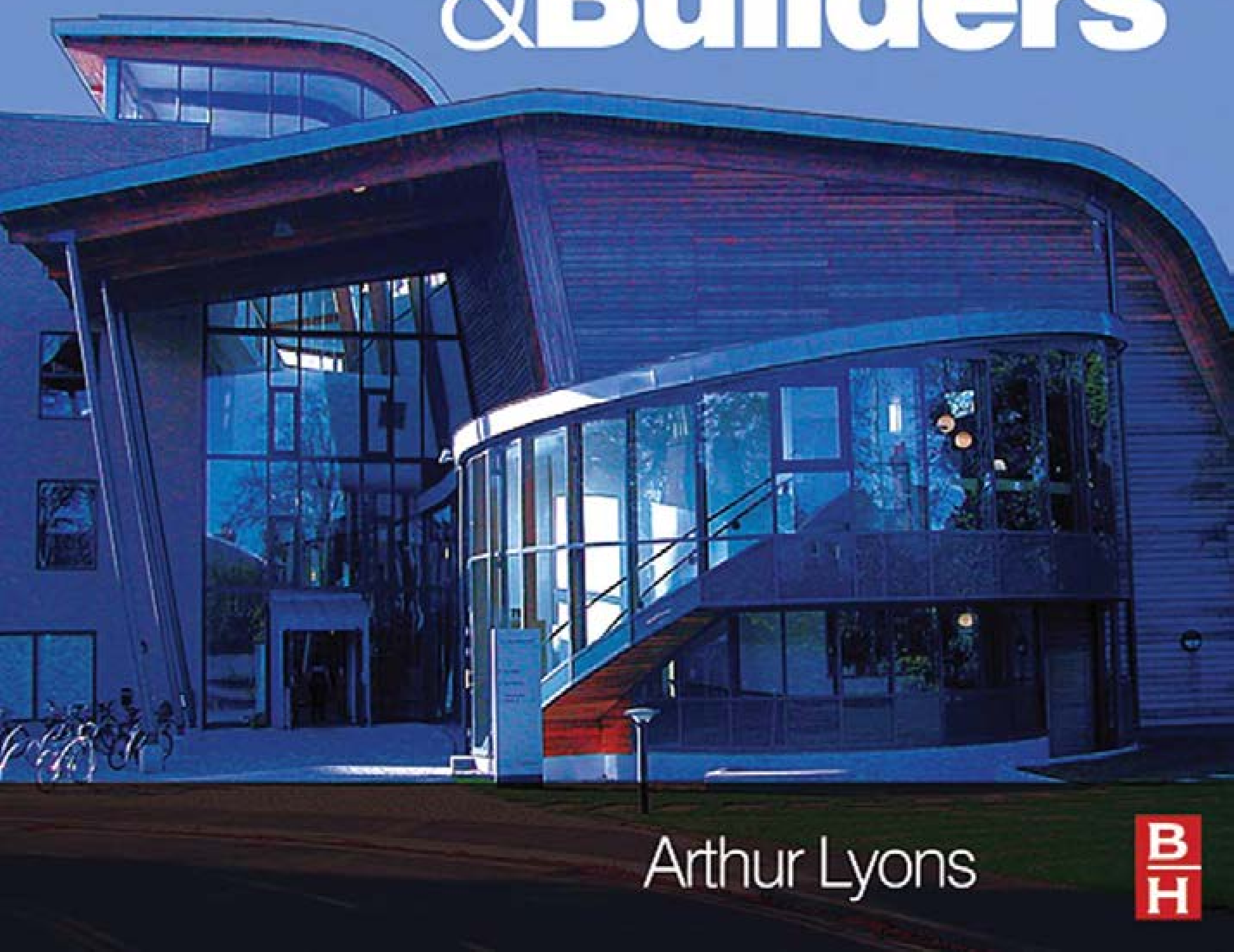
Third Edition

Materials for Architects & Builders



Arthur Lyons

MATERIALS FOR ARCHITECTS AND BUILDERS

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Third edition

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Dr Arthur Lyons is Head of Quality in the Faculty of Art and Design at De Montfort University, Leicester, UK. He also holds the position of principal lecturer and teacher fellow in building materials in the Leicester School of Architecture, Department of Product and Spatial Design, within the Faculty. He was educated at Trinity Hall, Cambridge, and Warwick and Leicester Universities in the fields of natural sciences and polymer science and has a postgraduate diploma in architectural building conservation. He has been a lecturer in building materials within schools of architecture and surveying for over thirty years. Arthur Lyons was honoured with life membership of the Leicestershire and Rutland Society of Architects in recognition of his services to architects and architecture. He continues his teaching and research role in building materials with students of architecture, architectural technology and interior design, in parallel with his senior faculty position.

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PREFACE

Materials for Architects and Builders is written as an introductory text to inform students at undergraduate degree and national diploma level of the relevant visual and physical properties of a wide range of building materials. The third edition has been significantly enhanced by the incorporation of full colour images throughout, illustrating the materials and in many cases their use in buildings of architectural merit. The text includes the broad environmental debate with sections on energy saving and recycled materials. There are seventeen chapters covering the wide range of materials under standard headings. Each chapter describes the manufacture, salient properties and typical uses of the various materials, with the aim of ensuring their appropriate application within an awareness of their ecological impact.

European Standards are taking over from the previous British Standards, and for most key materials the European Norms have now been published. Generally, this has led to an increase in the number of relevant standards for building materials. However, in many cases, both the British and European Standards are current and are therefore included in the text and references.

New and rediscovered old materials, where they are becoming well integrated into standard building processes are described; other materials no longer in use are generally disregarded, except where increased concern for environmental issues has created renewed interest. The use of chemical terminology is kept to the minimum required to understand each subject area, and is only significantly used within the context of the structure of plastics. Tabulated data is restricted to an informative level appropriate to student use. An extensive bibliography and listed sources of technical information are provided at the end of each chapter to facilitate direct reference where necessary.

The text is well illustrated with over 250 line drawings and colour photographs, showing the production, appearance and appropriate use of materials, but it is not intended to describe construction details as these are well illustrated in the standard texts on building construction. Environmental concerns including energy-conscious design, and the effects of fire, are automatically considered as part of the broader understanding of the various key materials.

The text is essential reading for honours and foundation degree, BTEC and advanced GNVQ students of architecture, building, surveying and construction, and those studying within the broad range of built environment subjects, who wish to understand the principles relating to the appropriate use of construction materials.

Arthur Lyons
March 2006

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I should like to thank the following organisations for giving permission to use illustrations:

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The text uses the generic names for building materials and components wherever possible. However, in a few cases, products are so specific that registered trade names are required. In these cases the trade names are italicised in the text.

INFORMATION SOURCES

Specific information relating to the materials described in each chapter is given at the end of the appropriate section; however, the following are sources of general information relating to construction materials.

- Building Regulations 2000, Amendments and Approved Documents
- Specification
- RIBA Office Library and Barbour Index
- Building Research Establishment (BRE) publications
- Trade association publications
- Trade literature
- Architecture and built environment journals
- British Board of Agrément certificates
- British Standards
- European Standards
- Eurocodes.

European Standards (EN) have been published for a wide range of materials. A full European Standard, known in the UK as BS EN, is mandatory and overrules any conflicting previous British Standard which must be withdrawn. Prior to full publication, the draft European Standards are coded pr EN and are available for comment, but not implementation. Prospective standards, where documentation is in preparation, are published as European pre-standards (ENV). These are similar to the previous British Drafts for Development (DD) and would normally be converted to full European Standards (EN) after the three-year experimental period, when any conflicting national standards would have to be withdrawn. BRE Information Paper IP 3/99 (1999) identifies the issues relating to the adoption in the UK of the structural Eurocodes.

The Building Research Establishment (BRE) publishes informative and authoritative material on a wide range of subjects relating to construction. Trade associations produce advisory and promotional literature relating to their particular area of interest within the building industry. Architecture and building journals give news of innovations and illustrate their realisation in quality construction.

Information for this text has been obtained from a wide selection of sources to produce a student text with an overview of the production, nature and properties of a diverse range of building materials. New individual products and modifications to existing products frequently enter the market; some materials become unavailable. Detailed information and particularly current technical data relating to any specific product for specification purposes must therefore be obtained directly from the manufacturers or suppliers and cross-checked against current standards and regulations.

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ABBREVIATIONS

General

AAC	autoclaved aerated concrete
ABS	acrylonitrile butadiene styrene
AC	aggressive chemical (environment)
ACEC	aggressive chemical environment for concrete
APM	additional protective measures
APP	atactic polypropylene
AR	alkali-resistant
ASR	alkali-silica reaction
BER	building emission rate
BRE	Building Research Establishment
BS	British Standard
CAD	computer-aided design
CEN	European committee for standardisation
CFCs	chlorofluorocarbons
CG	cellular glass
CPE	chlorinated polyethylene
CPVC	chlorinated polyvinyl chloride
CS	calcium silicate
CSPE	chlorosulfonated polyethylene
DC	design chemical (class)
DC	direct current
DD	draft for development
DPC	damp-proof course
DPM	damp-proof membrane
DR	dezincification-resistant
DS	design sulfate (class)
EN	Euronorm
ENV	Euronorm pre-standard
EP	expanded perlite
EPDM	ethylene propylene diene monomer
EPR	ethylene propylene rubber
EPS	expanded polystyrene
ETFE	ethylene tetrafluorethylene copolymer
EV	exfoliated vermiculite
EVA	ethylene vinyl acetate
FEF	flexible elastomeric foam
FPA	flexible polypropylene alloy
FRP	fibre reinforced polymer
GGBS	ground granulated blastfurnace slag
GRC	glass-fibre reinforced cement
GRG	glass-fibre reinforced gypsum
GRP	glass-fibre reinforced plastic or polyester
GS	general structural (timber)
HAC	high alumina cement
HCFCs	hydrochlorofluorocarbons
HD	high density
HDPE	high density polythene
HL	hydraulic lime
HLS	hue lightness saturation
ICB	expanded corkboard
ISO	international organisation for standardisation
LD	low density
LDPE	low density polythene
MAF	movement accommodation factor
MDF	medium density fibreboard
MF	melamine formaldehyde
MPa	mega pascal
MW	mineral wool
NCS	natural color system®
NHL	non-hydraulic lime
ODP	ozone depletion potential
OPC	ordinary Portland cement
OSB	oriented strand board
PAS	publicly available specification
PBAC	polystyrene-bead aggregate cement
PC	polycarbonate
PE	polyethylene
PEF	polyethylene foam
PEX	crosslinked polyethylene
PF	phenolic foam
PFA	pulverised fuel ash
PIB	polisobutylene
PIR	polyisocyanurate foam
PMMA	polymethyl methacrylate
PP	polypropylene

pr EN	draft Euronorm
PTFE	polytetrafluroethylene
PUR	rigid polyurethane foam
PV	photovoltaic
PVA	polyvinyl acetate
PVB	polyvinyl butyral
PVC	polyvinyl chloride (plasticised)
PVC-U	polyvinyl chloride (unplasticised)
PVC-UE	extruded polyvinyl chloride
RGB	red green blue
SAP	standard assessment procedure
SBEM	simplified building energy model
SBS	styrene butadiene styrene
Sg	specific gravity
SIP	structural insulated panel
SS	special structural (timber)
ST	standard (concrete mix)
T	tolerance (class)
TER	target emission rate
TFS	thin film silicon
THF	tetrahydro furan
UF	urea formaldehyde
UHPC	ultra high performance concrete
VET	vinyl ethylene terpolymer
VOC	volatile organic compounds
WF	wood fibre
WW	wood wool
XPS	extruded polystyrene

Units

dB	decibel
MPa	mega pascal
µm	micron (10^{-6}m)
nm	nanometre (10^{-9}m)

Chemical symbols

Al	aluminium
C	carbon
Ca	calcium
Cr	chromium
Cl	chlorine
Cu	copper
F	fluorine
Fe	iron
Mn	manganese
Mo	molybdenum
N	nitrogen
Ni	nickel
O	oxygen
S	sulfur
Si	silicon
Sn	tin
Ti	titanium
Zn	zinc

Cement notation

C_2S	dicalcium sicilate
C_3S	tricalcium silicate
C_3A	tricalcium aluminate
C_4AF	tetracalciumaluminoferrite

1

BRICKS AND BRICKWORK

Introduction

Originally, bricks were hand-moulded from moist clay and then sun-baked, as is still the current practice in certain arid climates. The firing of clay bricks dates back well over 5000 years, and is now a sophisticated and highly controlled manufacturing process; yet the principle of burning clay, to convert it from its natural plastic state into a dimensionally stable, durable, low-maintenance ceramic material, remains unchanged.

The quarrying of clay and brick manufacture are high-energy processes, which involve the emission of considerable quantities of carbon dioxide and other pollutants including sulfur dioxide. The extraction of clay also has long-term environmental effects, although in some areas former clay pits have now been converted to bird sanctuaries or to recreational use. However, well-constructed brickwork has a long life with low maintenance and although the use of Portland cement mortar prevents the recycling of individual bricks, the crushed material is frequently recycled as aggregate in further construction.

Clay bricks

The wide range of clays suitable for brick making in the UK gives a diversity to the products available. The effects of blending clays, the various forming processes, the application of surface finishes, and the adjustment of firing conditions further increase this variety. Earlier this century most areas had their own brickworks with characteristic products; however, ease of road transportation and continuing amalgamations within the industry have left a reduced number of major producers and only a few small independent works. Most UK bricks are defined as high density (HD) fired-clay masonry units with a gross dry density greater than 1000 kg/m^3. The European standard (BE EN 771–1: 2003) refers also to low density (LD) fired-clay masonry units and these blocks are described in Chapter 2.

