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Composite Materials

<u>Introduction: -</u> A Composite material is formed when two or more materials are combined on a macroscopic scale, So that the properties of composite are different (usually better) from those of the individual constituents.

<u>Properties that can be improved by composite materials</u>

- Strength
- stiffness
- fatigue life
- corrosion resistance
- high temperature performance
- wear resistance
- thermal insulation
- thermal conductivity
- a acoustical insulation
- weight
- hardness
- etc…………..

<u>Composite materials have a wide range of practical application in the industry like:</u>

- Car body manufacturing
- Air plane structure
- Space land and space satellite
- Boats manufacturing
- Storage containers
- House appliances

The important property that recognizes the composite material on metal is the <u>strength</u> to the <u>density</u> ratio or <u>strength</u> to <u>weight</u> ratio.

Composite are made of → Continuous medium "matrix"
→ Discontinuous medium "Reinforcement "
(which is usually harder and stronger one)

Therefore the properties of composite are depend on the properties of the matrix and reinforcement materials, their distribution and interaction.

Matrix :- It is the material that work to bind the reinforcing material together in order to make a composite material that can carry loads or stresses .

It is also called "**medium** ", it is may be **metal , polymer or ceramic**.

The polymers are most widely used as a "matrix". And are also called resins .

Polymers are very complex organic compounds whose molecular weight exceed 5000

Polymers have low electrical and thermal conductivity ,therefore use for electrical and thermal insulation .

The molecules of polymers may have the linear ,branch (fig 1) or three dimensional (spatial) structure repeated many times .

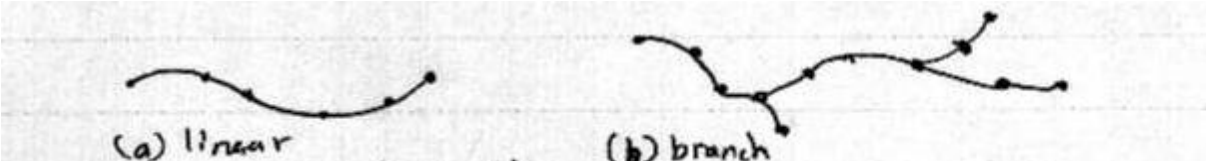


figure (1)

Polymers may be classified as :-

1- **Thermoplastic resins**: - for examples "nylon ", "polyethylene ".

   Soften when heated and become hard again when the heat is removed. And have linear chains or branch chains for their structure.

2- **Thermosetting resins :-** for example " epoxy" , " polyester".

   Do not soften when heated, but char and decompose and have cross linked structure.

3- **Elastomers resin** :- for example " rubber".

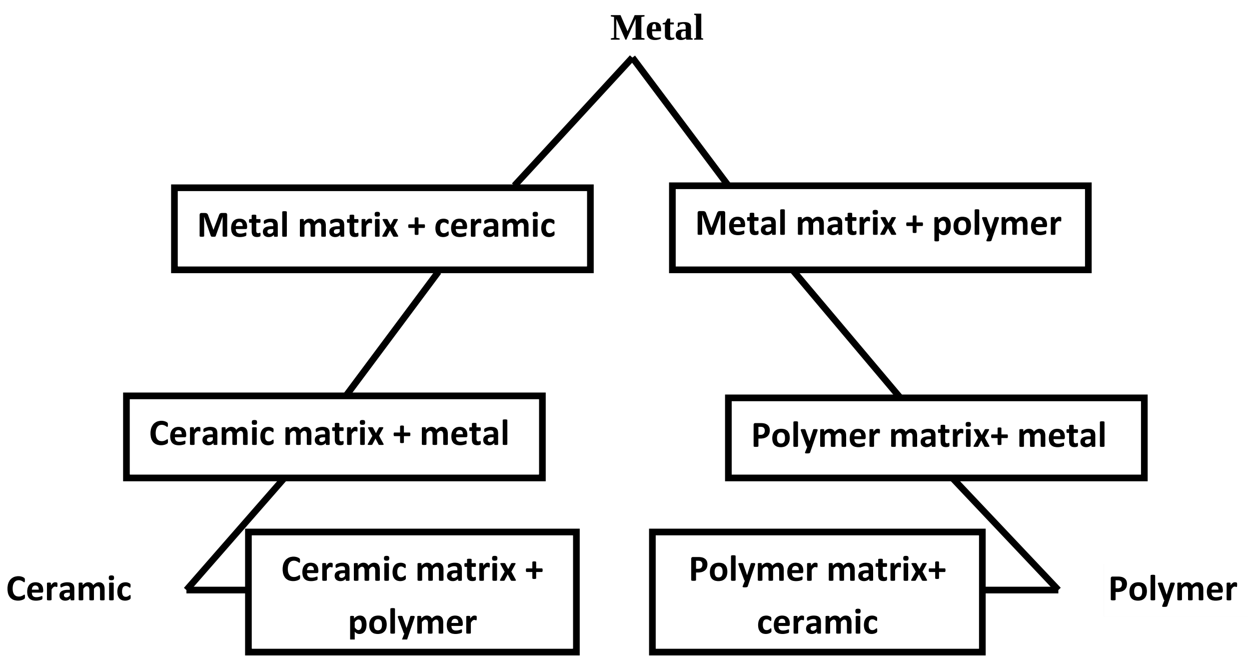
   Is a polymer having considerable extensions and reversible. It is chains have some degree of cross- linking.

Reinforcing materials:- It is the materials that make the reinforcing to the matrix. It is have different form may be fibers, particles, flakes, fillers and woven made from glass, carbon , Kevlar or steel…….etc.

The diagram of the composite materials illustrated as following:-

Metal matrix+ metal

- Have high density.
- Thermal and electrical conductivity.
- Good strength, ductility and toughness.
- Working at medium and high temperature.
- Low corrosive resistance.

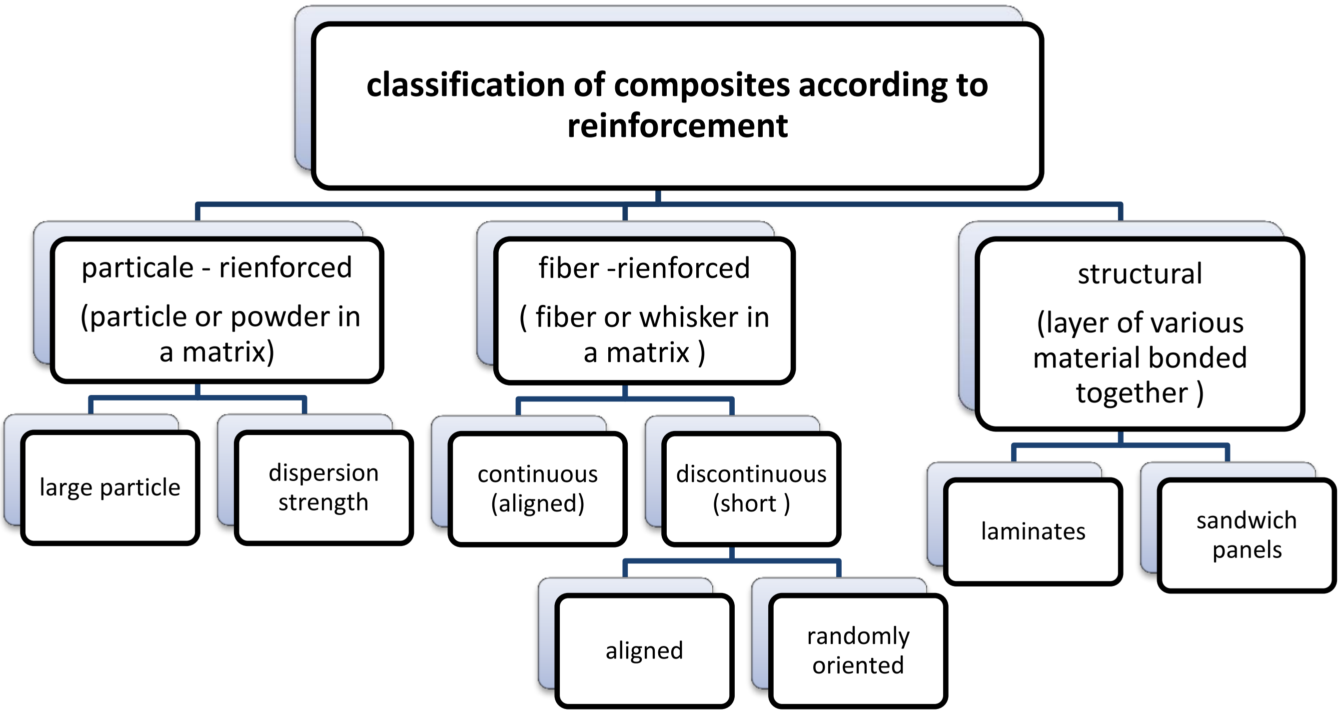


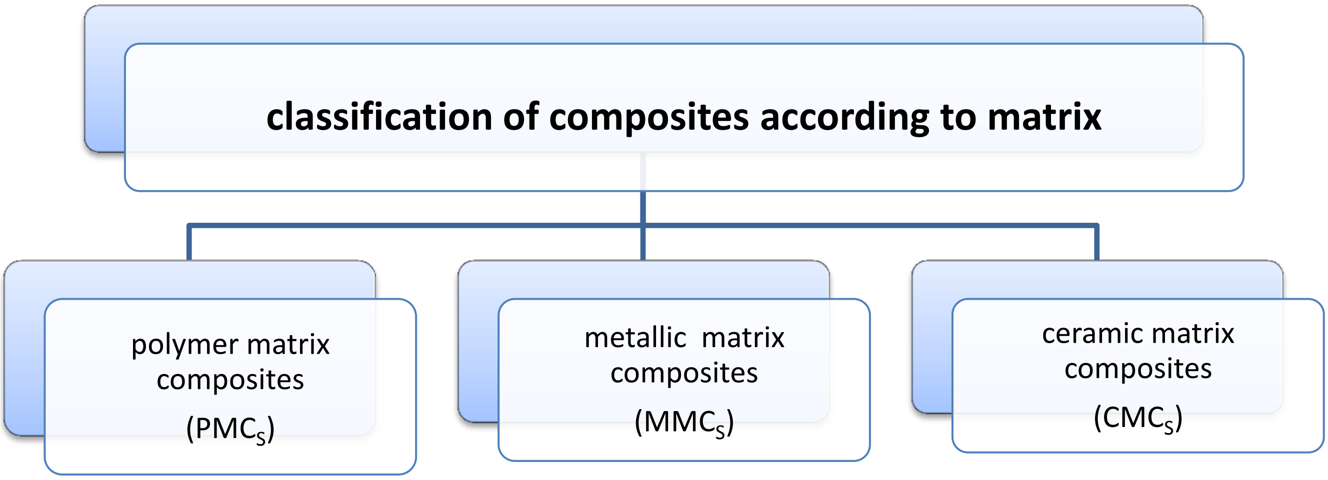
- Medium density.
- Electrical and thermal insulating.
-wear and corrosive resistance.
-difficult to form/machine.
-working at high temperature.

- Low density.
- High strength to weight ratio.
-have high corrosion resistance.
-easy to form.
-working at low temperature.

Ceramic matrix + ceramic

Polymer matrix + polymer





Particulate composite:- Consist of one or more materials suspended in a matrix of another material .The particles can be either metallic or non-metallic .

Particulate composite classified as:
- Large particles reinforced composite
- Dispersion strength composite

A classic example of polymers as a particulate composite material is carbon black in rubber (in manufacturing of tires).A carbon black improves strength, stiffness, wears resistance.

Large particle reinforced composite :- Have particles with diameter of (1μm)or more and volume concentration (25-50) % or more of the composite .

One of their applications cermet or (cemented carbides), composite involving ceramic particles in a metal matrix which are widely used for the tips of cutting tools.

(e.g.)

