CHAPTER 14

Composites

The hull of this sailing yacht is a sandwich structure, with the outer skin made of an epoxy resin reinforced with Kevlar fibers. The core is an expanded polyvinyl chloride foam. This composite material system is light weight while providing high impact strength and tear resistance. In addition, the sail is not mere cloth but a fiber-reinforced Mylar film. (Courtesy of Allied Signal.)

Figure 14-1 *Glass fibers to be used for reinforcement in a fiberglass composite. (Courtesy of Owens-Corning Fiberglas Corporation)*

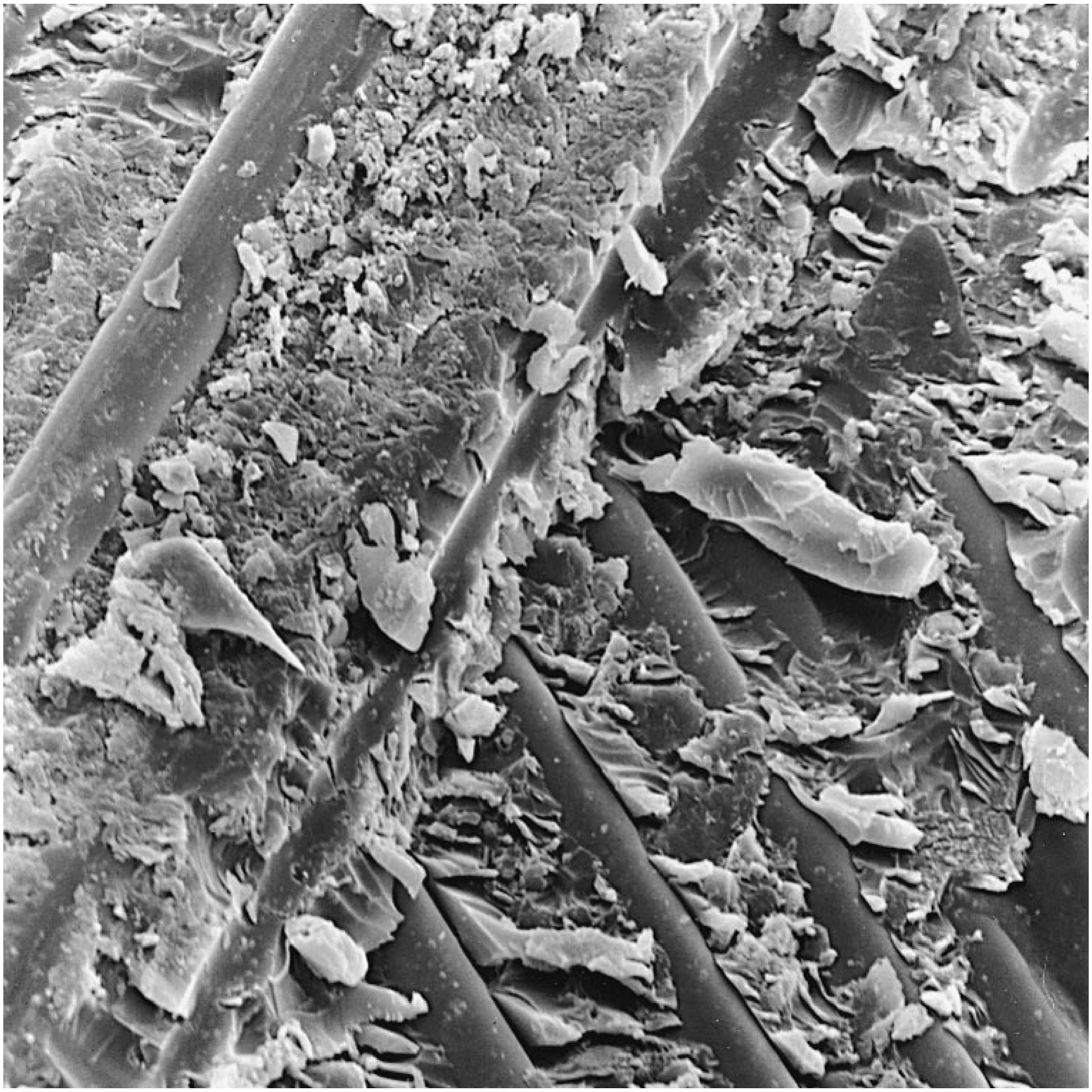


Figure 14-2 *The glass fiber reinforcement in a fiberglass composite is clearly seen in a scanning electron microscope image of a fracture surface. (Courtesy of Owens-Corning Fiberglas Corporation)*

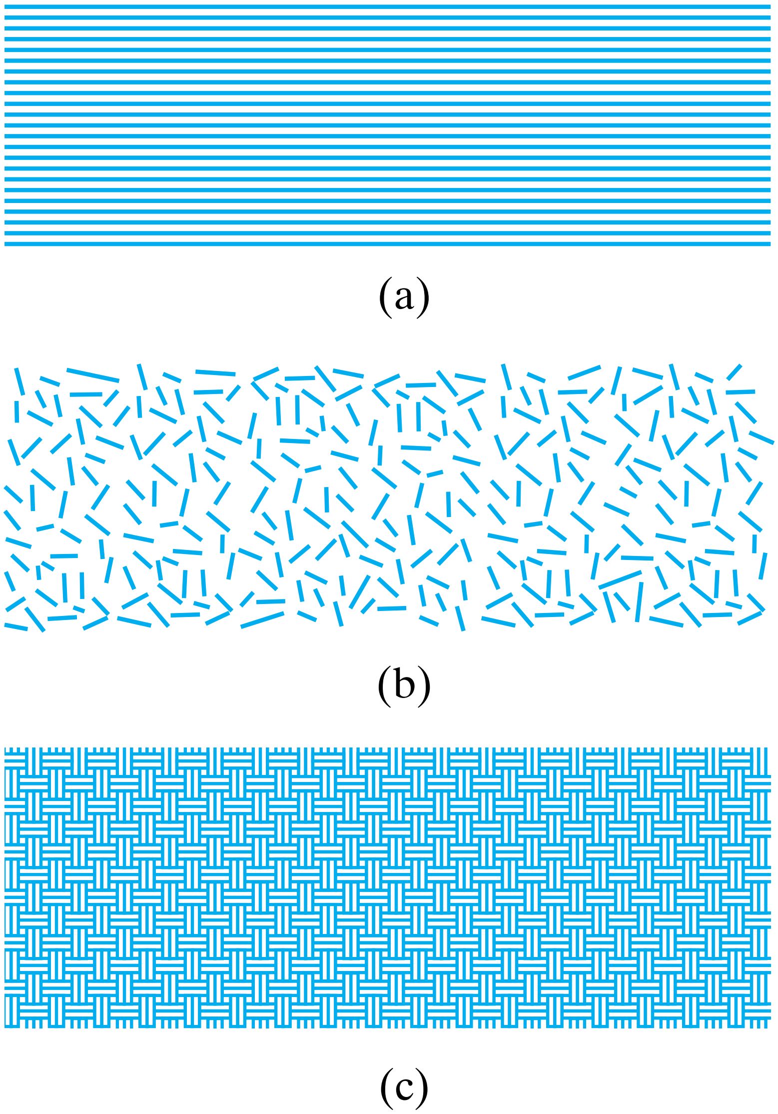
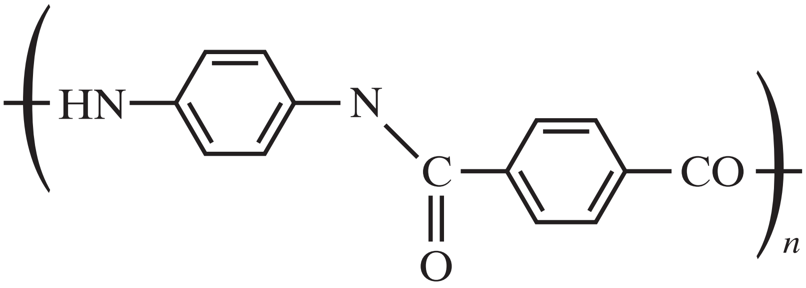


