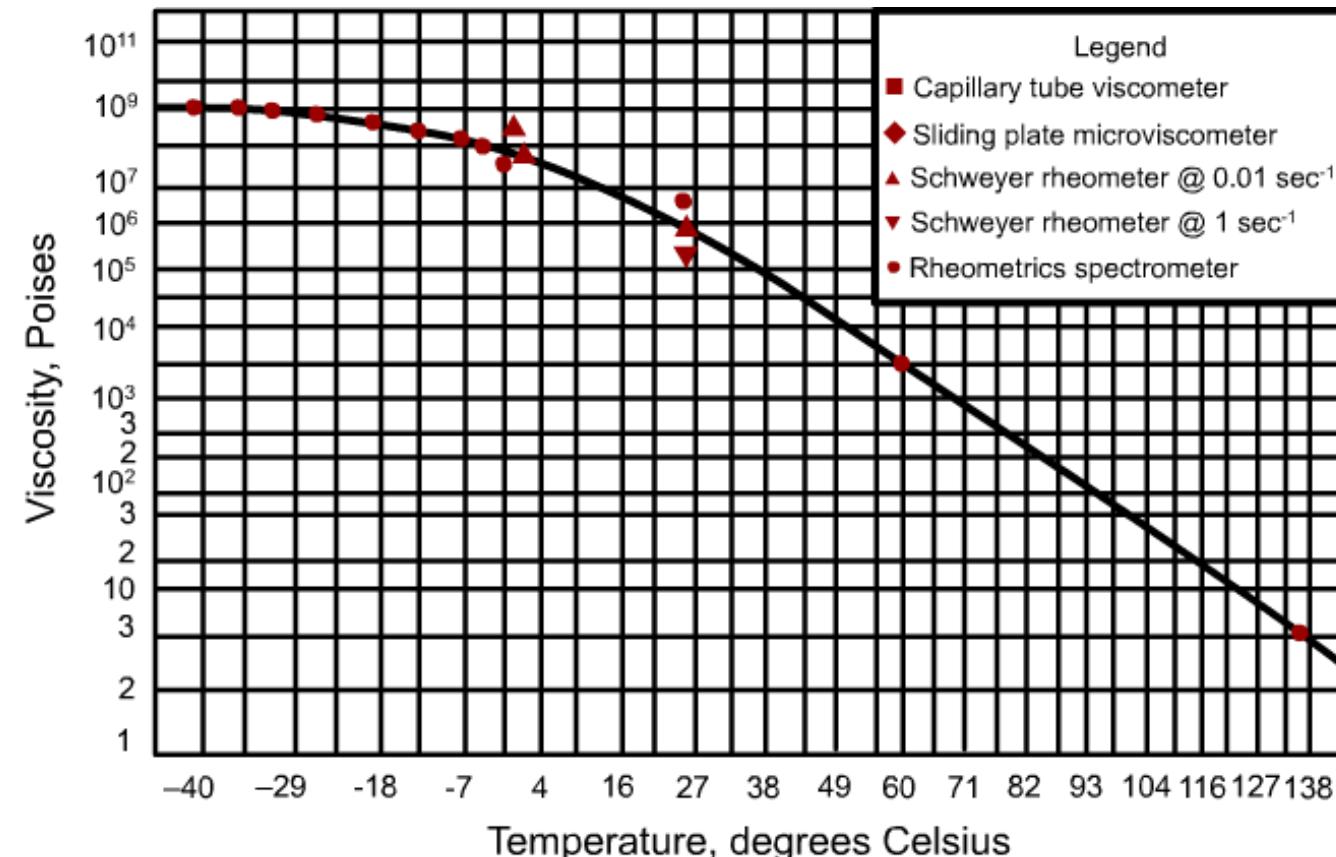
Structure of Bitumen

- The structure and properties of bitumen are a function of its temperature, as well as its chemical nature and the relative proportions of its constituents.
- As the temperature increases, the asphaltenes flow more freely and the material becomes less viscous.
- As the temperature decreases, the asphaltenes become less soluble and the micelles are bound in an ordered structure, and the material becomes more viscous.
- Eventually, as the temperature is decreased below the glass transition temperature the structure is frozen, and the material behaves as a rigid and brittle solid.

