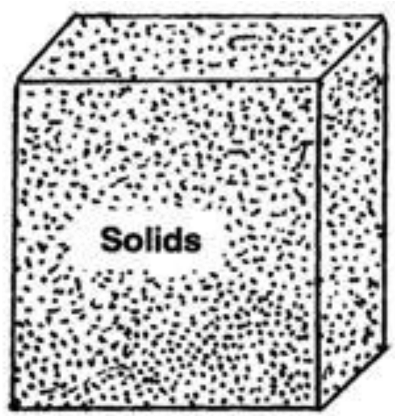
Physical Properties of Materials

Density

- **Density (ρ),** the volumetric mass density, is the mass of a unit volume of homogeneous material, practical density. The density at all points of a homogeneous object equals its total mass divided by its total volume. The mass is normally measured with a scale or balance; the volume may be measured directly (from the geometry of the object) or by the displacement of a fluid.



Particle Density

$$\rho = \frac{M}{V} \ \text{g/cm}^3$$

M = mass (g)

V = volume (cm^3)

Density: is the dry mass per unit volume of a substance under absolute compact conditions. It is defined by:

$$\rho = \frac{m}{V}$$

ρ **is the density (g/cm³);**

m **is the mass under dry conditions (6);**

V **is the volume under absolute compact conditions (cm³).**

The volume under absolute compact conditions refers to the solid volume without the volume of inner pores. Except steel, glass, asphalt and a few other materials, most materials contain some pores in natural state. In the measurement of the density of a porous material, the material is ground into powder at first; the powder is dried to fixed mass; and then the solid volume is measured by Lee's density bottle; finally the density is calculated by the above formula. The finer the powder is ground, the more real the size will be. Thus the density value is more correct.

Apparent Density

Apparent density is the dry mass per unit volume of a substance under natural conditions. It is defined by:

$$\rho_0 = \frac{m}{V_0}$$

ρ_0 is the apparent density (kg/m3);

m is the mass under dry conditions (kg);

V_0 is the volume under natural conditions (m^3).

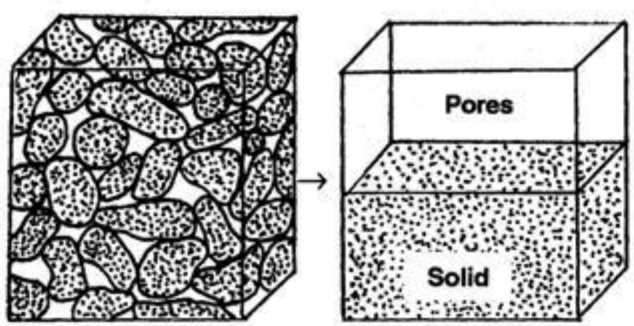
The volume of a substance under natural conditions refers to the solid volume and the volume of inner pores.

If it is a regular shape, the volume can be directly measured; if it is in an irregular shape, the volume can be measured by the liquid drainage method after sealing pores with wax; the liquid drainage method can be directly used to measure the volume of sandstone aggregate utilized in concrete but the volume here is the solid volume plus the volume of closed pores-without the volume of the pores open to the outside. Because the sandstone is compact with only a few pores, the volume of the pores open to the outside is little. Thus the volume measured by the liquid drainage method can be called apparent density which is called virtual density in the past.

The quality and volume change with the water content. Generally, apparent density refers to the density of a substance under dry conditions. Other moisture conditions should be specified.

Bulk Density

Bulk Density (ρ_b): is a property of powders, granules, and other "divided" solids, especially used in reference to mineral components (soil, gravel). It is defined as the mass of many particles of the material divided by the total volume they occupy. The total volume includes particle volume, interparticle void volume, and internal pore volume. The bulk volume of a material—inclusive of the void fraction—is often obtained by a simple measurement (e.g. with a calibrated measuring cup) or geometrically from known dimensions.