Ceramic (Tungsten carbides)
[hard, brittle]

Metal
[soft, ductile]

Composite
[strong, hard, tough]

Dispersion strengthened composite :- The strength of a metal can be increased by small particles dispersed throughout the matrix .The diameter of particle (0.1μm)and volume concentration (1-15)% of the composite . For example the dispersion of aluminum – copper compound throughout of alloy. To product composite for general application, like piston, connecting rod for automotive application.

Also one way of introducing a dispersion of small particles throughout a metal uses sintering .Like dispersion of aluminum oxide (AL_2O_3) about (14%) throughout an aluminum matrix .

Where the tensile strength is
400 MPa for sintered aluminum powder
90 MPa for aluminum

The following table give an example and applications of selected dispersion strengthened composites:

Composite	Applications
Ag-CdO	electrical contact material
Al-Al_2O_3	nuclear reaction
Pb- PbS	battery grids

The General Applications of Particulate Composite Materials

1- Non-metallic in non-metallic
   - *Concrete*
   - *Flakes glass in plastic matrix – for electrical insulating*
2- Metallic in non-metallic
   - *Silver flakes in paint – for good conductivity*
   - *Aluminum flakes in paint – aluminum paint for surface protection*
3- Non-metallic in metallic composites
   - *Cermets are examples of ceramic and metallic*
4- Metallic in metallic composites
   - *Lead particles in copper alloys to improve machineability*

Rule of mixture

The rule of mixtures can predict the properties of the particulate composite material because the particulate composite materials depend only on relative amount and properties of the individual constituents . e.g.

$$\rho_c = \sum V_i * \rho_i = V_1 * \rho_1 + V_2 * \rho_2 + V_3 * \rho_3 + \cdots V_n * \rho_n$$

Where :

ρ_c= density of the composite

ρ_1 , ρ_2 , …. , ρ_n = are the density of each constituent

V_1 , V_2 , ….. , V_n = are the volume of fractions of each constituent

$$V_i = \frac{v_i}{v_c}$$

where v_i volume of the item (matrix or reinforcement)

v_c total volume of the composite

$$v_i = \frac{m_i}{\rho_i}$$

where m_i mass

ρ_i density

$$v_c = \frac{m_c}{\rho_c}$$

Or $$v_c = \frac{m_c}{\rho_c} = \frac{m_1}{\rho_1} + \frac{m_2}{\rho_2} + \frac{m_3}{\rho_3} \dots \dots + \frac{m_n}{\rho_n}$$

Example :-

A cemented carbide cutting tool used for machining contains (54.7 vol.%) of WC (Tungsten carbide) , (34.9 vol.%) of TiC (Titanium carbide), (4 vol.%) TaC (Tantalum carbide), and (6.4 vol.%) Co (Cobalt) . Estimate the desity of the composite . where the densities are ($\rho_{WC} = 15.77\ \text{g/cm}^3$, $\rho_{TiC} = 4.94\ \text{g/cm}^3$, $\rho_{TaC} = 14.5\ \text{g/cm}^3$, $\rho_{CO} = 8.90\ \text{g/cm}^3$)

Solution :-

$\rho_c = \sum V_i * \rho_i =$ 0.547*15.77+0.349*4.94+0.04*14.5+0.064*8.9 = 11.5 g/cm^3

Lower bound on apparent Young's modulus

The basic for the determination of a lower bound on the apparent Young' s modulus is application of the principle of minimum complementary energy.

$$E_{(L)} = \frac{E_m * E_p}{V_m * E_p + V_p * E_m}$$

Where, E= modulus of composite material

E_m= modulus of basic matrix

E_p= modulus of dispersed material (particles)

V_m = volume fraction of matrix

V_p = volume fraction of dispersed material

Upper bound on apparent Young' s modulus :-

The basic of determination of an upper bound on the apparent Young's modulus is application of the principle of minimum potential energy.

$$E_{(U)} = E_p * V_p + E_m * V_m$$

There are many considerations must be taken in the account of choosing of dispersed material (particles) which are :-

1- No chemical reaction with the matrix.
2- Hard and solid to obstacle the slip (dislocation movement).
3- Stable at high temperature and insoluble in matrix.

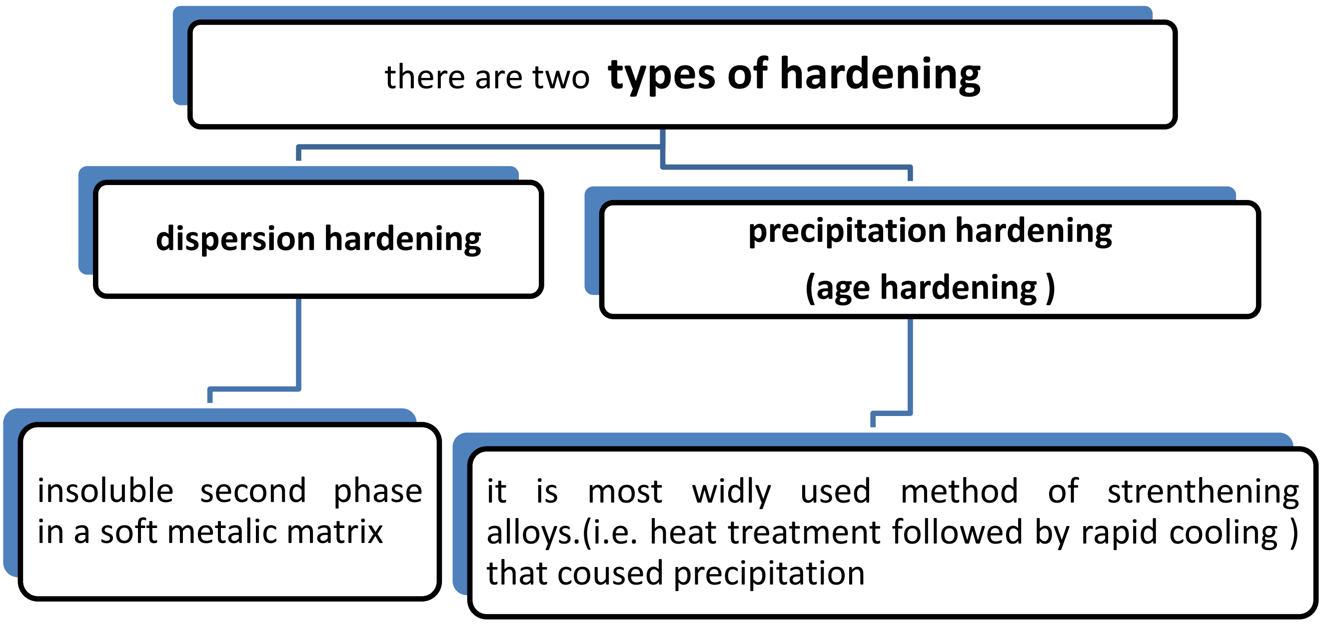
The following formula is used to determine the activity of dispersed particles as obstacle to dislocation movement as following:

$$D_p = \frac{2*d^2}{3*v_p}(1 - v_p)$$

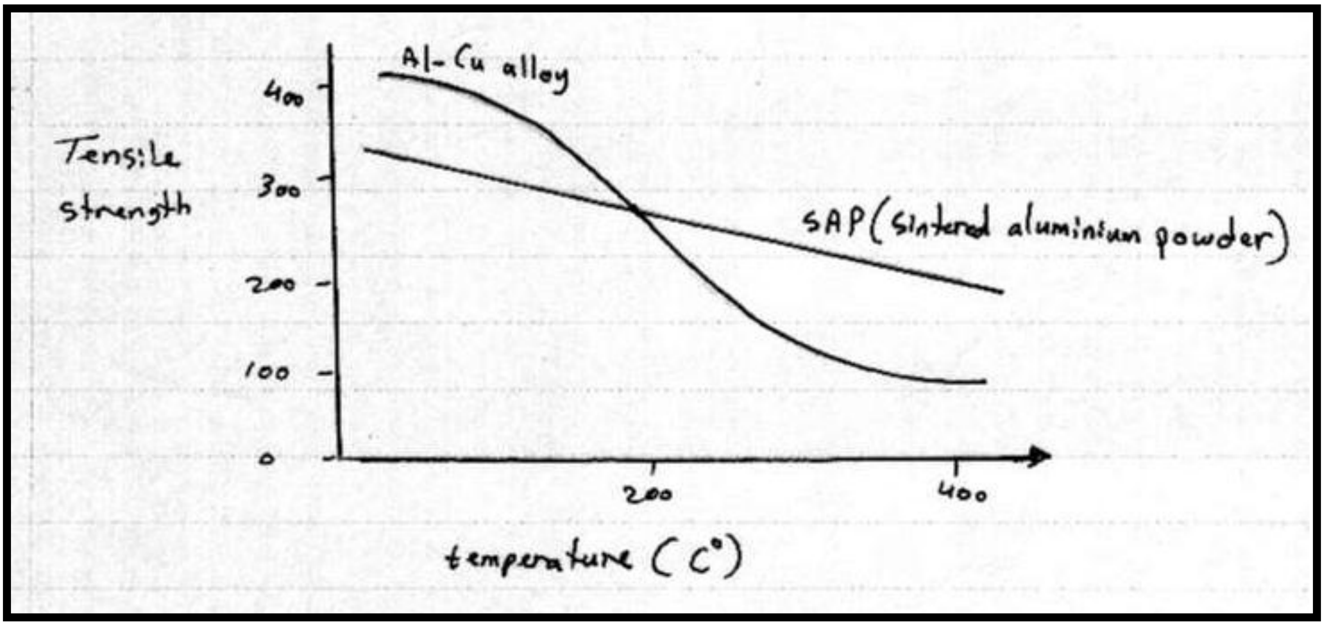
Where - v_p = volume fraction of particles

d = particle diameter

D_p = the distance between particles



The (dispersion) sintered aluminum has advantage over precipitation hardened aluminum alloys in that it retains it strength better at high temperature as showing:-



This is because at the higher temperatures, the precipitate particles in precipitation hardened alloys tend to coalesce or go into solution in the metal. While in dispersion composite material the particle remain (insoluble) to obstacle the dislocation movement.

There are some examples of naturally composite

Wood -
- Matrix (lignin)
- Reinforcement (cellulose fiber)

Bone and teeth -
- Matrix (collagen)
- Reinforcement (Calcium and phosphate ions and hydroxyapatite)

Nano composite :-

Is a multiphase material in which at least one of the phases has at least one dimension in order of nanometers (less than 100nm, i.e. 0.1 µm)

Bone – natural nano composite.

Fibrous Composite

The fibers may be continuous throughout the matrix or short fibers, and aligned in all the same direction or randomly arranged as shown in figure (1).Like glass or carbon fibers in polymers and ceramic fiber in metal.

