

Chapter 5

Construction materials

INTRODUCTION

A wide range of building materials is available for the construction of rural buildings and structures. The proper selection of materials to be used in a particular building or structure can influence the original cost, maintenance, ease of cleaning, durability and, of course, appearance.

Several factors need to be considered when choosing the materials for a construction job, including:

1. Type and function of the building or structure and the specific characteristics required of the materials used, i.e. great strength, water resistance, wear resistance, attractive appearance, etc.
2. Economic aspects of the building/structure in terms of original investment and annual cost of maintenance.
3. Availability of materials in the area.
4. Availability of the skilled labour required to install some types of material.
5. Quality and durability of different types of material.
6. Transportation costs.
7. Selection of materials with compatible properties, dimensions and means of installation.
8. Cultural acceptability or personal preference.

WOOD

Wood is a commonly used construction material in many parts of the world because of its reasonable cost, ease of working, attractive appearance and adequate life if protected from moisture and insects. However, forests are a valuable natural resource that must be conserved, particularly in areas with marginal rainfall. As good a material as wood may be, there are regions where other materials should be considered first, simply on a conservation basis.

Wood for building is available from many different species with widely varying characteristics. Some species are used in the form of small poles for light construction, while other species are allowed to mature so that timber (*lumber* in many countries) may be sawn from the large logs. The species that produce small, inexpensive poles in rather short growing periods often grow in the fringes of agricultural land and can be used without danger to the ecology of the region.

The various species of wood have a number of physical characteristics that will be discussed in relation to their use in building construction.

Hardwoods versus softwoods

Wood cut from deciduous trees (which drop their leaves sometime during the year) is considered to be hardwood, while that cut from coniferous (needle-bearing) trees is considered to be softwood. However, this classification does not accurately reflect whether the wood itself is soft or hard. In this book, hardwood will be used to classify wood with hard characteristics.

Wood characteristics

Strength in wood is its ability to resist breaking when it is used in beams and columns. Not only is strength related to the species, but also to moisture content (MC) and defects. Strength is also quite closely related to density.

Hardness is the resistance to denting and wear. While hardwoods are more difficult to work, they are required for tools, tool handles, flooring and other applications subject to wear, or where a high polish is desired.

Woods that are stiff resist deflection or bending when loaded. Stiff woods are not necessarily very strong. They may resist bending up to a point and then break suddenly.

Tough woods will deflect considerably before breaking. Even after fracturing, the fibres tend to hang together and resist separation. Tough woods are resistant to shock loading.

Warping is the twisting, bending or bowing distortions shown by some woods. The method of sawing and curing affects the amount of warping, but some species are much more prone to warping than others.

Nail-holding resistance for hardwoods is greater than for softer woods. However, woods that are so hard that they tend to split when nailed, lose much of their holding ability. Preboring to 75 percent of the nail size avoids splitting.

The workability, such as sawing, shaping and nailing, is better for soft, low-density woods than for hardwoods, but usually they cannot be given a high polish.

Natural-decay resistance is particularly important in the warm, humid regions of east and southeast Africa. A wide range of resistance is shown by different species. However, for all species, the heartwood (the darker centre area of the tree) is more resistant than the sapwood (the lighter outer area of the tree). In addition to selection for natural-decay resistance, wood

preservatives should be considered where contact with the ground is likely.

Paint-holding ability differs between woods and, as a general rule, this should be considered when selecting materials.

Defects in wood

Defects to watch for when selecting timber are:

Brittle heart, found near the centre of many tropical trees, makes the wood break with a brittle fracture.

Wide growth rings indicate rapid growth resulting in thin-walled fibres with consequent loss of density and strength.

Fissures include checks, splits, shakes and resin pockets. Knots are the part of a branch that has become enclosed in a growing tree. Dead knots are often loose and therefore reduce the effective area that can take tensile stress. Knots can also deflect the fibres, thereby reducing strength in tension.

Decay, which results from moisture levels between 21 percent and 25 percent in the presence of air, reduces the strength of the wood and spoils its appearance.

Insect damage caused by borers or termites.

The fungi that feed on wood can be divided into three main categories: staining fungi, moulds and decay fungi. Most fungi thrive under moist conditions. Staining fungi live mainly on the sapwood but they may penetrate deeply into the wood and spoil the timber's attractive appearance. Moulds do not penetrate below the surface and do not seem to affect the strength of the wood, but they look unsightly. Decay fungi eat the cell walls of the wood. This causes the tree to lose its strength and often reduces it to a crumbling, rotting mass. These decay fungi never attack timber that is seasoned to a moisture content of less than 20 percent and kept well ventilated and dry.

The main species of borer that attack tropical woods are the pinhole borer and the *Lyctus*, or powderpost beetle. The pinhole borer attacks newly felled logs and sometimes standing trees. The attack can occur within hours of felling. The beetles do not normally continue to operate in seasoned timber. The powderpost beetle attacks seasoned tropical hardwoods – particularly those that contain starch on which the larvae feed. Timber is sometimes sprayed in the yard to protect it until it is transported.

Termites are normally of two kinds: the dry wood types that are able to fly and the subterranean type. Termites usually operate under cover and it is only after the first signs of damage appear that the full extent is realized. Flying termites usually enter the end-grain of untreated timber and build up a colony from inside, finally devouring all the interior wood and leaving only a thin skin behind. Some subterranean termites, white ants, operate from a central colony and travel in search of food. Their nests or hills sometimes achieve great size and house millions of ants. While no timber is completely immune to attack from ants or other

insects, there are great variations among the species. The density of the timber is no guide to its resistance to termite damage, as some of the lighter timbers are more immune than heavier varieties.

Weathering is the disintegration of wood caused by alternate shrinkage and swelling as a result of rain, rapid changes in temperature, humidity and the action of sunlight. Painting, when properly carried out, does much to prevent weathering. The paint must be of exterior quality, however, and applied according to the maker's instructions.

POLES AND TIMBER

Wooden poles

In farm buildings and rural structures, wood is often used in the form in which it has grown, i.e. round poles. In some areas where enough trees are grown on the farm or in local forests, wooden poles can be obtained at very low cost. These poles have many uses in small building construction, such as columns for the load-bearing structure, rafters, trusses and purlins. Sticks and thin poles are often used as wall material or as a framework in mud walls.

Where straight poles are selected for construction, it is as easy to work with round timber as with sawn timber. However, somewhat crooked poles can also be used if they are turned and twisted and put into positions in which the effects of the bends are unimportant.

Round timber can generally be considered stronger than sawn timber of the same section area because the fibres in round timber are intact. The pole is normally tapered and therefore the smallest section, the top end, must be used in the calculation of compressive and tensile strength.

A great number of species can be considered when selecting poles for construction, but only a limited number are available on the commercial market. Some species are more suitable for silviculture (growing on farms) and silvipasture (growing on pastures) than others, but must always be selected to suit local climatic and soil conditions. Generally there are several species suitable for each location that are fast and straight-growing, and produce strong and durable timber. In addition to building poles or timber, some species will produce fodder for animals, fruit, fuelwood, etc.

Many species of eucalyptus, from which gum poles are obtained, are very fast and straight-growing hardwoods. However, they warp and split easily. Dimensions suitable for building construction are obtained by harvesting the still immature trees. Gum poles provide a strong and durable material if chemically treated.

In high-altitude areas, several species of acacia produce good building poles. *Acacia melanoxylon* (Australian blackwood) is very resistant to attack by termites, but grows more slowly than eucalyptus. In low- to medium-altitude areas with sandy soils and low rainfall, *Casuarina* produces straight and durable poles.

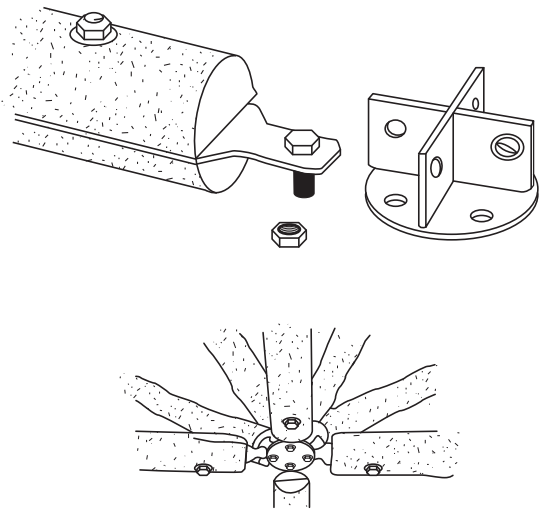


Figure 5.1 Pole connectors

Cedar posts for fencing are obtained by splitting large logs. The posts are durable and resistant to rot and attack by termites. They are also suitable for wall posts in the construction of buildings.

In coastal areas, mangrove poles are widely used for posts in walls and trusses in roofs.

Unprocessed round wood material can be joined by being nailed or tied with string or wire. A special connector has been developed to join round wood in trusses where several members may have to be connected at each point.

Sawing timber

The rate at which a tree grows varies with the season. The resulting growth rings of alternate high and low density form the grain in the sawn timber (lumber). The method of sawing has a considerable effect on the appearance, resistance to warping, shrinking, paint-holding ability and wear resistance of the final piece.

There are several methods of sawing a log into boards and planks, giving different relationships between the growth rings and the surface, i.e. more or less parallel to the surface in plain sawn timber and at right angles in radial sawn timber.

Radially sawn boards shrink less, are less liable to cup and twist and are easier to season. Unfortunately, cutting methods that produce a high proportion of quarter-sawn timber are wasteful and therefore only used to produce material for high-class joinery work (see Figures 5.2 and 5.3).

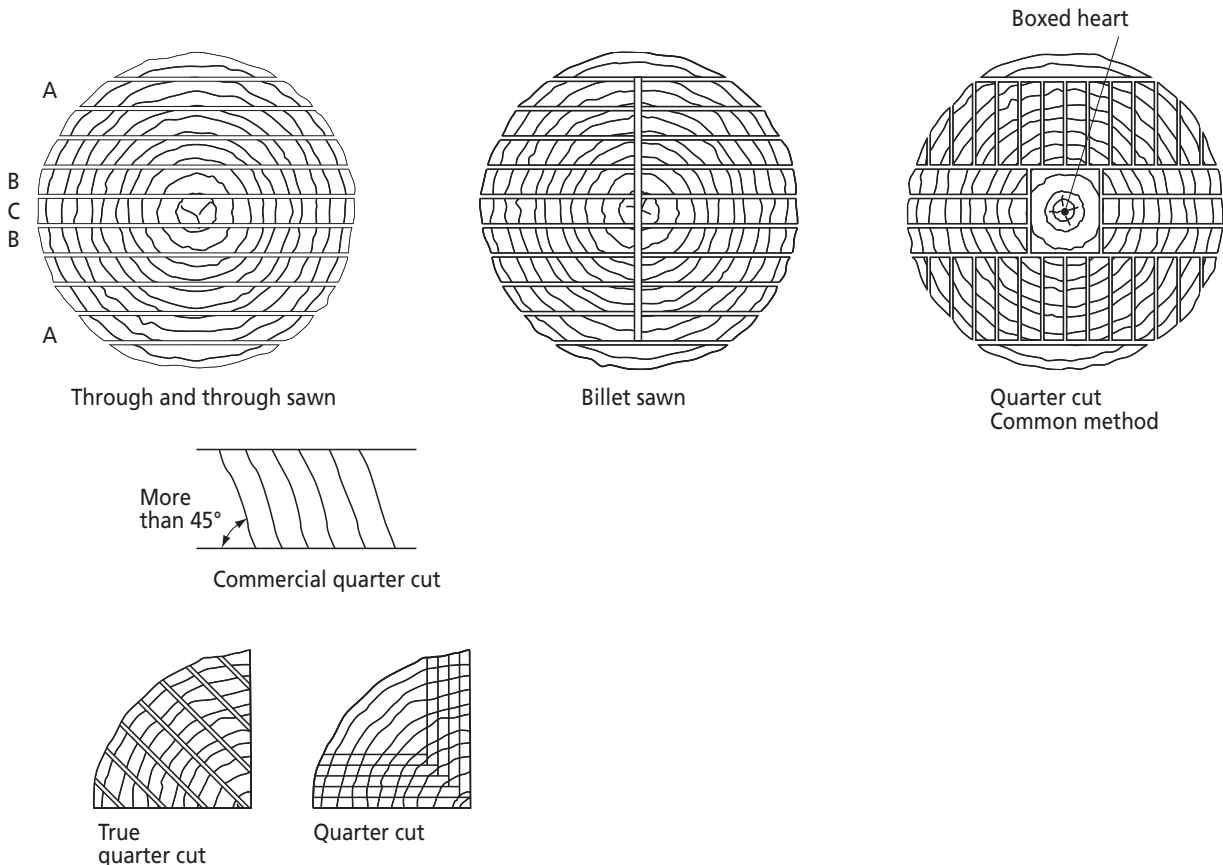


Figure 5.2 Methods of sawing timber

Offcuts

A tree is tapered and cylindrical, whereas boards and planks are rectangular. This results in the outer pieces with tapered edges and less than full dimensions throughout the length. Such pieces, called offcuts, can sometimes be obtained at low cost and used for rough building.

Seasoning of timber

The strength, stiffness and dimensional stability of wood are related to its moisture content. Hence, if wood is dried (seasoned) before use, not only can higher strength values be used in a design, but a more durable structure will result. In developing countries, most timber is not seasoned and it is sold in what is called its 'green' state.

Timber must be stacked, supported and sometimes restrained so as to minimize distortion during seasoning. If drying is too rapid, the outer parts, in particular the unprotected ends, shrink before the interior does, and this leads to surface checking and splitting, as well as the possible extension of ring and heart shakes. Some timber species are more difficult to season satisfactorily than others.

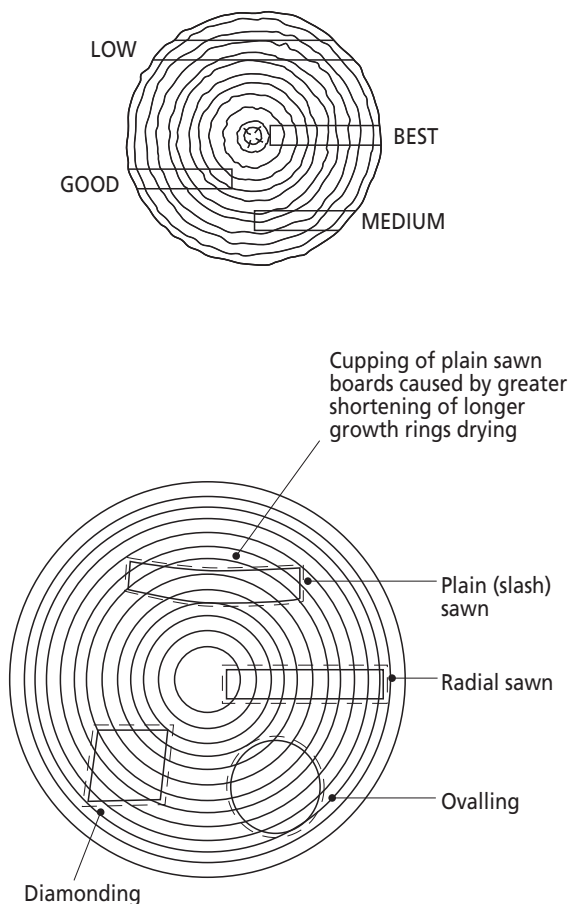


Figure 5.3 Effects of cupping and shrinkage of different methods of sawing

Air seasoning

Timber should be protected from rain and from the ground. It should therefore be stacked so that air can circulate freely around all surfaces, reducing the risk of twisting and cupping, as well as minimizing attacks by fungi and insects. In favourable conditions, thin softwoods can be air-seasoned in weeks but in unfavourable conditions some hardwoods require a year or more.

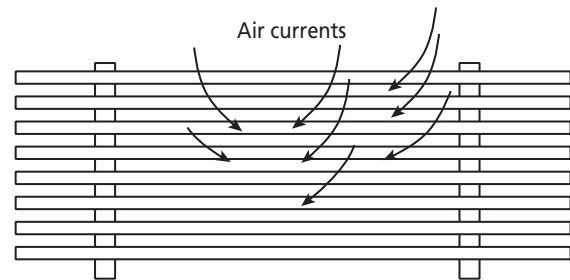


Figure 5.4 Air-drying of timber

Artificial seasoning

Artificial seasoning can be either moderate or rapid, depending on the temperature of the air injected into the chamber where the timber is piled, and on the rate at which the air is circulated and extracted from the chamber. This method is expensive and can only be applied on small quantities of timber. Timber can be artificially seasoned from the green condition, but often hot-air seasoning is used only at a later stage, after most of the moisture has been removed by air seasoning.

Smoke seasoning is a moderate process and involves placing the timber over a bonfire. It can take a month or two, depending on the size and type of wood being seasoned. This method is considered to be both a seasoning and a treatment method for timber. Presumably it protects the timber against pest attacks and increases durability. However, it is not very reliable and can lead to splitting of the timber because of the lack of control over the heat from the bonfire.

Care of seasoned timber

Timber should be protected from moisture on the building site. Close piling and covering with tarpaulins delays the absorption of atmospheric moisture, particularly in the interior of the pile.

Grades and sizes for timber

Grades

Grades are established by various government agencies. Even within a single country, more than one grading system may be in use. While the grade may not be important for small construction jobs, in large projects

where materials are bought by specification, it is important to indicate the required grade.

Grades that provide specific information in structural design are most useful. The grade standard established by the Kenya Bureau of Standards, shown in Table 5.1, is a good example.

TABLE 5.1
Timber grades and application

Grade	Applications
F	Furniture, high-class joinery
GJ	General joinery
S-75	Structural grade, having a value of 75% of basic stress
S-50	Structural grade, having a value of 50% of basic stress
C	A general construction grade for non-stressed construction
L	A low grade for low quality work

It is the S-75 and S-50 grades that are significant in building construction, as will be seen in later sections.

Sizes

Timber in eastern and southeastern Africa is available in a number of *Système Internationale* (SI) metric sizes, but not all are available in all localities. The dimension indicates actual size as sawn. Smoothing will reduce the timber to less than dimension size.

Timber measurement for trade

Even though timber is normally sold by length (running metre or foot), the price may be calculated per cubic metre when sold in large quantities. Basic lengths are between 1.8 metres and 6.3 metres, although pieces longer than about 5.1 metres are scarce and costly. Timber normally comes in running lengths, that is to say, not sorted by length.

Strength of wood

Building materials of any type that are under load are said to be subjected to fibre stress. The safe fibre stress for a material is the load that the material will safely

resist. Wood, like other materials, has safe fibre stress values given in N/mm² that have been determined by destructive testing to obtain first an ultimate stress, and then, by the use of various correction and safety factors, the safe fibre stress to be used for designing a structure.

Table 5.2 lists basic working-stress values for several types of loadings in five strength groups. Table 5.3 divides some representative species into the strength groups used in Table 5.2.

TABLE 5.3
Some representative timbers grouped according to strength and density

Group	Latin name	Common name
1	<i>Pinus radiata</i> (12 years)	Young pine
	<i>Polyscias kikuyuensis</i>	Mutati
2	<i>Cordia abyssinica</i>	Muringa
	<i>Pinus patula</i> (17 years)*	Pine
	<i>Pinus radiata</i> (17 years)	Pine
	<i>Cupressus lusitanica</i> **	East African cypress
3	<i>Podocarpus</i>	Podo/musengera
	<i>Juniperus procera</i>	African pencil cedar/mutarakwa
	<i>Ocotea usambarensis</i>	East African camphorwood/muzangi
	<i>Acacia melanoxylon</i>	Australian blackwood
	<i>Grevillia robusta</i>	Grevillea/silky oak
	<i>Vitex keniensis</i> *	Vitex/muhuru/meru oak
	<i>Pterocarpus angolensis</i>	Muninga
	<i>Khaya anthot heca</i>	African mahogany
4	<i>Eucalyptus regnans</i>	Australian mountain ash
	<i>Cassipourea malosana</i>	Pillarwood/musaisi
	<i>Dombeya goezenii</i>	Mueko
	<i>Eucalyptus saligna</i>	Saligna gum/Sydney blue gum
	<i>Premna maxima</i> *	
5	<i>Azelaia quanensis</i>	Azelaia
	<i>Olea hochstetteri</i>	East African olive/musharagi

* One group lower in compression perpendicular to grain

** One group lower in joint shear

There are dozens more tree species found in eastern and southern Africa, many of which are used only in very local areas. In order to obtain approximate working-stress data for these indigenous species, their densities may be used to place them in the proper group in Table 5.2. If the density is not known, a good

TABLE 5.2
Guide to basic working-stress values and modulus of elasticity for timber

Strength group	Strength rating	Density green	Density 12% MC	Maximum bending strength and tension parallel to grain	Modulus of elasticity	Maximum compression strength		Maximum shearing strength	
						Parallel to grain	Perpendicular to grain	Beams	Joints
		kg/m ³	kg/m ³	N/mm ²	kN/mm ²	N/mm ²	N/mm ²	N/mm ²	N/mm ²
1	Weak	< 520	< 400	10	4.0	2.5	0.6	1.0	0.4
2	Fairly strong	521–650	401–500	15	6.0	10.0	1.2	1.3	1.6
3	Strong	651–830	501–640	20	7.5	13.0	2.0	1.9	2.4
4	Very strong	831–1 040	641–800	30	9.0	20.0	3.2	2.4	3.5
5	Exceptionally strong	> 1 041	> 801	50	10.5	29.0	5.0	3.2	4.1

approximation can be found quite easily. A bucket, a graduated cylinder (millilitres) and an accurate scale for weighing a sample of the wood will be needed. The procedure is as follows:

1. Weigh the sample.
2. Place the bucket on a level surface and fill to the rim with water.
3. Carefully submerge the sample and then remove.
4. Refill the bucket from the graduated cylinder, noting the amount of water needed to refill the bucket.
5. Density = weight / volume = kg/m³
6. Place the species in the appropriate group using the appropriate density column for a green or dry sample (see Table 5.2, column 3 or 4).

Table 5.2 lists basic working-stress values. For design purposes, these should be adjusted for a number of different variables, including: grade, moisture content, duration of load, exposure and use of the structure.

