Chapter 24

Polymer Composites

PRP

FRP

Nanocomposites

Composites [複合素材, 複合材料]

- dream: strength of steel with resilience of rubber
- goal: enhancing stiffness [modulus] and (tensile) strength
- composite = introducing 2nd phase of high modulus
  - composite vs blend vs toughened plastic
- matrix polymers
  - thermosets (crosslinked) ~ epoxy, unsaturated polyesters, --
  - thermoplastics ~ nylon, PP, PEEK, ---
- 2nd phase [reinforcement]
  - particulate ~ talc, mica, silica, --
    - often for low cost
  - fiber
    - glass fiber [GF], carbon [graphite] fiber [CF], Aramid, ---

Table 24.2

Fibre	Density ρ_f/Mg m^{-3}	Tensile Modulus E_f/GPa
E-glass	2.55	76
Aramid (Kevlar 49)	1.45	125
PBO (Zylon HM)	1.56	270
Carbon (high strength)	1.77	230
Carbon (high modulus)	1.90	360

Particulate composites

- modulus
  - upper bound ~ uniform strain [parallel, rule of mixture]

$$e_p = e_m = e_c \qquad \sigma_p = E_p e_p \quad \text{and} \quad \sigma_m = E_m e_m$$

$$\sigma_c = \phi_p \sigma_p + \phi_m \sigma_m = \phi_p E_p e_p + \phi_m E_m e_m$$

$$\frac{\sigma_c}{e_c} = E_c = \phi_p E_p + \phi_m E_m$$

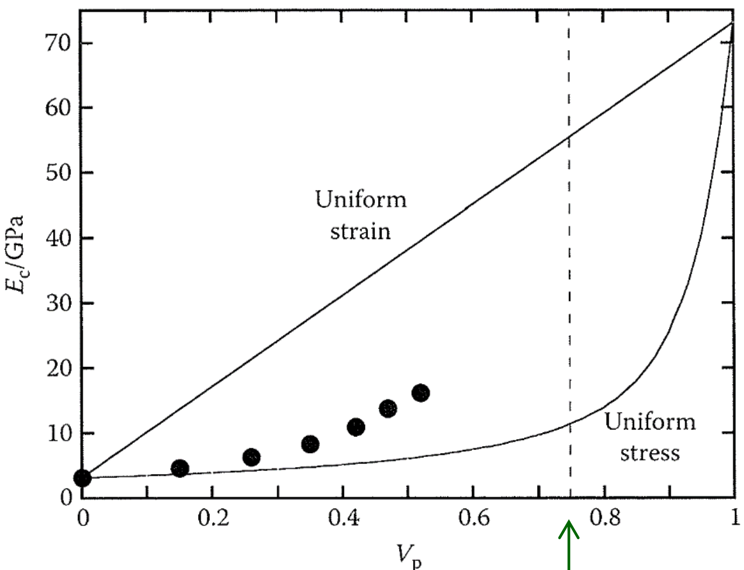
  - lower bound ~ uniform stress

$$\sigma_p = \sigma_m = \sigma_c$$

$$E_c = \frac{E_p E_m}{\phi_m E_p + \phi_p E_m}$$

  - experimental? close to lower bound
    - why? low level of stress transfer → non-uniform strain
    - hard to get high E by particulate
      - higher E by FRP; PRP for cost

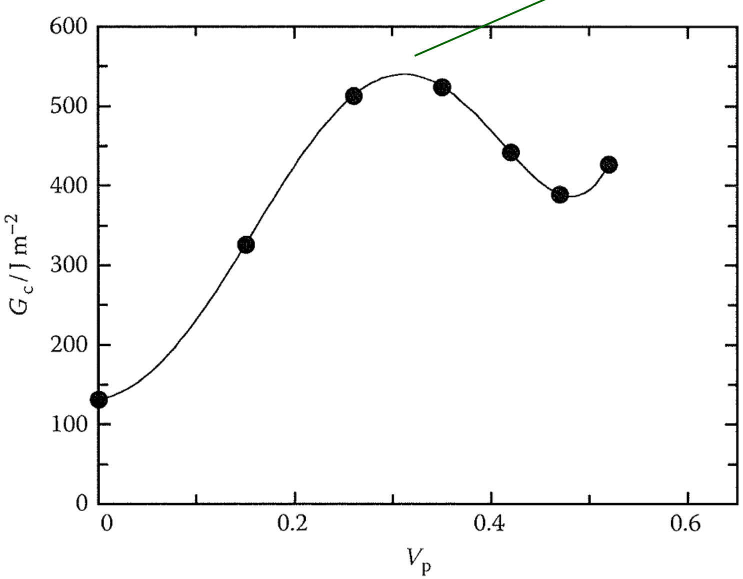
Fig 24.6 p600



$\phi_{p,\,max} = .75$

- fracture toughness
  - G_c actually enhanced
  - toughening mechanism
    - crack pinning
    - multiple crazing and cavitation-yielding also

