Chapter 7. Polymer Additives, Blends and Composites

* *Additives* -- plasticizers, flame retardants, lubricants, stabilizers & fillers
    . PVC : thermally unstable polymer

   > For use as packaging film, blended with plasticizers to reduce T_g and additives to improve its thermal stability

    . PPO (poly(2,6-dimethyl-1,4-phenylene oxide) : high T_g, difficult to process, susceptible to thermal oxidation

   > ==> mPPO (Noryl) : blends of PPO & HIPS to reduce T_g

* *Polymer composites* -- mixtures of a polymer and a reinforcing filler

7.1 Additives

TABLE 7.1 THE U.S. MARKET FOR ADDITIVES[a]

Additive	Millions of lb	%
Fillers	5,750	56.2
Plasticizers	1,770	17.3
Reinforcements	925	9.0
Flame retardants	690	6.7
Colorants	507	5.0
Impact modifiers	140	1.4
Others	448	4.4
Total	10,230	100

[a] 1991 statistics (*Chemical and Engineering News*, August 31, 1992).

7.1.1 Plasticizers

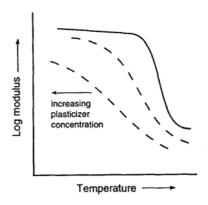   to reduce the modulus of polymer at the use temperature by lowering its T_g

Figure 7.1. Effect of increasing plasticizer concentration on the modulus–temperature plot.

Requirements : partial or complete miscibility with host polymer, low T_g

* T_g of plasticized polymer

    . Kelly-Bueche eq'n <--- T_g의 free volume 이론으로부터 나온 식

$$T_g = \frac{\alpha_1\phi_1 T_{g,1} + \alpha_2(1-\phi_1)T_{g,2}}{\alpha_1\phi_1 + \alpha_2(1-\phi_1)}$$

        1 : diluent, 2 : polymer

        α : thermal expansion coeff.

        ϕ : volume fraction

    . Wood eq'n <--- random copolymer의 T_g 예측 위해 개발된 식인데

        plasticized polymer의 T_g 예측에도 사용

$$T_g = \frac{T_{g,1} + (kT_{g,2} - T_{g,1})w_2}{1 - (1-k)w_2}$$

        k : adjustable parameter

        w : weight fraction

. 열역학에 기초한 식

$$\ln\left(\frac{T_g}{T_{g,1}}\right) = \frac{w_2\ln(T_{g,2}/T_{g,1})}{w_1(T_{g,2}/T_{g,1}) + w_2} \qquad \text{(See Fig. 7.2)}$$

    <--- 원 식 $\ln\left(\dfrac{T_g}{T_{g,1}}\right) = \dfrac{w_2\triangle C_{p,2}\ln(T_{g,2}/T_{g,1})}{w_1\triangle C_{p,1}(T_{g,2}/T_{g,1}) + w_2\triangle C_{p,2}}$ 에서

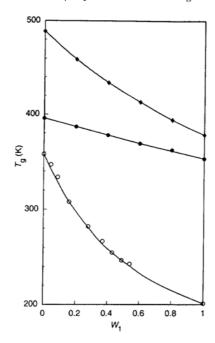   모든 polymers에 대해 $T_g\triangle C_p$가 const.하다고 가정한 경우.

Figure 7.2. DSC-determined values of the glass-transition temperature (T_g) of two polymer blends and plasticized PVC as a function of the weight fraction (W_1) of the low-T_g component (component 1).[2] Data include: (♦) poly(2,6-dimethyl-1,4-phenylene oxide)/polystyrene (1); (●) poly(vinyl chloride)/α-methylstyrene–acrylonitrile–styrene (66/31/3) terpolymer (1); (○) poly(vinyl chloride)/tris-(2-ethylhexyl)trimellitate (TOTM) plasticizer (1). Solid curves represent T_g values predicted by eq. 7.2.

Useful for a wide variety of polymer mixtures, including polymer blends, for which the T_g of both components are roughly comparable, and plasticized polymers, for which the T_gs of the polymer and plasticizer are widely apart.

이 식을 Taylor series expansion (T_gs of polymer & diluent are not too different)하면 다음의 Fox equation이 된다.