Bulk Density

$$\rho_b = \frac{M}{V} \ \text{kg/m}^3$$

M = mass of specimen (kg)
V = volume of specimen in its natural state (m^3)

Bulk density refers to the per unit volume of a substance under the conditions that powdery or granular materials are packed. It is defined by:

$$\rho_0{}' = \frac{m}{V_0{}'}$$

$\rho_0{}'$ is the bulk density (kg/m^3);

m is the mass under dry conditions (kg);

$V_0{}'$ is the volume under packing conditions (m^3) .

Bulk density is measure by volumetric container. The size of volumetric container depends on the size of particles. For example, 1L volumetric container is used to measure sand and IOL, 20L, 30L volumetric containers are used in the measurement of stone.

Density of some building materials is as follows:

Building materials	Practical Density [kg/m3]	Bulk Density [kg/m3]
Brick	2500 – 2800	1600 - 1800
Granite	2600 – 2900	2500 - 2700
Cement	2900 – 3100	
Wood	1500 – 1600	Pine wood: 500 - 600
Steel	7800 – 7900	7850
Concrete	2400	

True density, Apparent Density, Bulk Density, and Porosity of common building materials

Name	Density *(gm/cm^3)*	Apparent Density *(kg/m^3)*	Bulk Density *(kg/m^3)*	Porosity (%)
Steel	7.85	7850	---	---
Granite	2.6-2.9	2500-2850	---	0-0.3
Limestone	2.6-2.8	2000-2600	---	0.5-3.0
Gravels and Pebbles	2.6-2.9	---	1400-1700	---
Ordinary sand	2.6-2.8	---	1450-1700	---
Sintered Clay Bricks	2.5-2.7	1500-1800	---	20-40
Cement	3.0-3.2	---	1300-1700	---
Ordinary Concrete	---	2100-2600	---	5-20
Asphalt Concrete	---	2300-2400	---	2-4
Wood	1.55	400-800	---	55-75

Solidity and Porosity

Solidity refers to the degree how the volume of **a material is packed with solid** substances, which is the ratio of the solid volume to the total volume. It is defined by:

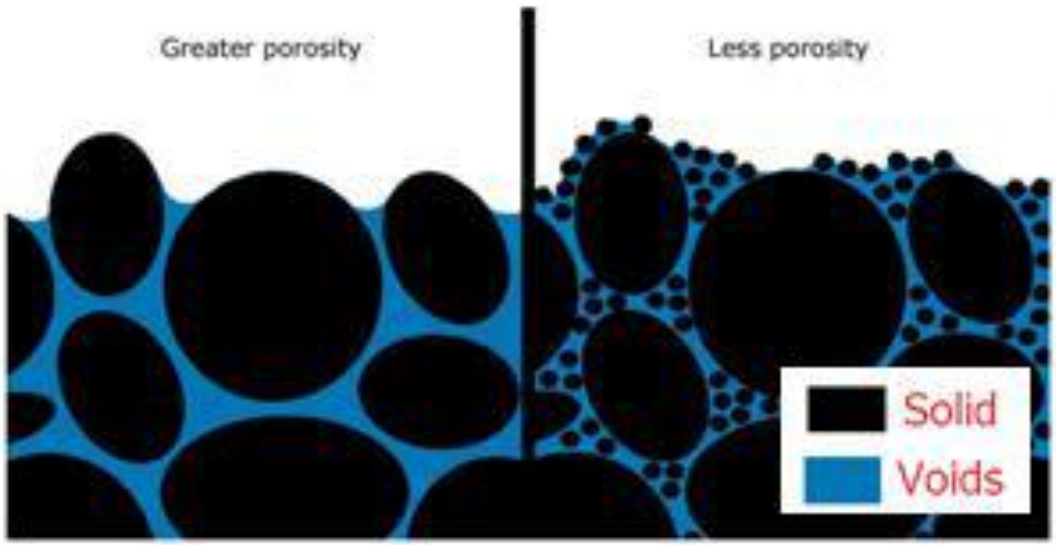
$$D=\frac{V}{V_0}\times 100\% \quad \text{or} \quad D=\frac{\rho_0}{\rho}\times 100\%$$