ϕ_p can be 75% p598
practically < 35%



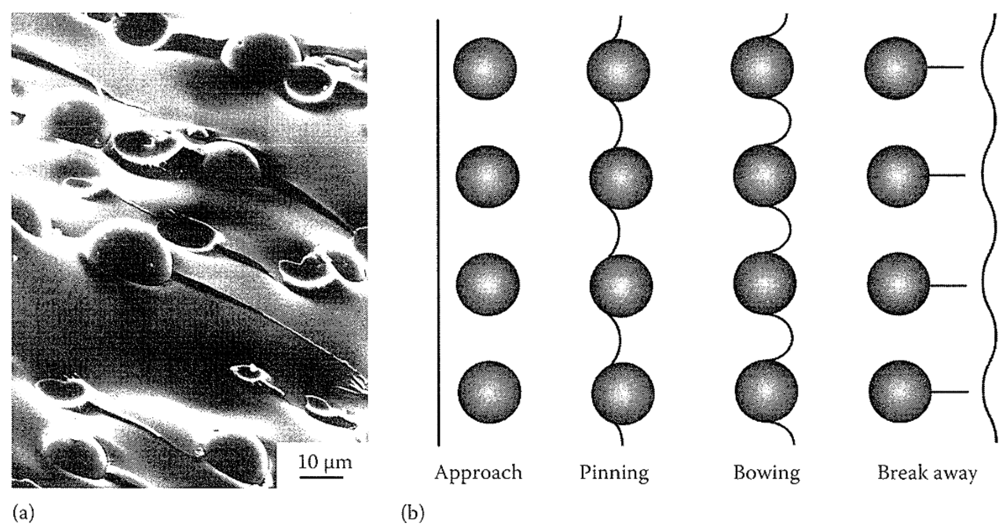


Fig 24.7 and 8 p601
glass-particle-filled epoxy

Fiber reinforced plastics [FRP]

- types
  - continuous-fiber composite
    - stack of plies [prepregs]
      - unidirectional
      - crossply (0/90)
      - angle-ply (0/45/90---)
    - woven fabric
  - short-fiber composite
    - direction random
    - length important

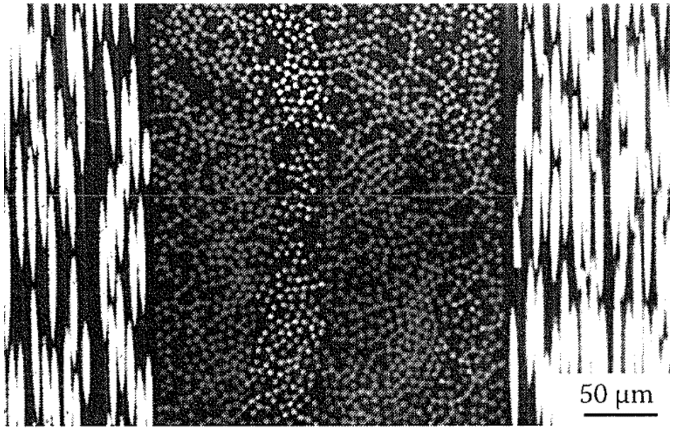
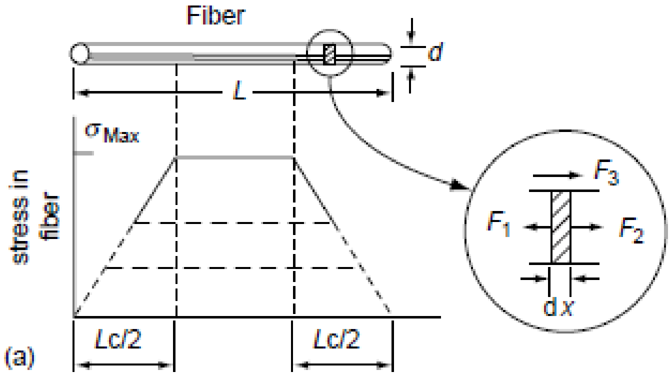
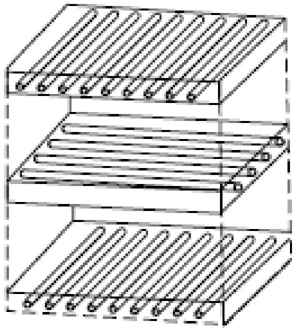


