Testing the fracture behaviour of chocolate

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Abstract

In teaching the materials science aspects of physics, mechanical behaviour is important due to its relevance to many practical applications. This article presents a method to experimentally examine the toughness of chocolate, including a design for a simple test rig, and a number of experiments that can be performed in the classroom. Typical data for some of these experiments is given, along with reflection on the activity.

1. Introduction

The mechanical properties of materials are very important in most engineering situations, from the construction of a nuclear reactor to an artificial hip joint or the hard disc inside a computer. It is very important therefore that students of physics meet these concepts in ways that will engage them and be memorable. In this article we present a simple method to demonstrate the toughness of materials using chocolate.

1.1 The Difference between Stiffness, Strength and Toughness

When considering the mechanical properties of materials, it is important to note the distinction between materials that are stiff (i.e. resistant to elastic, recoverable deformation), strong (i.e. hard to permanently deform) and tough (i.e. resistant to fracture). Figure 1 ranks some materials for each of these properties; note that some materials, such as glass, can be good in certain properties but poor in others. The experiment that is discussed here examines the toughness only, by looking at the energy required to break a sample of material. If a lot of energy is required, as would be the case for a material that tears apart, then it has a high toughness. If little energy is needed, which would be the case for a material that snaps with a single crack, it has a low toughness (it shows brittle behaviour).

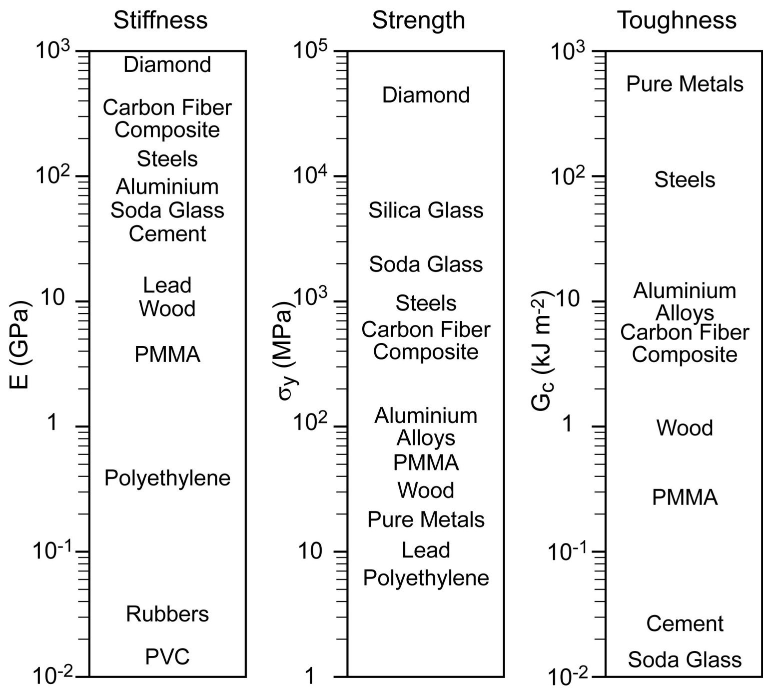

Figure 1 – Approximate ranking of different common materials for stiffness (Young's modulus, E), strength (yield or fracture stress, σ_f) and toughness (Critical strain energy release rate, G_C) Adapted from [1].

2. Chocolate

Chocolate is, like a lot of materials, made by combining different substances together. Typically, chocolate will include cocoa mass, extracted cocoa butter, sugar and vegetable oil, with milk added to make milk chocolate. Up to 5% vegetable fat is added, and this, along with the fat in the cocoa butter, controls the melting point, responsible for the apparent texture of the chocolate [2]. Another similarity that chocolate has with engineering materials is the effect on the final properties of how it is processed. When blending together the ingredients, it is important to get a fine particle size (typically <36 μm) so that the resulting texture is not gritty [3]. The fat present coats the particles, lubricating their movement past each other, and so finer particles also result in better flow properties for the chocolate in the liquid state. Mixing, reducing the particle size and coating the particles with fat are achieved in a process known as conching [2]. A conching machine will consist of two or three linked containers with a rotating arm in each section. The arms spread molten chocolate onto the temperature-controlled wall of the container, and it is then scraped off (breaking up the particles) and thrown through the air, enabling the unwanted chemical compounds to escape [2].