Porosity (P) is the percentage of the pores volume to the total volume with the volume of a substance. It is defined by:

$$P=\frac{V_0-V}{V_0}\times 100\%=\left(1-\frac{V}{V_0}\right)\times 100\%=\left(1-\frac{\rho_0}{\rho}\right)\times 100\%$$

The relationship between solidity and porosity can be expressed as:

$$D+P=1$$



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

Vv = volume of voids
V = total volume of the material

Fill Rate and Voidage

Fill Rate (D')is the degree how granules pack the granular materials in the bulk volume. It is defined by:

$$D' = \frac{V_0}{V_0'} \times 100\% \quad \text{or} \quad D' = \frac{\rho_0'}{\rho_0} \times 100\%$$

Voidage (P') is the percentage of the void volume among granules to the bulk volume in the bulk volume of granular materials. It is defined by:

$$P' = \frac{V_0' - V_0}{V_0'} \times 100\% = \left(1 - \frac{\rho_0'}{\rho_0}\right) \times 100\%$$

Voidage reflects the compactness among granules of the granular materials. The relationship between fill rate and voidage can be expressed as:

$$D' + P' = 1$$

Hydro-properties of Materials

Hydrophilicity and Hydrophobicity:

When the material is exposed to water in the air, it will be hydrophilic or hydrophobic according to whether it can be wetted by water or not. If it can be wetted by water, it is the hydrophilic material; if not, it is the hydrophobic material.

When materials are exposed to water droplets in the air, there will be two cases, shown as Figure 2.1. In the intersection of the material, water and air, a tangent is drown along the surface of the water droplet, and the angle between the surface and the tangent is angle θ, **known as wetting angle.**

When angle θ **is smaller than or equals to 90"** ***(θ<90°),*** the material is **hydrophilic**, such as wood, brick, concrete and stone. The atttactive force between materials molecules and water molecules is stronger than the cohesive force between water molecules, so the materials can be wetted by water.

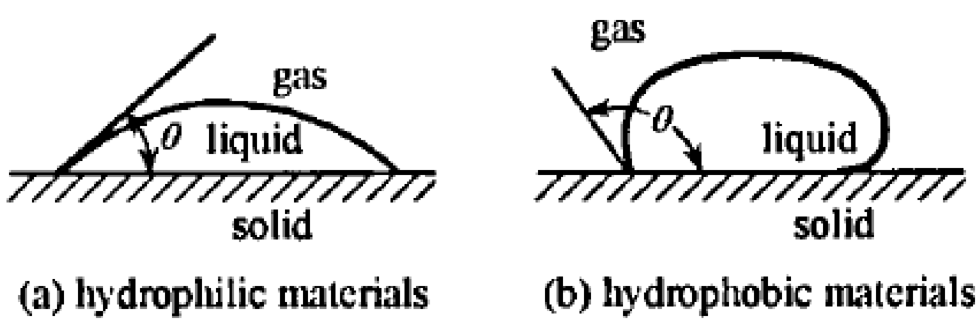


Figure 2.1 The Wetting Schematic Diagram of Materials

The hydrophobic materials are moisture-proof and waterproof, usually used for water-resistant materials or the surface treatment for the hydrophilic materials in order to reduce water absorption and improve impermeability.

The Water Absorption and Hygroscopicity

Water absorption refers to the property of absorbing water when materials are exposed to water. It is expressed by the water-absorption ratio. And there are two types of expression:

(1)Specific Absorption of Quality:

Specific absorption of quality refers to the percentage of the absorbed water to the dry mass when the material absorbs water to saturation. It is defined by:

$$W_m = \frac{m_b - m_g}{m_g} \times 100\%$$

In this formula: W_m is the specific absorption of quality(%);

m_b is the mass when the material absorbs water to saturation(g);

m_g is the mass when the material is dry (g).