Fig 24.2
0/90/90/0 laminate





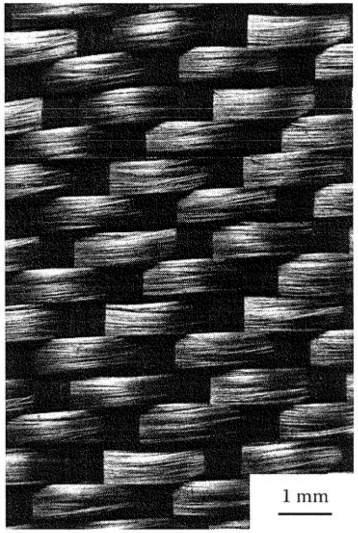


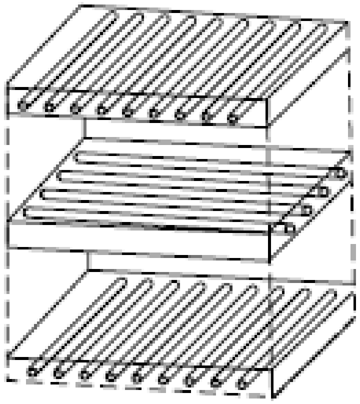
Fig 24.2
woven

- modulus
  - continuous fiber composite
    - axial (0°-ply) ~ uniform strain

$$E_1 = E_f\phi_f + E_m\phi_m = E_f\phi_f + E_m(1-\phi_f)$$

    - transverse (90°-ply) ~ uniform stress

$$\frac{1}{E_2} = \frac{\phi_f}{E_f} + \frac{\phi_m}{E_m} = \frac{\phi_f}{E_f} + \frac{(1-\phi_f)}{E_m}$$



  - short-fiber composite

$$E_c = K_e E_f\phi_f + E_m(1-\phi_f)$$

    - K_e = fiber efficiency factor
      - depends on fiber length [aspect ratio], orientation, interface
    - K_e = 0.1 – 0.6

- strength [fracture]
  - continuous fiber better in tension
    - tensile strength
  - short fiber better in compression or shear
    - flexural strength

Fig 24.18

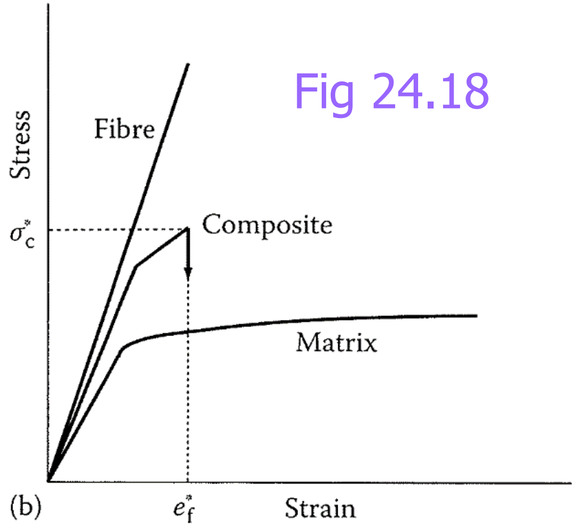


Fig 24.19

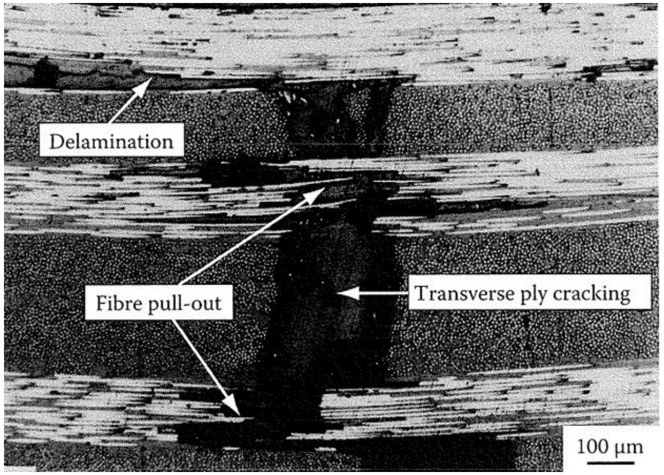
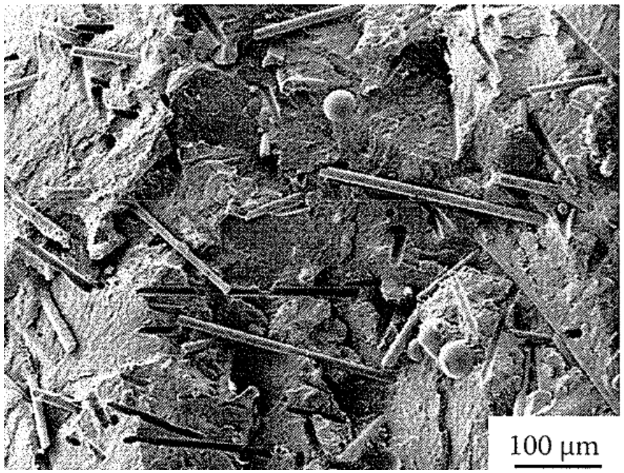