Chocolate is a polymorphic material with a complex structure. This is due to the cocoa butter having 6 different ways of packing together in its crystalline form, giving rise to 6 different forms of chocolate (chemically identical, but structurally different), known as polymorphs I-VI [4]. Form I has the lowest stability, with a melting point of ~17ºC, and stability increases through each polymorph with forms V and VI being the most widely used by commercial manufacturers. A transition between these forms over long times is responsible for the whitish "fat-bloom" on the surface of old chocolate, as different amounts of fat are stable in different forms [3, 4]. Getting the correct form, and therefore the correct melting temperature (controlling it to "melt in your mouth, not in your hand") is another challenge, which has similarities to the industrial processing of materials. The solutions used are the same, sometimes adding "seed" crystals of the correct type, to promote growth of this form, sometimes a carefully-designed series of heat treatments, to encourage the desirable structures to form and remove the undesirable [2].

For our purposes chocolate is a highly suitable material, sharing many aspects with real engineering materials, being sufficiently weak that we can test it without advanced equipment, and being non toxic and readily available. In addition, it is obviously an attractive material to work with, and has been previously used for activities involving students for this reason [5].

3. Fracture Test Rig

The test we will perform is based on an actual materials test procedure known as Charpy impact testing [6], where a sample is broken by a pendulum. It is a quick test to perform which measures the energy required to break a sample. In practice, this test is often applied as a rapid test for quality assurance on materials such as steels.