Factors that affect timber strength include:

1. Sloping grain

As timber is a material with maximum mechanical properties in the direction of the grain, any load not applied in this direction will be resisted by lower strength and stiffness characteristics. The effect of a sloping grain on the strength of beams must be considered in the design. For example, lowering the grain slope from 1 in 20 to 1 in 8 reduces the strength of timber by over 50 percent. The reduction in strength resulting from the sloping grain (deviation) may be calculated from the relationship.

$$N = \frac{PQ}{P \sin \theta + Q \cos \theta} \quad (5.1)$$

where N is the strength at angle θ from the fibre direction; P is the strength parallel to the grain ($\theta = 0^\circ$) and Q is the strength perpendicular to the grain ($\theta = 90^\circ$).

2. Moisture

When moisture decreases below the fibre saturation point, it begins to affect the mechanical properties of wood. A decrease in moisture content increases the strength of wood because the cell walls become more compact. Cell walls are compacted because, with the loss of moisture, the mass of wood substance contained in a certain volume increases.

Given any mechanical property at standard values of moisture content, it is possible to predict the values of that property at any moisture content using Equation 5.2:

$$P_x = P_{12} \left(\frac{P_{12}}{P_g} \right)^e \left(\frac{M_x - 12}{M_p - 12} \right) \quad (5.2)$$

where P_x is the mechanical property at a given moisture content, for example, tensile strength at 8% MC; P_{12} is the property at 12% MC; P_g is the property value in green condition; M_x is the MC at which property is desired and M_p is the moisture content at the intersection of a horizontal line representing the strength of greenwood and an inclined line representing the logarithm of the strength/MC relationship for dry wood. It is usually taken to be 25% MC.

Owing to the effect of moisture, mechanical properties are determined in green condition (above fibre saturation) or in air-dry conditions (12% MC). This makes it possible to have comparable results. Correction factors are used to adjust moisture content to these two standard values.

3. Density

Density is a measure of the wood substance contained in a given volume. The substance of which wood is composed has a specific gravity of about 1.5, yet wood floats on water. This would indicate that wood contains numerous cell cavities and pores. As the strength of timber is a function of the wood material present, density is a good indicator of strength, and the relationship is given by Equation 5.3:

$$\frac{S}{S'} = \frac{g^n}{g'^n} \quad (5.3)$$

where S and S' are values of strength corresponding to densities g and g' and n is an index with a value in the range 1.25 to 2.50.

4. Temperature

The influence of temperature can be analyzed at two levels:

(i) Reversible effects

In general, the mechanical properties of wood decrease when heated and increase when cooled. At constant MC and below 150 °C, the relationship between mechanical properties and temperature is approximately linear. At temperatures below 100 °C, the immediate effect is essentially reversible, i.e. the property will return to the value at the original temperature if the change is rapid.

(ii) Irreversible effects

This occurs at high temperatures. This permanent effect results in degradation of the wood substance, which results in the loss of weight and strength. However, wood will not often reach the daily extremes in temperature of the air around it in ordinary construction. Long-term effects should therefore be based on the accumulated temperature experience of critical structural parts.

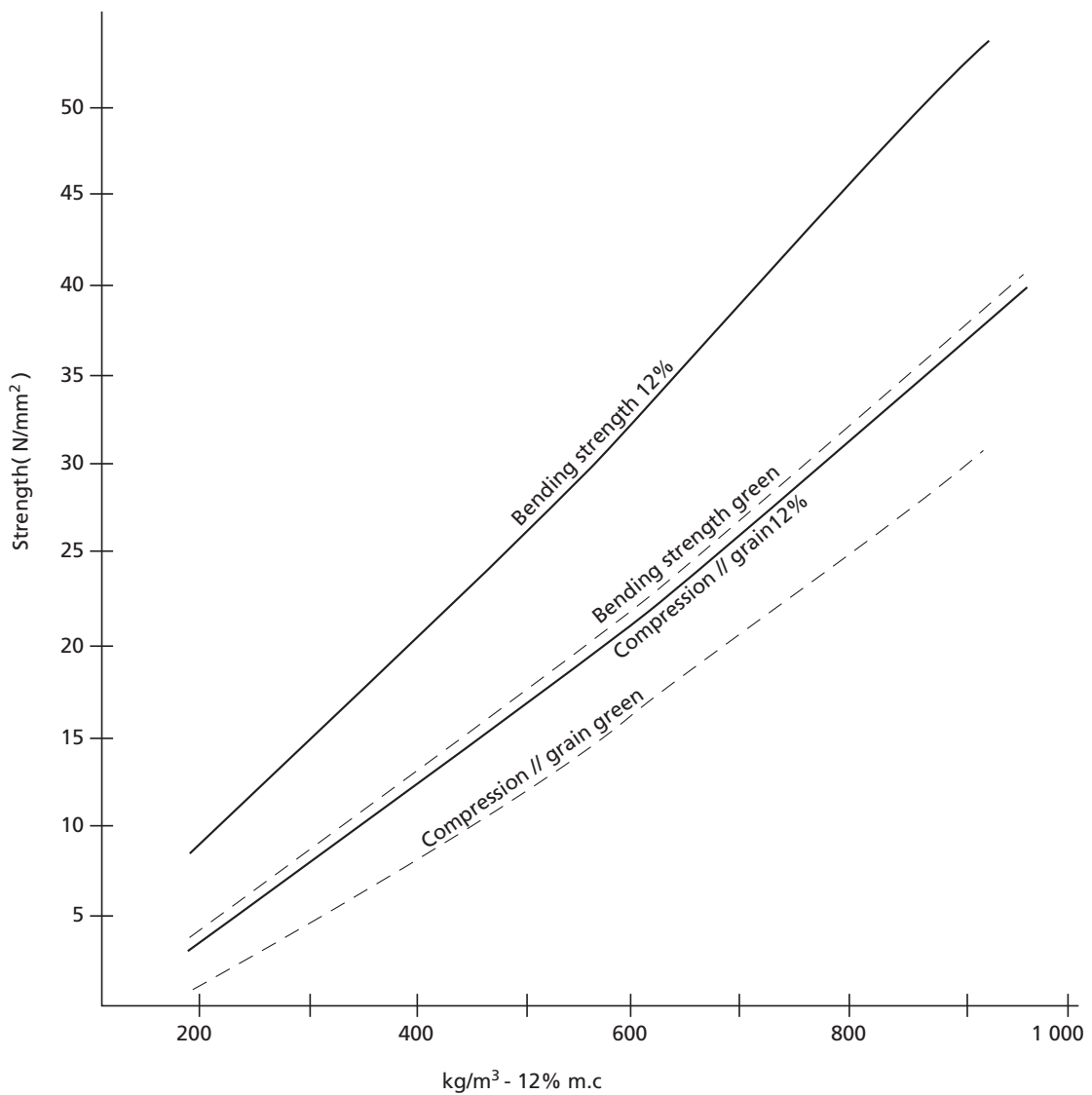
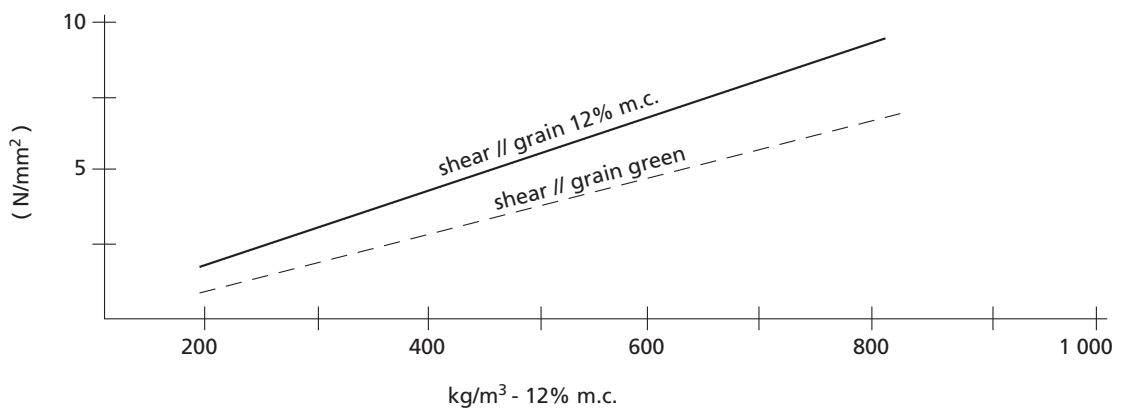


Figure 5.5 Basic working stresses for timber

(iii) Time under load

Static strength tests are typically conducted at a rate of loading to attain maximum load in about 5 minutes. Higher-strength values are obtained for wood loaded at more rapid rates, and lower values are obtained at slower rates. For example, the load required to produce failure in a wood member in 1 second is approximately 10 percent higher than that obtained in a standard strength test.

Grades

As an example, the Kenya Forest Department recommends that the following grades should be used:

Grade 1	75% of basic working-stress value
Grade 2	50% of basic working-stress value
Grade 3	35% of basic working-stress value
Grade 4	15% of basic working-stress value

Moisture

Table values need to be reduced when timber is installed green and will remain wet and uncured continuously. Use Figure 5.5 to find a suitable stress value for green wood corresponding to the dry value in Table 5.2.

Exposure

Timbers exposed to severe weather and decay hazards should be designed using a 25 percent stress-value decrease, particularly for columns and for bearing points.

TIMBER PRESERVATION

The main structural softwood timbers of eastern and southeastern Africa are not naturally durable. If used in conditions subject to fungal, insect or termite attack, they will fail after some time. To avoid this, the timber used in permanent structures should be treated with a preservative.

Effective preservation depends on the preservative and how it is applied. An effective preservative should be poisonous to fungi and insects, permanent, able to penetrate sufficiently, cheap and readily available. It should not corrode metal fastenings, nor should the timber be rendered more flammable by its use. It is sometimes desirable to have a preservative-treated surface that can be painted.

If a structure is correctly designed and built, and the moisture content of its timber does not exceed 20 percent, then a preservative treatment is generally unnecessary for protection against fungal attack. However, where the above conditions are not present, there will be a risk of fungal decay, and proper preservation is recommended.

Wood preservatives

Creosote is an effective general-purpose preservative that is cheap and widely used for exterior work and, to a lesser degree, indoors. It is a black to brownish

oil produced by the distillation of coal tar and, while it has many of the properties required of a preservative, it increases flammability, is subject to evaporation, and creosoted wood cannot be painted. It should not be used on interiors where the characteristic smell would be objectionable. Unfortunately, creosote has been found to be a carcinogen and must be used with caution.

Coal tar is not as effective a preservative as the creosote produced from it. Tar is less poisonous, does not penetrate the timber because of its viscosity, is blacker than creosote and is unsuitable for interior wood work.

Unleachable metallic salts are based mostly on copper salts. A combination of copper/chrome/arsenate is used. The copper and arsenical salts are toxic preservatives that are rendered non-leaching (cannot be washed out) by the chrome salt, which acts as a fixing agent. The timber is impregnated using a 'vacuum-pressure' process. Preservation by metallic salt is being used increasingly because the treated surfaces are odourless and can be painted or glazed.

Water-soluble preservatives are not satisfactory for exterior use as they are liable to be washed out of the timber by rain.

By contrast, they are very suitable for interior work as they are comparatively odourless and colourless and the timber can be painted.

Used engine oil can often be obtained free of charge, at least in small quantities. The oil contains many residual products from combustion and some of them act as preservatives, but it is not nearly as effective as commercial preservatives. It can be thinned with diesel fuel for better penetration. The combination of 40 litres of used engine oil and 1 litre of Dieldrin is a viable alternative in rural construction.

Methods of wood preservation

There are two categories of timber preservation methods:

Non-pressure methods

These are applicable for both green and dried timber (less than 30 percent MC) and include:

1. Soaking (steeping), used for small quantities of timber.
2. Hot and cold soaking: the tank with the preservative and timber is heated to nearly boiling point for 1-2 hours and allowed to cool. During the heating period, the air in the cells expands and some is expelled. When cooling, a partial vacuum develops in the cells and liquid is absorbed.
3. Steam and cold quenching.
4. Superficial methods such as painting and spraying.

To make non-pressure methods more effective, storage in a closed environment is recommended.

Pressure methods

The treatment in pressure processes is carried out in steel cylinders, or 'retorts'. Most units conform to size limits of 2–3 metres in diameter and up to 46 metres or more in length, and are built to withstand working pressures of up to 1 720 kPa. The wood is loaded on special tram cars and moved into the retort, which is then closed and filled with the preservative.

Pressure forces preservatives into the wood until the desired amount has been absorbed. Three processes – full-cell, modified full-cell and empty-cell – are commonly used. These processes are distinguished by the sequence in which vacuum and pressure are applied to the retort. The terms 'empty' and 'full' refer to the level of preservative retained in the wood cells.

The full-cell process achieves a high level of preservative retention in the wood cells, but less penetration than the empty-cell process. On the other hand, the empty-cell process achieves relatively deep penetration with less preservative retention than the full-cell process.

1. Full-cell process

The Bethel full-cell process is generally used with water-based preservatives, especially for timber that is difficult to treat and also requires high retention. The full-cell process steps are listed below:

- The wood is sealed in the treatment cylinder and an initial vacuum is applied for approximately 30 minutes to remove as much air as possible from the wood and from the cylinder.
- The preservative, either heated or at ambient temperature depending on the system, enters the cylinder without breaking the vacuum.
- After the cylinder is filled, the cylinder is pressurized until no more preservative will enter the wood, or until the desired preservative retention is obtained.
- At the end of the pressure period, the pressure is released and the preservative is removed from the cylinder.
- A final vacuum may be applied to remove excess preservative that would otherwise drip from the wood.

2. Empty-cell process

The empty-cell process results in deep penetration of the preservative with a relatively low net preservative retention level. If oil preservatives are used, the empty-cell process will most probably be used, provided it will yield the desired retention level. The Rueping process and the Lowry process are the two most commonly used empty-cell processes. Both use compressed air to drive out a portion of the preservative absorbed during the pressure period.

(i) Rueping process

In the Rueping process, compressed air is forced into the treatment cylinder containing the charge

of wood, in order to fill the wood cells with air prior to preservative injection. Pressurization times vary with wood species. For some species, only a few minutes of pressurization are required, while more resistant species may require pressure periods of 30–60 minutes. Air pressures used typically range from 172 kPa to 690 kPa, depending on the net preservative retention desired and the resistance of the wood.

After the initial pressurization period, preservative is pumped into the cylinder. As the preservative enters the treatment cylinder, the air escapes into an equalizing, or Rueping, tank at a rate that maintains the pressure within the cylinder. When the treatment cylinder is filled with preservative, the pressure is raised above the initial air pressure and maintained until the wood will take no more preservative, or until enough has been absorbed to leave the desired preservative retention level after the final vacuum. After the pressure period, the preservative is removed from the cylinder and surplus preservative is removed from the wood with a final vacuum. This final vacuum may recover 20–60 percent of the gross amount of preservative injected. The retort then is unloaded, and the treated wood stored.

(ii) Lowry process

The Lowry process is an empty-cell process without the initial air pressure. Preservative is pumped into the treatment cylinder without either an initial air pressurization or vacuum, trapping the air that is already in the wood. After the cylinder is filled with the preservative, pressure is applied and the remainder of the process is identical to the Rueping process. The advantage of the Lowry process is that full-cell equipment can be used without the accessories required for the Rueping process, such as an air compressor, an extra tank for the preservative, or a pump to force the preservative into the cylinder against the air pressure. However, both processes are used widely and successfully.

MANUFACTURED BUILDING BOARDS

There are a number of building boards made from wood veneers or the waste products of the timber industry that are convenient and economical materials to use in building construction. In general, they offer excellent bracing for the building frame, together with labour savings because they are available in large sizes requiring a minimum of fitting.

Some manufactured boards are designed with specific characteristics, such as fire resistance, ease of cleaning, high insulation value or resistance to weathering.

Plywood

Plywood is produced by gluing together three to seven veneers that have been peeled from logs. The grain of each successive veneer is angled at 90° from the previous one, resulting in a board that has considerable strength and rigidity in all directions. Waterproof glue is most commonly used, giving a product that is highly resistant to moisture. Waterproof glue panels should always be chosen for farm buildings. As the wood itself is not waterproof, the panels are still subject to swelling and shrinkage from moisture changes.

Grades of plywood

Plywood is generally given four to five grades, based on the appearance of the surface veneers. Each panel has a double-letter grade to indicate the grade of the face of the panel and the back of the panel. The top-grade surface is generally free enough from defects to be finished naturally, while the second-best grade is good for painting. Lower grades are used for structural applications where appearance is of little importance. Theoretically, between 10 and 15 different grade combinations are possible. In practice, only a few tend to be available from timber merchants.

Sizes of plywood panel

As an example of a standard used in the region, the Kenya Bureau of Standards provides a standard with 12 panel sizes and 9 different thicknesses. Combining grades, panel sizes and thicknesses, there are numerous permutations, but only a few will be manufactured. The most common panel size is 2 400 by 1 200 mm, in thicknesses of 9 mm, 12 mm, 15 mm and 19 mm.

Plywood for structural members

Plywood panels are made from many different species of wood and have a wide range of strengths and stiffnesses. Specific strength characteristics for plywood can be provided by either the manufacturer or a trade association that publishes grade standards to which manufacturers adhere. In general, plywood panels should equal or exceed the strengths shown in Table 5.4.

TABLE 5.4

Safe spans for plywood panels parallel to the grain of the plys

Thickness	Load	
	167 Pa (170 kg/m ²)	4 790 Pa (490 kg/m ²)
9 mm	400 mm	-
12 mm	600 mm	-
15 mm	770 mm	300 mm
19 mm	925 mm	400 mm

Other manufactured boards

Blockboards and laminboards are made of strips of wood between 8 mm and 25 mm wide, glued together and covered with one or more veneers on each side. At least one pair of corresponding veneers will have the grain at right angles to the grain of the core. If the finish grain is to run parallel with the core, there must be at least two veneers per side.

The same 12 panel sizes listed for plywood are also listed for blockboard. However, the thicknesses are greater, ranging from 15 mm to 50 mm, in 5 mm increments. The same appearance, grades and types of glue listed for plywood also apply to blockboards. Blockboard panels are often used for doors.

Particleboards are formed by pressing chips or flakes of wood between pairs of heated platens so that the particles lie in random fashion with their longer dimensions parallel to the surface of the board. The chips are bonded with thermosetting synthetic resins. Depending on the size of the particles, these boards are variously known as *particleboard*, *chipboard* or *waferboard*. Strength and rigidity generally increase with density, but that alone is not a measure of quality, as moisture resistance varies considerably and most particleboards should not be used in moist locations.

Softboards are made from uncompressed woodchips or sugarcane fibres mixed with water and glue or resins, giving a density of less than 350 kg/m³. They are inexpensive and can be used for wall or ceiling surfaces that are not subject to high-moisture conditions.

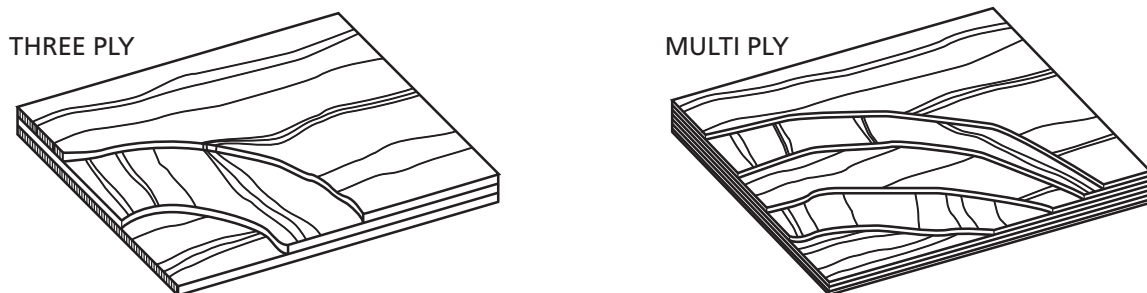


Figure 5.6 Plywood

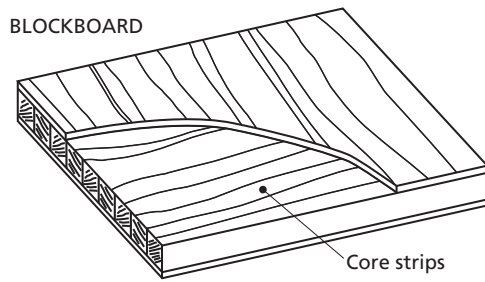


Figure 5.7a Blockboard

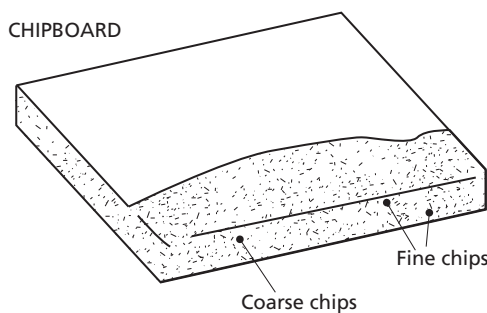


Figure 5.7b Particleboard

Softboards have little resistance to rupture and must be supported frequently (300–400 mm) when installed. The 2 400 mm by 1 200 mm size is most common in thicknesses of 6.4 mm to 25 mm.

Mediumboards, with a density ranging from 350 kg/m³ to 800 kg/m³, are used for panelling, in particular those with a density at the higher end of the range. The most common size is 2 400 mm by 1 200 mm, and thicknesses range from 6.4 mm to 19.0 mm.

Hardboards are made of wood fibres compressed to more than 800 kg/m³. They are usually smooth on one surface and textured on the other. The most common size is 2 400 mm by 1 200 mm size in thicknesses of 3–12.7 mm. An oil-treated grade labelled 'tempered' has good resistance to moisture.

OTHER WOOD PRODUCTS

Woodwool slabs consist of long wood shavings, mixed with cement, and formed into slabs 25–100 mm thick with a high proportion of thermal insulating voids. Although combustible, they are not easily ignited and provide good sound absorption.

Shingles are cut from clear rot-free timber logs. They are made about 2 mm thick at the top end and 10 mm thick at the bottom, and usually about 400 mm long. Some woods need treatment with preservatives before being used as roofing shingles, whereas others will last 10–15 years without treatment.

Sawdust is a by-product from sawmills. It is a good natural insulating material, and also a good bedding material for use in animal housing.

Wicker made from shrubs, bushes and trees is used either directly, for fencing or wall cladding, or sealed by smearing on mud, plaster, etc.

