

Public understanding of science

Strange but true: the physics of glass, gels and jellies is all related through rheology

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ABSTRACT Rheology is an enormously far-reaching branch of physics (or physical chemistry) and has a number of different guises. Rheological descriptions define fluids, semi-solids and conventional solids, and the application of this science defines the performance and utility of materials and substances as diverse as foods (such as yogurt and marmalade), body tissues (such as blood, skin and bone) and civil and mechanical engineering materials (such as glass, iron girders and copper wire). Two of the most commonly used terms are viscosity and elasticity, and in some sense these are exact opposites, in which energy put in is either dissipated or stored, respectively. Other useful rheological terms include brittleness, stiffness and stickiness. The experiments considered, described and explained in this article represent accessible manifestations of this rather complex branch of science.

Introduction

Rheology is the branch of physics concerned with the way in which materials distort, flow or interact, and store or dissipate mechanical energy. It is also considered to be a fundamental concept in parts of physical chemistry, physics, material science and engineering. Materials distort and flow over widely differing time frames. We all know you can propel gas, pour liquid and stir rice pudding but perhaps you didn't know that materials such as a seaside stick of rock or tar are glass-like (glassy) and are often deemed to flow but over very large time periods. It is rheology that deals with the deformation and flow of matter, especially the non-conventional (non-Newtonian) flow of liquids and the plastic flow of solids. The philosopher Heraclitus (also ascribed to Simplicius and to Plato) suggested *panta rhei*, which is variably translated as 'everything changes' or 'everything flows', a theme we will return to when covering glasses.

The term rheology derives from the Greek *rheos*, 'flow' or 'stream', and *-logia*, 'study of', and was coined by Eugene Bingham in 1920. Measurements concerning the flow of matter are usually undertaken in the liquid state but also as 'soft solids' (semi-solids) or solids under conditions where they become 'sloppy' or 'yield', and respond by flowing. We refer to this state as

'plastic'. The term is a physics term and does not relate to a chemical material (such as polythene); however, it has been hijacked by chemists because oil-derived plastics exhibit 'plasticity'. Plastics do not deform uniformly (elastically) in response to an applied force but dissipate energy in a non-uniform way. Shear rate (agitation/deformation speed), shear stress (physical 'resistivity' of the material) and the quotient of the two, viscosity (coefficient of viscosity), and plasticity and elasticity or rigidity are the building blocks leading to an understanding of *rheological properties* (Anderson, Leaver, Rawlings and Alexander, 1998; Aulton, 2007; Ball, 2003; Binns, 2010; Goodwin and Hughes, 2000). Viscosity is a measure of a fluid's resistance to flow, a measure of dissipation for force applied throughout the material. This resistance to flow is defined (equation 2) by Newton's law (Figure 1A).

$$\tau = F/A \quad (1)$$

$$\tau = \eta \times \frac{du}{dy} \quad (2)$$

$$\eta = \tau/\dot{\gamma} \quad (3)$$

Where, shear stress (τ) is force (F) divided by area (A), and strain, $\frac{du}{dy}$, is represented by the shear rate, gamma-dot ($\dot{\gamma}$), and η is the coefficient of viscosity (see Table 1) usually or, more simply, 'viscosity', measured in pascal seconds (Pa.s).

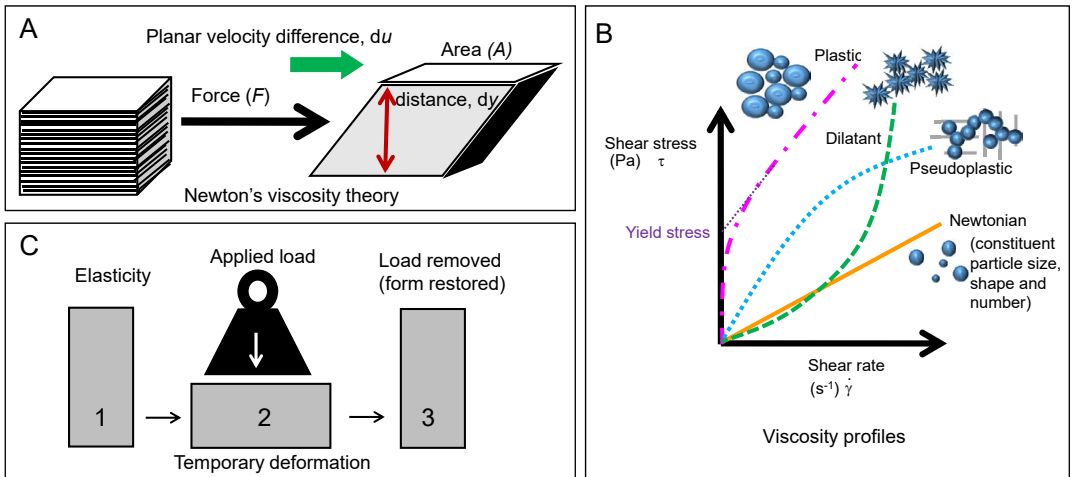


Figure 1 Composite figure showing three rheological models. The components are: (A) the Newtonian model of liquid flow modelled as a series of plates within a cube of liquid; (B) a plot of shear stress (τ) versus shear rate ($\dot{\gamma}$), indicating the four types of viscosity (η); (C) (1) elasticity and elastic deformation of a material in the absence of an applied load, (2) presence of applied load and (3) subsequent restoration of form on removal of the weight.

The planar velocity is u and the thickness of the sample is y . Viscosity is simply stress divided by strain. The scale of viscosity ranges from an inviscid liquid (a simple non-viscous liquid; a Newtonian fluid) to a rigid solid (an elastic body or a glassy material), as illustrated in Figure 1B.