Young et al.



Properties of Bitumen: Viscosity



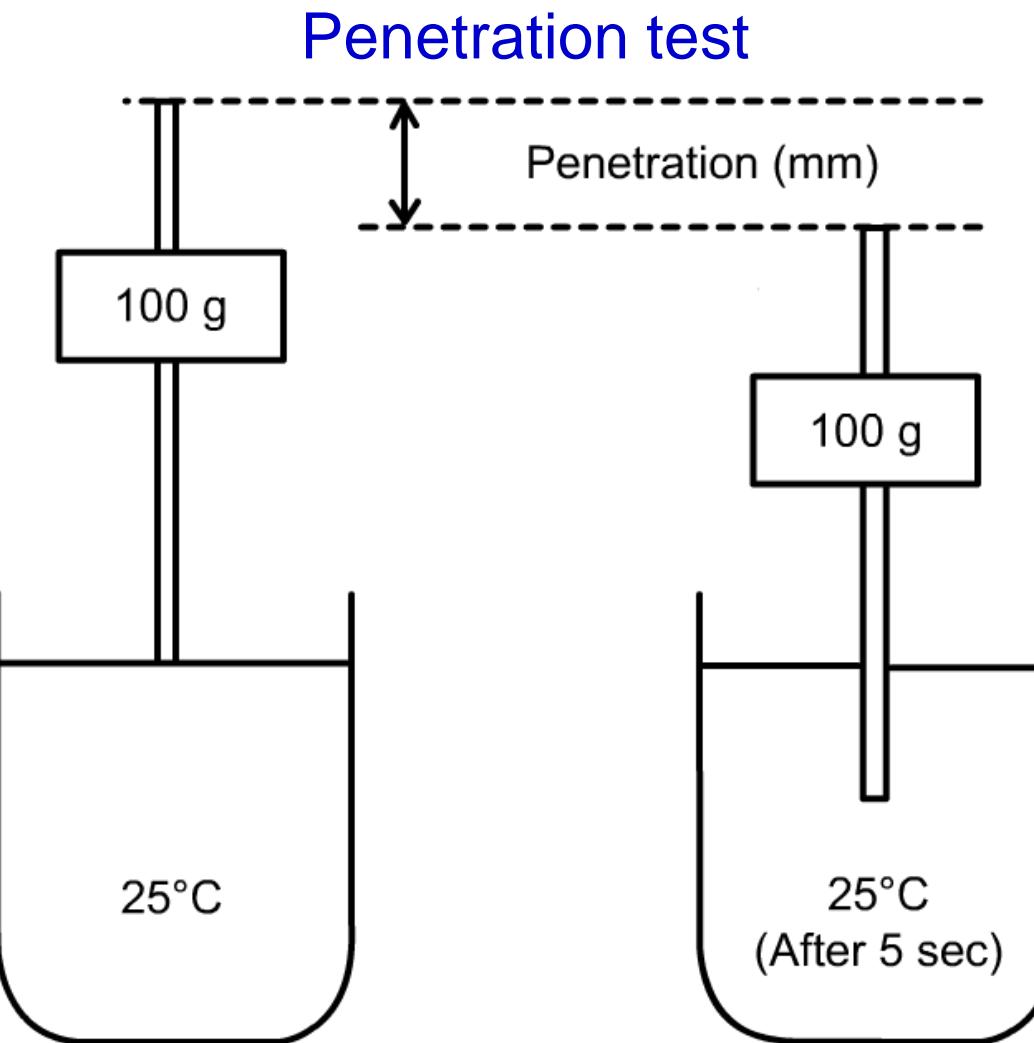
The rheological behavior is **highly temperature dependent**. Viscosity decreases as temperature increases.

Young et al.



Rheological Test of Bitumen

- The penetration of a standard needle, in 5 seconds at 25°C, is measured in one-tenths of a millimeter.
- For example, the specification of a penetration grade 80/100 means that the penetration should be between 8 and 10 mm.



Varghese



Specification of Bitumen

- Bitumen should normally be specified in terms of the apparent viscosity at a reference temperature, say 60°C. This reflects the resistance against plastic deformation of the pavement.
- Bitumen was often specified only in terms of a penetration grade. Nowadays, the penetration value is sometimes specified in addition to viscosity. The penetration value is a measure of the hardness of the bituminous material. It represents the potential for resisting cracks at low temperatures.