Fig 24.20

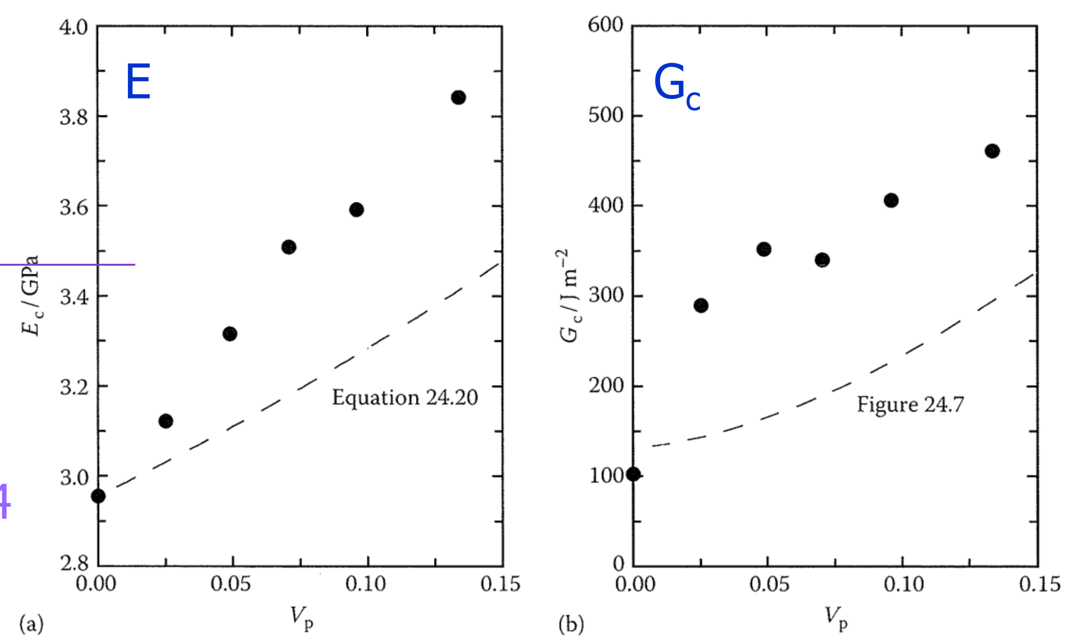


Nanocomposites

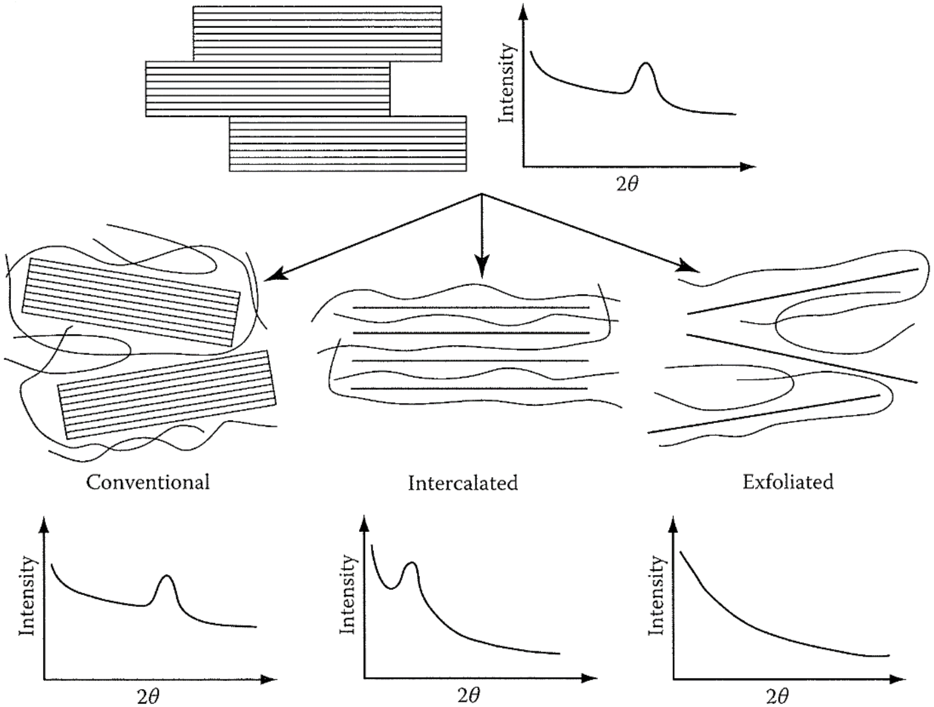
- nanosized (< 100 nm) reinforcement
  - compared to macro- or micro-composites;
    - smaller flaw
    - larger interfacial area
  - higher performance at much lower content (< 5%)
    - modulus, strength, heat resistance, transparency, processability