Plasticity is a truly important concept for the things that surround us and also as a subject in physics and engineering, and is a type of viscosity (Figure 1B). Its characteristic feature is seen as the material undergoes permanent deformation under an applied load. It usually implies an internal friction (thus facilitating energy loss, like all viscous systems) within the system components. Very often plastic samples are made of threads that rupture or are formed by interconnected miniature beads. The plasticity of a material is defined by Bingham's law and the materials are sometimes referred to as Bingham materials.

Elasticity, on the other hand, can be described as the ability of an object or material to return to its normal shape after being compressed or stretched out (Figure 1C). Other terms commonly used might be bendiness, stretchiness, flexibility or rubber-likeness (Table 1). Elasticity comes from the Greek *elastos*, meaning 'ductile', and is the ability of a body to resist a distorting or deforming force and to return to its original size and shape when that force is removed (Figure 1C); it is defined by Hooke's law (for a Hookean solid). Solid objects that are

inelastic permanently deform when adequate forces are applied on them. This would be like driving over a pencil eraser with a many-tonne steamroller. The quantity known as Young's modulus (equation 4) of rigidity (elasticity, E) may also be used to infer elastic properties (Table 1). Consequently, we can show that rheology is important as it defines the properties of the materials around us and we are familiar with concepts such as watery soup, brittle candy, creamy custard or springy and stretchy cycle shorts and other clothing made from

Table 1 Rheological parameters and their units

Property	Conventional units	Alternative units
Liquids		
Dynamic viscosity (η)	Pa s	P (poise)
Kinematic viscosity (ν)	$\text{m}^2 \text{s}^{-1}$	St (stokes)
Solids		
Elasticity/rigidity (E , Young's modulus)	Pa	
Ultimate tensile strength (σ_T)	Pa	
Break point (σ_{Br})	Pa	
Yield point (σ_Y)	Pa	
Percentage elongation ($I_{EL\%}$)	m	
Bending stiffness (k_B)	N m	

Lybra® (Marion and Hornyak, 1982; Martin, 1993; Nicholson, 1997; Pashley and Karaman, 2004; Petrick, 2007).

$$E = \sigma / \varepsilon \tag{4}$$

$$\varepsilon = \Delta L / L \tag{5}$$

Here we define a new term for the strain (ε) of a solid body, which is based on dimensional change, in terms of length (L), and stress here has the symbol σ and is derived from F/A .

The pascal (Pa) is a unit of pressure equal to a newton per square meter ($N\,m^{-2}$); the newton (N) unit of force is $kg\,m\,s^{-2}$. The alternative unit for dynamic viscosity is the centipoise (cP) and an alternative unit for kinematic viscosity is the centistokes (cSt) named after Poiseuille and Stokes, respectively. Dynamic viscosity (η) = kinematic viscosity (ν)/sample density (ρ).

Rheology, a branch of physics or of physical chemistry, depending on your perspective, is an important concept in so many things in life and defines lots of activities, from the ease of drinking thick milkshakes to delivery of injections of medicines to the functioning of the drive shaft fluid of automatic cars. It can also be used to chart the form of materials, which exist in a spectrum or scale ranging from the simple Newtonian

liquid (e.g. water) to the ideal Hookean rigid solid (e.g. copper sheet), with glassy materials lying somewhere in the middle. There are many rheological parameters that represent the properties of the things we touch and experience; we often refer to the word ‘texture’ to describe these physical properties. Particles or collections of species are often referred to as condensed matter and exist in two forms:

- soft condensed matter (soft matter), such as gels;
- hard condensed matter, such as silica.

A range of common textural characteristics with familiar examples of soft and hard matter is given in Table 2.

Various types of material

Amorphous and crystalline structure

There are two types of solid material, described in terms of their internal composition (the terminology is based on the Greek word *morphe*, meaning shape and form). These are amorphous (unstructured or disordered) and crystalline (symmetrically structured, ordered) solids. These two types of solid vary in terms of physical properties such as density, fracture format, melting point (T_m), hardness/pliability, solubility and transparency. Amorphous structure, which lacks long-range order, leads to the formation of a ‘glassy solid’ (glass), of which normal window soda glass is an example, whereas an ionic, atomic or molecular lattice-based structure results in a crystalline solid (e.g. metals and common salt). Amorphous materials, for example the protein insulin used in drug delivery, typically also have better dissolution characteristics.

Crystalline solids, as opposed to glassy materials in terms of long-range order, usually demonstrate well-defined melting points because all the component ions, atoms or molecules are the same distance from adjacent species. However, glassy materials, such as gels and those formed from a polymer, for example the amylose and amylopectin from starch, have microscopic-scale (nanometre) disordered or heterogeneous structure, as in a liquid, but the mechanical properties of a solid, and with enormous viscosities of around 10^{13} – 10^{16} Pa.s. Amorphous solids melt over a wide range of temperature rather than at a sharp melting point as observed with crystalline solids. In addition, when an amorphous solid is kept at a temperature just below its melting point,

Table 2 The texture and consistency (rheology) of common materials

Textural characteristic	Example	Measured by
Brittleness	Window glass, boiled sweets	Impaction
Deformation	Polypropylene Tupperware®, polystyrene foam	Pliability
Hardness	Diamond, carbide steel	Impaction
Softness	Cotton wool, fleece clothing	Probing
Elasticity	Eraser, crème caramel dessert, wire	Probing
Viscosity	Yogurt, pâté	Stirring
Tackiness	Adhesive/glue, syrup	Probing
Sliminess	Mucus, dandelion sap	Spreading
Rubberiness	Jelly sweets, elastic band, young skin	Probing

Probing = slow vertical force; impaction = rapid vertical force; pliability = bending; stirring = constant tangential force; spreading = limited tangential force.

for some time, the component elements (ions, atoms or molecules) slowly rearrange into a more highly ordered crystalline form, and this is often seen with polymers and plastics where the transparent material turns opaque or hazy owing to the formation of these semi-crystalline regions. This is often followed by the polymeric material, such as a polypropylene sandwich box, becoming more brittle and being more likely to break on rough handling. Condensed matter physics is a part of modern trendy materials science that talks about nanometre and sub-nanometre structure. We will return to the idea of nanomaterials below. Amorphous glassy substances have low toughness but high strength.

