1

Introduction to Physics

LEARNING OUTCOMES
1) Define speed, velocity and acceleration. 2) Explain mass, gravitation and weight. 3) Explain Newton's laws of motion and solve numerical problems based on these laws. 4) Explain work, energy and power, and solve numerical problems.

1.1 Speed and Velocity

In the study of moving objects, one of the important things to know is the rate of motion. The rate of motion of a moving object is what we call **speed**. It may be defined as the distance covered in a given time:

$$\text{Speed} = \frac{\text{Distance covered}}{\text{Time taken}}$$

If the distance covered is in metres (m) and the time taken in seconds (s), then speed is measured in metres per second (m/s). If the distance is in kilometres (km) and the time in hours (h), the unit of speed is kilometres per hour (km/h).

When the direction of movement is combined with the speed, we have the **velocity** of motion. Quantities that have both magnitude and direction are known as **vector** quantities. Velocity is a vector quantity; its magnitude and direction can be represented by an arrow. Speed, on the other hand, has magnitude but no direction; therefore it is called a **scalar** quantity.

1.2 Acceleration

An object is said to accelerate if its velocity increases. The rate of increase of velocity is called the **acceleration**.

$$\text{Acceleration} = \frac{\text{Increase in velocity}}{\text{Time taken}}$$

Construction Science and Materials, Second Edition. Surinder Singh Virdi.

Companion website: www.wiley.com/go/virdiconstructionscience2e

If velocity is measured in metres and time in seconds, then acceleration is measured in metres per second per second (m/s/s) or metres per second squared (m/s^2). If the velocity of a moving object decreases, it is said to decelerate, i.e. the acceleration is negative. The following relationships may be used to solve problems involving velocity and acceleration:

- $v^2 - u^2 = 2as$
- $v = u + at$
- $v = ut + \frac{1}{2}at^2$

where, u = initial velocity
v = final velocity
a = acceleration
t = time
s = distance

1.3 Mass

The amount of matter contained in an object is known as its **mass**. The basic SI unit of mass is the kilogram (kg).

$$1 \text{ gram}(g) = 1000 \text{ milligrams}(mg)$$
$$1000 \text{ grams} = 1 \text{ kilogram}$$
$$1000 \text{ kilograms} = 1 \text{ tonne}(t)$$

The mass of an object remains constant irrespective of wherever it is.

1.4 Gravitation

Gravitation can be defined as the force of attraction that exists between all objects in the universe. According to Isaac Newton, every object in the universe attracts every other object with a force directed along the line of centres for the two objects that is proportional to the product of their masses and inversely proportional to the square of the distance between their centres.

$$F_g = \frac{G\, m_1\, m_2}{r^2}$$

where F_g = gravitational force between two objects
m_1 = mass of first object
m_2 = mass of second object
r = distance between the centres of the two objects
G = universal constant of gravitation

The value of constant G is so small that the force of attraction between any two objects is negligible. In 1798, Henry Cavendish performed experiments to determine the value of G and found it to be 6.67×10^{-11} Nm^2/kg^2.

If we consider an object and the Earth, the mass of Earth is so large (5.98×10^{24} kg) that, depending on the mass of the object, there could be a considerable force of attraction between the two. That is why when an object is dropped from a height, it falls towards the Earth, not away from it. The initial velocity of the object is zero m/s, but as the distance increases, the velocity of the falling object also increases. The rate of increase in velocity is called acceleration and, in the case of a free-falling object, it is known as the **acceleration due to gravity** (symbol: g).

The value of g is 9.807 m/s^2, but for all calculations in this book it will be approximated to 9.81 m/s^2 (m/s^2 can also be written as ms^{-2}).

Example 1.1 Find the gravitational force between the Earth and:

a) An object with a mass of 1 kg.
b) A person with a mass of 80 kg.