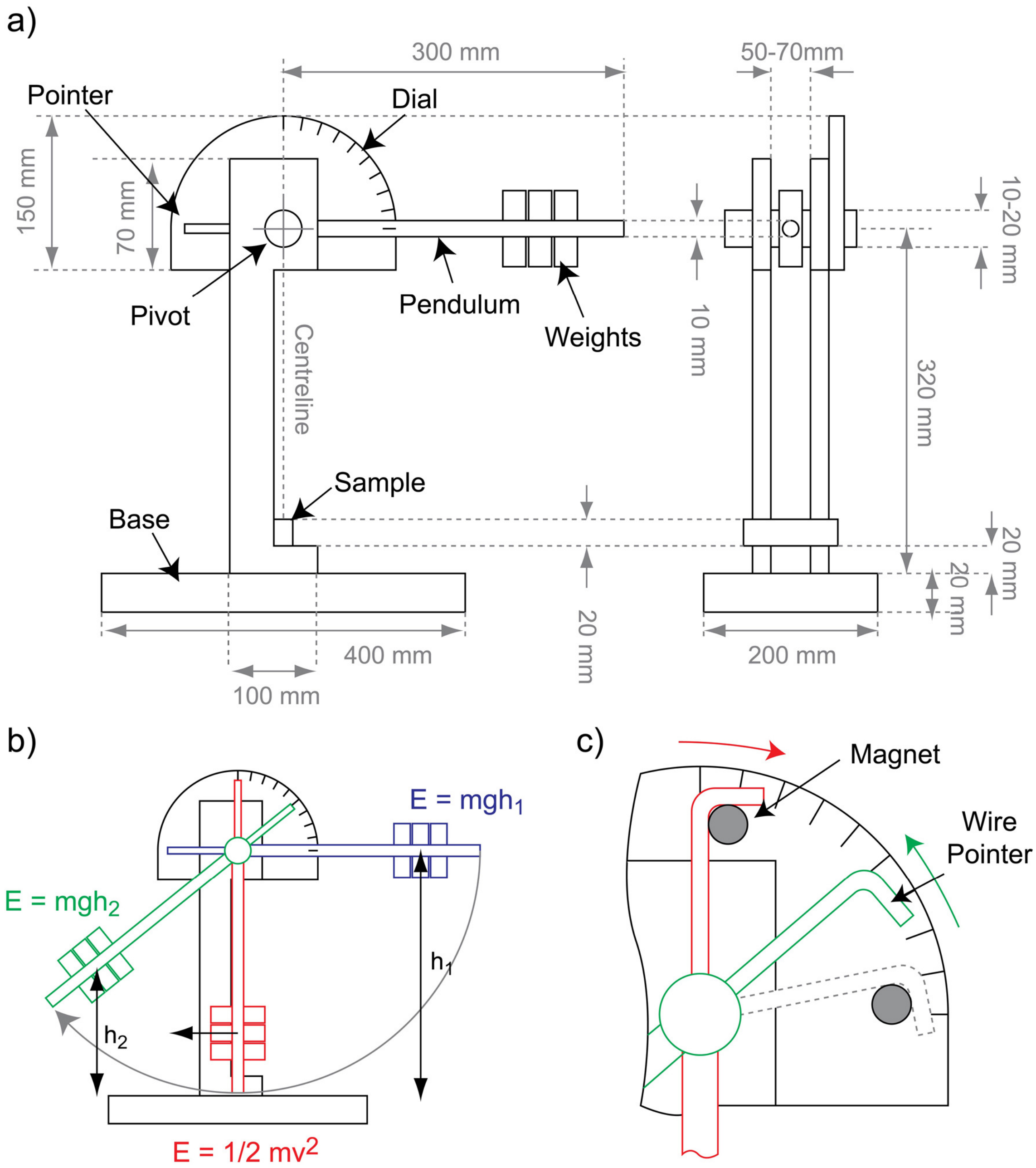

Figure 2 – a) Schematic diagram of a suitable test rig, with suggested suitable dimensions. b) A diagram of the test procedure, showing the energy present in the system at each stage. c) one suggested mechanism for recording the maximum swing in each test.

3.1 Principle of Operation

Figure 2b shows a simple schematic of the energy present in the system. In the start position, when the pendulum is held horizontally, there is a certain amount of potential energy. When the pendulum is released, this is converted to kinetic energy, and the pendulum is at its fastest when it is vertical. Past this point, the kinetic energy converts back to potential energy, and for a system with no sample and no friction we would expect the pendulum to reach horizontal on the other side. However, some energy will be absorbed by breaking the sample, and so the pendulum will not go so high up on the swing through. By measuring how far it does swing we can determine how much energy was used up.

These energies can be calculated simply in the case where the weight of the pendulum is low and the added weights dominate. In this case the weight added can be used with the equation for potential energy ($E = mgh$), and the difference in height between the initial horizontal position and the final highest swing on the other side to calculate the energy absorbed by breaking the sample. In the rig we made (shown in Figure 3a), the pendulum arm needed no additional weight, so we simply measured the percentage of the initial energy absorbed.

3.2 Test Rig Design

The basic design of the test rig is shown schematically in Figure 2a, with typical suitable dimensions indicated (these can be varied). Our rig was made out of aluminium, Figure 3a, but any material robust enough to stand up to the test may be used (for example wood, Meccano, etc). The key parts are:

Base and Supports – The base must be relatively heavy, and at least as wide along the swing direction as the pendulum is long for stability. Fixed firmly to the base should be 2 sturdy vertical supports that will hold the pivot, and hold the sample directly beneath the pivot point near the base on small shelves cut into both supports.

Pivot – The pivot for the pendulum should be as low friction as possible. We used a system with bearings, but a metal rod passing through a hole in the pendulum or a simple dowel rod loosely fitting through a hole in the supports would be suitable.

Pendulum – The pendulum should be strong enough to resist the impact. The length, in combination with the weight, will determine the energy available to break the sample. A suitable pendulum would be made of 1 cm diameter wood and be about 30cm long, though the length may need to be reduced if heavier or bulkier material is used.