The main constituents of brick-making clays are silica (sand) and alumina, but with varying quantities of chalk, lime, iron oxide and other minor constituents, e.g. fireclay, according to their source. The largest UK manufacturer uses the Lower Oxford clays of Bedfordshire, Buckinghamshire and Cambridgeshire to produce the *Fletton* brick. This clay contains some carbonaceous content that reduces the amount of fuel required to burn the bricks, lowering cost and producing a rather porous structure. Other particularly characteristic bricks are the strongly coloured *Staffordshire Blues* and *Accrington Reds* from clays containing high iron content and the yellow *London Stocks* from the Essex and Kent chalky clays with lower iron content.

SIZE

The standard metric brick is 215 × 102.5 × 65 mm, weighing between 2 and 4 kg, and is easily held in one hand. The length of a brick (215 mm) is equal to twice its width (102.5 mm) plus one standard 10 mm joint and three times its height (65 mm) plus two standard joints (Fig. 1.1).

The building industry modular co-ordination system (BS 6750: 1986) is based on the module (M) of 100 mm and multimodules of 3M, 6M, 12M, 15M, 30M and 60M. For metric brickwork, the base unit is 3M or 300 mm. Thus four courses of 65 mm brickwork with joints give a vertical height of 300 mm, and four stretchers with joints co-ordinate to 900 mm.

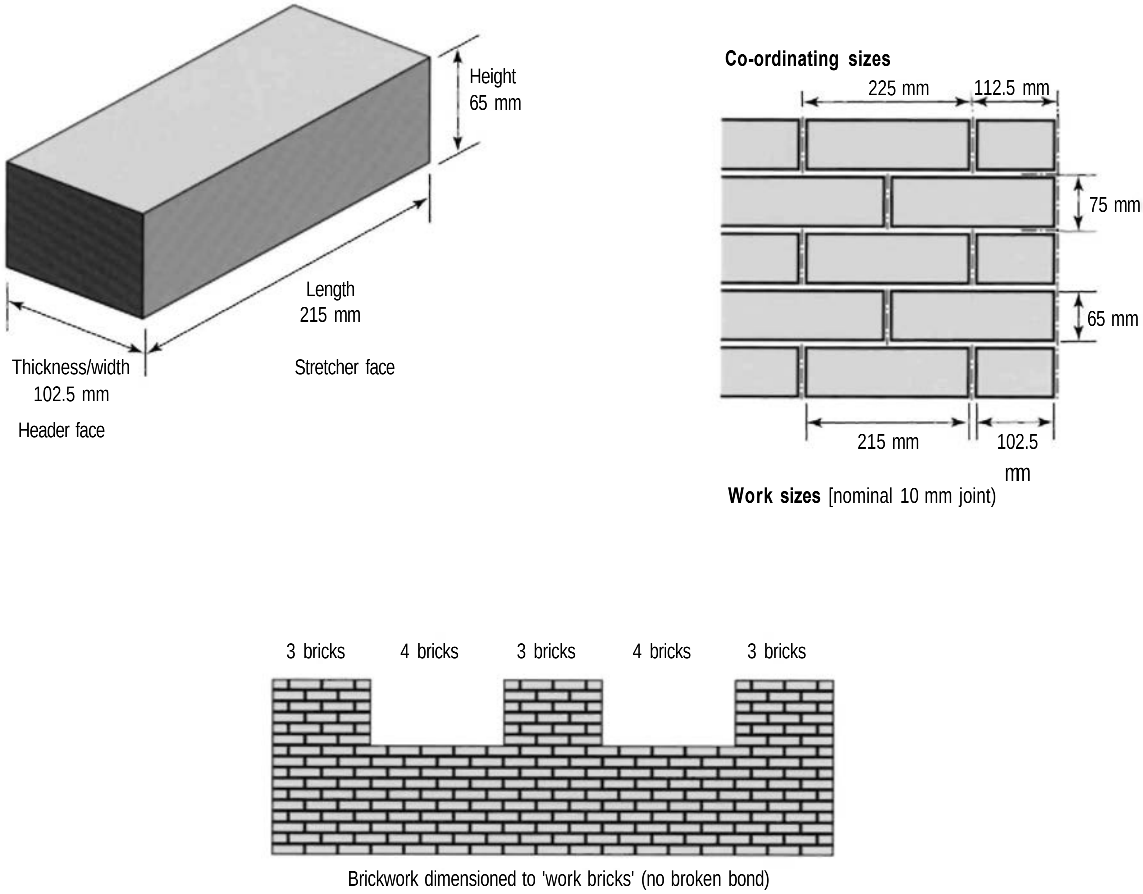

Fig. 1.1 Brick and co-ordinating sizes

Table 1.1 illustrates the two types of dimensional tolerance limits set for clay masonry units including the metric brick, which relate to the square root of the work size dimension. Measurements are based on a random sample of ten bricks. The calculation based on the use of the square root of work size ensures that the dimensional tolerance limits are appropriate for the wide range in size of clay masonry units used within the European Union (BS EN 771–1: 2003).

Tolerances

Mean value
Tolerance limits are set for the difference between the stated work size (e.g. 215, 102.5 and 65 mm) and the

Table 1.1 Tolerances on brick sizes

	Brick (work) dimensions (mm)	Maximum deviation (±) of mean from declared work dimension (mm)		Maximum range of size within sample of ten bricks (mm)	
		T1	T2	R1	R2
Length	215	6	4	9	4
Width	102.5	4	3	6	3
Height	65	3	2	5	2

Limits for Tm and Rm are as declared by the manufacturer.

measured mean from the samples, for each of the three brick dimensions (length, width and height). These are categorised as T1, T2 and Tm where Tm is a tolerance quoted by the manufacturer.

T1	$\pm$ 0.40 $\sqrt{}$(work size dimension) mm or 3 mm if greater
T2	$\pm$ 0.25 $\sqrt{}$(work size dimension) mm or 2 mm if greater
Tm	deviation in mm declared by the manufacturer

Range
The maximum range of size for any dimension is designated by categories R1, R2 and Rm.

R1	0.6 $\sqrt{}$(work size dimension) mm
R2	0.3 $\sqrt{}$(work size dimension) mm
Rm	range in mm declared by the manufacturer

There is no direct correlation between the limits on mean value (T) and those for the range (R), thus a brick conforming to category T2 may be within the wider range R1. Category R2 bricks may only be required for very tight dimensional control, as in short runs of brickwork.

Alternative sizes

The metric standard evolved from the slightly larger Imperial sizes, typically $9 \times 4^{7/8} \times 2^{5/8}$ in ($229 \times 111 \times 66$ mm). Some manufacturers offer a limited range of bricks to full Imperial dimensions, alternatively to a depth of 66 mm for bonding in to Imperial brickwork for restoration and conservation work.

The 1970s also saw the introduction of metric modular bricks with co-ordination sizes of either 200 or 300 mm in length, 100 mm wide and either 75 or 100 mm in height. The popularity of these bricks has now declined but they did give the architect opportunities for increasing or reducing horizontal emphasis and scale within the context of traditional brickwork. The British Standard BS 6649: 1985 now only refers to the $200 \times 100 \times 75$ mm modular co-ordinating format.

MANUFACTURE OF CLAY BRICKS

There are five main processes in the manufacture of clay bricks:

- extraction of the raw material;
- forming processes;
- drying;
- firing;
- packaging and distribution.

EXTRACTION OF THE RAW MATERIAL

The process begins with the extraction of the raw material from the quarry and its transportation to the works, by conveyor belt or road transport. Topsoil and unsuitable overburden is removed first and used for site reclamation after the usable clay is removed.

The raw material is screened to remove any rocks, then ground into fine powder by a series of crushers and rollers with further screening to remove any oversize particles. Small quantities of pigments or other clays may be blended in at this stage to produce various colour effects; for example, manganese dioxide will produce an almost black brick and fireclay gives a teak brown effect. Occasionally, coke breeze is added into the clay as a source of fuel for the firing process. Finally, depending on the subsequent brick forming process, up to 25% water may be added to give the required plasticity.

Forming processes

Handmade bricks
The *handmade* process involves the throwing of a suitably sized clot of wet clay into a wooden mould on a bench. The surplus clay is struck off with a framed wire and the green brick removed. The bricks produced are irregular in shape with soft arrises and interestingly folded surfaces. Two variations of the process are pallet moulding and slop moulding.

In pallet moulding, a stock board, the size of the bed face of the brick, is fixed to the bench. The mould fits loosely over the stock board, and is adjusted in height to give the appropriate thickness to the green brick. The mould and board are sanded to ease removal of the green brick, which is produced with a *frog* or depression on one face. In the case of slop moulding, the stock mould is placed directly on the bench, and is usually wetted rather than sanded to allow removal of the green brick, which unlike the pallet-moulded brick is smooth on both bed faces (Fig. 1.2).

Soft mud process
The handmade process has now been largely automated, with the clay being mechanically thrown into pre-sanded moulds; the excess clay is then removed and the bricks released from the mould. These *soft mud*

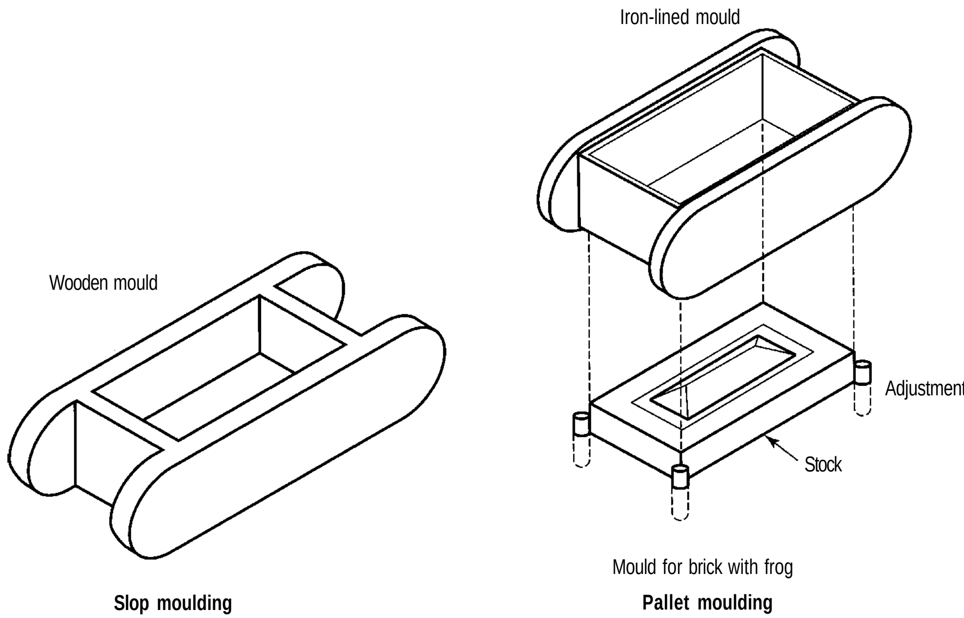

Fig. 1.2 Moulds for handmade bricks

process bricks retain much of the individuality associated with true handmade bricks, but at a lower cost.

Pressed bricks

In the *semi-dry* process used for *Fletton* bricks the appropriate quantity of clay is subjected to a sequence of four pressings within steel moulds to produce the green brick. These bricks usually have a deep frog on one bed face. For facing bricks, texturing on both headers and one stretcher may be applied by a series of rollers. A water spray to moisten the surface, followed by a blast of a sand/pigment mixture produces the sand-faced finish.

With clays that require a slightly higher water content for moulding, the *stiff plastic* process is used in which brick-size clots of clay are forced into the moulds. A single press is then required to form the brick. Engineering bricks made by this process often have shallow frogs on both bed faces. In all cases the size of the mould is calculated to allow for the anticipated drying and firing shrinkage.

Extruded wire-cut bricks

In this process clay with a water content of up to 25% is fed into a screw extruder which consolidates the clay and extracts the air. The clay is forced through a die and forms a continuous column with dimensions equal to the length and width of a green brick (Fig. 1.3). The

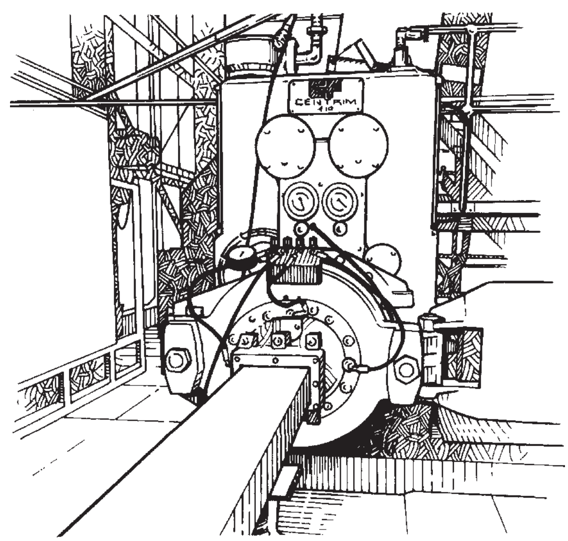

Fig. 1.3 Extruding wire-cut bricks

surface may then be textured or sanded, before the clay column is cut into brick units by a series of wires. The bed faces of wire-cut bricks often show the drag marks where the wires have cut through the extruded clay. Perforated wire-cut bricks are produced by the incorporation of rods or tines between the screw extruder and the die. The perforations save clay and allow for a more uniform drying and firing of the bricks without significant loss of strength. Thermal performance is not significantly improved by the incorporation of voids.

Drying

To prevent cracking and distortion during the firing process, green bricks produced from wet clays must be allowed to dry out and shrink. Shrinkage is typically 10% on each dimension depending upon the moisture content. The green bricks, laid in an open chequerwork pattern to ensure a uniform loss of moisture, are stacked in, or passed through, drying chambers which are warmed with the waste heat from the firing process. Drying temperatures and humidity levels are carefully controlled to ensure shrinkage without distortion.