Figure 14-3 *Three common fiber configurations for composite reinforcement are (a) continuous fibers, (b) discrete (or chopped) fibers, and (c) woven fabric, which is used to make a laminated structure.*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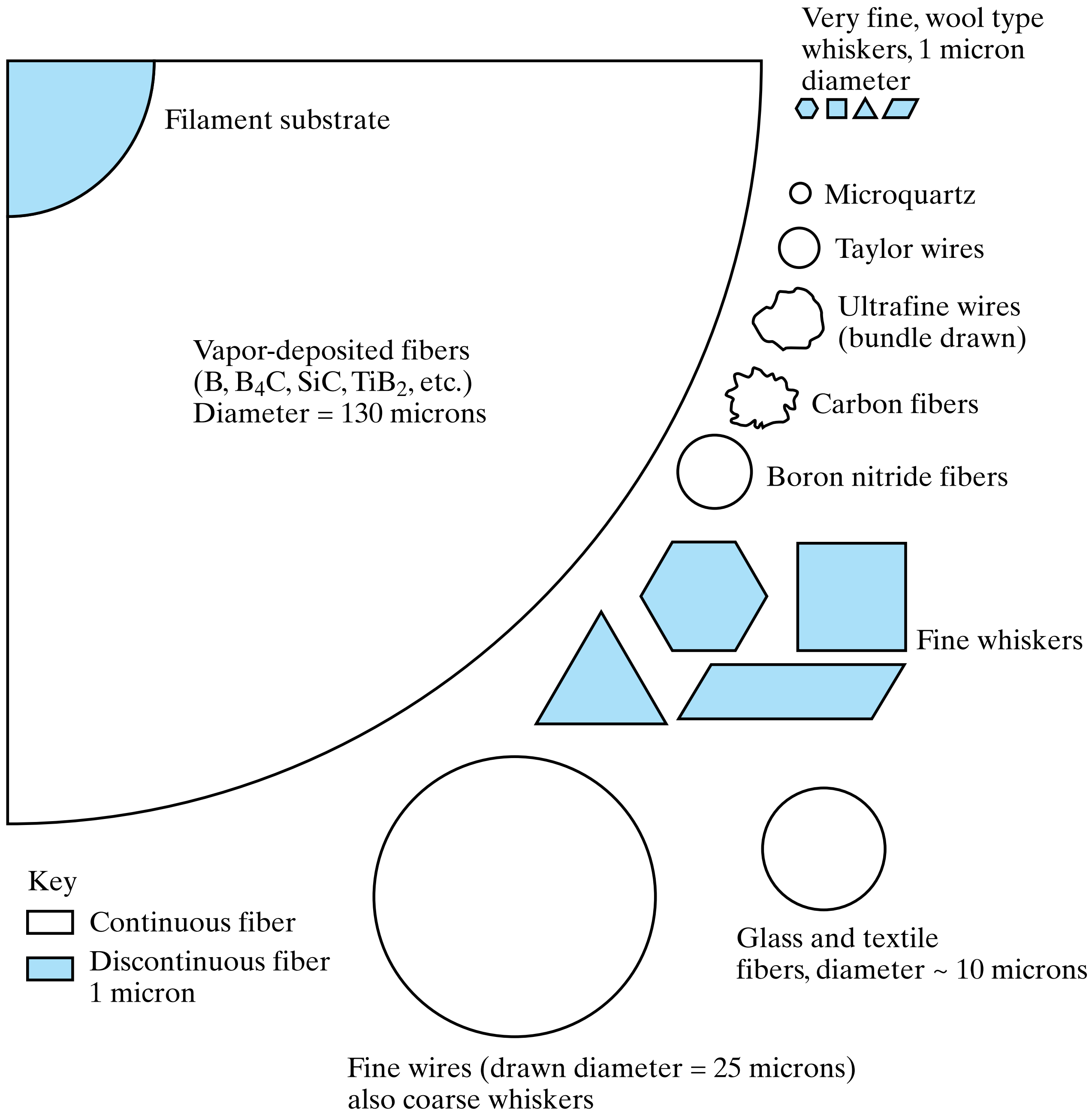
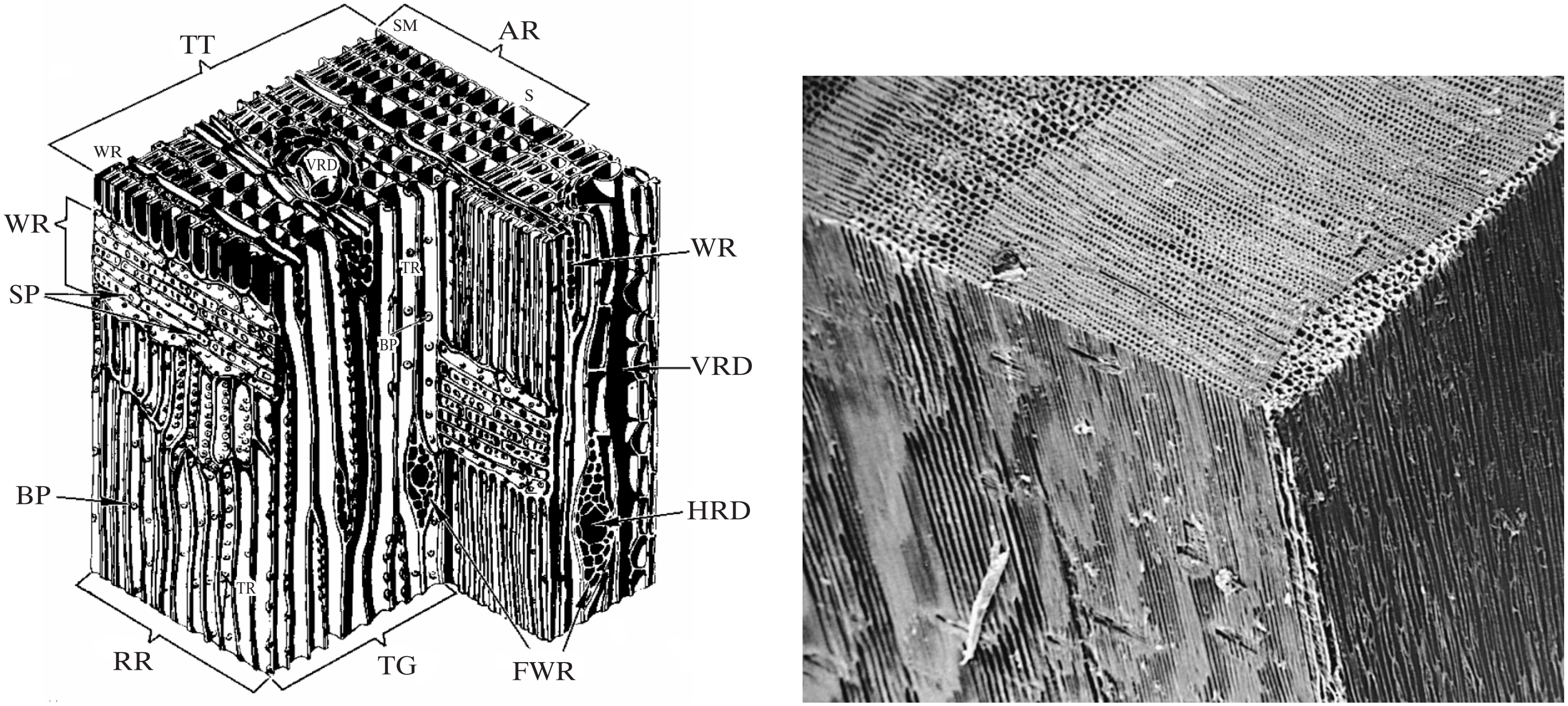


Figure 14-4 *Relative cross-sectional areas and shapes of a wide variety of reinforcing fibers. (After L. J. Broutman and R. H. Krock, Eds.,* Modern Composite Materials, *Addison-Wesley Publishing Co., Inc., Reading, Mass., 1967, Chapter 14.)*



(a) (b)

Figure 14-5 *(a) Schematic of the microstructure of wood. In this case, a softwood is illustrated. The structural features are TT, cross-sectional face; RR, radial face; TG, tangential face; AR, annual ring; S, early (spring) wood; SM, late (summer) wood; WR, wood ray; FWR, fusiform wood ray; VRD, vertical resin duct; HRD, horizontal resin duct; BP, bordered pit; SP, simple pit; and TR, tracheids. (b) A scanning electron micrograph showing the microstructure of southern pine (at 45×). (Courtesy of U.S. Dept. of Agriculture, Forest Service, Forest Products Laboratory, Madison, Wis.)*

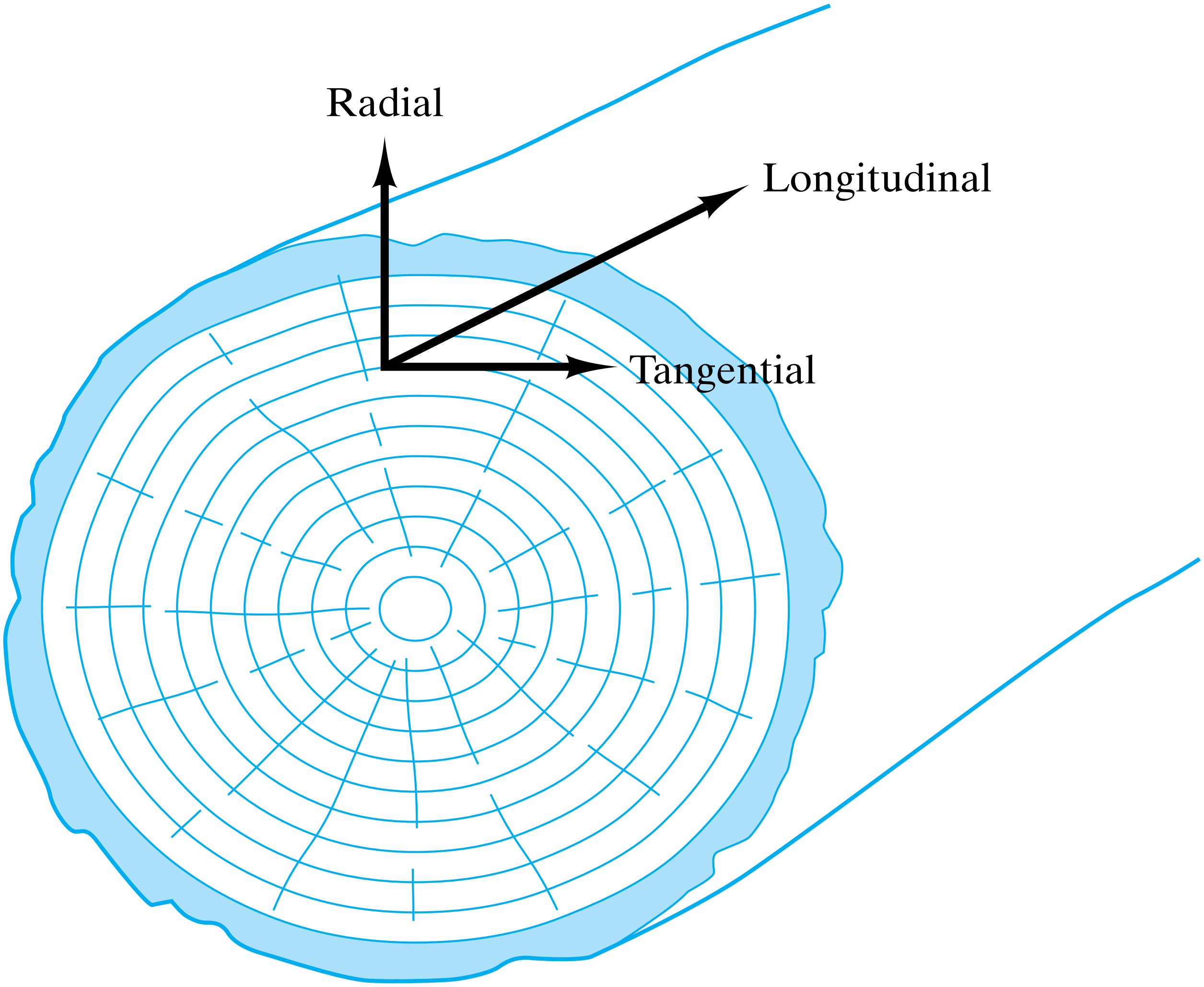
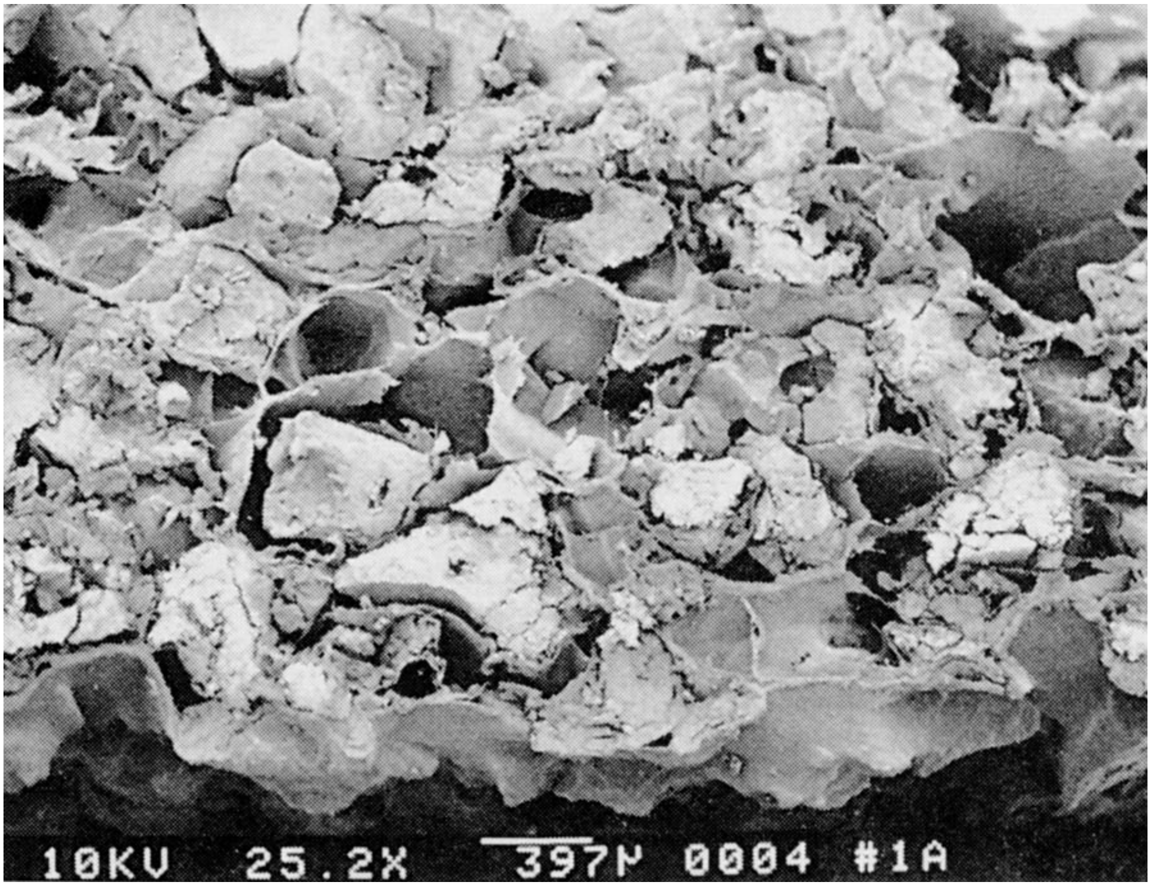


