Chapters 17

Composites

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Composite

Definition

Mater made by purposefully combining two or more distinct materials, to offer combined property better than a single material

Examples:

Low density and high modulus & strength composites

Carbon fiber reinforced polymer composite

Tennis racket

https://www.sourcifychina.com/tennis-racket-custom/

Glass fiber reinforced polymer composite

Wind turbine blades

https://www.windsystemsmag.com/fundamentals-of-wind-turbines/

Composite Structure & Classification

<u>Two</u> (or more) <u>parts</u> in general

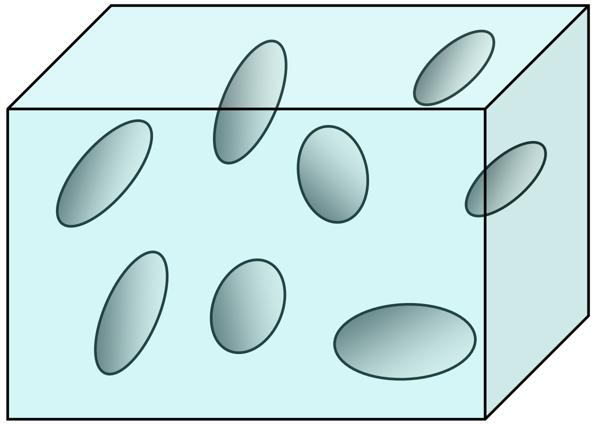
Matrix – continuous phase

- Contain the dispersed phase and, in some cases, protect it
- Transfer the load (e.g., stress) to the dispersed phase
- **MMC**/metal matrix composite, **CMC**/ceramics matrix composite, **PMC**/polymer matrix composite

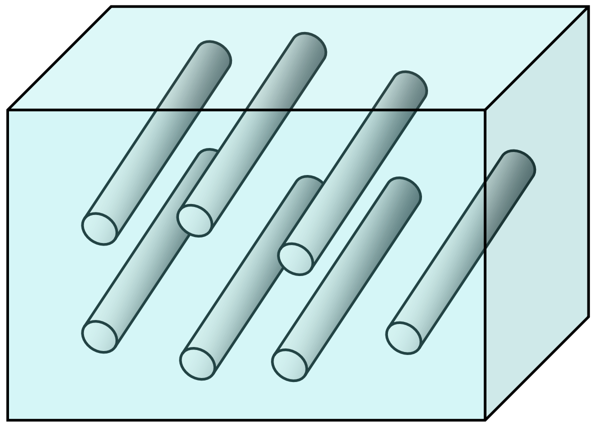
Dispersed phase – phase(s) separated and surrounded by the matrix