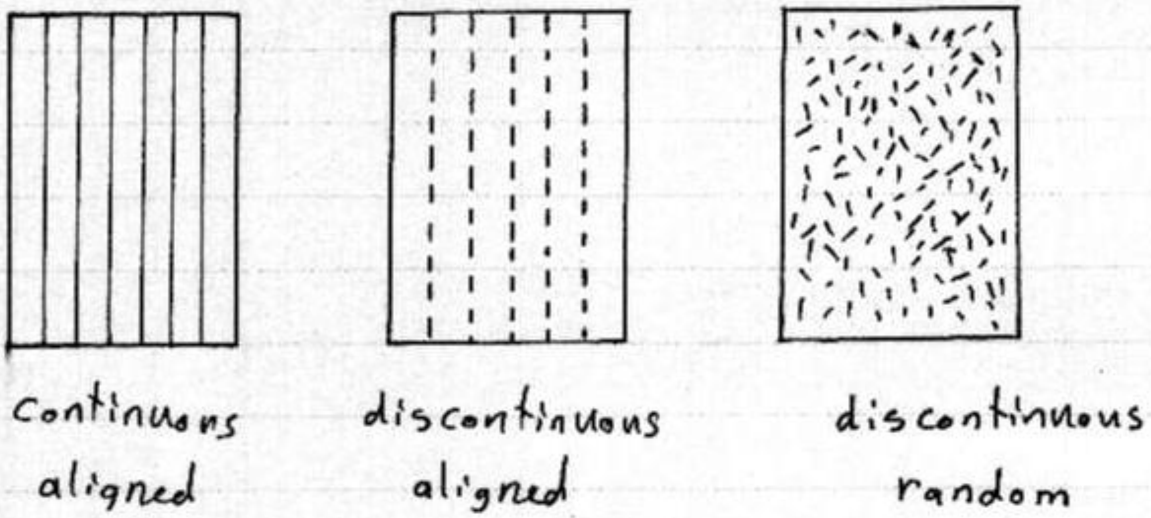


Fig. (1)

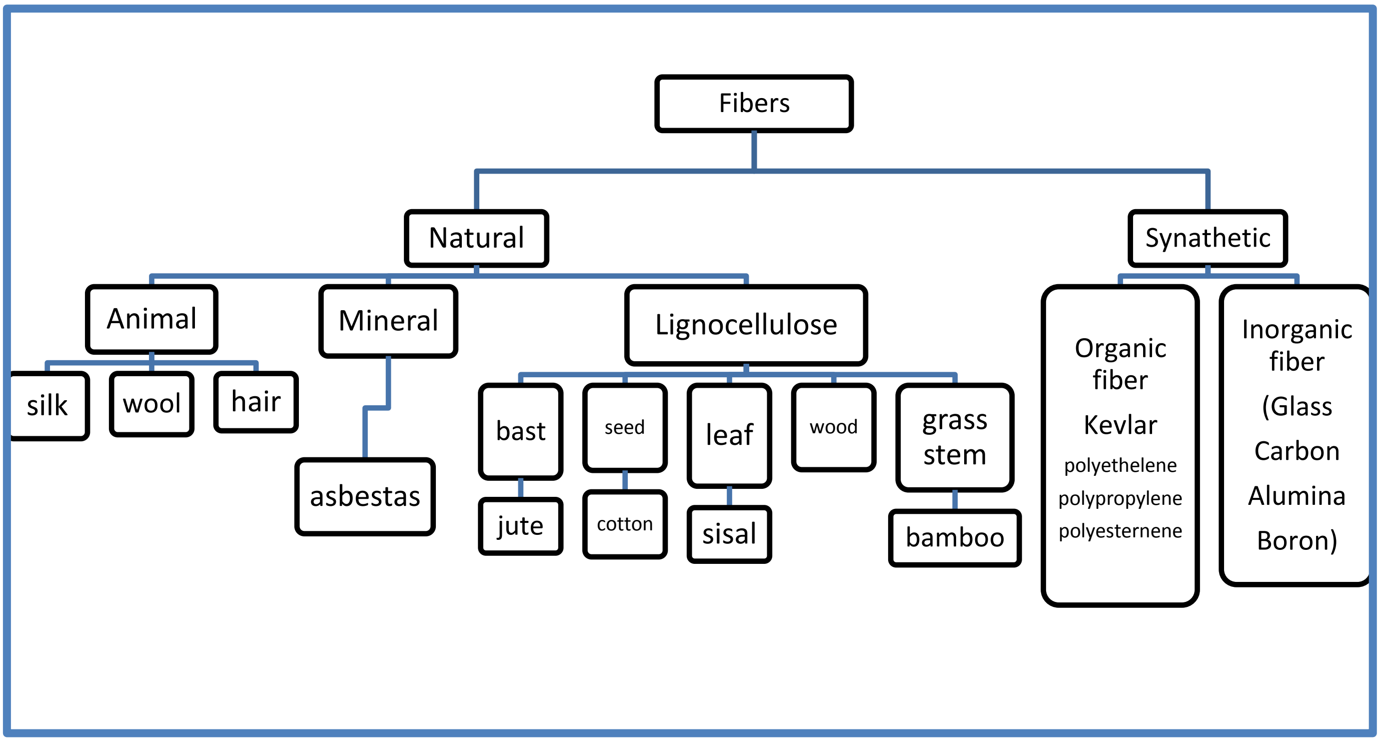
Fibrous form give the rigidity and strength of the composite

Continuous fiber composite: - A composite whose reinforcement is made by fibers of indefinite length .

Discontinuous fiber composite:- A composite whose fibers have a limited length, typically (3-50) mm.

Unidirectional composite:- A composite in which the fibers are aligned according to the principal orientation .

Fibers may be classified according to its nature as following:-



The most **common fibers used for engineering applications** one :-

- Glass
- Carbon (graphite)
- Kevlar (aramid)
- Boron

While the most widely used as a matrix for fibrous composites are epoxy ,polyester and organic " supper polymer " material commonly called plastics.

Properties of fiber

1- High modulus of elasticity.
2- High ultimate strength.
3- Low variation of strength between individual fibers.
4- Uniform fiber cross- section.
5- Stability and retention of strength during fabrication.

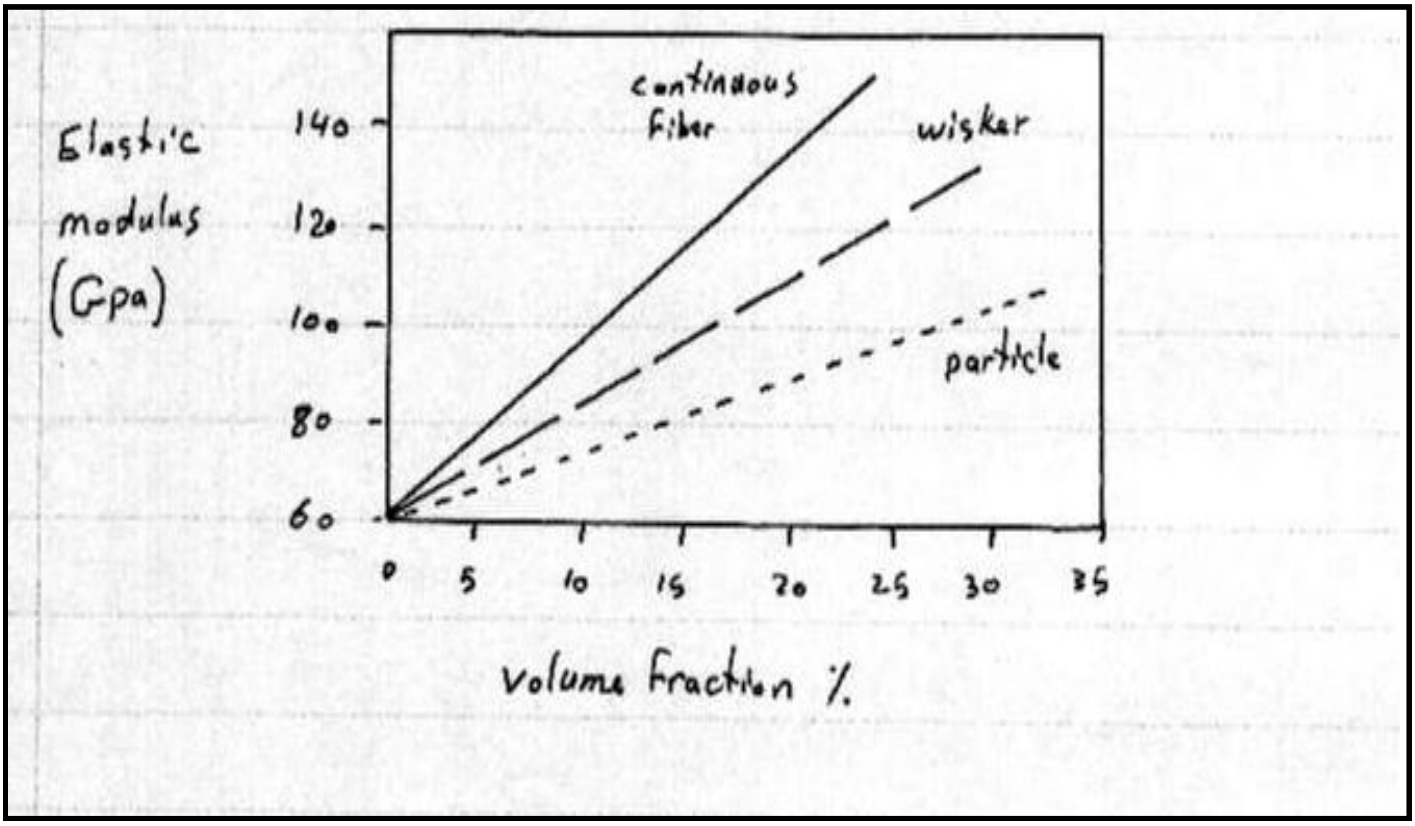
Properties of matrix

1- Low density.
2- Low strength.
3- Bind the fibers together.
4- Transfer the load to the fiber.
5- Stop, to some extent, a crack from propagation.

6- Protect the fibers surfaces from damage in service.
7- Be chemically and thermally compatible with fiber.

Fibers may be wires or wisker (wiskers are very fine fibers have short length to diameter ratio).

The following figure shows the increase modulus with increase the volume fraction for the same reinforcement but different shape (continuous fiber, wisker or particle). This schematic shows the loss of reinforcement efficiency as one goes from continuous fiber to particle.



Rule of mixture in fiber – reinforced composite

As for particulate composites, the rule of mixtures always predicts the density of fiber – reinforced composites.

The mass (m_c) of a composite is made up of masses of the matrix (m_m) and the fiber (m_f) i.e.

$$m_c=m_m+m_f \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots(1)$$

since mass is volume (v) time density (ρ) then equation (1) can be written as :-

$$v_c * \rho_c = v_m * \rho_m + v_f * \rho_f$$

And so :-

$$\rho_c = \frac{v_m}{v_c}\rho_m + \frac{v_f}{v_c}\rho_f$$

$\frac{v_m}{v_c}$ is the matrix volume fraction (V_m)

$\frac{v_f}{v_c}$ is the fiber volume fraction (V_f)

Thus ,

$$\rho_c = V_m * \rho_m + V_f * \rho_f \ldots\ldots\ldots\ldots\ldots\ldots (2)$$

And $V_m=1-V_f$

Therefore equation (2) can be termed a law of mixtures.