Supercooled fluids

Under-cooling of materials, mostly known as supercooling, is the process of lowering the temperature of a liquid below its actual freezing point (T_f) without it becoming a solid. Despite its appearance and hardness, the outwardly solid 'glass' exists in a form without structure and is referred to as a supercooled liquid (Figure 2A). In reality, a glass-like material is actually neither liquid matter nor solid matter but rather an amorphous solid, existing in a state somewhere between the two. Once a liquid traverses its standard freezing point, it will crystallise but only in the presence of a 'seeding crystal', thereby forming a solid. In the absence of such 'seeds', the liquid matter can be maintained below the

temperature at which normal crystallisation takes place. When the start of crystallisation has not occurred below this temperature, a non-crystalline (amorphous) solid forms. The process of vitrification requires that the liquid matter be pure and free of so-called 'nucleation' sites. In the case of vitreous or glassy materials, such as aqueous polymer suspensions largely devoid of water, despite appearing to be a solid, the sample is much closer to a hyper-viscous liquid. For this reason, Thomas Parnell's tar experiment and studies of the glass used in windows show the material does indeed flow as described by Heraclitus (Zhao, Simon and McKenna, 2013).

Complex fluids

Complex fluids and soft matter materials are substances that lie between standard liquids and solids, displaying fluid characteristics and solid-like behaviour. If there is extensive interaction between adjacent species and formal links or bonds of the covalent, ionic or hydrogen bond type then gels form. Examples of complex fluids might include colloidal (fine) particle dispersions (also called sols), gels, foams, animal fat, liquid crystals, emulsions, solutions and glasses. These 'fluids' are binary mixtures that have a coexistence between two types of matter: solid-liquid (e.g. suspensions of macromolecules such as the protein in egg white), liquid-gas (e.g. fire-fighting foams) or liquid-liquid (e.g. emulsions such as mayonnaise). Structure and molecular mobility

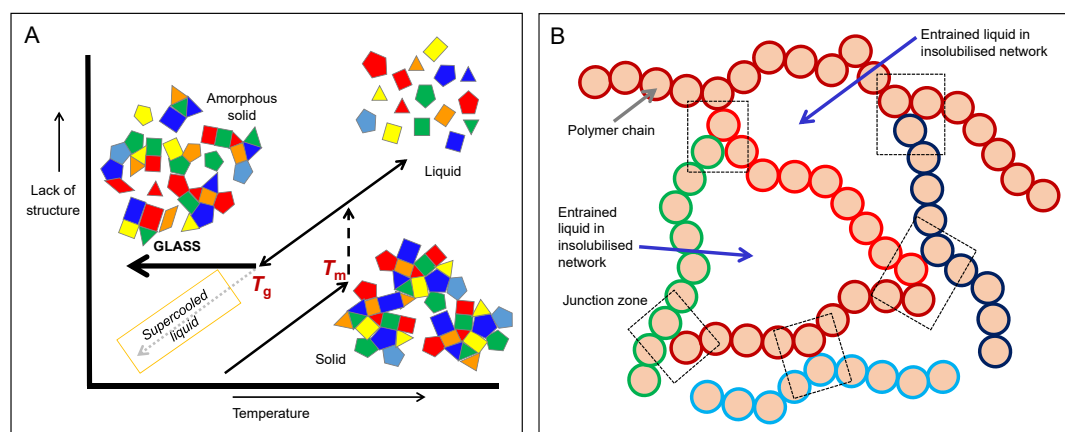


Figure 2 Pictorial representations of: (A) a 'supercooled liquid' (remaining liquid below its freezing point) or glass and the supercooling process of a liquid in the absence of 'crystallisation nucleation sites' in the amorphous structured 'frozen' vitreous liquid; (B) a gel based on a long thread-like molecule as the component 'building block' of a continuous network, joined by so-called 'junction zones', with internal entrainment of liquid

range from the invisible (microscopic) to the just visible (mesoscopic), and on to the large-scale (macroscopic) lengths of buildings and engineered products. Complex fluids cover a multitude of materials made of many components of soft matter that can flow (Shaw, 1992; Stuart, 2002) but display non-Newtonian rheology (such as dilatancy, thixotropy and plasticity).

Gelation and network formation

Gelation can be considered to be the creation of a solid by cooling down, which usually involves the formation of an interconnected network or gel from a nanoparticle or nanoscale dispersion (sol). The term derives from the Latin *gelatio*, meaning ‘a freezing’, with probably one of the most familiar gels being those fabricated from gelatin. Pectin can be used in vegetarian dishes in place of animal-derived gelatin. Gelation is the formation of gel or the solidification of any polymer-bearing fine dispersion (colloidal suspension), which may appear to be a solution to the untrained eye. In many foods, gelation is referred to as the setting or cooling of the gelling agent (pectin, alginate, gelatin, xanthan, etc). In gelation, liquid is trapped within a confining network of polymeric chains; for example, various forms of acrylate or cellulose polymers are used in hair-care products such as hair gel. Variations in temperature (or in salt content or pH) can destabilise the gel (jelly in colloquial language) and cause leakage of the trapped liquid. A suspension and a gel are in the true sense exact opposites, as a dispersion of solid in liquid is converted into a dispersion of liquid in solid for a gel. The points of contact that form the network are known as junction zones or cross-links (Figure 2B). In general, gels only form if there is a sufficient amount of gelling agent present and the number of junction zones is sufficient to hold the entrained liquor. The junction zones form by molecular entanglement, and covalent linkage of adjacent strands or ionic bridges, as with calcium (Ca^{2+}) ions and the seaweed polymer alginic acid containing the $-\text{COO}^-$ functional group above pH 3.0 when it is ionised (Sarker, Axelos and Popineau, 1999; Sarker, 2013). The dual interaction (bifunctionality) of cross-link-forming agents is instrumental in determining the strength of the gel formed. Gelatin, a common ‘gelling agent’, is sometimes referred to as gelatine and is used in sweets (marshmallows, chewy toffee), cosmetics and photographic film, to fabricate the capsules used for medicines and