- Strengthen the overall material by carrying the load/stress

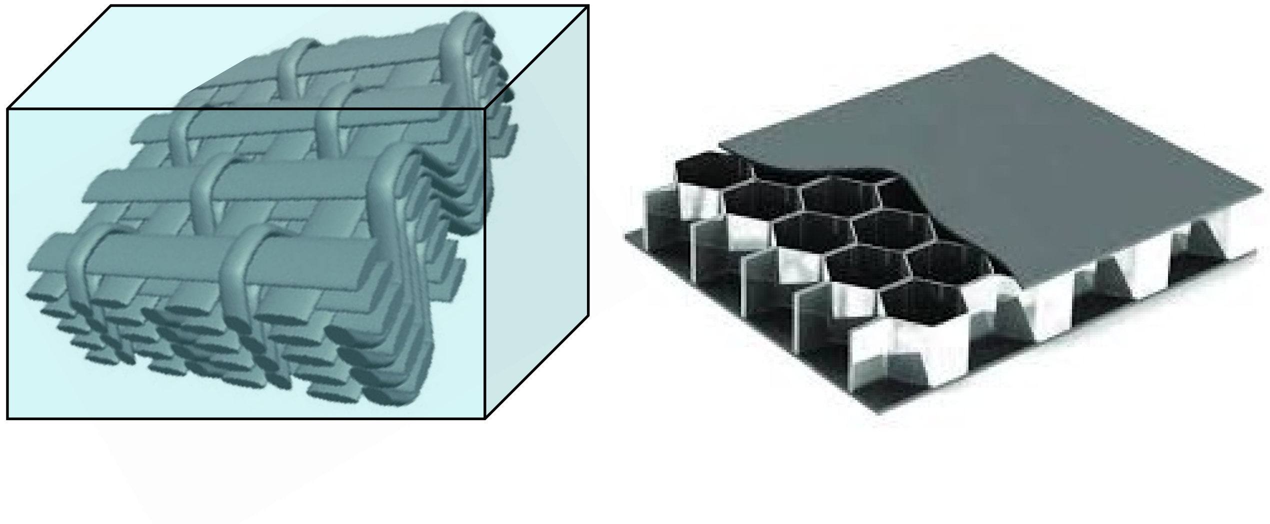
Particulate reinforced



Fiber reinforced



Structural Composite

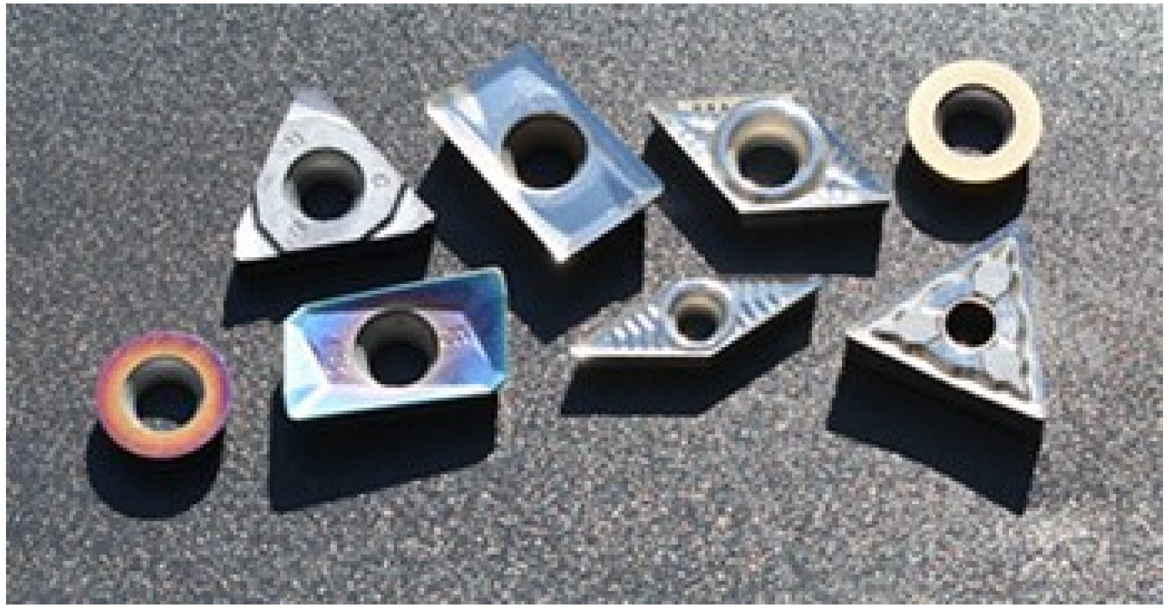


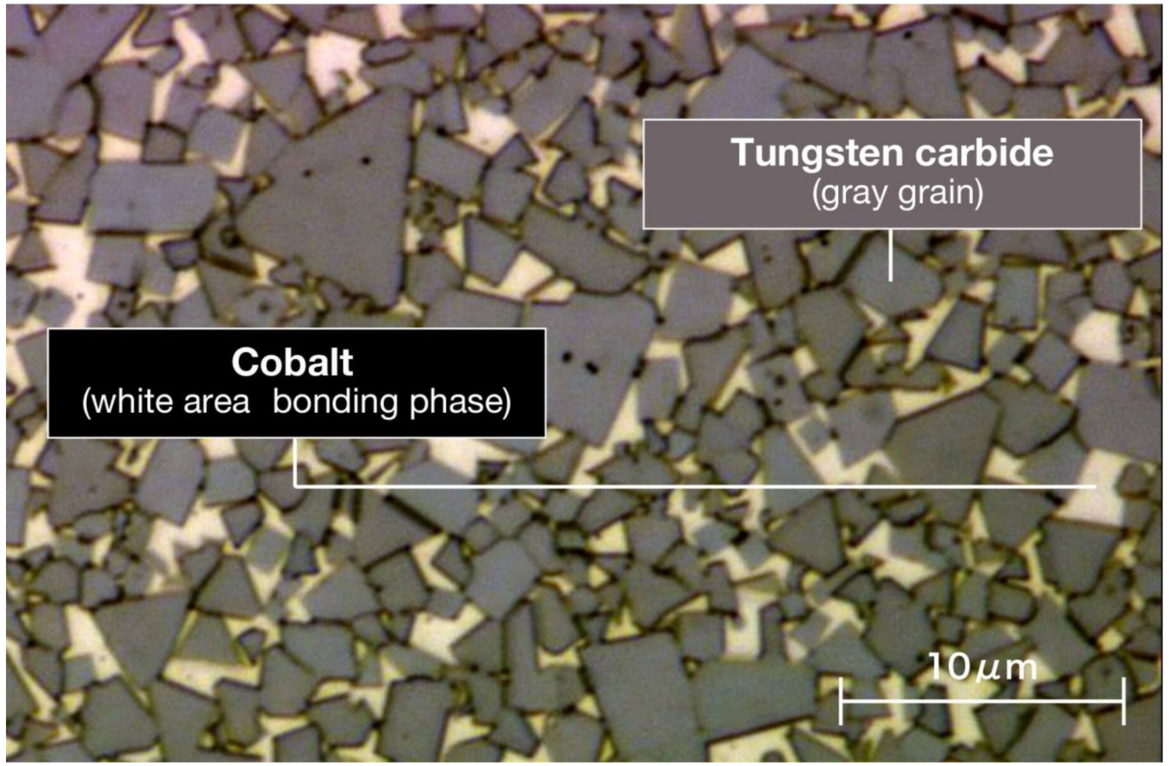
Particulate Composites (1)

- For improved hardness, strength, and wear resistance, while preserving decent toughness
- Example WC-Co composite for cutting/machining

Material	E (GPa)	Hardness (HRc)	Flexural strength (MPa)	K_{ic} (MPa•$^{m0.5}$)
AISI4340 steel	203	46	1365	79-91
Ti-6Al-4V Ti alloy	113	41	950	45
IN 718 superalloy	211	36	1050	> 90
D2 tool steel	206	60	3200	33
Si_3N_4 ceramics	304	70	850	3.5 – 6
WC-10%Co cermet	**552**	**72**	**3545**	**15**
WC-6%Co cermet	**641**	**77**	**3151**	**12**

WC-Co cemented carbide cutting tool

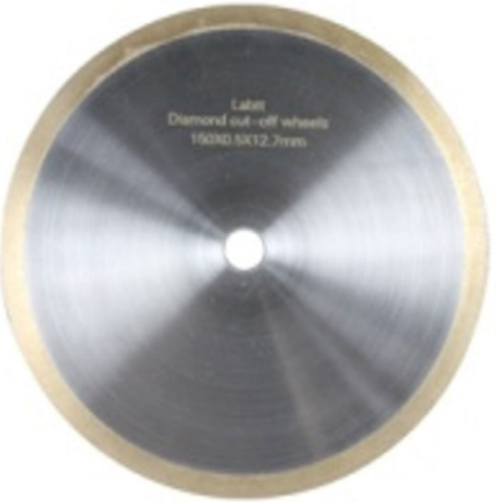




Chandran, Nano and Structural Design of Advanced Materials (2003), p.157
https://www.betalentcarbide.com/products/carbide-cutting-tools/
https://www.nhm.co.jp/english/technical_info/whatis/

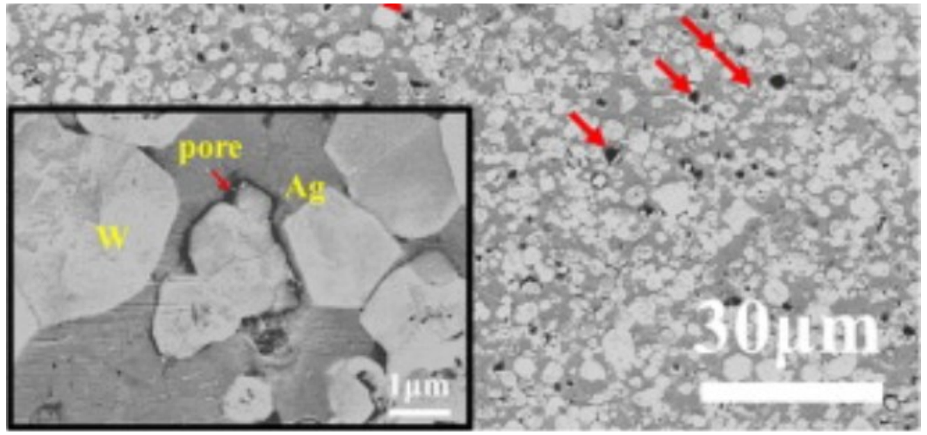
Particulate Composites (2)