OTHER ORGANIC MATERIALS

Bamboo

Bamboo is a perennial grass with over 550 species, found in tropical, subtropical and temperate zones. It contains a large percentage of fibre, which has high-tensile, bending and straining capacity.

However, bamboos have some shortcomings that limit their application. The low durability of bamboo is one of its most serious defects, along with its flammability and tendency to split easily. This usually prevents the use of nails. Cutting a notch or a mortise in a bamboo drastically reduces its ultimate strength. The remedy is the use of nodes as places of support and joints, and the use of lashing materials (strings) in place of nails. Dry bamboo is extremely susceptible to fire, but it can be covered or treated with a fire-retardant material.

The strength properties of bamboo vary widely with species, growing conditions, position within the culm, seasoning and moisture content. Generally bamboo is as strong as timber in compression and very much stronger in tension. However, bamboo is weak in shear, with only about 8 percent of compressive strength, whereas timber normally has 20–30 percent. It is used mainly in building construction, for wall poles, frames, roof construction, roofing and water pipes and, after splitting, to form flattened boards or woven wall, floor and ceiling panels.

New stalks of bamboo are formed annually in clumps growing out of the spreading roots. The individual bamboo shoots complete their growth within a period of 4–6 months in the first growing season. A strengthening process takes place during the subsequent 2–3 years, and the culm reaches maturity after the fifth or sixth year, or even later depending on the species. It must be cut before blooming because it loses its resistance and dies after blooming. Some bamboos grow to 35 metres in height, while others are no more than shrubs. Diameters vary from 10 mm to 300 mm.

Bamboo without proper seasoning and preservative treatment will rot and be attacked by insects, particularly if used in moist locations, such as in earth foundations.

Bamboo joints

As nailing causes splitting and notching, drastically reducing the strength of a bamboo culm, lashes are generally used as binding elements for framing. They may be split from the bamboo itself, or made from vines, reeds or the bark of certain trees. Soft galvanized wire is also used for binding. Bamboo can be kept from splitting when bending by boiling or steaming it first, then bending it while hot.

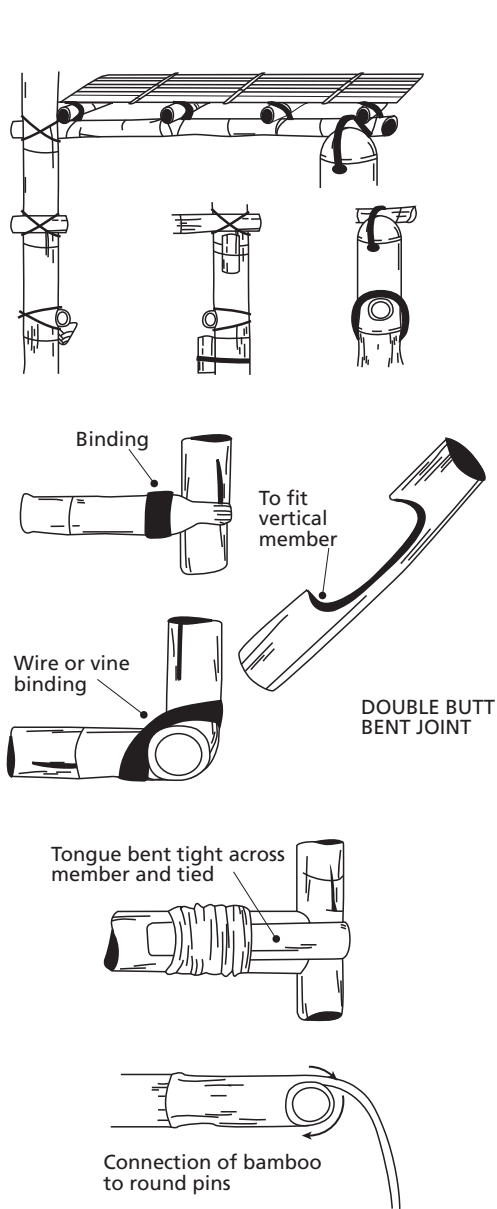


Figure 5.8 Lashing bamboo joints

Several methods can be used for splitting bamboo culms. The edges of the strips can be razor sharp and should be handled carefully (see Figure 5.9).

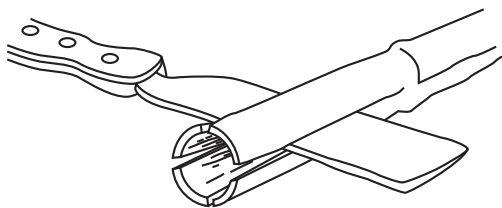


Figure 5.9a Make four cuts in the upper end of the culm with a splitting knife

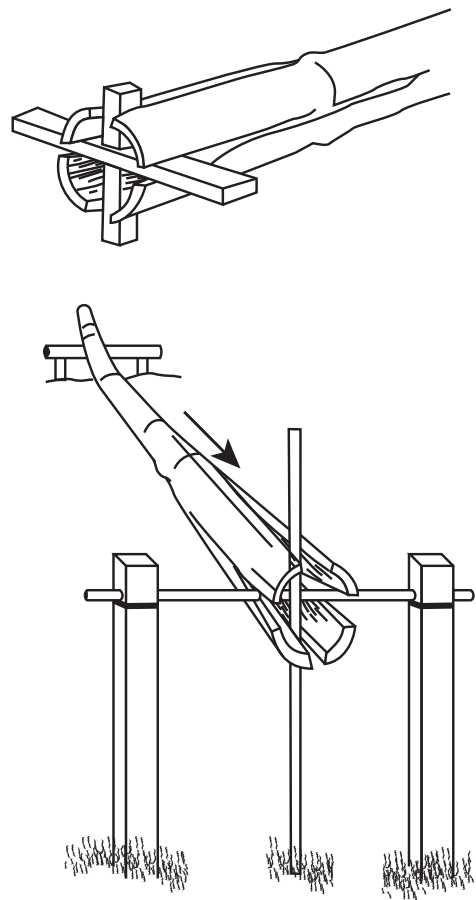


Figure 5.9b Split the culm the rest of the way by driving a hardwood cross along the cuts

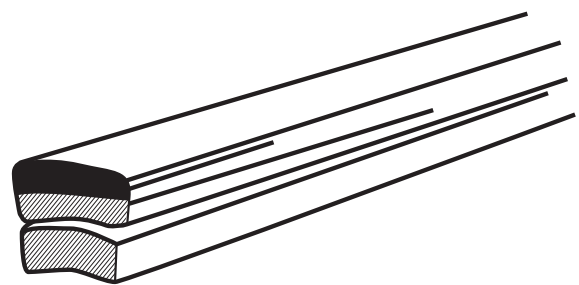


Figure 5.9c Use a knife to split the harder outer strip from the soft, pithy inner strip, which is usually discarded

Bamboo preservation

Immediately after cutting, the freshly cut lower end of the culm should be dusted with insecticide. The bamboo is then air seasoned for 4–8 weeks, depending on the ambient humidity. Bamboo should be stacked well off the ground so that air can circulate freely. When the culms have dried as much as conditions permit,

they should be trimmed and all cut surfaces should be dusted with insecticide immediately. The seasoning is finished in a well ventilated shelter where the culms are protected from rain and dew.

If the bamboo is to be stored for a long time, stacks and storage shelves should be treated with an insecticide every 6 months. Bamboo that has already been attacked by insects, fungus or rot should never be used for construction. Culms that have fissures, cracks or cuts in the surface should also be rejected.

Natural fibres

Natural fibres have been used for building since ancient times. Fibrous materials can be used by themselves as roofing material or for walls and mats. Natural fibres can also be combined with hydraulic-setting binders to make various types of roofing board, wall board, block and shingle. Animal hair is often used for reinforcing plaster.

Thatch

Thatch, whether made of grass, reeds, palm or banana leaves, is susceptible to decay caused by fungi and insects, and to destruction by fire. Preservative treatment is desirable but expensive. A treatment combining copper sulphate, sodium chromate and acetic acid reduces attack by rot and may considerably increase the life span of a thatched roof (see Chapter 8).

Grass

The use of thatched roofs is common in many countries, and suitable grass can be found almost everywhere. When well laid and maintained, it can last for 10–20 years or longer.

A good-quality thatching grass must be fibrous and tough, with a minimum length of 1 metre. It should also have thin stems without hollows, a low content of easily digestible nutrients and the ability to withstand repeated wetting without decaying.

An annual treatment with a mixture of the following chemicals will improve the fire-resistance of a thatched roof, and also give some protection against decay: 14 kg ammonium sulphate, 7 kg ammonium carbonate, 3.5 kg borax, 3.5 kg boric acid, 7 kg alum and 200 kg water.

Reeds

Reeds must be dry before use as a building material, and can be impregnated or sprayed with copper-chrome preservatives to prevent rotting. Ammonium phosphate and ammonium sulphate are used to protect the reeds against fire (see Chapter 8).

Reeds can be woven into mats for use as wall or ceiling panels, shade roofs, etc. The mats can be plastered easily. In tropical areas, thatch from untreated reeds may last only 1 year but, if well laid, treated and maintained, it can last 5–10 years.

Sisal stems

Before dying, at 7–12 years of age, the sisal plant forms a pole shoot to carry the flowers. The pole may reach a height of 6 metres or more and has a fibrous circumference, which makes it tough, but the inner parts are quite soft. Sisal poles have limited structural strength and durability, but are sometimes used for wall cladding in semi-open structures, such as maize cribs. The poles can be split and are joined in the same way as bamboo.

Sisal fibre

Sisal fibre is one of the strongest natural fibres. It has traditionally been used as reinforcement in gypsum plaster sheets. Sisal fibres have the ability to withstand degradation from bacteriological attack better than other organic fibres, but are attacked by the alkalinity of cement. However, research has been carried out to make sisal fibre, like other natural fibre composites, into a reliable cement reinforcement for long-term use in exposed situations. Refer to the section on fibre-reinforced concrete.

Coir waste

Coir is a by-product of coconuts. The husk is used for making coir mats, cushions and as fuel. It can be mixed with cement, glue or resins, either to produce low-density boards with good insulating and sound-absorption properties, or to be compressed to make building boards. It is also used as reinforcement in cement for making roofing sheets.

Elephant grass

Elephant grass is a tall plant similar to bamboo, but with the difference that the stem is not hollow. The fibres of the grass can be used to partly or wholly replace the asbestos in net and corrugated roofing sheets. However, the sheets are more brittle and have a slightly lower strength than asbestos-cement sheets.

Straw

Baled straw, if supported by a framework of wooden poles, can be used to construct temporary walls. Straw has also been used as raw material for manufactured building boards. Straw and split bamboo can be cement-plastered to permanent structures, such as vaults and domes, at low cost.

NATURAL STONE PRODUCTS

Natural stones are strong in compression and are generally extremely durable, although deterioration may result from the action of soluble salts, wetting and drying, or thermal movement. According to the manner of their geological formation, all stones used in building fall into one of three classes: *igneous*, *sedimentary* or *metamorphic*.

Igneous rocks are mostly very hard and difficult to cut to size and shape. However, they are very durable.

Sedimentary rocks, such as sandstone and limestone, are used extensively for building. They are not difficult to work, yet are quite durable. Coral stone is found in coastal areas, where chips or small stones are used in mud walls. Coral stone is also cut into blocks and, although not very strong, can be used in foundations and walls in multistorey houses.

Metamorphic stones consist of older stones that have been subjected to intense heat and pressure, causing structural change. Thus clay becomes slate, limestone becomes marble and sandstone becomes quartzite. Slate develops cleavage planes during formation. Roofing slates are split along these planes. They make very durable roof surfaces, but require strong frames because of their weight.

At the building site, the stones can be dressed to obtain a smooth surface. Often only the side(s) that will be visible are dressed.

Stones may also be used in the forms and sizes in which they naturally occur, and be embedded in mortar for foundation and wall construction. Stones are also crushed and sorted for size and use. Small crushed stones are used in making concrete. Large sizes are used as hardcore for filling purposes.

EARTH AS A BUILDING MATERIAL

Earth is one of the oldest materials used for building construction in rural areas. The advantages of earth as a building material are:

1. It is resistant to fire.
2. It is cheaper than most alternative wall materials, and is readily available at most building sites.
3. It has a very high thermal capacity, which enables it to keep the inside of a building cool when it is hot outside and *vice versa*.
4. It absorbs noise well.
5. It is easy to work using simple tools and skills.

These qualities encourage and facilitate self-help and community participation in house building.

Despite its good qualities, earth has the following drawbacks as a building material:

1. It has low resistance to water penetration, resulting in crumbling and structural failure.
2. It has a very high shrinkage/swelling ratio, resulting in major structural cracks when exposed to changing weather conditions.
3. It has low resistance to abrasion, and requires frequent repairs and maintenance when used in building construction.

However, there are several ways to overcome most of these weaknesses that make earth a suitable building material for many purposes.

Soil classification

Soil and earth are synonymous when used in relation to building construction. The term 'soil' refers to

subsoil, and should not be confused with the geological or agricultural definition of soil, which includes the weathered organic material in topsoil. Topsoil is generally removed before any engineering works are carried out, or before soil is excavated for use as a building material. Mud is the mixture of one or more types of soil with water.

There are several ways in which soil may be classified: by geological origin, by mineral content (chemical composition), by particle size or by consistency (mainly related to its moisture content).

Particle size

Soils are grouped and named according to their particle size, as shown in Table 5.5.

Grading

The soil materials in Table 5.6 seldom occur separately, and this necessitates a further classification according to the percentage of each contained in the soil. This is shown in the soil classification triangle, which shows, for example, that a sandy clay loam is defined as soil that contains 50–80 percent sand, 0–30 percent silt and 20–30 percent clay.

Only a few mixes can be used successfully for building construction in the state in which they are found. However, many mixes can be improved to make good building material by correcting the mix and/or adding stabilizers.

The clay fraction is of major importance in earth construction because it binds the larger particles together. However, soils with more than 30 percent clay tend to have very high shrinkage/swelling ratios which, together with their tendency to absorb moisture, may result in major cracks in the end product. High-clay soils require very high proportions of stabilizer or a combination of stabilizers.

Some soils produce unpredictable results, caused by undesirable chemical reactions with the stabilizer. Black cotton soil, a very dark coloured clay, is an example of such a soil. Generally speaking, soils that are good for building construction purposes are characterized by good grading, i.e. they contain a mix of different-sized particles similar to the ratios in Table 5.6, where all voids between larger particles are filled by smaller ones. Depending on use, the maximum size of coarse particles should be 4–20 mm.

Laterite soils, which are widely distributed throughout the tropical and subtropical regions, generally give very good results, especially if stabilized with cement or lime. Laterite soils are best described as highly weathered tropical soils containing varying proportions of iron and aluminium oxides, which are present in the form of clay minerals, usually together with large amounts of quartz. Their colours range from ochre, through red, brown and violet to black. The darker the soil, the harder, heavier and more resistant it is to moisture. Some laterites harden on exposure to air.

TABLE 5.5
Classification of soil particles

Material	Size of particles	Means of field identification
Gravel	60–2 mm	Coarse pieces of rock, which are round, flat or angular.
Sand	2–0.06 mm	Sand breaks down completely when dry; the particles are visible to the naked eye and gritty to the touch.
Silt	0.06–0.002 mm	Particles are not visible to the naked eye, but slightly gritty to the touch. Moist lumps can be moulded but not rolled into threads. Dry lumps are fairly easy to powder.
Clay	Smaller than 0.002 mm	Smooth and greasy to the touch. Holds together when dry and is sticky when moist.
Organic	Up to several centimetres	Spongy or stringy appearance. The organic matter is fibrous, rotten or partially rotten, several centimetres deep, with an odour of wet, decaying wood.

Gravel, sand and silt are sometimes subdivided into coarse, medium and fine fractions.

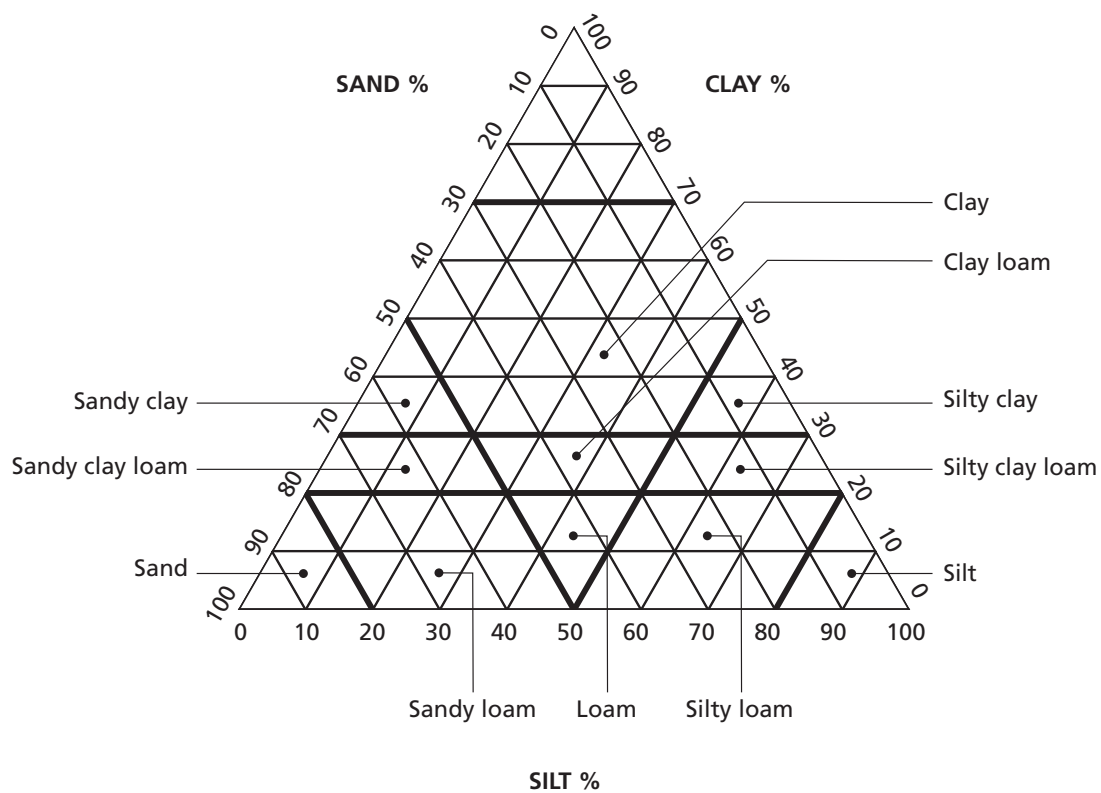


Figure 5.10 Soil-classification triangle

TABLE 5.6
Soil gradings suitable for construction

Use	Clay (%)	Silt (%)	Clay & Silt (%)	Sand (%)	Gravel (%)	Sand & Gravel (%)	Cobble (%)	Organic Matter (%)	Soluble salts (%)
Rammed-earth walls	5–20	10–30	15–35	35–80	0–30	50–80	0–10	0–0.3	0–1.0
Pressed-soil blocks	5–25	15–35	20–40	40–80	0–20	60–80	-	0–0.3	0–1.0
Mud bricks (adobe)	10–30	10–40	20–50	50–80	-	50–80	-	0–0.3	0–1.0
Ideal, general-purpose mix	15	20	35	60	5	65	-	0	0

If the soil at hand is not suitable, it may be improved by adding clay or sand. The best soils for construction are sandy loam and sandy clay loam. Sandy clay gives fair results if stabilized.

Plasticity index

Clays vary greatly in their physical and chemical characteristics. Although the extremely fine particles make it very difficult to investigate their properties, some can be conveniently expressed in terms of plasticity using standard tests.

Depending on the amount of moisture it contains, a soil may be liquid, plastic, semisolid or solid. As a soil dries, the moisture content decreases, as does the volume of the sample. With very high moisture content, the soil will flow under its own weight and is said to be liquid. At the liquid limit, the moisture content has fallen to the extent that the soil ceases to flow and becomes plastic; it is continuously deformed when a force is applied, but retains its new shape when the force is removed.

A further reduction of the moisture content will eventually cause the soil to crumble under load and not deform plastically. The moisture content at this point is known as the 'plastic limit'. The numerical difference between the moisture content at the liquid limit and at the plastic limit is called the 'plasticity index'. Both the liquid limit and the plasticity index are affected by the amount of clay and the type of clay minerals present.

A high liquid limit and plasticity index indicates a soil that has great affinity for water and will therefore be more susceptible to moisture movements, which can lead to cracks.

Example 5.1

The following index properties were determined for two soils X and Y.

Property	X	Y
Liquid limit	0.62	0.34
Plastic limit	0.26	0.19

Determine the plasticity index of X and Y.

Solution

The plasticity index is the range of moisture content over which the soil remains plastic. The bigger this range, the greater the proportion of clay particles.

For soil X, plasticity index = liquid limit - plastic limit = 0.62 - 0.26 = 0.36.

For soil Y, plasticity index = 0.34 - 0.19 = 0.15

Soil X contains more clay particles.

Soil-testing methods

As indicated above, some soils are more suitable for building material than others. It is therefore essential to have a means of identifying different types of soil. There are a number of methods, ranging from laboratory tests to simple field tests. Laboratory soil tests are recommended for the production of buildings on a large scale (i.e. several houses).

As soils can vary widely within small areas, samples of the soil to be tested must be taken from exactly the area where soil is going to be dug for the construction. Soil samples should be collected from several places distributed over the whole of the selected area. First remove the topsoil (any dark soil with roots and plants in it), which is usually less than 60 cm. Then dig a pit to a depth of 1.5 metres, and collect soil for the sample at various depths between 0.8 metres and 1.5 metres. The total volume required for a simple field test is about a bucketful, whereas a complete laboratory test requires about 50 kg. Mix the sample thoroughly, dry it in the sun, break up any lumps and pass it through a 5–10 mm screen.

In the laboratory, the classification by particle size involves sieving the coarse-grained material (sand and gravel) and sedimentation for fine-grained material (silt and clay). The plasticity index is determined using the Atterberg limit test.

Soil tests will only give an indication of the suitability of the soil for construction purposes and the type and amount of stabilizer to be used. However, other properties, such as workability and behaviour during compaction, may eliminate an otherwise suitable soil. Soil tests should therefore be combined with tests on the finished products, at least where high strength and durability are required for the design and use.

For small projects, a simple sedimentation test combined with a bar shrinkage test normally gives enough information about the proportions of various particle sizes and the plastic properties of the soil.

