MATERIALS OF CONSTRUCTION

Introduction

The engineering structures are composed of materials. These materials are known as the engineering materials or building materials or materials of construction. It is necessary for the civil engineer to become conversant with the properties of such materials.

The service conditions of buildings demand a wide range of materials and various properties such as water resistance, strength, durability, temperature resistance, appearance, permeability, etc. are to be properly studied before making final selection of any building material for a particular use.

Classification of Engineering material

The factors which form the basis of various systems of classifications of materials in material science and engineering are: (i) the chemical composition of the material, (ii) the mode of the occurrence of the material in the nature, (iii) the refining and the manufacturing process to which the material is subjected prior it acquires the required properties, (iv) the atomic and crystalline structure of material and (v) the industrial and technical use of the material.

Common engineering materials that falls within the scope of material science and engineering may be classified into one of the following six groups:

(i) Metals (ferrous and non-ferrous) and alloys

(ii) Ceramics

(iii) Polymers

(iv) Composites

NOTES:
(vii) Advanced Materials

Properties of Engineering Materials

It is possible to classify material properties as follows:

1- **Physical properties:**

Density, specific gravity, porosity, water absorption, etc.

2- **Mechanical properties:**

Tensile strength, compressive strength, rigidity, hardness. Creep, fatigue, etc.

3- **Thermal properties:**

Thermal conductivity, thermal expansion and other.

4- **Chemical properties:**

Resistance to acids, alkalis, brines and oxidation.

5- **Economic characteristics:**

Cost savings

6- **Aesthetic properties:**

Color, surface smoothness, the reflection of light...

Physical properties

**Density** \(( \rho )\): Density is defined as mass per unit volume for a material. The derived unit usually used by engineers is the \( \text{kg/m}^3 \). Relative density is the density of the material compared with the density of the water at 4°C.
The formula of density and relative density are:

Density of the material \( (\rho) = M / V \)

Relative density \((d) = \text{Density of the material} / \text{Density of pure water at } 4^\circ\text{C}\)

where;

\(M\) is material mass \(g, \text{kg}, \ldots\) etc

\(V\) is material volume \(m^3, \text{cm}^3, \ldots\) etc

Density units: \(\text{kg/m}^3, \text{gr/cm}^3, \ldots\) etc

There are two types of density:

1- bulk density \(\rho_b\): It is the ratio of material mass to total volume of material, including spaces.

\[ \rho_b = \frac{M}{V} \]

\[ V = V_s + V_v \]

• \(V_s = \text{Volume of solids}\)

• \(V_v = \text{volume of voids}\)

\(V, M = \text{total volume and total mass}\)

• \(M = M_s + M_w\)

• \(M_s = \text{solid Mass}\)

• \(M_w = \text{water mass}\)

Table (1) gives densities for some materials in \(\text{kg/m}^3\).

<table>
<thead>
<tr>
<th>Materials</th>
<th>Bulk density (kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brick</td>
<td>1700</td>
</tr>
<tr>
<td>Mastic asphalt</td>
<td>2100</td>
</tr>
<tr>
<td>Cement:sand</td>
<td>2306</td>
</tr>
<tr>
<td>Glass</td>
<td>2520</td>
</tr>
<tr>
<td>Concrete 1:2:4</td>
<td>2260</td>
</tr>
</tbody>
</table>

NOTES:
2-Solid density $\rho_s$

It is the ratio of the mass of solid material to the volume of solid material without any spaces.

$$\rho_s = \frac{M_s}{V_s}$$

**Unit weight $\gamma$**

It is the ratio of material weight to material volume.

$$\gamma = \frac{W}{V}$$

$\gamma$ = Unit weight ($N/mm^3$)  
$W$ = weight ($N$)  
$V$ = volume ($m^3$)  

$$\gamma = \frac{(M \cdot g)}{V} \quad \gamma = \rho \cdot g$$

$\gamma$ is the specific weight of the material (weight per unit volume, typically N/m$^3$ units)  
$\rho$ is the density of the material (mass per unit volume, typically kg/m$^3$)
4- specific gravity( $G_s$)
A ratio of solid density of material and density of distilled water at a temperature of $4^\circ C$.