Diamond cutting wheel w/ diamond embedded in metal for high hardness of toughness



https://www.msesupplies.com/products

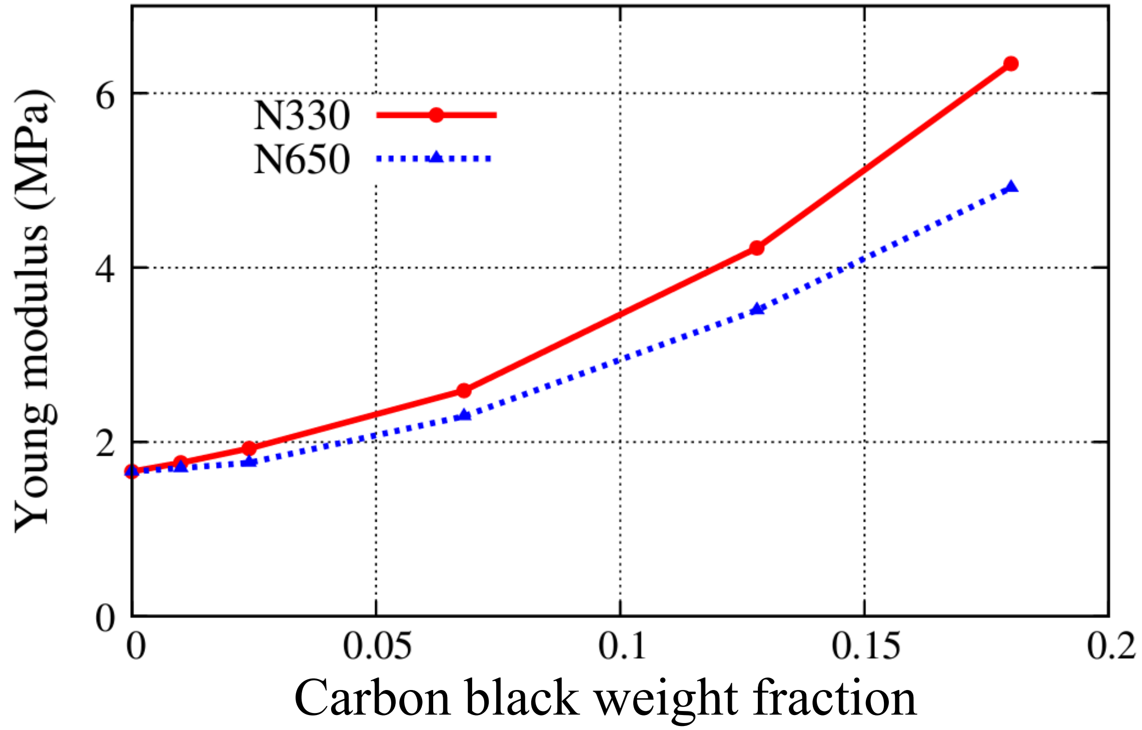
W-Ag composite for electrical contact w/ high wear resistance, while maintaining high electrical conductivity



https://www.samaterials.com/tungsten-alloy-composites/138-tungsten-silver.html

Luo et al., Materials & Design, v219, p110733 (2022)

Carbon-black reinforced rubber for higher elastic modulus & wear resistance

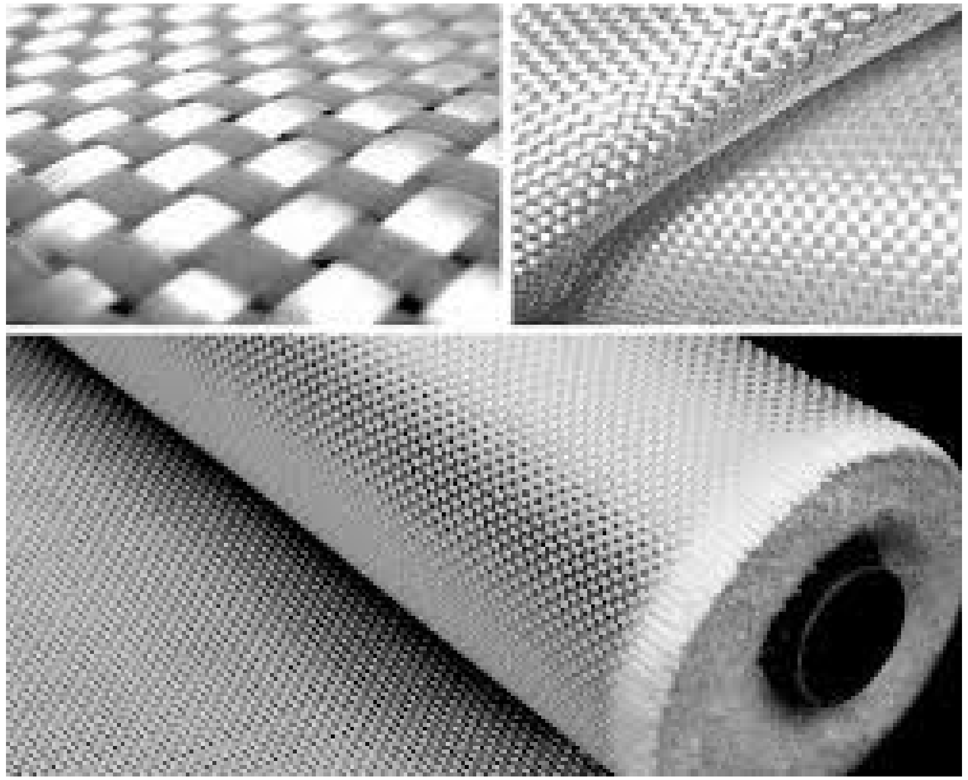


Omnes, et al., Composites Part A: Applied Science and Manufacturing, v39 (7), p. 1141 (2008)

https://www.intechopen.com/chapters/44966

Fiber Reinforced Composites (1)

- For significantly improved strength and modulus, over the matrix



https://application.wiley-vch.de/books/sample/3527349308_c01.pdf
https://www.reddit.com/r/EngineeringPorn/comments/lbln0n/wind_turbine_blade/#lightbox