oils, and in numerous desserts, such as supermarket crème caramel and party jelly (Figure 2B). Gelatin is manufactured by the acid or alkaline treatment of collagen derived from skin, hides and animal horns.

Nanomaterials

Nanomaterials are talked about a lot these days. While the term used to be used to refer to colloidal materials, it now describes materials where the dimensions of at least one of the components lie between 1 and 1000 nanometres (nm; 10^{-9} metres). A recent definition suggests that, to be classified as such entities (molecules, ions, polymers, particles), the dimensions should be between 1 and 100 nm. There are many types of nanomaterial. The pigment in a photocopier is nano-carbon with a diameter of about 500 nm, enzymes found in biology often have diameters of around 3 nm, nanoparticles found in engine oils are about 20 nm in diameter, and the oil droplets and solids found in medicines and vaccines for injection are often 100–200 nm in diameter (Hiemenz and Rajagopalan, 1997; Jones, 2004). Nanomaterials can form dispersions, emulsions, foams, glasses and intact solids. However, the nanoparticles themselves can be constituted from simpler smaller components that ‘congeal’ to make microscopic or nanoscale gel particles with interconnected beads and chains. These are frequently the basis of the materials used to entrap drugs for use in chemotherapy, cancer radiotherapy or X-ray and magnetic resonance imaging (MRI) scans.

Experiments to illustrate material properties

The equipment and raw materials needed for the experiments described in this section are listed in Box 1 and some are shown in Figure 3.

Dynamic viscosity – the falling sphere method according to the Stokes equation

Prepare rice starch slurry using 100 g of unrinsed long-grain rice boiled for 10 minutes with 500 cm^3 tap water. Decant off the liquor, allow it to cool to room temperature (25 °C) and retain it for tests.

The 15.3 mm diameter marble (Figure 3C) weighing 4.7 g is more dense than the liquid it is placed in (most water-based solutions have a density of about 1 g cm^{-3}). The liquid being measured must be sufficiently clear to follow the sedimentation of the marble. Shear is generated, producing stress in the liquid as the glass marble falls through it. Measure the time taken for the marble to fall from the surface of the liquid at

BOX 1 Raw materials and standard equipment

1. Food store cupboard provisions:
 - long-grain rice
 - seedless jam and peel-free marmalade
 - golden syrup
 - runny clear honey
 - olive oil
 - homogenised tomato soup
 - instant dessert, e.g. crème caramel
 - jelly sweets or gums
 - condensed milk
 - glycerol (glycerine)
2. Cosmetics and hygiene products:
 - sterilising hand gel
 - hair gel
 - infant shampoo
3. Commercial over-the-counter medicines:
 - infant teething gel
 - sugar-free cough syrup
4. Packaging materials:
 - 500 cm³ yogurt pot
 - freezer bag
 - supermarket-type 1 litre opalescent milk bottle packaging
5. Top pan balance (with two decimal places precision)
6. Fridge with freezer compartment (−18 °C)
7. Stack of low-value coins (1p, 2p, 5p, etc.)
8. Paper/polystyrene cup (>50 cm³ volume)
9. Crocodile clips, small
10. Elastic bands
11. Petri dish
12. String or strong cord (>0.5 mm thickness)
13. Chopping board and scissors or sharp knife
14. Ruler with 'cm' and 'mm' gradations
15. Hammer or weight
16. Glass beakers (250–500 cm³)
17. Bunsen burner
18. Marbles or larger ball-bearings
19. Clean tap water

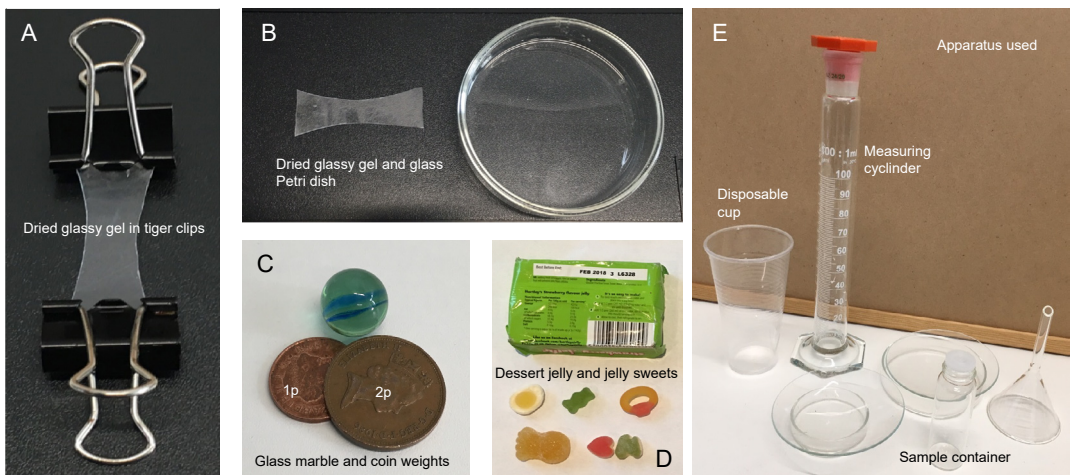


Figure 3 Some of the materials and equipment used for the experiments: (A) clamping of a sample; (B) Petri dish used to dry the starch slurry; (C) weights and a falling sphere; (D) gelatin- and polysaccharide-based jelly and jelly-like sweets; (E) a selection of core apparatus needed

a height of 15 cm to the base of the measuring cylinder (equation 6), as shown in Figure 4.