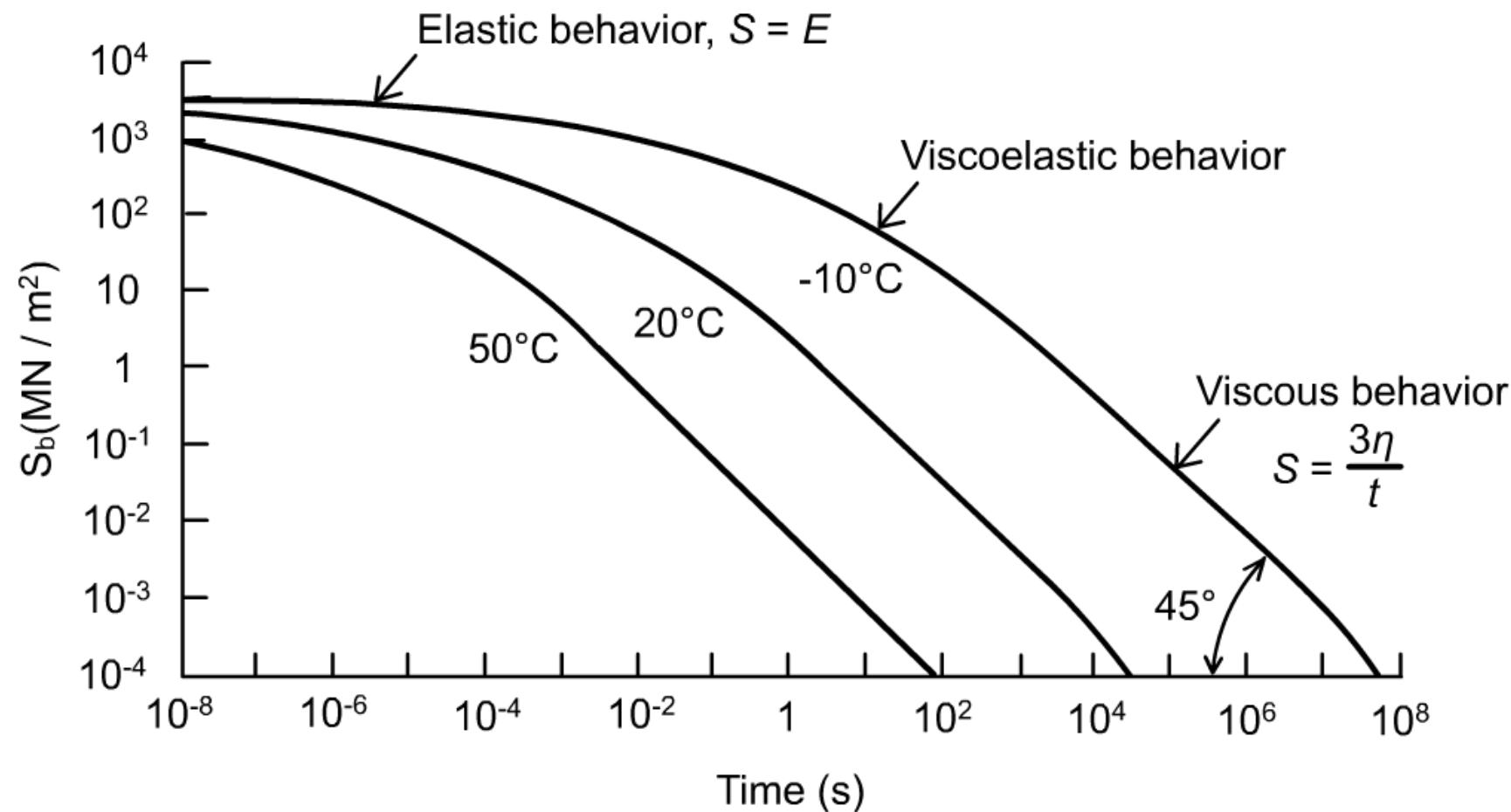
Properties of Bitumen: Stiffness

- Bitumen is a viscoelastic material, the response to an applied load depends on the size of the load, the temperature and the duration of its application.
- There is no simple relationship between stress and strain, and it is therefore difficult to predict the elastic modulus of bitumen.
- To take account of the viscoelastic nature of bitumen, Van der Poel (1954) introduced the concept of stiffness modulus.
- $S_b = (\sigma/\varepsilon)_{t,T}$ where S_b is the stiffness modulus of the material at a loading time t and a temperature T .