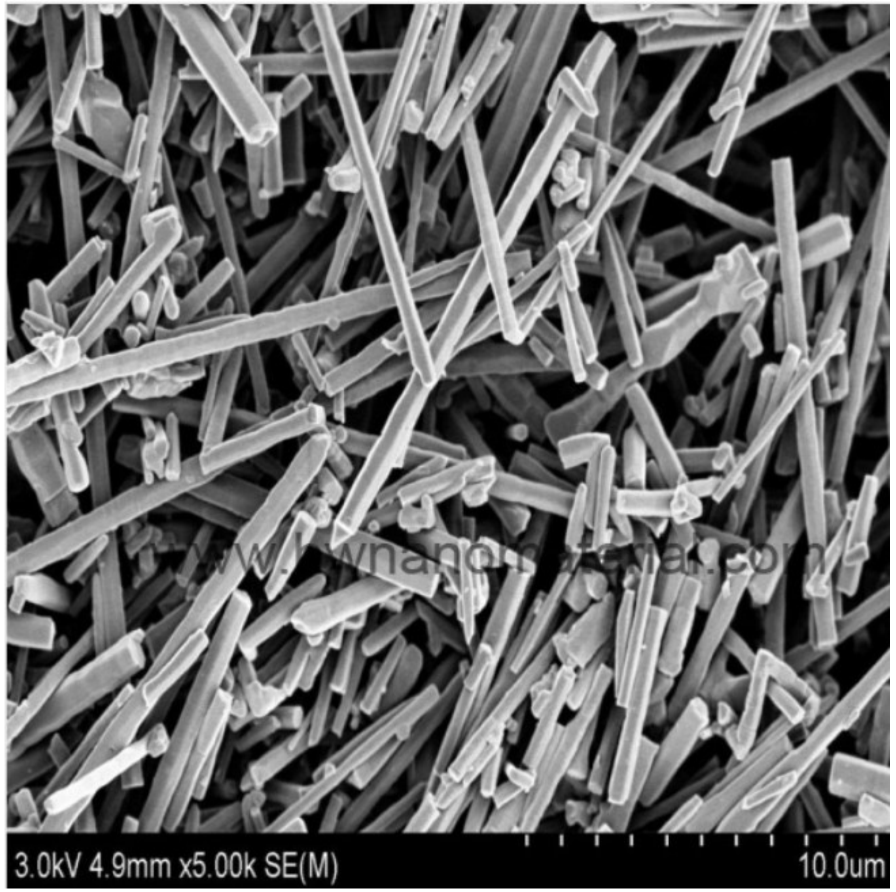
https://www.windsystemsmag.com/nrel-determines-how-to-transport-wind-turbine-blades/
https://www.iberdrola.com/sustainability/wind-blade-recycling

Type of Fibers

Whiskers (short fiber)

Single crystal w/ large $L : d$ ratio (only µm to mm long)

- SiC, Si_3N_4
- Extremely strong
- Costly, difficult to disperse



https://www.hwnanomaterial.com/beta-sic-whiskers-for-strength-and-toughness-enhancement-of-plastic-metal-ceramic_p1102.html

Fibers (long)

Polycrystalline or amorphous w/ very large $L : d$ ratio

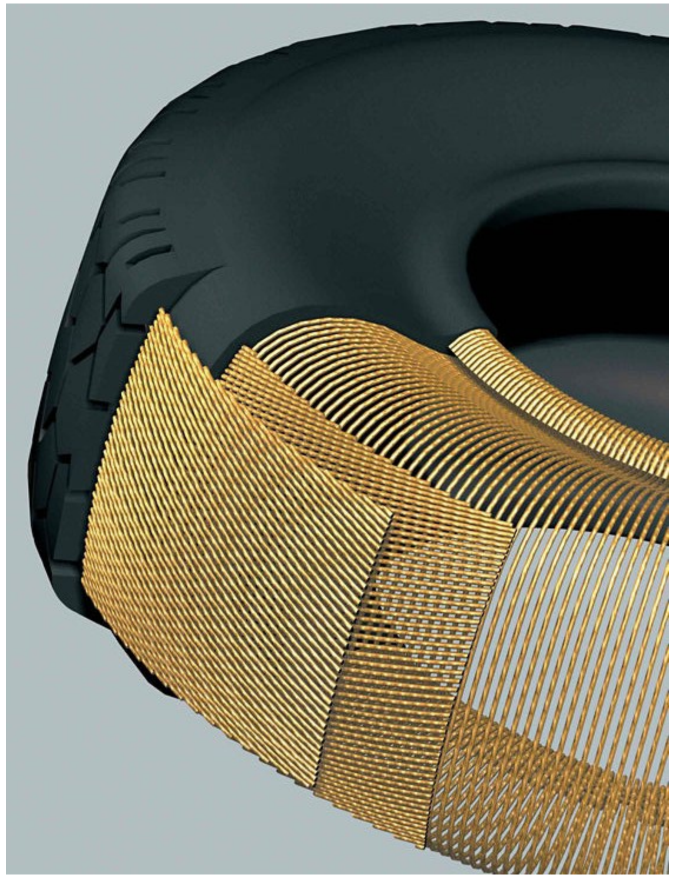
- Polymers or ceramics (graphite, E-glass, boron, etc.)

https://www.fiberglassfiber.com/s-glass-fiber-high-strength-product/
https://www.teijin.com/products/carbon-fiber/

Wires

Often metals (steel, Mo, W, etc.)

- Strong

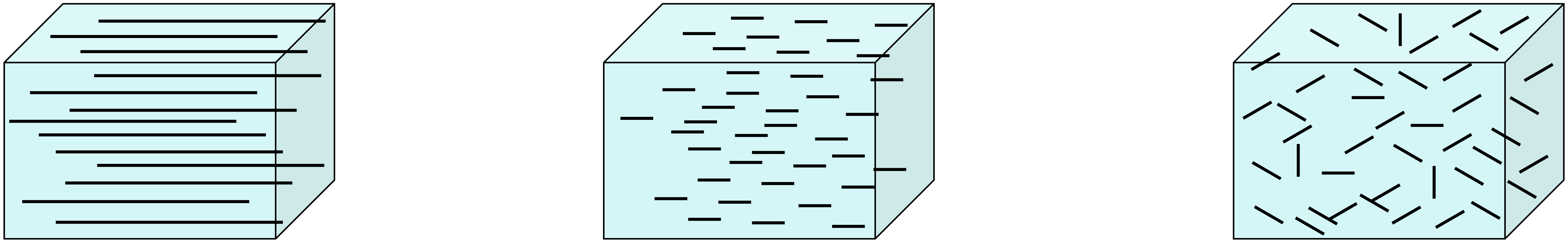


https://www.bekaert.com/en/products/automotive/exterior/steel-cord-for-tire-reinforcement

Fiber Alignment Feature & Rule of Mixture (ROM)

- Effects of strengthening depends on fiber alignment

Aligned long fiber **Aligned short fiber** **Random short fiber**



- For aligned long-fiber reinforced composites,

Elastic modulus along fiber direction, $E_{c,\ parallel}$, follow rule-of-mixture (ROM)

$$E_{c,parallel} = V_m E_m + V_f E_f$$

E_m	Elastic modulus for matrix
E_f	Elastic modulus for fiber
V_m	Volume fraction for matrix
V_f	Volume fraction for fiber

Same for some other properties such as tensile strength, electrical conductivity, etc.