(2) Specific Absorption of Volume:

The specific absorption of volume refers to the percentage of the absorbed water's volume to the material's natural volume when the material absorbs water to saturation. It is defined by:

water to saturation. It is defined by:

$$W_V = \frac{m_b - m_g}{V_0} \times \frac{1}{\rho_w} \times 100\%$$

In this formula: W_V is the specific absorption of volume(%);

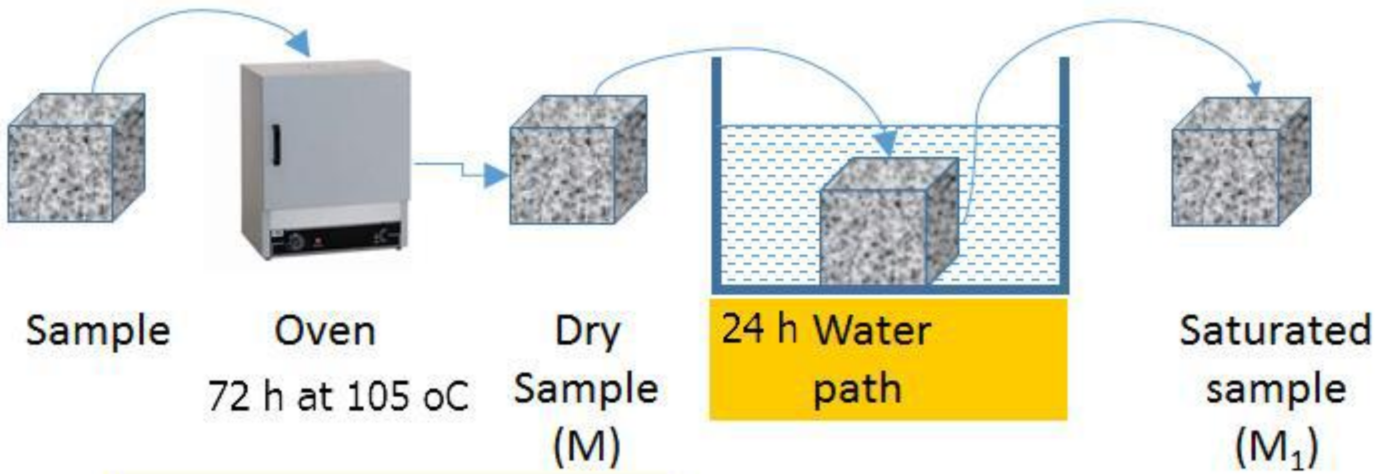
V_0 is the volume of the dry material in natural state(cm^3);

ρ_w is the density of water(g/cm^3), usually $1.0 g/cm^3$ at the room temperature.

The relationship between specific absorption of quality and that of volume is as follows:

$$W_v = W_m \cdot \rho_0$$

In this formula: ρ_0 is the apparent density of the material in dry state (simply called dry apparent density)(g/cm^3).



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

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

M_1 = mass of saturated material (g)

M = mass of dry material (g)

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

The water absorption depends on not only hydrophilicity and hydrophobicity of the material but also the porosity and characteristics of the pores. For normal materials, the higher the porosity is, the stronger the water absorption is. The more the open and connected tiny pores are, the stronger the water absorption is; it is not easy for water to be absorbed if the pores are closed; if they are large and open, water is easy to be absorbed but is hard to be hold, and thus the water absorption is weak. The water-absorption ratios of various materials vary greatly. For example, the specific absorption of quality of granite rock is 0.2%~0.7%, that of ordinary concrete is 2%~3%, that of ordinary clay brick is 8%~20%, and that of wood or other light materials is often above 100%.

The water absorption will have a negative impact on materials' nature. If a material absorbs water, its quality will increase, its volume will expand, its thermal conductivity will increase and its strength and durability will decrease.

(2) Hygroscopicity

Hygroscopicity is the property of materials to absorb water in the air. It can be expressed by moisture content.

Moisture content is the percentage of the water quality contained in a material to its dry mass, expressed by W_h. It is defined by:

$$W_h = \frac{m_s - m_g}{m_g} \times 100\%$$

In this formula: W_h is the moisture content(%);

m_s is the mass when the material contains water(g);

m_g is the mass when the material is dry(g).

