Cambridge

IGCSE

Physics

CODE: (9702)

Chapter 07

Matter and the materials

Density

Density is a property of matter. It tells us about how concentrated the matter is in a particular material. Density is a constant for a given material under specific conditions. Density is defined as the mass per unit volume of a substance:

$$\text{density} = \frac{\text{mass}}{\text{volume}}$$

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

Pressure

A fluid (liquid or gas) exerts pressure on the walls of its container, or on any surface with which it is in contact. A big force on a small area produces a high pressure.

Pressure is defined as the normal force acting per unit cross-sectional area.
We can write this as a word equation:

$$\text{pressure} = \frac{\text{normal force}}{\text{cross-sectional area}}$$

$$p = \frac{F}{A}$$

The units of pressure are thus newtons per square metre (Nm^{-2}), which are given the special name of pascals (Pa).

$1Pa = 1Nm^{-2}$

Pressure in a fluid

The pressure in a fluid depends on three factors:
- the depth h below the surface
- the density ρ of the fluid
- the acceleration due to gravity, g.

In fact, pressure p is proportional to each of these and we have: pressure = density × acceleration due to gravity × depth $p = \rho g h$ We can derive this relationship using Figure 7.2

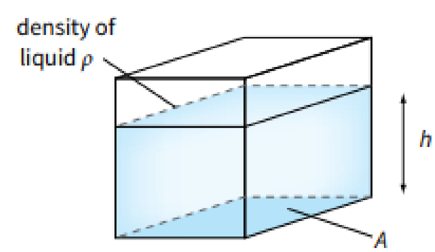


Figure 7.2 The weight of water in a tank exerts pressure on its base.

$$\text{weight of water} = \text{mass} \times g = \rho \times A \times h \times g$$

$$\text{pressure} = \frac{\text{force}}{\text{area}} = \rho \times A \times h \times \frac{g}{A}$$

$$= \rho \times g \times h$$

Compressive and tensile forces

A pair of forces is needed to change the shape of a spring. If the spring is being squashed and shortened, we say that the forces are **compressive**. More usually, we are concerned with stretching a spring, in which case the forces are described as tensile (Figure 7.4).

Figure 7.5 shows that the line AA becomes longer when the wire is bent and the line BB becomes shorter. The thicker the wire, the greater the compression and tension forces along its edges

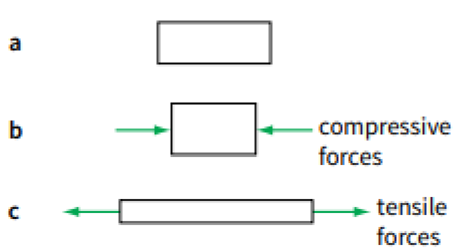


Figure 7.4 The effects of compressive and tensile forces.

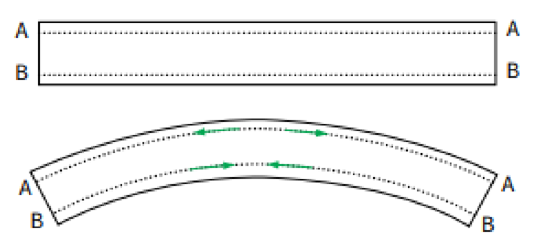


Figure 7.5 Bending a straight wire or beam results in tensile forces along the upper surface (the outside of the bend) and compressive forces on the inside of the bend.

The **extension** of a helical spring is measured as it increases with the applied force or load, indicating the change in its length, which is crucial for understanding its behavior.

Hooke's law

The conventional plotting of results involves force along the horizontal axis and extension along the vertical axis. However, Figure 7.7 shows an alternative, with extension on the horizontal axis and force on the vertical axis, revealing the **force constant** of the spring, which is directly proportional to the applied force.