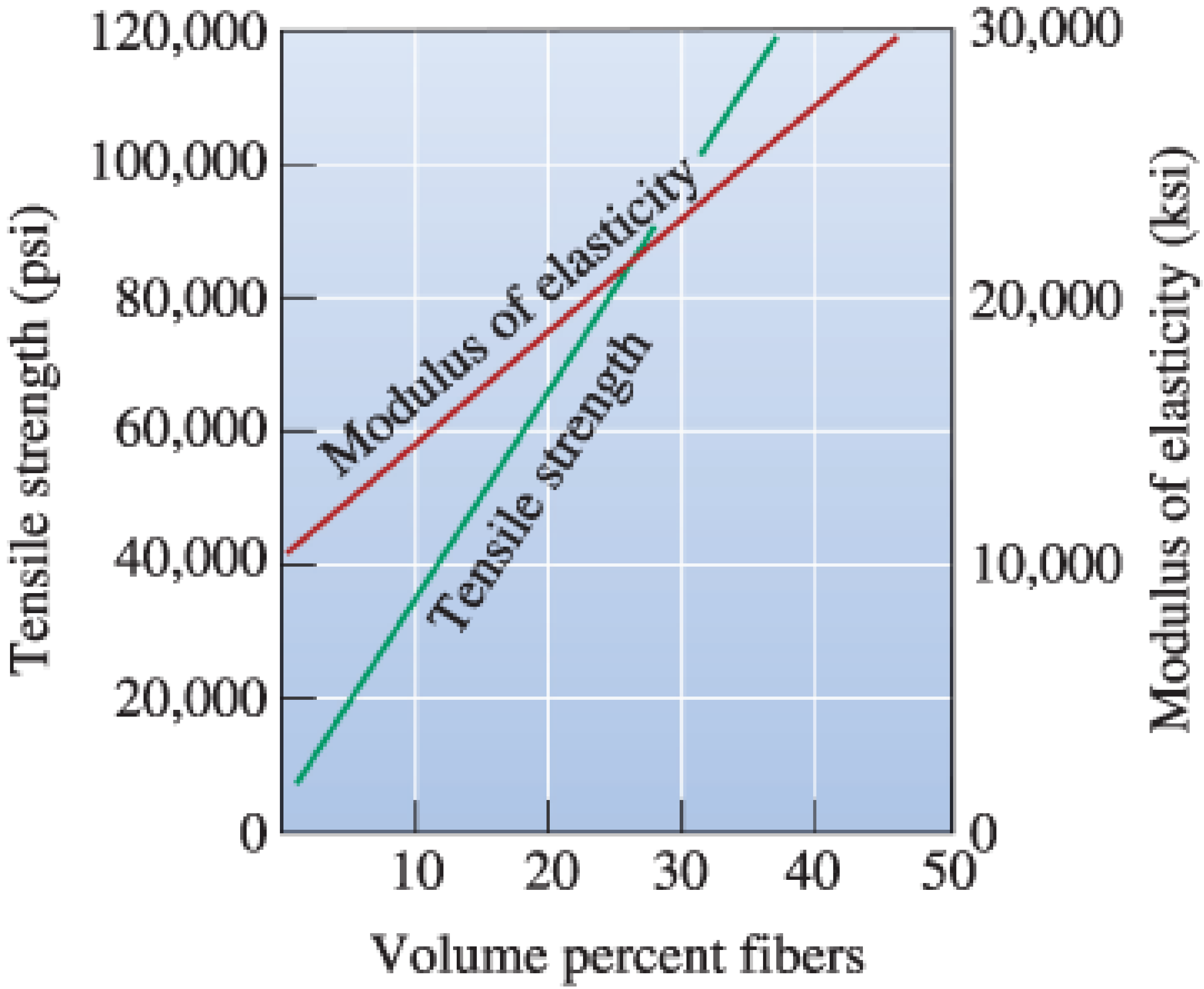
Strengthening of E and σ for Fiber Reinforced Composites

- Linear increase in E and σ_U with increasing fiber (SiC in this case) volume content