The hygroscopicity of materials is related to air temperature and air humidity. The higher humility is and the lower the temperature is, the higher hygroscopicity will be; contrarily, the hygroscopicity will be low. Both the factors affecting hygroscopicity and the influence on materials' properties after absorbing water are the same to the water absorption of materials.

3. Water Resistance

Water resistance is the ability to maintain its original properties when the material is affected by water in a long-term.

The water-resistant ability of different materials varies in expressing ways. For example, the water resistance of structural materials mainly refers to the changes in intensity, and with softening coefficient it is defined by:

$$K_R = \frac{f_b}{f_g}$$

In this formula: K_R is the softening coefficient of a material;

f_b is the compressive strength of a material in water saturation state (MPa);

f_g is the compressive strength of a material in dry state(MPa).

The softening coefficient of a material K_R varies between 0 (clay) ~1 (steel).

The value of K_R reveals the decreasing degree of the strength after the material absorbs water to saturation. The bigger K_R is, the stronger the water resistance is, which indicates that the decreasing degree of the strength in saturation state is low; contrarily, the water resistance is weak. Generally, the material whose K_R is bigger than or equals to 0.85 is known as water-resistant material. K_R is an important basis for selecting building materials. If the major structures are often in water or wetted seriously, the materials whose K_R is bigger than or equals to 0.85 ($K_R \geqslant 0.85$) should be chosen; if they are the minor structures or wetted lightly, the materials whose K_R is bigger than or equals to 0.75 ($K_R \geqslant 0.75$) should be chosen.

4. Impermeability

Impermeability is the ability of a material to resist the pressure water or the infiltration of other liquids. It is expressed by permeability coefficient which is defined by:

$$K=\frac{Qd}{AtH}$$

In this formula: K is the permeability coefficient (cm/s);

Q is the volume of water seepage(cm^3);

d is the thickness of a specimen(cm);

A is the seepage area(cm^2);

t is the seepage time(s);

H is the water head(cm).

Permeability coefficient K reflects the rate of water flowing in a material. The bigger K is, the faster the flow rate of water is and the weaker the impermeability.

The impermeability of some materials (such as concrete and mortar) can be expressed by impermeable level which is represented by the maximum water pressure resisted by materials. For example, P6, P8, P10 and P12 reveal that the materials can resist 0.6MPa, 0.8MPa, 1.0MPa, and 1.2MPa water pressure without water seepage.

The impermeability of a material is related not only to its own hydrophilicity and hydrophobicity but also to its porosity and the characters of pores. The smaller the porosity is and the more the closed pores are, the stronger the impermeability is. Impermeable materials should be used in water conservancy projects and the underground projects usually affected by pressure water. Waterproof materials should be impermeable.

5. Frost Resistance

Frost resistance is the property that a material can withstand several freeze-thaw cycles without being destroyed and its strength does not decrease seriously when the material absorbs water to saturation. It is expressed by frost-resistant level.

Frost-resistant level is indicated by the biggest freeze-thaw-cycle times of a specimen that both its quality loss and strength reduction are within provisions when it is affected by freeze-thaw cycles in water saturation state, such as F25, F50, F100 and F150.

The reason for the freeze damage is a volume expansion (about 9%) caused by freeze of the water within the material's pores. If a material's pores are full of water, its volume will expand and there will be a great tensile stress to pore walls when water is frozen into ice. If this stress exceeds the tensile strength, the pore walls will crack, the porosity will increase and the strength will decrease. The more the freeze-thaw cycles are, the greater damages there will be. And it will even cause the complete destruction of a material.

There are internal and external factors affecting frost resistance of a material. The internal factors are the composition, structures, construction, porosity, the characteristics of pores, strength, water resistance, and so on. The external factors are the water filling degree within a material's pores, freezing temperature, freezing speed, freeze-thaw frequency, and so on.