Illston and Domone



Properties of Bitumen: Stiffness



E = elastic modulus; η = coefficient of viscosity; t = time

Young et al.



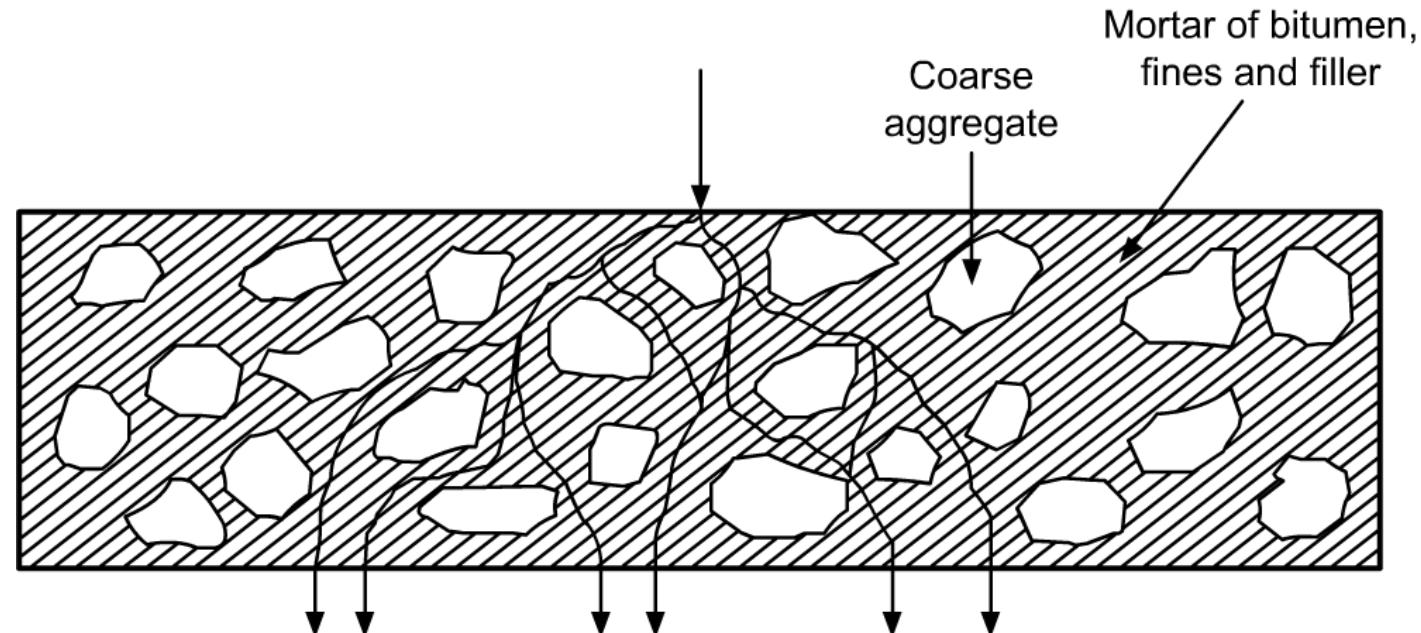
Properties of Bitumen: Tensile Strength

- The tensile strength of bitumen decreases with an increase in temperature and time under load.
- The strength of bitumen increases with decreasing film thickness. This has been attributed to the:
 - Decrease in the ability to flow
 - Decrease in the probability of large flaws
 - Increase in the orientation of molecules at the surface of the material

Young et al.