$$E_{c,parallel} = V_m E_m + V_f E_f$$

$$\sigma_{U\_c,parallel} = V_m \sigma_{U\_m} + V_f \sigma_{U\_f}$$

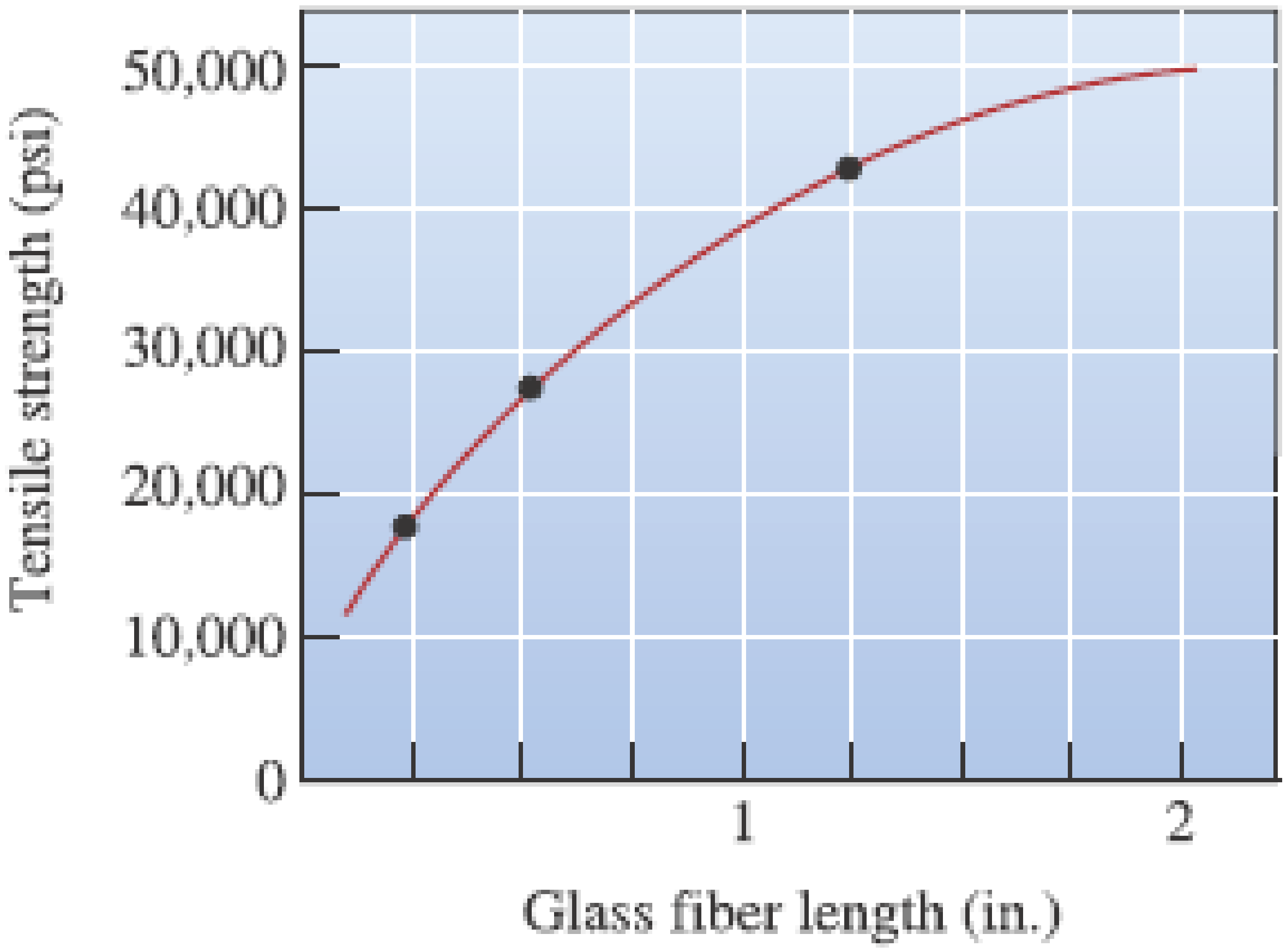
SiC fiber reinforced Al composite

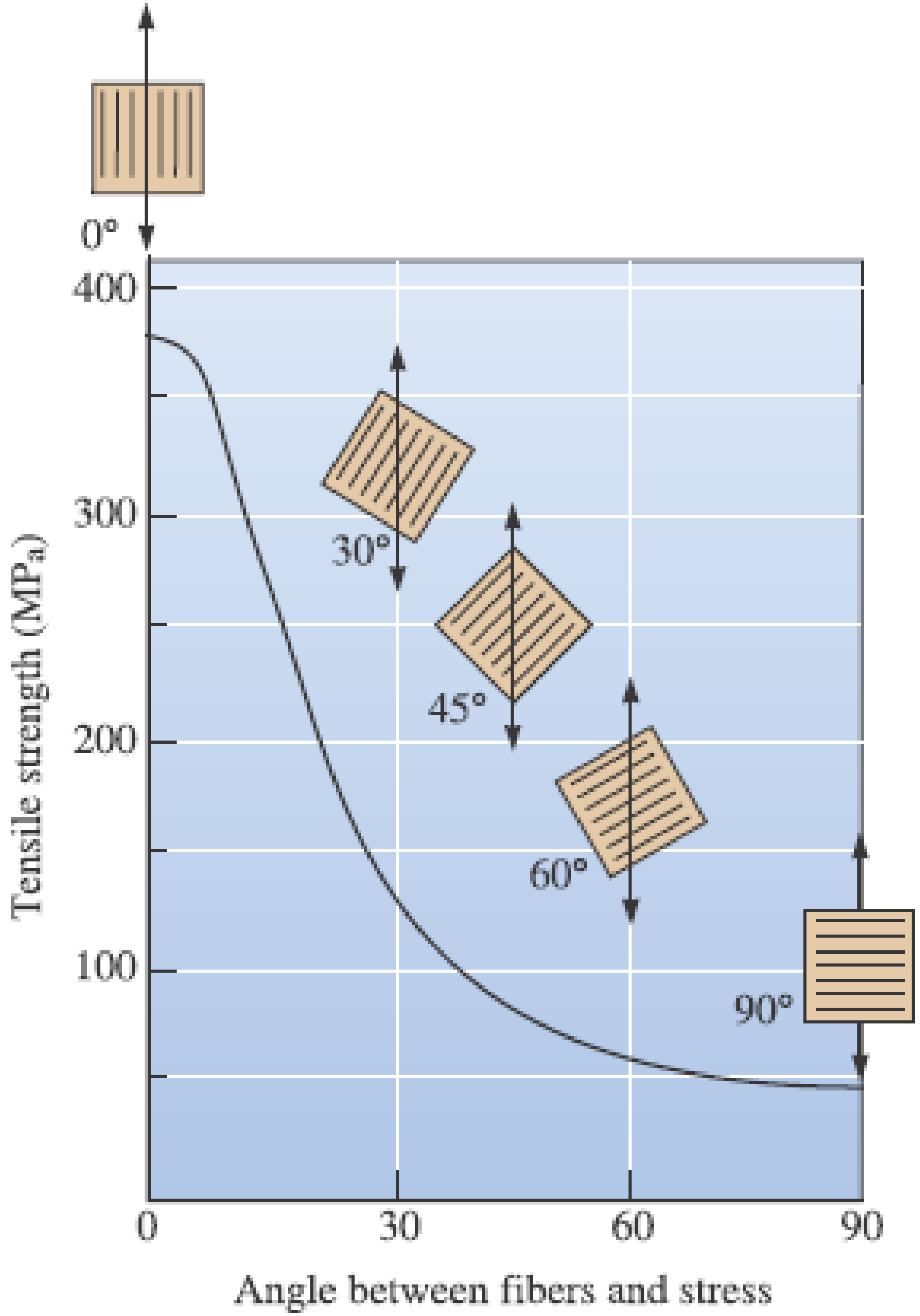


Length & Orientation for Fibers in Composite

- Increasing fiber length makes strengthening effect more effective

E-glass fiber reinforced epoxy





- Alignment of fiber with stress/load direction also impacts strengthening

Common Models to Estimate Composites' Properties

For property P, if volume fraction for each phase is V_1 and V_1, with $V_1 + V_2 = 1$

Upper limit (often thought of "parallel"): $P_{comp} = V_1 P_1 + V_2 P_2$

- Density;
- Elastic modulus & tensile strength (assuming same strain);
- Electrical & thermal conductivity (assuming same electrical field or temperature gradient)

Lower limit (often thought of "in series"): $\frac{1}{P_{comp}} = \frac{V_1}{P_1} + \frac{V_2}{P_2}$