Firing

Both intermittent and continuous kilns are used for firing bricks. The former is a batch process in which the single kiln is loaded, fired, cooled and unloaded. In continuous kilns, the firing process is always active; either the green bricks are moved through a fixed firing zone, or the fire is gradually moved around a series of interconnecting chambers to the unfired bricks. Both continuous systems are more energy efficient than the intermittent processes. Generally, for large-scale production, the continuous tunnel kiln (Fig. 1.4) and the Hoffman kiln (Fig. 1.5) are used. Down-draught kilns, clamps and intermittent gas-fired kilns are used for the more specialised products. Dependent on the composition of the clay and the nature of the desired product, firing temperatures are set to sinter or vitrify the clay. Colour variations called *kiss-marks* occur where bricks were in contact with each other within the kiln and are particularly noticeable on *Flettons*.

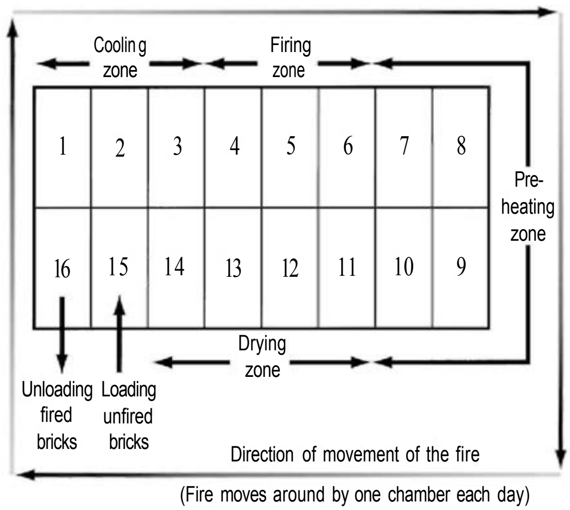

Fig. 1.5 Hoffman kiln plan

Tunnel kiln
In the *tunnel kiln* process the bricks are loaded 10 to 14 high on kiln cars which are moved progressively through the preheating, firing and cooling zones. A carefully controlled temperature profile within the kiln and an appropriate kiln car speed ensures that the green bricks are correctly fired with the minimum use of fuel, usually natural gas. The maximum firing temperature within the range 940°C and 1200°C depends upon the clay, but is normally around 1050°C, with an average kiln time of three days. The oxygen content within the atmosphere of the kiln will affect the colour of the brick products. Typically a high temperature and low oxygen content are used in the manufacture of blue bricks. A higher oxygen content will turn any iron oxide within the clay red.

Hoffman kiln
Introduced in 1858, the Hoffman kiln is a continuous kiln in which the fire is transferred around a series of

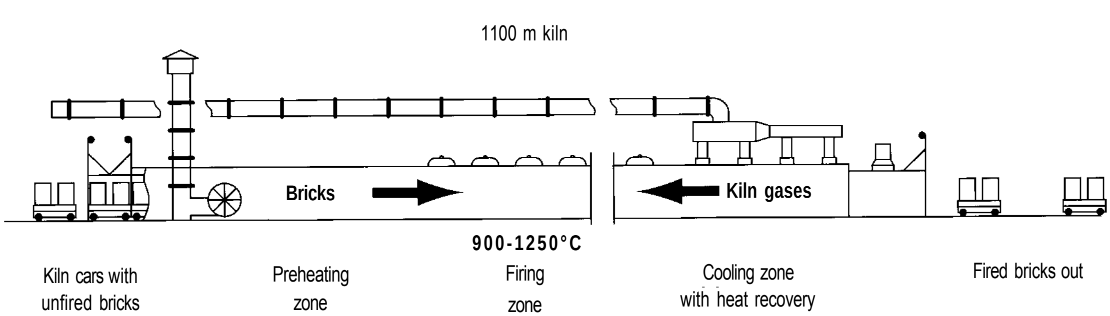

Fig. 1.4 Tunnel kiln

chambers which can be interconnected by the opening of dampers. There may be 12, 16 or 24 chambers, although 16 is usual. The chambers are filled with typically 100 000 green bricks. The chambers in front of the fire, as it moves around, are preheated, then firing takes place (960°–1000°C), followed by cooling, unloading and resetting of the next load. The sequence moves on one chamber per day, with three days of burning. The usual fuel is natural gas, although low-grade coal and landfill methane are used by some manufacturers.

Intermittent gas-fired kilns

Intermittent gas-fired kilns are frequently used for firing smaller loads, particularly *specials*. In one system, green bricks are stacked onto a concrete base and a mobile kiln is lowered over the bricks for the firing process. The firing conditions can be accurately controlled to match those within continuous kilns.

Clamps

The basis of clamp firing is the inclusion of coke breeze into the clay, which then acts as the major source of energy during the firing process. In the traditional process alternate layers of unfired bricks and additional coke breeze are stacked up and then sealed over with waste bricks and clay. The clamp is then ignited with kindling material and allowed to burn for two to five weeks. After firing, the bricks are hand selected because of their variability from under- to over-fired. More recently, gas-fired clamps have been developed which give a fully controlled firing process but still produce bricks with the characteristic dark patches on their surfaces due to the burnt breeze content.

Down-draught kilns

Down-draught kilns are used for the high-temperature firing, especially of engineering bricks, in an intermittent process. Fuel is burnt around the perimeter of the kiln, which is stacked with green bricks. The hot gases rise towards the domed roof, forcing down the cooler gases through a perforated floor and out to the chimney. Thus the heat is retained and the very high temperatures for hard-burnt bricks are achieved.

Packaging and distribution

Damaged or cracked bricks are removed prior to packing. Most bricks are now banded and shrink-wrapped into packs of between 300 and 500, for easy transportation by fork-lift truck and specialist road vehicles. Special shapes are frequently shrink-wrapped onto wooden pallets.

SPECIFICATION OF CLAY BRICKS

To specify a particular brick it is necessary to define certain key criteria, which relate to form, durability and appearance. The British Standard BS 3921: 1985 gives a performance specification based on size, frost resistance, soluble-salt content, compressive strength and visual appearance. The European Standard BS EN 771–1: 2003 requires an extensive minimum description for masonry units including, the European Standard number and date (e.g. BS EN 771–1: 2003), the type of unit (e.g. high density – HD), dimensions and tolerances from mean value, configuration (e.g. a solid or frogged brick), compressive strength and freeze/thaw resistance. Also, depending upon the particular end use, additional description may be required. This may, as appropriate, include dry density, dimensional tolerance range, water absorption, thermal properties, active soluble salts content, moisture movement, reaction to fire and vapour permeability.

Within the building industry the classification usually also includes some traditional descriptions:

- place of origin and particular name (e.g. *Staffordshire smooth blue*);
- clay composition (e.g. Gault, Weald or Lower Oxford Clay, Etruria Marl, Keuper Marl [Mercian Mudstones] or shale);
- variety – typical use (e.g. Class A engineering, common or facing);
- type – form and manufacturing process (e.g. solid, frogged, wire cut);
- appearance – colour and surface texture (e.g. coral red rustic).

Variety

Bricks may be described as common, facing or engineering.

Common bricks

Common bricks have no visual finish, and are therefore usually used for general building work especially where the brickwork is to be rendered, plastered or will be unseen in the finished work.

Facing bricks
Facing bricks are manufactured and selected to give an attractive finish. The particular colour, which may be uniform or multicoloured, results from the blend of clay used, and the firing conditions. Additionally, the surface may be smooth, textured or sand-faced as required. Facing bricks are used for most visual brickwork where a pleasing and durable finish is required.

Engineering bricks
Engineering bricks are dense and vitreous, with specific load bearing characteristics and low water absorption. The two classes (A and B) are defined specifically according to their minimum crushing strengths and maximum water absorption (Table 1.2), but in addition most engineering bricks have high density, good frost resistance and low soluble-salt content. Engineering bricks are used to support heavy loads, and also in positions where the effects of impact damage, water absorption or chemical attack need to be minimised. They are generally *reds* or *blues* and more expensive than other machine-made facing bricks because of their higher firing temperature.

Type

Type refers to the form of the brick and defines whether it is solid, frogged, cellular, perforated, or of a special shape (Figs. 1.6 and 1.7). Bricks may be frogged on one or both bed faces; perforations may be few and large or many and small. Cellular bricks have cavities closed at one end. Keyed bricks are used to give a good bond to plaster or cement rendering. Because of the wide range of variation within brick types, the manufacturer is required to give details of the orientation and percentage of perforations in all cases.

For maximum strength, weather resistance and sound insulation, bricks should be laid with the frogs uppermost so that they are completely filled with mortar; with double-frogged bricks the deeper frog should be uppermost. However, for cheapness, speed and possibly to minimise the dead weight of construction, frogged bricks are frequently laid frog-down. Inevitably this leads to a resultant reduction in their load-bearing capacity.

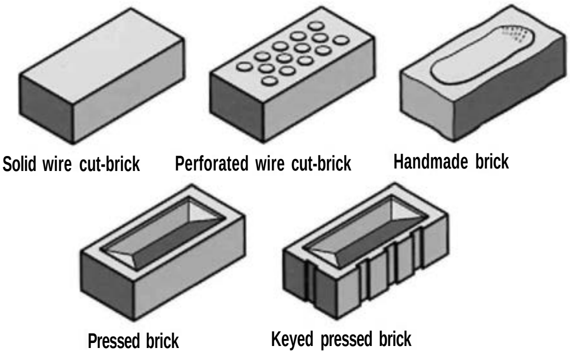

Fig. 1.6 Brick types

Table 1.2 Properties of clay engineering bricks

Physical property	Clay engineering bricks	
	Class A	Class B
Defined properties		
Minimum compressive strength (MPa)	≥ 70	≥ 50
Maximum water absorption (% by mass)	< 4.5 (and DPC1)	< 7.0 (and DPC2)
Typical additional properties		
Net dry density (kg/m^3)	≥ 2200	≥ 2100
Freeze/thaw resistance class	F2	F2
Active soluble salts content class	S2	S2

Note: The water absorption limits for all clay bricks used for damp-proof courses for buildings (DPC1) and external works (DPC2) are included in the table.

Standard specials

Increasingly, *specials* (special shapes) are being used to enhance the architectural quality of brickwork. British Standard BS 4729: 2005 illustrates the range of standard specials, which normally can be made to order to match standard bricks (Fig. 1.7).

Designation of standard specials:

Angle and cant bricks
Bullnose bricks
Copings and cappings
Plinth bricks
Arch bricks
Radial bricks
Soldier bricks
Cuboid bricks
Bonding bricks
Brick slips

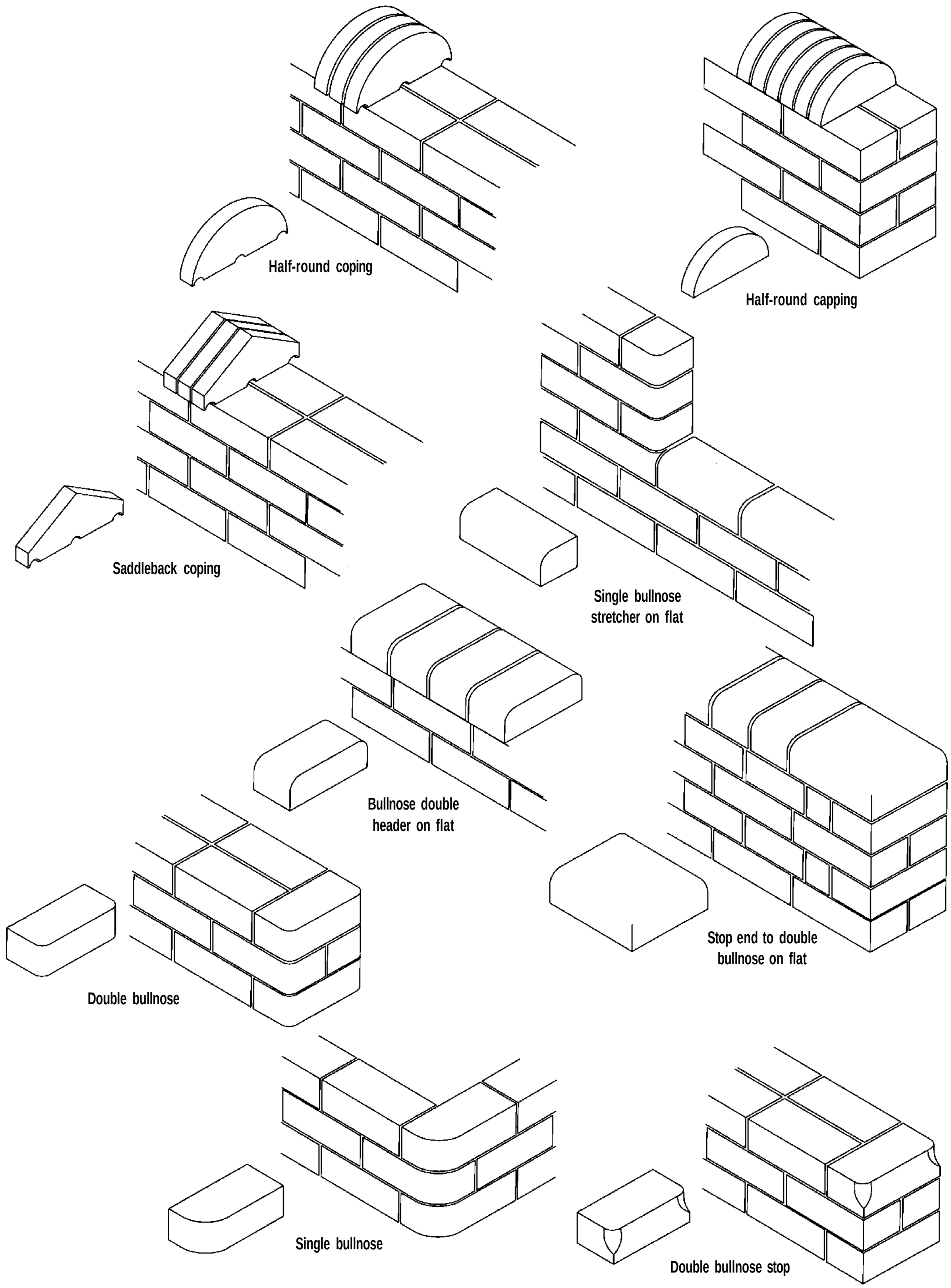

Fig. 1.7 Specials.