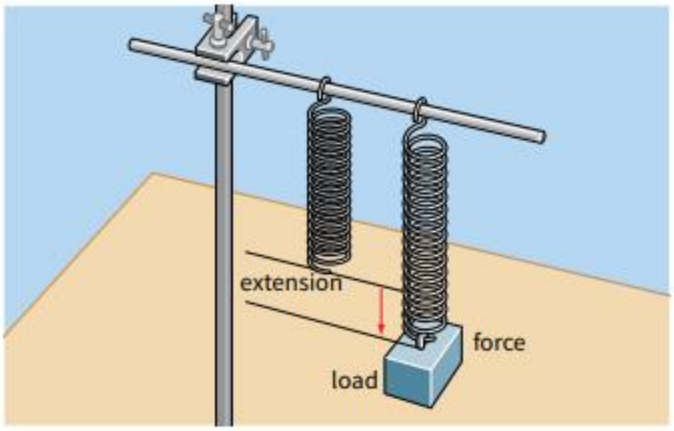


Figure 7.6 Stretching a spring.

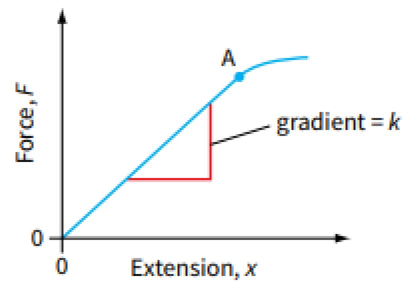


Figure 7.7 Force–extension graph for a spring.

If a spring or anything else responds to a pair of tensile forces in the way shown in section OA of Figure 7.7, we say that it obeys Hooke's law:

> A material obeys Hooke's law if the extension produced in it is proportional to the applied force (load).

Elastic behavior refers to a spring's ability to return to its original length when applied with a small force, while a large force may permanently deform the spring, with the **elastic limit** being the force beyond which it becomes deformed.

$$\text{strain} = \frac{\text{extension}}{\text{original length}}$$

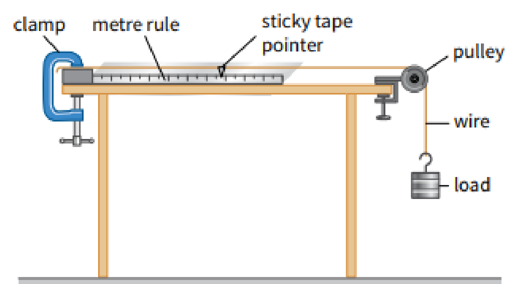


Figure 7.10 Stretching a wire in the laboratory. WEAR EYE PROTECTION and be careful not to overload the wire.

Stretching materials

When we determine the force constant of a spring, we are only finding out about the stiffness of that particular spring. However, we can compare the stiffness of different materials.

Stress and strain

The **strain** produced by the load is a crucial factor in calculations, as it represents the fractional increase in the original length of the wire, indicating that a long wire is preferred due to its greater stretch capacity.
This may be written as: strain = x / L

$$\text{stress} = \frac{\text{force}}{\text{cross-sectional area}}$$

This may be written as:

$$\text{stress} = \frac{F}{A}$$

where F is the applied force on a wire of cross-sectional area A.

The units of stress are newtons per square metre (N m^{-2}) or pascals (Pa), the same as the units of pressure:

$1\text{ Pa} = 1\text{ N m}^{-2}$

The young modules

We can now find the **stiffness** of the **material** we are stretching. The ratio of stress to strain is called the Young modulus of the material. That is:

$$\text{Young modulus} = \frac{\text{stress}}{\text{strain}}$$

$$\text{or} \qquad = \frac{\sigma}{\varepsilon}$$

where E is the Young modulus of the material, σ (Greek letter sigma) is the stress and ε (epsilon) is the strain. The unit of the Young modulus is the same as that for stress, Nm^{-2} or Pa. In practice, values may be quoted in MPa or GPa. These units are related as;

$$1\,\text{MPa} = 10^6\,\text{Pa}$$

$$1\,\text{GPa} = 10^9\,\text{Pa}$$

Table 7.1 gives some values of the Young modulus for different materials.