Asphalt (Concrete) Paving Mixtures



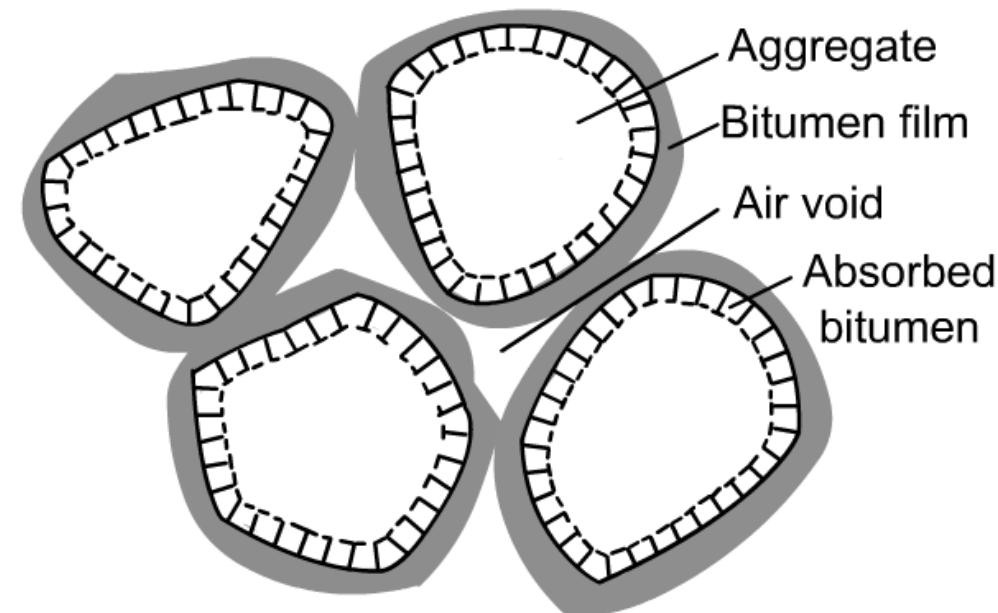
Characteristics

- Dense mortar providing strength and stiffness
- High bitumen content
- High filler/finer content
- Low coarse aggregate content
- Load transmitted through mortar

Illston and Domone

Aggregate-Bitumen Interaction

- The **aggregate content** in asphalt concretes is high, about **90% or more, by weight**. It has, therefore, an important effect on the stiffness and flexibility of the mixture.
- The bitumen generally forms a thin layer around the aggregate particles.
- The interaction between the bitumen and aggregate occurs during all the three stages of the life of the asphalt:
 - **Mixing** (bitumen is liquid at high temperature)
 - **Curing** (mixture cools down; is viscoelastic)
 - **Ageing** (exposed to environment and loading)



Young et al.



Aggregate-Bitumen Interaction

- The ability of a bitumen to form a good bond depends on how well it can wet the aggregate surface.
- In the absence of water, the bitumen can wet the surface of most common aggregates. However, when the aggregates are moist, the bitumen-aggregate bond could be prevented or disrupted since the surface energy of water is lower.
- Bonding is achieved by the mechanism of wetting, as well as mechanical interaction when the bitumen can flow into the pores and irregularities on the surface of the aggregate.
- Bond failure occurs when flaws propagate due to the applied loading or when the bitumen detaches from the surface because of water (stripping).

Young et al.



Mechanical Behavior of Asphalt (Concrete)

- **Stability:** The property of the asphalt to resist permanent deformation under traffic loading. It is maximum for a mix with dense-graded aggregates and the minimum bitumen content to fill the void system.
- **Flexibility:** The ability of the asphalt to conform to minor, long-term settlement of the base layers beneath it without cracking. It is higher for mixtures with open-graded aggregates and high bitumen content.

A compromise is needed between good stability and sufficient flexibility.

Young et al.