. Fox eq'n

$$\frac{1}{T_g} = \frac{w_1}{T_{g,1}} + \frac{w_2}{T_{g,2}}$$

TABLE 7.2 COMMON PLASTICIZERS FOR PVC

Plasticizer Class	Chemical Structure	Examples[a]
Dialkyl phthalate		DOP, DIOP
Aliphatic diester	$RO-\overset{O}{\overset{\|}{C}}-(CH_2)_n-\overset{O}{\overset{\|}{C}}-OR$	DOA
Trialkyl phosphate	$RO-\overset{O}{\overset{\|}{P}}-OR$ $\underset{OR}{\|}$	TCP
Trialkyl trimellitate		TOTM

[a] Common names for plasticizers: DOP, dioctyl phthalate; DIOP, diisoctyl phthalate; DOA, dioctyl adipate; TCP, tricresyl phosphate; and TOTM, trioctyl trimellitate.

- plasticizer *efficiency* : reduction in T_g/wt. of plasticizer

  " *permanence* : susceptibility to migration

- *external* plasticization : compounding a polymer w/ a low T_g compound

  internal " : copolymerizing a polymer w/ the monomer of low T_g polymer

- *antiplasticization* : 소량의 가소제를 사용했을 때 modulus나 strength가 오히려 커지는 것.

7.1.2 Fillers and reinforcements

. fillers : to reduce resin cost, improve processability, dissipate heat, reduce mold shrinkage, minimize electrostatic charging

  ex) wood flour, clay, talc, fly ash, sand, mica & glass beads

. reinforcements : to improve some mechanical property or properties, such as modulus, tensile or tear strength, abrasion resistance, and fatigue strength

ex) carbon black, silica, fibers, woven fabrics, and chopped fibers

TABLE 7.3 PROPERTIES OF FIBERS USED IN COMPOSITE APPLICATIONS

Fiber	Tensile Modulus GPa[a]	Tensile Strength GPa[a]	Density g cm^{-3}
Boron	386	3.4–3.7	2.38–2.66
Graphite			
high-modulus	483–517	1.86	1.97
high-strength	234–255	2.83	1.77
Kevlar-49	138	2.76	1.44
E-glass	72.4	3.45	2.55
S-glass	85.5	4.83	2.49
Steel	407	4.14	7.81

[a] To convert GPa to psi, multiply by 145,000.

7.1.3 Other important additives

PVC 수도 압출 파이프 제조시의 formulation (phr : parts per 100 unit wt. of resin)

TABLE 7.4 TYPICAL FORMULATION OF A PVC RESIN FOR POTABLE-WATER PIPE EXTRUSION

Component	Concentration (phr)
PVC (0.9 to 1.0 IV[a])	100
Processing aids	1–5
Impact modifier	0–10
Calcium carbonate	0–10
Alkyltin or antimony mercaptide	0.3–2.0
Calcium stearate	0.5–1.5
Paraffin wax	0.5–1
Pigment	1–2

[a] Inherent viscosity.

* Stabilizers

Antioxidants

to protect a polymer against the effects of temperature and oxygen

low MW compounds which have high diffusivity, "free-radical scavengers"

UV stabilizers

to absorb UV radiation or deactivate free radicals

cf) UV radiation(wavelength 290-400nm) -- discoloration, embrittlement, degradation

ex) carbon black : good absorption in UV range, abrasion resistance

benzophenone derivatives : protection against yellowing & embrittlement

converting radiation to heat

* Flame retardants

   pyrolysis : thermal degradation in the absence of oxygen

   oxidative pyrolysis(or thermal-oxidative degradation) : thermal degradation

                                                  in the presence of oxygen

   Strategies for effective flame retardants

     1. Inhibition of the vapor-phase combustion of the fuel gases

     2. Alteration of the thermal-degradation pathway by providing a low-energy
       process that promotes solid-state reactions leading to carbonization

     3. Formation of a protective coating to insulate against thermal energy

   ex) organochlorine compounds, organobromine compounds, organophosphorus,
     antimony oxides, boron compounds, and alumina trihydrate

* Biocides

   : a chemical that controls or destroys bacterial growth

   important applications --- latex paints and textiles

   ex) tributyltin oxide, and 10,10'-oxybisphenoxyarsine(OBPA)

   ideal biocides --- toxic to the targeted mocroorganism

                           safe to humans & other animal life

* Processing additives

   : to improve flow during processing

     internal lubricants : reducing melt viscosity

     external lubricants : reducing adhesion between metallic surface & polymer melt

   ex) amides, esters, metallic stearates, waxes, acids, mineral oil, low MW polyolefins