Given: mass of the Earth = 6.0×10^{24} kg; radius of the Earth = 6.4×10^6 m; G = 6.7×10^{-11} Nm^2/kg^2

Solution:

a)
$$\begin{aligned} F_g &= \frac{G\, m_1\, m_2}{r^2} \\ &= \frac{6.7 \times 10^{-11} \times 6 \times 10^{24} \times 1}{\left(6.4 \times 10^6\right)^2} \\ &= 9.81 \text{ N} \end{aligned}$$

b)
$$\begin{aligned} F_g &= \frac{G\, m_1\, m_2}{r^2} \\ &= \frac{6.7 \times 10^{-11} \times 6 \times 10^{24} \times 80}{\left(6.4 \times 10^6\right)^2} \\ &= 785.16 \text{ N} \end{aligned}$$

1.5 Weight

The **weight** of an object is the force with which it is attracted towards Earth. When an object falls freely towards Earth, the average value of the acceleration produced (g) is 9.81 m/s^2. The force (F) acting on the object due to Earth's gravitational pull (or the weight of the object) can be calculated as:

$$F = m \times g$$

where m is the mass of the object in kg.

The units of weight are the same as the units of force. If the mass is in kilograms, the unit of weight will be newtons (N).

The weight of a 1 kg mass will be:

$$F = 1 \times 9.81 = 9.81 \text{ N}$$

Similarly, the weight of a 5 kg mass is:

$$F = 5 \times 9.81 = 49.05\ \text{N}$$

For larger forces, kilonewtons or meganewtons may be used.

$$1000\ \text{N} = 1\ \text{kilonewton}(\text{kN})$$
$$1000000\ \text{N} = 1\ \text{meganewton}(\text{MN})$$

The weight of a body is not constant but changes slightly when we move from the Equator to the North Pole. The Earth is not a perfect sphere: it bulges at the Equator. This affects the gravitational force, which varies from 9.78 m/s^2 at the Equator to 9.83 m/s^2 at the North Pole.

1.6 Volume

All substances, whether they are solid, liquid or gas, occupy space. The amount of space occupied by an object is called its **volume**.

$$\begin{aligned}\text{Volume} &= \text{length} \times \text{width} \times \text{height} \\ &= \text{area} \times \text{height}\end{aligned}$$

(Units: m^3, cm^3 or mm^3.)

1.7 Density

If equal volumes of bricks, concrete, timber and other materials are compared, the values of their mass will be different. This is because different materials do not have the same density.

The **density** of a material is defined as its mass per unit volume.

$$\text{Density} = \frac{\text{Mass}}{\text{Volume}}$$

If the units of mass and volume are kg and m^3 respectively, then the unit of density will be kilograms per metre cubed (kg/m^3). The density of pure water is 1000 kg/m^3. The density of a material is an important property and is used in several areas of building technology, for example:

1) To find the self-weight (dead load) of a component like a beam, column etc., its density must be known.
2) The strength of a material, generally, depends on its density.
3) The thermal insulation of a material is inversely proportional to its density.

Table 1.1 shows the densities of a selection of materials.

Table 1.1

Material	Density (kg/m^3)
Concrete blocks (lightweight)	450–675
Aluminium	2720
Brick (common)	2000
Brick (engineering)	2200
Cement	1500
Concrete	2400
Copper	8800
Cork	200
Glass	2500
Granite	2720
Gravel (coarse)	1450
Gravel (all-in)	1750
Lead	11300
Limestone	2250
Marble	2720
Mercury	13500
Mild steel	7820
Sand (dry)	1600
Sandstone	2250
Slate	2800
Timber (Oak)	600–900
Timber (Beech)	700–900

Example 1.2 The mass of a concrete block measuring 250 mm × 200 mm × 200 mm is 24.0 kg. Find the density of concrete.