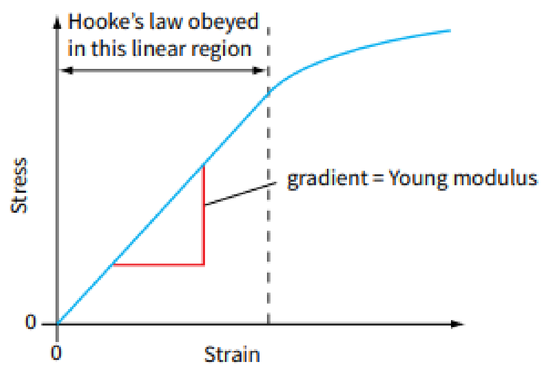


Figure 7.11 Stress–strain graph, and how to deduce the Young modulus. Note that we can only use the first, straight-line section of the graph.

Material	Young modulus / GPa
aluminium	70
brass	90–110
brick	7–20
concrete	40
copper	130
glass	70–80
iron (wrought)	200
lead	18
Perspex®	3
polystyrene	2.7–4.2
rubber	0.01
steel	210
tin	50
wood	10 approx.

Table 7.1 The Young modulus of various materials. Many of these values depend on the precise composition of the material concerned. (Remember, 1 GPa = 10^9 Pa.)

Elastic potential energy

Whenever you stretch a material, you are doing work. This is because you have to apply a **force** and the material **extends** in the direction of the force.

Exercise machines with springs for muscle development are known for their ability to transfer energy. When pushing down on a springboard before diving, you work by transferring energy to the springboard and recovering it when pushing you up.

We call the energy in a deformed solid the elastic **potential energy** or **strain energy**

The energy of a material can be recovered if it has been elastically strained, while if it has been plastically deformed, the energy is lost due to atom

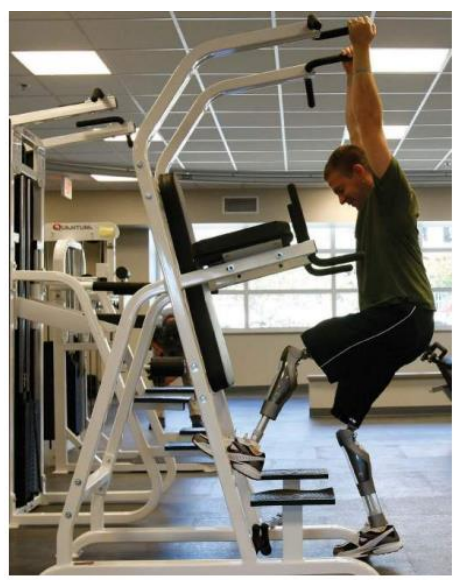


Figure 7.14 Using an exercise machine is hard work.

movement. The amount of elastic potential energy can be determined using a force-extension graph and the force-work equation.
That is: work done = force × distance moved in the direction of the force

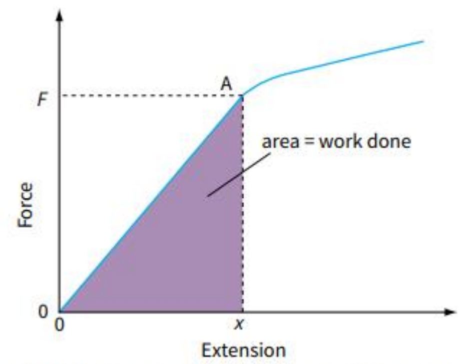


Figure 7.15 Elastic potential energy is equal to the area under the force–extension graph.

Method 1

We can think about the average force needed to produce an extension x. The average force is half the final force F, and so we can write:

$$\text{elastic potential energy} = \text{work done}$$

$$\text{elastic potential energy} = \frac{\text{final force}}{2} \times \text{extension}$$

$$\text{elastic potential energy} = \tfrac{1}{2}Fx$$

$$\text{or} \qquad E = \tfrac{1}{2}Fx$$

Method 2

The other way to find the elastic potential energy is to recognise that we can get the same answer by finding the area under the graph. The area shaded in Figure 7.15 is a triangle whose area is given by:

$$\text{area} = \tfrac{1}{2} \times \text{base} \times \text{height}$$

This again gives:

$$\text{elastic potential energy} = \tfrac{1}{2}Fx$$

$$\text{or} \qquad E = \tfrac{1}{2}Fx$$

The work done in **stretching** or **compressing** a material is always equal to the area under the graph of force against extension.