In addition, the rule of mixtures accurately predicts the electrical and thermal conductivity of fiber –reinforced composites along the fiber direction

$$K_c=V_m*K_m+V_f*K_f$$

$$\sigma_c=V_m*\sigma_m+V_f*\sigma_f$$

where :- K- is the thermal conductivity

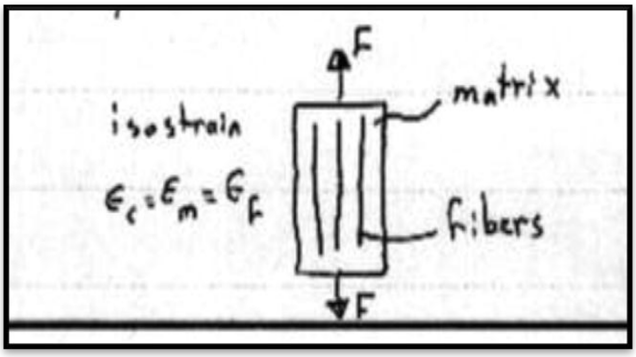
σ - is the electrical conductivity

Modulus of elasticity

The rule of mixtures is used to predict the modulus of elasticity

Parallel to the fiber (along the axis of fibers)

The total force acting on the composite is the sum of the forces carried by each constituent



$$F_c=F_m+F_f$$

Scine, $F= \sigma * A$

$$\sigma_c*A_c=\sigma_m*A_m+\sigma_f*A_f$$

$$\sigma_c = \sigma_m(\frac{A_m}{A_c}) + \sigma_f(\frac{A_f}{A_c})$$

The area fraction (A) equal to the volume fraction (V)

$$\sigma_c=\sigma_m*V_m+\sigma_f*V_f$$

from Hooke's law , $\boldsymbol{\sigma = E*\varepsilon}$, therefore

$$E_c*\varepsilon_c=E_m*\varepsilon_m*V_m+E_f*\varepsilon_f*V_f$$

If the fibers are rigidly bonded to the matrix, both the fibers and matrix must stretch equal a mounts (iso-strain conditions)

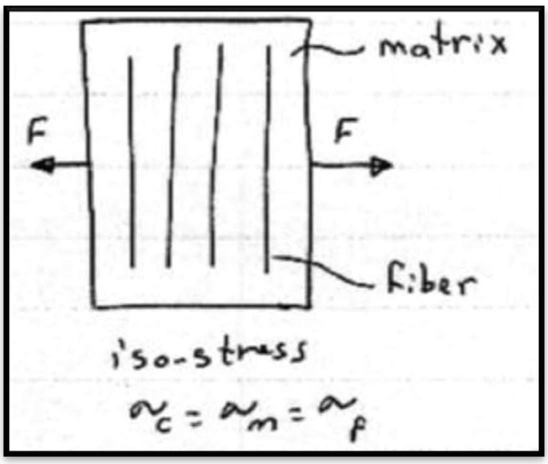
$$\varepsilon_c=\varepsilon_m=\varepsilon_f$$

so, $E_{c,II}=E_m*V_m+E_f*V_f$ *(upper bound)*

The modulus of elasticity may be high .

while in perpendicular direction (at right angle to fiber)

The sum of strains in each component equals to the total strain in the composite, where as the stresses in each component are equal (iso- stress condition).



$$\varepsilon_c=\varepsilon_m*V_m+\varepsilon_f*V_f$$

$$\frac{\sigma_c}{E_c} = \frac{\sigma_m}{E_m} * V_m + \frac{\sigma_f}{E_f} * V_f$$

Science $\sigma_c=\sigma_m=\sigma_f$

$$\therefore \frac{1}{E_{c,\perp}} = \frac{V_m}{E_m} + \frac{V_f}{E_f} \Longrightarrow E_{c,\perp} = \frac{E_m * E_f}{E_m * V_f + E_f V_m} \quad (lower\ bound)$$

It can also be shown, for longitudinal loading that the ratio of load carried by the fibers to that carried by the matrix is:

$$\frac{F_f}{F_m} = \frac{E_f * V_f}{E_m * V_m}$$

This can be proved as following :-

In the longitudinal direction both matrix and fiber have equal strain if bonding is good, so :

$$\varepsilon_c = \varepsilon_m = \varepsilon_f$$

$$\varepsilon_m = \frac{\sigma_m}{E_m} \quad , \quad \varepsilon_f = \frac{\sigma_f}{E_f}$$

$$\therefore \frac{\sigma_m}{E_m} = \frac{\sigma_f}{E_f} \quad , \quad \sigma = \frac{F}{A}$$

$$\frac{F_m}{E_m * A_m} = \frac{F_f}{E_f * A_f}$$

$$\therefore \frac{F_f}{F_m} = \frac{E_f * A_f}{E_m * A_m}$$

Dividing the right side by A_c

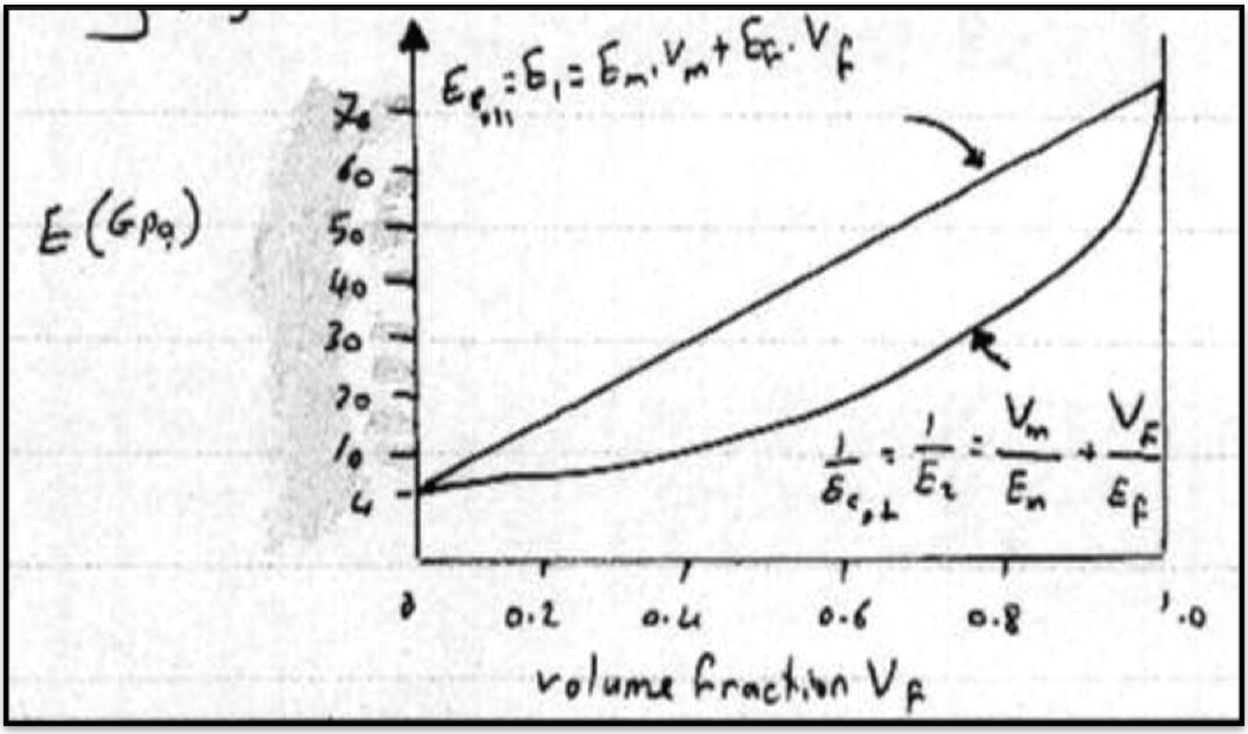
$$\frac{F_f}{F_m} = \frac{E_f * \frac{A_f}{A_c}}{E_m * \frac{A_m}{A_c}}$$

$$V_f = \frac{A_f}{A_c} \quad , \quad V_m = \frac{A_m}{A_c} \quad for\ the\ same\ length\ (L)$$

$$\therefore \frac{F_f}{F_m} = \frac{E_f * V_f}{E_m * V_m}$$

It is represent the ratio of the load carried by the fibers to that carried by the matrix.

According to the formula, the volume fraction has effect on the modulus of elasticity in both directions .For example Rule- of –mixtures Prediction for longitudinal (E_1) and transverse (E_2) modulus for glass- polyester composite (E_f = 73.7 G pa),(Em = 4 G pa) as shown in the following figures .



Note: To calculate the volume fraction of fiber and matrix

1. **<u>In term of weight fraction</u>**

$$V_f = \frac{\rho_c}{\rho_f} . w_f \qquad , \qquad V_m = \frac{\rho_c}{\rho_m} . W_m$$

(w_f) is the **weight fraction of fiber = $\frac{W_f}{W_c}$**

(W_f)means **fiber weight ,** (W_c)means **composite weight**

(w_m) is the **weight fraction of matrix = $\frac{W_m}{W_c}$**

(W_m)**means matrix weight**

2. **<u>In term of volume</u>**

$$V_f + V_m = 1$$

$$V_f = \frac{\nu_f}{\nu_c}$$

$$V_m = \frac{\nu_m}{\nu_c}$$

<u>Example</u> :-_borsic (boron coated with Sic) reinforced aluminum 40 % volume fibers is an important high - temperature .Estimate the density, modulus of elasticity ,and tensile strength parallel to the fiber axis. Also estimate the modulus of elasticity perpendicular to the fibers.

Material	Density g/cm^2	Modulus of elasticity (Gpa.)	Tensile strength Mpa.
Fibers (Borosic)	2.36	380	2760
Matrix(aluminum)	2.7	69	34.5

<u>Solution</u> : $V_f = 0.4$ ⇨ $V_m = 0.6$

From the rule of mixtures

$$\rho_c = \rho_m * V_m + \rho_f * V_f \quad = 2.7*0.6+2.36*0.4=2.56 \text{ g/cm}^3$$

$$E_{c,11} = E_m * V_m + E_f * V_f = 69*0.6+380*0.4=193.4 \text{ GPa}$$

$$T_{Sc} = T_{Sm} * V_m + T_{Sf} * V_f$$

$$= 34.5*0.6+2760*0.4=1124.7 \text{ MPa}$$

Perpendicular to the fibers

$$\frac{1}{E_{c,\perp}} = \frac{V_m}{E_m} + \frac{V_f}{E_f} = \frac{0.6}{69} + \frac{0.4}{380} = 9.75 * 10^{-3}$$

$$\therefore E_{c,\perp} = 102.56 \; GPa$$

Example: - A continuous and aligned glass fiber – reinforced composite consist of (40%) volume fraction of glass fibers having a modulus of elasticity of (69Gpa). ,and (60%) volume fraction of polyester resin , when hardened , displays a modulus of (3.4 GPa).

a) Compute the modulus of elasticity of this composite in the longitudinal direction.
b) If the cross- sectional area is (250 mm^2) and a stress of (50 MPa). Is applied in this longitudinal direction, compute the magnitude of the load carried by each of the fiber and matrix phases.
c) Determine the strain that is sustained by each phase when the stress in part (b) is applied.
d) Compute the modulus of elasticity of this composite in the perpendicular direction.

Solution:-

a) $E_{c,11}=E_m*V_m+E_f*V_f = 3.4*0.6+69*0.4 = 30$ GPa

b) $\frac{F_f}{F_m} = \frac{E_f*V_f}{E_m*V_m} = \frac{69*0.4}{3.4*0.6} = 13.5$

or $F_f = 13.5\, F_m$

$F_c = A_c * \sigma = 250*50 = 12500$ N

This total load is just the sum of load carried by fiber and matrix

$F_c = F_f + F_m$

$13.5\, F_m + F_m = 12500$

$F_m = 860$ N

Where , $F_f = F_c - F_m = 12500-860 = 11640$ N

The fibers support the majority of the load.

c) $A_m = V_m * A_c = 0.6*250 = 150\ mm^2$

$A_f = V_f * A_c = 0.4*250 = 100\ mm^2$

$$\sigma_m = \frac{F_m}{A_m} = \frac{860}{150} = 5.73\ MPa$$

$$\sigma_f = \frac{F_f}{A_f} = \frac{11640}{100} = 116.4\ MPa$$

Finally the strain are computed as :

$$\varepsilon_m = \frac{\sigma_m}{E_m} = \frac{5.73}{3.4 * 10^3} = 1.69 * 10^{-3}$$

And , $\varepsilon_f = \frac{\sigma_f}{E_f} = \frac{116.4}{69*10^3} = 1.69 * 10^{-3}$

$$\varepsilon_c = \frac{\sigma_c}{E_c} = \frac{50}{30 * 10^3} = 1.69 * 10^{-3}$$

d) $E_{c,\perp} = \frac{E_m * E_f}{V_m * E_f + V_f * E_m} = \frac{3.4*69}{0.6*69+0.4*3.4}$

$E_{c,\perp}$ = 5.5 GPa

Ex :- For an glass fiber- epoxy matrix composite with the volume fraction of fiber as (65%). Estimate the modulus of elasticity when the load is at (0^o) with the fibers and the modulus of elasticity when the load is at (90^o) with the fiber.

Note:- modulus of elasticity for epoxy = 3.5 GPa.

modulus of elasticity for glass fiber = 70 GPa.