$$G_s = \frac{\rho_s}{\rho_w}$$

**porosity (n)**
It is the ratio of the volume of the spaces in the material to the overall volume.

$$n = \frac{V_v}{V}$$

$V_v =$ volume of voids

**voids ratio (e)**
It is the ratio between the size of voids to the volume of solid material.

$$e = \frac{V_v}{V_s}$$

**Water absorption**
It denotes the ability of the material to absorb and retain water. It is expressed as a percentage in weight or of the volume of dry material:

$$W_w = \frac{M_1 - M}{M} \times 100$$

$$W_v = \frac{M_1 - M}{V} \times 100$$

where $M_1 =$ mass of saturated material (g)

$M =$ mass of dry material (g)

$V =$ volume of material including the pores (mm$^3$)

Water absorption by volume is always less than 100 per cent, whereas that by weight of porous material may exceed 100 percent.
The properties of building materials are greatly influenced when saturated. The ratio of compressive strength of material saturated with water to that in dry state is known as coefficient of softening and describes the water resistance of materials. For materials like clay which soak readily it is zero, whereas for materials like glass and metals it is one. Materials with coefficient of softening less than 0.8 should not be recommended in the situations permanently exposed to the action of moisture.

**Weathering resistance**
It is the ability of a material to endure alternate wet and dry conditions for a long period without considerable deformation and loss of mechanical strength.

**Water permeability**
It is the capacity of a material to allow water to penetrate under pressure. Materials like glass, steel and bitumen are impervious.

**Frost Resistance**
It denotes the ability of a water-saturated material to endure repeated freezing and thawing with considerable decrease of mechanical strength. Under such conditions the water contained by the pores increases in volume even up to 9 percent on freezing.

**Mechanical Properties**
The properties which relate to material behavior under applied forces define as mechanical properties. The common mechanical properties: Tensile strength, compressive strength, rigidity, hardness. Creep, fatigue ...... etc.

- **Strength** is the ability of the material to resist failure under the action of stresses caused by loads.
- **Stress** ($\sigma$) is the applied force $P$ divided by the original area $A_o$.

$$ (\sigma = \frac{P}{A_o}) $$

See Fig.1.

**NOTES:**
There are several types of stress which depend on types of applied load. These stresses can be classified as:

1- Compression stress
2- Tension stress
3- Shear stress
4- Bending stress
5- Torsion stress

When bar is stretched, stresses are tensile (taken to be positive)
If forces are reversed, stresses are compressive (negative)

**Example**: Steel bar has a circular cross-section with diameter $d = 50$ mm and an axial tensile load $P = 10$ kN. Find the normal stress.

$$\sigma = \frac{P}{A_o} = \frac{P}{(\pi d^2 / 4)} = \frac{4(10 \times 10^3)}{\pi (50 \times 10^{-3})^2} \frac{N}{m^2} = 5.0929 \times 10^6 \frac{N}{m^2}$$

Units are force per unit area = N / m$^2$ = Pa (pascal). One Pa is very small, so we usually work in MPa (mega-pascal, Pa x 10$^6$).

$\sigma = 5.093$MPa
Note that N / mm² = MPa.

\[
\frac{N}{\text{mm}^2} = \frac{N}{\text{mm}^2 \left( \frac{10^3 \text{mm}}{\text{m}} \right)^2} = \frac{N}{\text{m}^2 \times 10^6} = \text{Pa} \times 10^6 = \text{MPa}
\]

- **Strain** (ε) is the change in length δ divided by the original length Lo (ε = δ / Lo). See Fig. 1.

When bar is elongated, strains are **tensile** (positive).

When bar shortens, strains are **compressive** (negative).