Simple sedimentation test

This test gives an impression of the grading of the soil and allows the combined silt and clay content to be calculated. Take a large, clear glass bottle or jar with a flat bottom and fill it one-third full with soil from the sample. Add water until the bottle is two-thirds full. Two teaspoons of salt may be added to dissolve the soil more rapidly. Close the bottle, shake it vigorously, and allow the contents to settle for 1 hour. Shake it again and let it settle for at least 8 hours.

The soil sample should now show a fairly distinct line, below which the individual particles can be seen with the naked eye. Measure the thickness of the combined silt and clay layer above the line, and calculate it as a percentage of the total height of the soil sample.

The test tends to give a lower figure than laboratory tests, as a result of some silt and clay being trapped in the sand, and because some material remains suspended in the water above the sample.

The main disadvantage with this test is that the silt and clay fractions cannot be determined separately. As silt behaves differently from clay, this could result in mistaken conclusions about the soil's suitability for stabilization and as a building material.

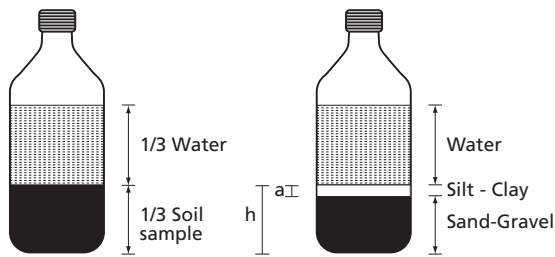


Figure 5.11 Simple sedimentation

Bar shrinkage test

This test gives an indication of the plasticity index of the soil, because the shrinkage ratio of the soil when dried in its plastic state is related to its plasticity index.

A wooden or metal box without a top and with a square cross-section of 30–40 mm per side and a length of 500–600 mm, is filled with soil from the sample (see Figure 5.12). Before filling, the soil should be mixed with water to slightly more than the liquid limit. The consistency is right when a V-shaped groove cut in the soil will close after about five taps on the box. Grease or oil the box, fill with the soil and compact it well, paying special attention to filling the corners. Smooth the surface by scraping off the excess soil. Place the box in the shade for 7 days. The drying can be hastened by placing the box at room temperature for 1 day, and then in an oven at 110 °C until the soil is dry.

If, after drying, the soil bar has more than three large cracks in addition to the end gaps the soil is not suitable. Measure the shrinkage ratio by pushing the dried sample to one end of the box and calculate the length of the gap as a percentage of the length of the box. The soil is not suitable for stabilization if the shrinkage ratio is more than 10 percent, i.e. a gap of 60 mm in a 600 mm long box. The higher the shrinkage ratio, the more stabilizer has to be used. The shrinkage ratio is calculated as follows:

Shrinkage ratio =

$$\frac{(\text{Length of wet bar}) - (\text{Length of dried bar})}{\text{Length of wet bar}} \times 100 \quad (5.4)$$

Soil stabilization

The main weakness of earth as a building material is its low resistance to water. While overhanging eaves and verandas help considerably, tropical rains of any intensity can damage unprotected walls. Due to the clay fraction, which is necessary for cohesion, walls built of unstabilized soil will swell on taking up water, and shrink on drying. This may lead to severe cracking and difficulty in making protective renderings adhere to the wall.

However, the quality as a building material of nearly any inorganic soil can be improved considerably by the addition of a suitable amount of the correct stabilizer. The aim of soil stabilization is to increase the soil's resistance to destructive weather conditions, in one or more of the following ways:

1. By cementing the soil particles together, leading to increased strength and cohesion.
2. By reducing the movements (shrinkage and swelling) of the soil when its moisture content varies according to weather conditions.
3. By making the soil waterproof, or at least less permeable to moisture.

A great number of substances may be used for soil stabilization. Owing to the many different kinds of soil and types of stabilizer, there is no single solution for all cases. It is up to the builder to make trial blocks with various amounts and types of stabilizer.

Stabilizers in common use are:

- sand or clay;
- portland cement;
- lime;
- bitumen;

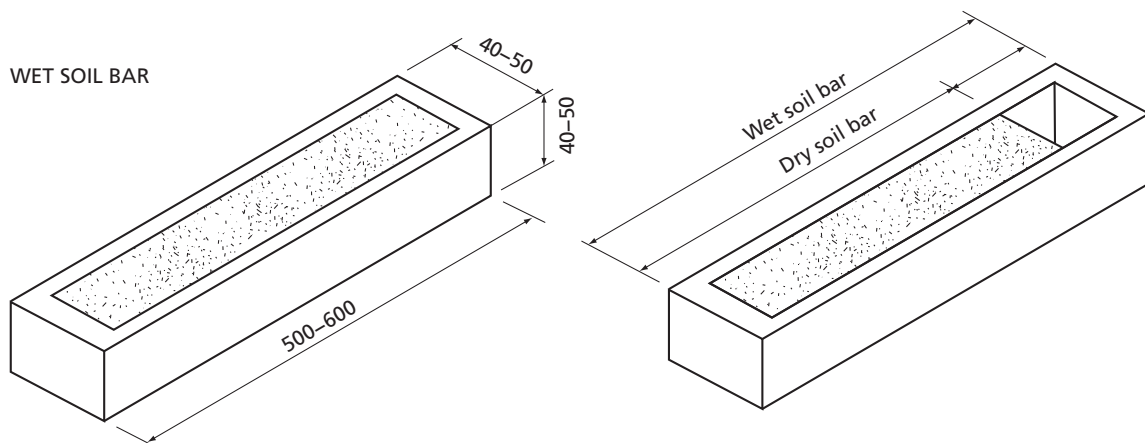


Figure 5.12 Box for bar shrinkage test

- pozzolana (e.g. fly ash, rice husk ash, volcanic ash);
- natural fibres (e.g. grass, straw, sisal, sawdust);
- sodium silicate (water-glass);
- commercial soil stabilizers (for roads);
- resins;
- whey;
- molasses;
- gypsum;
- cow dung.

Many other substances may also be used for soil stabilization, although their use is not well documented and test results are scarce.

Sand or clay is added to improve the grading of a soil. Sand is added to soils that are too clayey, and clay is added to soils that are too sandy. The strength and cohesion of the sandy soil is increased, while moisture movement of a clay soil is reduced. Improved grading of the soil material does not stabilize the soil to a high degree, but will increase the effect, and reduce the required amount, of other stabilizers. The clay or clayey soil must be pulverized before mixing with the sandy soil or sand. This may prove difficult in many cases.

Portland cement greatly improves the soil's compressive strength and imperviousness, and may also reduce moisture movement, especially when used with sandy soils. As a rough guide, sandy soils need 5–10 percent cement for stabilization, silty soils, 10–12.5 percent and clayey soils, 12.5–15 percent. Compaction when ramming or pressing blocks will greatly improve the result.

The cement must be thoroughly mixed with dry soil. This can be rather difficult, especially if the soil is clayey. As soon as water is added, the cement starts reacting and the mix must therefore be used immediately (1–2 hours). If the soil-cement hardens before moulding, it must be discarded. Soil-cement blocks should be cured for at least 7 days under moist or damp conditions.

Non-hydraulic lime, or slaked lime, gives best results when used with fine soils, i.e. silty and clayey soils. Lime decreases moisture movement and permeability, by reaction with the clay, to form strong bonds between the soil particles. The amount of lime used varies between 4 percent and 14 percent. Lime breaks down lumps and makes it easier to mix clayey soils. Curing at high temperatures strengthens the cementing molecules, which should be an advantage in the tropics. The curing time is longer than for soil-cement.

A *combination of lime and cement* is used when a soil has too much clay for cement stabilization, or too little clay for an extensive reaction with the lime. Lime will make the soil easier to work and the cement will increase the strength. Equal parts of lime and cement are used. Mixing the dry soil with lime first makes the soil more workable. Blocks are cured for at least 7 days under moist conditions.

Bitumen (or asphalt) emulsion and cutback are used mainly to improve the impermeability of the soil and keep it from losing its strength when wet, but may cause some decrease in dry strength. They are only used with very sandy soils because it would be very difficult to mix them with clayey soils. In its natural form, bitumen is too thick to be added to soil without heating, so it has to be thinned with other liquids to make it workable. The easiest way is to mix it with water to make an emulsion. After the emulsion has been added to the soil, the water will separate, leaving a bitumen film on the soil grains.

If the bitumen emulsion is fast-settling (i.e. the water separates too quickly before it is mixed into the soil), the bitumen must instead be dissolved in kerosene or naphtha. This mix is called 'cutback' and should be handled with care because it represents a fire hazard and explosion risk. After a soil has been treated with cutback, it must be spread out to allow the kerosene to evaporate.

The bitumen content used is 2–4 percent, as any more may seriously reduce the compressive strength of the soil.

A *combination of lime and pozzolana* makes a binder that can be almost as good as portland cement. It is used in the same way as a combination of lime and cement, but 2–4 parts of pozzolana are mixed to 1 part of lime, and the curing time is longer than for ordinary cement.

Natural fibres, used in a mixing ratio of about 4 percent, greatly reduce moisture movement, but will make dry-soil blocks weaker and more permeable to water.

Sodium silicate, or water-glass, is best used to coat the outside of soil blocks as a waterproofing agent.

Cob

Cob is used extensively in tropical Africa, where suitable soils are obtainable over wide areas. The best soil mix consists of gravel, sand, silt and clay in roughly equal proportions. Sometimes chopped grass or straw is added to reduce cracking. If the clay content is high, sand may be added. Laterite makes an excellent material for cob walling.

When a suitable soil has been found, the topsoil is removed and the subsoil dug up. Water is slowly added to the loose soil, which is then kneaded by treading until the soil has a wet, plastic consistency. Natural fibres are added for stabilization if required.

The wet cob is rolled into balls or lumps measuring about 20 cm in diameter, which are then bedded on the wall to form courses about 60 cm high. The outside of the wall may be scraped smooth. In arid and semi-arid climates, this type of wall may last for years if built on a proper foundation and protected from rain by a roof overhang or veranda.

Wattle and daub (mud and wattle)

This method of building small houses is very common in areas where bamboo or stalks (e.g. sisal) are available.

It consists of a framework of split bamboo, stalks or wooden sticks, supported by wood or bamboo poles. The soil, prepared as cob, is daubed on either side of the laths, which act as reinforcement. Although most soil is suitable for this construction, if it is too clayey there may be excessive cracking. To minimize cracking, stones are mixed with the soil, or laid in the wooden skeleton. When mudding the inside of a building, the soil is often taken from the floor. Although this increases the ceiling height, it greatly increases the likelihood of flooding during the rainy season.

During drying, the weight of the soil is transferred to the wooden structure, with the total weight of the construction eventually resting on the poles.

Wattle and daub construction generally has a short lifespan because of soil erosion, and the uneven settling of poles and damage by fungi and termites. However, the durability can be improved considerably (20–40 years) by using a proper foundation, raising the building off the ground, applying a surface treatment and using termite-resistant or treated poles.

Clay/straw

The technique of building walls of clay/straw has been highly developed in China, where grain storage bins of up to 8 m in diameter, 8.5 m in height and a 250-tonne holding capacity have been constructed with these materials.

Any type of straw can be used, but it must be of good quality. The clay should be of strong plasticity, containing less than 5 percent sand. Some lime may be added for stabilization if the sand content is a bit too high.

First, the straw bundles are produced. The straw is pruned level at the root ends and then divided into two halves, which are turned in opposite directions and placed together so that they overlap by about two-thirds of the length of the straw. The straw bundle is then spread out flat and soaked with clay mud. Thorough covering of each straw is essential for the final strength. The straw is then twisted together, and any excess mud removed. The final clay/straw bundle should be thick in the middle and tapered at both ends, be of 80–100 cm in length and roughly 5 cm in diameter at the middle. The ideal proportion of straw and clay is 1:7 on a dry weight basis.

The clay/straw bundles are placed on the wall either straight and flat, or slightly twisted together. Walls for grain bins should have a thickness in centimetres equal to the internal diameter in metres + 12, i.e. a 6-metre diameter bin should have a wall thickness of at least 18 cm. It is important to compact the wall thoroughly during construction to ensure high density, strength and durability. The wall must be built in separate layers, usually about 20 cm, and be left to dry out to about 50 percent moisture content before the next layer is added.

Rammed earth

This consists of ramming slightly damp soil between stout formwork using heavy rammers. It makes fairly strong and durable walls and floors when it is made thick enough with properly prepared, stabilized soil.

When used for walls, the soil may contain some cobble, but the maximum size should be less than one-quarter of the thickness of the wall. When cement is used for stabilization, it must be mixed with the dry soil by hand, or in a concrete mixer, until the dry mixture has a uniform greyish colour. The amount of cement required is approximately 5–7 percent for interior walls, 7–10 percent for foundations and exterior walls, and 10–15 percent for floors. However, the amount of stabilizer required will vary with the composition of the soil, the type of stabilizer and the use. For this reason, trial blocks should be made and tested to determine the correct amount of stabilizer.

Water is sprinkled on the soil while it is being mixed. If the soil is sticky because of high clay content, hand mixing will be necessary. When the correct amount of water has been added, the soil will form a firm lump when squeezed in the hand, and just enough moisture should appear on the surface to give a shiny appearance.

After the mixing has been completed, the soil should be placed in the formwork immediately. The formwork can be either fixed or sliding, but must be stout. The soil is placed in layers of about 10 cm, and each layer is thoroughly compressed with a ram weighing 8–10 kg before the next layer is placed. If water shows on the surface during ramming, the soil mix is too wet.

If cement or pozzolana has been used for stabilization, the product should be cured for 1–2 weeks in a moist condition before it is allowed to dry out. This can be done either by keeping the product enclosed in the formwork, or by covering it with damp bags or grass that are watered daily.

Adobe or sun-dried soil (mud) blocks

The best soil for adobe can be moulded easily, when plastic, into an egg-size ball, and when it is allowed to dry in the sun it becomes hard, shows little deformity and no more than very fine cracks. If wide cracks develop, the soil does not contain enough silt or sand, and sand may be added as a stabilizer.

Preparing the soil

When a suitable soil has been found, all topsoil must be removed. The soil is then loosened to a depth of 15 cm. If needed, water and sand are added and worked into the loose soil by treading it barefoot while turning the mass with a spade.

Water is added slowly and the soil mixed thoroughly until all lumps are broken up and it becomes homogeneous and plastic. When it is the right consistency for moulding, it is cast in a wooden mould made with one to three compartments and with dimensions as shown in Figure 5.13.

Before the mould is used for the first time it should be thoroughly soaked in oil. Because of the shrinkage, the finished blocks will be smaller than the moulds and, depending on bonding, will give a wall thickness of about 230 mm, 270 mm or 410 mm.

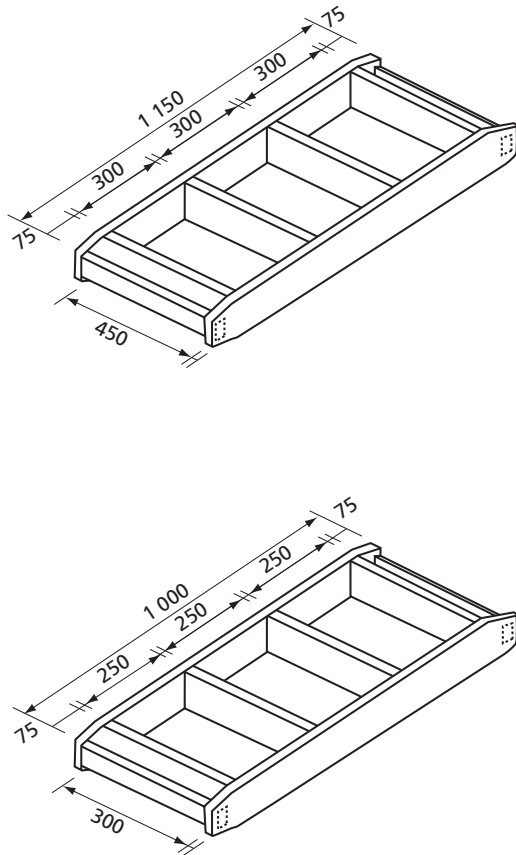


Figure 5.13 Wooden moulds for making adobe blocks made of 100 × 25 mm sawn timber

Moulding the blocks

To prevent sticking, the mould must be soaked in water before being placed on level ground, and filled with mud. The mud is kneaded until all corners of the mould are filled, and the excess is scraped off. The mould is lifted and the blocks are left on the ground to dry. The mould is dipped in water each time before repeating the process.

After drying for 3–4 days, the blocks will have hardened sufficiently to be handled, and are turned on edge to hasten drying. After a further 10 days, the blocks can be stacked loosely in a pile. Adobe blocks should dry out as slowly as possible to avoid cracks, with a total curing time of at least 1 month.

The quality of the blocks depends largely on the workmanship, especially the thoroughness with which they are moulded. If the quality is good, only 1 in 10 blocks should be lost from cracking, breakage or deformities.

Stabilized-soil blocks

When a suitable soil has been found, the topsoil should be removed and the subsoil dug out and spread out to dry in the sun for a few days.

Large particles and lumps must be removed before the soil is used, by breaking the larger lumps and passing all the soil through a 10 mm screen. If the proportion of gravel in the soil is high, a finer screen, of 4.5–6 mm, should be used. The wire screen, usually measuring about 1 metre square, is rocked in a horizontal position by one person holding handles at one end, with the other end suspended in ropes from above. The amount of loose, dry soil needed will normally be 1.4–1.7 times its volume in the compacted blocks.

Mixing

The amount of stabilizer to be used will depend on the type of soil, the type of stabilizer and the building component being made. Tables 5.7 and 5.8 give a guide to the necessary minimum mixing ratio of soil-cement for blocks compacted in a mechanical press. For blocks compacted in a hydraulic press, the cement requirement can be reduced considerably, whereas slightly more will be needed for hand-rammed blocks. The correct proportion of stabilizer is determined by making test blocks with varying proportions of stabilizer, as described later.

TABLE 5.7
Cement/soil ratio related to shrinkage ratio in the bar shrinkage test

Shrinkage	Cement to soil ratio
0–2.5%	1:18
2.5–5%	1:16
5–7.5%	1:14
7.5–10%	1:12

TABLE 5.8
Cement/soil ratio related to the combined silt and clay content in the simple sedimentation test

Clay & silt content	Interior walls	Exterior walls	Foundations	Floor slab
0–10%	1:16	1:16	1:16	1:8
10–25%	1:22	1:16	1:16	1:11
25–40%	1:22	1:11	1:11	1:11

The importance of thoroughly mixing the dry soil first with the stabilizer and then with the moisture, in two distinct steps, cannot be emphasized too strongly.

The quantity of cement and dry soil is measured with a measuring box, bucket or tin (never with a shovel), and put either on a clean, even and hard surface for hand mixing, or into a drum-type mixer (concrete mixer). They are mixed until the dry mixture has a uniform

TABLE 5.9
Batching for stabilized-soil blocks

Proportions cement/soil by volume	Approximate cement content by weight	Requirement of loose soil per 50 kg cement	Number of blocks per 50 kg cement				
			Size of blocks				
			290×140×50	290×140×90	290×140×120	290×140×140	290×215×140
1:22	5%	1 080 litres	366	203	152	130	85
1:18	6%	880 litres	301	167	125	107	70
1:16	7%	780 litres	268	149	111	95	62
1:14	8%	690 litres	235	131	98	84	54
1:12	9%	590 litres	203	113	84	72	47
1:11	10%	540 litres	187	104	78	66	43
1:10	11%	490 litres	170	94	71	61	39
1:9	12%	440 litres	154	85	64	55	36
1:8.5	13%	420 litres	146	81	61	52	34
1:8	15%	390 litres	138	76	57	49	32

greyish colour. Water is added, preferably through a sprinkler, while continuing the mixing. When the correct amount of water has been added, the soil, when squeezed into a ball, should retain its shape without soiling the hand. The ball should be capable of being pulled apart without disintegrating, but it should disintegrate when dropped from shoulder height on to a hard surface.

Compaction by hand-ramming

Moulds with one or more compartments can be made from either hardwood or steel. The mould should have hinges at one or two corners to enable it to be opened easily without spoiling the block. As mould has no bottom, it is preferable to place it on a pallet, rather than directly on the ground, when moulding the block.

The mould is treated as often as required with oil to make the block surface smooth and to prevent the block from sticking to the mould. The soil mixture should be placed in layers in the mould, and each layer thoroughly compacted with a flat-bottomed ram weighing 4–5 kg. Each block may need as many as 80 good blows with the ram. The top of the block is levelled off, the block and mould are carried to the curing store where the mould is removed, then the whole process is repeated.

Compaction with a mechanical press

There are many mechanical block-making machines on the market, both motor-driven (enabling several blocks to be made at a time), and hand-operated.

They all consist of a metal mould in which a moist soil mix is compressed.

The moulding for a hand-operated press is carried out as follows:

1. The inside of the compaction chamber is cleaned and oiled, and a pallet is placed in the bottom, if required.
2. A measured amount of soil mix is poured into the compaction chamber and the soil is compacted into the corners by hand.

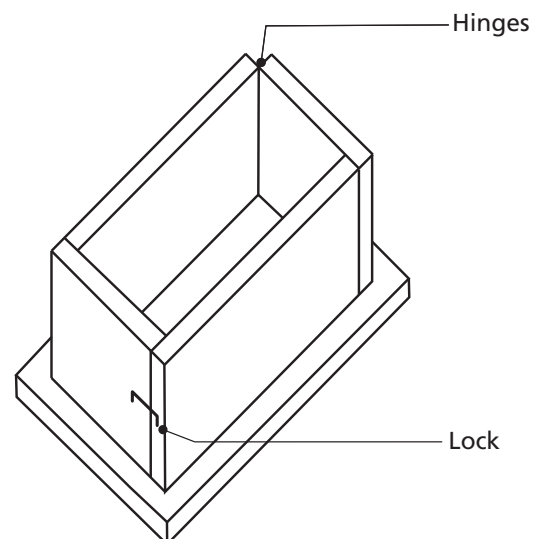


Figure 5.14 Mould for hand-rammed stabilized-soil blocks made of 20 mm planed timber

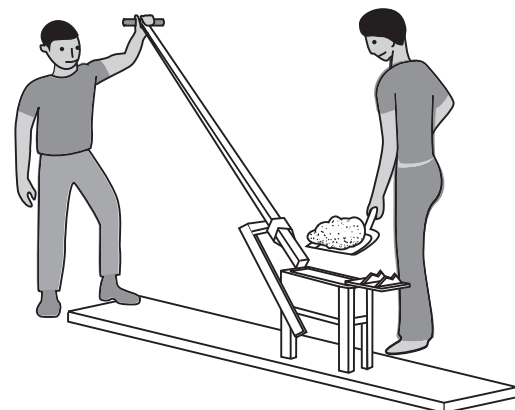


Figure 5.15 Mechanical press for block making

3. The lid is closed and the handle pulled down. The amount of soil mix is correct if the handle can be moved down to stop slightly above a horizontal level.
4. The block is ejected and carried on the pallet to the curing site, before returning the pallet to the press for reuse.