Weights – It may be that the pendulum is not heavy enough to cause fracture, and in this case weights can be added as shown in Figure 2a. **Critically, the weight should not be low enough that no harm will come if someone accidentally puts their finger in the machine during a test**. In practice, some experimentation will be needed to find the right weights for a particular set of samples.

Dial and Pointer – In order to make measurements, it is important to be able to record how high the pendulum gets once it has broken the specimen. On a simple level, this could be done by fixing a thin wire on the opposite side of the pivot to the pendulum, and visually comparing this against a scale, although this can be difficult to do with accuracy. One possible improvement is shown in Figure 2c. If the dial is made of steel, then magnets can be used to mark the position of maximum swing, using the pointer wire to push them into place. In our rig we used a similar system, but with a second mobile pointer that was held in place with a magnet. Many alternative ideas are possible, such as placing a sheet of paper on the dial, and having a pen attached to the pointer, or by placing some plasticene on the dial front, and arranging the pointer to scribe a line along it. In each case these can of course be reset between tests.

Sample – The sample should be a bar of chocolate, with a notch in the centre part, opposite where the pendulum will strike, to ensure that fracture happens at this point (this is necessary for a valid test, and is done in Charpy testing of engineering materials). Such samples can be cast into a mould, but in practice it can be easily achieved using segmented bars of chocolate, broken into strips. If there is a join between two segments in the centre of a sample bar (as shown in the samples in Figure 3b; it does not matter how many segments there are across the whole sample), then this will be enough to ensure it breaks in the middle. Any particular chocolate can be used, but to make comparisons all samples should be the same shape and size; some supermarket own brands of chocolate are available in many types in the same shape bars.