**Example:**

Steel bar has length Lo = 2.0 m. A tensile load is applied which causes the bar to extend by δ = 1.4 mm.

Find the normal strain.

\[
\varepsilon = \frac{\delta}{L_o} = \frac{1.4 \times 10^{-3}}{2.0} \text{ m} = 0.0007
\]

**Greek letters**

δ (delta) \[\varepsilon = \frac{\delta}{L_o}\]

σ (sigma)

ε (epsilon) \[\varepsilon = 0.0007 = 7 \times 10^{-4} = (7 \times 10^2) \times 10^{-4} \times 10^{-2} = 700 \times 10^{-6}
\]

**The Poisson Effect**

A positive (tensile) strain in one direction will also contribute a negative (compressive) strain in the other direction, just as stretching a rubber band to make it longer in one direction makes it thinner in the other directions (see Fig. 2). This

**NOTES:**
lateral contraction accompanying a longitudinal extension is called the **Poisson effect**.

![Figure 2: The Poisson Effect](image)

So there is a tensile strain in the axial direction and a compressive strain in the other two (lateral) directions.

The ratio of lateral strain of material to axial strain within elastic limit define as **Poisson’s ratio**.

\[ \nu = \frac{\text{lateral strain}}{\text{axial strain}} = \frac{\varepsilon_{\text{lateral}}}{\varepsilon_{\text{longitudinal}}} \]

**Greek letter \( \nu \) (nu)**

The Poisson’s ratio is a dimensionless parameter that provides a good deal of insight into the nature of the material. The major classes of engineered structural materials fall neatly into order when ranked by Poisson’s ratio:

<table>
<thead>
<tr>
<th>Material Class</th>
<th>Poisson’s Ratio</th>
<th>( \nu )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ceramics</td>
<td>0.2</td>
<td></td>
</tr>
<tr>
<td>Metals</td>
<td>0.3</td>
<td></td>
</tr>
<tr>
<td>Plastics</td>
<td>0.4</td>
<td></td>
</tr>
<tr>
<td>Rubber</td>
<td>0.5</td>
<td></td>
</tr>
</tbody>
</table>

**NOTES:**
Example:

Two points fixed on steel bar of 10 mm diameter, the distance between points was 50 mm. Tensile force applied on its ends (8 kN). The distance increased by 0.025 mm and the diameter decreased by 0.0015 mm.

Determine:
1- Normal stress
2- Longitudinal and lateral strains
3- Poisson's ratio

\[ A = \frac{\pi D^2}{4} = \frac{\pi 10^2}{4} \]
\[ = 78.57 \text{ mm}^2 \]

\[ \sigma = \frac{P}{A} = \frac{8 \times 10^2}{4} \]
\[ = 101.82 \text{ MPa} \]

\[ \varepsilon_{\text{longitudinal}} = \frac{\Delta L}{L_0} = \frac{0.025}{50} \]
\[ = 0.0005 \]

\[ \varepsilon_{\text{lateral}} = \frac{\Delta D}{D_0} = \frac{0.0015}{10} \]
\[ = 0.0015 \]

\[ \nu = \frac{\varepsilon_{\text{lateral}}}{\varepsilon_{\text{longitudinal}}} = \frac{0.0015}{0.0005} = 0.3 \]

NOTES:

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Stress – Strain Relationship

The relation between stress and strain is an extremely important measure of a material’s mechanical properties. Stress - strain curve is graphical representation of it.

1- The proportional limit

Up to the proportional limit for the material, the graph is a straight line and so the stress is proportional to elastic strain and Hooke’s Law applies.
Proportional limit on Stress-Strain Curve

- Load is proportional to deformation.
- Stress is proportional to strain, material behaves **elastically**, There is no permanent change to the material; when the load is removed, the material resumes its original shape.
- After the proportional limit, the graph changes from a straight line.

**Hooke’s Law**

Within the elastic region of the stress-strain diagram, stress is linearly proportional to strain (up to proportional limit).