Curing of blocks

Soil-cement blocks should be placed on the ground, in the shade, as close together as possible, and be kept damp (e.g. with wet grass). After 1–2 days, the blocks can be carefully stacked and again kept damp for 1–2 weeks. After this period, the blocks are allowed to air dry for 2–3 weeks in a stacked pile before use.

Testing of blocks

In the laboratory, dry strength and wet strength are determined by crushing two well-cured blocks in a hydraulic press: the first in a dry state, and the second after having been soaked in water for 24 hours. Durability is tested by spraying the blocks with water according to a standard procedure, and making observations for any erosion or pitting.

In order to find out how much stabilizer is required, the following simple weather-resistance test carried out in the field may give a satisfactory answer.

At least three different soil mixes with different stabilizer-soil ratios are prepared, and at least three blocks are made from each of the different mixes.

Mixing, compaction and curing must be done in the same way as for the block production process. At the end of the curing period, three blocks are selected from each set, immersed in a tank, pond or stream all night, and dried in the sun all day. This wetting and drying process is repeated for 7 days.

The correct amount of stabilizer to use is the smallest amount with which all three blocks in a set pass the test. While a few small holes are acceptable on the compaction surface, if many holes appear on all surfaces the blocks are too weak. If the blocks have passed the test and the dry block produces a metallic ring when tapped with a hammer, they will have satisfactory durability and hardness.

If the blocks fail the test, the reason may be any of the following:

- unsuitable soil;
- insufficient amount of stabilizer;
- incorrect type of stabilizer;
- inadequately dried or lumpy soil;
- lumpy cement;
- insufficient mixing of the stabilizer;
- too much or too little water added;
- not enough compaction;
- incorrect curing.

Comparison of masonry units made of various materials

There are many methods for making bricks and blocks, several of which are suitable for local production because they are labour-intensive but do not require especially skilled labour.

The decision concerning which method of blockmaking or brickmaking to use depends on several factors, such as:

- the raw materials available;
- the characteristics of the soil;
- raw material and production costs;
- the requisite standards of stability, compression strength, water resistance, etc. (3 N/mm² is often regarded as the minimum compressive strength for use in one-storey buildings);
- the existing facilities for the maintenance of production tools and machines;
- the required productivity.

BURNT-CLAY BRICKS

Burnt-clay bricks have good resistance to moisture, insects and erosion, and create a good room environment. They are moderate in cost and have medium to high compressive strength.

Bricks can be made using sophisticated factory methods, simple labour-intensive methods, or a range of intermediate mechanized technologies. Labour-intensive production methods are the most suitable for rural areas where the demand for bricks is limited. Handmade bricks will be of comparatively lower quality, especially in terms of compressive strength, and will tend to have irregular dimensions. However, they are economical and require little capital investment or transportation costs. Bricks made in this manner have been used in buildings that have lasted for centuries. Their longevity depends on the quality of the ingredients, the skill of the artisans and the climate in which they are used.

Brickmaking

Five main ingredients are required for brickmaking: suitable clay and sand, water, fuel and manpower. The clay must be easily available, plastic when mixed with small amounts of water, develop strength upon drying and develop hard and durable strength when burned.

Suitable soils contain 25–50 percent clay and silt and 50–75 percent coarser material, as determined by the simple sedimentation test. The soil must be well graded. Another test consists of hand-rolling moistened soil into a long cylinder 10 mm in diameter on a flat surface, and then picking it up by one end and letting it hang unsupported.

A soil is adequate for brickmaking if the piece of cylinder that breaks off is between 50 mm and 150 mm long. In the bar shrinkage test, using a mould 300 mm long and 50 mm wide and deep, a suitable soil should show no cracking, or only a little on the surface, and should shrink less than 7 percent, i.e. less than 20 mm.

TABLE 5.10
Characteristics of masonry units

	Cost	Compressive strength	Resistance to moisture	Resistance to erosion	Uniformity of shape	Room comfort	Speed of production	Skill required to make	Labour requirements	Ease of transport	Energy requirements	Remarks
Sun-dried bricks (adobe bricks)	1	1	1	1	1-3	4	3	1	3	3	1	Most easily produced locally; much improved with stabilizers; least stable and durable.
Manually rammed stabilized-soil blocks	2	1-2	1-2	1-2	2-3	5	1	2	5	2	2	A little more effort; better quality and stability.
Mechanically pressed stabilized-soil blocks	2	2	2	2	4	5	2	2	4	3	2	Stronger; more durable.
Hydraulically pressed stabilized-soil blocks	3	3	3	3	4	5	3	3	3	3	2	Even stronger and more durable.
Locally made burnt-clay bricks	3-4	2-3	3	3-4	1-3	4	2	4	4	3-4	4	Labour-intensive production. Bricks are generally of low quality.
Factory-produced burnt-clay bricks	5	5	5	5	5	4	5	5	1-3	5	3	Commercial production is common. The plant requires large investment.
Concrete blocks (sand and cement)	5	5	4	5	5	3	3-4	4	2-3	4	5	Long life; strong but heavy. Local production is generally more labour-intensive than commercial.
Building stones	4	5	5	5	1-4	3	1	5	5	4	2	When locally available, a strong, durable and attractive material

Scale 1-5 1 = lowest 5 = highest

The clay is obtained by chipping it out of a clay bank and, where necessary, mixing it with sand to form a mixture that will not crack during drying. Water is gradually added to make the clay plastic.

When making bricks, the mould must be cleaned periodically with water. Before each brick is formed, the mould is sprinkled with sand. A lump, or 'clot,' of clay that is only slightly larger than required for a brick is rolled into a wedge shape and then dipped in sand, before being thrown, point down, into the mould. When thrown correctly, the mould will be completely filled, and the excess clay is then shaved off the top with a bowcutter. The sand in the mould and on the clot helps to release the newly formed brick.

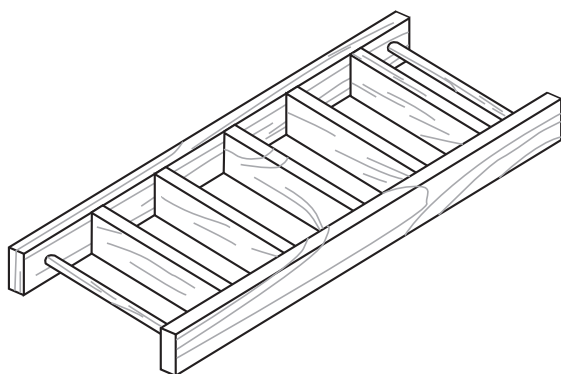


Figure 5.16 Mould for brick-forming

The bricks should be left to dry for about 3 days in the place where they were made. They will then be strong enough to be stacked, as shown in Figure 5.17, for

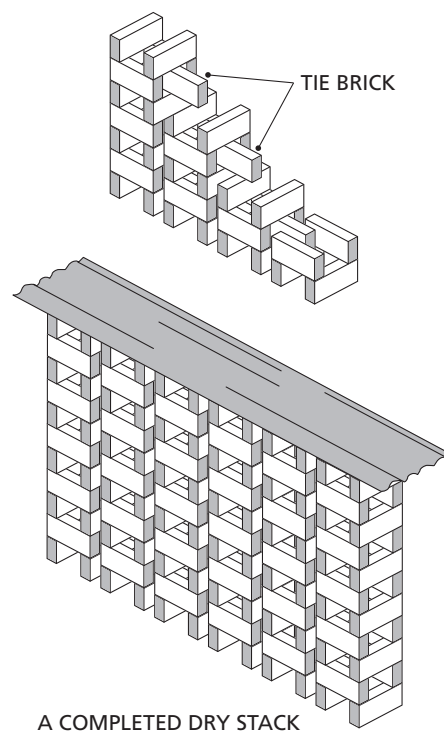


Figure 5.17 Stacking pattern for brick-drying

at least 1 week of further drying. Clay tends to become lighter in colour when dry and, when sufficiently dried, the brick should show no colour variation throughout the section area when it is broken in half. During drying, the bricks should be protected from rain.

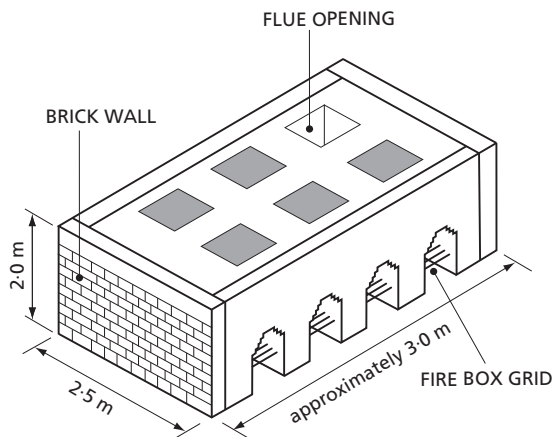


Figure 5.18 Kiln for brick-firing

Kiln construction and brick-firing

It is during firing that the bricks gain their strength. In high temperatures, the alkalis in the clay, together with small amounts of oxides of iron and other metals, chemically bond with the alumina and silica in the clay to form a dense and durable mass.

A kiln is a furnace or oven in which bricks are fired or heat-treated to develop hardness. Where brickmaking is carried out on a large scale, the firing operation is performed in a continuous-process kiln, referred to as a 'tunnel' kiln. For brickmaking on a small scale, firing is a periodic operation where the bricks are placed in the kiln, the fire started and heat developed, and then, after several days of firing, the fuel is cut off from the fire and the entire kiln and its load are allowed to cool naturally.

The kiln is filled with well-dried bricks, stacked in the same manner as during the drying process. The top of the stack in the kiln is then sealed with mud. Some openings are left for combustion gases to escape. Pieces of sheet metal are used to slide over the openings to control the rate at which the fire burns.

Although a range of fuels can be used in a kiln, wood or charcoal are the most common. When the kiln is at the prime heat for firing, a cherry-red hue develops (corresponding to a temperature range of 875–900 °C). This condition is maintained for about 6 hours. Sufficient fuel must be available when the burning starts because the entire load of bricks could be lost if the fires are allowed to die down during the operation. Firing with wood requires 4–5 days.

During firing, the bricks will shrink by as much as 10 percent. As they are taken out of the kiln, they should be sorted into different grades, the main

criteria being strength, irregular dimensions, cracks and, sometimes, discoloration and stain.

BINDERS

When binders are mixed with sand, gravel and water, they make a strong and long-lasting mortar or concrete.

Binders can be broadly classified as non-hydraulic or hydraulic. The hydraulic binders harden through a chemical reaction with water, making them impervious to water and therefore able to harden under water. Portland cement, blast furnace cement (super sulphated), pozzolanas and high-alumina cement belong to the category of hydraulic binders. High-calcium limes (fat or pure limes) are non-hydraulic because they harden by reaction with the carbon dioxide in the air. However, if lime is produced from limestone containing clay, compounds similar to those in portland cement will be formed, i.e. hydraulic lime.

Lime

Non-hydraulic lime refers to high-calcium limes that are produced by burning fairly pure limestone (essentially calcium carbonate), in order to drive off the carbon dioxide, leaving calcium oxide or quicklime. The burning process requires a temperature of 900–1 100 °C. Quicklime must be handled with great care because it reacts with moisture on the skin and the heat produced may cause burns. When water is added to quicklime, considerable heat is generated, expansion takes place, breaking down the quicklime pieces into a fine powder, and the resulting product is calcium hydroxide, also called hydrated lime, or slaked lime.

After drying, the powder is passed through a 3-mm sieve, before being poured into bags for storage (in dry conditions) and distribution.

Process	Substance	Chemical formula
Burning	Limestone – quicklime	$\text{CaCO}_3 - \text{CaO} + \text{CO}_2$
Slaking	Quicklime – slaked lime	$\text{CaO} + \text{H}_2\text{O} - \text{Ca(OH)}_2$
Hardening	Slaked lime – limestone	$\text{Ca(OH)}_2 + \text{CO}_2 - \text{CaCO}_3 + \text{H}_2\text{O}$

Slaked lime is used mainly in building because it is fat, i.e. it makes workable mortar and rendering and plaster mixes. Initially, a lime mortar becomes stiff by evaporation loss of water to absorptive materials such as bricks, but subsequent hardening depends on the chemical reaction with carbon dioxide from the air (carbonation) reforming the original calcium carbonate (limestone).

Non-hydraulic lime is also produced from limestone with a high content of magnesium carbonate. It is less easily slaked, but some of the remaining unslaked magnesium oxide may carbonate and produce greater strength than high-calcium lime.

Hydraulic lime is produced by mixing and grinding together limestone and clay material, and then burning it in a kiln.

It is stronger but less fat, or plastic, than non-hydraulic lime. During burning, the calcium oxide from the limestone reacts with siliceous matter from the clay to form dicalcium silicate. This compound may react with water, forming ‘mineral glue’ – tricalcium disilicate hydrate. The reaction is slow and may take weeks or months, but after some time a very good degree of strength is achieved.

The reaction that forms dicalcium silicate requires a very high temperature to be complete. In practical production, a lower temperature of 1 200 °C is used, leaving some of the ingredients in their original state. At this temperature, the limestone will lose the carbon dioxide and thus form quicklime. If the correct amount of water is added, the quicklime will slake, forming a fine powder. Note, however, that excess water will lead to premature hardening caused by hydraulic reaction.

Cement

Portland cement hardens faster and develops considerably higher strength than hydraulic lime. This is because cement contains tricalcium silicate. However, the manufacturing process is much more complicated than for lime. The ingredients are mixed in definite and controlled proportions, before being ground to a very fine powder. The fine grinding is necessary because the formation of tricalcium silicate can only take place in a solid state, and therefore only the surface of the particles in the mix is accessible for the chemical reaction, which requires a temperature of 1 250–1 900 °C to be completed.

During burning, the small particles of limestone and clay are sintered together to form clinker. After cooling, the clinker is ground to cement powder, with a small amount of gypsum being added during the grinding. The finer the cement particles, the larger the surface area available for hydration by water, and the more rapidly setting and hardening occurs. Cement is normally sold in 50 kg bags, but occasionally is available in bulk at a lower price.

Ordinary portland cement is the least expensive, and by far the most widely used, type of cement. It is suitable for all normal purposes.

Rapid-hardening portland cement is more finely ground, which accelerates the chemical reaction with water and develops strength more rapidly. It has the same strength after 7 days as ordinary portland cement does after 28 days. Early hardening may be useful where early stripping of formwork and early loading of the structure is required.

Low-heat portland cement develops strength very slowly. It is used in very thick concrete work where the heat generated by the chemical reactions in ordinary portland cement would be excessive and lead to serious cracking.

Chemistry of cement

The main components of standard portland cement are:

- lime (calcium oxide: 66%) in the form of limestone;
- silica (silicium dioxide: 22%), a component in most quartz, which forms the particles of clays;
- aluminium oxide (4%), found in large quantities in many clays. The proportion of aluminium oxide in the clay can be adjusted by the addition of bauxite, which is mainly water-soluble aluminium oxide;
- iron oxide (3%), found in iron ore and in clay;
- magnesium oxide (2%);
- sulphur dioxide (2%);
- miscellaneous components (1%).

The manufacturing process aims to produce a material with a high content of tricalcium silicate, usually 55–62 percent of the crystals in the clinker. Other crystals formed are: about 15 percent dicalcium silicate (the same component as the hydraulic binder in hydraulic lime), 8–10 percent tricalcium aluminate and 9 percent tetracalcium aluminate ferrite. As cement sinters during burning, it is very important for no calcium oxide (quicklime) to remain in the finished product.

The quicklime will remain embedded in the clinker, even after very fine grinding, and will not be available for slaking until the hardening process of the cement is quite far advanced. When the quicklime particles are finally slaked, they expand and break the structure already developed. The proportion of limestone in the initial mix must therefore be no more than 0.1 percent.

When cement is mixed with water, it initiates the chemical reactions that are so important for hardening. The most important of these is the formation of tricalcium disilicate hydrate, ‘mineral glue’, from hydrated calcium oxide and silica.



and



The reaction between dicalcium silicate and water is slow and does not contribute to the strength of the concrete until a considerable time has elapsed. Aluminate would interfere with these processes, hence the addition of gypsum at the end of the manufacturing process. The gypsum forms an insoluble compound with the aluminate.

During the hydration process, the cement chemically binds water corresponding to about one-quarter of its weight. Additional water evaporates, leaving voids, which reduce the density, and therefore the strength and durability, of the end products.

Pozzolana

A pozzolana is a siliceous material which, in finely divided form, can react with lime in the presence of

moisture at normal temperatures and pressures to form compounds possessing cementing properties. Unfortunately, the cementing properties of pozzolana mixtures are highly variable and unpredictable.

A wide variety of materials, both natural and artificial, may be pozzolanic. Silica constitutes more than half the weight of the pozzolana. Volcanic ash was the first pozzolana that the Romans used to make concrete for a host of large and durable buildings. Deposits of volcanic ash are likely to be found wherever there are active, or recently active, volcanoes.

Other natural sources of pozzolana are rock or earth in which the silica constituent contains the mineral opal, and the lateritic soils commonly found in Africa. Artificial pozzolana includes fly ash from the combustion of coal in thermoelectric power plants, burnt clays and shales, blast furnace slag formed in the process of iron manufacture, rice husk ash and the ash from other agricultural wastes.

The energy requirement for the manufacture of portland cement is very high. By comparison, lime and hydraulic lime can be produced with less than half the energy requirement, and natural pozzolana may be used directly without any processing. Artificial pozzolana requires some heating, but less than half that required for lime production.

Pozzolana and lime can be produced with much less sophisticated technology than portland cement. This means that pozzolana can be produced at relatively low cost and requires much less foreign exchange than cement. However, it takes 2–3 times the volume of pozzolana to make a concrete with the same strength as with portland cement, and this adds to the cost of transport and handling.

The main use of pozzolanas is for lime-pozzolana mortars, for blended pozzolanic cements and as an admixture in concrete. Replacing up to 30 percent of the portland cement with pozzolana will produce 65–95 percent of the strength of portland cement concrete at 28 days. The strength nominally improves with age because pozzolana reacts more slowly than cement, and at 1 year about the same strength is obtained.

CONCRETE

Concrete is a building material made by mixing cement paste (portland cement and water) with aggregate (sand and stone). The cement paste is the 'glue' that binds the particles in the aggregate together. The strength of the cement paste depends on the relative proportions of water and cement, with a more diluted paste being weaker. In addition, the relative proportions of cement paste and aggregate affect the strength, with a higher proportion of paste making stronger concrete.

The concrete hardens through the chemical reaction between water and cement, without the need for air. Once the initial set has taken place, concrete cures well under water. Strength is gained gradually, depending on the speed of the chemical reaction. Admixtures

are sometimes included in the concrete mix to achieve certain properties. Reinforcement steel is used for added strength, particularly for tensile stresses.

Concrete is normally mixed at the building site and poured into formwork of the desired shape, in the position that the unit will occupy in the finished structure. Units can also be precast, either at the building site or at a factory.

Properties of concrete

Concrete is associated with high strength, hardness, durability, imperviousness and mouldability. It is a poor thermal insulator, but has high thermal capacity. Concrete is not flammable and has good fire resistance, but there is a serious loss of strength at high temperatures. Concrete made with ordinary portland cement has low resistance to acids and sulphates but good resistance to alkalis.

Concrete is a relatively expensive building material for farm structures. The cost can be lowered if some of the portland cement is replaced with pozzolana. However, when pozzolanas are used, the chemical reaction is slower and strength development is delayed.

The compressive strength depends on the proportions of the ingredients, i.e. the cement/water ratio and the cement aggregate ratio. As the aggregate forms the bulk of hardened concrete, its strength will also have some influence. Direct tensile strength is generally low, only $\frac{1}{8}$ to $\frac{1}{14}$ of the compressive strength, and is normally neglected in design calculations, especially in the design of reinforced concrete.

Compressive strength is measured by crushing cubes measuring 15 cm on all sides. The cubes are cured for 28 days under standard temperature and humidity conditions, before being crushed in a hydraulic press. Characteristic strength values at 28 days are those below which not more than 5 percent of the test results fall. The grades used are C7, C10, C15, C20, C25, C30, C40, C50 and C60, each corresponding to a characteristic crushing strength of 7.0 N/mm², 10.0 N/mm², 15.0 N/mm², etc.

TABLE 5.11
Typical strength development of concrete

Age at test	Average crushing strength	
	Ordinary Portland cement	
	Storage in air 18 °C RH 65% (N/mm ²)	Storage in water (N/mm ²)
1 day	5.5	-
3 days	15.0	15.2
7 days	22.0	22.7
28 days	31.0	34.5
3 months	37.2	44.1

(1 cement/6 aggregate, by weight, 0.6 water/cement ratio).

In some literature, the required grade of concrete is defined by the proportions of cement, sand and stone (so called nominal mixes), rather than the compressive strength. Therefore some common nominal mixes have been included in Table 5.12. Note, however, that the amount of water added to such a mix will have a great influence on the compressive strength of the cured concrete.

The leaner of the nominal mixes listed opposite the C7 and C10 grades are workable only with very well graded aggregates ranging up to quite large sizes.

Ingredients

Cement

Ordinary Portland cement is used for most farm structures. It is sold in paper bags containing 50 kg, or approximately 37 litres. Cement must be stored in a dry place, protected from ground moisture, and the storage period should not exceed a month or two. Even damp air can spoil cement. It should be the consistency of powder when used. If lumps have developed, the quality has decreased, although it can still be used if the lumps can be crushed between the fingers.

Aggregate

Aggregate or ballast is either gravel or crushed stone. Aggregates that pass through a 5 mm sieve are called fine aggregate or sand, and those retained are called coarse aggregate or stone. The aggregate should be hard, clean and free from salt and vegetable matter. Too much silt and organic matter makes the aggregate unsuitable for concrete.