Solution:-

$E_{c,II}=E_m*V_m+E_f*V_f$ =3.5*0.35+70*0.65= 47 GPa

$$\frac{1}{E_{c,\perp}} = \frac{V_m}{E_m} + \frac{V_f}{E_f} = \frac{0.35}{3.5} + \frac{0.65}{70} = 0.11 \rightarrow E_{c,\perp} = 9\ GPa$$

EX:- Consider a uniaxial fiber reinforced composite of aramid fibers in an epoxy matrix. The volume fraction of fibers is (60 %) .The composite is subjected to an axial strain of (0.1 %) .Compute the modulus and strength along the axial direction of the composite, E_f=140 GPa (aramid fiber), E_m=5 GPa (epoxy)

Solution:-

$E_{c,II}= E_f*V_f+ E_m*(1-V_f)$

$= 140*0.6+5*0.5 =86$ GPa

$$\sigma_{c1} = \varepsilon * E$$

$$= 0.001 * 86 = 86 \quad MPa$$

Example :-what is the ratio of the longitudinal modulus of elasticity to the transverse modulus for a composite with continuous aligned fiber constituting (50 %) of the volume if the tensile modulus of the fiber (50 times) that of the matrix .

Solution :-

$E_{c,11}=E_m*V_m+E_f*V_f$

$= E_m*0.5+50\ E_m*0.5= 25.5\ E_m$

a) $$E_{c,\perp} = \frac{E_f*E_m}{E_m*V_f+E_f*V_m}$$

$$= \frac{50\text{ Em}* \text{Em}}{\text{Em}*0.5+50\text{ Em}*0.5} = \frac{50\text{ Em}}{25.5}$$

$$\therefore \frac{\text{Ec,II}}{E_{c,\perp}} = \frac{25.5\text{ Em}+25.5}{50\text{ Em}} \quad = \frac{650.25}{50} = 13.005$$

Ex:- A composite material has a longitudinal modulus of elasticity of (18.2 GPa). Containing unidirectional S – glass fibers in on epoxy matrix. Determine,

a) Volume fraction of glass fiber and the epoxy matrix.
b) The density of the composite.
c) The ratio of load carried by the fibers to that carried by the matrix.

Note :- Density of epoxy = 1.3 gm/cm^3

Density of glass = 2.2 gm/cm^3

Modulus of epoxy = 2.75 GPa.

Modulus of glass =380 GPa.

Solution :-

a) $E_c=E_m*(1-V_f)+E_f*V_f$

$18.2=2.75*(1-V_f)+380*V_f$

$V_f=0.041 \Longrightarrow V_{m=}(1-V_f)=0.959$

b) $\rho_c = \rho_m * V_m + \rho_f * V_f$

$=1.3*0.959+2.2*0.041$

$=1.2467+0.9902=1.3369$ gm/cm^3

c) $\frac{F_f}{F_m} = \frac{E_f*V_f}{E_m*V_m} = \frac{380*0.041}{2.75*0.959} = 5.91$

Principles of fiber reinforcement

Many factors must be considered when designing a fiber – reinforced composite, including the length , diameter , orientation , amount , properties of the fibers, properties of matrix and the bonding between fibers and matrix .

Influence of fiber length

Length of short discontinuous fibers has greater effect on the properties of the composite materials.

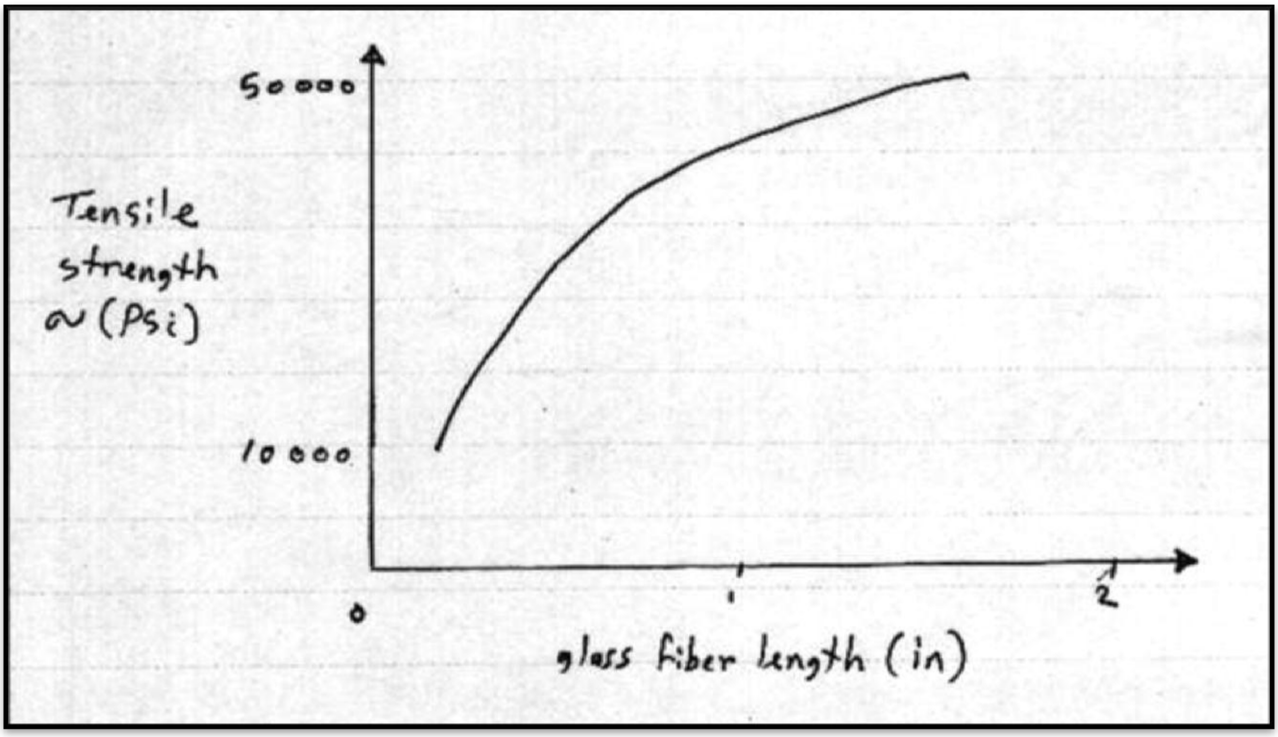
Fibers dimensions are often characterized by the aspect ratio ($\frac{l}{d}$) where

l - Fiber length

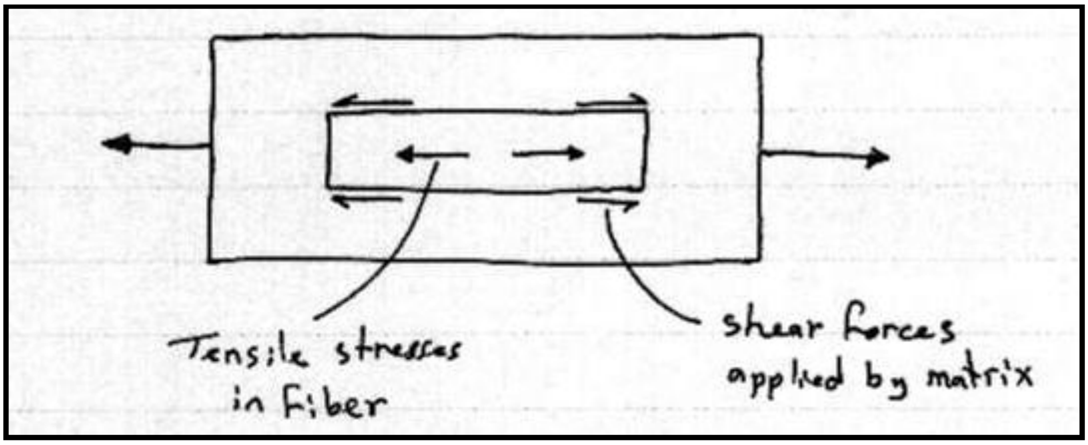
d - Fiber diameter

The strength of composite improves when the aspect ratio is large.

For example increasing the length of chopped E – glass fibers in an epoxy matrix increases the strength of the composite. as shown in figure below :



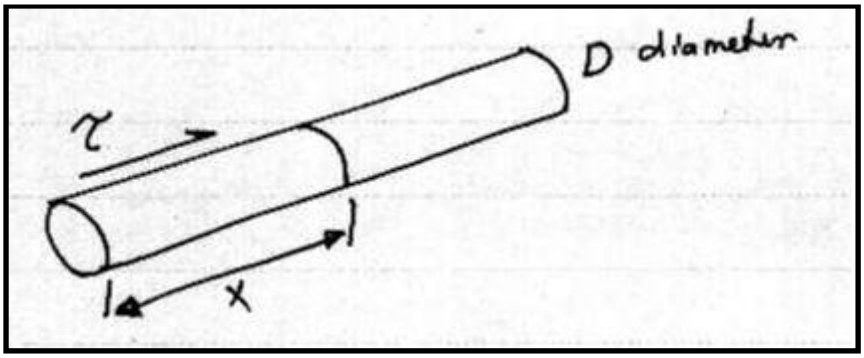
When a load is applied to a composite it is applied to the matrix and transferred to the fibers by some combination of shear and tensile stresses acting across the interface. as showing in following figure .



The discontinuous fiber in the matrix stretched as a result of interfacial shear stresses acting on the surfaces of the fiber.

Theses shear stresses will be maximum at the ends of the fiber. While the tensile stresses is zero at the ends and maximum at the middle.

Consider the interfacial shear stress acting on single fiber in a matrix in the following figure.



If (τ) is the average interfacial shear stress, then the shear force acting on a section of the fiber length (x) and of uniform cross-sectional diameter (D) is the:

Shear force =shear stress * area

$$= \tau * \pi D x$$

This shear force is equal to normal force on the fiber, therefore

$$\sigma_f * \frac{1}{4}\pi D^2 = \tau * \pi D x$$

and so $$\sigma_f = \frac{4\tau x}{D}$$

The stress increases from zero at the end of a fiber, i.e. When (x=0) , to its maximum possible value when ($X=\frac{1}{2}L_c$)

Hence , the maximum value of the tensile stresses is given by:

$$\text{Maximum } \sigma_f = \frac{2 * \tau * Lc}{D}$$

Then the critical fiber length (L_c), for any given fiber diameter (D) can be determined

$$L_C = \frac{\sigma_f * D}{2 * \tau}$$

Critical length :- It is the minimum length at which the tensile stress in the fiber reaches the maximum value.

If the fiber length ($L=L_C$)

The stress position profile shown in fig. (1,a).it can be seen that the maximum fiber load is achieved only at the axial center of the fiber.

If the fiber length ($L > L_C$)

The fiber reinforcement becomes more effective as shown in fig. (1,b).

If the fiber length ($L < L_C$)

It is observing little reinforcing effect as shown in fig. (1,c).

When fibers have length($L >> L_C$) (normally $L >> 15L_C$)

Are termed continuous.