Thermal Properties

1. Thermal Conductivity

The property of a material that indicates its ability to conduct heat is known as thermal conductivity. It is expressed by the coefficient of thermal conductivity λ, which is defined by:

$$\lambda = \frac{Qd}{(T_2 - T_1)At}$$

In this formula: λ is the coefficient of thermal conductivity [W/(m • K)];

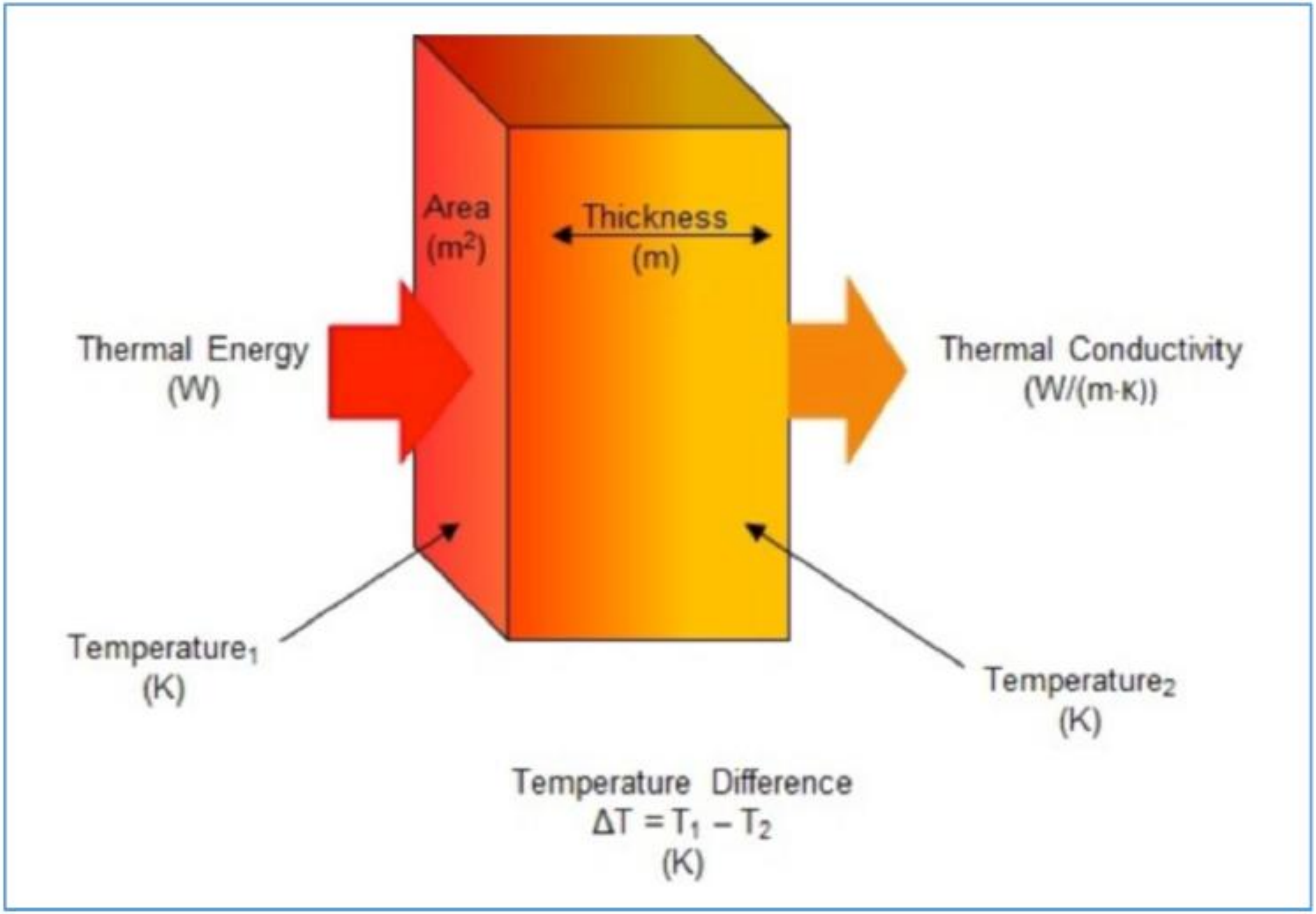
Q is the conducted heat quantity (J);

d is the thickness of a material (m);

A is the heat-transfer area (m^2);

t it the time for the heat transfer (s);

$T_2 - T_1$ is the temperature difference of the two materials (K).