To test for silt, place 80 mm of sand in a 200 mm-high transparent bottle. Add water up to a height of 160 mm. Shake the bottle vigorously and allow the contents to settle until the following day. If the silt layer, which will settle on top of the sand, is less than 6 mm, the sand can be used without further treatment. If the silt content is higher, the sand must be washed.

To test for organic matter, place 80 mm of sand in a 200 mm-high transparent bottle. Add a 3 percent solution of sodium hydroxide up to 120 mm. Note that sodium hydroxide, which can be bought from a chemist, is dangerous to the skin. Cork the bottle and shake it vigorously for 30 seconds, then leave it standing until the following day. If the liquid on top of the sand turns dark brown or coffee-coloured, the sand should not be used. A 'straw' colour is satisfactory for most jobs, but not for those requiring the greatest strength or water resistance. Note, however, that some ferrous compounds may react with the sodium hydroxide to cause the brown colour.

Grading of the aggregate refers to proportioning of the different sizes of the aggregate material and greatly influences the quality, permeability and workability of the concrete. With a well-graded aggregate, the various particle sizes intermesh, leaving a minimum volume

TABLE 5.12

Suggested use for various concrete grades and nominal mixes

Grade	Nominal mix	Use
C7 C10	1:3:8 1:4:6 1:3:6 1:4:5 1:3:5	Strip footings; trench fill foundations; stanchion bases; non-reinforced foundations; oversite concrete and bindings under slabs; floors with very light traffic; mass concrete, etc.
C15 C20	1:3:5 1:3:4 1:2:4 1:3:3	Foundation walls; basement walls; structural concrete; walls; reinforced floor slabs; floors for dairy and beef cattle, pigs and poultry; floors in grain and potato stores, hay barns, and machinery stores; septic tanks and water storage tanks; slabs for farmyard manure; roads, driveways, paving and walks; stairways.
C25 C30 C35	1:2:4 1:2:3 1:1.5:3 1:1:2	All concrete in milking parlours, dairies, silage silos, and feed and drinking troughs; floors subject to severe wear and weather conditions, or weak acid and alkali solutions; roads and paving in frequent use by heavy machinery and lorries; small bridges; retaining walls and dams; suspended floors, beams and lintels; floors used by heavy, small-wheeled equipment, such as lift trucks; fencing posts and precast concrete components.
C40 C50 C60		Concrete in very severe exposure; prefabricated structural elements; prestressed concrete.

of voids to be filled with the more costly cement paste. The particles also flow together readily, i.e. the aggregate is workable, enabling less water to be used. The grading is expressed as a percentage by weight of aggregate passing through various sieves. A well-graded aggregate will have a fairly even distribution of sizes.

The *moisture content* in sand is important because the sand mixing ratio often refers to kilograms of dry sand, and the maximum amount of water includes the moisture in the aggregate. The moisture content is determined by taking a representative sample of 1 kg. The sample is accurately weighed and spread thinly on a plate, soaked with spirit (alcohol) and burned while stirring. When the sample has cooled, it is weighed again. The weight loss amounts to the weight of the water that has evaporated, and is expressed as a percentage by dividing the weight lost by the weight of the dried sample. The normal moisture content of naturally moist sand is 2.5–5.5 percent. The amount of water added to the concrete mixture should be reduced by the same percentage.

Density is the weight per volume of the solid mass, excluding voids, and is determined by placing 1 kilo of dry aggregate in 1 litre of water. The density is the weight of the dry aggregate (1 kg) divided by the volume of water forced out of place. Normal values for density of aggregate (sand and stone) are 2 600–2 700 kg/m³ and, for cement, 3 100 kg/m³.

Bulk density is the weight per volume of the aggregate, including voids, and is determined by weighing 1 litre of the aggregate. Normal values for coarse aggregate are 1 500–1 650 kg/m³. Although completely dry and very wet sand have the same volume, the bulking characteristic of damp sand gives it greater volume. The bulk density of typical naturally moist sand is 15–25 percent lower than coarse aggregate of the same material, i.e. 1 300–1 500 kg/m³.

The *size and texture of aggregate* affects the concrete. The larger particles of coarse aggregate should not exceed one-quarter of the minimum thickness of the concrete member being cast. In reinforced concrete, the coarse aggregate must be able to pass between the reinforcement bars, 20 mm being generally regarded as the maximum size.

While aggregate with a larger surface area and rough texture, i.e. crushed stone, allows greater adhesive forces to develop, it will give less workable concrete.

Stockpiles of aggregate should be situated close to the mixing place. Sand and stone should be kept separate. If a hard surface is not available, the bottom of the pile should not be used in order to avoid defilement with soil. In hot, sunny climates, a shade should be provided, or the aggregate should be sprinkled with water to cool it. Hot aggregate materials make poor concrete.

Water

Water should be reasonably free of impurities such as suspended solids, organic matter and salts. This requirement is usually satisfied by using water which is fit for drinking. Sea water can be used if fresh water is not available, but not for reinforced concrete, as the strength of the concrete will be reduced by up to 15 percent.

Batching

The concrete mix should contain enough sand to fill all the voids between the coarse aggregate, enough cement paste to cover all particles with a complete film, and enough water to complete the chemical reaction. Requirements for batching ordinary concrete mixes of various grades and workability are given in Appendix V: 1-2.

The *water–cement ratio* is an expression for the relative proportions of water, including the moisture in the damp aggregate, and cement in the cement paste. The strongest concrete is obtained with the lowest water–cement ratio which gives a workable mix that can be thoroughly compacted. Note that every 1 percent of water in excess of what is needed will reduce the strength by up to 5 percent. Water–cement ratio should however, not be below 0.4:1 since this is the minimum required to hydrate the cement.

The *aggregate–cement ratio* will influence on the concrete price since the amount of cement used per cubic meter will be changed. It is not possible to give a specific relationship between water–cement ratio, aggregate–cement ratio and workability, since it is

influenced by the grading, shape and texture of the aggregate.

Workability describes the ease with which the concrete mix can be compacted. Workability can be increased by adding water to a given mixing ratio since this will increase the water–cement ratio and thereby reduce the strength. Instead it should be obtained by use of a well-graded aggregate (adjustment of the relative proportions of sand and stone), use of smooth and rounded rather than irregular shaped aggregate or by decreasing the aggregate–cement ratio.

Batching measuring is done by weight or by volume. Batching by weight is more exact but is only used at large construction sites. Batching by volume is used when constructing farm buildings. Accurate batching is more important for higher grades of concrete. Batching by weight is recommended for concrete of grade C30 and higher. Checking the bulk density of the aggregate will result in greater accuracy when grade C20 or higher is batched by volume. A 50 kg bag of cement can be split into halves by cutting across the middle of the top side of a bag lying flat on the floor. The bag is then grabbed at the middle and lifted so that the bag splits into two halves.

A bucket or box can be used as a measuring unit. The materials should be placed loosely in the measuring unit and not compacted. It is convenient to construct a cubic box with 335 mm sides, as it will contain 37 litres, which is the volume of 1 bag of cement. If the box is made without a bottom and placed on the mixing platform while being filled, it is easy to empty by simply lifting it. The ingredients should never be measured with a shovel or spade.

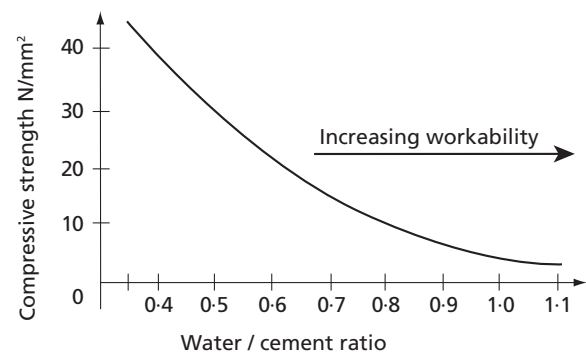


Figure 5.19 Relation between compressive strength and water/cement ratio

Calculating of the amount of ingredients is done from the number of cubic metres of concrete required.

The sum of the ingredient volumes will be greater than the volume of concrete, because the sand will fill the voids between the coarse aggregate. The volume of the materials will normally be 30–50 percent greater than in the concrete mix – 5 percent to 10 percent is

TABLE 5.13
Requirements per cubic metre for batching nominal concrete mixes

Proportions by volume	Cement (number of 50 kg bags)	Naturally moist aggregate ¹				Aggregate: cement (ratio)	Sand to total aggregate (%)
		Sand		Stones			
		(m ³)	(tonnes)	(m ³)	(tonnes)		
1:4:8	3.1	0.46	0.67	0.92	1.48	13.4	31
1:4:6	3.7	0.54	0.79	0.81	1.30	11.0	37
1 5:5	3.7	0.69	1.00	0.69	1.10	10.9	47
1:3:6	4.0	0.44	0.64	0.89	1.42	10.0	31
1:4:5	4.0	0.60	0.87	0.75	1.20	9.9	41
1:3:5	4.4	0.49	0.71	0.82	1.31	8.9	35
1:4:4	4.5	0.66	0.96	0.66	1.06	8.7	47
1:3:4	5.0	0.56	0.81	0.74	1.19	7.7	40
1:4:3	5.1	0.75	1.09	0.57	0.91	7.6	54
1:2:4	5.7	0.42	0.62	0.85	1.36	6.7	31
1:3:3	5.8	0.65	0.94	0.65	1.03	6.5	47
1:2:3	6.7	0.50	0.72	0.74	1.19	5.5	37
1:1:5:3	7.3	0.41	0.59	0.82	1.30	5.0	31
1:2:2	8.1	0.60	0.87	0.60	0.96	4.4	47
1:1:5:2	9.0	0.50	0.72	0.67	1.06	3.9	40
1:1:2	10.1	0.37	0.54	0.75	1.19	3.3	31

¹ These quantities are calculated on the assumption that sand has a bulk density of 1 450 kg/m³ and stone has a density of 1 600 kg/m³. The density of the aggregate material is 2 650 kg/m³.

allowed for waste and spillage. Adding cement does not noticeably increase the volume. The above assumptions are used in Example 5.2 to estimate roughly the amount of ingredients needed. Example 5.3 gives a more accurate method of calculating the amount of concrete obtained from the ingredients.

Example 5.2

Calculate the amount of materials needed to construct a rectangular concrete floor measuring 7.5 m by 4.0 m and 7 cm thick. Use a nominal mix of 1:3:6. Fifty kilograms of cement is equal to 37 litres.

Total volume of concrete required =
7.5 m × 4.0 m × 0.07 m = 2.1 m³

Total volume of ingredients, assuming 30 percent decrease in volume when mixed and 5 percent waste =
2.1 m³ + 2.1 (30% + 5%) m³ = 2.84 m³

The volume of the ingredients is proportional to the number of parts in the nominal mix. In this case, there is a total of 10 parts (1+3+6) in the mix, but the cement does not affect the volume, so only the 9 parts of sand and stone are used.

Cement = (2.84 × 1) / 9 = 0.32 m³ or 320

Sand = (2.84 × 3) / 9 = 0.95 m³

Stone = (2.84 × 6) / 9 = 1.89 m³

Number of bags of cement required =
320 / 37 = 8.6 bags, i.e. 9 bags have to be bought.

Weight of sand required =
0.95 m³ × 1.45 tonnes / m³ = 1.4 tonnes

Weight of stone required =
1.89 m³ × 1.60 tonnes / m³ = 3.024 tonnes

Maximum size of stones = 70 mm × 1 / 4 = 17.5 mm

Example 5.3

Assume a 1:3:5 cement-sand-stone concrete mix by volume, using naturally moist aggregates and adding 62 litres of water. What will be the basic strength and volume of the mix if 2 bags of cement are used?

Additional assumptions:

Moisture content of sand: 4%

Moisture content of stones: 1.5%

Bulk density of the sand: 1 400 kg/m³

Bulk density of the stones: 1 600 kg/m³

Solid density of aggregate materials: 2 650 kg/m³

Solid density of cement: 3 100 kg/m³

Density of water: 1 000 kg/m³

1. Calculate the volume of the aggregate in the mix.

Two bags of cement have a volume of
 $2 \times 37 \text{ litres} = 74 \text{ litres}$

The volume of sand is $3 \times 74 \text{ litres} = 222 \text{ litres}$

The volume of stones is $5 \times 74 \text{ litres} = 370 \text{ litres}$

2. Calculate the weight of the aggregates.

Sand $222 / 1\,000 \text{ m}^3 \times 1\,400 \text{ kg/m}^3 = 311 \text{ kg}$

Stones $370 / 1\,000 \text{ m}^3 \times 1\,600 \text{ kg/m}^3 = 592 \text{ kg}$

3. Calculate the amount of water contained in the aggregate.

Water in the sand is $311 \text{ kg} \times 4 / 100 = 12 \text{ kg}$

Water in the stones is $592 \text{ kg} \times 1.5 / 100 = 9 \text{ kg}$

4. Adjust amounts in the batch for water content in aggregate.

Cement 100 kg (unaltered)

Sand $311 \text{ kg} - 12 \text{ kg} = 299 \text{ kg}$

Stones $592 \text{ kg} - 9 \text{ kg} = 583 \text{ kg}$

Total amount of dry aggregate =
 $299 \text{ kg} + 583 \text{ kg} = 882 \text{ kg}$

Water = $12 \text{ kg} + 9 \text{ kg} = 21 \text{ kg}$

5. Calculate the water–cement ratio and the cement–aggregate ratio

Water–cement ratio =
 $(21 \text{ kg water}) / 100 \text{ kg cement} = 0.21$

Aggregate–cement ratio =
 $(882 \text{ kg aggregate}) / 100 \text{ kg cement} = 8.8$

The water–cement ratio indicates that the mix has a basic strength corresponding to a C10 mix. See Appendix V: 12.

6. Calculate the 'solid volume' of the ingredients in the mix, excluding the air voids in the aggregate and cement.

Cement $100 \text{ kg} / 3\,100 \text{ kg/m}^3 = 0.032 \text{ m}^3$

Aggregate $882 \text{ kg} / 2\,650 \text{ kg/m}^3 = 0.333 \text{ m}^3$

Water $21 \text{ kg} / 1\,000 \text{ kg/m}^3 = 0.021 \text{ m}^3$

Total = 0.448 m^3

The total volume of 1:3:5 mix obtained from 2 bags of cement is 0.45 m^3 .

Note that the 0.45 m^3 of concrete is only two-thirds of the sum of the volumes of the components - $0.074 + 0.222 + 0.370$.

Mixing

Mechanical mixing is the best way of mixing concrete. Batch mixers with a tilting drum for use on building sites are available in sizes of 85–400 litres. Power for drum rotation is supplied by a petrol engine or an electric motor, whereas the drum is tilted manually. The pear-shaped drum has internal blades for efficient mixing. Mixing should be continued for at least 2.5 minutes after all the ingredients have been added. For small-scale work in rural areas it may be difficult and rather expensive to use a mechanical mixer.

TABLE 5.14

Mixing-water requirements¹ for dense concrete for different consistencies and maximum sizes of aggregate

Maximum size of aggregate ²	Water requirement (litres / m ³) for concrete		
	1/2–1/3	1/3–1/6	1/6–1/2
	High workability	Medium workability	Plastic consistency
10 mm	245	230	210
14 mm	230	215	200
20 mm	215	200	185
25 mm	200	190	175
40 mm	185	175	160

¹ Includes moisture in aggregate. The quantities of mixing water are the maximum for use with reasonably well-graded, well-shaped, angular, coarse aggregate.

² For slump see Table 5.15.

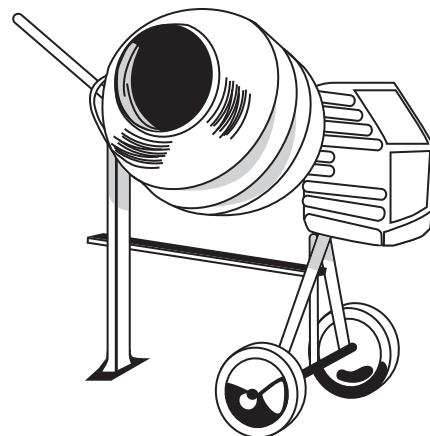


Figure 5.20 Batch mixer

A simple hand-powered concrete mixer can be manufactured from an empty oil drum set in a frame of galvanized pipe. Figure 5.21 shows a hand crank, but the drive can be converted easily to machine power.

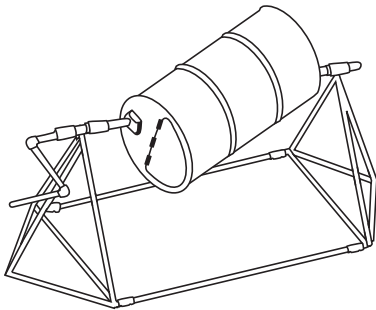


Figure 5.21 Home-built concrete mixer

Hand mixing is normally used for small jobs. Mixing should be done on a close-boarded platform or a concrete floor near to where the concrete is to be placed, and never on bare ground because of the danger of earth contamination.

The following method is recommended for hand mixing:

1. The measured quantities of sand and cement are mixed by turning them over with a shovel at least 3 times.
2. About three-quarters of the water is added to the mixture a little at a time.
3. Mixing continues until the mixture becomes homogeneous and workable.
4. The measured quantity of stones, after being wetted with part of the remaining water, is spread over the mixture and mixing continues, with all ingredients being turned over at least 3 times during the process, using as little water as possible to obtain a workable mix.

All tools and the platform should be cleaned with water when there is a break in the mixing, and at the end of the day.

Slump test

The slump test gives an approximate indication of the workability of the wet concrete mix. Fill a conically shaped bucket with the wet concrete mix and compact it thoroughly. Turn the bucket upside down on the mixing platform. Lift the bucket, place it next to the concrete heap and measure the slump, as shown in Figure 5.22.

Placing and compaction

Concrete should be placed with a minimum of delay after the mixing is completed, and certainly within 30 minutes. Special care should be taken when transporting wet mixes, because the vibrations of a moving wheelbarrow may cause the mix to segregate. The mix should not be allowed to flow, nor should it be dropped into position from a height of more than 1 metre. The concrete should be placed with a shovel in layers no deeper than 15 cm, and compacted before the next layer is placed.

When slabs are cast, the surface is levelled with a screed board, which is also used to compact the concrete mix as soon as it has been placed, to remove any trapped air. The less workable the mix, the more porous it is, and the more compaction is necessary. The concrete loses up to 5 percent of its strength for every 1 percent of entrapped air. However, excessive compaction of wet mixes brings fine particles to the top, resulting in a weak, dusty surface.

Manual compaction is commonly used for the construction of farm buildings. It can be used for mixes with high and medium workability, and for plastic mixes. Wet mixes used for walls are compacted by punting with a batten, stick or piece of reinforcement bar. Knocking on the formwork also helps. Less workable mixes, such as those used for floors and paving, are best compacted with a tamper.

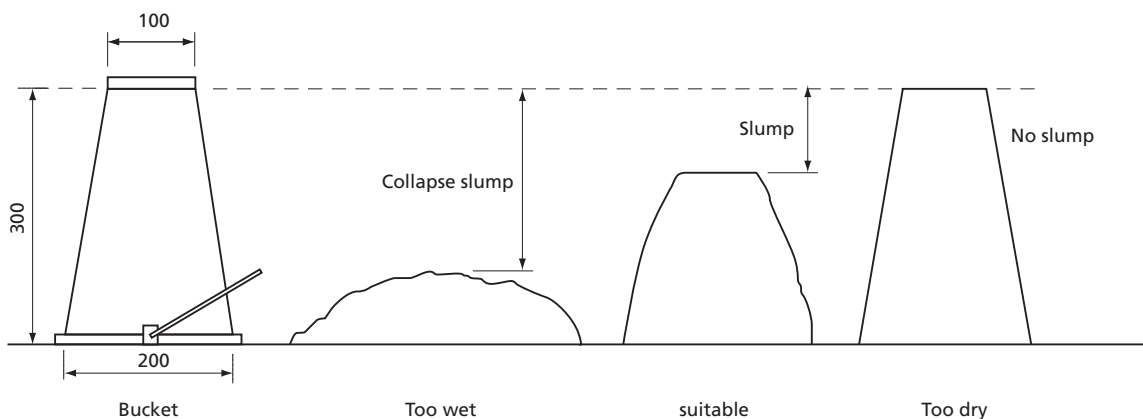


Figure 5.22 Concrete slump test

TABLE 5.15
Concrete slump for various uses

Consistency	Slump	Use	Method of compaction
High workability	$\frac{1}{2}$ – $\frac{1}{3}$	Constructions with narrow passages and/or complex shapes. Heavily reinforced concrete.	Manual
Medium workability	$\frac{1}{3}$ – $\frac{1}{6}$	All normal uses. Non-reinforced and normally reinforced concrete.	Manual
Plastic	$\frac{1}{6}$ – $\frac{1}{12}$	Open structures with fairly open reinforcement, which are heavily worked manually for compaction, such as floors and paving. Mass concrete.	Manual or mechanical
Stiff	0– $\frac{1}{2}$	Non-reinforced or sparsely reinforced open structures, such as floors and paving, which are mechanically vibrated. Factory prefabrication of concrete goods. Concrete blocks.	Mechanical
Damp	0	Factory prefabrication of concrete goods.	Mechanical or pressure

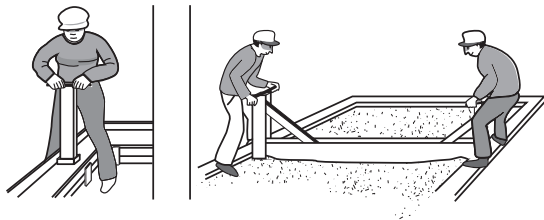


Figure 5.23 Manual compaction of foundation and floor slab

Only mechanical vibrators are capable of compacting stiffer mixes thoroughly. For walls and foundations, a poker vibrator (a vibrating pole) is immersed in the poured concrete mix at points up to 50 cm apart. Floors and paving are vibrated with a beam vibrator.

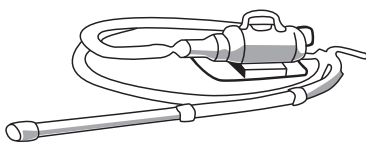


Figure 5.24 Mechanical vibrators

Construction joints

The casting should be planned in such a way that the work on a member can be completed before the end of the day. If cast concrete is left for more than 2 hours, it will set so much that there is no direct continuation between the old and new concrete. Joints are potentially weak and should be positioned where they will affect the strength of the member as little as possible. Joints

should be straight, either vertical or horizontal. When resuming work, the old surface should be roughened and cleaned before being treated with a thick mixture of water and cement.