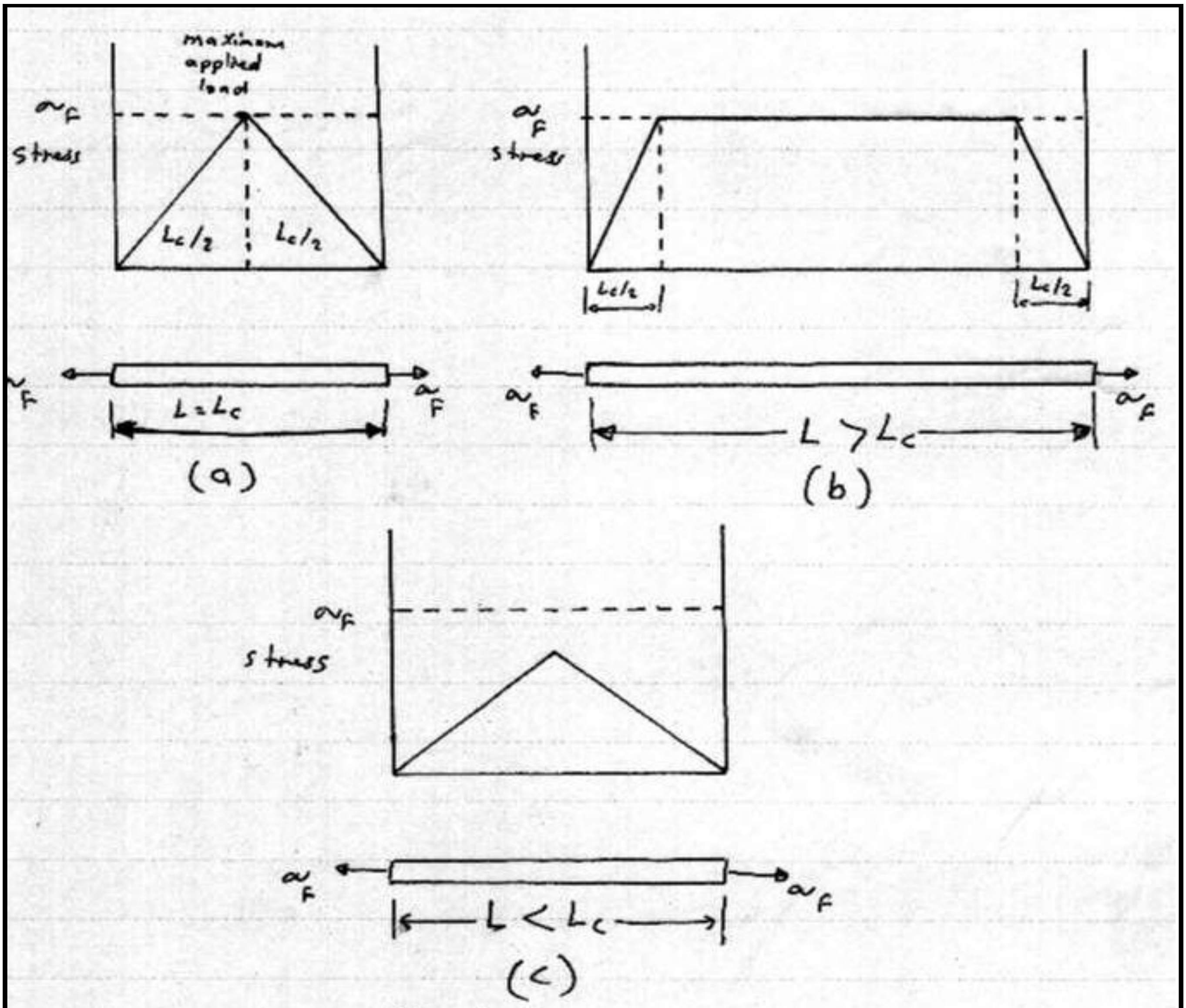


Fig.(1)

Summary

For $L<L_C$ strength is relatively low (low effective)

For $L=L_C$ moderate strength

For $L>L_C$ strength is relatively high (more effective)

For $L>>L_C$ ($L>15L_C$) strength equivalent to iso- strain model

(Continuous)

Calculations of Average Stress

Average stress = $\left[1-\frac{Lc}{2L}\right]\frac{2\tau Lc}{D}$ $\quad for \quad L > Lc$

$$= \left[1-\frac{L_C}{2L}\right] * \sigma_{f\ max}$$

Average stress $= \frac{\tau Lc}{D}$ $\quad for \quad L = Lc$

Average stress $= \frac{\tau Lc}{D}$ $\quad for \quad L < Lc$

Calculation of the Strength of the Composite

$$\sigma_C = V_f * \sigma_f * \left[1-\frac{L_C}{2L}\right] + V_m * \sigma_m \quad when \quad L \geq L_C$$

$$\sigma_C = V_f * \sigma_f * \left[\frac{L}{2L_C}\right] + V_m * \sigma_m \quad when \quad L \leq L_C$$

$$\sigma_C = \frac{V_f * \sigma_f}{2} + V_m * \sigma_m \quad when \quad L = L_C$$

Example:- A glass fiber polyester composite contains (60%) by volume of fibers. The fibers being of length (3mm) with diameter (0.005mm). If the failure stress for the fibers is (1500 MPa), the shear strength (25 MPa), and the matrix has a tensile strength of (50 MPa) . Determine:

- Critical length of the fiber
- Max. average stress
- Strength of the composite

And compare the strength when used a continuous fiber, and when used fiber equal to critical length.

Solution

$$Lc = \frac{\sigma_f * D}{2\tau} = \frac{1500 * 0.005}{2 * 25} = 0.15mm$$

Max. average stress $= \left[1 - \frac{L_C}{2L}\right] * \sigma_{f\ max} = \left[1 - \frac{0.15}{6}\right] * 1500 = 1462.5\ MPa$

Hence, the strength of the composite is:

$$\sigma_C = V_f * \sigma_f * \left[1 - \frac{L_C}{2L}\right] + V_m * \sigma_m$$

$$= 0.6 * 1500 \left[1 - \frac{0.15}{2*3}\right] + 0.4 * 50 = 897.5\ MPa$$

When used a continuous fiber

$$\sigma_c = V_f * \sigma_f + V_m * \sigma_m = 0.6 * 1500 + 0.4 * 50 = 920\ MPa$$

When used a critical length

$$\sigma_C = \frac{V_f * \sigma_f}{2} + V_m * \sigma_m = \frac{0.6 * 1500}{2} + 0.4 * 50 = 470\ MPa$$

Example:- The longitudinal modulus of elasticity for an aligned discontinuous fiber composite if the fibers constitute (40%) of the volume fraction is equal to (131GPa) , the fibers have a modulus of elasticity of (400GPa),and the matrix modulus of (5GPa) . Calculate the critical length, if the length of the fiber = (2 mm) and the critical length is less than the fiber length.

Solution:

$$E_c = E_m * V_m + \left[1 - \frac{L_c}{2L}\right] E_f * V_f$$

$$131 = 5 * 0.6 + \left[1 - \frac{L_c}{2 * 2}\right] * 400 * 0.4$$

$$\therefore L_c = 0.8\, mm$$

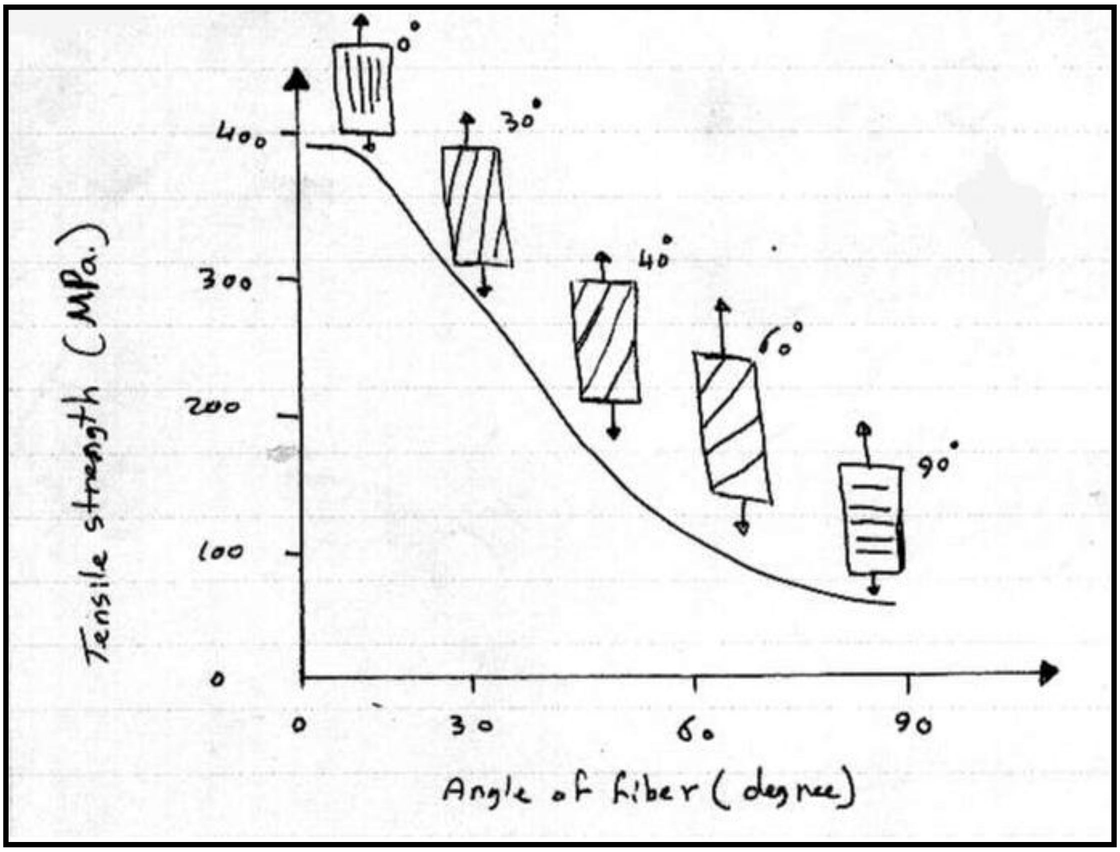
- Influence of volume fraction of fibers

A greater volume fraction of fibers increases the strength and stiffness of the composite, as expected from the rule of mixtures. Howerer, the maximum volume fraction is about (80%) beyond fibers can no longer be completely surround be the matrix.

- Influence of fiber orientation and concentration

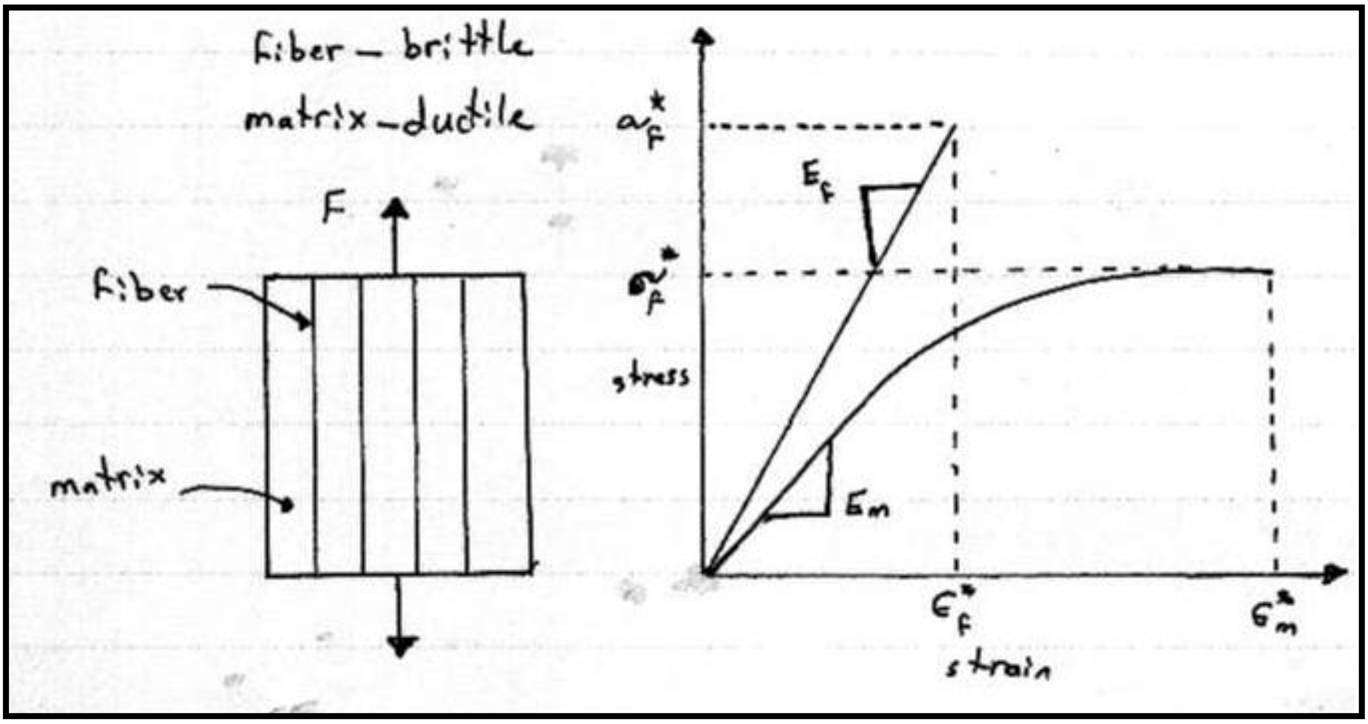
The arrangement or orientation of fibers, fiber concentration and the distribution all have a significant influence on the strength and other properties of fiber –reinforced composite.