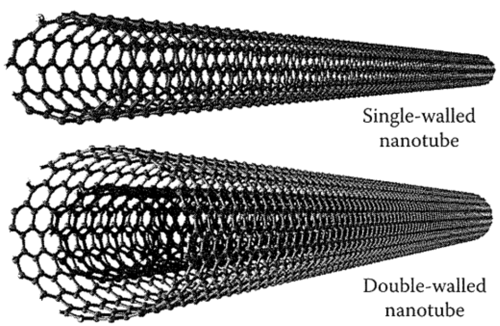
- nanoparticles
  - carbon black
  - nanosilica
  - fullerene

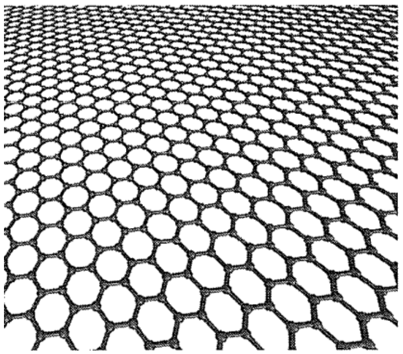
Fig 24.24



- nanoplatelets
  - nanoclay [nanosilicate]
  - graphene
  - graphene nanoplate [GNP]
  - intercalated or exfoliated
  - barrier (and conducting) properties
- nanotubes
  - CNT ~ SWNT, MWNT
  - conducting property







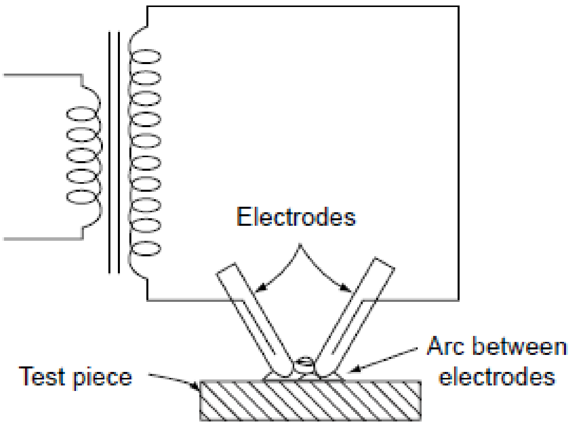
Chapter 25 + Extra 2

Electrical and Other Properties

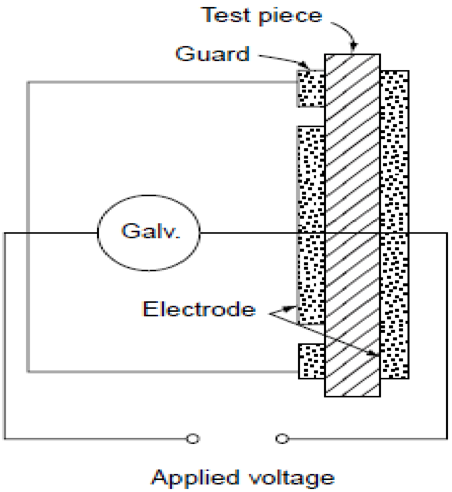
Electrical properties
Permeability
Stability
Optical properties

Electrical properties

- at high electric field
  - electrical failure, treeing
  - arc resistance
    - arcing ~ forming carbonized conducting path across surface
  - No direct relation to chemical structure



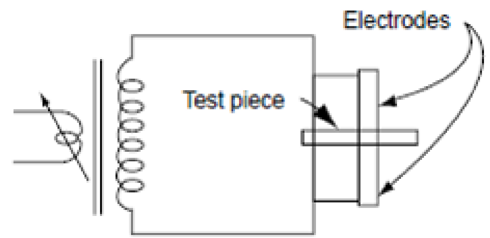
- at low electrical field 1: resistivity
  - Polymers are insulators.
    - resistivity ~ $10^8 - 10^{20}$ Ωcm
  - insulation resistance
    - composite of
      - volume resistivity ~ depends on material
      - surface resistivity ~ depends on surface finish
    - 3-electrode measurement