Formwork

Formwork provides the shape and surface texture of concrete members and supports the concrete during setting and hardening.

The simplest type of form is sufficient for pavement edges, floor slabs, pathways, etc.

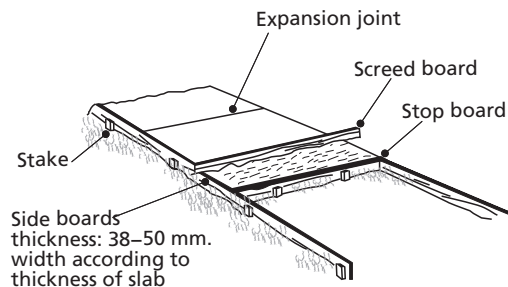


Figure 5.25 Simple type of formwork for a concrete slab

In large concrete slabs, such as floors, cracks tend to occur early in the setting period. In a normal slab where watertightness is not essential, this can be controlled by laying the concrete in squares, with joints between them, allowing the concrete to move slightly without causing cracks in the slab. The distance between the joints should not exceed 3 metres. The simplest type is called a *dry joint*. The concrete is poured directly against the already hardened concrete of another square.

A more sophisticated method is a *filled joint*. A minimum gap of 3 mm is left between the squares, and filled with bitumen or any comparable material.

Forms for walls must be strongly supported because when concrete is wet it exerts great pressure on the side boards. The greater the height, the greater the pressure. A concrete wall will not normally be thinner

than 10 cm, or 15 cm in the case of reinforced concrete. If it is higher than 1 metre, it should not be less than 20 cm thick, to make it possible to compact the concrete properly with a tamper. The joints of the formwork must be tight enough to prevent loss of water and cement.

If the surface of the finished wall is to be visible, and no further treatment is anticipated, tongued and grooved boards, planed on the inside, can be used to provide a smooth and attractive surface. Alternatively, 12-mm plywood sheets can be used. The dimensions and spacing of studs and ties are shown in Figure 5.26. The proper spacing and installation of the ties is important to prevent distortion or complete failure of the forms.

Not only must forms be well braced, they must also be anchored securely to prevent them from floating up, allowing the concrete to run out from underneath.

The forms should be brushed with oil and watered thoroughly before filling with concrete. This is done to prevent water in the concrete from being absorbed by the wooden boards, and to stop the concrete from sticking to the forms. Although soluble oil is best, used engine oil mixed with equal parts of diesel fuel is the easiest and cheapest material in practice.

If handled carefully, wooden forms can be used several times before they are abandoned. If there is a recurrent need for the same shape, it is advantageous to make the forms of steel sheets.

Although the formwork can be taken away after 3 days, leaving it for 7 days makes it easier to keep the concrete wet.

In order to save on material for the formwork and its supporting structure, tall silos and columns are cast using a slip form. The form is not built to the full height of the silo, and may in fact be only a few metres high. As casting of the concrete proceeds, the form is lifted. The work needs to proceed at a speed that allows the concrete to set before it leaves the bottom of the form. This technique requires complicated design calculations, skilled labour and supervision.

Curing concrete

Concrete will set in 3 days, but the chemical reaction between water and cement continues for much longer. If the water disappears through evaporation, the chemical reaction will stop. It is therefore very important to keep the concrete wet (damp) for at least 7 days.

Premature drying out may also result in cracking caused by shrinkage. During curing, the strength and impermeability increases and the surface hardens against abrasion. Watering of the concrete should start as soon as the surface is hard enough to avoid damage, but not later than 10–12 hours after casting. Covering the concrete with sacks, grass, hessian, a layer of sand or polythene helps to retain the moisture and protects the surface from dry winds. This is particularly important in tropical climates.

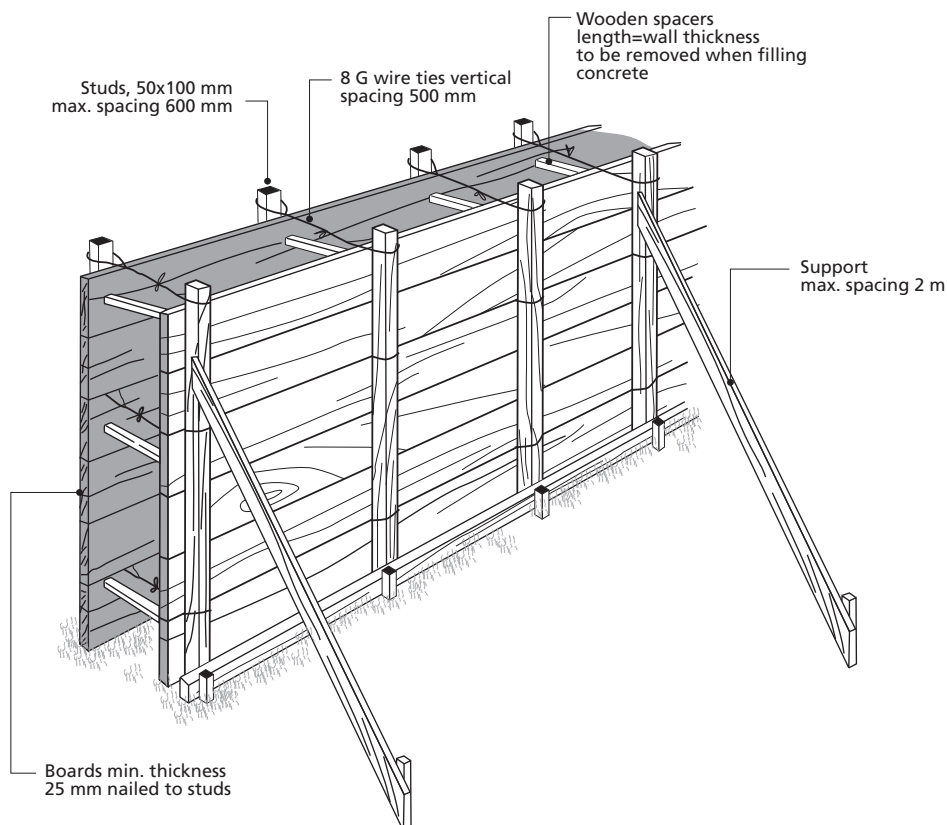


Figure 5.26 Dimensions and spacing of studs and ties in formwork for walls

Temperature is also an important factor in curing. For temperatures above 0 °C and below 40 °C, strength development is a function of temperature and time. At temperatures above 40 °C, the stiffening and hardening may be faster than desired and result in lower strength.

Figure 5.27 shows the approximate curing time needed to achieve characteristic compressive strength at various curing temperatures for concrete mixes using ordinary portland cement.

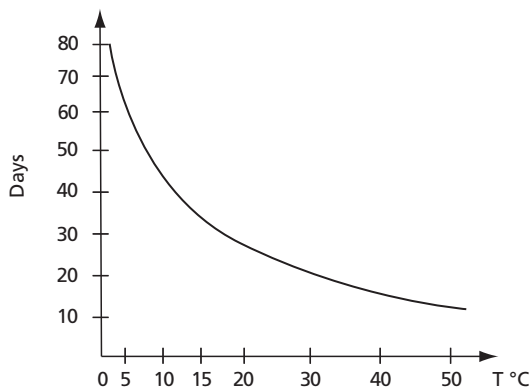


Figure 5.27 Curing times for concrete

Finishes on concrete

The surface of newly laid concrete should not be worked until some setting has taken place. The type of finish should be compatible with the intended use. In the case of a floor, a non-skid surface for humans and animals is desirable.

Tamped finish: The tamper leaves a coarse, rippled surface when it has been used to compact the concrete.

Tamper-drawn finish: A less pronounced ripple can be produced by moving a slightly tilted tamper on its tail end over the surface.

Broomed finish: A broom of medium stiffness is drawn over the freshly tamped surface to give a fairly rough texture.

Wood-float finish: For a smooth, sandy texture the concrete can be wood-floated after tamping. The float is used with a semicircular sweeping motion, the leading edge being slightly raised; this levels out the ripples and produces a surface with a fine, gritty texture, a finish often used for floors in animal houses.

Steel trowel finish: Steel trowelling after wood floating gives a smoother surface with very good wearing qualities. However, it can be slippery in wet conditions.

Surfaces with the aggregate exposed can be used for decorative purposes, but can also give a rough, durable surface on horizontal slabs. This surface can be obtained by removing cement and sand by spraying water on the new concrete, or by positioning aggregate by hand in the unset concrete.

Reinforced concrete

Concrete is strong in compression but relatively weak in tension. The underside of a loaded beam, such as a lintel over a door, is in tension.



Figure 5.28 Stresses in a concrete lintel

Concrete subject to tension loading must be reinforced with steel bars or mesh. The amount and type of reinforcement should be carefully calculated or, alternatively, a standard design obtained from a reliable source should be followed without deviating from the design.

Important factors affecting reinforced concrete:

1. The steel bars should be cleaned of rust and dirt before they are placed.
2. In order to obtain good adhesion between the concrete and the steel bars, the bars should be overlapped where they join by at least 40 times the diameter. When plain bars are used, the ends of the bars must be hooked.
3. The reinforcement bars should be tied together well and supported so that they will not move when concrete is placed and compacted.
4. The steel bars must be in the tensile zone and be covered with concrete to a thickness of 3 times the diameter, or by at least 25 mm, to protect them from water and air, which causes rusting.
5. The concrete must be well compacted around the bars.
6. Concrete should be at least C20 or 1:2:4 nominal mix, and have a maximum aggregate size of 20 mm.

Concrete floors are sometimes reinforced with welded steel mesh or chicken wire, placed 25 mm beneath the upper surface of the concrete, to limit the size of any cracking. However, such load-distributing reinforcement is necessary only when loadings are heavy, the underlying soil is not dependable, or when cracking must be minimized, as in water tanks.

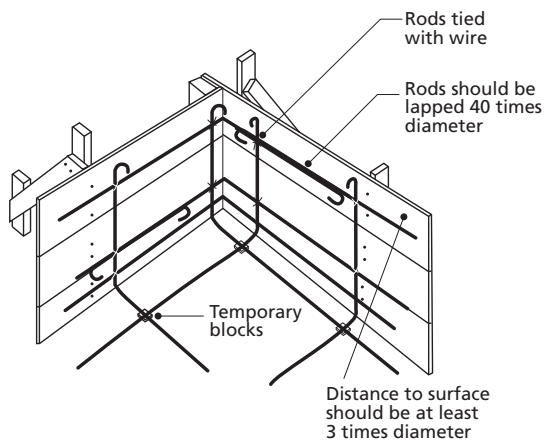


Figure 5.29 Placing reinforcement bars

CONCRETE BLOCKS, SAND AND CEMENT BLOCKS

It is faster to build with concrete blocks than with bricks, and using concrete blocks reduces the mortar requirement by half or more. If face-shell bedding is used, in which the mortar is placed only along the edges of the blocks, the consumption of mortar is reduced by a further 50 percent. However, the total amount of cement required for the blocks and mortar is far greater than that required for the mortar in a brick wall.

Concrete blocks are often made of 1:3:6 concrete with a maximum aggregate size of 10 mm, or a cement-sand mixture with a ratio of 1:7, 1:8 or 1:9. If properly cured, these mixtures produce concrete blocks with compression strength well above what is required in a one-storey building. The blocks may be solid, cellular or hollow. Cellular blocks have cavities with one end closed, while in hollow blocks the cavities pass through. Lightweight aggregate, such as cracked pumice stone, is sometimes used.

Blocks are made to a number of coordinating sizes, the actual sizes being about 10 mm less in order to allow for the thickness of the mortar.

Block manufacturing

Blocks can be made using a simple block-making machine driven by an engine, or operated by hand. They can also be made using simple wooden moulds on a platform or floor. The mould can be lined with steel plates, to prevent damage during tamping and to reduce wear on the mould. Steel moulds are often used in large-scale production. The wooden mould is initially oiled overnight and need not be oiled each time it is filled. It is sufficient to wipe it clean with a cloth. The concrete, with a stiff or plastic consistency, is placed in the mould in layers, and each layer is compacted with a 3-kg rammer.

The mould in Figure 5.30 has a lid made so that it can pass through the rest of the mould. The slightly tapered sides can be removed by lifting the handles, while holding down the lid with one foot.

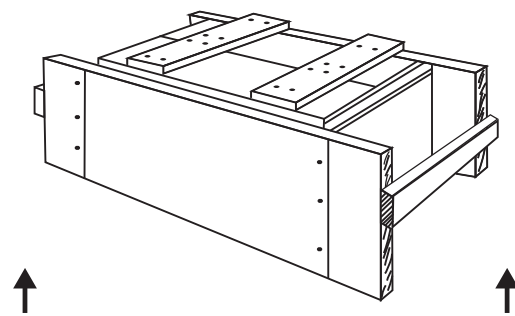


Figure 5.30 Wooden mould for solid concrete blocks

The mould illustrated in Figure 5.31 has a steel plate cut to the shape of the block, which is used as a lid and held down as the hollow-making pieces are withdrawn. Bolts are then loosened and the sides of the mould are removed with a swift motion. All parts of the mould should be slightly tapered so that they can be removed easily from the block.

As from the day after the blocks have been made, water is sprinkled on the blocks for 2 weeks during curing. After 48 hours, the blocks can be removed for stacking, but wetting must continue. After curing, the blocks are dried. If damp blocks are placed in a wall, they will shrink and cause cracks. To ensure maximum drying, the blocks are stacked interspaced, exposed to the prevailing wind and, in the case of hollow blocks, with the cavities laid horizontal to form a continuous passage for the circulating air.

Decorative and ventilating blocks

Decorative concrete or sand-cement blocks serve several purposes:

- to provide light and security without installing windows or shutters;
- to provide permanent ventilation;
- to give an attractive appearance.

In addition, some are designed to keep out rain, while others include mosquito proofing.

While blocks with a simple shape can be made in a wooden mould by inserting pieces of wood to obtain the desired shape, more complicated designs usually require a professionally made steel mould.

MORTAR

Mortar is a plastic mixture of water and binding materials, used to join concrete blocks, bricks or other masonry units.

It is desirable for mortar to hold moisture, be plastic enough to stick to the trowel and the blocks or bricks, and to develop adequate strength without cracking.

Mortar need not be stronger than the units it joins. In fact, cracks are more likely to appear in the blocks or bricks if the mortar is excessively strong.

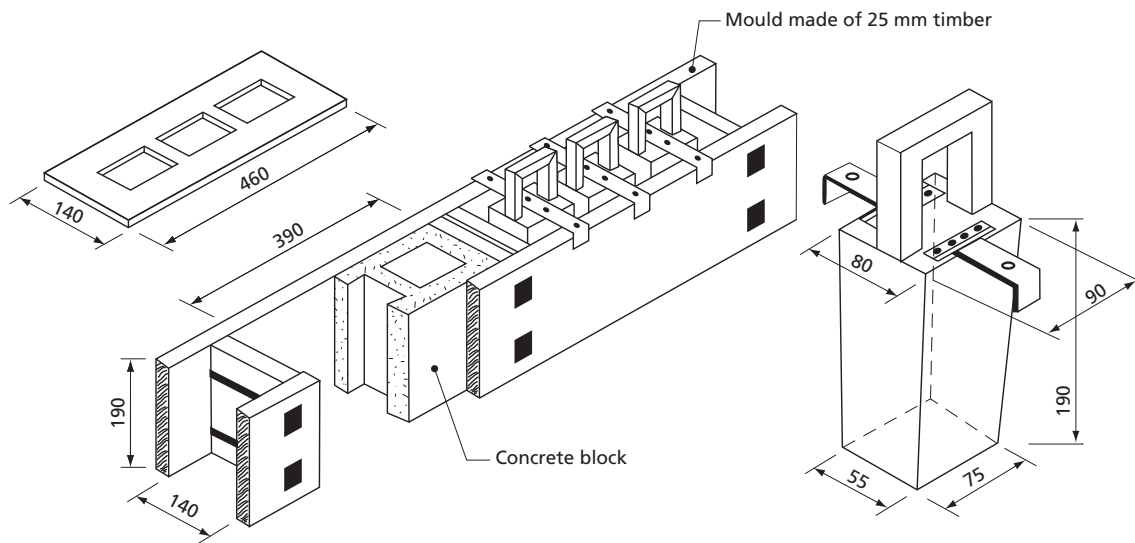


Figure 5.31 Mould for hollow or cellular concrete blocks

There are several types of mortar, each suitable for particular applications and varying in cost. Most of these mortars include sand as an ingredient. In all cases, the sand should be clean, free of organic material, well graded (a variety of sizes) and not exceed 3 mm of silt in the sedimentation test. In most cases, particle size should not exceed 3 mm, as this would make the mortar 'harsh' and difficult to work with.

Lime mortar is typically mixed using 1 part lime to 3 parts sand. Two types of lime are available. Hydraulic lime hardens quickly and should be used within an hour. It is suitable for both above- and below-ground applications. Non-hydraulic lime requires air to harden, and can only be used above ground. If it is smoothed off while standing, a pile of this type of lime mortar can be stored for several days.

Cement mortar is stronger and more waterproof than lime mortar, but it is difficult to work with because it is not 'fat' or plastic and falls away from the blocks or bricks during placement. In addition, cement mortar is more costly than other types. Consequently, it is used in only a few applications, such as a damp-proof course or in some limited areas where heavy loads are expected. A 1:3 mix using fine sand is usually required to obtain adequate plasticity.

Compo mortar is made with cement, lime and sand. In some localities, a 50:50 cement-lime mix is sold as mortar cement. The addition of the lime reduces the cost and improves workability. A 1:2:9, cement-lime-sand mix is suitable for general purposes, while a 1:1:6 is better for exposed surfaces, and a 1:3:12 can be used for interior walls, or stone walls, where the extra plasticity is helpful.

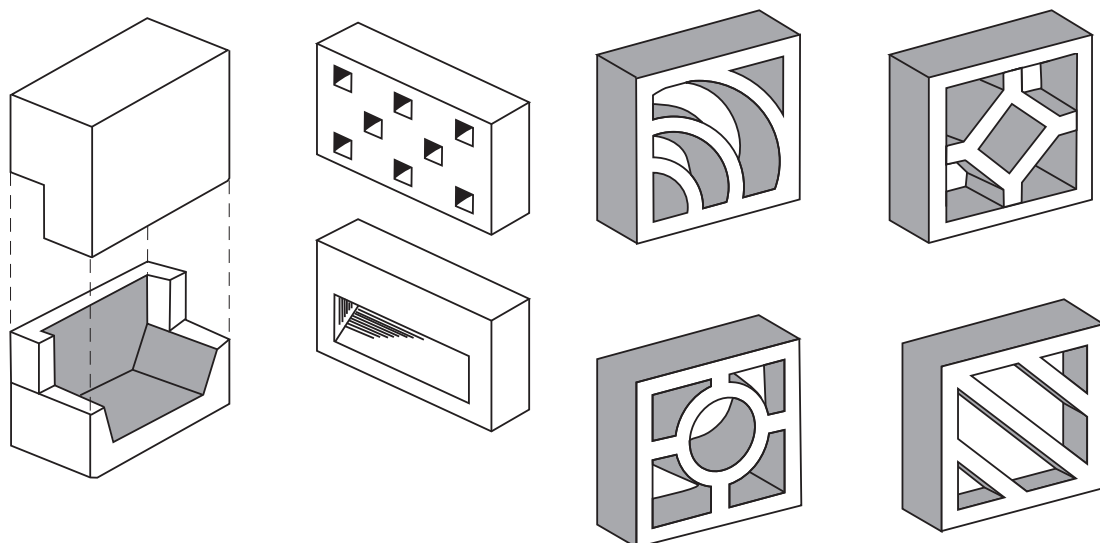


Figure 5.32 Ventilating and decorative concrete blocks

Mortar can also be made using pozzolana, bitumen, cutback or soil. A 1:2:9 lime-pozzolana-sand mortar is roughly equivalent to a 1:6 cement-sand mortar. Adobe and stabilized soil blocks are often laid in a mortar of the same composition as the blocks.

Tables 5.16 and 5.17 provide information on the materials required for a cubic metre of various mortars, and the amount of mortar per square metre, for several building units.

Starting with cement mortar, strength decreases with each type, although the ability to accommodate movement increases.

TABLE 5.16
Materials required per cubic metre of mortar

Type	Cement bags	Lime (kg)	Sand (m ³)
Cement mortar 1:5	6.0	-	1.1
Compo mortar 1:1:6	5.0	100.0	1.1
Compo mortar 1:2:9	3.3	13.5	1.1
Compo mortar 1:8	3.7	-	1.1
Compo mortar 1:3:12	2.5	150.0	1.1
Lime mortar 1:3	-	200.0	1.1

TABLE 5.17
Mortar required for various types of wall

Type of wall	Amount required per m ² wall
11.5 cm brick wall	0.25 m ³
22.2 cm brick wall	0.51 m ³
10 cm sand-cement block wall	0.008 m ³
15 cm sand-cement block wall	0.011 m ³
20 cm sand-cement block wall	0.015 m ³

Finishing mortar

This is sometimes used on floors and other surfaces to give a smooth finish, or as an extremely hard coating to increase resistance to wear. While such a top coating is prone to cracking, it seldom increases strength, and is difficult to apply without causing loose or weak parts. Concrete floors can normally be cast to the finished level directly, and be given a sufficiently smooth and hard surface without a top coating.

For coating, a mix of 1 part cement and 2–4 parts sand is used. The coating is placed in a 1–2 cm thick layer with a steel trowel. Before application, the surface of the underlying concrete slab should be cleaned and moistened.

Plastering and rendering

The term 'plastering' is usually applied to interior walls and ceilings to give jointless, hygienic and usually smooth surfaces, often over uneven backgrounds. Exterior plastering is usually called 'exterior rendering'.

Cement plaster can be used on most types of wall, but it does not adhere well to soil-block walls, as shrinking and swelling tend to crack the plaster. The mixing ratio is 1 part cement and 5 parts sand and, if the plaster is too harsh, 0.5–1 part of lime can be added. The wall is first moistened and then the plaster is applied in two coats of about 5 mm each, allowing at least 24 hours between layers. Cement plaster should not be applied on a wall while it is exposed to the sun.