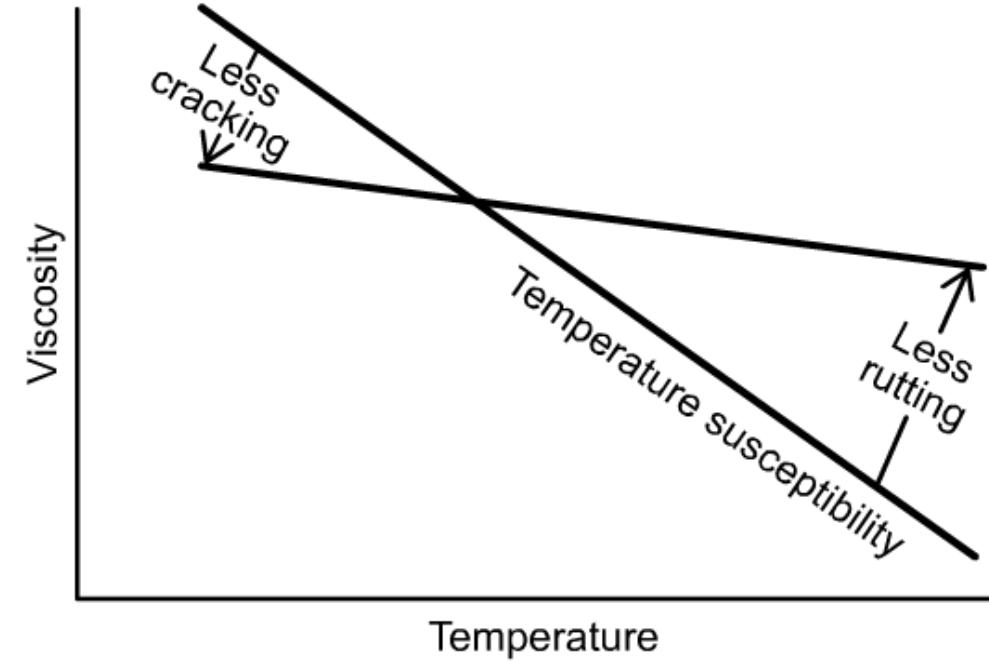
Mechanical Behavior of Asphalt (Concrete)

- **Fatigue resistance:** Mixtures with higher bitumen contents and densely-graded aggregates have better fatigue resistance.
- **Tensile strength:** The maximum tensile stress depends on the properties of the bitumen, the bitumen-aggregate bond, bitumen content and the voids content of the mixture. At rapid loading rates and low temperatures, the tensile strength of asphalt is in the range of 4-10 MPa.
- **Skid resistance:** The skid resistance of a road surface is provided mainly by the exposed aggregates and their surface texture.
- **Permanent deformation:** Excessive plastic deformation in asphalt can result from normal and/or shear stresses caused by applied loads. Rutting is the most common form of plastic deformation.

Illston and Domone, Young et al.



Mechanical Behavior of Asphalt (Concrete)



Temperature susceptibility: The change in stiffness and viscosity with temperature affects the performance of the asphalt pavement. It is more susceptible to cracking at low temperatures and rutting at higher temperatures.

Young et al.



Durability Problems

Ageing: Bitumen (during service) becomes harder or less ductile with time due to changes in the structure and composition. The rate of hardening depends on oxidation of the resins and loss of volatiles and is higher at elevated temperatures and under ultraviolet radiation.

Stripping: Breakdown of the bond between the bitumen and aggregate may occur due to the action of traffic, weathering and moisture, normally acting in combination.

Illston and Domone



Failure Modes in Bituminous Materials

- Functional distress: usually associated with the road surface through deterioration with time. This may be through breakdown of the surface material, for example through fretting or stone loss (raveling), or alternatively, the surface texture of the surface course may be reduced, through polishing or abrasion, so that the skidding resistance drops below an acceptable level.
- Structural distress: develops gradually with the continued application of wheel loads. In the early stages, the rate of deterioration is very small, and the structural changes are not perceptible and are difficult to measure. But with continued service, signs of structural change become clearer and the rate of deterioration accelerates.