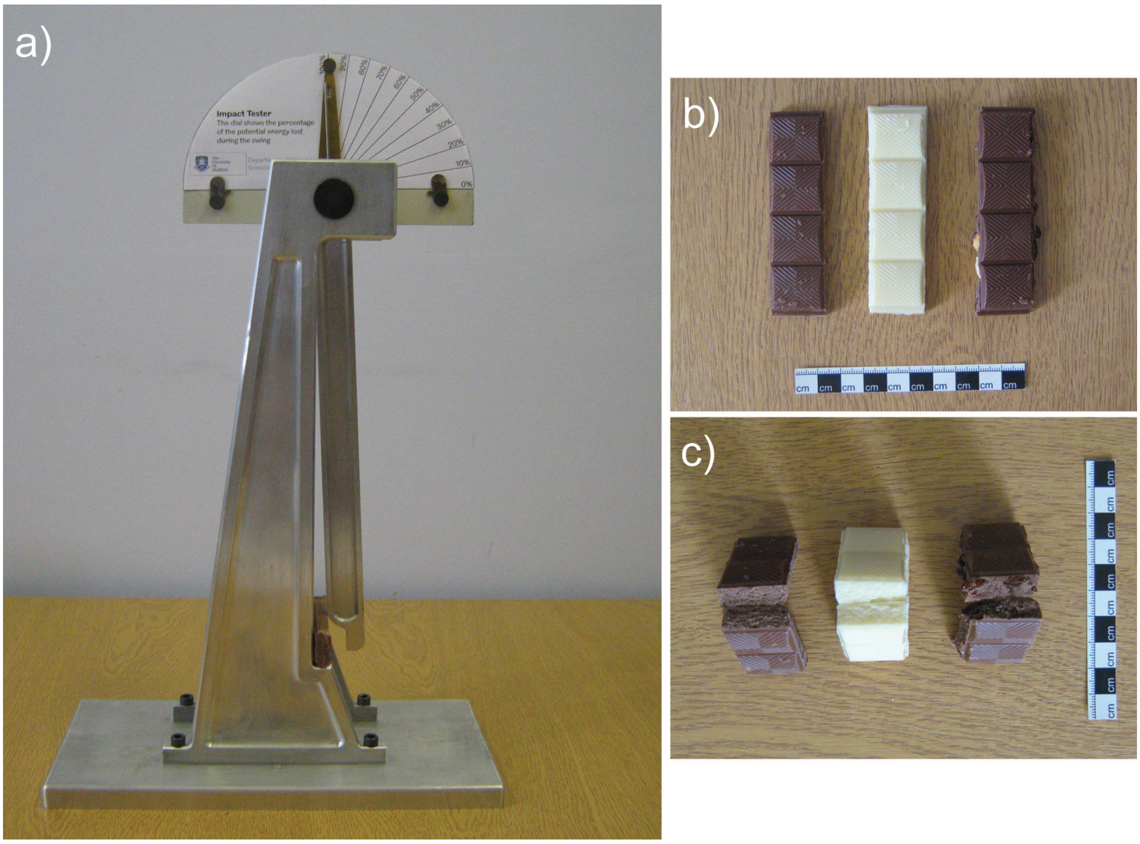

Figure 3 – a) Image of the rig produced for this work, with a sample in the test position (the rig pendulum is 30 cm long). b) Suitable segments of chocolate bars that can be used as specimens (milk, white and fruit and nut chocolate respectively). c) The same samples after testing, positioned to show their fracture surfaces (energy absorbed in these tests were: milk 77%, white 85% and fruit and nut 55%).

3.3 Test Procedure

A standard test procedure might be as follows:

i) Place the device on a flat surface, check the pendulum is swinging freely, and carry out one test without any sample inside, in order to determine the amount of energy lost to friction, air resistance, etc.

ii) Zero the dial and place a sample on the supports. Raise the pendulum to horizontal.

iii) When sure no one has their hand in the machine, release the pendulum so it falls and breaks the sample.

iv) Record the reading, remove the broken sample and reset the dial for the next test.

4. Typical Experiments and Results

A wide range of experiments are possible with such a device. Some of these are outlined below.

4.1 Comparison of Different Materials

If chocolate of different types (e.g. dark/plain, milk, white, fruit and nut, etc) can be obtained in the same shape, then the fracture energy of each can be compared directly. Table 1 gives some results for such a comparison that we generated during a recent demonstration. As can be seen, different materials display different properties, and it could be attempted to plot these results against, for example, the percentage cocoa solids in the chocolate; a general trend is that darker (higher percentage cocoa solids) chocolate is more brittle (lower fracture energy) than milk chocolate, and this accords with most people's experience with chocolate. A variation in material properties with composition is something commonly seen. For example, most metals will get stronger when mixed with another element (alloying). From Table 1 we can also see that fruit and nut was toughest, likely to be due to the crack being held up by the added materials, which is very similar to the processes occurring in composite materials. We also see that these samples had a higher standard deviation, which is related to the random locations of the reinforcements in the chocolate; sometimes they are in the right places to be effective, sometimes not.

Table 1 – Results obtained using the rig for to test different types of chocolate. In each case at least 10 samples were tested.

Chocolate	Energy absorbed on fracture (%)	
	Average	Standard Deviation
Milk	69.6	7.1
Plain	64.4	5.3
White	77.6	9.1
Fruit & Nut	83.1	10.4

Taking this further, experiments could also be performed comparing different types of chocolate bar to see which is the toughest. This could include bars with soft layers or bars with bubbles (comparable to foamed materials). In comparing these, some attention would have to be given to the different size of the bars. By taking the energy measured and dividing it by the cross sectional area of the fracture surface, the fracture energy per unit area can be calculated.

An additional activity would be to get students to design, make and test their own materials. The low melting point of chocolate means that students could manufacture their own composites, including different amounts of such additions as nuts, raisins, spaghetti, etc in different amounts, and carry out tests to see what the most effective addition is and determine the effect of the amount added.