- That relationship was formalized by Robert Hooke in 1678.
- In mathematical terms Hooke’s Law

\[
\sigma = E \varepsilon
\]

\( \sigma \) (sigma) is the axial/normal stress
\( E \) is the elastic modulus or the Young’s modulus
\( \varepsilon \) (epsilon) is the axial/normal strain

For shear stress in the same region Hooke's Law

\[
\tau = G \gamma
\]

\( \tau \) (tau) is the shear stress
\( G \) is the shear modulus or the modulus of rigidity
\( \gamma \) (gamma) is the shear strain

**Modulus of Elasticity or Young's Modulus\( (E)\)**

It is the slope of the initial linear portion of the stress-strain diagram. In other words it is the ratio of stress to elastic strain.

\[
E = \frac{\sigma}{\varepsilon}
\]
The modulus of elasticity may also be characterized as the “stiffness” or ability of a material to resist deformation within the linear range.

E (Steel) ≈ 200 x 10^3 MPa
E (Aluminum) ≈ 70 x 10^3 MPa
E (Concrete) ≈ 30 x 10^3 MPa

**Tangent Modulus** (Et)

It is the slope of the stress-strain curve above the proportional limit. In other words, it is the ratio of stress to strain above the proportional limit. There is no single value for the tangent modulus; it varies with strain.

**Shear Modulus the modulus of rigidity (G)**

It is the slope of the initial linear portion of the shear stress-strain diagram. In other words, it is the ratio of shear stress to elastic shear strain,

\[ G = \frac{\sigma}{\gamma} \]

2- **The Elastic Limit**

It is the point after which the sample will not return to its original shape when the load is released.

- The proportional limit and the elastic limit are very close. For most purposes,
we may consider them to be the same point.

- There is permanent change to the structure of the material.

3- **Yield point**

There may be a region of increased deformation without increased load. This point is known as the *yield point*. The stress at this point is called the *yield strength*.

![Yield point on stress strain curve](image)

- After yield point, the material behaves *plastically* (when the load is removed, the sample does not return to its original shape).

- It is not always easy to identify the yield point from the stress-strain (load-deformation) curve. In these cases the *offset method* is used.
  1. An offset for the material is given.

For the tension and compression labs, we use the following offsets:

- For steel, use 0.2% strain
- For brass, use 0.35% strain
- For cast iron, use 0.05% strain

**NOTES:**
2- It is marked on the deformation (strain) axis.

3- A line through the offset point, parallel to the straight (proportional) part of the curve, is drawn. The intersection of the line with the stress-strain curve is taken to be the yield point.

4- The Strain-Hardening
After the yield point, there may be a region of where increased load is necessary for increased deformation. This is the strain-hardening region

5- Ultimate strength
Load (stress) rises to a maximum; this is the ultimate strength of the material

6- Failure point
Load required for further deformation is reduced as the failure or breaking point is approached.

NOTES:
Ductile and Brittle Materials

Each material has its own stress-strain curve, with different characteristics, examples:

1- Ductile Material

NOTES:
Materials that are capable of undergoing large strains (at normal temperature) before failure.

An advantage of ductile materials is that visible distortions may occur if the loads be too large. Ductile materials are also capable of absorbing large amounts of energy prior to failure.

Ductile materials include mild steel, aluminum and some of its alloys, copper, magnesium, nickel, brass, bronze and many others.

2- **Brittle Material**

Materials that exhibit very little inelastic deformation. In other words, materials that fail in tension at relatively low values of strain are considered brittle.

Brittle materials include concrete, stone, cast iron, glass and plaster.

**Modulus of Elasticity Determination**

- Ductile Material, the modulus of elasticity is the slope of straight line of stress strain curve.

\[ E = \frac{\sigma}{\varepsilon} \]

- Brittle materials, use one of followings:
  1- Secant modulus

    The slope of straight line between origin point and point on curve has stress equal to \((2/3)\) of ultimate stress.

    \[ E = \tan \alpha = \frac{\sigma}{\varepsilon} = -\frac{\varepsilon}{\varepsilon_1} \]

  2- Initial tangent modulus

    The tangent slope of stress-strain curve at origin point.