Area
(m2)
Thickness
(m)
Thermal Energy
(W)
Thermal Conductivity
(W/(m·K))
Temperature1
(K)
Temperature2
(K)
Temperature Difference
ΔT = T1 – T2
(K)

The smaller the value of λ is, the better insulation the material has.

The thermal conductivity of a material is related to its composition and structure, the porosity and the characteristics of its pores, the water content, temperature and other conditions. The coefficient of thermal conductivity of metallic materials is bigger than that of non-metallic materials. The bigger the porosity is, the higher the coefficient will be. Tiny and closed pores indicate low coefficient; big and open pores are easy to create convection heat, which indicates that the coefficient is high. The thermal conductivity coefficient of a material containing water or ice increases dramatically because the coefficient of water and ice is bigger than that of air.

2. Thermal Capacity

Thermal capacity is the property of a material to absorb heat when it is heated and to release heat when it is cooled. It is defined by:

$$Q = m \times C(T_2 - T_1)$$

or

$$C = \frac{Q}{m(T_2 - T_1)}$$

In this formula: Q is the heat absorbed or released by a material (J);

m is the mass of a material (g);

C is the specific heat of a material [J/(g·K)];

$T_2 - T_1$ is the temperature difference before and after heating or cooling (K).

The specific heat, also called specific heat capacity, is the measure of the heat energy that a substance in a unit quality absorbs or releases when the temperature increases or decreases 1K. The bigger the specific heat is, the better the stability of the indoor temperature will be.

Thermal conductivity coefficient and specific heat should be known when thermal calculations are conducted to buildings. There are thermal conductivity coefficients and specific heat capacities of several common materials are listed in Table 2.2.

Table 2.2 Thermal Conductivity Coefficients and Specific Heat Capacities

Substance	Heat Conductivity Coefficient λ [W/(m • K]	Specific Heat Capacity C [J/(g • K)]	Substance	Heat Conductivity Coefficient λ [W/(m • K]	Specific Heat Capacity C [J/(g • K)]
Copper	370	0.38	Fiberboard for Thermal Insulation	0.05	1.46
Steel	55	0.46	Glass Wool Board	0.04	0.88
Granite	2.9	0.80	Foam	0.03	1.30
Ordinary Concrete	1.8	0.88	Sealed Air	0.025	1.00
Ordinary Clay Brick	0.55	0.84	Water	0.60	4.19
Pine (Cross Striations)	0.15	1.63	Ice	2.20	2.05

3. Thermal Deformation

Thermal deformation is the property of a substance to expand with heat and contract with cold, customarily called temperature deformation. It is expressed by linear expansion coefficient α, which is defined by:

$$\alpha = \frac{\Delta L}{L \times \Delta t}$$

In this formula: α is the linear expansion coefficient of a substance (l/K);

ΔL is the expansion or contraction value of a specimen(mm);

L is the length before heating or cooling(mm);

Δt is the temperature difference(K).

The bigger the linear expansion coefficient α is, the greater the thermal deformation will be.