4.2 Effect of Temperature

Samples of chocolate can also be tested at different temperatures. We carried out an experiment with some bars of chocolate (of different types to those in Table 1) tested after some hours in a freezer (-3°C), in a refrigerator (3°C) and at room temperature (25°C), to obtain the results in Figure 4. We see that all types are less tough at lower temperature, and also that milk chocolate is the most sensitive to temperature in this range, becoming softer and much tougher at room temperature. This behaviour is in agreement with normal experience of chocolate. Testing properties at different temperatures is important in real applications. For example, steel can become brittle at low temperatures, an effect which is thought to have contributed to the breaking up of several Second World War Liberty ships in Arctic waters [7].

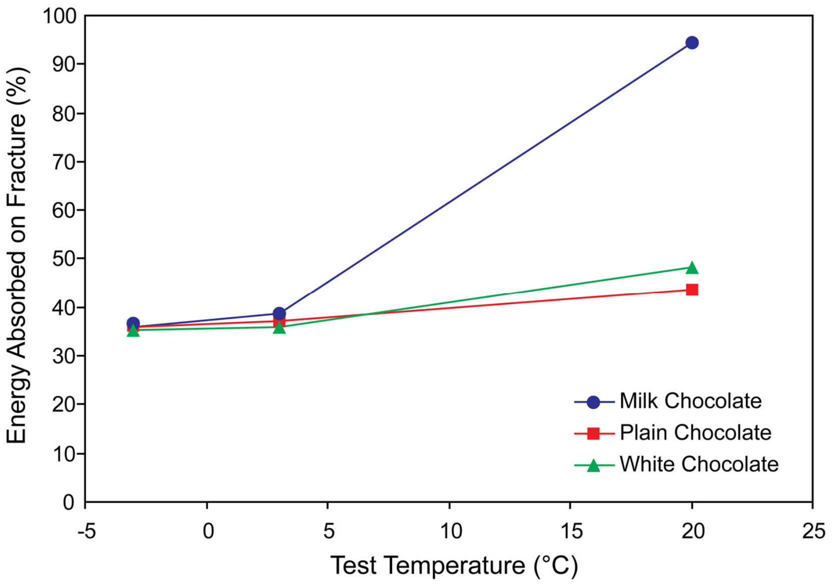

Figure 4 – Energy absorbed on fracture at different test temperatures for different types of chocolate.

4.3 Examination of Fracture Surface

After testing, it can be very instructive to examine the broken surfaces (as in Figure 3c) to see whether it is smooth (generally corresponding to brittle materials with low fracture energy) or rough (generally ductile materials with high fracture energy). Also, it may be possible to identify features, such as air bubbles or second phases (e.g. the nuts in fruit and nut) that may have contributed to failure by providing a weakness. In testing of engineering materials, and the investigation of failures, examination of the broken surface often provides critical clues to how the fracture process has occurred.

4.4 Experimental Error and Variation

Finally, if a large number of tests are carried out, there will be some scatter, due to slight variations in the test conditions, in material properties or sample dimensions. These can be used to introduce to students the need to treat results statistically; in testing engineering materials a large number of repeats will be used.

5. Evaluation and Conclusions

In this paper we have described a test rig that we have developed, and given some general guidelines on how similar equipment could be produced. We have used this rig in a number of different demonstrations to different students, at both GCSE and AS-level, in schools as the basis of hour long lessons to physics classes and for shorter demonstrations to students visiting the University. In each case we have allowed the students to carry out experiments, and then made the link between what they have observed and the properties and behaviours of materials more generally, as explained throughout this article. In all of these situations we have obtained excellent feedback from students, frequently, it has to be said, making reference to the use of chocolate. Nevertheless, with some effort to show the students the issues beyond this, we have found it a very engaging way to introduce concepts relating to mechanical properties of materials.

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Brief Biographies

Lucy Parsons studied Material Science & Engineering at the University of Sheffield, and undertook a final year project that focussed on the study of the fracture properties of chocolate and the conveyance of the engineering principles behind the study to wider audiences.

Russell Goodall is a Lecturer in Metallurgy at the Department of Materials Science & Engineering, the University of Sheffield, where he coordinates the Outreach and Schools activities. His research is focussed on the processing and mechanical properties of metallic materials, in particular metal foams and sponges.

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