$$\text{elastic potential energy} = \tfrac{1}{2}Fx = \tfrac{1}{2} \times kx \times x$$

$$\text{elastic potential energy} = \tfrac{1}{2}kx^2$$

Revision questions

1) (a) Define the density of a material

(b) Brass, an alloy of copper and zinc, consists of 70% by volume of copper and 30% by volume of zinc.

density of copper $= 8.9 \times 10^3$ kg m^{-3}

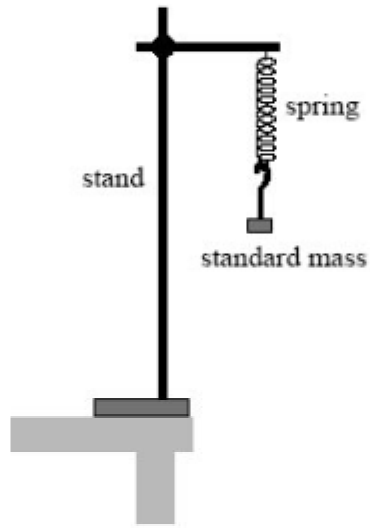
density of zinc $= 7.1 \times 10^3$ kg m^{-3}

(i) Determine the mass of copper and the mass of zinc required to make a rod of brass of volume 0.80×10^{-3} m^3

(ii) Calculate the density of brass.

2) (a) State Hooke's law.

(b) A student is asked to measure the mass of a rock sample using a steel spring, standard masses and a metre rule. She measured the unstretched length of the spring and then set up the arrangement shown in the diagram below.



(i) Describe how you would use this arrangement to measure the mass of the rock sample. State the measurements you would make and explain how you would use the measurements to find the mass of the rock sample. The quality of your written communication will be assessed in this question.

ii) State and explain one modification you could make to the arrangement in the diagram above to make it more stable.

3) a) State Hooke's law for a material in the form of a wire and state the conditions under which this law applies.

(b) A length of steel wire and a length of brass wire are joined together. This combination is suspended from a fixed support and a force of 80 N is applied at the bottom end, as shown in the figure below.

Each wire has a cross-sectional area of 2.4×10^{-6} m^2.

length of the steel wire = 0.80 m

length of the brass wire = 1.40 m

the Young modulus for steel $= 2.0 \times 10^{11}$ Pa

the Young modulus for brass $= 1.0 \times 10^{11}$ Pa

(i) Calculate the total extension produced when the force of 80 N is applied.

(ii) Show that the mass of the combination wire $= 4.4 \times 10^{-2}$ kg.

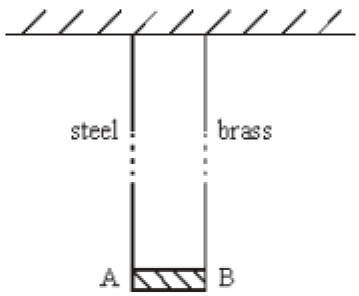
density of steel $= 7.9 \times 10^3$ kg m^{-3}

density of brass $= 8.5 \times 10^3$ kg m^{-3}

(c) A single brass wire has the same mass and the same cross-sectional area as the combination wire described in part (b). Calculate its length.

4. (a) State Hooke's law for a material in the form of a wire

(b) A rigid bar AB of negligible mass, is suspended horizontally from two long, vertical wires as shown in the diagram. One wire is made of steel and the other of brass. The wires are fixed at their upper end to a rigid horizontal surface. Each wire is 2.5 m long but they have different cross-sectional areas.



When a mass of 16 kg is suspended from the centre of AB, the bar remains horizontal.

the Young modulus for steel = 2.0×10^{11} Pa
the Young modulus for brass = 1.0×10^{11} Pa

(i) What is the tension in each wire?
(ii) If the cross-sectional area of the steel wire is 2.8×10^{-7} m^2 , calculate the extension of the steel wire.
(iii) Calculate the cross-sectional area of the brass wire.
(iv) Calculate the energy stored in the steel wire.
(c) The brass wire is replaced by a steel wire of the same dimensions as the brass wire. The same mass is suspended from the midpoint of AB.
(i) Which end of the bar is lower?
(ii) Calculate the vertical distance between the ends of the bar.