Manufacturers also frequently make purpose-made specials (*special specials*) to the particular requirements of the architect or builder. Inevitably, delivery on specials takes longer than for ordinary bricks, and their separate firing frequently leads to some colour variation between the specials and the standard bricks, even where the clay used is identical. The more complex specials are handmade, usually in specially shaped stock

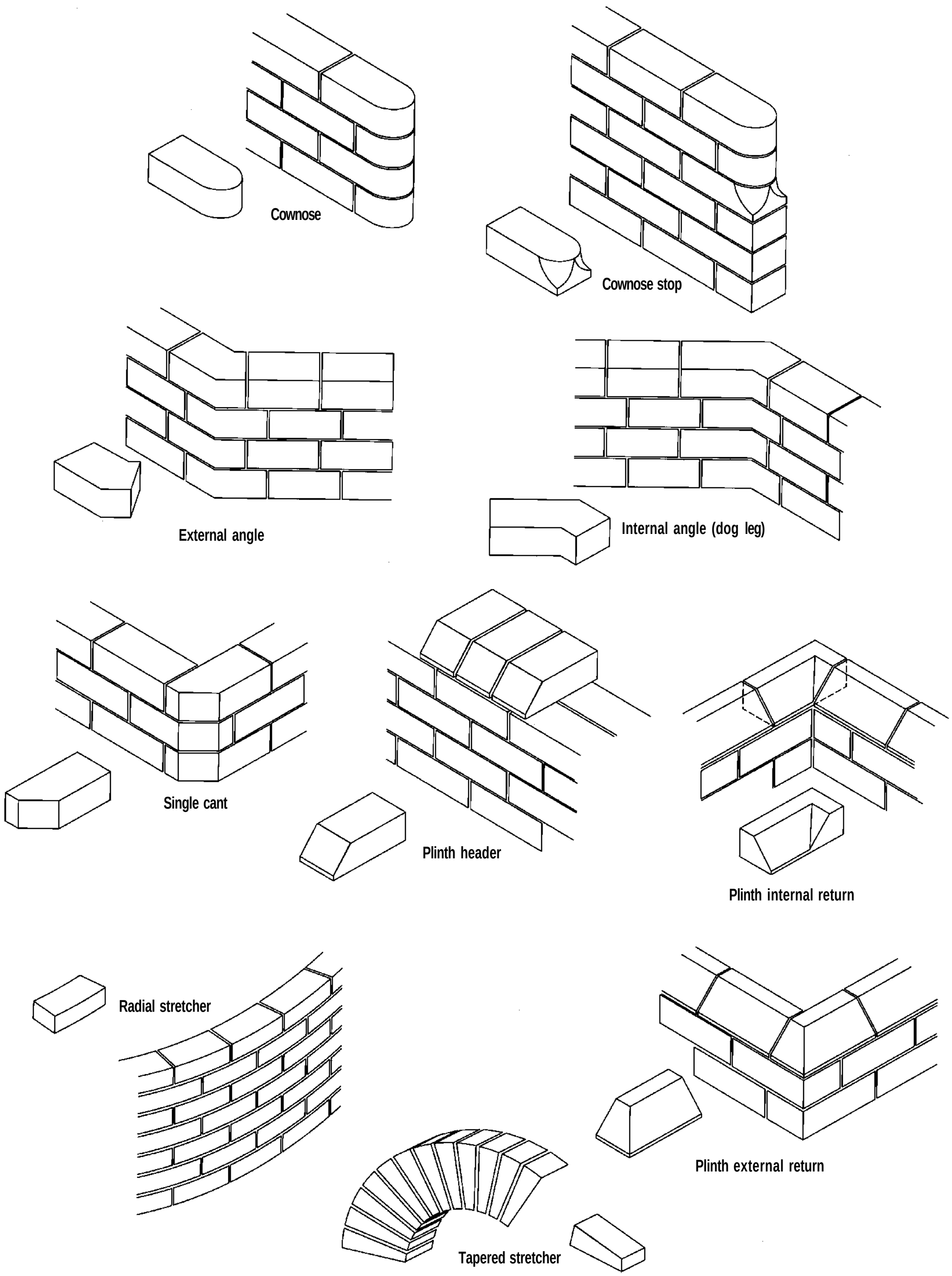

Fig. 1.7 Specials. (continued)

moulds, although some can be made by modifying standard bricks before firing. The range of shapes includes copings and cappings (for parapets and freestanding walls), bullnose (for corner details, e.g. window and door reveals), plinths (for corbelling details and cills), cants (for turning angles), arches and brick slips (to mask reinforced concrete lintels, etc.). Special bricks are also manufactured by cutting standard bricks, then, if

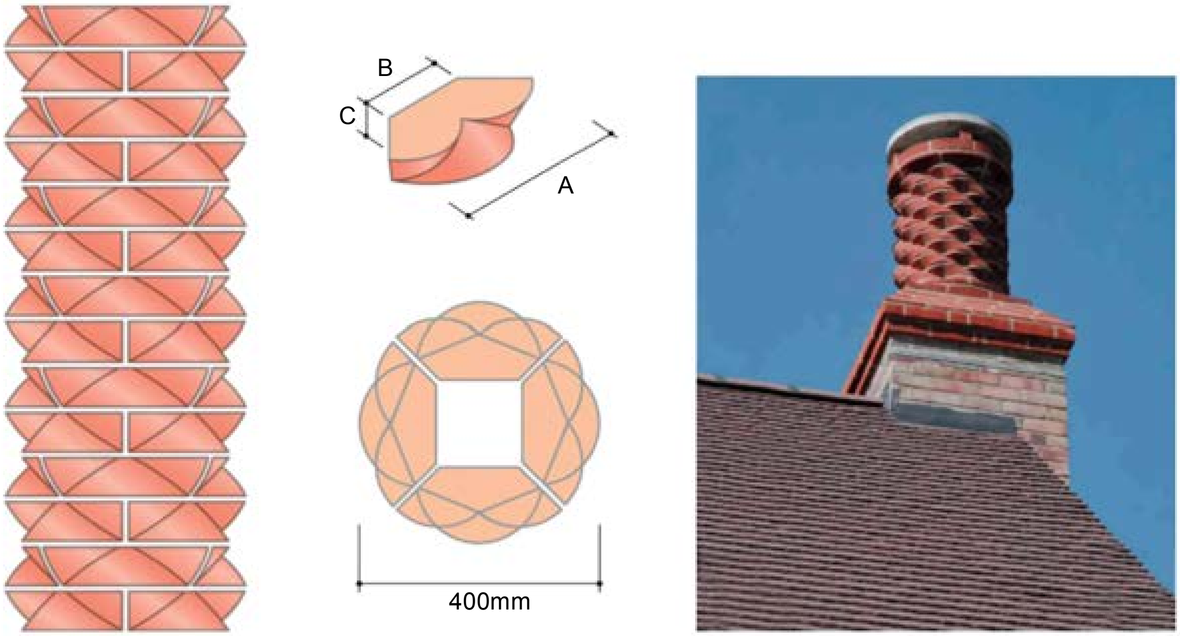

Fig. 1.7 Specials (continued). Photograph: Courtesy of Ibstock Brick Ltd

necessary, bonding the pieces with epoxy resins. This has the advantage of ensuring an exact colour match to the standard bricks. Many brick slips and arch voussoir sets (bricks to create an arch) are produced by this method.

APPEARANCE

The colour range of bricks manufactured in the UK is extensive. The colours range from the light buffs, greys and yellows through pastel pink to strong reds, blues, browns and deep blue/black, depending mainly upon the clay and the firing conditions, but also on the addition of pigments to the clay or the application of a sand facing. Colours may be uniform, varied over the surface of individual bricks or varied from brick to brick. The brick forms vary from precise to those with rounded arrises; textures range from smooth and sanded to textured and deeply folded, depending upon the forming process (Fig. 1.8).

In view of the variability of bricks from batch to batch it is essential that they should be well mixed, preferably at the factory before palleting, or failing this, on site. If this is not done sufficiently, accidental colour banding will appear as the brickwork proceeds. Sand-faced bricks are liable to surface damage on handling, which exposes the underlying colour of the brick. Chipping of the arrises on bricks with *through colour* is visually less detrimental. Where rainwater run-off is an important factor, e.g. on cills and copings, smooth rather than heavily rusticated bricks should be used, as the latter would saturate and stain. Handmade bricks with deep surface folds should be laid frog-up so that the creases or *smiles* tend to shed the rainwater from the face of the brickwork.

Glazed bricks, available in a wide range of intense colours, are sometimes used for their strong aesthetic effect (Fig. 1.9) or resistance to graffiti. They are commonly manufactured in a two-stage process, which involves the initial firing of the green brick to the *biscuit* stage, followed by the application of a *slip* glaze and a second firing. In an alternative one-stage process, a clear slip glaze is applied before firing to allow the natural colour of the brick to show through.

The visual acceptability of facing bricks and the quality of the bricklaying would normally be assessed on site by the construction of a reference panel to an agreed standard, using at least 100 randomly selected bricks with examples of any colour banding, the proposed bonding, mortar and jointing. All subsequent

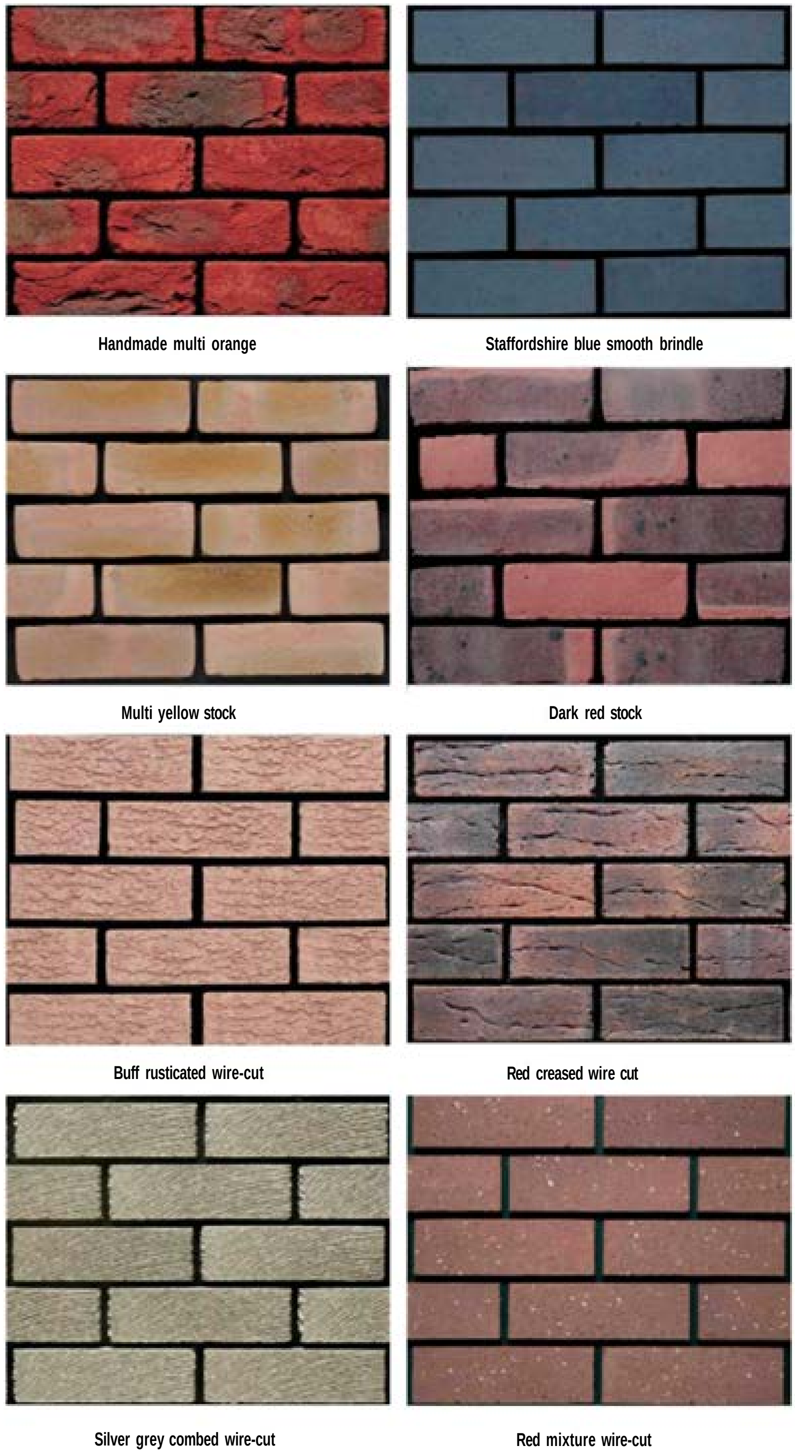

Fig. 1.8 Typical range of clay brick textures and colours. Photographs: Courtesy of Ibstock Brick Ltd

Fig. 1.9 Glazed bricks – Atlantic House, London. Architects: Proun Architects. Photograph: Courtesy of Ibstock Brick Ltd

brick deliveries and constructed brickwork should then be checked against the reference panel.

DURABILITY

Frost resistance

Bricks are classified into one of the three categories, F2, F1 and F0 according to their frost resistance within a standardised freezing test (Table 1.3). Only category

Table 1.3 Designation of freeze/thaw resistance and active soluble salts content for clay bricks

Durability designation	Freeze/thaw resistance
F2	masonry subjected to severe exposure
F1	masonry subjected to moderate exposure
F0	masonry subjected to passive exposure
	Active soluble salts content
S2	sodium/potassium 0.06%, magnesium 0.03%
S1	sodium/potassium 0.17%, magnesium 0.08%
S0	no requirement

F2 bricks are totally resistant to repeated freezing and thawing when in a saturated condition. Category F1 bricks are durable, except when subjected to repeated freezing and thawing under saturated conditions. Therefore, category F1 bricks should not be used in highly exposed situations such as below damp-proof courses, for parapets or brick-on-edge copings, but they are suitable for external walls which are protected from saturation by appropriate detailing. Category F0 bricks must only be used where they are subject to passive exposure, as when protected by cladding or used internally.

Soluble-salt content

The soluble-salt content of bricks is defined by three categories: low (S2), normal (S1) and no limits (S0) (Table 1.3). Both the S2 and S1 categories have defined maximum limits for sodium/potassium and magnesium salt contents. The soluble salts derive from the original clay or from the products of combustion during the firing process. Soluble salts can cause efflorescence and soluble sulfates may migrate from the bricks into the mortar or any rendering, causing it to expand and deteriorate by sulfate attack. If used in an exposed situation S1 and S0 category bricks should be bonded with sulfate-resisting cement mortar.

Efflorescence

Efflorescence sometimes appears as a white deposit on the surface of new brickwork. It is caused by moisture carrying salts from inside the bricks and mortar to the surface where the water evaporates leaving the crystalline salts. Under most conditions it disappears without deleterious effect within one year. In exposed brickwork that is constantly subjected to a cycle of wetting and drying, efflorescence can occur at any time; further, a build-up and expansion of crystalline salts under the surface (*crypto-efflorescence*) may cause the face of the brickwork to crumble or spall.

Staining

The surface of brickwork may be stained by cement during the building process, or by lime leaching out of the fresh mortar (Fig. 1.10). In either case the excess should be brushed and washed off, without saturating the brickwork.

PHYSICAL PROPERTIES

Compressive strength

High density (HD) clay bricks are available with a range of compressive strengths from around 5 MPa to well over 100 MPa. The criteria for general use, damp-proof courses and engineering use are set out in Table 1.2 (p. 7).

To determine the crushing strength of bricks, both bed faces are ground down until flat and parallel. The bricks are then crushed without filling the voids or frogs. Where frogs are to be laid upwards and filled in the construction, the crushing strength (MPa) is based on the net bearing area. Where frogs or voids are not to be filled, the crushing strength is based on the full gross area of the bed face.

Water absorption and suction

The level of water absorption is critical when bricks are to be used for damp-proof courses, or as engineering bricks. Appropriate limits are shown in Table 1.2, although generally absorption ranges from 1 to 35%. Suction rates are now quoted by most brick manufacturers, as high values can adversely affect the bricklaying process. Bricks with high suction rates absorb water rapidly from the mortar, making it insufficiently plastic to allow for repositioning of the bricks as the work proceeds. Generally, low or medium suction rates (1.0–2.0 kg/m^2 per min) are advantageous. In warm weather, high-suction-rate bricks may be wetted in clean water before laying, but any excess water will cause the brick to float on the mortar bed and will also increase the risk of subsequent efflorescence and staining.

Fig. 1.10 Lime leaching on brickwork

Moisture and thermal movement

After the firing process bricks absorb moisture from the atmosphere and expand irreversibly, up to a maximum of 0.1%. It is therefore recommended that bricks should not be used for at least two weeks after firing, (although it is now recognised that this irreversible process may continue at a decreasing rate for 20 years). Subsequent moisture and thermal movements are largely reversible and movement joints allowing for a 1 mm movement per 1 m of brickwork should be allowed, typically at 10–12 m centres and at a maximum of 15 m, in restrained walls. Unrestrained or lightly restrained walls should have movement joints at 7–8 m centres. Horizontal movement joints should be at approximately 12 m intervals, as the vertical movement is of the same order as movement in the horizontal direction.

For many buildings the necessary movement joints can be made inconspicuous by careful detailing or featured as part of the design. Appropriate locations for movement joints would be where differing structural forms adjoin, such as abutments between walls and columns or where the height or thickness of a wall changes; alternatively, at design details such as brickwork returns, re-entrant corners, or the recesses for downpipes. In expansion joints, fillers such as cellular polythene, polyurethane or foam rubber should be used, as these are easily compressible. Pointing should be with a flexible sealing compound such as two-part polysulfide.

Typical reversible moisture movement = 0.02%
Typical reversible thermal movement = 0.03%
Thermal movement = $5–8 \times 10^{-6}$ deg C^{-1}

Thermal conductivity

The thermal conductivity of brickwork is dependent upon its density and moisture content but generally clay bricks are poor thermal insulators. Brick manufacturers quote thermal conductivities at a standard 5% moisture content for exposed brickwork, and may also give the 1% moisture content figure for protected brickwork.

Using bricks with an average thermal conductivity of 0.96 W/m K, a typical partially filled cavity system is:

102.5 mm fairfaced brickwork
50 mm clear cavity
50 mm foil-faced rigid polyurethane insulation (λ = 0.023 W/m K)
100 mm lightweight blockwork (λ = 0.15 W/m K)
12.5 mm plasterboard on dabs

giving a U-value of 0.27 W/m^2 K

The thermal conductivity of clay bricks at 5% moisture content typically ranges between 0.65 and 1.95 W/m K.

Fire resistance

Clay brickwork generally offers excellent fire resistance by retaining its stability, integrity and insulating properties. The standard (BS 5628–3: 2001) indicates that 100 mm and 200 mm of load-bearing solid clay brick masonry will give 120 minutes and 360 minutes of fire resistance, respectively. Bricks with less than 1% organic material are automatically categorised as Euroclass A1 with respect to reaction to fire.

Acoustic properties

Good-quality brickwork is an effective barrier to airborne sound, provided that there are no voids through the mortar for the passage of sound. All masonry joints should be sealed and bricks laid with filled frogs to achieve the necessary mass per unit area and avoid air pathways.

At the junction between a cavity blockwork separating wall and an external brick and blockwork wall, if the external cavity is not fully filled with thermal insulation, then the separating wall cavity must be closed with a flexible cavity stop to reduce sound transmission sufficiently to comply with the Building Regulations Part E performance requirements.

Impact sound absorption by brickwork over the normal frequency range is fairly low and further decreased by the application of dense plaster or paint. However, the application of acoustic plasters or the addition of an independent panel of plasterboard backed by absorbent material improves impact sound insulation.

QUALITY CONTROL

To meet the consistent standards of quality required by clients, many brick manufacturers are now operating quality-assurance systems. These require manufacturers to document all their operational procedures and set out standards to which products must adhere. Quality is controlled by a combination of an internal self-monitoring system and two to four independent spot-check reviews per year. Both the content of the technical literature and the products themselves are subjected to this scrutiny.

Brickwork

CLAY BRICKWORK

The bonding, mortar colour and joint profile have a significant visual effect on brickwork. The overall effect can be to emphasise as a feature, or reduce to a minimum, the impact of the bonding mortar on the bricks. Additionally the use of polychromatic brickwork with complementary or contrasting colours for quoins, reveals, banding and even graphic designs can have a dramatic effect on the appearance of a building. The three-dimensional effects of decorative dentil courses and projecting corbelled features offer the designer further opportunities to exploit the effects of light and shade. Normally, a projection of 10–15 mm is sufficient for the visual effect without causing increased susceptibility to staining or frost damage. Curved brickwork constructed in stretcher bond shows faceting and the overhang effect, which is particularly accentuated in oblique light. With small-radii curvatures, the necessary change of bonding pattern to header bond can also be a visual feature, as an alternative to the use of curved-radius bricks.

The *Gothic Revival* exterior of the Queens Building, De Montfort University, Leicester (Fig. 1.11), illustrates the visual effects of polychromatic brickwork and voussoir specials. The energy-efficient building maximises use of natural lighting, heating and ventilation, using massive masonry walls to reduce peak temperatures. The mortar, which matches the external coral-red brickwork, reduces the visual impact of the individual bricks, giving the effect of planes rather than walls. This is relieved by the colour and shadow effects of the polychromatic and corbelled features, which are incorporated in the ventilation grilles and towers. The special bricks, cill details and banding are picked out in a deeper cadmium red and silver buff to contrast with the characteristic Leicestershire red-brick colouring.

Mortars

The mortar in brickwork is required to give a bearing for the bricks and to act as a sealant between them. Mortars should be weaker than the individual bricks, to ensure that any subsequent movement does not cause visible cracking of the bricks, although too weak a mix would adversely affect durability of the brickwork. Mortar mixes are based on blends of either cement/lime/sand, masonry cement/sand or cement/sand with plasticiser. When the mix is gauged by volume an allowance has to be made for bulking of damp sand. The five mix designations are shown in Table 1.4. A typical 1 : 1 : 6 (cement : lime : sand) mix (designation (iii)) would generally be appropriate and durable for low-rise construction, but for calculated structural brickwork or for increased resistance to frost in exposed situations a greater-strength mortar (designation (i) or (ii)) may be required. In the repointing of old brickwork it is particularly important to match the porosity of the brick to the water-retention characteristics of the mortar. This prevents excessive loss of water from the mortar before hydration occurs, which may then cause the pointing to crumble.

The use of lime mortar, as in the Building Research Establishment environmental building in Garston, Watford, will allow for the ultimate reuse of the bricks at the end of the building's life-cycle. The recycling of bricks is not possible, except as rubble, when strong Portland cement mortar is used.

Sands for mortars are normally graded to BS EN 13139: 2002 into categories designated by a pair of sieve sizes d/D which define the lower and upper size limits in mm respectively. The majority of the particle size distribution should lie between the stated limits. The preferred grades are 0/1 mm, 0/2 mm, 0/4 mm, 0/8 mm, 2/4 mm and 2/8 mm. Typically, between 85 and 99% of the sand should pass through the larger sieve limit, and between 0 and 20% should pass through the smaller sieve size limit. The grades with more fines (63 micron or less) require more cement to achieve the same strength and durability as the equivalent mortars mixed with a lower fines content.

Ideally, brickwork should be designed to ensure the minimal cutting of bricks, and should be built with a uniform joint width and vertical alignment of the joints (perpends). During construction, brickwork should be kept clean and protected from rain and frost. This reduces the risk of frost damage, patchiness and efflorescence. Brickwork may be rendered externally or plastered internally if sufficient mechanical key is provided by appropriate jointing or the use of keyed bricks. For repointing existing brickwork, it is necessary to match carefully the mortar sand, and to use lime mortar where it was used in the original construction.

Fig. 1.11 Decorative brickwork – Queens Building, De Montfort University, Leicester. Architects: Short Ford & Associates. Photograph: Arthur Lyons

Bonding

Figure 1.12 illustrates the effects of bonding. The stretcher bond is standard for cavity walls and normally a half-lap bond is used, but an increase in horizontal emphasis can be achieved by the less standard quarter or third bond. In conservation work it may be necessary to use half bricks (snap headers) to match the appearance of bonding in solid brick walls. For one-brick-thick walls more variations are possible; most typical are the English and Flemish bonds. The equivalent English and Flemish garden wall bonds, which have more stretchers, are primarily used for one-brick-thick walls where the reduced number of headers makes it easier to build both sides fairfaced. Panels of herringbone brickwork (raking bond), or dog tooth and dentil courses as in Victorian brickwork, can generate interesting features.

In all cavity brickwork, wall ties manufactured from galvanised steel, stainless steel or polypropylene to BS EN 845–1: 2003 should be incorporated (Fig. 1.13). They should be laid drip down and level or sloping down towards the outer leaf. Where mortar bed-joints do not co-ordinate between masonry leaves, slope-tolerant cavity wall ties must be used. In partially filled cavities, the wall ties should clip the insulation cavity batts to the inner leaf. In all cases the cavity, insulation and ties should be kept clear of mortar droppings and other residues by using a protective board. With the widening of cavities associated with increased insulation, the use of the traditional butterfly, double triangle and vertical twist ties in galvanised steel will be increasingly replaced by longer stainless steel ties, which do not suffer from corrosion in the more aggressive environments. Asymmetric wall ties are used for fixing masonry to timber or thin-joint aircrete blockwork. Movement-tolerant wall ties bend, or slide within a slot system fixed to one leaf of the masonry.

Table 1.4 Mortar mix designations

Designation	Cement:lime: sand	Masonry cement: sand	Cement:sand with plasticiser
(i)	1:0:3 - 1:¼:3		
(ii)	1:½:4 - 1:½:4 ½	1:2 ½ - 1:3 ½	1:3 - 1:4
(iii)	1:1:5 - 1:1:6	1:4 - 1:5	1:5 - 1:6
(iv)	1:2:8 - 1:2:9	1:5 ½ - 1:6 ½	1:7 - 1:8
(v)	1:3:10 - 1:3:12	1:6 ½ - 1:7	1:8

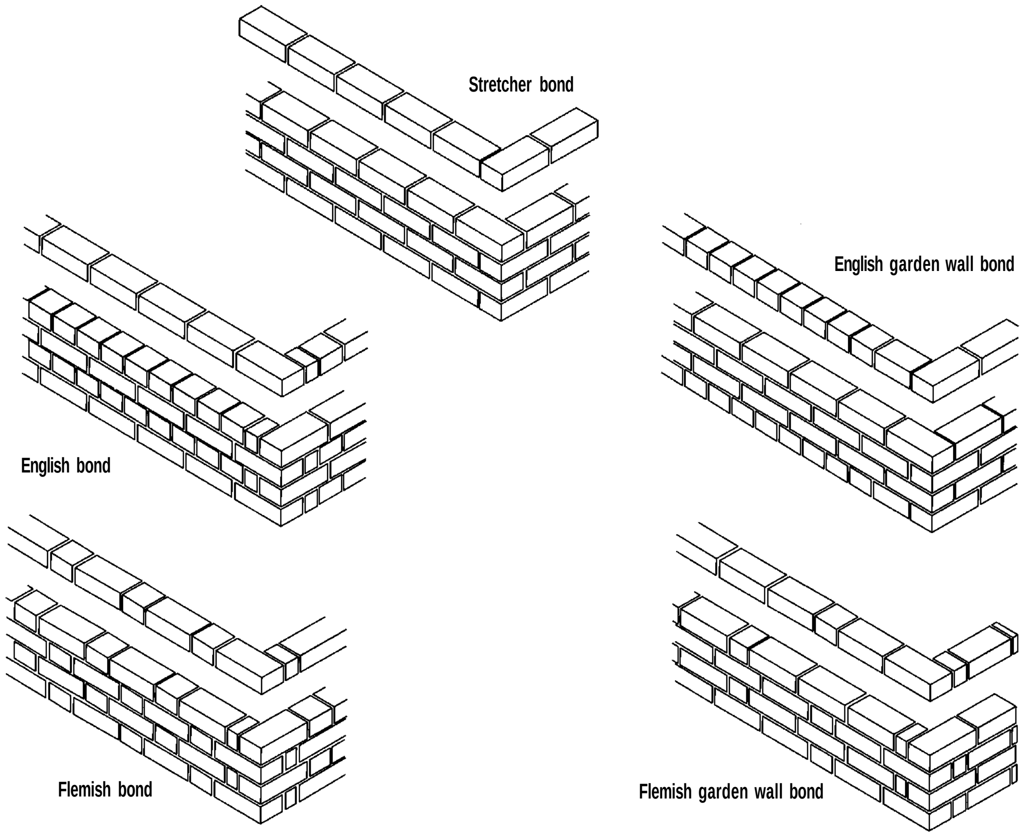

Fig. 1.12 Brick bonding

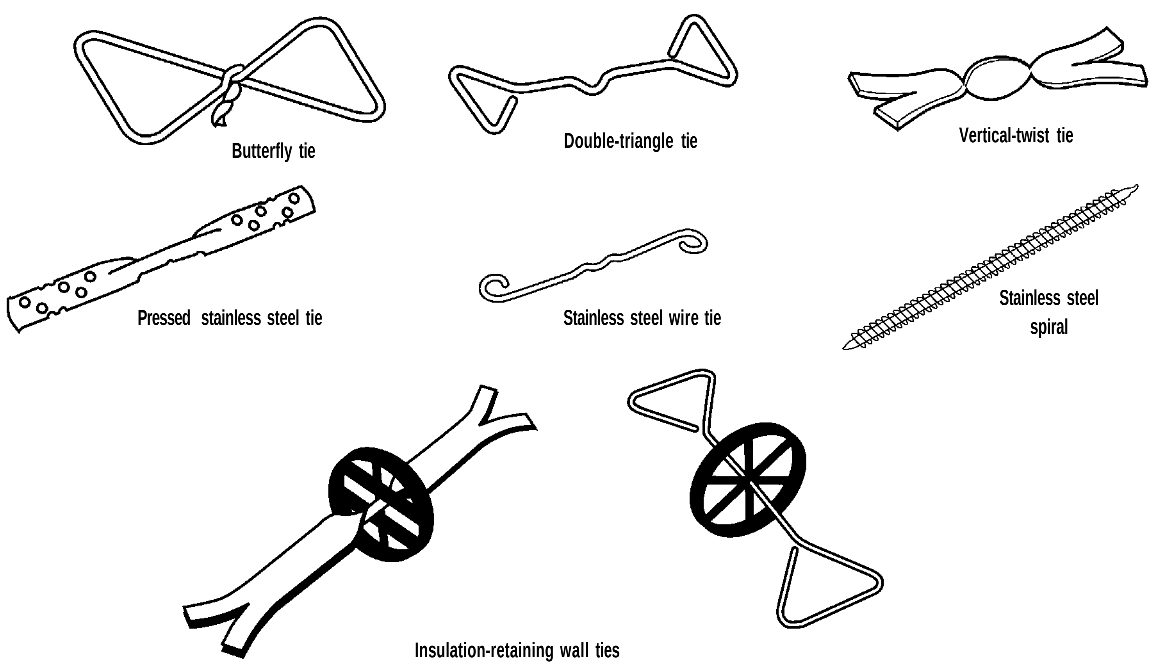

Fig. 1.13 Wall ties

Coloured mortars

Mortar colour has a profound effect on the overall appearance of the brickwork as, with stretcher bond and a standard 10 mm joint, the mortar accounts for 17% of the brickwork surface area. A wide range of light-fast coloured mortars is available which can be used to match or contrast with the bricks, thus highlighting the bricks as units or creating a unity within the brickwork. The coloured mortars contain inert pigments, which are factory-blended to a tight specification to ensure close colour matching between batches. Occasionally, black mortars may bloom due to lime migration to the surface. Coloured mortars can be used creatively to enhance the visual impact of the brickwork and even create designs on sections of otherwise monochromatic brickwork. The quantity of pigment should not exceed 10% by weight of the cement.

Mortar colours may also be modified by the use of stains after curing; however, such applications only penetrate 2 mm into the surface, and therefore tend to be used more for remedial work. Through-body colours are generally more durable than surface applications.

Joint profiles

The standard range of joint profiles is illustrated in Figure 1.14. It is important that the main criteria should be the shedding of water to prevent excessive saturation of the masonry, which could then deteriorate. Normally the brickwork is jointed as the construction proceeds. This is the cheapest and best method as it gives the least disturbance to the mortar bed. Pointing involves the raking out of the *green* mortar to a depth of 13–20 mm, followed by refilling the joint with fresh mortar. This is only appropriate when the desired visual effect cannot be obtained directly by jointing; for example, when a complex pattern of coloured mortar joints is required for aesthetic reasons.

The square recessed (raked) joints articulate the brickwork by featuring the joint, but these should only be used with durable (F2, S2) high-absorption bricks under sheltered conditions; furthermore, the recess should be limited to a maximum depth of 6 mm. The struck or weathered joint also accentuates the light and shade of the brickwork while, as a tooled joint, offering good weather resistance in all grades of exposure. If the visual effect of the joint is to be diminished, the flush joint may be used, but the curved recessed (bucket-handle) joint, which is compressed by tooling, offers better appearance and weathering properties. No mortar should be allowed to smear the brickwork, as it is difficult to remove subsequently without the use of dilute acid or pressure jets of water.

Reinforced brickwork

Reinforcement may be introduced vertically or horizontally into brickwork (Fig. 1.15). Bed-joint reinforcement, usually austenitic stainless steel, should be completely surrounded by mortar with a minimum cover of 15 mm. For continuity in long walls, sections of reinforcement should be sufficiently end lapped. Vertical reinforcement is possible in the cavity or in pocket-type walls, where the void spaces are formed in the brickwork, then reinforcement and concrete are introduced after the masonry is completed. Care should be taken in the use of vibrators to compact the concrete within new masonry.

Decorative brickwork

Plaques, motifs, murals and sophisticated sculptures (Fig. 1.16) can be manufactured to individual designs both for new buildings and for the renovation or refurbishment of Victorian *terracotta*. The designs are carved as a bas-relief in soft solid through-colour brickwork or moulded in the unfired clay in relatively small units and joined on site with a matching mortar.

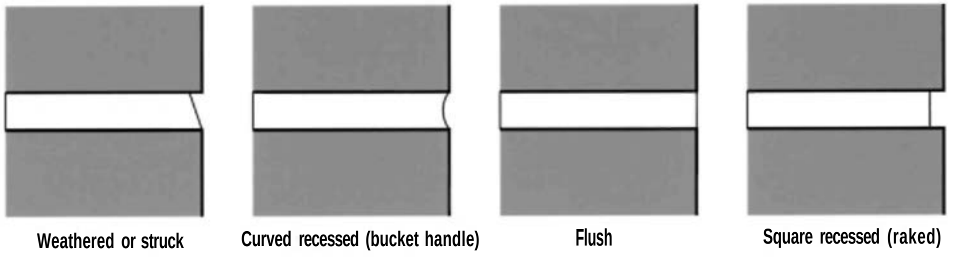

Fig. 1.14 Joint profiles

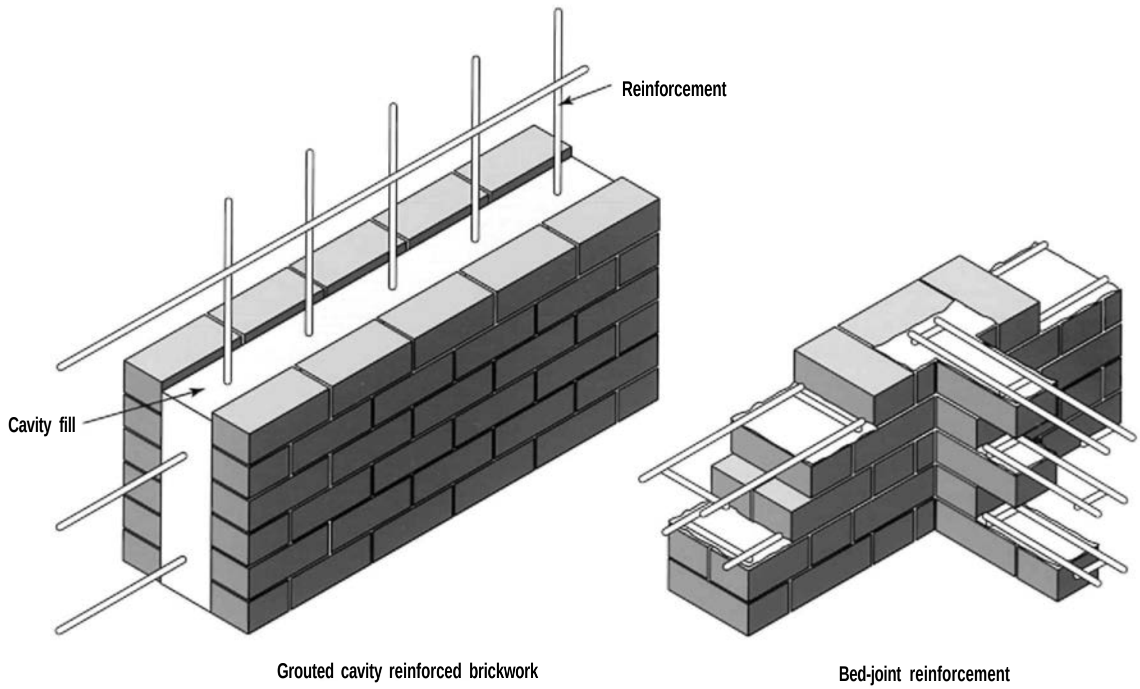

Fig. 1.15 Reinforced brickwork

Fig. 1.16 Decorative carved brickwork. Photograph: Courtesy of Baggeridge Brick plc

For repetitive units, the clay is shaped in an appropriate wooden mould. Relief depths of 10–30 mm give shadow and contrast sufficient for most sculptural effects to be seen, although the viewing distances and angles must be considered. For large brickwork sculptures, the whole unit may be built in green bricks, with allowances made for the mortar joints and drying contraction. The design is then carved, numbered, dismantled, fired and reassembled on site.

Thin-bed masonry

The use of thin-bed masonry, with joints of between 2 and 6 mm, significantly reduces the visual effect of the mortar joints from 17% in 10-mm-joint standard brickwork, to only 8% in 4 mm joints. This effect is further enhanced by the use of glue-mortars which are applied to create a recessed joint. Thus the joint becomes only a shade line and the visual effect of the wall is totally determined by the colour and texture of the bricks. Because the glue-mortar is stronger than traditional mortar and has tensile properties, the brickwork patterns are not constrained to standard stretcher bonding. The glue-mortar is applied in two lines to both the horizontal and vertical joints, and therefore solid or perforated bricks rather than frogged bricks are most appropriate. Thin-bed masonry wall ties and special aramid bed-joint reinforcement are used as appropriate. The system offers the creative designer significant alternative aesthetic opportunities.

Preassembled brickwork

The use of pre-assembled brickwork supported on reinforced concrete or steel frames offers the builder a potentially higher level of quality control and increased speed of construction on site (Fig. 1.17). It also offers the scope to create complex details, and forms such as long low arches, that would be expensive or impossible in traditional brick construction. Specialist manufacturers produce large complete brick-clad precast-concrete panels either with whole bricks or brick slips. Typically, the rear faces of brick slips are drilled at an angle, then stainless steel rods inserted and fixed with resin adhesive. The brick slips are laid out with spacers within the panel mould, prior to the addition of steel reinforcement and concrete. Finally, the brick slips are pointed up giving the appearance of normal brickwork.

Brick cladding systems

A significant revolution for brick-faced building has been the development of brick slip and brick tile cladding systems, designed to have the appearance and durability of traditional brickwork, but with a significantly reduced construction time. In one system, external walls are constructed with 215 mm aerated concrete blockwork and faced with an extruded polystyrene insulation panel to which 16 mm brick slips are applied onto the pre-formed grid, giving the appearance of standard external leaf brickwork. The polystyrene grid panels have an overlap to ensure horizontal joints are watertight and are tongued and grooved to interlock vertically. Adhesive is applied to the polystyrene and the brick slips are pushed into place with the appropriate horizontal spacing. Mortar is applied either with a pointing gun or a mortar bag and tooled to the required joint profile. With the use of highly insulating blocks, this type of construction can achieve U-values as low as 0.27 W/m^2 K.

An alternative system uses a plastic-coated galvanised steel profile fixed to the structural wall (Fig. 1.18). The specially shaped brick tiles then clip into the steel system with appropriate vertical joint spacing. Mortar (typically a 1 : 1 : 6 mix) is applied with a pointing gun and smoothed off to the required profile, usually bucket-handle. A range of special tiles is manufactured to produce dados,

Fig. 1.17 Preassembled brickwork. Photograph: Courtesy of Trent Concrete Ltd

Fig. 1.18 Brick cladding system. Photograph: Courtesy of Corium, a division of Baggeridge Brick plc

plinths, cills and external returns, giving the appearance of traditional brickwork. Because the brickwork is non-structural, a range of bond patterns including stack, quarter and diagonal is optional. This type of pre-fabrication offers the potential for increased off-site construction work, and some manufacturers supply pre-formed brick-tile panels ready for fixing on site.

CLAY BRICK PAVING

Many clay brick manufacturers produce a range of plain and chamfered paving bricks together with a matching range of paver accessories. Bricks for flexible paving are usually nibbed to set the spacing correctly. The material offers a human scale to large areas of hard landscape, especially if creative use is made of pattern and colour. Typical patterns (Fig. 1.19) include herringbone, running bond, stack bond, basket-weave and the use of borders and bands. Profiled brick designs include decorative diamond and chocolate-bar patterns, and pedestrian-management texturing. The paving bricks may be laid on a hard base with mortar joints or alternatively on a flexible base with fine sand brushed between the pavers. Edge restraint is necessary to prevent lateral spread of the units.

The British Standard (BS EN 1344: 2002) stipulates minimum paver thicknesses of 40 mm and 30 mm for flexible and rigid construction respectively. However, 50 mm pavers are generally used for flexible laying and 60 mm pavers are necessary when subjected to substantial vehicular traffic (BS 7533–1: 2001). Table 1.5 shows the standard sizes. Clay pavers are classified by freeze/thaw resistance. Pavers with designation FP0 are unsuitable for saturated freezing conditions, while pavers designated FP100 may be used under freeze/thaw conditions. The Standard BS EN 1344: 2002 classifies five categories (T0 to T4) of transverse breaking strength, with the lowest category T0 being only appropriate for rigid construction. Slip resistance for the unpolished pavers is categorised as high, moderate, low or extremely low. This factor needs to be considered particularly for potentially wet conditions to ensure safe pedestrian and traffic usage.

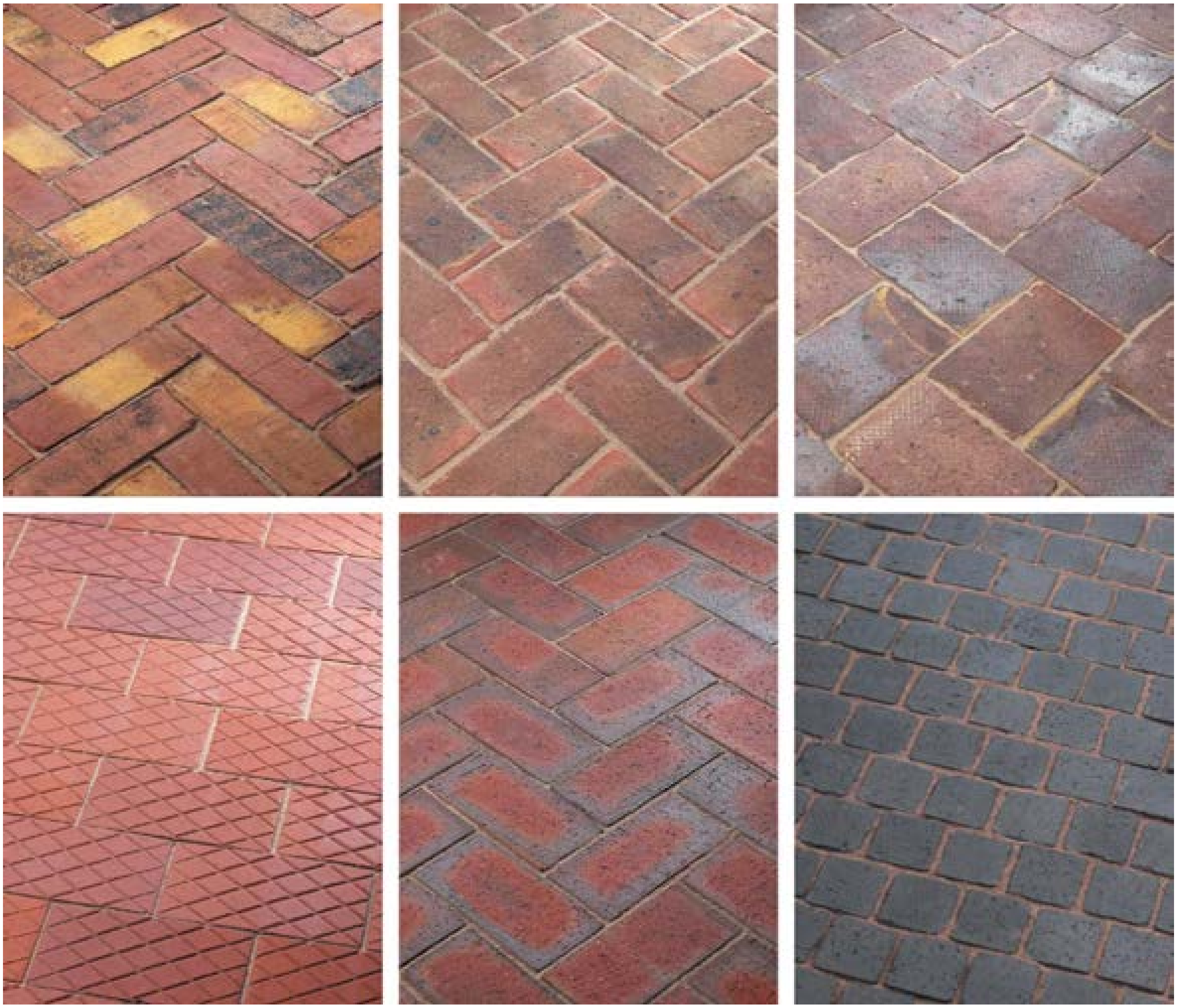

Fig. 1.19 Typical range of clay pavers. Photographs: Courtesy of Baggeridge Brick plc

Table 1.5 Standard work sizes for pavers

Length (mm)	Width (mm)	Thickness (mm)
215	102.5	50
215	102.5	65
210	105	50
210	105	65
200	100	50
200	100	65

Calcium silicate bricks

Calcium silicate bricks, also known as sandlime or flintlime bricks, were first produced commercially in Germany in 1894, and then in the UK in 1905. Initially their use was confined to common brick applications, but in the 1950s, their durability for foundations was exploited. Research into mix design and the development of improved manufacturing processes subsequently led to the production of a full range of load-bearing-strength classes and attractive facings. Calcium silicate bricks are competitively priced and account for about 3% of the UK brick market.

SIZE

The work size for calcium silicate bricks is $215 \times 102.5 \times 65$ mm, the same as for clay bricks, with a co-ordinating size of $225 \times 112.5 \times 75$ mm, allowing

Fig. 1.19 Continued. Typical range of clay pavers and hard landscape at Birmingham. Photographs: Courtesy of Baggeridge Brick Plc

for 10 mm mortar joints. Generally, calcium silicate bricks are more accurate in form and size than fired clay bricks, which inevitably distort in the manufacturing process. The dimensional tolerances for calcium silicate bricks defined in the standard (BS EN 771–2: 2003) are generally ±2 mm on each dimension, except for thin layer mortar when a maximum of only ±1 mm tolerance is permitted on the height.

MANUFACTURE OF CALCIUM SILICATE BRICKS (SANDLIME AND FLINTLIME BRICKS)

The raw materials are silica sand (approximately 90%), hydrated lime, crushed flint, colouring pigments and water. (If quicklime is used, it is fully hydrated before the bricks are pressed, to prevent expansion under the steam treatment.) A mixture of sand, lime and water is used to manufacture the natural white sandlime brick. The addition of colouring pigments or crushed-flint aggregate to the standard components, or the application of texturing to the brick surface, gives the wider product range.

The appropriately proportioned blend is pressed into brick units, stacked on bogies, moved into the autoclave and subjected to steam pressure (0.8–1.3 MPa) for 4 to 15 hours at 180°C (Fig. 1.20). This causes the hydrated lime to react chemically with the surface of the sand particles, enveloping them with hydrated calcium silicates which fill much of the void spaces between the sand particles. Subsequently the calcium silicates react slowly with carbon dioxide from the atmosphere to produce calcium carbonate, with a gradual increase in the strength of the bricks.

APPEARANCE

The manufacturing process results in accurate shapes and dimensions, and with the untextured calcium silicate bricks, a smooth finish. The colour range is extensive, from white and pastel shades through to deep reds, blues, browns, greens and yellows. The visual effect on the brickwork tends to be that of precision. The bricks tend to be more brittle than clay bricks and are therefore more susceptible to damage on their arrises.

SPECIFICATION OF CALCIUM SILICATE BRICKS

Types

Both solid and frogged calcium silicate bricks are available. Manufacturers produce a wide range of matching specials to BS 4729: 2005; *special specials* to clients' requirements; and brick slips for facing reinforced concrete.

Durability

Calcium silicate bricks have good frost resistance, but should not be exposed repeatedly to either strong salt solutions, acids or industrial effluent containing magnesium or ammonium sulfates. The bricks have a negligible salt content and therefore efflorescence, and sulfate attack on the mortar, cannot arise from within the bricks. The bricks are themselves resistant to sulfate attack and can therefore be used below ground with a suitable sulfate-resisting cement mortar. However, calcium silicate bricks should not be used as pavers where winter salting can be expected.

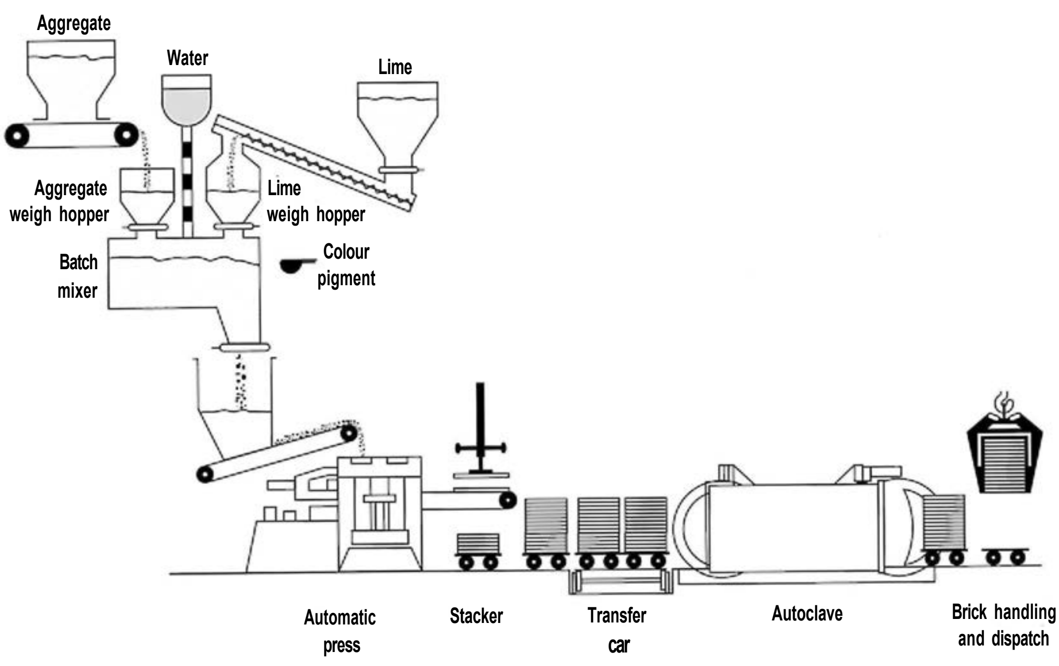

Fig. 1.20 Manufacture of calcium silicate bricks

PHYSICAL PROPERTIES

Compressive strength

The British Standard BS EN 771–2: 2003 defines the range of compressive strength classes, as shown in Table 1.6.

Weight

Most standard calcium silicate bricks weigh between 2.4 and 3.0 kg, but densities can range from below 500 to above 2200 kg/m^3.

Water absorption

Water absorption is usually in the range 8–15% by weight.

Moisture and thermal movement

Unlike clay bricks, which expand after firing, calcium silicate bricks contract. This shrinkage is increased if the bricks become wet before use, therefore site protection of brick stacks from saturation is essential. Similarly, unfinished brickwork should be protected from both saturation and freezing during construction. Reversible moisture movement for calcium silicate bricks is greater than for clay bricks, so expansion joints must be provided at intervals between 7.5 and 9.0 m. Such movement joints should not be bridged by rigid materials. Generally, a weak mortar mix should be used (e.g. 1 : 2 : 9 cement : lime : sand), except below damp-proof course level (DPC) and for copings, to prevent visible cracking of either the mortar or the bricks.

Typical reversible moisture movement = $\pm$ 0.05%
Typical reversible thermal movement = $\pm$ 0.05%
Thermal movement = $8-14 \times 10^{-6}$ deg C^{-1}

Table 1.6 Minimum compressive strength for calcium silicate bricks

Compressive strength class	Normalised compressive strength (MPa)
5	5.0
7.5	7.5
10	10.0
15	15.0
20	20.0
25	25.0
30	30.0
35	35.0
40	40.0
45	45.0
50	50.0
60	60.0
75	75.0

Thermal conductivity

The thermal conductivities are equivalent to those of clay bricks of similar densities.

The thermal conductivity of calcium silicate brick ranges from 0.6 W/m K (Class 20) to 1.3 W/m K (Class 40).

Fire resistance

The fire resistance of calcium silicate bricks is similar to that of clay bricks, with solid 100 mm calcium silicate brickwork giving 120 minutes and 200 mm giving 360 minutes' fire resistance, according to BS 5628–3: 2001. The standard illustrates only marginal differences in fire resistance between calcium silicate and clay bricks. Calcium silicate bricks (with less than 1% organic material) are designated Euroclass A1 with respect to reaction to fire.

Acoustic properties

Acoustic properties are related to mass and are therefore the same as for clay bricks of equivalent density.

CALCIUM SILICATE BRICKWORK

Most design considerations are the same for either clay or calcium silicate brick. However, calcium silicate bricks are particularly popular for their light reflecting properties, for example in light wells or atria. Their smooth crisp appearance with a non-abrasive surface is particularly appropriate for some interior finishes and also forms an appropriate base for painted finishes. The use of complementary coloured mortars enhances the aesthetic effect when using strongly coloured bricks. Their dimensional accuracy gives some advantage in the bricklaying process, and cost is comparable to that of the equivalent clay bricks.

The interior of the Queens Building of De Montfort University, Leicester (Fig. 1.21) illustrates

Fig. 1.21 Polychromatic calcium silicate brickwork – Queens Building, De Montfort University, Leicester. Architects: Short Ford & Associates. Photographs: Lens-based media, De Montfort University

the effective use of calcium silicate brickwork in creating a light internal space. Incorporated within the ivory Flemish-bond brickwork are restrained bands of polychromatic features and robust articulation of obtuse-angle quoins. The accuracy of the brickwork emphasises the clarity of the internal form, reflecting the disciplines of engineering that the building houses.

Table 1.7 Standard and modular sizes for concrete bricks

	Length (mm)	Width (mm)	Height (mm)
standard	215	103	65
modular	290	90	90
	190	90	90
	190	90	65

Concrete bricks

Developments in the use of iron oxide pigments have produced a wide range of colour-stable quality concrete-brick products. Currently concrete bricks are competitively priced and hold approximately 10% of the total brick market share.

SIZE

The standard size of concrete bricks is 215 × 103 × 65 mm as for clay bricks, but due to their manufacturing process, concrete bricks can be made to close tolerances, so accurate alignment is easy to achieve on site. Half-brick walls can readily be built fairfaced on both sides. Other sizes, as shown in Table 1.7, are listed in BS 6073–2: 1981.

MANUFACTURE OF CONCRETE BRICKS

Concrete bricks are manufactured from blended dense aggregates (e.g. crushed limestone and sand) together with cement under high pressure in steel moulds. Up to 8% of appropriately blended iron oxide pigments, depending on the tone and depth of colour required, is added to coat the cement particles which will then form the solid matrix with the aggregate. The use of coloured aggregates also increases the colour range. The accurate manufacturing process produces bricks that have clean arrises.

APPEARANCE

A wide range of colours, including multicolours, is available, from red, buff and yellow to green and black. Surfaces range from smooth to simulated natural stone, including those characteristic of handmade and textured clay bricks. Because of the wide range of pigments used in the manufacturing process, it is possible to match effectively new concrete bricks to old and weathered clay bricks for the refurbishment or extension of old buildings.

SPECIFICATION OF CONCRETE BRICKS

Types

Concrete bricks may be solid, perforated, or frogged, according to the manufacturer.

Three categories are defined: common, facing and engineering. The latter can be manufactured with a range of strengths and densities to specific requirements. A normal range of specials to BS 4729: 2005 is produced, although as with clay and calcium silicate bricks, a longer delivery time must be anticipated. The manufacturer's reference, the crushing strength, the dimensions and the brick type must be clearly identified with each package of concrete bricks. Engineering quality concrete bricks should be used below ground where significant sulfate levels are present according to the classification given in the BRE Special Digest 1, *Concrete in aggressive ground* (2005).

DURABILITY

Concrete bricks are resistant to frost and are therefore usable in all normal levels of exposure. Like all concrete products, they harden and increase in strength with age. As with calcium silicate bricks, they can be made free of soluble salts and thus free from efflorescence. Concrete bricks should not be used where industrial effluents or acids are present.

PHYSICAL PROPERTIES

Weight and compressive strength

The standard brick weighs approximately 3.2 kg and has minimum crushing strength of 7.0 MPa, although

20–40 MPa is the typical range. Engineering bricks have a strength of 40 MPa with a sulfate-resisting Portland or equivalent cement content of 350 kg/m^3 (BS 6073–2: 1981).

Water absorption

Water absorption is typically 8%, but engineering-quality bricks average less than 7% after 24 hours cold immersion, and are suitable for aggressive conditions such as retaining walls, below damp-proof course level and for inspection chambers.

Moisture and thermal movement

Concrete bricks have a typical drying shrinkage of 0.04%, with a maximum of 0.06%. Moisture and thermal movements are greater than for calcium silicate bricks and movement joints should be at 5–6 m centres. Because of their moisture movement, prior to laying, concrete bricks should not be wetted to overcome excessive suction, but the water retentivity of the mortar should be adjusted accordingly. Brick stacks should be protected on site from rain, frost and snow.

Thermal conductivity

The thermal conductivities of concrete bricks are equivalent to those of clay and calcium silicate bricks of similar densities. Partially filled cavities, maintaining a clear cavity, are recommended to prevent water penetration to the inner leaf.

The thermal conductivity of concrete bricks ranges between 1.4 and 1.8 W/m K.

An appropriate level of thermal insulation for external walls can be achieved using concrete brickwork. A typical partial cavity fill system is:

102.5 mm concrete-facing brick
50 mm clear cavity airspace
45 mm foil-faced rigid polyurethane insulation (λ = 0.023 W/m K)
115 mm high performance lightweight blockwork (λ = 0.11 W/m K)
12.5 mm plasterboard on dabs

giving a U-value of approximately 0.27 W/m^2 K depending on the thermal conductivity of the concrete bricks used.

Fire resistance

The fire resistance of concrete bricks is of the same order as clay and calcium silicate bricks. Concrete bricks (with less than 1% organic material) are designated Euroclass A1 with respect to reaction to fire.

Acoustic properties

Dense concrete bricks are suitable for the reduction of airborne sound transmission. On a weight basis, they are equivalent to clay and calcium silicate bricks.

CONCRETE BRICKWORK

With the wide range of colour and texture options now offered by concrete-brick manufacturers, it is frequently difficult to distinguish visually, except at close quarters, between concrete and clay brickwork. The visual effects of using coloured mortars and various jointing details are as for clay bricks, but for exposed situations the use of raked joints is not recommended.

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Fig. 3.24 Concrete roofing tiles and slates

Plain tiles Feature tiles

Face Underside Club

Interlocking tiles Double Roman Troughed Double pantile
Bold roll Flanders tile Stone slate Arrowhead
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Fig. 14.6 Wind catcher. Illustration: Courtesy of Monodraught Fresh air in Control clampers SECTION Stale air out Ceiling diffuser E N E R G Y S A V I N G M A T E R I A L S A N D C O M P O N E N T S 3 2 9 Smith, P. and Pitts, C.A. 1997: Concepts in practice – energy – building for the third millennium. London: Batsford. Thomas, R. (ed.) 2001: Photovoltaics and architecture. London: Spon. Thomas, R. 1999: Photovoltaics in buildings: a design guide. London: ETSU Department of Trade and Industry. Vale, B. and Vale, R. 2000: The new autonomous house: design and planning for sustainability. London: Thames and Hudson. BUILDING RESEARCH ESTABLISHMENT PUBLICATIONS BRE Digests BRE Digest 355: 1991 Energy efficiency in dwellings. BRE Digest 438: 1999 Photovoltaics integration into buildings. BRE Digest 446: 2000 Assessing environmental impacts of construction: industry consensus, BREAM and UK ecopoints. BRE Digest 452: 2000 Whole life-cycle costing and life-cycle assessment for sustainable building design. BRE Digest 457: 2001 The carbon performance rating for offices. BRE Digest 486: 2004 Reducing the effects of climate change by roof design. BRE Digest 489: 2004 Wind loads on roof-based photovoltaic systems. BRE Digest 495: 2005 Mechanical installation of roofmounted photovoltaic systems. BRE Information papers BRE IP 2/90 Ecolabelling of building materials and building products. BRE IP 11/93 Greenhouse-gas emissions and buildings in the United Kingdom. BRE IP 15/98 Water conservation. BRE IP 13/00 Green buildings revisited (Parts 1and 2). BRE IP 17/00 Advanced technologies for 21st century building services. BRE IP 5/01 Solar energy in urban areas. BRE IP 3/03 Dynamic insulation for energy saving and comfort. BRE IP 13/03 Sustainable buildings (Parts 1–4). BRE IP 10/04 Whole life value: sustainable design in the built environment. BRE IP 15/05 The scope for reducing carbon emissions from housing. BRE IP 16/05 Domestic energy use and carbon emissions: Scenarios to 2050. BRE Good practice guide (Building Research Energy Conservation Support Unit [BRECSU]) GPG 287: 2000 Design teams guide to environmentally smart buildings: energy efficient options for new and refurbished offices. BRE Reports Report 370: 1999 BRE methodology for environmental profiles of construction materials, components and buildings. Report 431: 2001 Cooling buildings in London. ADVISORY ORGANISATIONS British Photvoltaic Association, National Energy Centre, Davy Avenue, Knowhill, Milton Keynes, Buckinghamshire MK5 8NG (01908 442291). Centre for Alternative Technologies, Machynlleth, Powys SY20 9AZ (01654 705950).

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British Wood Preserving & Damp Proofing Association, 1 Gleneagles House, Vernon Gate, South Street, Derby DE1 1UP (01332 225100).
British Woodworking Federation, 55 Tufton Street, London SW13QL (0870 458 6939).
English Nature, Northminster House, Peterborough, Cambridgeshire PE1 1UA (01733 455100).
Finnish Plywood International, Stags End House, Gaddesden Row, Hemel Hempstead HP2 6HN (01532 794661).
Glued Laminated Timber Association, Chiltern House, Stocking Lane, Hughenden Valley, High Wycombe, Bucks. HP14 4ND (01494 565180).
Thatching Advisory Services Ltd., The Old Stables, Redenham Park Farm, Redenham, Andover, Hampshire SP11 9AQ (01264 773820).
Timber Research and Development Association, Stocking Lane, Hughenden Valley, High Wycombe, Bucks. HP14 4ND (01494 569600).
UK Timber Frame Association Ltd., 14 Kinnerton Place South, London SW1X 8EH (020 7235 3364).
Wood Panel Industries Federation, 28 Market Place, Grantham, Lincolnshire NG31 6LR (01467 563707).

produce an impermeable product and this may be applied before a single firing process or after the tiles have been fired at 1150°C to the biscuit stage in a tunnel kiln. Either the unfired or biscuit tiles are coated with a slip glaze followed by firing under radiant heat for approximately 16 hours. Damaged tiles are rejected for recycling; the quality-checked tiles are packaged for dispatch. Standard sizes are 108 × 108 mm, 150 – 150 mm, 200 – 150 mm, 200 – 200 mm and 250 × 200 mm.

VITREOUS CHINA

Vitreous china, used for the manufacture of sanitary ware, has a glass-like body which limits water absorption through any cracks or damage in the glaze to 0.5%. It is typically manufactured from a blend of kaolin (25%), ball clay (20%), feldspar (30%) and quartz (25%). For large units such as WCs and wash basins, a controlled drying out period is required before firing to prevent cracking. Glaze containing metallic oxides for colouration is applied before firing to all visually exposed areas of the components.

Vitreous china is also used in the manufacture of some floor tiles due to its impermeable nature. Unglazed floor tiles may be smooth, alternatively studded or ribbed to give additional non-slip properties. Standard sizes are 100 – 100 mm, 150 – 150 mm, 200 – 200 mm and 300 – 300 mm with thickness usually in the range 8 – 13 mm. For lining swimming pools, additional protection against water penetration is given by the application of a glaze.

REPRODUCTION DECORATIVE TILES

Reproduction moulded ceramic wall tiles (encaustic tiles with strong colours burnt into the surface) and geometrical floor tiles can be manufactured to match existing units with respect to form, colour and texture for restoration work. Some manufacturers retain both the necessary practical skills and appropriate detailed drawings to ensure high-quality conservation products, which may be used to replace lost or seriously damaged units. There is also an increasing demand for reproduction decorative tiles in new-build work.

MOSAICS

Mosaics in glazed or unglazed porcelain are hard wearing, frost-proof and resistant to chemicals. Unglazed mosaics may be used for exterior use and other wet areas such as swimming pools, where good slip resistance is important. Mosaics are usually supplied attached to paper sheets for ease of application. Figure 8.10 illustrates a formal mosaic floor, while Figure 8.11 shows the broken tile mosaic finish used by Calatrava on the Tenerife Concert Hall, following the technique developed by Gaudi.

CERAMIC GRANITE

Ceramic granite is a blend of ceramic and reconstituted stone, manufactured from a mixture of feldspar, quartz and clay. The components are crushed, graded, mixed and compressed under very high pressure, followed by firing at 1200°C. The material is produced in 20 and 30 mm slabs, which can be cut and polished to produce a hard shiny finish with the appearance of natural marble or granite, suitable for worktops. Colours range from ochre, off-white and grey to green and blue depending upon the initial starting materials.

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ADVISORY ORGANISATIONS

CERAM Research, Queens Road, Penkhull, Stoke-on-Trent ST4 7QL (01782 76444).
Clay Pipe Development Association Ltd., Copsham House, 53 Broad Street, Chesham, Bucks. HP5 3EA (01494 791456).
Clay Roof Tile Council, Federation House, Station Road, Stoke-on-Trent, Staffordshire ST4 2SA (01782 744631).
Tile Association, Forum Court, 83 Copers Cope Road, Beckenham, Kent BR3 1NR (020 8663 0946).