Illston and Domone



Problems Due to Excessive Plastic Deformation

Rutting



Thermal Cracking



Top-Down Cracking



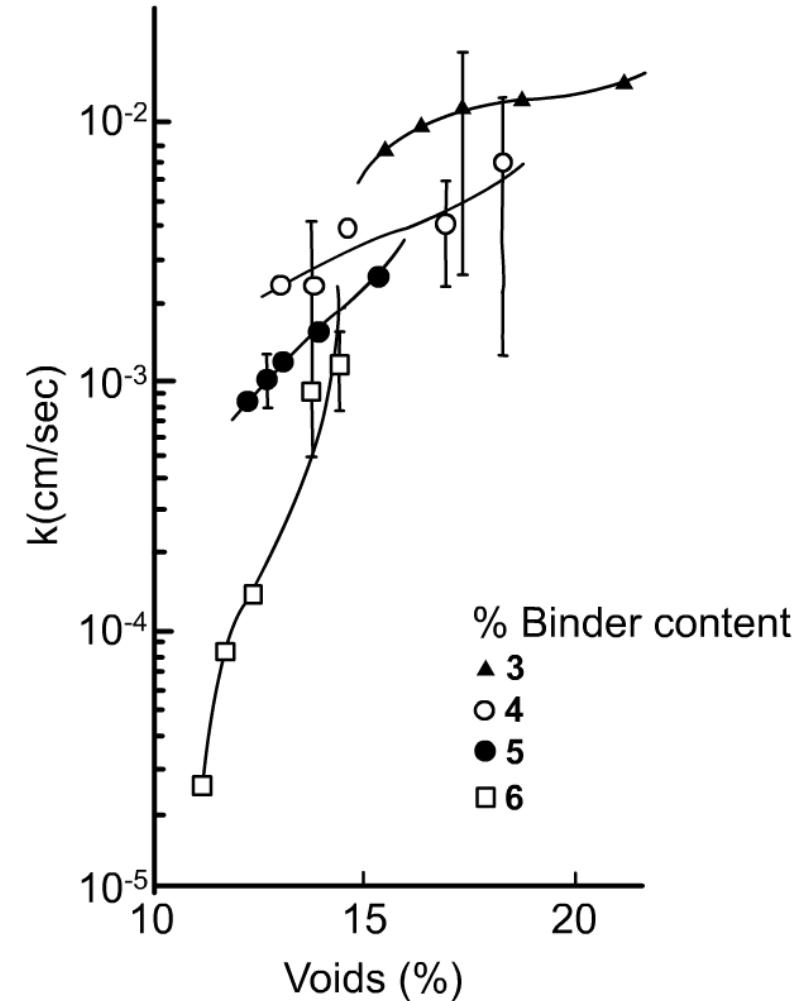
<https://www.asphaltwa.com/?s=low+temperature+cracking&x=0&y=0>



Permeability

- *Permeability* is important in asphalt since it controls the extent to which air and water can enter the material. Exposure to air can lead to hardening of the bitumen, and entry of water leads to deterioration of the bitumen-aggregate bond. Therefore, **permeability is a measure of the durability.**
- It is governed primarily by the quantity of voids, distribution of void sizes and the continuity of voids.
- Permeability is higher for lower bitumen (binder) content, and more sensitive to changes in void volume for higher bitumen content.

Permeability coefficient, k



Illston and Domone



Effect of Moisture

- At high temperatures, water blisters form on the bitumen surface. The blister ruptures at even higher temperatures to leave a pit.
- Hydraulic scouring due to the action of vehicle tires on a wet road can occur due to the compression-tension cycling of water in cavities.
- In poorly compacted mixtures, water may be trapped within the bitumen. Due to traffic pressure, the water migrates to the bitumen-aggregate interface causing disbonding.

Illston and Domone



Additives and Fillers

- **Antistripping agents:** Organic compounds or inorganic chemicals that migrate to the aggregate-bitumen interface and **enhance bonding and bond stability**.
- **Antioxidants:** Added to bitumen for **retarding the oxidative ageing or hardening process**. These materials must be stable and nonvolatile at the temperatures encountered in the mixing process. **Ex: lead diethyldithiocarbamate**.
- **Polymer modification:** Styrene butadiene rubber, and other natural and synthetic polymers are added in asphalt concrete to **increase the viscosity, improve adhesion and retard oxidation**.
- **Fillers:** Stone dust and other fine materials to **fill voids and improve the hardness**. **Ex: pulverized limestone, stone dust, hydrated lime, Portland cement, etc.**

Young et al.



References

- *The Science and Technology of Civil Engineering Materials*, J.F. Young, S. Mindess, R.J. Gray and A. Bentur, Prentice-Hall, 1998.
- *Construction Materials: Their nature and behaviour*, Eds. J.M. Illston and P.L.J. Domone, Spon Press, 2001.
- *Building Materials*, P.C. Varghese, Prentice-Hall, Delhi, 2005.