**NOTES:**
Example

The following information obtained in tension test on a material as the sectional area of the sample is 50 mm$^2$ and length 1000 mm, draw the stress - strain curve and then determine the value of proportional limit, yield stress and ultimate strength, failure stress, and modulus of elasticity.

<table>
<thead>
<tr>
<th>Load ( KN )</th>
<th>50</th>
<th>100</th>
<th>150</th>
<th>200</th>
<th>220</th>
<th>225</th>
<th>231</th>
<th>232</th>
<th>233</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extension ( mm )</td>
<td>5</td>
<td>10</td>
<td>15</td>
<td>20</td>
<td>25</td>
<td>30</td>
<td>33</td>
<td>36</td>
<td>40</td>
</tr>
<tr>
<td>Load ( KN )</td>
<td>238</td>
<td>250</td>
<td>275</td>
<td>295</td>
<td>300</td>
<td>290</td>
<td>275</td>
<td>240</td>
<td>225</td>
</tr>
<tr>
<td>Extension ( mm )</td>
<td>45</td>
<td>50</td>
<td>60</td>
<td>80</td>
<td>100</td>
<td>120</td>
<td>136</td>
<td>150</td>
<td>160</td>
</tr>
</tbody>
</table>

NOTES:
Solution

<table>
<thead>
<tr>
<th>Load, P (kN)</th>
<th>Stress = P/A (MPa)</th>
<th>Extention δ mm</th>
<th>Strain = δ /L</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>50</td>
<td>100</td>
<td>5</td>
<td>0.005</td>
</tr>
<tr>
<td>100</td>
<td>200</td>
<td>10</td>
<td>0.01</td>
</tr>
<tr>
<td>150</td>
<td>300</td>
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<tr>
<td>200</td>
<td>400</td>
<td>20</td>
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<td>220</td>
<td>440</td>
<td>25</td>
<td>0.025</td>
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<tr>
<td>225</td>
<td>450</td>
<td>30</td>
<td>0.03</td>
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<tr>
<td>231</td>
<td>462</td>
<td>33</td>
<td>0.033</td>
</tr>
<tr>
<td>232</td>
<td>464</td>
<td>36</td>
<td>0.036</td>
</tr>
<tr>
<td>233</td>
<td>466</td>
<td>40</td>
<td>0.04</td>
</tr>
<tr>
<td>238</td>
<td>476</td>
<td>45</td>
<td>0.045</td>
</tr>
<tr>
<td>250</td>
<td>500</td>
<td>50</td>
<td>0.05</td>
</tr>
<tr>
<td>275</td>
<td>550</td>
<td>60</td>
<td>0.06</td>
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<td>295</td>
<td>590</td>
<td>80</td>
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</tr>
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<td>300</td>
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<td>100</td>
<td>0.1</td>
</tr>
<tr>
<td>290</td>
<td>580</td>
<td>120</td>
<td>0.12</td>
</tr>
<tr>
<td>275</td>
<td>550</td>
<td>136</td>
<td>0.136</td>
</tr>
<tr>
<td>240</td>
<td>480</td>
<td>150</td>
<td>0.15</td>
</tr>
<tr>
<td>225</td>
<td>450</td>
<td>160</td>
<td>0.16</td>
</tr>
</tbody>
</table>

Example

The following information obtained in compression test on concrete cylinder, draw the stress - strain curve and then determine ultimate compressive strength

<table>
<thead>
<tr>
<th>Stress (MPa)</th>
<th>0</th>
<th>5</th>
<th>10</th>
<th>15</th>
<th>20</th>
<th>15</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strain x10^-4</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>15</td>
</tr>
</tbody>
</table>

NOTES:
NOTES: