Nuffield Advanced Chemistry Special Study
MATERIALS SCIENCE
Teachers' and Technicians' guide

Contents

Introduction to Materials science *page 3*

Chapter 1 **Living in a material world** ***5***

Chapter 2 **The crystal structure of materials** ***5***
Notes on teacher demonstration and study activity *5*
Notes on *Re:act* study guide activity *7*

Chapter 3 **Microstructure and macrostructure** ***8***
Experiment 1 As-cast grain structures *8*
Experiment 2 The microscopy of metals *10*
Experiment 3 Determination of a phase diagram *11*
Experiment 4 Modelling polymer crystallisation *12*
Experiment 5 Development of strength in concrete *13*

Chapter 4 **Engineering properties of materials** ***14***
Experiment 6 Investigating deformation *14*

Chapter 5 **Environmental effects on materials** ***15***
Experiment 7 Environmental crazing of polymers *15*
Notes on the *Re:act* study guide *16*
Experiment 8 Differential aeration and corrosion *17*
Experiment 9 Deformation and corrosion *18*

Chapter 6 **Choosing the right material** ***18***

Chapter 7 **Sustainable use of materials** ***18***

This teachers' and techicians' guide gives detailed information about the experiments for technicians and teachers

ISBN 0 904956 34 2

Nuffield Advanced Chemistry Co-ordinator: Alan Furse
Editor of this special study: Andrew Hunt
Adviser: Jenny Wells
Safety adviser: Peter Borrows

Based on the 3rd edition published by Longman in 1995
Editor of the 3rd edition: Michael Vokins
Contributors: Peter Gorton, Peter Millen
Authors: P.J. Goodhew, B. Caddock, C. Jones, F.W. Noble

Drawings by Hugh Neill and Oxford Illustrators Limited

First published by Longman in 1970
This edition downloaded from www.nuffieldchemistry.org

ISBN 0 904956 34 2

Health and Safety

See the safety notes given with each experiment.

Health and safety in school and college science affects all concerned: teachers and technicians, their employers, students, their parents or guardians, as well as authors and publishers.

As part of the reviewing process, these publications have been checked for health and safety. In particular, we have attempted to ensure that:
• all recognized hazards have been identified,
• suitable precautions are suggested,
• where possible, the procedures are in accordance with commonly adopted model (general) risk assessments,
• if a special risk assessment is likely to be necessary this has been pointed out
• where model (general) risk assessments are not available, we have done our best to judge the procedures to be satisfactory and of an equivalent standard.

It is assumed that:

• practical work is conducted in a properly equipped and maintained laboratory,
• rules for student behaviour are strictly enforced,
• mains-operated equipment is regularly inspected, properly maintained and appropriate records are kept,
• care is taken with normal laboratory operations such as heating substances and handling heavy objects,
• good laboratory practice is observed when chemicals are handled,
• eye protection is worn whenever risk assessments require it,
• any fume cupboard required operates at least to the standard of Building Bulletin 88,
• students are taught safe techniques for such activities as heating chemicals, smelling them, or pouring from bottles,
• hand-washing facilities are readily available in the laboratory.

Under the COSSH and the Management of Health and Safety at Work regulations, employers are responsible for carrying out risk assessments before hazardous procedures are undertaken or hazardous chemicals used or made. Teachers are required to co-operate with their employers by complying with such risk assessments.

However, teachers should be aware that mistakes can be made and, in any case, different employers adopt different standards. Therefore, before carrying out any practical activity, teachers should always check that what they are proposing is compatible with their employer's risk assessments and does not need modification for their particular circumstances. Any local rules issued by the employer must always be followed, whatever is recommended here.

Model (general) risk assessments have been taken from, or are compatible with:
CLEAPSS *Hazcards* (see annually updated CD-ROM)
CLEAPSS *Laboratory handbook* (see annually updated CD-ROM)
CLEAPSS *Recipe cards* (see annually updated CD-ROM)
ASE *Safeguards in the school laboratory* 10th edition 1996
ASE *Topics in Safety* 3rd edition, 2001
ASE *Safety reprints*, 2000 or later

Clearly, you must follow whatever procedures for risk assessment your employers have laid down. As far as we know, all the practical work and demonstrations in this course are covered by the model (general) risk assessments detailed in the above publications, and so, in most schools and colleges, you will not need to take further action.

If you or your students decide to try some procedure with hazardous substances beyond what is in this course, and you cannot find it in these or other model (general) assessments, then your employer will have to make a special risk assessment. If your employer is a member, then CLEAPSS will act for them. Otherwise the ASE may be able to help.

Only you can know when your school or college needs a special risk assessment. But thereafter, the responsibility for taking all the steps demanded by the regulations lies with your employer.

Investigations will involve independent action by the student. Our notes on investigations warn students to carry out a risk assessment; students should be responsible for safety in the first instance and credited in any assessment for making safe plans. Nevertheless, proposals must be seen by you the teacher and you must ensure that you make an appropriate check, particularly with respect to safety, on what will go on. You will need to take particular care if students consult library books published before modern safety standards came into force or get ideas from the internet.

Nuffield Advanced Chemistry Special Study
Materials science: Teachers' and Technicians' notes

Aims of the *Materials science* special study

1 To develop knowledge and understanding of the basic ideas in materials science.
2 To develop experimental skills in materials science, including the processing and interpretation of experimental results.
3 To provide an introduction to the industrial and technological aspects of materials science and also economic, environmental and social aspects.

Timing and programme

It is difficult to be prescriptive about timing because of the many and varied ways in which schools and colleges organise their timetables. Here is a guide to the use of class time, assuming 4 sessions in the week. Chapter 1 is read by students in advance. Chapters 6 and 7 are also covered in private study.

Students need a great deal of help with phase diagrams, and some guidance on wet and dry corrosion.

Week 1
Chapter 2 and part of Chapter 3
Study activity: Examining crystal structures (model-making)
Discussion of unit cells, co-ordination numbers, etc
Experiment 1: As-cast grain structures

Week 2
Chapter 3
Discussion of heat treatment, and cold- and hot-working
Experiment 2 The microscopy of metals
Experiment 3 Determination of a phase diagram, with discussion of phase diagrams and eutectic mixtures

Week 3
Finish Chapter 3 and Chapter 4
Experiment 4 Modelling polymer crystallisation
Experment 5 Development of strength in concrete, plus discussion of the setting process (examination of concrete samples continues until the exam)
Experiment 6 Deformation

Week 4
Chapter 5
Experiments 8 and 9 Differential aeration and corrosion, and Deformation and corrosion, are set up at the beginning of the week. Discuss dry corrosion
Experiment 7 Environmental crazing of polymers
Examine and discuss corrosion experiments; compare and discuss dry versus wet corrosion
Discuss wet corrosion: theory and control

Notes on this 2005 edition

We are publishing this edition of the Special Study on the *Re:act* web site (www.chemistry-react.org). This gives us the opportunity to take advantage of the interactivity of the Internet to make it easier for students to do more of the work on their own and prepare for the examination. For each chapter we now offer:

- a study guide under the tutorial heading in *Re:act* to lead students through the work,
- the illustrated text of the chapter as a downloadable file,
- instructions for the experiments as a separate downloadable file,
- webguides which link to other internet sites of specific relevance to the module,
- questions to help students revise.

Since the first edition of this Special Study was published in 1970, the importance of metals relative to other materials has diminished. This has been reflected in the development of the Special Study as the title has changed from *Metallurgy*, first to *Metals as materials* and then in 1995 to *Materials science*. This edition takes this trend a stage further by giving more prominence to the science of polymers and ceramics. However the practical work relates mainly to metals because the experiments are feasible in schools and colleges at this level.

We have taken the opportunity to rewrite and reorder the text so that it is more accessible. We have deleted a good deal of complex material that is not needed for examinations at A2. We have also shortened and simplified the programme of practical work. Given the pressure on teaching time we have focused all the resources on the ideas, techniques and examples which students need to learn for the examination.

What is examinable?

The examinable content of this Special Study is defined by the Edexcel specification. Clarification of the depth of treatment can be gauged by looking at the downloadable student chapters and instructions for experiments, published in the Special Study section of the Re:act website http:/www.chemistry-react.org

The content of the comment and case study boxes in the students' text does *not* have to be learnt.

Chapter 1 Living in a material world

This is for private study by students.

Chapter 2 The crystal structure of materials

This chapter involves the examination of some simple crystal structures and characterizing them with the help of the terms unit cell and coordination number. The topic of crystal structure is not covered in detail in the 4th edition main course and so these are new ideas. There are no experimental instructions for students. (The old Experiment 2.1 is now simplified and incorporated into the Study Guide for this chapter on the *Re:act* website.)

Study activity for Chapter 2 Examining simple crystal structures

Teacher demonstration and class discussion. There are no students' notes on this experiment.

The teacher will need:

Space-filling model of a body-centred cubic structure
White 25-mm diameter expanded polystyrene spheres, 43
Coloured 25-mm diameter expanded polystyrene spheres, 7
Shallow triangular-shaped boxes, 2, with sides approx 15 cm and depths approx 2 cm
Plastic or glass sheet for one side of the box.
Trays built to match the actual spheres being used, as the quoted 25-mm diameter can vary from batch to batch.

Teaching notes

Introduce the study of crystal structure with the examples given below. Give students the opportunity to handle the structures and where possible to build them up for themselves as they work through the Study Guide from the website.

Note that a webguide *in Re:act* linked to this chapter leads to a site about the structure of steel which explores metal structures in a semi-interactive way.

Procedure details

Hexagonal close-packing

Using a shallow triangular box, make two layers of polystyrene spheres, 5 × 5 × 5 and 4 × 4 × 4. The centre sphere in the second layer is surrounded by six other spheres. Point this out to the class. Replace the six spheres by coloured spheres to make the situation clear.

Now add a third layer by placing further spheres directly over spheres in the bottom layer, forming an ABA pattern. Three spheres may be placed in the third layer, and they surround the central spheres of the middle layer.

Ask the class to count how many nearest neighbours there are to the centre sphere in the middle layer. There are three above, six around it, and three below. This gives a total of twelve; it is the maximum number of equal-sized spheres which may be arranged around a given sphere of the same size, and represents one of the two closest possible packing arrangements.

The number of nearest neighbours is the co-ordination number; and this is therefore 12 for an hexagonal close-packed or hcp structure.

Examining simple crystal structures *continued*

Face-centred cubic

The second box should now be made up with $5 \times 5 \times 5$ in the bottom layer, and $3 \times 3 \times 3$ in the second layer; this is achieved by filling spaces one row back in the first layer, as compared with the previous HCP arrangement. For the third layer, one single sphere should be placed in the centre, forming an ABC pattern.

One side of a face-centred cube can be seen on the face of the pyramid. The central sphere of the face should be removed and replaced by a coloured sphere to make this clear.

The class should now count how many nearest neighbours the coloured sphere has on the pyramid face. It is four. There are also four nearest neighbours behind it.

And, if the array were extended forwards, the coloured sphere would, by symmetry, have four nearest neighbours in front. This gives a total of twelve nearest neighbours, and the co-ordination number for this packing is twelve, as in the HCP arrangement. It is the other one of the two closest possible packing arrangements, and is cubic close-packed.

The cubes in this structure are face-centred and the structure is known as face-centred cubic or FCC.

A further aid is to have an assembly with six spheres on each side of the base, $6 \times 6 \times 6$.

A face-centred cube can be glued together as a unit, and placed in the centre of the assembly (as in the $5 \times 5 \times 5$ array); the remaining spheres can then be placed around it.

To make the model more robust, use cocktail sticks and glue.

As a demonstration, this complete assembly can be dismantled and the glued cube pulled out.

Body-centred cubic

Now show the class a body-centred cubic model, made out of nine equal-sized spheres. The body-centred cube is *not* a close-packed system.

In the HCP and FCC systems there is only 26% of empty space; but in the BCC system there is 32% of empty space.

Metal crystals

Mention to the class that almost all metals crystallize into one (or more) of these three systems. Some examples, which are listed on the students' sheets, are:
hexagonal close-packed: magnesium, zinc, nickel
face-centred cubic: copper, silver, gold, aluminium
body-centred cubic: the alkali metals

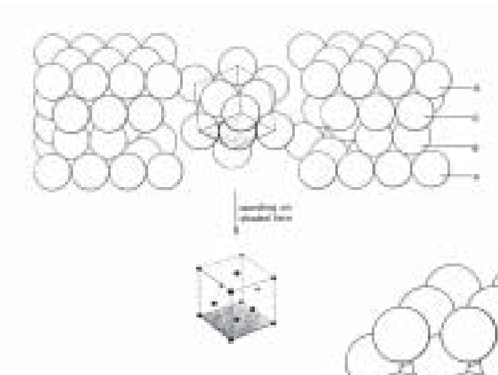
The close-packed systems account for about 50 metals, and the body-centred for about 20 metals.

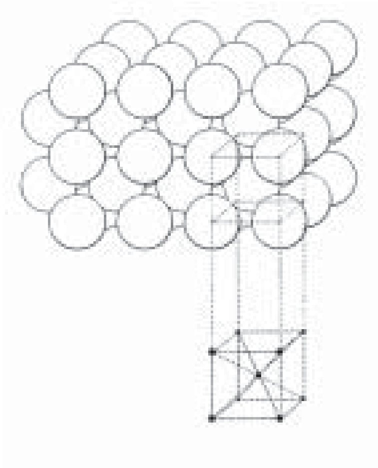
There is no obvious trend in structural type with position in the Periodic Table.

Re:act Study guide for Chapter 2

Each group of students will need:

Polystyrene sphere (25 mm) models of the structures fcc (14 spheres), hcp (17 spheres), and bcc (9 spheres – use pins to strengthen this structure)
A two-layer raft (24 spheres) made up as shown below, a raft (7 spheres) as shown below, and several single spheres.





The unit cell links the centres of the corner atoms in the cubes, hence each corner atom contributes $^{1}/_{8}$ to the unit cell, each face-centered atom contributes $^{1}/_{2}$, and the body-centered atom contributes 1.

In the FCC structure there are $(8 \times {}^{1}/_{8}) + (6 \times {}^{1}/_{2}) = 4$ atoms in the unit cell.

In the BCC structure there are $(8 \times {}^{1}/_{8}) + 1 = 2$ atoms in the unit cell.

Chapter 3 Microstructure and macrostructure

Crystallization, whether of inorganic salts, polymers, or metal castings, occurs by the processes of nucleation and growth. It is an exothermic process. The technological control of crystallization raises problems of energy transfer, because the way in which the latent heat energy is dissipated controls the relative contributions of nucleation and growth to the final solid.

Experiment 1 As-cast grain structures *(Chapter 3)*

Part 1 Stearic acid

Each group of students will need:

Eye protection
Plastic tubes, 2, 1.5 cm diameter, 7.5 cm long, and open at both ends
Rubber bungs for the plastic tubes, 4, size 13
Bunsen burner, tripod, gauze and heatproof mat
Beaker, 100 cm^3
Stearic acid (octadecanoic acid)

Access to a wooden rod 10 cm long and 1 cm diameter, with flat ends to push the sample out of the tube
Water bath with hot water

Teaching notes

In science, basic theory can be developed from the study of any of a wide variety of materials. It makes sense to choose one that is readily available and easily studied. Metals are difficult to study as they are invariably crystallized from the melt, have high melting points, and are opaque.

This part of experiment 1 is typical of the way in which an understanding gained by studying one material can be translated to the invariably more complex materials of technological significance.

Procedure

Melt the stearic acid in a beaker over a Bunsen burner and cast it into the plastic moulds. When solidified, remove the rubber bung used to seal the end of the mould and push the ingot out. Warm if necessary in a hot water bath to reduce sticking.

Part 2 Zinc

A demonstration is possible here, but in most classes it will be entirely satisfactory to provide commercial zinc rods from suppliers. Some of the rods show pipe as well as clear columnar growth patterns.

⚠ HAZARD Full safety precautions should be observed. If you decide to carry out this demonstration, wear face protection and heat-resistant gloves

The teacher will need:

Face protection and heat-resistant gloves
Steel pipes, 2, 1.5 cm diameter, 5 cm long, plugged at one end by a turned brass or steel plug which fits tightly into the pipe
Refractory crucible
Bunsen burner, tripod, and heatproof mat
Silica triangle
Charcoal
Zinc metal
Aquadag (suspension of carbon in water)

Access to:

Vice, hacksaw and hammer to section the sample

Procedure

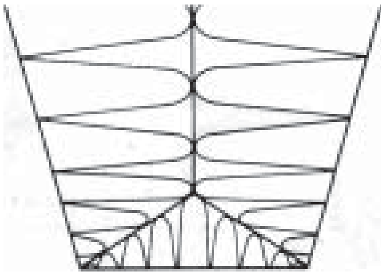
Melt the zinc under charcoal in a crucible over a Bunsen and cast into the steel tube moulds.

⚠ HAZARD Use a fume cupboard.

To reduce sticking, wash the inside of the metal tube with carbon in water (Aquadag) and then *dry thoroughly* before casting.

Experiment 1 As-cast grain structures *continued*

Both the stearic acid and the zinc should show columnar grains. Note the 'planes of weakness' associated with the strongly directional grain structures (see diagram below), and the possible presence of porosity (shrinkage and gas) and impurities between the grains. Slow cooling rates increase the probability of forming an equi-axed zone, especially in the stearic acid.



Planes of weakness formed at the junction of columnar columns

Question 1

a The faces of large crystals are those that grow at the slowest rate. Suggest to the students that they draw an octagon and then think about how its shape changes if four of the faces grow at a much greater rate than the other four.
b The best examples of large single crystals include
• diamonds and other jewels
• the wafers of Si or GaAs from which microchips are made. A single crystal ensures the same good electronic properties over large distances
• single crystal turbine blades for advanced aircraft engines, in which the absence of grain boundaries improves the stability of the structure at high temperatures.

Questions 2, 3 and 4

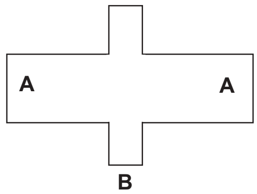
The energy in the melt, and the latent heat of solidification, must be dissipated before crystallization can proceed. This involves heat transfer from the liquid into the solid, through the solid, across the solid/mould interface, and then out of the mould. Nucleation always occurs preferentially on the mould walls.

A steep temperature gradient leads to the growth of these nuclei until all the liquid is consumed, giving a columnar structure. If the temperature gradient is reduced, then it is possible for independent nucleation to occur in the liquid ahead of this growing front and to obtain an equi-axed structure.

A steep gradient is favoured by a high casting temperature (relative to the melting point) and a chill mould, i.e. a metal or a water-cooled mould rather than a sand mould. As the size of the ingot increases, so the possibility of controlling the cooling by such means is reduced, and hence the importance of additions to control the as-cast grain structure.

Question 5

See diagram. The cooling rate in A is slower than B. Crystal sizes and maybe shapes in A and B will be different. Therefore different areas within the same cast object will have different properties.



Question 6

Pipe is a consequence of the shrinkage on going from liquid to solid. It can be minimized by reducing the heat loss at the top of the ingot, so maintaining a constant head of liquid to feed the shrinkage as it occurs. Such a 'hot top' may be an insulated enclosure at the top of the mould or an exothermic cover, i.e. a powder containing thermite mixture. Most metals contract on solidification and hence show pipe, but some of the elements around Groups 6 and 7 of the Periodic Table expand on solidification, as does water.

Question 7

The ice-cream recipe highlights the importance of nucleation, more nuclei giving finer ice crystals and a smoother texture. The gelatin provides 'foreign nuclei' and the whisking breaks up the initial crystals, so increasing the number of crystals.

Experiment 2 The microscopy of metals *(Chapter 3)*

Ideally each student should prepare at least one specimen.

Ensure that they have read the instructions beforehand. Both polishing and etching are skills requiring considerable practice, and problems often arise because the students do not know exactly what to expect.

The approach to metallography is greatly simplified compared with the previous edition of this special study. All that is required is to give students some insight into the techniques used to study metal microstructures. Hands-on experience can be complemented with the webguides in *Re:act*. These lead to web pages illustrating the procedures and link to galleries of images of microstructures.

Each group of students will need access to:

Metal sample for polishing (old brass 'weights' for balances polish well, have a built-in handle and a flat base)
Silicon carbide grinding papers, grades 220, 320, 400 and 600, cut into strips around 5 cm wide
Polishing cloths, a good quality duster, or Selvyt or Metron B grade
Metal polish, Silvo or Brasso (HAZARDS check label)
Glass plates, as a base for the silicon carbide papers and the polishing cloths
Soap solution
Propanone HIGHLY FLAMMABLE and IRRITANT
Etch - acidic iron(III) chloride (10 g $FeCl_3$, 20 cm^3 concentrated hydrochloric acid, and 80 cm^3 water). IRRITANT
Laboratory hot air drier, to dry specimens
Metallurgical (i.e. reflecting) microscope
Protective gloves (avoid latex if possible)

Procedure

Each grade of silicon carbide paper should be kept separate in order to avoid the carry-over of grit from one paper to the next. Silicon carbide grinding papers use water as a lubricant and so avoid carrying over grit from one paper to the next.

Encourage the students to look at their specimens, both visually and under the microscope, at all stages in the preparation. Ensure that they are not trying to interpret 'preparation artefacts', for example, too many scratches hiding the structure, or over-etching giving a general blurring of the structure.

The webguides in *Re:act* link to other sites with a wide range of images of polished and etched specimens. Recall or interpretation of the detail of photomicrographs is not required.

Question 1

Grains are seen on galvanized iron for two reasons. Firstly, it is produced by dipping mild steel into molten zinc, removing the steel, and allowing the zinc to crystallize out. The growth pattern is seen in relief on the surface. Secondly, some etching occurs in the natural environment. With old brass door handles etching is by the numerous sweaty hands of the users.

Question 2

Grains in metals are analogous to soap bubbles produced by shaking up a soap solution in a bottle. If a section is taken across the grains (bubbles) then a range of sizes will be observed, even though the actual grains (bubbles) all have the same size. A further example of this 'sectioning effect' is with a rod-like precipitate, when different sections will show shapes varying from a circle to a rod.

Experiment 3 Determination of a phase diagram *(Chapter 3)*

The treatment of phase diagrams has also been greatly simplified compared with the previous edition. Reference to the complex phase diagram for the copper-zinc system has been deleted. The web sites identified in the *Re:act* study guide for this chapter are very helpful.

The phase diagrams in the students' text omit the regions arising because of the formation of solid solutions. These regions do appear in some of the phase diagrams on web sites, but can be ignored for the purposes of this Special Study.

Each group of students will need:

Face protection
Boiling tubes to contain samples
Temperature sensor and datalogger
or thermometer 0–250 °C

Access to:

benzoic acid (HARMFUL)
stearic acid
balance
fume cupboard (optional)

Procedure

The procedure is described in the instructions for students. Using stearic and benzoic acids for this experiment greatly reduces the hazards.

The experiment might be carried out in a fume cupboard, because molten benzoic acid gives off fumes which are irritating to eyes and can trigger coughing. In the absence of a fume cupboard, it helps to put a plug of mineral wool in the top of each boiling tube to minimise the escape of vapour.

It saves time and money if a set of mixtures is prepared in advance with accurate mass ratios. These can then be reused year after year.

Warn students to heat samples to only just above the melting-point. Otherwise they will waste a lot of time. The mixture needs an occasional stir.

Obtaining cooling curves takes time, and so it helps to let students set up one experiment and collect the data. You can then provide data for the other samples.

Question 1

The experiment can be used to focus on the problems of designing experiments, including these questions.

- Does the thermometer record the actual temperature?
- Is the apparatus sufficiently sensitive to record the changes in cooling rate when latent heat is evolved during crystallization?

Experiment 4 Modelling polymer crystallization *(Chapter 3)*

⚠ HAZARD Warn students not to eat spaghetti.

Each group of students will need:

Eye protection
Bunsen burner, tripod and heatproof mat
Spaghetti, 500 g (or better still vermicelli)
Saucepan, for cooking (a beaker tends to break!)
Beaker, ideally about 30 cm high and 10 to 15 cm wide, for viewing
Stirring rod
Strainer
Sharp knife

Procedure

This experiment is designed to show that it is more difficult to arrange long chains into a regular pattern than it is spherical atoms. The demonstration works well if the diameter of the container is less than half the length of the spaghetti strands.

The experiment is more convenient as a teacher demonstration because of the quantity of spaghetti required.

The spaghetti structure is three-dimensional, but can only be examined easily in two-dimensional sections. The students should be encouraged to consider the nature of crystallinity: how many chains running approximately parallel will they need before defining a region of a crystal? They should note down the length of each region and its orientation with regard to an arbitrary axis.

The wall of the 'mould' can be expected to impose a higher local degree of crystallization, since it constrains the spaghetti chains to a two-dimensional array at the surface.

Topics for further discussion could include the effect of branching chains.

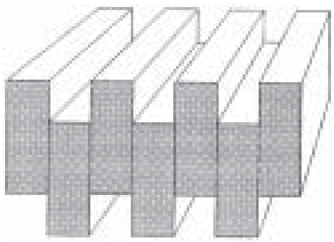
Experiment 5 Development of strength in concrete

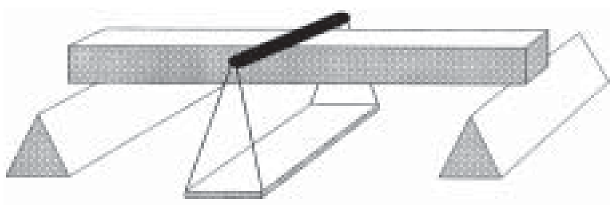
(Chapter 3)

⚠ HAZARD Wet concrete is corrosive. Students should be warned not to handle the wet material.

Each group of students will need:

Protective gloves
Cement (dust is very fine and IRRITANT)
Builders' sand
Aggregate (decorative grit)
Aluminium foil
Measures for solids (calibrated beakers)
Measuring cylinder, 10 cm^3
3 moulds (see diagram)
Test rig (see diagram)
Sand tray





Procedure

This experiment is time-consuming. It can be quite hard to get it to work well. It is important to use fine aggregate.

Suitable moulds can be built from softwood strips, 20 cm × 5 cm × 1.5 cm (nominal $1\frac{1}{2}$ inch by $\frac{1}{2}$ inch) nailed together from both sides. The rig has to be suitable for the size of the specimens made.

Normal builders' aggregate is too large for this experiment. A suitable material is the fine decorative grit designed for aquaria. Cement can be stored in plastic sweet jars from shops or large glass containers.

Teaching notes

The main purpose of this section of the special study is to show that ideas of structure are important at a variety of scale sizes.

The cement /sand/aggregate macrostructure is easily visible and easily understood, while the microstructure *within* each phase is actually rather complex.

The experiment shows that mechanical properties can change significantly over time, and is a nice illustration of a diffusion-controlled process in which the rate drops rapidly as the reactants have to diffuse across a thickening gel layer.

Question 1

Students should find that, with cement and water only, the strength drops as the water content is increased (e.g. using the range of cement/water ratios 1:0.3 to 1:1).

The addition of sand or aggregate actually weakens the concrete, and students should see a very marked drop in strength in the series of cement/water/sand ratios 1:1:1 to 1:1:10 and the series of cement/water/sand/aggregate ratios 1:1:2:1 to 1:1:2:10.

If students study the effect of setting time, you should be prepared to plot time on a log scale, using a range of times such as 1 hour, 4 hours, 1 day, 1 week and 1 month. Use a reasonably high cement/water ratio, or the shorter time specimens will not develop enough strength to be tested in an hour.

Question 2

Using a hand lens students should be able to see several features, including:

a the set 'concrete' almost always contains pores (visible as round holes).

b the fracture path exposes shiny grains of sand and aggregate, indicating that the material has failed at the interface between the cement and the sand or aggregate. Since the cement is the continuous phase, failure must pass through this phase.

c Students may see largish yellow regions of sand which result from inadequate mixing.

Chapter 4 Engineering properties of materials

Much of the reading will have to be done by students for homework.
Experiment 6 may be omitted if the students have done it in a Physics or Technology course.

Experiment 6 Investigating deformation

⚠ HAZARDS

Suitable precautions must be taken when wires are stretched and when brittle materials are deformed. Face protection is essential. Nylon fibres can whip fiercely and cause nasty cuts when they break. Everyone must wash hands after handling lead.

Students' plans must be checked for safety before they start work.

Each group of students will need:

Face protection and access to a safety screen.
A wide variety of materials of a size that can be readily handled.
Possible materials include the metals lead, copper and iron, and the non-metals wood, elastic, nylon, polythene, chalk, Plasticine and Potty Putty.

Procedure

The student instructions are deliberately open-ended.
Check students' plans before they start.

This experiment can be organized as a group discussion to bring out ideas such as how much load leads to how much change of shape, how similar loads cause different deformations in different materials, and how the way in which a load is applied to a material influences the resulting deformation.

Towers of Plasticine and Potty Putty left to deform under their own weight illustrate the importance of the time factor in deformation. An operational approach can be used to introduce the elastic, plastic and fracture responses to loading.

Load: what is observed?
Is there a change of shape or does the sample fracture?

Unload: what is observed?
If the sample returns to its original shape, it is elastic. If it does not, it is plastic.

Question 1

The simple answer is that all materials show elastic and fracture responses to loading, whilst metals show elastic, plastic and fracture responses to loading. However, all such generalizations can be confounded by some choice of material and/or conditions. For example, Potty Putty is not metallic but plastically deforms with time. Iron is a metal but behaves in a brittle manner with negligible plastic deformation if deformed at low temperature and/or by impact loading.

Chapter 5 Environmental effects on materials

Experiment 7 Environmental crazing of polymers

The experiment features a well-defined type of failure known as stress corrosion, in which the combined effect of an applied stress and an aggressive environment is very much more severe than the separate effect of the two factors.

Any material that can develop brittle cracks can exhibit this problem, and materials as diverse as stainless steel and glass fibre composites have given problems in service.

Because of stress corrosion, great care must be exercised in the design of loaded structures subject to exposure to corrosive environments.

Each group of students will need:

Face protection
Polystyrene specimens, 12 cm × 2 cm × 3 mm
Retort stand and clamps
Weights suitable for loading the polystyrene strips (or second retort stand)
Propanone, a few drops HIGHLY FLAMMABLE and IRRITANT
White spirit, a few drops FLAMMABLE
Butter or margarine, small amounts

Procedure

1 In the polystyrene experiment it will be found that the dry specimen is stable when loaded. Adding the propanone immediately causes large cracks to form which propagate within seconds and cause the specimen to break.

2 On applying propanone to an unstrained specimen it is seen that there is a powerful solvent effect. When the propanone evaporates from the surface, the dried-out contact zone has a whitened surface. Lightly polishing this zone with metal-cleaning wadding, and examining the surface with a lens or low-powered microscope, will reveal the presence of numerous microcracks on the surface. These will not propagate when the specimen is loaded as above, but they do have a strong effect in reducing the impact resistance of the material.

3 Water and aqueous acids do not wet the material and have no effect. Reducing the surface tension with household detergent enables these substances to wet the surface, but does not lead to crack formation. White spirit causes cracking and failure, but at a slower rate than the propanone. Molten butter or margarine will also promote cracking but at a very slow rate. The rate is increased as the temperature of the molten liquid increases.

Question 1

The essential interaction between the aggressive environment and the polymer leading to this type of failure is the solvent effect. This weakens the surface and promotes local swelling, to an extent that a network of tiny cracks form in the surface of the brittle material. When the specimen is under load, there is a very large increase in the local stress at the tip of a sharp crack. The crack fills with solvent, and the solvent effect weakens the intramolecular forces holding the material together at the crack tip, thereby lowering the stress needed to propagate the crack.

As the crack propagates, the newly exposed surfaces at the crack tip represent a partial vacuum. More solvent 'explodes' into this to generate a hydrostatic pressure pulse – an effect known as cavitation. This pushes up the local stress and promotes further propagation.

Continued overleaf

Experiment 7 Environmental crazing of polymers *continued*

These processes are favoured by

- the strength of the solvent effect
- the viscosity of the liquid
- the volatility of the liquid.

These arguments can be used to rank the order of severity of the liquids used in the experiment.

Question 2

The solvents have a strong effect in reducing the impact resistance of the material. At one time polycarbonate resin was used for the manufacture of the outer shell of motor cycle crash helmets. This material was self-coloured with pigmented fillers. Motor cyclists wishing to customize their helmets would paint logos or slogans on them with cellulose acetate-based paints. This led to severe surface crazing, with an attendant loss in the impact protection that the helmet was designed to provide.

Re:act Study guide for Chapter 5

2d There are many examples. These include: pipes for water mains, gas mains, household plumbing, baths, sinks, washing-up bowls, electric kettles, dustbins, car bumpers, boat hulls, etc. The principle factor restricting wider use is loss of mechanical properties at increased temperature.

3 Students might refer to standard electrode potentials when discussion this question. They may needed to be reminded that electrode potential refer to reactions in aqueous solution under standard condition. Even so they give a good indication of the relative reactivity of metals.

5c The anodic (corrosion) process produces electrons which must then be consumed at the cathode for the reaction to continue. A large cathode (copper) acting on a small anode (iron rivet) gives intense localized corrosion (pitting), whereas a small cathode and a large anode give relatively harmless general corrosion.

5d Zinc coating will protect the steel; with a chromium coating subsurface rusting will occur. Zinc provides cathodic protection and the chromium does not.