$$P_{comp} = \frac{1}{\frac{V_1}{P_1} + \frac{V_2}{P_2}}$$

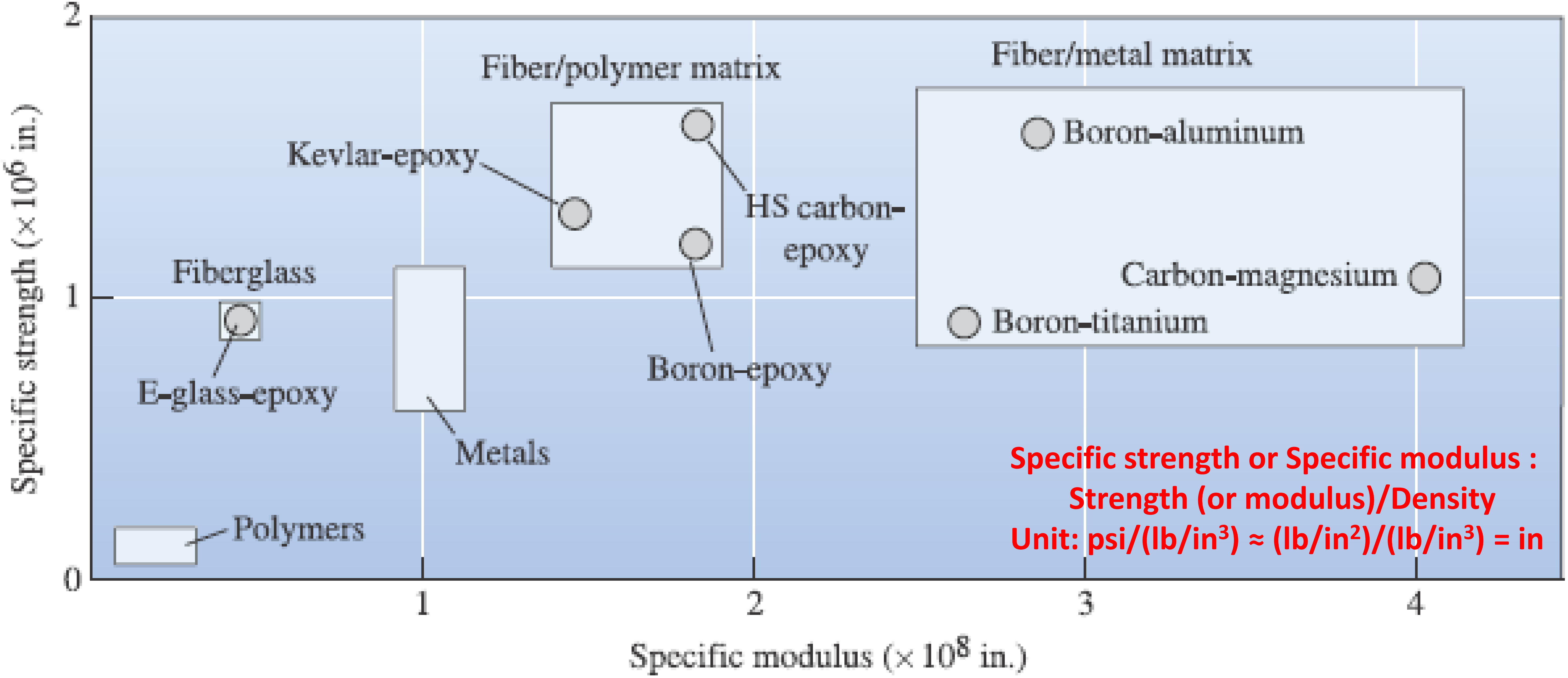
- Elastic modulus & tensile strength (assuming same stress);
- Electrical & thermal conductivity (assuming same current density or heat flux)

Arithmetic mean: $P_{comp} = \frac{P_1 + P_2}{2}$

Geometric mean: $P_{comp} = {P_1}^{V_1} \cdot {P_2}^{V_2}$

- **Many other models**
- Need **experimental verification**

Advantages of Composites



Specific strength or Specific modulus :
Strength (or modulus)/Density
Unit: psi/(lb/in^3) ≈ (lb/in^2)/(lb/in^3) = in

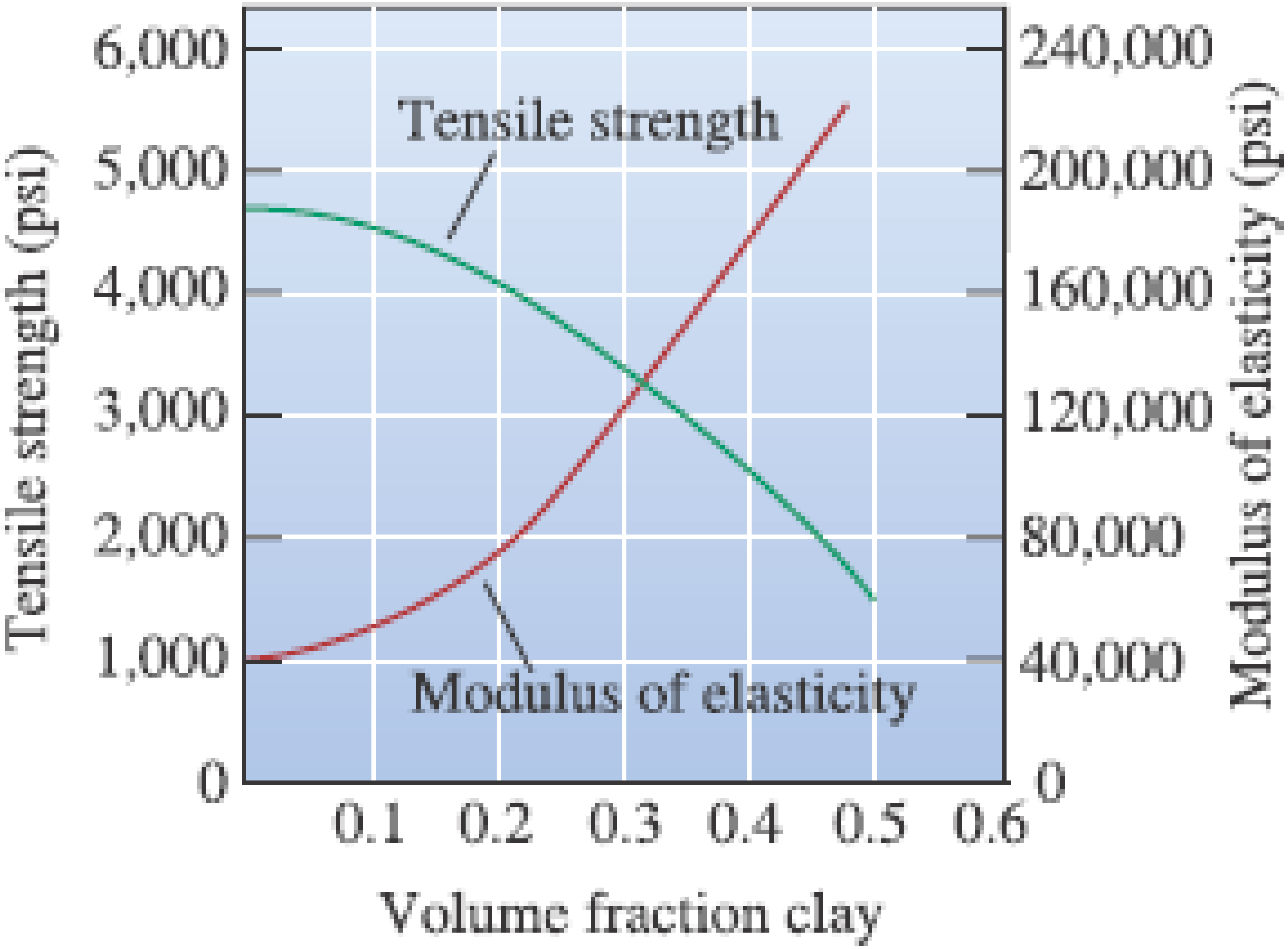
- (Often) drastically improved strength, modulus, or hardness, while maintaining relatively low density

Composites (Always) Lead to Some Compromises

Example 1

Clay addition to polyethylene

- ➢ Modulus *E* increase
- ➢ But tensile strength decrease!