Solution:
The dimensions of the concrete block are converted into metres to obtain the density in kg/m^3.

$$250 \text{ mm} = \frac{250}{1000} \text{ m} = 0.250 \text{ m}$$

Similarly, 200 mm = 0.200 m

$$\text{Volume of the concrete block} = 0.250 \times 0.200 \times 0.200 = 0.010 \text{ m}^3$$

$$\text{Density} = \frac{\text{Mass}}{\text{Volume}}$$

$$= \frac{24}{0.010} = 2400 \text{ kg/m}^3$$

Example 1.3 The cross-sectional measurements of a 7.0 m long concrete beam are 0.3 m × 0.75 m. Find the mass and the weight of the beam. Density of concrete = 2400 kg/m^3.

Solution:

$$\text{Volume of the beam} = 7.0 \times 0.3 \times 0.75 = 1.575\ \text{m}^3$$
$$\text{Mass} = \text{Density} \times \text{Volume}$$
$$= 2400 \times 1.575 = 3780\ \text{kg}$$
$$\text{Weight} = \text{Mass} \times \text{g}$$
$$= 3780 \times 9.81 = 37081.8\ \text{N}$$

1.8 Specific Gravity

The specific gravity of a substance is defined as the ratio of the density of the material to the density of water.

Specific gravity = Density of a material ÷ Density of water

The specific gravity of a material remains the same, irrespective of the units of density.

1.9 Newton's First Law of Motion

In the seventeenth century, Isaac Newton formulated three laws, which are known as Newton's laws of motion. The first law states that an object will remain in a state of rest or uniform motion in a straight line unless acted upon by an external force. This means that a book lying on a desk will lie there forever unless somebody applies an effort (external force) to pick it up. Similarly, imagine you are travelling in a car at, say, 60 km/hr and the ignition is turned off. The car will eventually come to a halt without the application of brakes. This is due to the friction between the car tyres and the road surface. Friction is a force that tries to stop moving objects. The car will not stop if there is no friction between the car tyres and the road surface. In space there is no influence of external forces. A spacecraft will continue to travel in a straight line at a constant speed. It does not need a force to keep it moving.

1.10 Newton's Second Law of Motion

Newton's second law of motion states that when an unbalanced force acts on an object, the object will accelerate in the direction of the force. The acceleration is directly proportional to the force and inversely proportional to the mass.

$$a = \frac{F}{m} \quad \text{or,} \quad F = ma$$

where F = the force (newtons)
m = the mass of the object (kg)
a = the acceleration produced (m/s^2)

A force of 1 newton gives a mass of 1 kg an acceleration of 1 m/s^2

Example 1.4 Calculate the acceleration of a 100 kg object if it is acted upon by a net force of 250 N.

Solution:

$$F = ma \text{ (a is the acceleration)}$$
$$250 = 100 \times a$$
$$\frac{250}{100} = a \text{ or, } a = 2.5\,\mathrm{m/s^2}$$

1.11 Newton's Third Law of Motion

Newton's third law of motion states that to every action there is an equal and opposite reaction. Consider a beam resting on two walls, as shown in Figure 1.1.

The weight of the beam plus any other force is the action. The reactions (R_1 and R_2) are offered by the walls as they support the beam and resist its downward movement. For the stability of the beam, the total reaction must be equal to the action.

$$\text{Weight of the beam} + \text{Forces acting on the beam} = R_1 + R_2$$

If the walls cannot support the beam, due either to some defect in the wall or to the use of weaker materials, the reaction will not be equal to the action and the beam will move away from its intended position. Depending on the magnitude of the movement, this might cause the failure of the component that the beam is supporting.

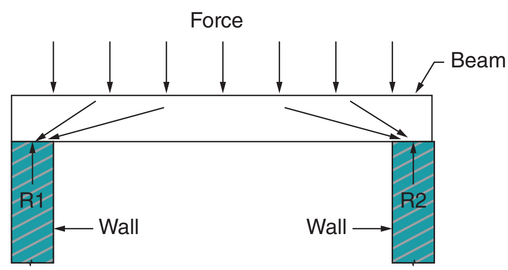

Figure 1.1

1.12 Friction

When an object rests on a surface, two forces act on it to maintain the balance: the weight acting downwards and the reaction (or normal reaction) acting upwards, as shown in Figure 1.2. If a force F is applied to slide the object, the movement is resisted by another force that acts in the opposite direction, as shown in Figure 1.3. The opposing force is called the **friction force** (R) and is due to the roughness of the surfaces in contact.