   Internal mold release agents for RIM : organofunctional silicone fluids

* Curing agents

   curing : the process of applying heat (& pressure) to change the properties of rubber
        or thermosetting resins.

   crosslinking of rubber (i.e., vulcanization)   ex) sulfur-containing compounds

   formation of thermoset network   ex) amines in the cure of epoxies

* Colorants

   soluble dyes, inorganic and organic pigments

   classes of dyes for plastics : azo compounds, anthraquinones, xanthenes, and azines

   inorganic pigments : iron oxides, cadmium, chrome yellow, and titanium dioxide

* Heat-distortion & impact modifiers

   Heat-distortion modifiers : to modify the T_g or HDT of a polymer

   Impact modifiers   ex) HIPS, CPE(chlorinated PE), SAN, ABS, EVA, MBS, MABS

* Antistatic agents

   Polymers are poor electrical conductors ---> static electrical charges can form.

   static charge --> dust collection and sparking

     external (or topical) antistats --- by spraying, wiping, or dipping the plastic surface

     internal antistats --- by compounding with the plastic during processing

       ex) hydroscopic additive (internal antistat) -- diffuses to the surface of

the plastic, absorbs moisture and provides a conductive layer of water.

ex) phosphate and fatty acid esters, polyhydric alcohol derivatives, sulfated waxes, ethoxylated and propoxylated aliphatics and aromatics, and quaternary ammonium compounds and amines.

* Blowing agents (or foaming agents)

PS or PUR foam -- to provide insulating properties (rigid foam) or

flexible products (flexible foam) for seat cushions

Physical blowing agents

ex) short-chain hydrocarbons (pentanes, hexanes, heptanes), fluorocarbons (trichloromethane), gases such as nitrogen, carbon dioxide, and air

Chemical blowing agents(CBA) --- solid additives generating gases when decomposed

ex) hydrazine derivatives   Unsaturated polyester is foamed by CBA.

* Compatibilizers

to promote miscibility by reducing interfacial tension

reactive compatibilizers

nonreactive compatibilizers   ex) block or graft copolymers

7.2 Polymer blends and interpenetrating networks

7.2.1 Polymer blends

Blending ---- to reduce the cost of expensive polymer,

to improve the processibility,

or to improve impact resistant

* Thermodynamics

Gibbs free energy of mixing

$$\triangle G_m = \triangle H_m - T \triangle S_m$$

For complete miscibility, two conditions are necessary,

i) $\triangle G_m < 0$

ii) $\left(\dfrac{\partial^2 \triangle G_m}{\partial \phi_2^2} \right)_{p,T} > 0$

(See Figs. 3.9-10 and 7.3)

cloud-point curve : a curve obtained by determining T at which a blend composition

scatters light due to phase separation over the entire range

(See Fig. 7.4)   LCST shifts upward with MW ↓

. Scott eq'n for a polymer blend

$$\triangle G_m = \left(\frac{RTV}{V_r} \right) \left[\left(\frac{\phi_1}{x_1} \right) \ln \phi_1 + \left(\frac{\phi_2}{x_2} \right) \ln \phi_2 + \chi_{12} \phi_1 \phi_2 \right]$$

where V_r : molar volume of repeating unit

x_i : degree of polymerization

x_i of high MW polymers is large ---> $\triangle S_m$ is small ---> miscibility $\downarrow$ (Fig. 7.5)

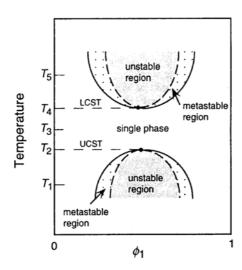$\chi_{12} \downarrow$ ---> LCST $\uparrow$ $\therefore$ miscibility window widens   (Fig. 7.6)

Figure 7.3. Idealized liquid–liquid phase diagram for a polymer blend. The solid curve indicates a binodal, while the broken curve represents a spinodal separating the unstable and metastable regions. The upper critical (UCST) and lower critical solution (LCST) temperatures are located at T_2 and T_4, respectively.
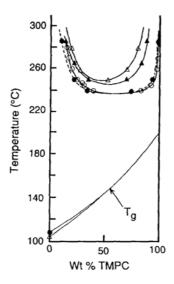