END

Homework 0

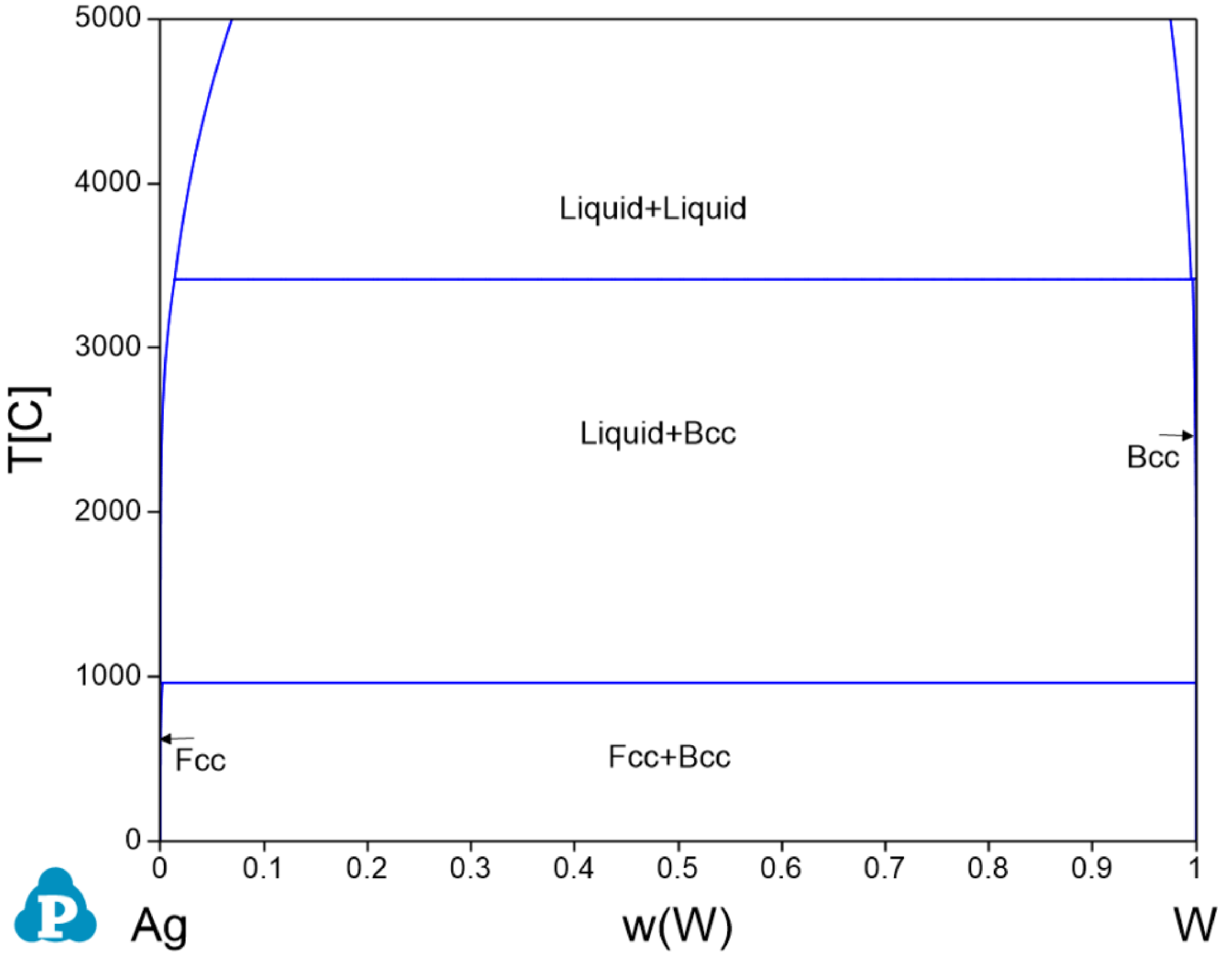
Carefully review chapter 17 lecture slides and, if interested, read textbook sections of Askeland 17 and give an honor statement confirming the reading

Homework 17.1

A fully dense tungsten-silver (W – Ag) composite is made from 70 wt.% W -30 wt% Ag. Knowing density is 19.2 g/cm^3 for W, 10.5 g/cm^3 for Ag

1) Based on W – Ag phase diagram, how many phases exist under equilibrium at 20^{o}C? What is the volume fraction for each phase?
2) Calculate density of the composite
3) If the electrical conductivity σ for the 2-phase composite can be approximated by

$$\frac{1}{\sigma_{composite}} = \frac{V_1}{\sigma_1} + \frac{V_2}{\sigma_2},$$ please estimate the electrical conductivity for the composite if electrical conductivity is 1.8x10^7 S/m for W and 6.3x10^7 S/m for Ag



https://computherm.com/ag-w

Homework 17.2

For fully dense WC-10 wt% Co cemented carbide, knowing density, Young's modulus, and fracture toughness for each phase

	Density (g/cm^3)	E (GPa)	K_{1C} ($MPa \cdot m^{0.5}$)
WC	15.6	700	~8
Co	8.9	209	~150

1) Calculate the volume fraction or V_i for each phase
2) Calculate density of the cemented carbide
3) If upper bound of the composite's Young's modulus is $E_{composite} = V_1 E_1 + V_2 E_2$
   lower bound of the composite's Young's modulus is $\frac{1}{E_{composite}} = \frac{V_1}{E_1} + \frac{V_2}{E_2}$
   Please give the range of the estimated Young's modulus of the cemented carbide.
4) Please estimate the fracture toughness of the WC-10 wt% Co using the geometric mean model, i.e., $K_{\mathrm{WC-10Co}} = K_{\mathrm{WC}}^{V_{\mathrm{WC}}} \cdot K_{\mathrm{Co}}^{V_{\mathrm{Co}}}$

Homework 17.3

A continuous and aligned long fiber-reinforced composite consisting of 60 vol.% of glass fiber with Young's modulus of 70 GPa and 40 vol% of polyester with Young's modulus of 3 GPa

1) Please estimate the modulus of elasticity of the composite along the fiber direction
2) Estimate the density of the composite, knowing glass fiber density of 2.5 g/cm^3, and epoxy density is 1.25 g/cm^3
3) If an external tensile force of 10000 N is applied along the fiber direction, calculate the load carried by each of the fiber and matrix phase, if iso-strain condition is satisfied along that direction