If the applied force is increased, the friction force increases as well. The maximal friction force is experienced when the object is about to move. This is called **static friction**. Friction also acts when the object is in motion, but this type of friction (called **dynamic friction**) is less than static friction.

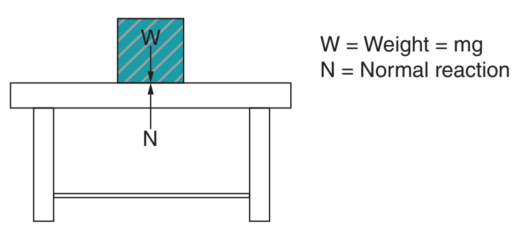

Figure 1.2

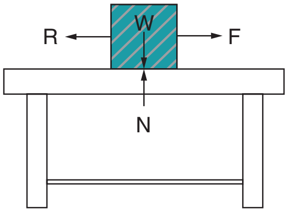

Figure 1.3

The amount of friction between two surfaces depends on:

1) The normal reaction, which acts at right angles to the two surfaces.
2) The roughness of the surfaces in contact.

The coefficient of friction (μ) is given by:

$$\mu = \frac{\text{Friction force (R)}}{\text{Normal reaction between surfaces (N)}}$$
$$= \frac{R}{N} = \frac{F}{W} \quad (R = F;\ N = W)$$

Example 1.5 A horizontal force of 9.0 N moves a brick on a metal surface at a uniform speed. Find the weight of the brick if the coefficient of friction between the two materials is 0.45.

Solution:

$$R = F = 9.0\ \text{N};\ N = W;$$
$$\mu = \frac{R}{N} = \frac{R}{W}$$
$$W = \frac{R}{\mu} = \frac{9.0\text{N}}{0.45} = 20.0\ \text{N}$$

1.13 Work

Work is said to be done when a force moves an object. The work done can be calculated from the following equation:

$$\text{Work done} = \text{Force} \times \text{Distance moved}$$
$$\text{or,} \quad W = F \times s$$

The SI unit of work is the **joule** (J), which can be defined as the work done when a force of 1 newton moves through a distance of 1 m in the direction of the force.

Example 1.6 A 50 cm × 50 cm × 50 cm block of concrete rests on a concrete floor. The coefficient of friction between the two surfaces is 0.6. Calculate:

a) The horizontal force necessary to move the concrete block.
b) The work done in moving the block by 10 m.

The density of concrete is 2400 kg/m^3

Solution:

a) $$\begin{aligned}\text{Mass} &= \text{Density} \times \text{Volume}\\ &= 2400 \times (0.5 \times 0.5 \times 0.5)(50\ \text{cm} = 0.5\ \text{m})\\ &= 300\ \text{kg}\end{aligned}$$

$$\text{Weight of the block } (W) = 300 \times 9.81 = 2943\ \text{N}$$

$$\text{Coefficient of friction, } \mu = \frac{F}{W} (\text{F is the horizontal force})$$

$$0.6 = \frac{F}{2943}$$

$$F = 0.6 \times 2943 = 1765.8\ \text{N}$$

b) $$\begin{aligned}\text{Work done} &= \text{Force} \times \text{Distance}\\ &= 1765.8 \times 10\\ &= 17658\ \text{J or } 17.658\ \text{kJ}\end{aligned}$$

1.14 Energy

The capacity to do work is known as **energy**. Energy may be available in various forms but it is not possible to create or destroy energy. However, it may change from one form to another, for example, from light energy into electrical energy, from electrical energy into heat energy, from heat energy into electrical energy etc.

Some of the main forms in which energy exists are:

- Chemical energy;
- Electrical energy;
- Kinetic energy;
- Light energy;
- Nuclear energy;
- Potential energy;
- Sound energy;
- Thermal energy.