Useful values of dynamic viscosity:

- water – 1 mPa s;
- olive oil – 60 mPa s;
- glycerol – 1420 mPa s;
- cough syrup – 150 mPa s;
- runny honey – 8000 mPa s.

What is the dynamic viscosity of condensed milk?

Equations to be used:

$$V = h/t \quad (6)$$

$$V = [d^2 g (\rho_s - \rho_l)] / 18\eta \quad (7)$$

where V is the settling velocity of the marble (m s^{-1}), t is the time to settle (s), d is the marble

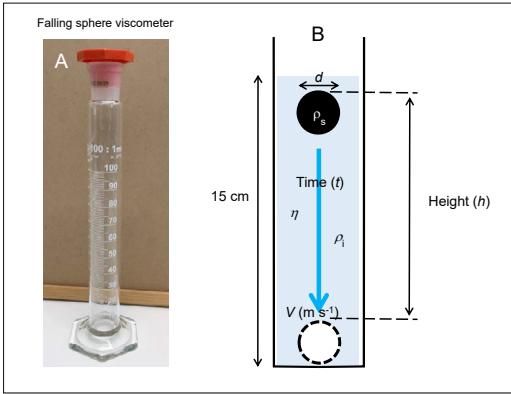


Figure 4 Experimental set-up of a ‘falling sphere’ viscosity measurement according to Stokes’ law of sedimentation, which uses a marble dropped in a 15 cm column of test fluid of viscosity η falling at velocity V

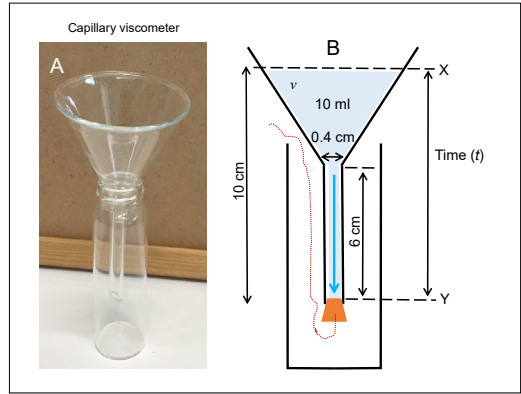


Figure 5 Experimental set-up of a simplified kinematic viscosity measurement based on a glass funnel, configured according to a simple flow model (non-turbulent, laminar flow), measuring flow time between two points marked X and Y; the liquid is initially prevented from movement by a cork

diameter (m), g is the gravitational constant (9.81 m s^{-2}), h is the distance settled in time t (m), ρ_s is the density of the marble (2500 kg m^{-3}), ρ_i is the density of the suspending fluid (which should be about 1000 kg m^{-3}) and η is the dynamic viscosity (Pa.s). The assumption is that the marble falls on its own without being moved by hand. Rearrange equation 7 for viscosity and collect the terms [$d^2g(\rho_s - \rho_i)$] to make the calculation simpler.

- (a) Generate a five-point calibration plot, with the y -axis being dynamic viscosity and the x -axis being time, to estimate the dynamic viscosity of canned condensed milk at 25°C . Clean the apparatus and measure the dynamic viscosity of tomato soup. Can you calculate the linear regression ($y = mx + c$, with y being dynamic viscosity, m being the graph slope, x being time and c being the intercept) of the settling velocity plot?
- (b) Calculate the dynamic viscosity of cooled rice starch slurry.

Kinematic (capillary) viscosity

Internal friction within a sample is a measure of the kinematic viscosity. One stipulation is that the sample must not contain particles with a larger diameter than that of the internal diameter of the stem of the funnel being used (Figure 5). Plug the end of the funnel with a small cork attached to a piece of string. Deposit 15 cm^3 of sample in the glass funnel. Remove the cork by tugging on the string and record the time (t). Using a stopwatch,

note the time taken for all the sample to flow out of the funnel stem (capillary). The kinematic viscosity (ν) is calculated as:

$$\nu = kt \tag{8}$$

(in units of $\text{mm}^2 \text{ s}^{-1}$, which is numerically the same as centistokes, cSt)

where the constant k is about 0.01 mm^2 , and you can derive this constant by using water which would have a kinematic viscosity of 0.01 cSt . Using the predetermined values listed below, undertake kinematic viscosity measurements using the funnel:

- water – 0.01 cSt ;
- olive oil – 0.9 cSt ;
- children’s mild/pure shampoo – 50 cSt ;
- golden syrup – 1000 cSt .

Useful unit conversions:

- $1 \text{ St} = 100 \text{ cSt}$;
- $1 \text{ St} = 10^{-4} \text{ m}^2 \text{ s}^{-1} = 1 \text{ cm}^2 \text{ s}^{-1} = 100 \text{ mm}^2 \text{ s}^{-1}$.

- (c) Knowing the kinematic viscosity of various samples, generate a four-point calibration plot, with the y -axis being kinematic viscosity (ν) and the x -axis being time (t), to estimate the kinematic viscosity of canned tomato soup at 25°C . Clean the apparatus after each use. Heat the soup to 30 , 40 and then 50°C in a glass beaker without causing burning, and measure the kinematic viscosity at each of these temperatures. What happens to the kinematic

viscosity as the temperature is raised? Plot kinematic viscosity against temperature. Can you calculate the linear regressions of the time and temperature plots?