Figure 14-6 *Anisotropic macrostructure of wood.*

(Courtesy of Zimmer Corporation)



Scanning electron micoscope image of the aggregate composite composed of ceramic (hydroxyapatite plus tricalcium phosphate) granules in a polymeric (collagen) matrix. The image shows collagen as a darker gray. (From J.P. McIntyre, J.F. Shackelford, M.W. Chapman, and R.R. Pool, Bull. Amer. Ceram. Soc. 70 1499 (1991))

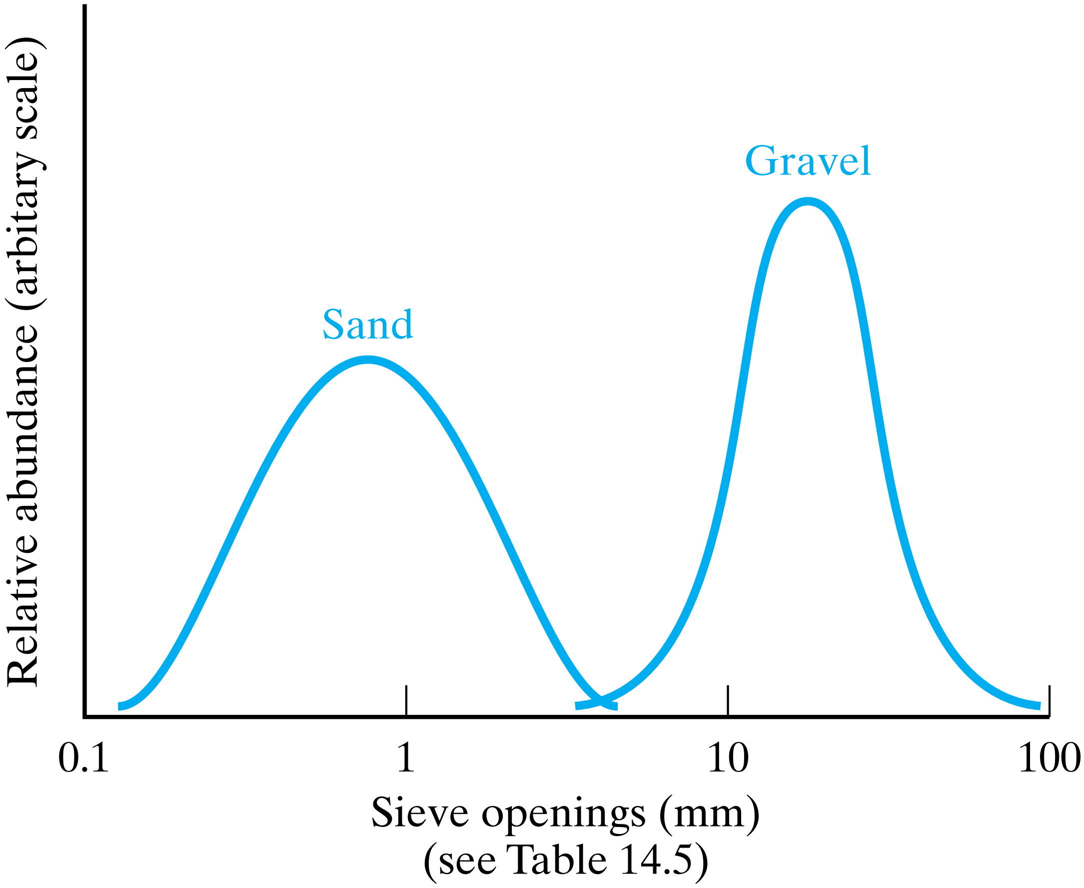


Figure 14-7 *Typical particle size distribution for aggregate in concrete. (Note the logarithmic scale for particle sizes screened through the sieve openings.)*

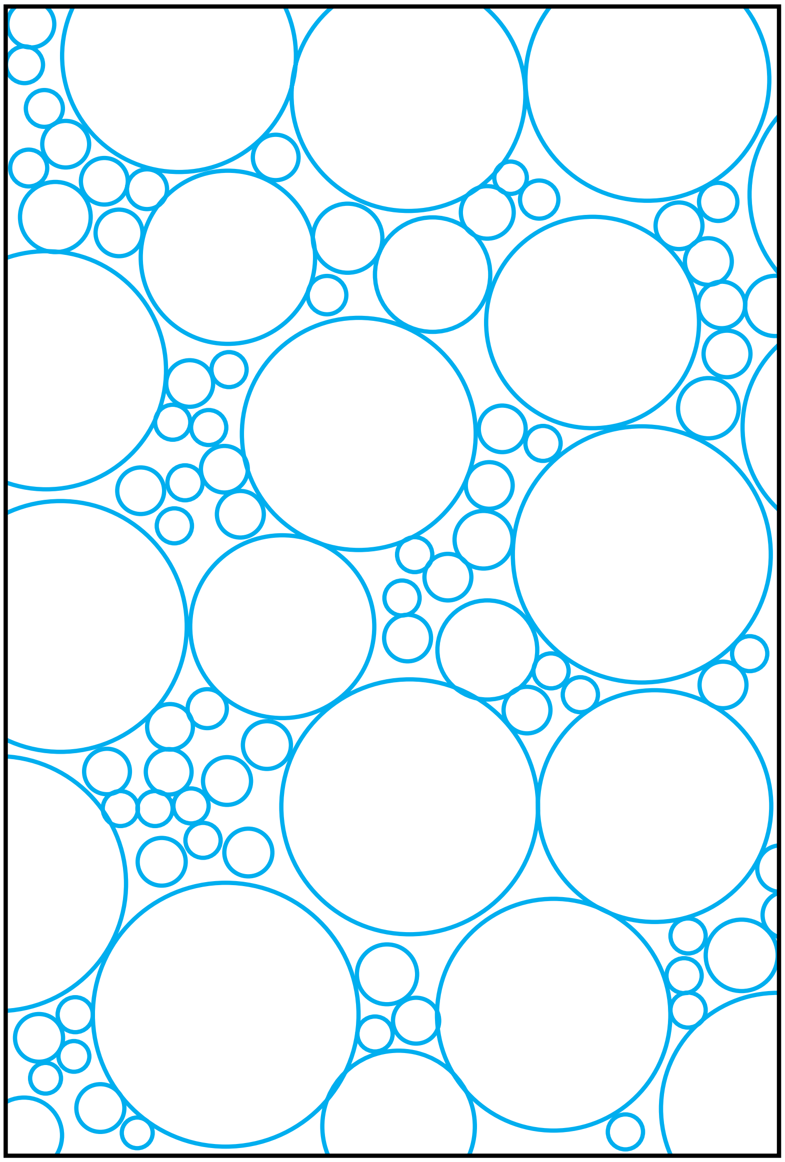
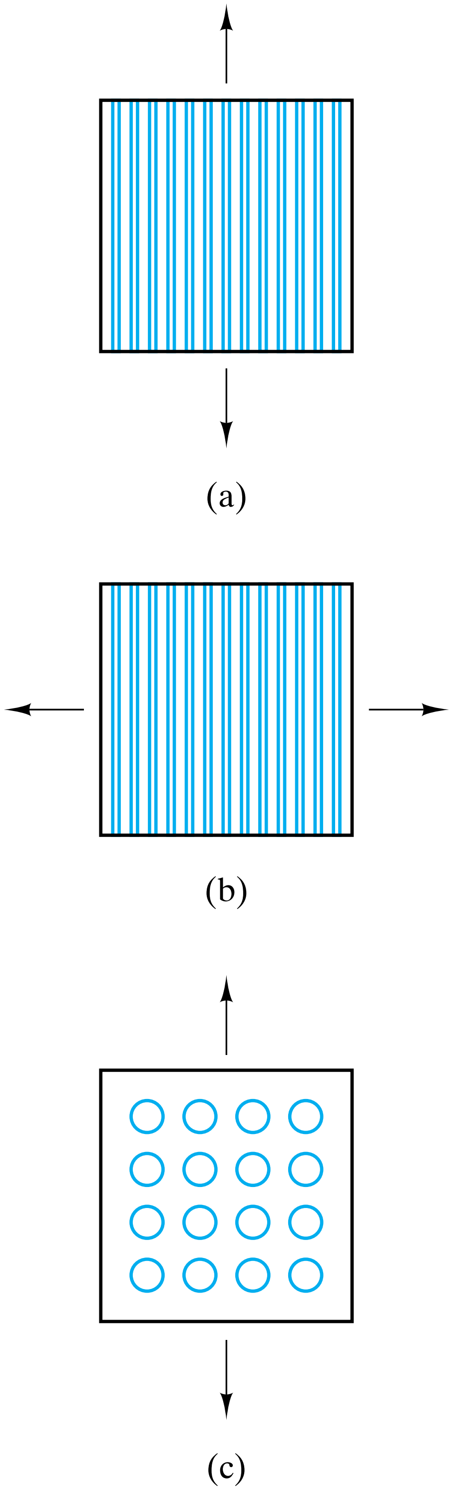