- at low electrical field 2: dielectric
  - dielectric constant, $\varepsilon = C / C_0$
    - $\varepsilon \propto$ polarizability [α] $\propto$ refractive index
      - non-polar polymers, $\varepsilon = n^2$
      - polar polymers, $\varepsilon > n^2$ ← electronic + orientational (dipole) polarization
    - ε (α and n also) related to chemical structure
      - $\varepsilon = \delta / 7.0$
  - dielectric strength
    - max V that produce dielectric breakdown [leak]
    - depends on thickness, temp, structure
  - dielectric relaxation

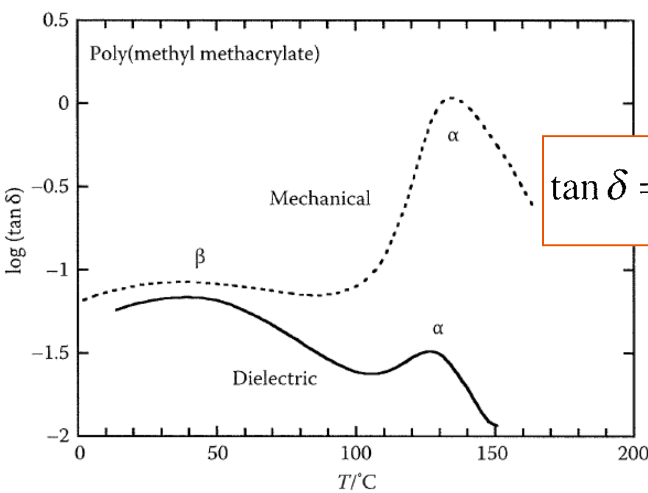
C_0 = capacitance of vacuum
C_{air} = 1.0005

p624



$$\varepsilon^* = \varepsilon' - i\varepsilon''$$

$$\frac{\varepsilon''}{\varepsilon'} = \tan\delta \propto \frac{\text{energy dissipated per cycle}}{\text{energy stored per cycle}}$$



$$\tan\delta = \frac{E_2}{E_1}$$

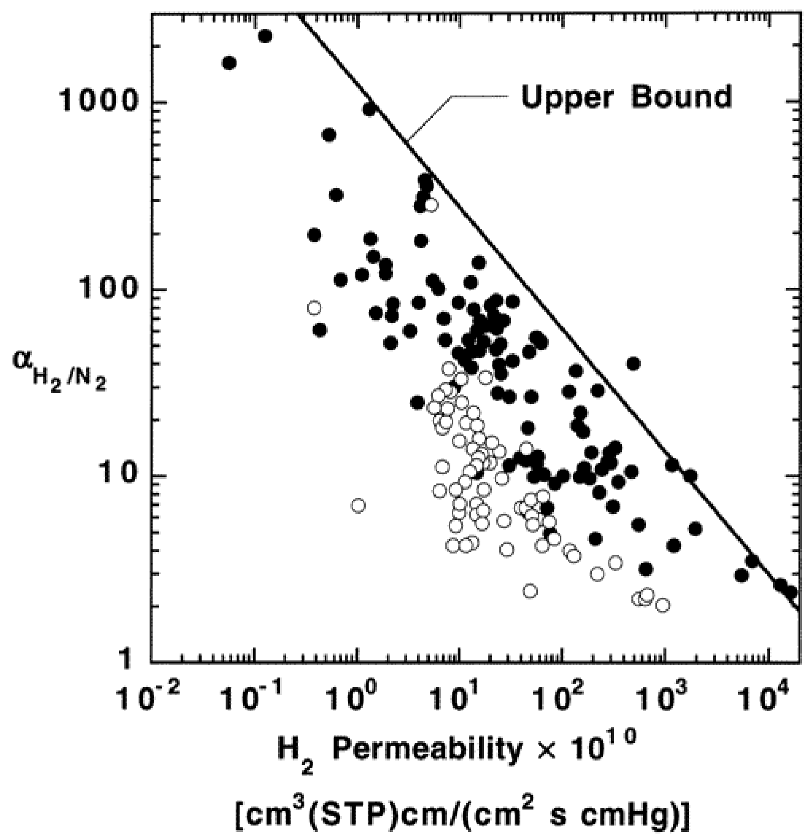
Properties of Polymers

- Material properties
  - chemical properties
    - stability, solubility, permeability, flammability
  - electrical properties
  - optical properties
  - thermal properties
  - mechanical properties
- Processing properties
- Product properties ~ product design

❖'There are <u>no</u> bad materials, but only bad articles.'