- (d) Calculate the kinematic viscosity of 15 cm³ cooled rice starch slurry.
- (e) Using common units (mPa s), compare the results from (b) and (d) above and with the values listed in Table 3.

Useful unit conversions:

- 1 mPa s or 1 cP = 1 g m⁻¹ s⁻¹;
- 1 cP = 1 mm² s⁻¹, or 1 cSt assuming a density of the liquid of 1.00 g cm⁻³.

Table 3 The dynamic viscosity (η) of common materials at 25 °C (unless otherwise specified)

Material	State of matter	Dynamic viscosity, mPa s
Hydrogen	Gas	0.8×10^{-5}
Air	Gas	1.7×10^{-5}
Helium	Gas	1.9×10^{-5}
Milk/apple juice	CF	2
Blood	CF	3.5
3% rice starch slurry	Glass	14
Vegetable oils	Liquid	40–80
Cream (50% fat)	CF	120
Cough syrup	Liquid	150
Strained yogurt	CF	300
Engine oil	Liquid	500
Ketchup	CF	1000
Glycerol/glycerine	Liquid	1420
Paraffin emulsion	CF	3000
Shower wash/shampoo	CF	5000
Runny clear honey	Liquid	8000
Hand gel	CF	8000–25 000
Jam/jelly (seedless)	CF	8000
Rice pudding	CF	10 000
Ice cream	CF	10 000–20 000
Mayonnaise	CF	20 000
Butter	CF	30 000
80% w/v sucrose	Glass	40 000
Cosmetic cream	CF	45 000–60 000
Firm hair wax	CF	50 000
Deodorant stick	CF	65 000–300 000
Toothpaste	CF	85 000
Peanut butter	CF	250 000
Butter/lard at 5 °C	CF	1 000 000
Window putty	CF	10 ⁸
Tar	Glass	10 ¹¹
Boiled sweets	Glass	10 ¹³

% w/v is the percentage weight in predetermined volume.
CF is a complex fluid.

- (f) Other experiments – how are viscosity and elasticity affected by temperature?
- Gels such as hair gel, infant teething gel, crème caramel, tomato soup: on heating up from room temperature (25 °C) to 40 °C, the viscosity goes down – try judging the ease of pouring from one glass beaker to another (wearing insulated gloves).
 - When a gummy sweet is frozen at –18 °C in a refrigerator, it becomes brittle, not pliable, when then hit with a hammer.
 - Syneresis: when you cut jam or marmalade, the entrained liquid leaks out.

Rigidity and elasticity

The rigidity and elasticity of a sample can be measured (Figure 6) and is a fundamental characteristic of solids. Measurements can be undertaken using a bow-tie-shaped piece of

Table 4 The Young's modulus (E) of common materials at 25 °C (unless otherwise specified)

Soft materials	Young's modulus (E), MPa
Polymer and colloidal solutions	10^{-6} – 10^{-4}
Alcohol sterilising gel	0.002
Adipose (fatty) tissue	0.1
Rubber	0.1–5
Gelatin gel	0.2
Banana	0.8–3
Human cornea at 37 °C	1.2
Peach	2–20
Potato	6–14
Raw apple	6–14
Pear	10–30
Carrot	20–40
Hard/tough materials	Young's modulus (E), GPa
Plastics	0.5–20
Wood	1–10
Leather	1–100
Dry spaghetti*	3
Human fingernail	3
Tooth enamel	8–96
Ice	10
Concrete	10–20
Human bone (skull)	14–21
Stones*	40–60
Glass*	70
Aluminium, copper	100
Steel	200
Graphene carbon	>1000

*Glassy materials

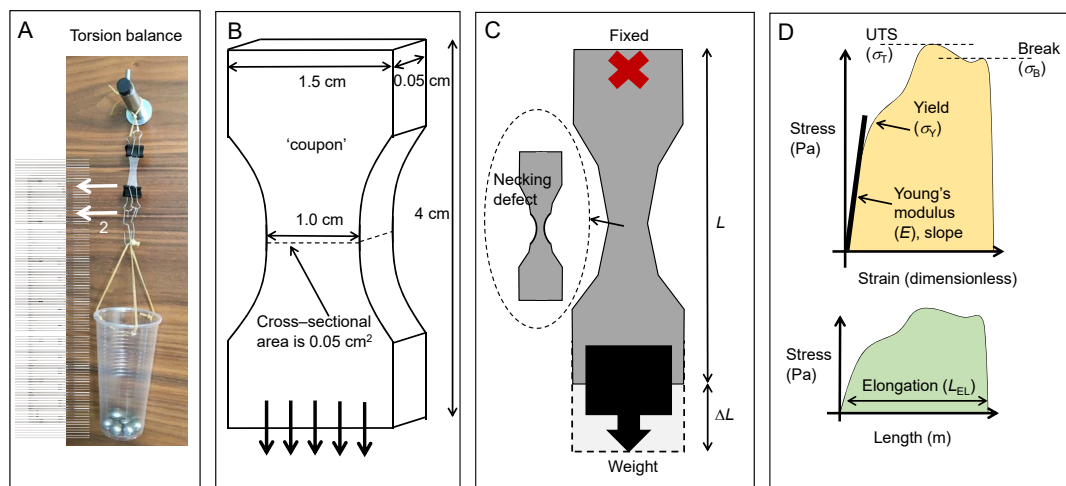


Figure 6 Experimental set-up for ‘stress–strain’ tension measurements of solids according to Hooke’s and Young’s laws. Part B shows a schematic of the ‘coupon’ and the required dimensions, and part C shows the procedure for measurement of mechanical properties. The mechanical properties of interest are represented in a plot of stress vs strain for solids and the parameters (E , σ_Y , σ_T and σ_B) derived from the plot are illustrated in part D. Young’s modulus (E) is derived from the initial slope. The percentage elongation ($L_{EL\%}$) can also be derived from a modified form of the plot with length on the x-axis, where percentage elongation is calculated with reference to the start length shown in the lower plot in part D.