Figure 14-8 *Filling the volume of concrete with aggregate is aided by a wide particle size distribution. The smaller particles fill spaces between larger ones. This view is, of course, a two-dimensional schematic.*

Figure 14-9 *Three idealized composite geometries: (a) a direction parallel to continuous fibers in a matrix, (b) a direction perpendicular to continuous fibers in a matrix, and (c) a direction relative to a uniformly dispersed aggregate composite.*



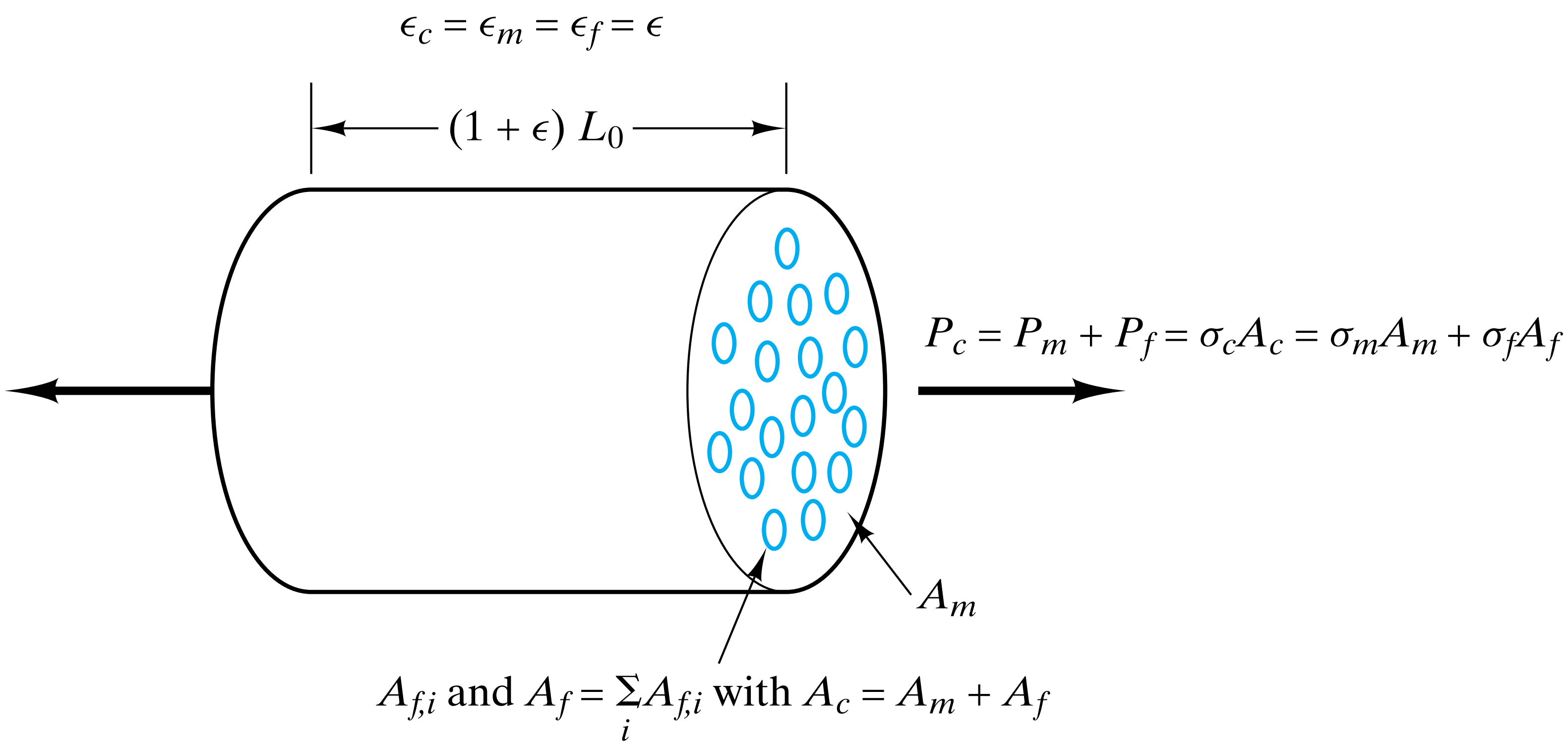


Figure 14-10 *Uniaxial stressing of a composite with continuous fiber reinforcement. The load is parallel to the reinforcing fibers. The terms in Equations 14.2 to 14.4 are illustrated.*

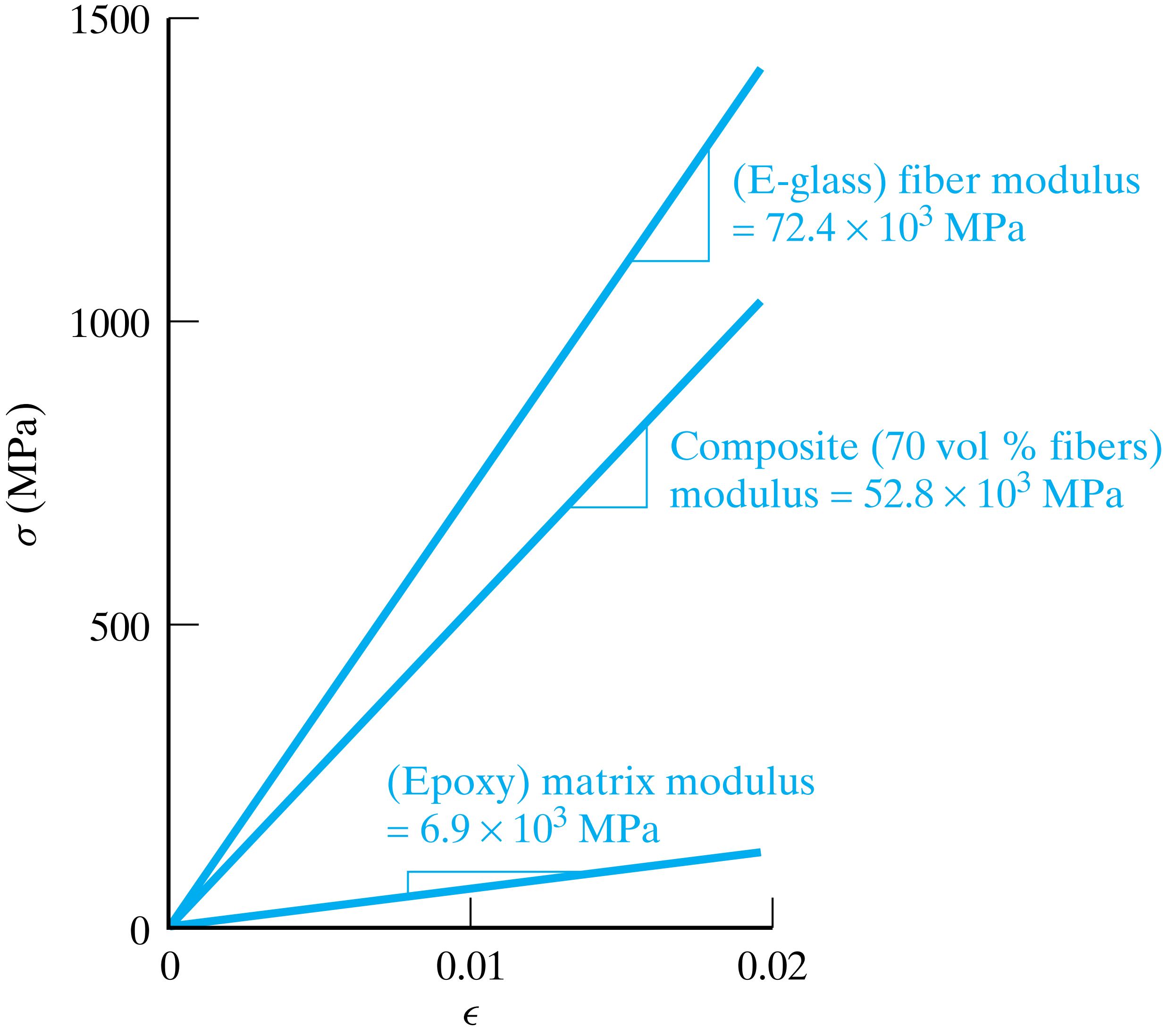


Figure 14-11 *Simple stress–strain plots for a composite and its fiber and matrix components. The slope of each plot gives the modulus of elasticity. The composite modulus is given by Equation 14.7.*