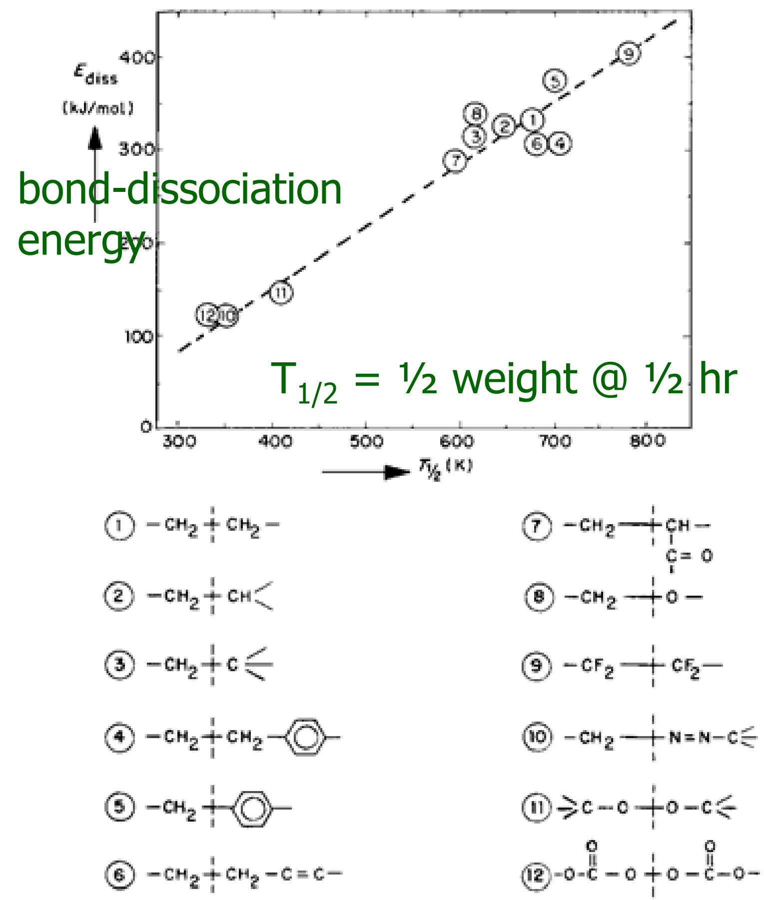
Permeability

- ➢ in membranes ~ permeability
- ➢ in packaging ~ barrier property
- diffusion-solution model
  - absorption-diffusion-desorption
  - P = D S
  - Diffusivity
    - T_g of polymer
    - size of gas
  - Solubility
    - boiling point of gas
    - polarity of gas and polymer [$\Delta\delta$]
- permeability vs selectivity



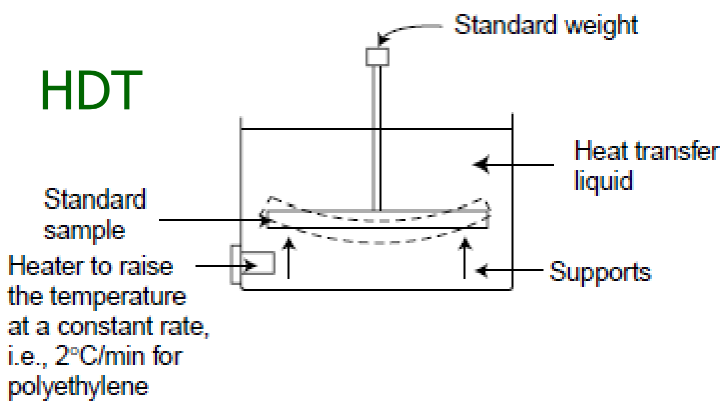
Stability

- thermal stability
  - depends on the dissociation energy of the weakest bond
  - measurement ~ thermal gravitational analysis [TGA]
- light [UV] stability
  - 300 nm ≈ 400 kJ/mol
  - depends on absorption wavelength
- oxidation stability
  - thermal and photochemical
    → related to thermal/light stability
- hydrolysis stability
  - depends on constituent groups
- weatherability [내후성]
- usually covered by addition of stabilizers