material referred to as a ‘coupon’ (Figure 6B and 6C) and by knowing the cross-sectional area of the middle portion of the coupon (Figure 6B). Using a range of materials such as those listed below (and that may be compared with the values given in Table 4), construct a stress (y -axis) versus strain (x -axis) plot:

- 1 litre milk bottle wall section (polyethylene);
- yogurt pot wall (polystyrene);
- freezer bag section (polypropylene);
- photocopier paper (cellulose-lignin).

Use crocodile clips to secure either end of the coupon. Using a disposable cup and string, apply a load to the base of the coupon. You can use coins to increase the load (Figure 3): convenient coins would be 5p (3.3 g), 1p (3.6 g), 2p (7.1 g) and £1 coins (9.5 g). The force F applied is a function of the mass m (in kg) and the acceleration g (9.81 m s^{-2}) due to imposed gravity:

$$F = mg \quad (10)$$

Force is measured in newtons (N), which can also be expressed as kg m s^{-2} . A 10 kg mass would result in a force of 98 N.

Stress is the applied force divided by the cross-sectional area, whereas strain would be the

change in coupon length divided by its original length. From the stress–strain plot for each material below you should be able to calculate:

- (g) the Young’s modulus (E) (values for many common materials are listed in Table 4), the yield stress (σ_Y), the ultimate tensile strength (UTS, σ_T) and the break point (σ_B) (refer to the upper plot in Figure 6D); and
- (h) percentage elongation ($L_{EL\%}$), in excess of the initial length, using the alternative graphical representation of stress against length, as shown in Figure 6D (lower plot).

$$L_{EL\%} = [(L_E - L_0)/L_0] \times 100 \quad (9)$$

where, L_0 is the initial sample length and L_E is the terminal length up to the point of rupture. The initial length would of course be 100%.

- (i) The prepared rice starch gel-suspension should be poured into a weighed Petri dish (Figure 3). Place in a warm space and plot a graph of weight versus time. After a period of water evaporation, the weight should stabilise – the remaining sample should then be a glass, composed of amorphous and disordered amylose and amylopectin (Figure 7). At this point, remove the dry paste and cut it into

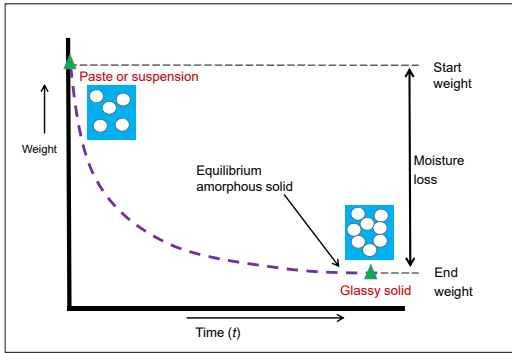


Figure 7 Graphical representation of an air-drying process for fabrication of a ‘glass’ of amorphous material from rice starch having lost water owing to evaporation by drying at room temperature over an extended time period; the material typically turns from being soft and pliable to rigid and glassy during this process

an initial rectangle of size greater than the dimensions of the bow-tie coupon template. Noting the dimensions, shape and trim to the correct size, as per the template. Use one coupon for creating a stress–strain plot so that you can calculate the Young’s modulus and another one for the bending stiffness test below.

Flexibility or bending stiffness

Flexibility or bending stiffness (k_B) is the ability of a material (solid or glass) to resist dimensional or

Table 5 The bending stiffness (k_B) of common materials at 25 °C

Material	Bending stiffness, N m
White lined paper	0.03–0.04
Rubbers	0.035–0.8
Three-ply wood pulp paper (40% w/v)	0.06–0.12
Fluted corrugated multilayered cardboard	15–60
High-density polyethylene (hard plastic)	~300
Wood	1300
Plywood	1500
Polycarbonate ‘plastic glass’	3000
Glass	5400
Metals	24 000
Ceramics	>60 000

%w/v is the percentage on a weight in volume basis.

deformational change. Referred to as stiffness, it can be measured by applying a load to a symmetrical rectangular coupon bent over a pivot (Figure 8).

$$k_B = c(F/w) \tag{11}$$

where F is the applied force, w is the deflection and c is the form constant, which depends on the sample and the form of the measurement. For ease of estimation, we can treat the quantity c as being equal to 1.0 N m^2 , though it is calculated as follows:

$$c = (ML^2)/d \tag{12}$$

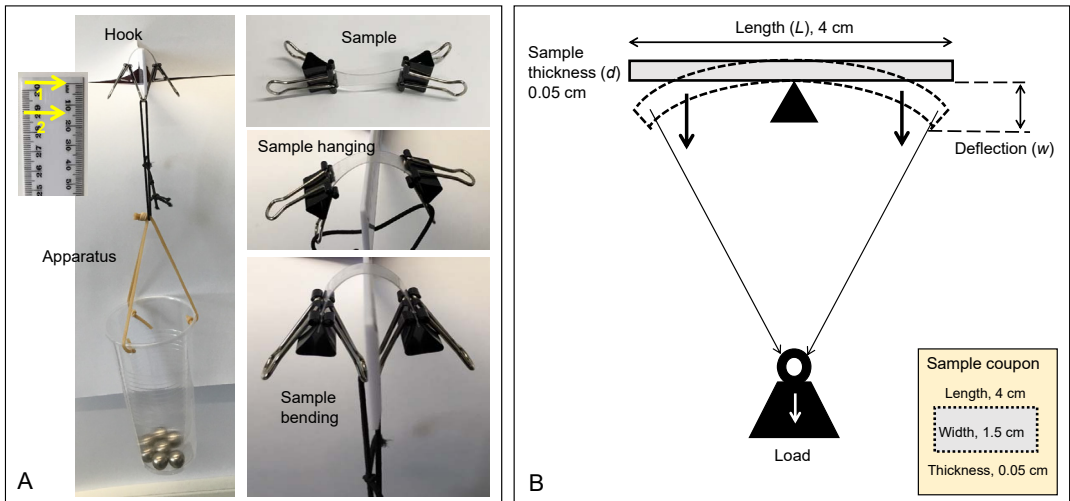


Figure 8 Experimental set-up for bending stiffness (k_B) measurements

where L is the sample length, d is the sample thickness and M is the bending moment or ‘internal structural reaction’ and is the product of the elasticity of the sample, its inertia and its curvature.

Bending stiffness values are customarily reported in N m units. Some interesting values for common materials are listed in Table 5.

- (j) Calculate the bending stiffness for dried rice starch slurry, a polystyrene yogurt pot container, a polyethylene milk bottle wall and paperboard. What can you infer about the stiffness of a glassy material and a polymer used for food packaging? Why do you think stiffness and rigidity are required?

Conclusions

The results of the experiments described are discussed below.

- **Dynamic viscosity:**
 - (a) The dynamic viscosities of soup and of condensed milk depend on measurements of regression based on the data in Table 3.
 - (b) The dynamic viscosity of cooled rice slurry is about 20 mPas.
- **Kinematic (capillary) viscosity:**
 - (c) Depends on data regression and the fit to data in Table 3. Viscosity goes down with increased temperature.
 - (d) The kinematic viscosity is $20 \text{ mm}^2 \text{ s}^{-1}$.
 - (e) You might find higher values than in the table. Is this due to error?
 - (f) Viscosity is inversely related to temperature according to the modified Arrhenius

equation $\eta = ke^{-RT}$, where R is the universal gas constant ($8.314 \text{ J mol}^{-1} \text{ K}^{-1}$) and T is the temperature. Decreasing viscosity with temperature means samples should be easier to pour when heated. Gelatin sweets change from elastic to brittle in texture when chilled. When frozen down to liquid nitrogen temperatures, the sweets take on the texture of soda glass. On cutting a gel, up to 50% of the entrained liquor can leak out.

- **Rigidity and elasticity:**
 - (g) In addition to the tabulated values in Table 6, refer to values in Table 4.
 - (h) Elongation is 5–20%.
 - (i) The Young’s modulus of rice glass is about 5 GPa, and it is entirely dependent on water content and on chemical cross-linking.
- **Flexibility or bending stiffness:**
 - (j) See Table 5. The values for dried rice starch and for a yogurt pot are estimated to lie between those of paper and cardboard. Stiffness and rigidity are needed to provide protection. This may be important, for example, in yogurt cartons, boxed eggs, medicine bottles and packaging for high-value electronic devices. Elasticity, viscosity, stiffness and other mechanical characteristics are often a determinant of product performance, shelf life of commercial products or the form and texture that we expect from a range of commercial products.

Table 6 Values relevant to findings

Material	Young’s modulus (E), MPa	Yield stress (σ_y), MPa	UTS (σ_T), MPa	Break point (σ_B), MPa	% elongation ($L_{EL}\%$)
Paper*	2–4	0.05–0.2*	15–70	18–100	5–20
Rubber	70–100	0.2	30	30–100	5–140
Plastics	40	2–10	20–80	100	20–80
Glass	70–100	5–10	35	70–500	~0.002
Steel	200	250	400–800	1000+	20

*Depends on hydration: normal water content of ‘dried’ material is 5–15% w/v; air content is 13–60%.

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Editor's comment

The pascal

The pascal is commonly known among science teachers as being the unit for pressure and it is defined as the force per unit area acting on a surface perpendicular to the area.

Perhaps less well known is the fact that, when a force is applied to compress a rod, the stress is the force per unit area of cross-section, and the unit for stress is also the pascal. The same applies to the stretching of a rod or wire.

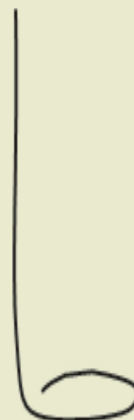
For shear stress (as explained by the resistance of layers sliding across each other (Figure 1A)), the equivalent calculation is 'force divided by the area over which it is applied' and, once again, the unit is the pascal. However, in this case, the force is not applied in a perpendicular direction but along the surface.

Practical notes on measuring terminal velocity

At school level, the popular method of measuring the terminal velocity of a falling sphere is to use a steel ball bearing in a liquid such as motor oil. It is possible to see the sphere falling slowly and, after it has fallen, it can be extracted using a magnet to bring it to the side of the cylinder and slowly pull it to the top by sliding the magnet up the outside.

In the experiments described here, even though these viscous fluids are opaque, the position of the slowly falling marble can be estimated from the disturbance of the fluid because a narrow cylinder is being used. The fall is so slow that adequate measurements can be taken from a single fall.

So that the marble can be removed after each observation if repeated falls are considered, a piece of stiff copper wire can be used to make a loop of diameter slightly less than that of the marble. The wire is then bent at right angles to the loop, to leave a straight section taller than the cylinder. This is placed in the cylinder before dropping the marble. After each fall, the wire can be used to lift the marble slowly out of the liquid.



Note that the lower density of a glass marble means that its terminal velocity will be less than that of a steel ball bearing of the same diameter.

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