Unidirectional arrangements of fibers properties give good strength these happen at (0^o). From the following figure, it can be seen the effect of fiber angle on the tensile strength. However, unidirectional orientations provide poor properties if the load is perpendicular to the fiber.

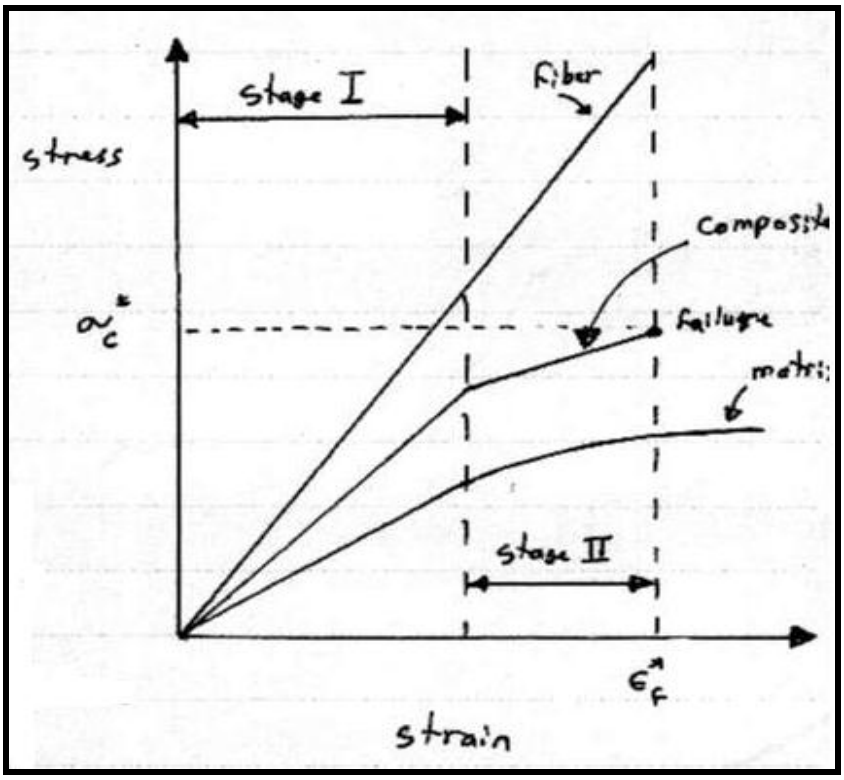


Stress-Strain behavior of aligned fiber composite

The following figure represented schematically stress-strain behaviors for the fiber and matrix (loaded in the longitudinal direction).



- In the stage I region,
  Both fibers and matrix deform elastically.
- In stage Π
The matrix starts to yield as the fibers continue to deform elasticity.
-The onset of composite failure begins as fibers start to fracture.



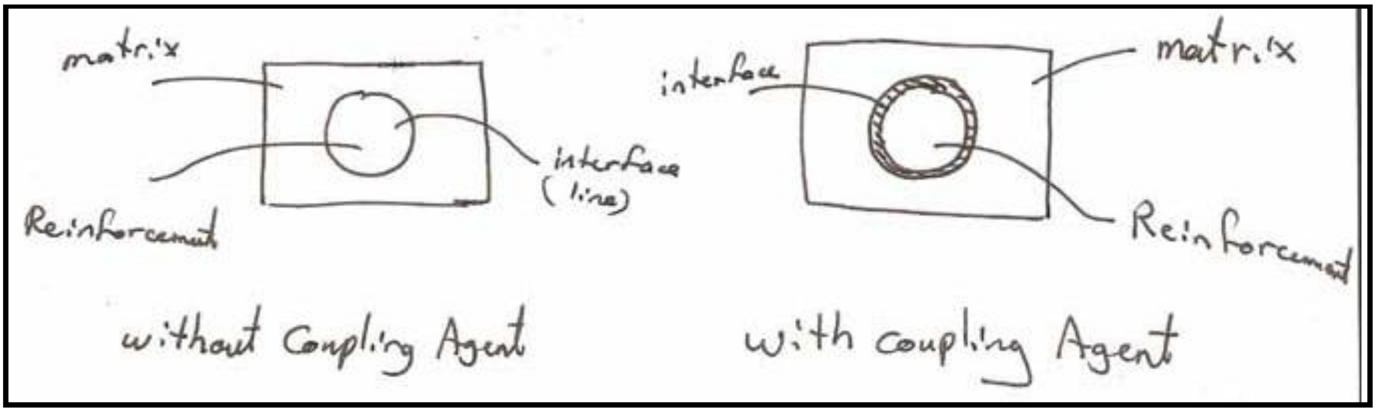
Therefore in composites the main causes of failure can be:

a) Breaking of fibers.
b) Deboning (separation of fibers and matrix).
c) Micro cracking of the matrix.
d) Delamination.

Components of composite materials

1. Matrix
2. Reinforcement
3. Interface

The interface is a bonding surface or zone between the reinforcement and matrix.

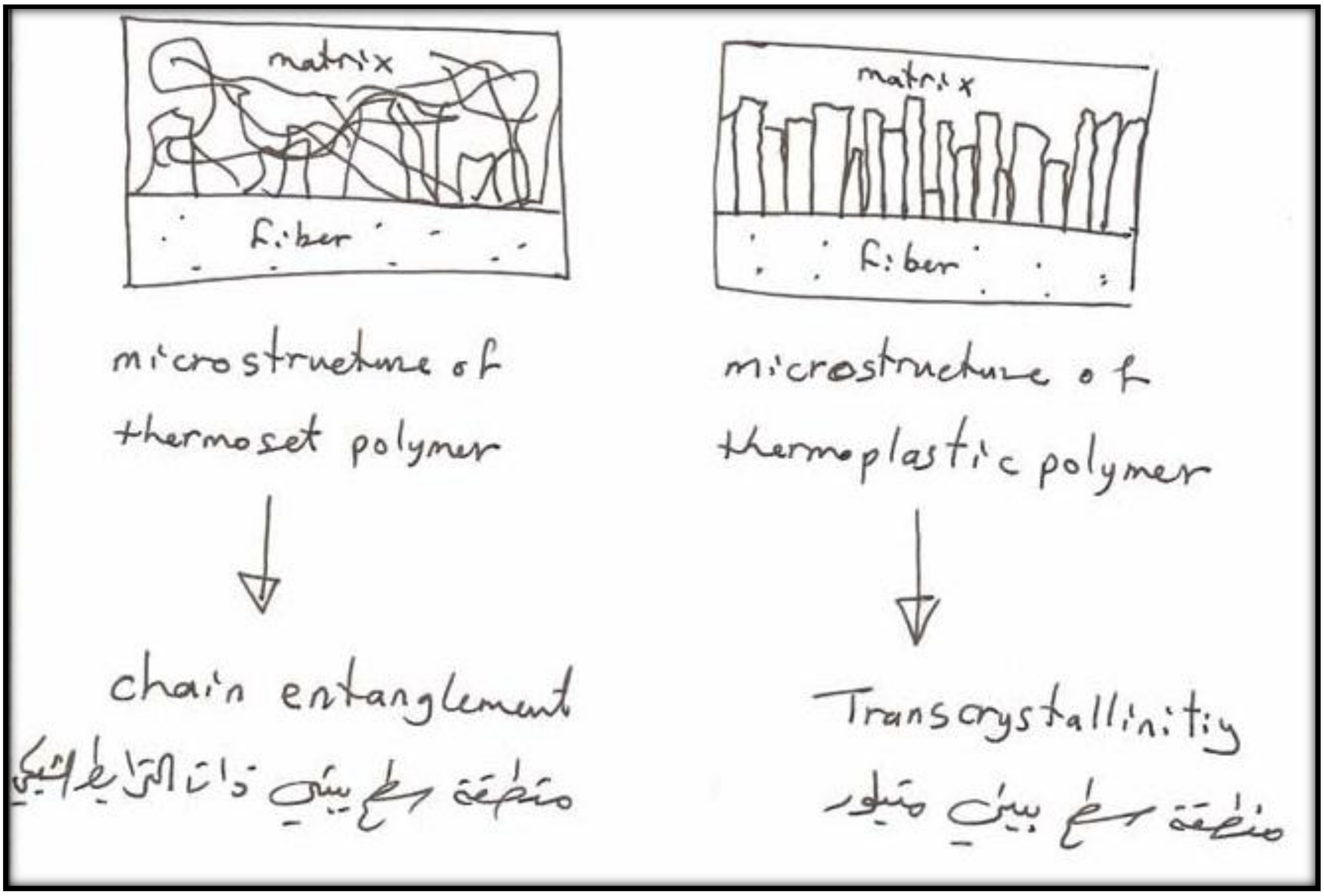


- The matrix material must "wet " the reinforcement. Coupling agents are frequently used to improve wettability.

(Wetted reinforcement increase the interface surface area and bonding).

- The applied load is transfer from matrix to the reinforcement via the interface. This means that the interface must be larger and exhibit strong adhesion between the reinforcement and matrix.
- Coupling Agents form the interphase which has different mechanical properties from that of matrix and reinforcement.

There for the mechanical properties depend on the properties of the interphase also .



The General Requirement of the interphase

- Big bond
- chemical stability

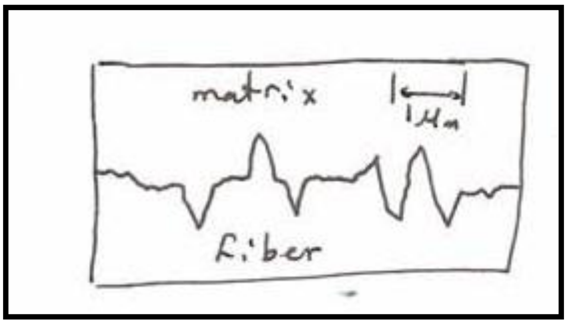
} In order to carry the load from the matrix to reinforcement

Therefore the interphase depend on

1) Reinforcement shape.
2) Surface roughness of the reinforcement.
3) Treated the surface by coupling agent (wettability).

Types of bond

1) Mechanical bond



That depends on surface roughness

2) chemical bond

عن طريق الترابط بأواصر تساهمية أو أيونية أو معدنية

When the wettability increase → increase chemical bonding.

- Failure at the interface (called deboning)
- The interfacial strength (max. shear stress)

Adhesion failure between the reinforcement and matrix is measured by three - point bending test by founding max. Shear stress (τ_{max}).

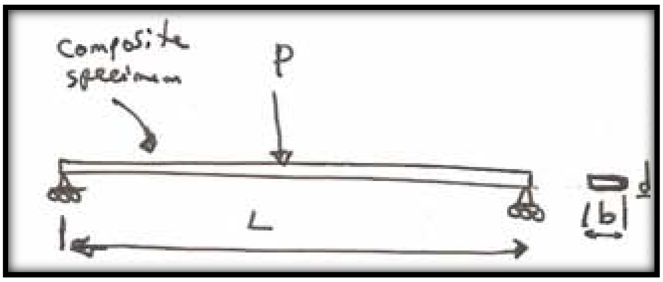
$$\tau_{max} = \frac{3P}{4bd} \qquad (MPa)$$

Where:-

P= force at the fracture (N).

b = width of the composite specimen (mm).

d = thickness of the composite specimen (mm).