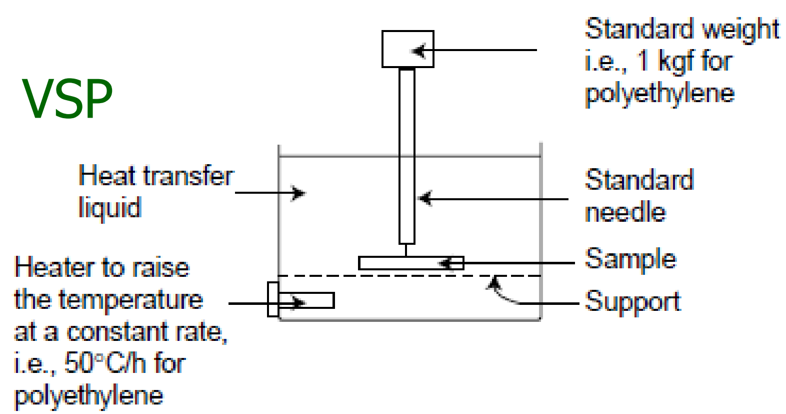


- thermal stability [열안정성] vs heat resistance [내열성]
  - thermal stability ← bond strength
  - heat resistance ← T_g or T_m
  - different property, but related usually
- heat resistance evaluation
  - heat distortion [deflection] temperature [HDT]
    = deflection temperature under load [DTUL]
  - Vicat softening temperature [VSP]

HDT



VSP

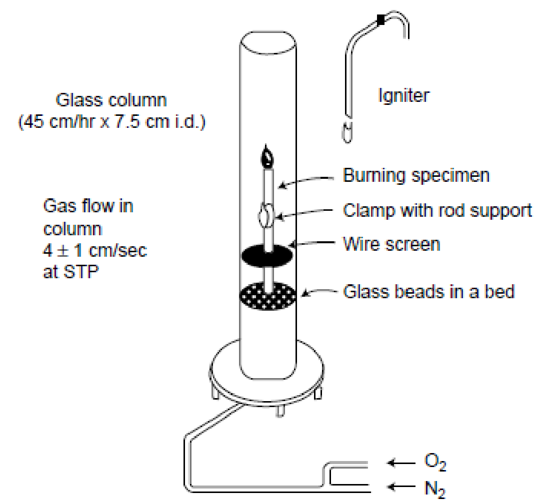


Flammability

- burning = 2-step process
  - pyrolysis [decompose] → gas + char – Q_1
  - combustion [ignite-flame] → combustion product + Q_2
- for fire resistance [flame retardation]
  - high thermal stability
  - low gas (Q_2) and high char ← low H/C (like ring)
  - inhibiting gas like halogen; e.g. PVC
- evaluation ~ limited oxygen index [LOI]

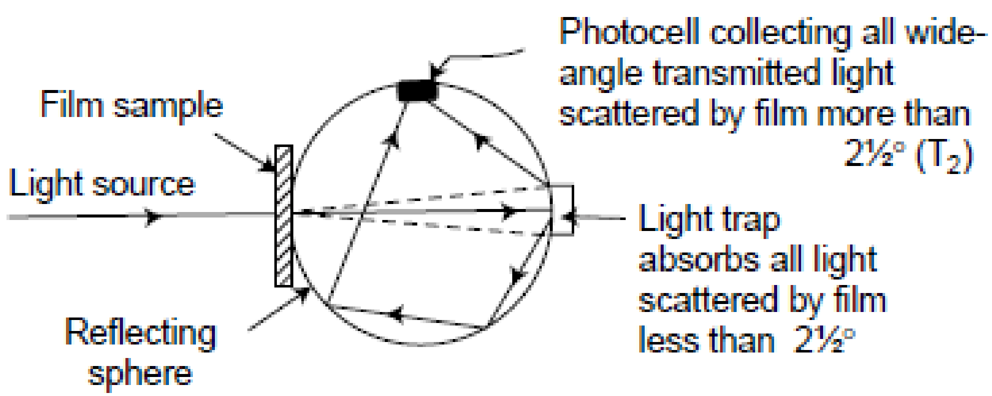
$$\mathrm{LOI} = \frac{[O_2]}{[O_2] + [N_2]} \times 100$$

  - high LOI ~ high flame retardancy [난연성]



Optical properties

- Light upon interaction with polymer
  - reflected ~ gloss ← surface roughness
  - absorbed ~ color ← chromophore
  - refracted, scattered, transmitted ~ clarity ← 2nd phase
- optical clarity
  - transparent < 30% haze < translucent < opaque
    - haze ~ fraction of light 2.5º deviated by scattering



- opaque due to
  - scattering by heterogeneity [different refractive index]
  - larger than wavelength of visible light [340 nm]
    - impurity
    - 2nd phase
    - crystallite
- for a semicrystalline polymer to be transparent
  - small crystallites
  - $\rho_{crystal} \approx \rho_{amorphous}$
  - biaxial orientation
- refractive index
  - optical lenses
  - optical fibers ~ total reflection