Potential energy and kinetic energy are discussed further in the next two sections.

1.14.1 Potential Energy

Potential energy may be defined as the energy possessed by a body due to its position above the ground. If an object of mass m kilograms is raised to a height h metres, then the work done in doing so is given by:

$$\begin{aligned}\text{Work done} &= \text{Force} \times \text{Distance}\\ &= (m \times g) \times h = mgh\end{aligned}$$

The potential energy (PE) possessed by the object, at height h metres, is mgh.
The work done by the object, if allowed to fall, is also mgh.
The unit of energy is the joule (J).

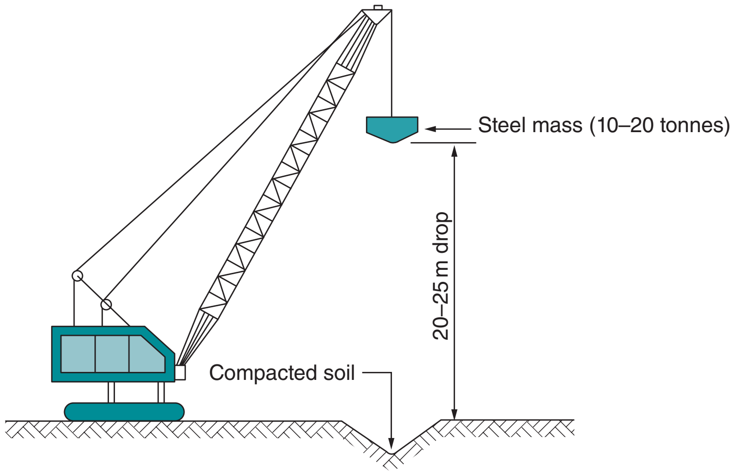

Figure 1.4 Dynamic compaction.

1.14.2 Kinetic Energy

The energy possessed by a moving object is known as the **kinetic energy** (KE).

$$\text{Kinetic energy} = \frac{1}{2}mv^2$$

where m = the mass of the object in kg
v = the velocity of the object in m/s

There are several uses of potential energy and kinetic energy in civil engineering, two of which are: hydroelectric power stations and the improvement of loose subsoil.

In hydroelectric power stations, water is stored in the form of a lake by constructing a concrete dam or an earth dam. The water level rises and, due to its height, possesses energy. The water is allowed to fall through a pipe (penstock) and its energy is used to drive a turbine. The turbine, in turn, generates electricity.

Loose subsoils are not very strong and hence may not be able to support a building/structure satisfactorily. The strength of the subsoils may be improved by several techniques, one of which is called **dynamic compaction**. The method involves dropping a heavy block of steel from a suitable height (Figure 1.4). As the block falls on the ground, its energy is used to compact the soil. The compaction of a soil results in the improvement of its density and strength.

Example 1.7 A 10 tonne block of steel was raised to a height of 12.0 m and then dropped. Calculate the energy possessed by the block at heights of 12 m, 9 m, 6 m, 3 m and when it hit the ground.

Solution:

$$10 \text{ tonnes} = 10000 \text{ kg}$$

The steel block is at rest at a height of 12 m, i.e. its velocity, and hence the kinetic energy, is zero. The energy possessed by it is entirely due to its height above the ground surface.

$$\begin{aligned}\text{Total energy at 12 m height} &= \text{Potential energy} = mgh \\ &= 10000 \times 9.81 \times 12.0 = 1177200 \text{ J}\end{aligned}$$

Table 1.2

Height (m)	$v^2 = 2as + u^2$	Kinetic energy $= \frac{1}{2}mv^2$ (J)	Potential energy = mgh (J)	Total energy = P E + K E (J)
12	0	0	1177200	1177200
9	58.86	294300	882900	1177200
6	117.72	588600	588600	1177200
3	176.58	882900	294300	1177200
0	235.44	1177200	0	1177200