Figure 7.4. Phase behavior of blends of tetramethylbisphenol–A polycarbonate (TMPC) and polystyrene (PS). Bottom curve shows the dependence of T_g on the wt % of TMPC in the homogeneous blend below the lower critical solution temperature (LCST), which is near 240°C for high-molecular-weight PS. The top curves represent the phase diagrams (i.e., cloud-point curves) for TMPC/PS blends illustrating LCST behavior. The LCST shifts upward in temperature with decreasing PS molecular weight, and the cloud-point curve becomes skewed toward the low-molecular-weight component, TMPC ($\overline{M}_w = 41,000$). In contrast, there is only a small effect of PS molecular weight on the T_g–composition curve for the homogeneous blend at temperatures below the LCST. The effect of molecular weight is seen as a divergence of the T_g–composition curve at low TMPC composition due to the small effect of molecular weight on the T_g of the PS component. Molecular weight ($\overline{M}_w$) of PS: ($\triangle$), 42,000; ($\blacktriangle$), 59,000; ($\bigcirc$), 180,000; and ($\bullet$), 320,000. (Adapted from ref. 3 with permission of the publisher.)
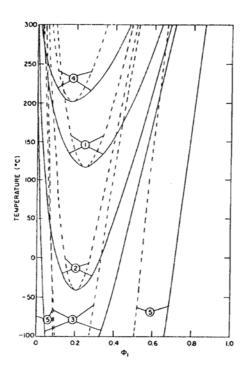
Figure 7.5. Effect of molecular weight of polymer 1 (curve 1, 30,000 molecular weight; curve 2, 50,000 molecular weight; and curve 3, 80,000 molecular weight) and polymer 2 (curve 4, 3000 molecular weight; curve 5, 6000 molecular weight) on the binodal (solid line) and spinodal (broken line) predicted by a modified version of the Flory equation-of-state theory. (Adapted with permission from ref. 5. Copyright 1977 American Chemical Society.)
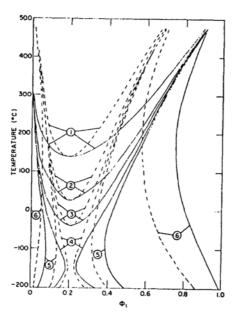

Figure 7.6. Effect of the value of the interaction energy on the binodal (solid line) and spinodal (broken line) predicted by a modified version of the Flory equation of state theory. Values of X_{12} (cal cm^{-3}): curve 1, -0.050; curve 2, -0.100; curve 3, 0; curve 4, 0.005; curve 5, 0.010; and curve 6, 0.100). (Adapted with permission from ref. 5. Copyright 1973 American Chemical Society).

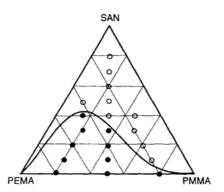Blends containing three-component polymers --> triangular diagram

Figure 7.7. Triangular phase diagram for ternary blends of poly(methyl methacrylate) (PMMA), poly(ethyl methacrylate) (PEMA), and poly(styrene-*co*-acrylonitrile (SAN). Filled circles (●) represent blend compositions that are phase separated as indicated by the detection of multiple T_g's. Open circles (○) represent homogeneous compositions. (Adapted from ref. 6 with permission of the publisher).

Examples of miscible polymer blends

TABLE 7.5 EXAMPLES OF MISCIBLE POLYMER BLENDS

Polymer 1	Polymer 2
Polystyrene	Poly(2,6-dimethyl-1,4-phenylene oxide)
	Poly(methyl vinyl ether)
	Tetramethylbisphenol-A polycarbonate
Poly(vinyl chloride)	Polycaprolactone
	Nitrile rubber[a]
Poly(vinylidene fluoride)	Poly(ethyl methacrylate)
	Poly(methyl methacrylate)

[a] For limited acrylonitrile content of the copolymer.

7.2.2 Toughened plastics and phase-separated blends

Impact strength of brittle plastics can be improved by incorporating a rubbery phase in the form of small dispersed particles.

(See Fig. 7.10)

Crazes are oriented perpendicular to tensile direction but fibrils are aligned in tensile direction.