Advantages of composite Materials

1) High resistance to fatigue and corrosion degradation.
2) High strength - to - weight ratio, as shown in the following table.

Material	Strength (lb/in^2)	Density (lb/in^3)	Strength-to-weight ratio (in)
Poly ethylene	1000	0.030	$0.03*10^6$
Pure aluminum	6500	0.098	$0.07*10^6$
Epoxy	1500	0.050	$0.3*10^6$
Alloy steel	240000	0.28	$0.86*10^6$
Aluminum alloy	86000	0.098	$0.88*10^6$
Titanium alloy	170000	0.16	$1.06*10^6$
Carbon-carbon composite	60000	0.065	$0.92*10^6$
Carbon-epoxy composite	80000	0.050	$1.6*10^6$

3) Due to greater reliability, there are fewer structural repair.
4) Composite are dimensionally stable, i.e. they have low thermal conductivity and low coefficient of thermal expansion.
5) Manufacture and assembly are simplified.

Limitation of Composite Materials

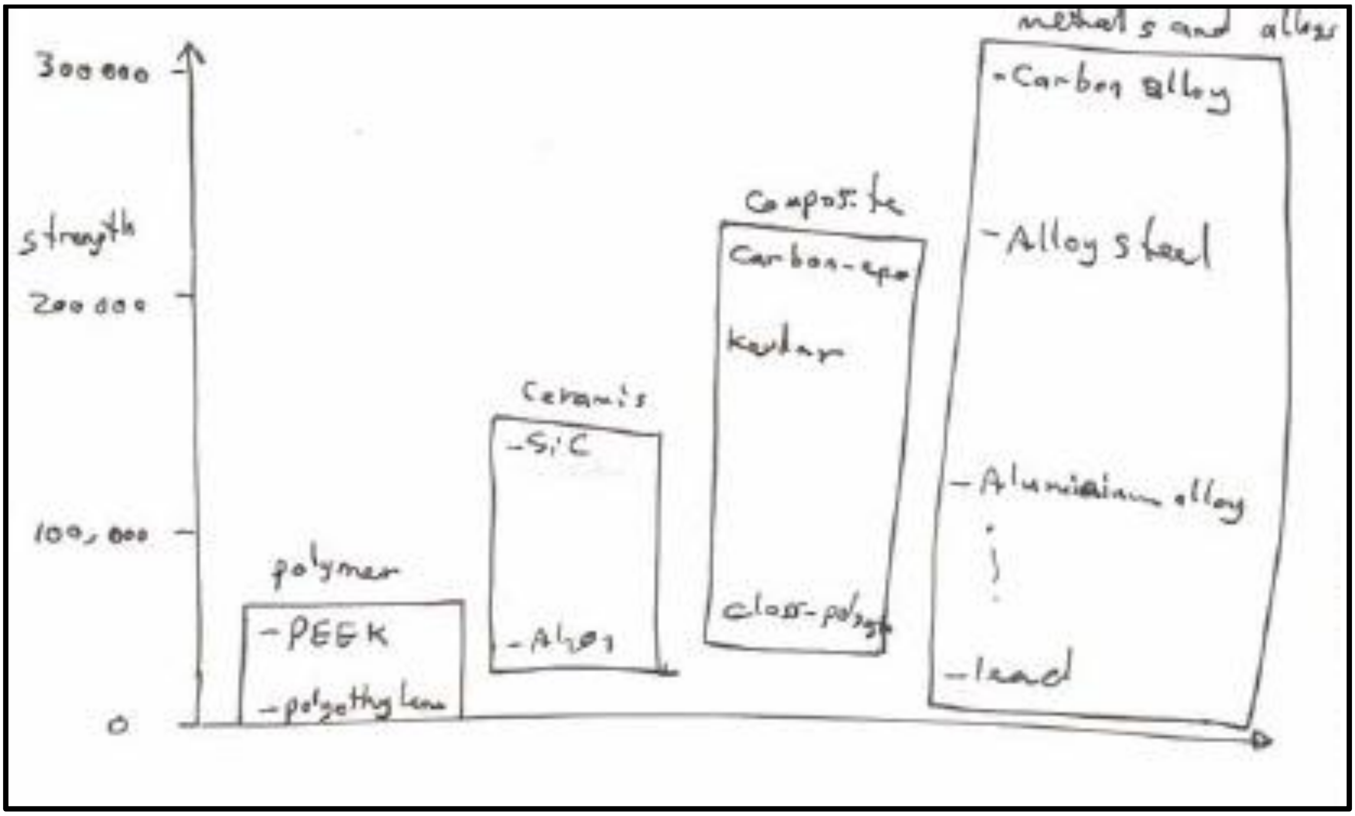
1) High cost of raw materials and fabrication.
2) Composites are more brittle than metals and thus are more easily damaged.
3) Transverse properties may be weak.
4) Reuse may be difficult.
5) Difficult to attach.
6) Analysis is difficult.

Comparison between Composite and Metals

1) Composites offer significant weight saving over existing metals. Composite can provide structures that are (25-45%) lighter than the conventional metal structure for the save functional requirement. This is due to lower density of the composites.

i.e. densities of composites range from (1.26-1.82 gm/cm^3) as compared to (2.8 gm/cm^3) for aluminum.

2) Unidirectional fiber composite have specific tensile strength (ratio of material strength to density) about (4- 6) times greater than that of steel and aluminum.
3) Unidirectional composites have specific – modulus (ratio of the material stiffness to density) about (3 -5) times greater than of steel and aluminum.



Durability of Polymer Composites

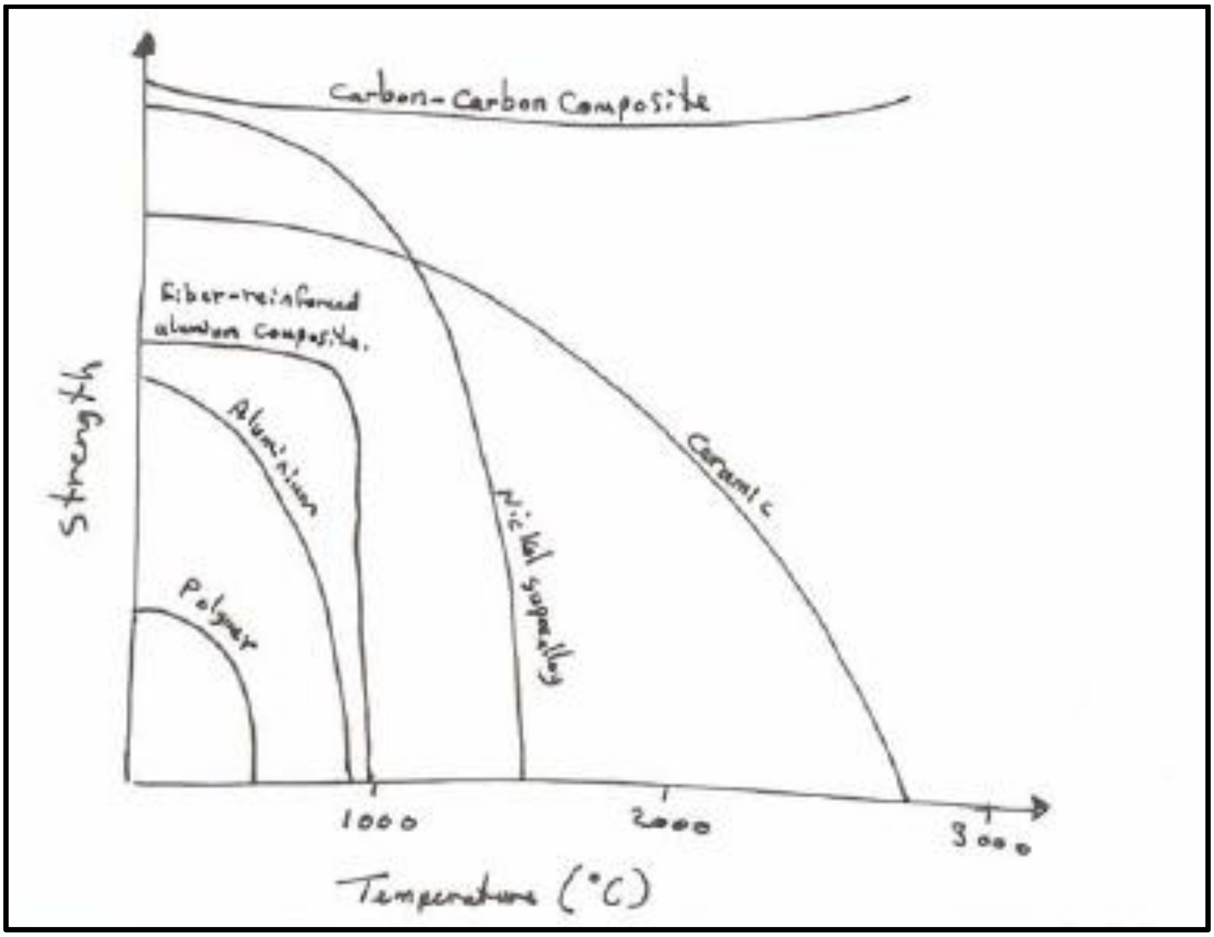
Polymer composites change with time and most significant factors are:-

1) Elevated temperature.
2) Fire.
3) Moisture.
4) Adversed chemical environments.
5) Natural weathering when exposed to sun's ultra- violet radiation.

Temperature

- ❖ Fluctuating temperature have greater deterioration effect on the properties of composites. Different in coefficient of thermal expansion coefficient of reinforcement and matrix may cause deponding.
- ❖ Exposed to high temperatures lead to discoloration of the resin becoming yellow. As a result of exposure to high temperature, the composite becomes brittle.

- ❖ The effect of temperature on strength of materials represented by the following figure.



Fire

A composite material must meet appropriate standards of fire performance.

- Aluminum trihydrate
- Antimony trioxide

Are used as fillers to enable flame – retardant properties

Moisture

Polymer absorbs water which may cause a decrease in strength and modulus of elasticity. Absorption of water by polyesters and epoxies lead to swelling of laminate.

Water will also cause some surface flaws on fibers, long-term of water absorption may cause weakening of the bond between fiber and polymer.

Weathering

Natural weathering can affect mechanical properties of composite through surface deboning.

Because of weathering is surface effect, thickness of laminate becomes important.

3mm thickness ⟹ (12-20%) reduction in flexural stress after 15 years

10 mm thickness ⟹ ~ 3% reduction in flexural stress after 50 years

Disadvantages of polymers in construction are

1) High cost of materials.
2) Low stiffness and strength.
3) Poor scratch resistance.
4) Degradation under UV light (stabilizers used)
5) Low resistance to fire and high temperature (additive used).

The most fibers used in composite material are :-

1) Glass fiber

- The most common and inexpensive fiber, usually used for the reinforcement of polymer matrices.
- Typical composition is (50-60% SiO_2), and other oxides of (Al, Ca, Mg, Na,…….etc.).
- Glass fibers are available as:-
  a) Chopped strands.
  b) Continuous yarn.
  c) Roving.
  d) Fabric sheet.
- Properties of Glass fiber
  - Good dimensional stability.
  - Resistant to heat.
  - Strength - to – density is high.

2) Carbon fibers

a) Carbon is very light element, with density about (2.39 gm/cm^3).
b) Carbon has excellent compression properties.
c) Good thermal properties.
d) Carbon fiber adds electrical conductive properties to composite.

3) <u>Ceramic fiber</u>

- Such as
  - Alumina (Al_2O_3)
  - Silicon carbide (SiC)
- It is used in very high temperature applications.
- It has poor properties in tension and shear.

4) <u>Metallic fiber</u>

- Such as steel and tungsten.
- Have high strength.
- Density is very high for these fibers.

5) <u>Natural fibers</u>

- Cotton
- Flax
- Jute
- Hemp
- Ramie
- Wood
- Straw
- Hair
- Wool
- Silk