At a height of 9 m: As the block is dropped, it accelerates due to gravitational force. The energy possessed by the block is a combination of kinetic energy and potential energy. Its velocity, v, can be determined from:

$$v^2 - u^2 = 2as \text{ or, } v^2 = u^2 + 2as \quad (\text{initialvelocity, } u = 0)$$

$$v^2 = 0^2 + 2 \times 9.81 \times 3.0 = 58.86 \quad (s = 12 - 9 = 3 \text{ m})$$

$$\text{Kinetic energy} = \frac{1}{2}mv^2$$

$$= \frac{1}{2} \times 10000 \times 58.86 = 294300 \text{ J}$$

$$\text{Potential energy} = mgh$$

$$= 10000 \times 9.81 \times 9.0 = 882900 \text{ J}$$

$$\text{Total energy at a height of 9.0 m} = KE + PE$$

$$= 294300 + 882900 = 1177200 \text{ J}$$

The calculations at the other heights can be made in a similar way and are summarised in Table 1.2.

These calculations show that the total energy possessed by the steel block at the 12 m height is entirely due to the potential energy. The total energy is entirely due to its kinetic energy when the block hits the ground, i.e. at zero height. At other heights, the total energy of the block is a combination of kinetic and potential energies.

1.15 Power

Power is defined as the work done per second, i.e. the rate of doing work.

$$\text{Power} = \frac{\text{Work done}}{\text{Time taken}}$$

Power is measured in joules per second (J/s) or watts (W).

$$\text{One watt} = \text{one joule of work done per second}$$

$$\text{or, } 1 \text{ W} = 1 \text{ J/s}$$

$$\text{also, Power} = \frac{\text{Work done}}{\text{Time taken}} = \frac{F \times s}{t}$$

$$= \text{Force} \times \text{Velocity}\left(\frac{s}{t} = \text{velocity}\right)$$

Example 1.8 A crane lifts a block of concrete with a mass of 2.0 tonnes to a height of 8.0 m in 12 seconds. Find the work done in lifting the block and the power output of the crane.

Solution:

$$\begin{aligned} 2.0 \text{ tonnes} &= 2000 \text{ kg} \\ \text{Work done} &= \text{Force} \times \text{Distance} \\ &= (2000 \times 9.81) \times 8.0 \\ &= 156960 \text{ J} \\ \text{Power} &= \frac{156960}{12} = 13080 \text{ W} \end{aligned}$$

Exercise 1.1

1 Find the gravitational force between the Earth and:
A An object with a mass of 10 kg.
B A person with a mass of 60 kg.
Given: mass of the Earth = 6.0×10^{24} kg; radius of the Earth = 6.4×10^{6} m; $G = 6.7 \times 10^{-11}$ Nm^2/kg^2.

2 A block measuring 300 mm × 200 mm × 200 mm is made from concrete with a density of 2300 kg/m^3. Find the mass of the block.

3 The cross-sectional measurements of a 6.0 m long concrete beam are 0.3 m × 0.7 m. Find the mass and the weight of the beam. The density of concrete is 2400 kg/m^3.

4 Calculate the acceleration of an 80 kg object if it is acted upon by a net force of 960 N.

5 A horizontal force of 85.0 N moves a concrete component on a metal surface at a uniform speed. Find the weight of the component if the coefficient of friction is 0.45.

6 An 80 cm × 50 cm × 50 cm block of concrete rests on a concrete floor. The coefficient of friction between the two surfaces is 0.6. Calculate:
A The horizontal force necessary to move the concrete block.
B The work done in moving the block by 15 m.
The density of concrete is 2300 kg/m^3

7 An 8 tonne block of steel is raised to a height of 9.0 m and then dropped. Calculate the energy possessed by the block at heights of 9 m, 6 m, 3 m and when it hits the ground.

8 A crane lifts a block of concrete with a mass of 2.5 tonnes to a height of 10.0 m in 12 seconds. Find:
A The work done in lifting the block.
B The power output of the crane.

Reference/Further Reading

1 Breithaupt, J. (2008). *AQA Physics A*. Cheltenham: Nelson Thornes.