HIPS & ABS are blended with other polymers to improve impact strength.

ex) ABS-modified PC, ABS-modified PVC, HIPS-modified PPO

Other impact modifiers : chlorinated polyethylene (CPE), ethylene-vinyl acetate (EVA), MMA-butadiene-styrene (MBS), MMA-ABS (MABS)

Macrophase-separated blends ← compatibilizing agents, such as block copolymers

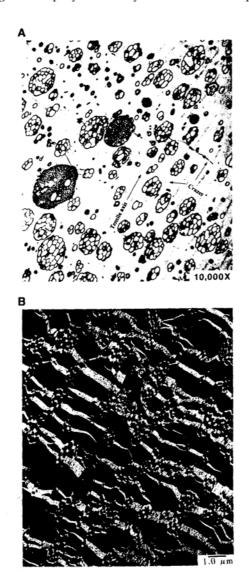containing blend polymers may be useful to improve interfacial coupling.

Figure 7.10. Transmission electron micrographs of high-impact polystyrene (HIPS). **A.** Stained microtomed section. **B.** In situ crazing using specimen deformation cartridge. (Courtesy of R. C. Cieslinski, The Dow Chemical Company.)

7.2.3 Interpenetrating neworks

IPNs --- combinations of two or more polymers in network form

advantages of both polymer blends and network polymers

As the crosslinking process restricts phase separation, the sizes of the dispersed phase are much smaller (10-100nm).

Polymers used in the preparation of IPNs : PUR, PS, PEA, PMMA, EPDM

. Types of IPN preparation

Sequential IPN -- is formed by first crosslinking one polymer. The network is swollen with a mixture of a monomer of the second polymer and a crosslinking agent. The swollen film is then heated to initiate the polymerization and to crosslink

the second network   (See Fig. 7.11)

Semi-IPN -- is prepared by only a single network of the initial polymer, in the case
that no crosslinking agent is used for the second polymer in the formation of a
sequential IPN.

Gradient IPN -- is prepared by polymerizing the second monomer before equilibrium
sorption occurs.

Simultaneous IPN -- is formed when both polymers are synthesized and crosslinked
simultaneously.

. Applications : toughened plastics, ion-exchange resins, pressure-sensitive adhesives,
soft contact lenses, controlled release of drugs, membranes, and
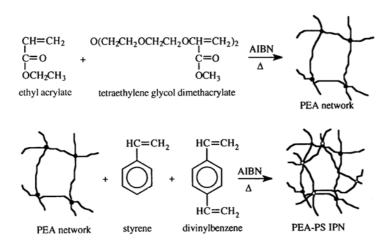sound- and vibration-damping material

Figure 7.11. Illustration of the preparation of a sequential interpenetrating net-
work (IPN) formed by first forming a poly(ethyl acrylate) (PEA) network by free-rad-
ical polymerization of ethyl acrylate with a difunctional monomer, tetraethylene
glycol dimethacrylate, using AIBN as an initiator. The PEA network is then
swollen with styrene and with the difunctional monomer, divinylbenzene, which are
then polymerized to form an interpenetrating polystyrene network. The resulting
IPN may be termed *cross*-poly(ethyl acrylate)-*inter-cross*-polystyrene, where the
connectives *cross* and *inter* indicate crosslinked and interpenetrating, respectively.
[Adapted from L. W. Barrett and L. H. Sperling, *Trends in Polymer Science*, **1**, 45
(1993) with permission of the publisher.]

7.3 Polymer composites

Applications : automotive, marine & construction

(See Table 7.6)

Fibers for composites : carbon, graphite, glass, aromatic polyamide

Composite matrices : thermosets, thermoplastics, carbon, ceramic or metallic matrices

epoxies : inexpensive, easy to process, brittle, high moisture absorption

PSF : high impact strength, susceptible to solvent attack,
low dimensional stability under load

PEEK : solvent resistance, impact strength

PI --- thermosets : easy to process, higher heat resistance

--- thermoplastics : greater toughness

(See Table 7.7)

Factors affecting the mechanical properties of composites

: size, type, concentration, dispersion of filler, extent of interfacial adhesion, properties of matrix

TABLE 7.6   APPLICATIONS FOR POLYMER COMPOSITES[a]

Industry	Millions of lb	Wt %
Aerospace and military	41.1	1.54
Appliances and business	153.3	5.75
Construction	495.4	18.6
Consumer products	170.9	6.41
Corrosion-resistant equipment	350.8	13.2
Electrical and electronics	234.8	8.81
Marine	432.8	16.2
Transportation	703.6	26.4
Other	82.2	3.09
Total	2664.9	100

[a] 1989 statistics; *Chemical and Engineering News*, September 25, 1989, p. 29.