5. (a) (i) Describe the behaviour of a wire that obeys Hooke's law.
(ii) Explain what is meant by the elastic limit of the wire.
(iii) Define the Young modulus of a material and state the unit in which it is measured.

(b) A student is required to carry out an experiment and draw a suitable graph in order to obtain a value for the Young modulus of a material in the form of a wire. A long, uniform wire is suspended vertically and a weight, sufficient to make the wire taut, is fixed to the free end. The student increases the load gradually by adding known weights. As each weight is added, the extension of the wire is measured accurately.

(i) What other quantities must be measured before the value of the Young modulus can be obtained?
(ii) Explain how the student may obtain a value of the Young modulus.
(iii) How would a value for the elastic energy stored in the wire be found from the results?

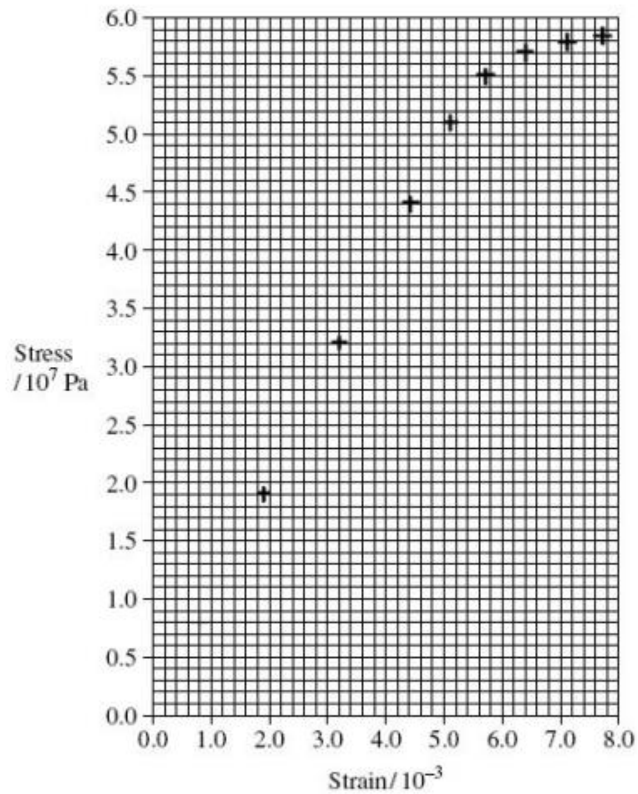
6) (a) Describe how to obtain, accurately by experiment, the data to determine the Young modulus of a metal wire.

A space is provided for a labelled diagram.

The quality of your written answer will be assessed in this question.

(b) The diagram below is a plot of some results from an experiment in which a metal wire was stretched.

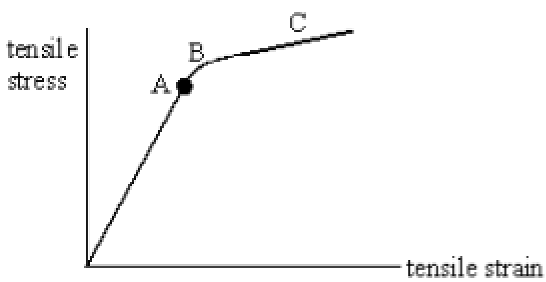
(i) Draw a be t fit line u ing the data point
(ii) Use your line to find the Young modulus of the metal, stating an appropriate unit.
(c) After reaching a strain of 7.7 × 10^{-3} , the wire is to be unloaded. On the diagram above, sketch the line you would expect to obtain for this.