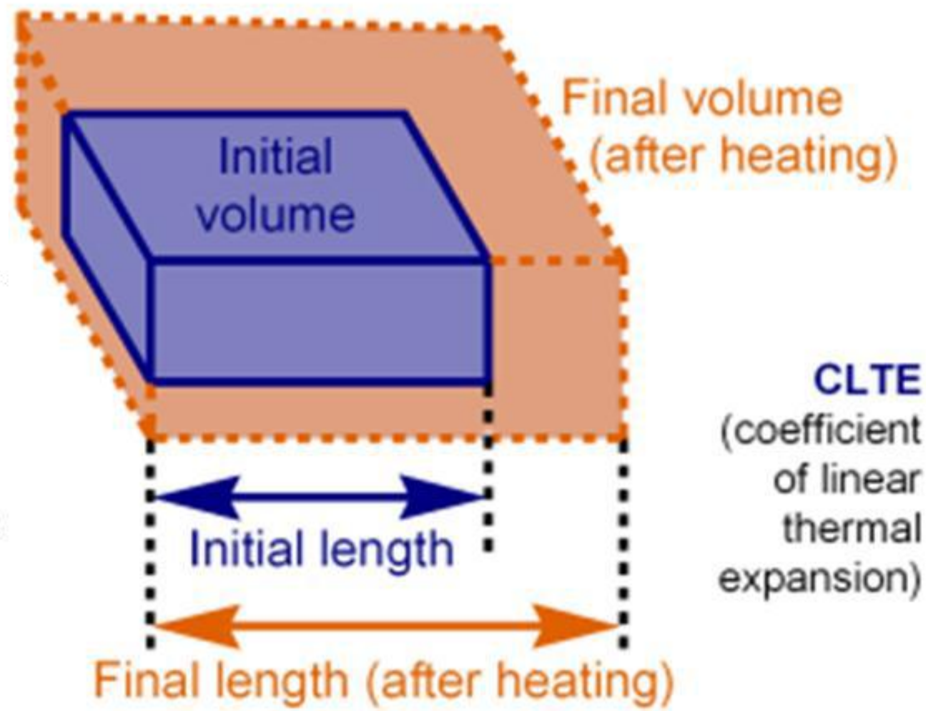
The thermal deformation is detrimental to the civil engineering. For example, in a large-area or large-volume concrete project, temperature cracks can be caused if the expansion tensile stress is beyond the tensile strength of concrete; in a large-volume construction work, expansion joints are set to prevent the cracks caused by thermal deformation; and Petroleum asphalt will have brittle factures when temperature drops to a certain extent.

$$\alpha_L = \frac{\Delta L}{L_o \Delta T}$$

where L_0 is the initial length, and $\Delta L = L - L_0$ is the change in length.

$$\alpha_V = \frac{\Delta V}{V_o \Delta T}$$

where V_0 is the initial volume and $\Delta V = V - V_0$ is the change in volume



Thermal Expansion: (9)

✓Practically all materials expand as temperature increases and contract as temperature falls. The amount of expansion per unit length due to one unit of temperature (DT) increase is a material constant and is expressed as the coefficient of thermal expansion.

✓ The coefficient of thermal expansion is very important in the design of structures. Generally, structures are composed of many materials that are bound together. If the coefficients of thermal expansion are different, the materials will strain at different rates. The material with the lesser expansion will restrict the straining of other materials. This constraining effect will cause stresses in the materials that can lead directly to fracture.

✓ Stresses can also be developed as a result of a thermal gradient in the structure. As the temperature outside the structure changes and the temperature inside remains constant, a thermal gradient develops. When the structure is restrained from straining, stress develops in the material.

4. Flame Resistance

Flame resistance is the property of a substance not to flame in case of contacting with fire in the air. Materials can be divided into non-flammable materials, fire-retardant materials and flammable materials according to their reaction to fire.

(1) Non-flammable Materials

Non-flammable materials are the ones that cannot be fired, carbonized or slightly burned when contacting with fire or high temperature in the air, such as brick, natural stone, concrete, mortar and metal.

(2) Fire-retardant Materials

Fire-retardant materials are the ones that are hard to be burned or carbonized when contacting with fire or high temperature in the air and stop burning or slightly flaming immediately when leaving fire, such as gypsum board, cement asbestos board, and lath and plaster.

(3) Flammable Materials

Flammable materials are the ones that are ignited or flame immediately when contacting with fire or high temperature in the air and continue to burn or slightly flame when leaving fire, such as plywood, fiberboard, wood and foil.

In construction, the selection of non-flammable materials or fire-retardant materials depends on fire-resistant levels of buildings and the parts where materials are used. Fire prevention should be dealt with when flammable materials are used.

THANK YOU