TABLE 7.7   PROPERTIES OF COMPOSITE MATRICES

Property	Thermosets		Thermoplastics	
	Epoxy	PI[a]	PSF[b]	PEEK[c]
Modulus, GPa	2.8–4.2	3.2	2.5	3.9
Tensile strength, MPa	55–130	56	70	91
Compressive strength, MPa	140	187	96	—
Density, g cm⁻³	1.15–1.2	1.43	1.24	1.32
Thermal expansion coefficient, 10^{-6} per °C	45–65	50	—	47
Thermal conductivity, W (m K)⁻¹	0.17–0.21	0.36	—	0.25
T_g, °C	130–250	370	185	1.43

[a] PI, thermosetting polyimide.
[b] PSF, bisphenol-A polysulfone (Udel P1700).
[c] PEEK, polyetheretherketone; ca. 35% crystalline with T_m of 334°C.

7.3.1 Mechanical properties

* Modulus

Principal function of reinforcing fillers : to increase the modulus & HDT

Modified Halpin-Tsai equation (modulus of glassy-polymer composite with rigid filler)

$$\frac{M}{M_m} = \frac{1 + AB\phi_f}{1 - B\psi\phi_f}$$

where M : modulus(tensile, shear, or bulk) of composite

M_m : modulus of unreinforced matrix polymer

A : constant related to filler geometry and Poisson's ratio of matrix

$2(L/D)$ for E_{11} : longitudinal Young's modulus

0.5 for $E_{22}, E_{33}, G_{23}, G_{32}$: transverse Young's or shear modulus

1.0 for $G_{12}, G_{21}, G_{13}, G_{31}$: longitudinal shear modulus

$0.$ for K   : bulk modulus

ψ : parameter depending on maximum packing volume fraction

$$\simeq 1 + \left(-\frac{1 - \phi_{max}}{\phi_{max}} \right) \phi_f$$

B : function of A and relative moduli of filler and matrix

$$B = \frac{(M_f/M_m) - 1}{(M_f/M_m) + A}$$

For uniaxially oriented fibers,

Longitudinal modulus : $E_L = (1 - \phi_f)E_m + \phi_f E_f$

Transverse modulus : $\dfrac{E_T}{E_m} = \dfrac{1 + AB\phi_f}{1 - B\psi\phi_f}$

where A is equal to twice the aspect ratio (L/D) for uniaxially oriented fibers.

* Strength

depends on many factors, such as the adhesive strength of interphase.

may be reduced by the presence of water adsorbed on the filler surface.

   "   "   by thermal stresses resulting from a mismatch of thermal expansion
        coefficients.   (polymer -- high, filler -- low)

Ultimate strength of a particulate-filled composite (proposed by Schrager)

$$\sigma_u = \sigma_m \exp(-r\phi_f)$$

where r : interfacial factor (typically 2.66 for many composites)

For uniaxially oriented fibers,

maximum strength : $\sigma_L = (1 - \phi_f)\sigma_m + \phi_f \sigma_f$

minimum strength : $\sigma_T \approx 0.5\,\sigma_m$

Example of fiber-reinforced polymer composites --->   Table 7.8

TABLE 7.8   PROPERTIES OF PEEK COMPOSITES

Property	PEEK	30% Carbon Fiber	30% Glass Fiber
Heat-deflection temperature °C at 1.82 MPa (264 psi)	148	300	300
Tensile strength (MPa) at 23°C	91.0	146.0	140.0
Flexural modulus (GPa) at 23°C	3.89	15.5	8.0

* Interfacial adhesion and coupling agents
    Coupling agent bridging the matrix-filler boundary
    ex) low MW organofunctional silanes (or titanates)   (See Table 7.9)
        . silanes : organic-inorganic additives
                        --- one group for bonding with mineral surfaces
                        --- the other for bonding with matrix resin
    effect of coupling agents on dry and wet flexural strength   (See Table 7.10)
    Modification or functionalization of the fiber surface ---> improves interfacial adhesion
    ex) interfacial adhesion of UHMWPE <--- plasma treatment in pure oxygen