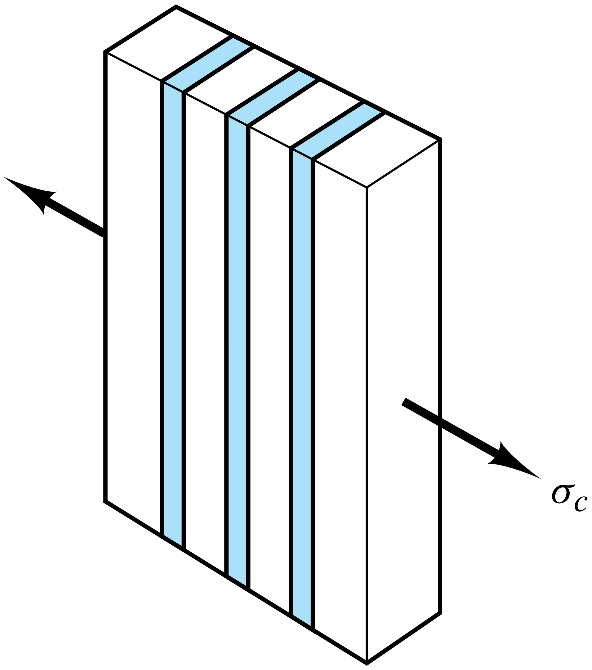


Figure 14-12 *Uniaxial loading of a composite perpendicular to the fiber reinforcement can be simply represented by this slab.*

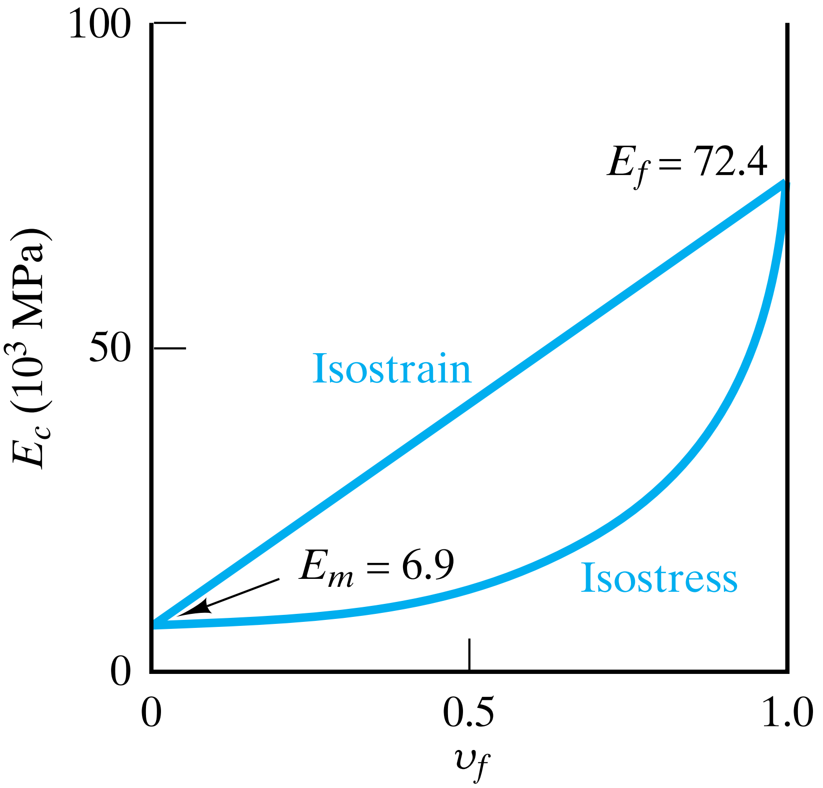


Figure 14-13 *The composite modulus, E_c, is a weighted average of the moduli of its components (E_m = matrix modulus and E_f = fiber modulus). For the isostrain case of parallel loading (Equation 14.7), the fibers make a greater contribution to E_c than for isostress (perpendicular) loading (Equation 14.19). The plot is for the specific case of E-glass-reinforced epoxy (see Figure 14–11).*

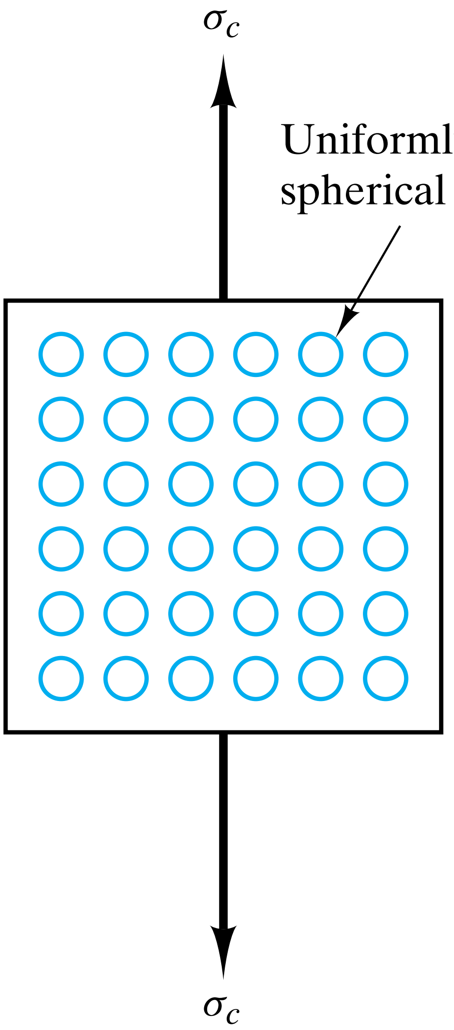


Figure 14-14 *Uniaxial stressing of an isotropic aggregate composite.*

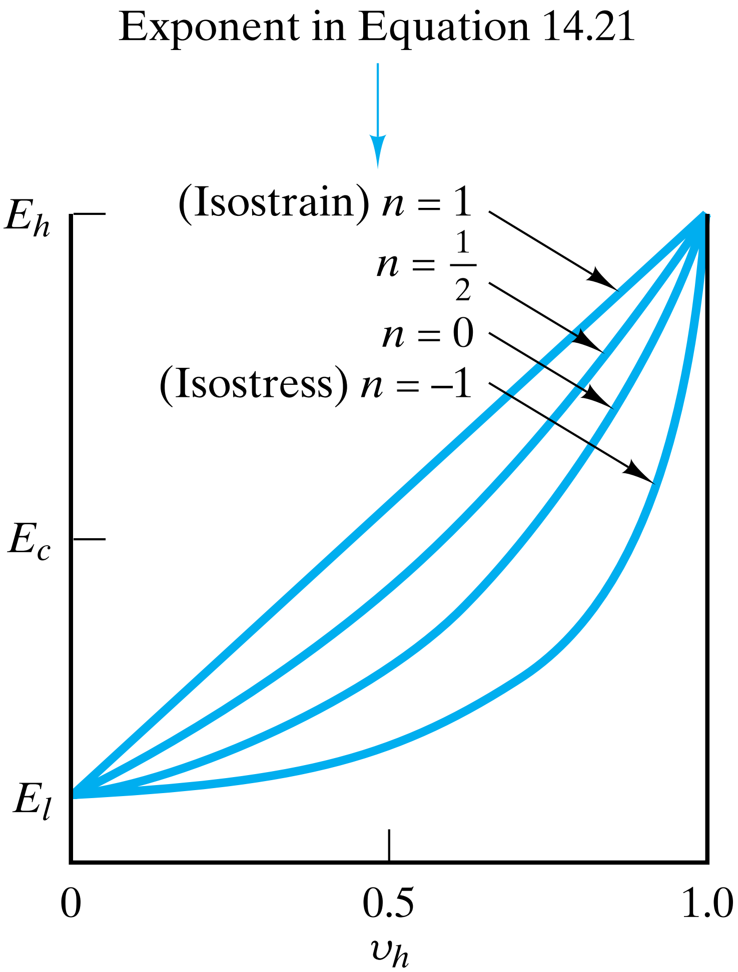
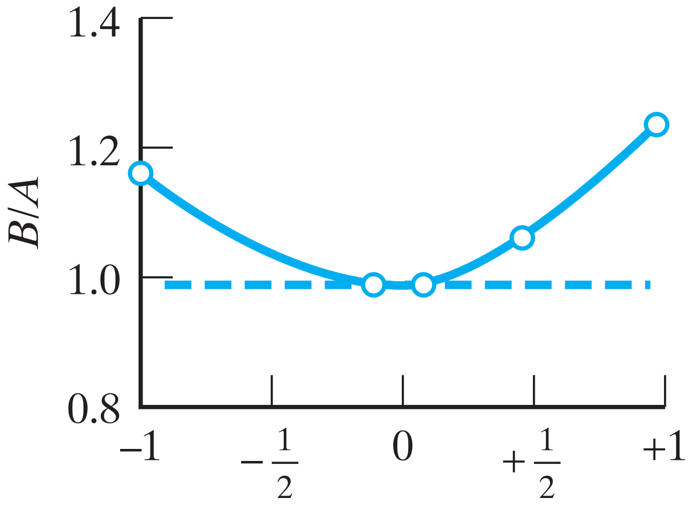
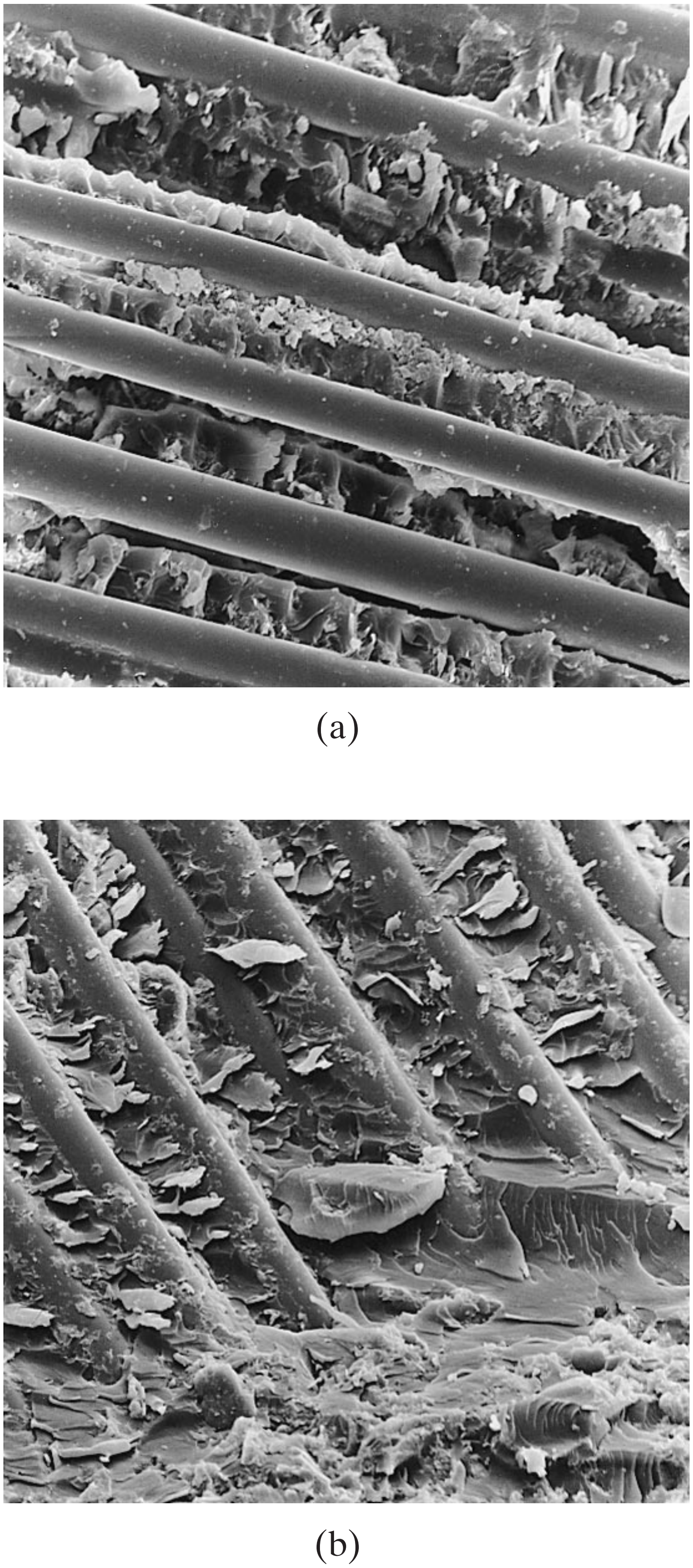


Figure 14-15 *The dependence of composite modulus, E_c, on the volume fraction of a high-modulus phase, υ_h, for an aggregate composite is generally between the extremes of isostrain and isostress conditions. Two simple examples are given by Equation 14.21 for $n = 0$ and $\frac{1}{2}$. Decreasing n from a $+1$ to -1 represents a trend from a relatively low-modulus aggregate in a relatively high-modulus matrix to the reverse case of a high-modulus aggregate in a low-modulus matrix.*



Therefore,

$$n \simeq 0$$



(a)

(b)

Figure 14-16 *The utility of a reinforcing phase in this polymer–matrix composite depends on the strength of the interfacial bond between the reinforcement and the matrix. These scanning electron micrographs contrast (a) poor bonding with (b) a well-bonded interface. In metal–matrix composites, high interfacial strength is also desirable to ensure high overall composite strength. (Courtesy of Owens-Corning Fiberglas Corporation)*

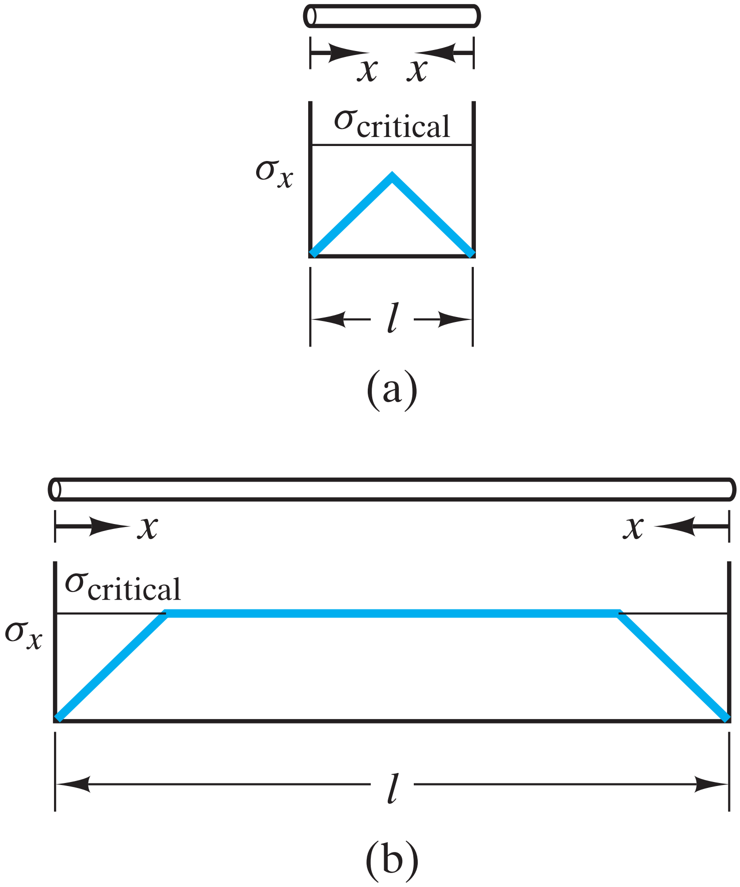


Figure 14-17 *(a) Plot of the tensile stress along a "short" fiber in which the build-up of stress near the fiber ends never exceeds the critical stress associated with fiber failure. (b) A similar plot for the case of a "long" fiber in which the stress in the middle of the fiber reaches the critical value.*

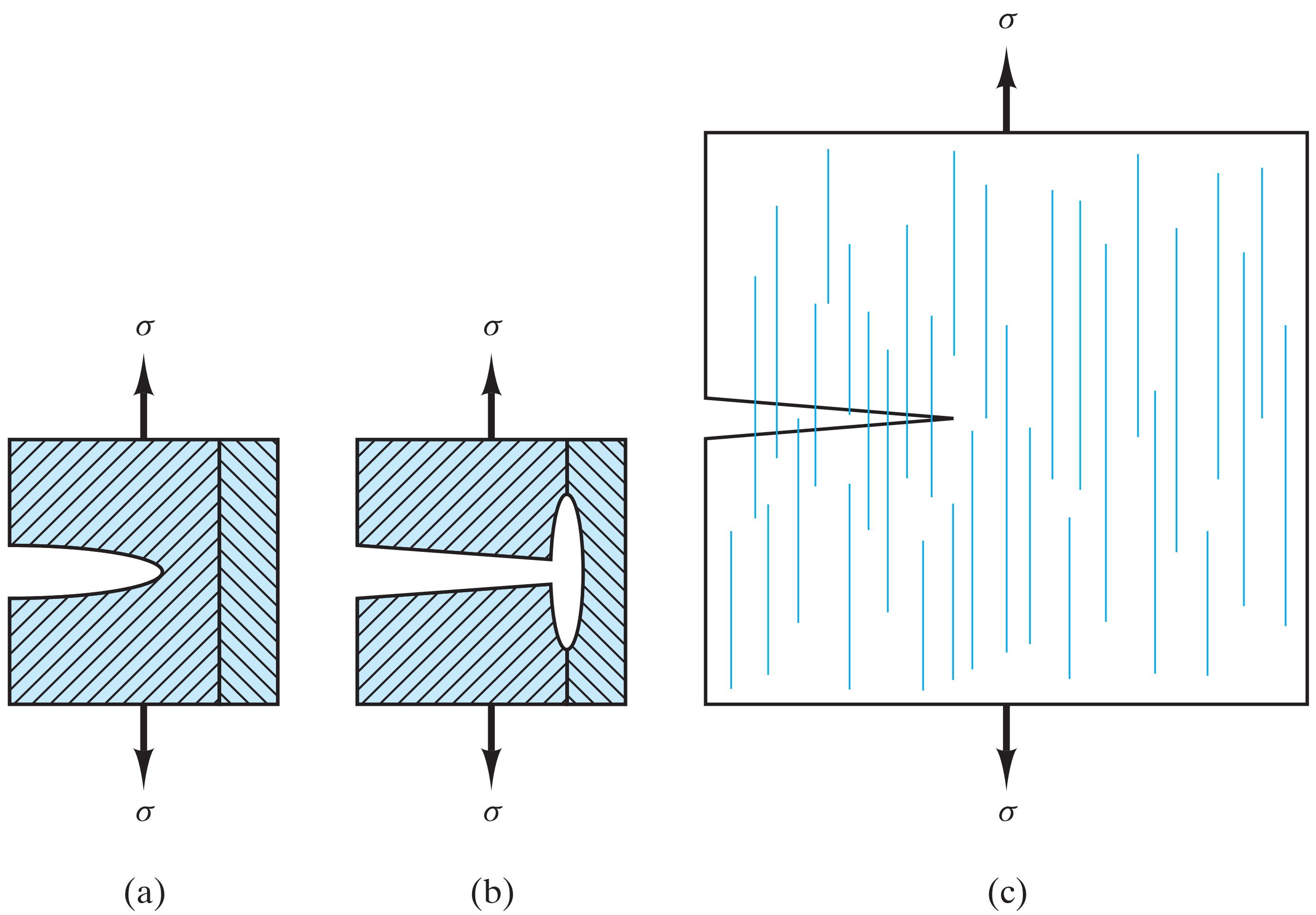


Figure 14-18 *For ceramic–matrix composites, low interfacial strength is desirable (in contrast to the case for ductile–matrix composites, such as in Figure 14–16). We see that (a) a matrix crack approaching a fiber is (b) deflected along the fiber–matrix interface. For the overall composite (c), the increased crack path length due to fiber pull-out significantly improves fracture toughness. (Two toughening mechanisms for unreinforced ceramics are illustrated in Figure 8–7.)*