7) (a) When a tensile stress is applied to a wire, a tensile strain is produced in the wire. State the meaning of

tensile stress,
tensile strain

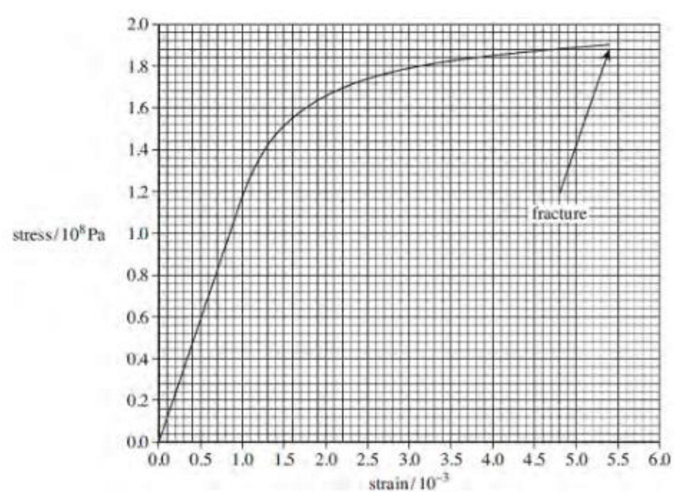
(b) A long thin line metallic wire is suspended from a fixed support and hangs vertically. Weights are added to increase the load on the free end of the wire until the wire breaks. The graph below shows how the tensile strain in the wire increases as the tensile stress increases.



With reference to the graph, describe the behaviour of the wire as the load on the free end is increased. To assist with your answer refer to the point A, and regions B and C.

You may be awarded marks for the quality of written communication in your answer.

8) The figure below shows a stress-strain graph for a copper wire
(a) Define tensile strain.
(b) State the breaking stress of this copper wire.
(c) Mark on the figure above a point on the line where you consider plastic deformation may start. Label this point A.
(d) Use the graph to calculate the Young modulus of copper. State an appropriate unit for your answer.
(e) A certain material has a Young modulus greater than copper and undergoes brittle fracture at a stress of 176 MPa. On the figure above draw a line showing the possible variation of stress with strain for this material.



9) a) (i) Describe the behaviour of a wire that obeys Hooke's law.
(ii) Explain what is meant by the elastic limit of the wire.
(iii) Define the Young modulus of a material and state the unit in which it is measured.

(b) A student is required to carry out an experiment and draw a suitable graph in order to obtain a value for the Young modulus of a material in the form of a wire. A long, uniform wire is suspended vertically and a weight, sufficient to make the wire taut, is fixed to the free end. The student increases the load gradually by adding known weights. As each weight is added, the extension of the wire is measured accurately.

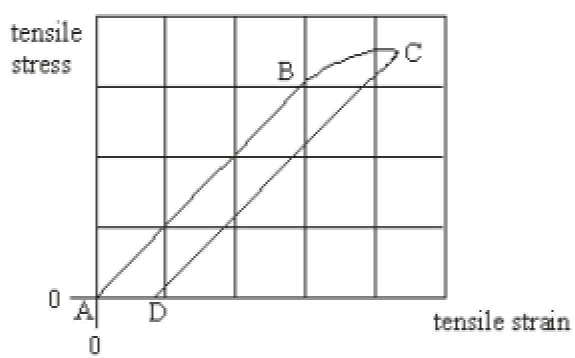
(i) What other quantities must be measured before the value of the Young modulus can be obtained?

(ii) Explain how the student may obtain a value of the Young modulus.

(iii) How would a value for the elastic energy stored in the wire be found from the results?

10) a) When a tensile stress is applied to a wire, a tensile strain is produced in the wire. State the meaning of
tensile stress,
tensile strain.

b) A long, thin metal wire is suspended from a fixed support and hangs vertically. Masses are suspended from its lower end. As the load on the lower end is increased from zero to a certain value, and then decreased again to zero, the variation of the resulting tensile strain with the applied tensile stress is shown in the graph.



(i) Describe the behaviour of the wire during this process. Refer to the points A, B, C and D in your answer. You may be awarded marks for the quality of written communication in your answer.

(ii) State, with a reason, whether the material of the wire is ductile or brittle.

(iii) What does AD represent?

(iv) State how the Young modulus for the material may be obtained from the graph.

(v) State how the energy per unit volume stored in the wire during the loading process may be estimated from the graph.