TABLE 7.9   COMMON COUPLING AGENTS

Type	Representative Structure
Vinyl silane	$CH_2=CH-Si(OCH_3)_3$
Epoxy silane	$H_2C-CHCH_2OCH_2CH_2CH_2CH_2-Si(OCH_3)_3$ (epoxide O)
Primary amine silane	$H_2NCH_2CH_2CH_2-Si(OC_2H_5)_3$
Methacrylate	$H_2C=C-\overset{CH_3}{\underset{O}{C}}-O-CH_2CH_2CH_2-Si(OCH_3)_3$
Titanate	$\left(H_2C=C-\overset{CH_3}{\underset{O}{C}}-O\right)_3TiOCH(CH_3)_2$

TABLE 7.10   FLEXURAL STRENGTH OF A GLASS-REINFORCED POLYESTER

	Flexural Strength, GPa[a]	
Coupling Agent	Dry	2-Hour Boil
None	0.38	0.23
Vinyl silane	0.46	0.41
Methacrylate silane	0.62	0.59

[a] To convert GPa to psi, multiply by 145,000.

* Dynamic-mechanical properties
    Takayanagi's "equivalent model"
    : Dynamic-mechanical properties of any two-phase morphology, such as an immiscible
    blend, composite, laminate, or semicrystalline polymer, can be modeled as a series
    and parallel combination of contributions from the individual components.
                                (Fig. 7.12)
    Final relationship for the dynamic modulus of the composite in Fig. 7.13,

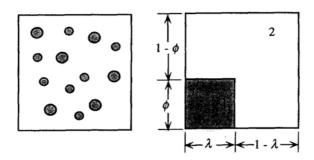$$\frac{1}{E} = \frac{1-\phi}{E_2} + \frac{\phi}{\lambda E_1 + (1-\lambda)E_2}$$

Figure 7.12. Equivalent model of Takayanagi.[10] An idealized two-phase system consisting of a dispersed phase (shaded regions) dispersed in a matrix of component 1 is shown at the left. This composite structure can be modeled as a unit cube ($1 \times 1 \times 1$) (pictured at right) with the dispersed phase (component 1) having dimensions of $\phi \times \lambda \times 1$ (i.e., the volume fraction is $\phi\lambda$).
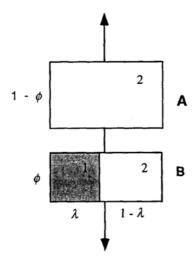

Figure 7.13. Parallel and series elements of equivalent model illustrated in Figure 7.12. Elements A and B are in series combination to the applied strain (arrows). Element B is composed of two elements (dispersed phase and matrix) in parallel.

7.3.2 Composite fabrication

Composite fabrication techniques : compression molding, resin transfer molding(RTM),

SMC, BMC, preform molding, injection molding, & spray-up

For structural applications ---> filament winding & pultrusion

* Filament winding

(See Fig. 7.14)

* Pultrusion

(See Fig. 7.15)

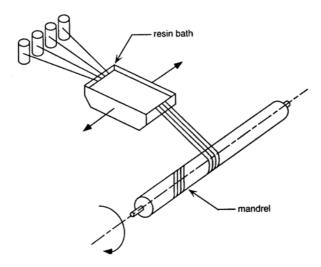On-line cure step ==> continuous process ==> suitable for commercial production

Figure 7.14. Filament-winding operation. (Adapted from R. C. Hayes, in the *Concise Encyclopedia of Polymer Science and Engineering*, J. I. Kroschwitz, ed. Copyright ©1990 by John Wiley & Sons. Reprinted by permission of John Wiley & Sons, Inc.)
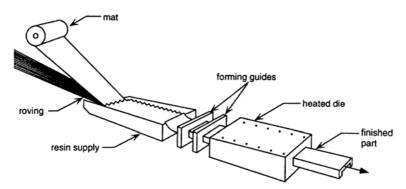

Figure 7.15. Pultrusion line. (Adapted from D. Evans, in the *Concise Encyclopedia of Polymer Science and Engineering*, J. I. Kroschwitz, ed. Copyright ©1990 by John Wiley & Sons. Reprinted by permission of John Wiley & Sons, Inc.)