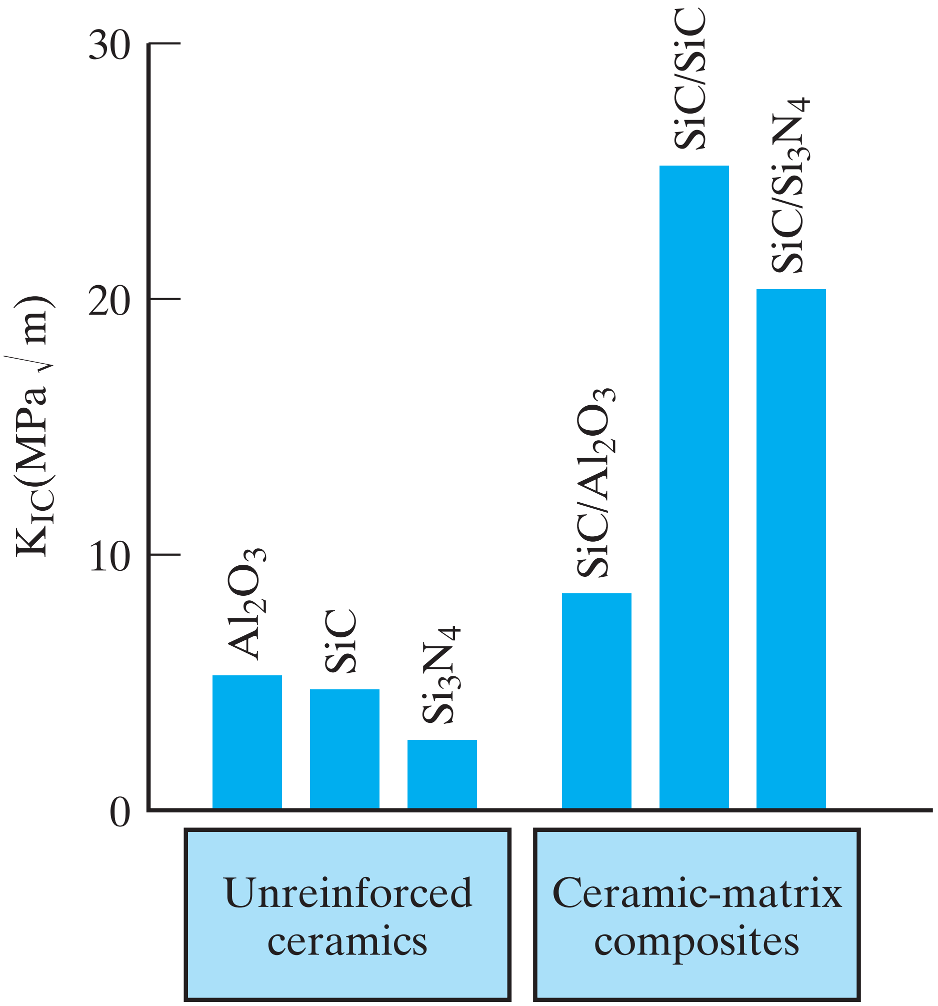


Figure 14-19 *The fracture toughness of these structural ceramics is substantially increased by the use of a reinforcing phase. (Note the toughening mechanism illustrated in Figure 14–18.)*

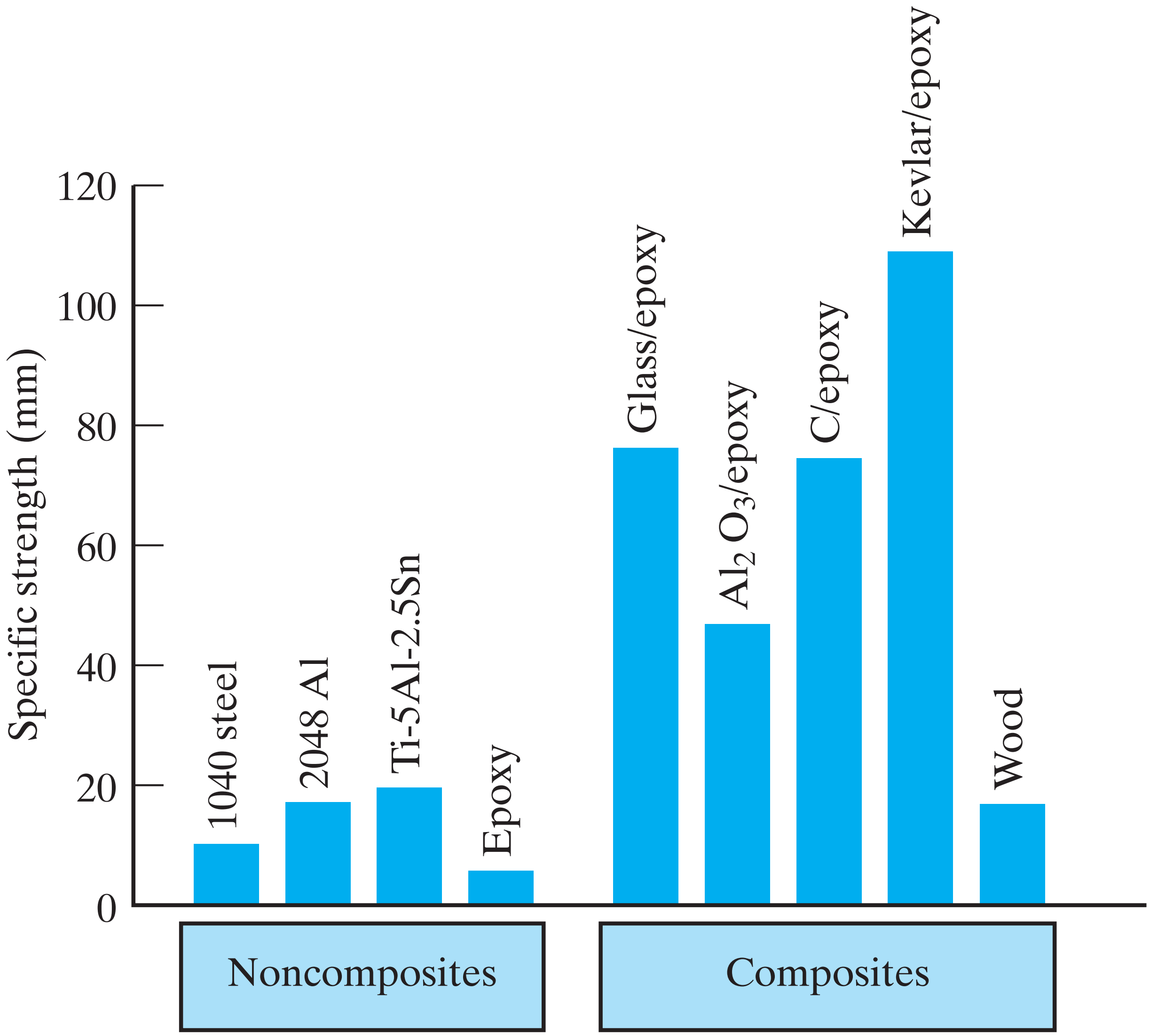
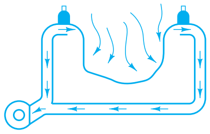


Figure 14-20 *A bar graph plot of the data of Table 14.13 illustrates the substantial increase in specific strength possible with composites.*

Open mold processes

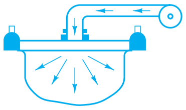
Contact Molding

Resin is in contact with air. Lay-up normally cures at room temperature. Heat may accelerate cure. A smoother exposed side may be achieved by wiping on cellophane.



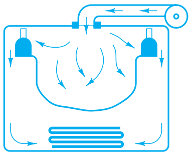
Vacuum Bag

Cellophane or polyvinyl acetate is placed over lay-up. Joints are sealed with plastic; vacuum is drawn. Resultant atmospheric pressure eliminates voids and forces out entrapped air and excess resin.



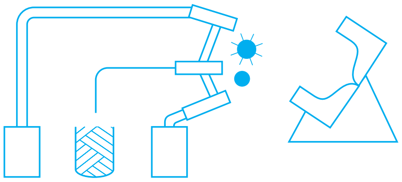
Pressure Bag

Tailored bag–normally rubber sheeting–is placed against lay-up. Air or steam pressure up to 50 psi is applied between pressure plate and bag.



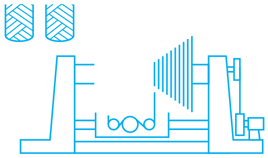
Autoclave

Modification of the pressure bag method: after lay-up, entire assembly is placed in steam autoclave at 50 to 100 psi. Additional pressure achieves higher glass loadings and improved removal of air.



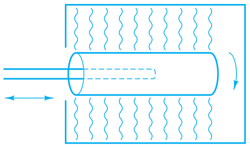
Spray-up

Roving is fed through a chopper and ejected into a resin stream, which is directed at the mold by either of two spray systems: (1) A gun carries resin premixed with catalyst, another gun carries resin premixed with accelerator. (2) Ingredients are fed into a single run mixing chamber ahead of the spray nozzle. By either method the resin mix precoats the strands and the merged spray is directed into the mold by the operator. The glass-resin mix is rolled by hand to remove air, lay down the fibers, and smooth the surface. Curing is similar to hand lay-up.



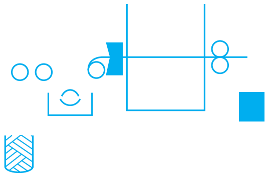
Filament Winding

Uses continuous reinforcement to achieve efficient utilization of glass fiber strength. Roving or single strands are fed from a creel through a bath of resin and wound on a mandrel. Preimpregnated roving is also used. Special lathes lay down glass in a predetermined pattern to give max. strength in the directions required. When the right number of layers have been applied, the wound mandrel is cured at room temperature or in an oven.