General requirements for Experiments 8 and 9

Ferroxyl solution
Pure water
Propan-1-ol   HIGHLY FLAMMABLE and IRRITANT
3% sodium chloride solution
Cotton wool
Emery papers (grade 100)

Procedure

To prepare ferroxyl solution dissolve 10 g of sodium chloride and 1 g of potassium hexacyanoferrate(III) in pure water and add 1 cm^3 of phenolphthalein solution. Make up to 500 cm^3 with pure water. It is best to use a freshly prepared solution.

A second solution is required containing magnesium chloride instead of sodium chloride.

It may be useful for the teacher to have a number of semi-permanent demonstrations made up in agar gel.

To prepare agar gel, dissolve 6 g of sodium chloride in 200 cm^3 of distilled water and add 4 g of agar. Boil until the agar is dispersed. Add 4 cm^3 of ferroxyl as the solution cools. The demonstrations can be kept for a longer time when refrigerated.

Students will need to abrade and clean a variety of specimens. It is important to keep a separate piece of emery paper for each metal.

Experiment 8 Differential aeration and corrosion

Each group of students will need:

(See also 'General requirements for experiments 7 and 8' above)
50 × 50 × 1 mm (approximately) mild steel (iron) and brass sheet
Petri dishes, 2
Fine sand

Question 1

The results of the first part of the experiment must be considered in detail. Initially the ferroxyl solution is uniformly saturated with oxygen and hence corrosion starts at random beneath the droplet, giving a random array of pink and blue regions in the droplet.

As corrosion proceeds, the oxygen in solution is consumed, and replenishment occurs from the air preferentially at the edges of the drop. This leads to the development of a blue anodic central zone and a pink cathodic outer zone. These effects can be seen over a period of around half an hour.

After a day or so, the actual rust is seen in a zone between the anodic and the cathodic areas, and the central corroded zone is seen to correspond with the earlier blue coloration.

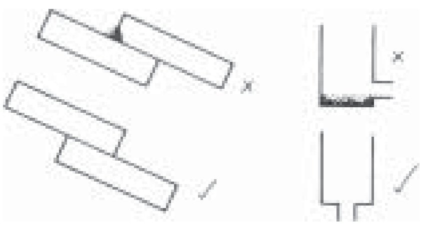
In discussion emphasize the importance of differential aeration.

Question 2

The instructions suggest blowing over the surface of the ferroxyl solution. Students should notice that this will continue the random corrosion by continuing to supply oxygen to all parts of the solution.

Question 3

The two main points to consider are the need for an electrolyte (moisture) to complete the corrosion circuit, and the effect of the differential aeration of the electrolyte. Since the question refers to 'design' the answer should be illustrated by diagrams, as in shown below.
Possible examples of corrosion caused by design are entrapment of moisture in crevices or in curved components, and mud poultices in car wheel arches or sediments in pipes, which trap moisture.



Component design to avoid corrosion

Experiment 9 Deformation and corrosion

Each group of students will need:

(See also the 'General requirements for experiments 7 and 8' page)
Eye protection
3 iron nails, 5 cm
Bunsen burner and heatproof mat
Tongs
Pliers or a hammer
3 Petri dishes
Ferroxyl solution

Question 1

The head and the point of a nail are formed by cold deformation. Hammering the centre of the nail will produce cold deformation around the centre of the nail. In the heat-treated nail, the effects of the differential cold-working have been annealed out.

The question is intended to remind students that metallic components are frequently produced by some form of mechanical working, and that in the majority of cases this working is not uniform.

Question 2

In a uniform environment, the driving force for corrosion comes from the differential deformation in the component. The heavily deformed areas of the nails become anodic relative to the less deformed or undeformed areas, and thus corrode. The original nail shows blue regions around both the head and the point with a pink region in the middle, indicating that the head and the point are formed by cold deformation. Hammering the centre of the nail will reinforce this observation by giving an extra blue region adjacent to the hammered region. Finally, the heat-treated nail should show no particular pattern of pink and blue since the effects of the differential cold-working have been annealed out.

You could produce a demonstration example of this experiment by placing the nails in Petri dishes containing a ferroxyl–agar gel mix.

Chapter 6 Choosing the right material

Previous chapters have been more concerned with specific properties of materials rather than their overall suitability for a particular purpose. As Chapter 1 shows, the choice of materials has changed as new materials have become available. There is a vast and complex range available to an engineer nowadays.

The importance of considering yield strength and Young's modulus relative to density is introduced through a simplified versions of one of the plots first devised by Professor Ashby.

It is worth pointing out that no amount of scientific analysis does away with the need to build and test a prototype in novel applications.

Chapter 7 Sustainable use of materials

No study of an applied science is complete without some consideration of the social and environmental issues involved. This chapter is designed to present some of the issues, and to provide an opportunity for them to be debated in the classroom if so wished.

The main concept introduced is life cycle analysis, LCA, demonstrating that scientific study has a contribution to make even in an emotive area of public discussion.