Centrifugal Casting

Round objects such as pipe can be formed using the centrifugal casting process Chopped strand mat is positioned inside a hollow mandrel. The assembly is then placed in an oven and rotated. Resin mix is distributed uniformly throughout the glass reinforcement. Centrifugal action forces glass and resin against walls of rotating mandrel prior to and during the cure. To accelerate cure, hot air is passed through the oven.



Continuous Pultrusion

Continuous strand–roving or other forms of reinforcement–is impregnated in a resin bath and drawn through a die which sets the shape of the stock and controls the resin content. Final cure is effected in an oven through which the stock is drawn by a suitable pulling device.

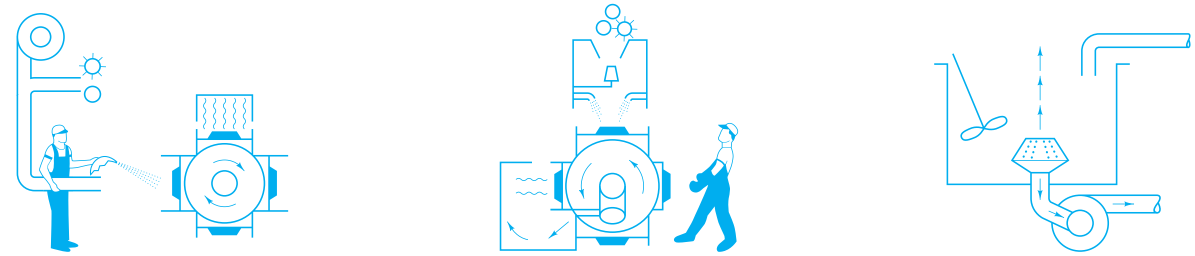
Encapsulation

Short chopped strands are combined with catalyzed resin and poured into open molds. Cure is at room temperature. A post-cure of 30 minutes at 200 F is normal.

(a)

Figure 14-21 *Summary of the diverse methods of processing fiberglass products: (a) open-mold processes.*

Preforming methods



Directed Fiber

Roving is cut into 1 to 2 inch lengths of chopped strand which are blown through a flexible hose onto a rotating preform screen. Suction holds them in place while a binder is sprayed on the preform and cured in an oven. The operator controls both deposition of chopped strands and binder.

Plenum Chamber

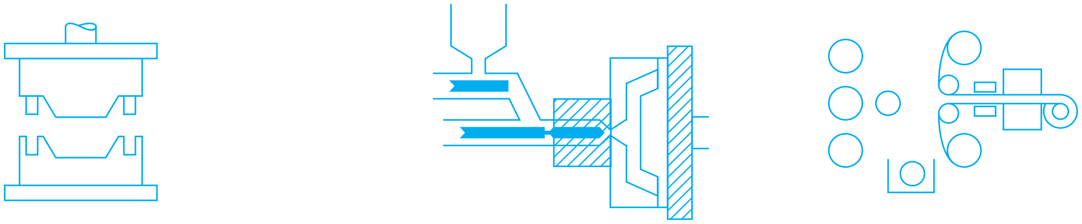
Roving is fed into a cutter on top of plenum chamber. Chopped strands are directed onto a spinning fiber distributor to separate chopped strands and distribute strands uniformly in plenum chamber. Falling strands are sucked onto preform screen. Resinous binder is sprayed on. Preform is positioned in a curing oven. New screen is indexed in plenum chamber for repeat cycle.

Water Slurry

Chopped strands are pre-impregnated with pigmented polyester resin and blended with cellulosic fiber in a water slurry. Water is exhausted through a contoured, perforated screen and glass fibers and cellulosic material are deposited on the surface. The wet preform is transferred to an oven where hot air is sucked through the preform. When dry, the preform is sufficiently strong to be handled and molded.

(b)

Closed mold processes



Premix/Molding Compound

Prior to molding, glass reinforcement, usually chopped spun roving, is thoroughly mixed with resin, pigment, filler, and catalyst. The premixed material can be extruded into a rope-like form for easy handling or may be used in bulk form.
The premix is formed into accurately weighed charges and placed in the mold cavity under heat and pressure. Amount of pressure varies from 100 to 1500 psi. Length of cycle depends on cure temperature, resin, and wall thickness. Cure temperatures range from 225 F to 300 F. Time varies from 30 seconds to 5 minutes.

Injection Molding

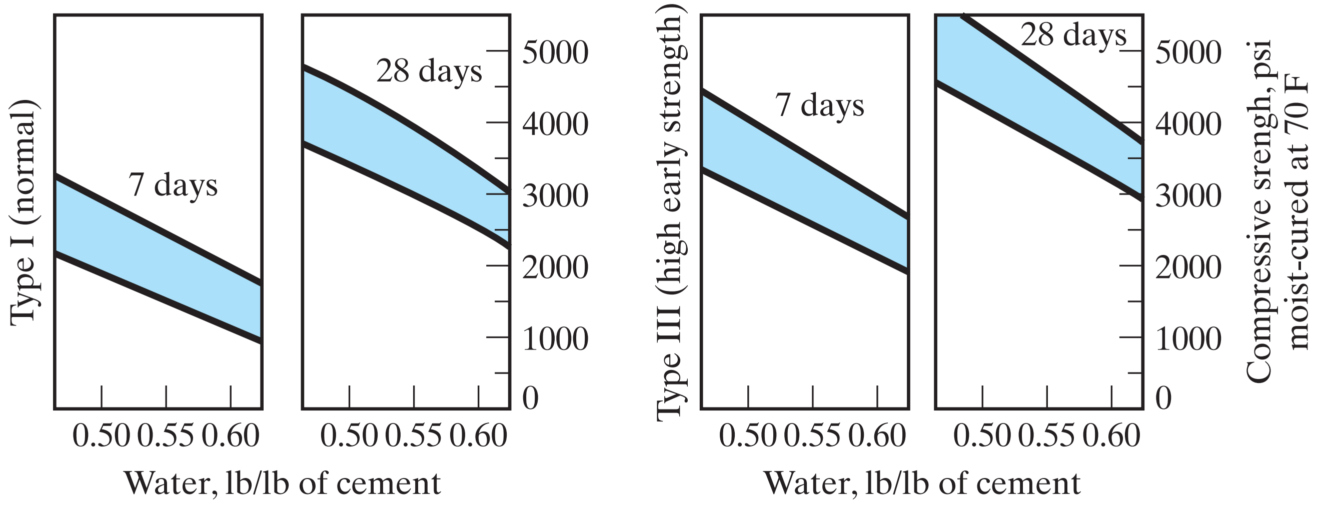
For use with thermoplastic materials. The glass and resin molding compound is introduced into a heating chamber where it softens. This mass is then injected into a mold cavity that is kept at a temperature below the softening point of the resin. The part then cools and solidifies.

Continuous Laminating

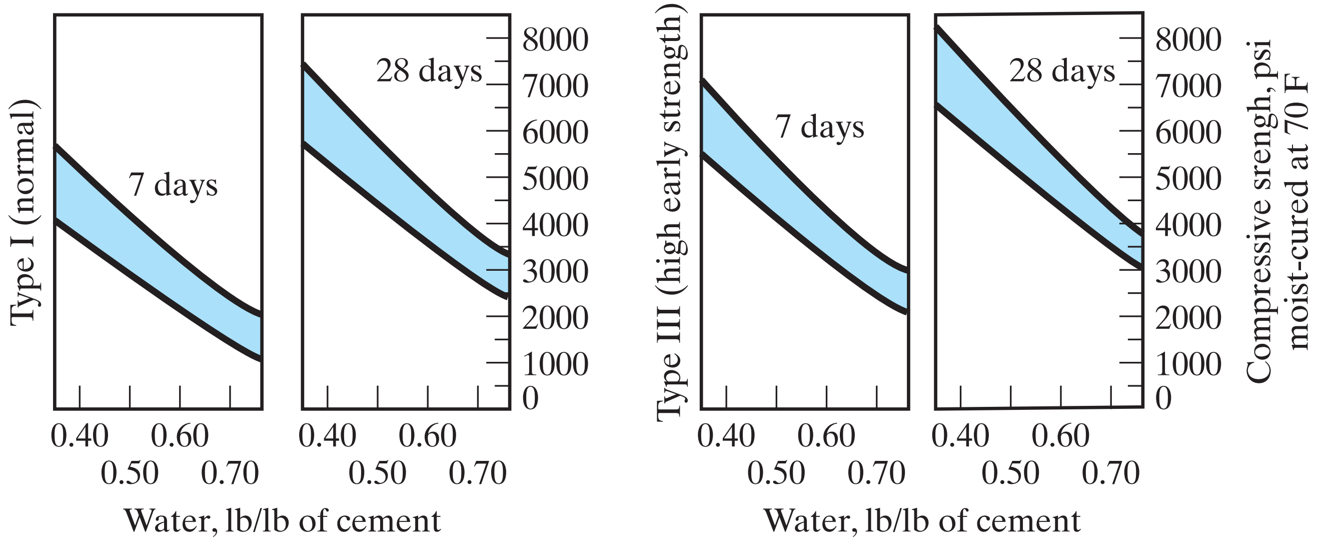
Fabric or mat is passed through a resin dip and brought together between cellophane covering sheets; the lay-up is passed through a heating zone and the resin is cured. Laminate thickness and resin content are controlled by squeeze rolls as the various plies are brought together.

(c)

Figure 14-21 *(Continued) (b) preforming methods, (c) closed-mold processes. (After illustrations from Owens-Corning Fiberglas Corporation as abstracted in R. Nicholls,* Composite Construction Materials Handbook, *Prentice Hall, Inc., Englewood Cliffs, N.J., 1976.)*



(a) Air-entrained concrete: Air within recommended limits and 2 in. max aggregate size



(b) Non-air-entrained concrete

Figure 14-22 *Variation in compressive strength for typical concretes (of different cement types, cure times, and air entrainment) as a function of water/cement ratio. (From* Design and Control of Concrete Mixtures, *11th Ed., Portland Cement Association, Skokie, Ill., 1968.)*