Dagga plaster is a mixture of clay soil (such as red or brown laterite), stabilizer and water. The plaster is improved by adding lime or cement as a stabilizer and bitumen for waterproofing. A good mixture is 1 part lime or cement, 3 parts clay, 6 parts sand, 0.2 parts bitumen and water. Dagga plaster is applied on previously moistened earth or adobe brick walls in a layer 10–25 mm thick.

FERROCEMENT

Ferrocement is a highly versatile form of reinforced concrete made with closely spaced light reinforcing rods or wire mesh, and a cement and sand mortar. It can be worked with relatively unskilled labour.

The function of the wire mesh and reinforcing rods is first to act as a lath, providing the form to support the mortar in its plastic state, while, in the hardened state, it absorbs the tensile stresses in the structure, which the mortar alone is not able to withstand.

The reinforcing can be assembled in any desired shape, and the mortar applied in layers to both sides. Simple shapes, such as water tanks, can be assembled using wooden sticks as support for the reinforcing while the first coat of mortar is applied.

The mortar should have a mixing ratio of 1:2 to 1:4 cement/sand by volume, using the richer mix for the thinnest structures. The water/cement ratio should be below 0.5/1.0. Lime can be added in the proportion 1 part lime to 5 parts cement in order to improve workability.

The mechanical behaviour of ferrocement depends on the type, quantity, orientation and strength of the mesh and reinforcing rods. The most common types of mesh used are illustrated in Figure 5.33.

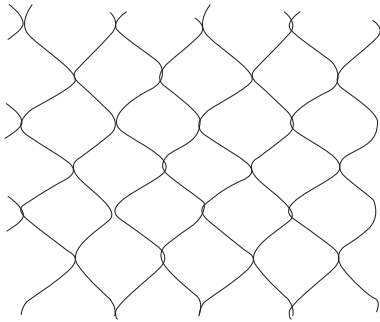
Standard galvanized mesh (galvanized after weaving) is adequate. Although non-galvanized wire has adequate strength, the problem of rusting limits its use.

A construction similar to ferrocement has recently been developed for small water tanks, sheds, huts, etc. It consists of welded 150 mm-square reinforcement mesh (6 mm rods), covered with hessian and plastered in the same way as ferrocement.

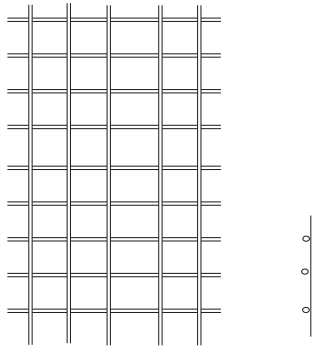
FIBRE-REINFORCED CONCRETE

Fibre-reinforced concrete members can be made thinner than those with conventional reinforcement because there is no need for a corrosion-protection covering over the steel bars. The fibres improve flexible strength and resistance to cracking.

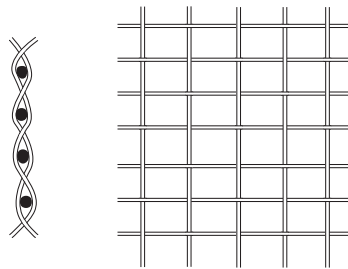
Commonly used fibres include asbestos, steel (0.25 mm diameter), sisal and elephant grass.



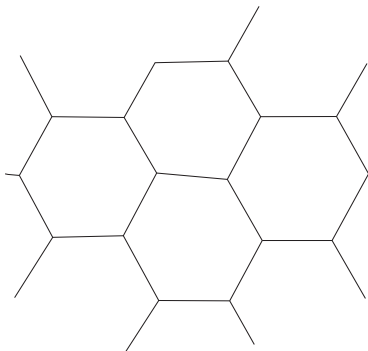
a. Hexagonal wire mesh (chicken wire mesh)



b. Welded wire mesh - strongest



c. Woven mesh - strong



d. Expanded wire mesh

Asbestos cement (AC)

Asbestos, which is a silicate of magnesium, is found as a rock that can be split into extremely thin fibres ranging from 2 mm to 900 mm long. These have good resistance to alkalis, neutral salts and organic solvents, and the varieties used for building products have good resistance to acids. Asbestos is non-combustible and able to withstand high temperatures without alteration.

Inhalation of asbestos dust causes asbestosis (a disease of the lungs) and asbestos is now used only where no alternative fibre is available. Workers must wear masks and take great care not to inhale any asbestos dust!

As the fibres are strong in tension and flexible, they are used as reinforcement with Portland cement, lime and bitumen binders, in asbestos-cement and asbestos-silica-lime products, vinyl floor tiles and in bitumen felts. Asbestos-cement is used in farm structures for corrugated roofing sheets, ridges and sanitary pipes.

Sisal-fibre-reinforced cement (SFRC)

Sisal and other vegetable fibres have only recently come into use for cement reinforcement.

Sisal fibre can be used as short, discontinuous fibres (15–75 mm in length), or as continuous long fibres exceeding 75 mm in length. Sometimes both short and long fibres are used together. The manner in which the fibres are incorporated into the matrix affects the properties of the composite, both in the fresh state and in the hardened state.

Sisal fibres may deteriorate if not treated. Although the alkalinity of the concrete helps to protect the fibres from outside attack, it may itself attack the fibres chemically by decomposing the lignin.

Sisal fibre reinforcing is used with various cement-sand mixing ratios, depending on the use:

Wall plastering	1:3
Guttering	1:2
Roofing tiles	1:1
Corrugated roofing sheets	1:0.5

The sand should be passed through a sieve with 1.5 mm to 2 mm holes (e.g. mosquito netting). The mixing water must be pure and the mix kept as dry as possible, while still being workable.

Between 16 grams and 17 grams of short (25 mm), dry sisal fibres are added to the mix for each kilogram of cement. The short fibres are mixed into the dry cement and sand before adding water. As sisal fibres have a high water-absorption capacity, some extra water may have to be added to the mix to compensate for this.

When mixing, there is a tendency for the fibres to ball and separate out from the rest of the mix. This tendency will increase with longer fibres but, if fibres shorter than 25 mm are used, the reinforcing effect will be reduced. In most cases, the mix is then trowelled onto a mesh of full-length sisal fibres.

Figure 5.33 Reinforcement meshes for ferrocement

Making corrugated reinforced roofing sheets

Home-made reinforced corrugated roofing is usually cast to standard width, but to only 1 metre in length because of its additional weight. Commercial asbestos-cement roofing is heavier than corrugated steel, and the home-made sheets are still heavier. Special attention must therefore be given to rafter or truss sizes to ensure a safe structure.

Although the casting procedure for sisal-fibre-reinforced cement is tricky, once the proper equipment has been assembled and several sheets have been made, the process becomes much easier.

A concrete block cast over a 1-metre length of asbestos-cement roofing is needed as a face for casting the roof sheets. The block is cast within a 100 mm-high form, which will give a block of sufficient strength after a few days curing. Two or more 1-metre lengths of asbestos-cement roofing will be needed, as well as a piece of 18 mm plywood, measuring 1.2 metres by 1.2 metres, and a sheet of heavy-duty polythene, measuring 2.25 metres long and 1 metre wide. The polythene is folded in the middle and a thin batten, measuring 9 mm by 15 mm, is stapled at the fold. Strips of 9 mm plywood or wood are nailed along two edges of the plywood sheet, leaving exactly 1 metre between them, as shown in Figure 5.34.

Below are the steps to follow in the casting procedure:

1. Fit an asbestos cement sheet onto the moulding block and cover with the piece of plywood, with the edge strips at the ends of the sheet. The polythene is placed over the plywood and the top sheet is folded back off the plywood.
2. Prepare a mix of 9 kg cement, 4.5 kg sand, 150 grams of short sisal fibres (25 mm) and 4.5 litres of water. Also prepare four 60-gram bundles of sisal fibres that are as long as possible.
3. Use one-third of the mortar mix to trowel a thin, even layer over the polythene. Take two of the four sisal bundles and distribute the fibres evenly, with the second bundle at right angles to the first, forming a mat of fibres. This is covered

with mortar and another mat made from the remaining two bundles. Finally, all the sisal is covered with the remaining mortar, and the surface is screeded even with the edge strips on the plywood.

4. Cover with the top sheet of polythene, ensuring that the mortar is of even thickness all over and that no air bubbles remain under the polythene.
5. While holding the batten strip at the fold in the polythene, carefully remove the plywood sheet to allow the new sisal-cement sheet to fall onto the asbestos-cement sheet. At the same time, press the new sheet into the corrugations using a PVC drain pipe 90 mm in diameter. Compact the new sheet by placing another asbestos sheet on top, and treading on it. Holes for mounting are punched with a 5 mm dowel 25 mm from the end in the gulleys (crests when mounted on the roof) of the fresh sheet.
6. Remove from the moulding block the asbestos sheet bearing the sisal-cement sheet, and leave it until the cement in the new sheet has set (preferably 2 days). Then carefully remove the new sheet, peel off the polythene and cure the new sheet for at least 1 week, preferably immersed in a water tank.
7. If more polythene and asbestos-cement sheets are available, casting can proceed immediately.

Walls using the sisal-cement plastering technique

Soil blocks can be used for inexpensive walls with good thermal insulation. However, they are easily damaged by impact and eroded by rain. One way of solving these problems is to plaster the face of the wall. Ordinarily, mortar plaster tends to crack and peel off, as it does not expand at the same rate as the soil. This can be overcome by letting long sisal fibres pass through the wall, to be incorporated into the mortar on each face. The double skin so formed provides sufficient strength

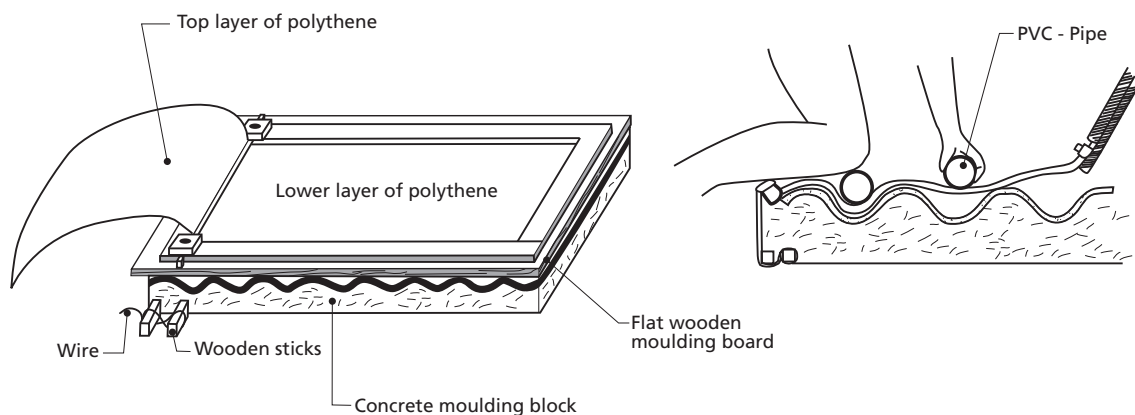


Figure 5.34 Plywood casting board and polythene 'envelope'

and waterproofing to the wall to enable soil blocks to be laid without mortar between the blocks to join them.

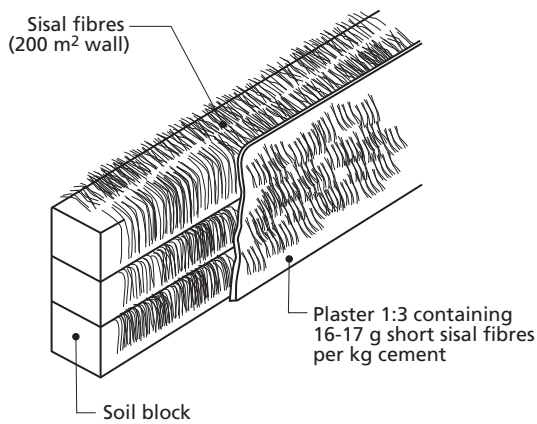


Figure 5.35 Sisal-cement plastering technique

METALS

Several ferrous metals (those containing iron) are useful in the construction of farm buildings and other rural structures. Cast iron is used for making sanitary waste pipes and fittings.

Steel consists of iron, plus a small percentage of carbon in chemical combination. High-carbon or 'hard' steel is used for tools with cutting edges. Medium-carbon steel is used for structural members such as I-beams, reinforcing bars and implement frames. Low-carbon or 'mild' steel is used for pipes, nails, screws, wire, screening, fencing and corrugated roof sheets.

Non-ferrous metals, such as aluminium and copper, are corrosion-resistant and are often chosen for this quality. Copper is used for electric wire, tubing for water supply and for flashing. Aluminium is most commonly used for corrugated roofing sheets, gutters and the accompanying nails. Using nails of the same material avoids the problem of corrosion caused by electrolytic action. Brass is a corrosion-resistant alloy of copper and zinc used extensively for building hardware.

Corrosion

Air and moisture accelerate corrosion in ferrous materials unless they are protected. Acids tend to corrode copper, while alkalis, such as that found in animal waste, portland cement and lime, as well as in some soils, cause rapid corrosion of aluminium and zinc. Electrolytic action, caused by slight voltages set up when dissimilar metals are in contact with each other in the presence of water, also encourages corrosion in some metals. Aluminium is particularly prone to electrolytic corrosion.

Corrosion can be reduced by the careful selection of metal products for the application, by reducing the time that the metal will be wet by preventing condensation

and promoting good drainage, by avoiding contact between dissimilar metals, and by using corrosion-inhibiting coatings.

Corrosion-inhibiting coatings

Copper, aluminium, stainless steel and cast iron tend to form oxide coatings that provide a considerable amount of self-protection from corrosion. However, most other steels require protective coatings if they are exposed to moisture and air. Methods used include zinc coating (galvanizing), vitreous enamel glazing and painting. Painting is the only practical method for field application, although grease and oil will provide temporary protection.

Before painting, the metal surface must be clean, dry and free from oil. Both bituminous and oil-based paints with metallic oxide pigments offer good protection, if they are carefully applied in continuous layers. Two to three coats provides the best protection.

BUILDING HARDWARE

Nails

A nail relies on the grip around its shank and the shear strength of its cross-section to give strength to a joint. It is important to select the right type and size of nail for any particular situation. Nails are specified by their type, length and gauge (the higher the gauge number, the smaller the shank diameter). See Table 5.18. Most nails are made from mild steel wire. In a corrosive environment, galvanized, copper-plated, copper or aluminium nails are used. A large number of nail types and sizes are available on the market. Below is a description of the nails most commonly used in farm buildings.

Round plain-headed nails or round wire nails are used for general carpentry work. As they have a tendency to split thin members, the following rule is often used: the diameter of the nail should not exceed $1/7$ of the thickness of the timber.

TABLE 5.18
Dimensions and approximate number per kilogram
of commonly used sizes of round wire nails

Length		Diameter (mm)	Approximate number/kg
(inches)	(mm)		
6	150	6.0	29
5	125	5.6	42
4	100	4.5	77
3	75	3.75	154
2.5	65	3.35	230
2	50	2.65	440
1.5	40	2.0	970
1	25	1.8	1 720

Lost-head nails have a smaller head, which can be set below the surface of the wood. Their holding power is lower because the head can be pulled through the wood more easily.

Panel pins are fine wire nails with small heads, used for fixing plywood and hardboard panels.

Clout or slate nails have large heads and are used for fixing tiles, slates and soft boards. Felt nails have even larger heads.

Concrete nails are made from harder steel, which allows them to be driven into concrete or masonry work.

Staples are U-shaped nails with two points, and are used mainly to fasten wires.

Roofing nails have a square, twisted shank and a washer attached to the head. Roofing felt or rubber may be used under the washer to prevent leakage. The nail and the washer should be galvanized to prevent corrosion. They are used for fixing corrugated-sheet materials and must be long enough to penetrate at least 20 mm into the wood. Alternatively, wire nails with used bottle caps for washers can be used.

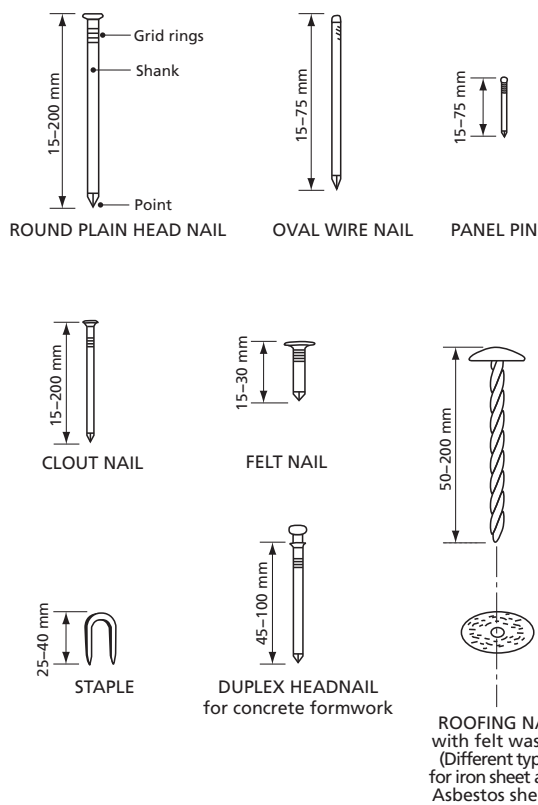


Figure 5.36 Types of nails

Screws and bolts

Wood screws have a thread, which gives them greater holding power and resistance to withdrawal than nails, and they can be removed easily without damaging the wood. For a screw to function properly, it must be

inserted by rotation, and not by being driven with a hammer. It is usually necessary to drill a pilot hole for the shank of the screw. Screws made of mild steel are normally preferred because they are stronger. A wide range of finishes, such as galvanized, painted and plated, are available.

Screws are classified according to the shape of their head, as countersunk, raised, round or recessed (not slotted across the full width). Coach screws have a square head and are turned with a spanner. They are used for heavy construction work and should have a metal washer under the head to prevent damage to the wood surface. Screws are sold in boxes containing a gross (144 screws), and are specified by their material, finish, type, length and gauge. Unlike the wire gauge used for nails, the larger the screw-gauge number, the greater the diameter of the shank.

Bolts provide even stronger joints than either nails or screws. As the joint is secured by tightening the nut onto the bolt, in most cases the load becomes entirely a shear force. Bolts are used for heavy loads, such as at the joints in a gantry hoist frame, at the corners of a ring beam installed for earthquake protection, or to secure the hinges of heavy doors. Most bolts used with wood have a rounded head, with a square shank just under the head. Only one spanner is required for these ‘coach’ bolts. Square-head bolts, requiring two spanners, are also available. Washers help to prevent the nuts from sinking into the wood.

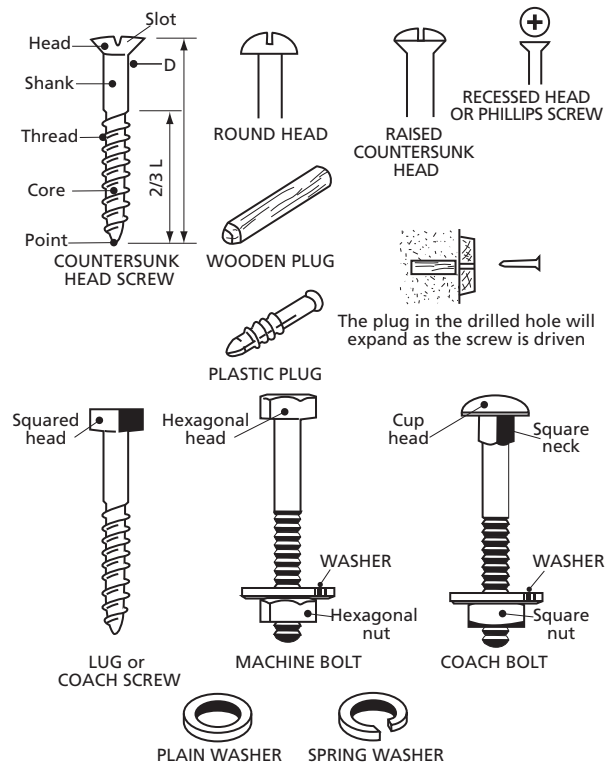


Figure 5.37 Types of wood screws and bolts

TABLE 5.19
Conversion of screw gauge to millimetres

Screw gauge	0	1	2	3	4	5	6	7	8	9	10	12	14	16	18	20	24	28	32
Nominal diameter of unthreaded shank (mm)	1.52	1.78	2.08	2.39	2.74	3.10	3.45	3.81	4.17	4.52	4.88	5.59	6.30	7.01	7.72	8.43	9.86	11.28	12.70

Hinges

Hinges are classified by their function, length of nap and the material from which they are made, and come in many different types and sizes. Hinges for farm buildings are manufactured mainly from mild steel and are provided with a corrosion-inhibiting coating. The most common types are described below.

The *steel butt hinge* is commonly used for windows, shutters and small doors, as it is cheap and durable. If the pin can be removed from the outside, it is not burglarproof. The flaps are usually set in recesses in the door or window and the frame.

The *H-hinge* is similar to the butt hinge but is usually surface mounted.

The *T-hinge* is used mostly for hanging match-boarded doors. For security reasons, the strap of the T-hinge should be fixed to the door with at least one coach bolt, which cannot be unscrewed easily from the outside.

The *band-and-hook hinge* is a stronger type of T-hinge and is used for heavy doors and gates. This type is suitable for fabrication at the site or by the local blacksmith.

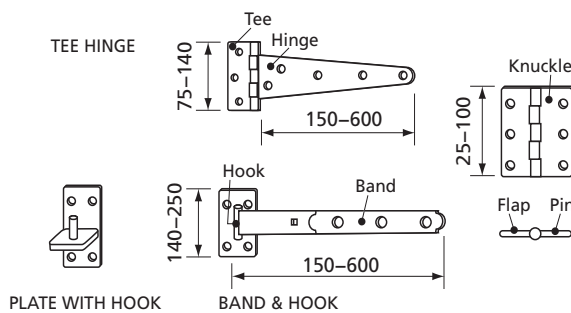


Figure 5.38 Types of hinges

Locks and latches

Any device used to keep a door in the closed position can be classified as a lock or latch. A lock is activated by means of a key, whereas a latch is operated by a lever or bar. Locks can be obtained with a latch bolt so that the door can be kept in a closed position without using the key. Locks in doors are usually fixed at a height of 1 050 mm. Some examples of common locks and latches used in farm buildings are illustrated in Figure 5.39.

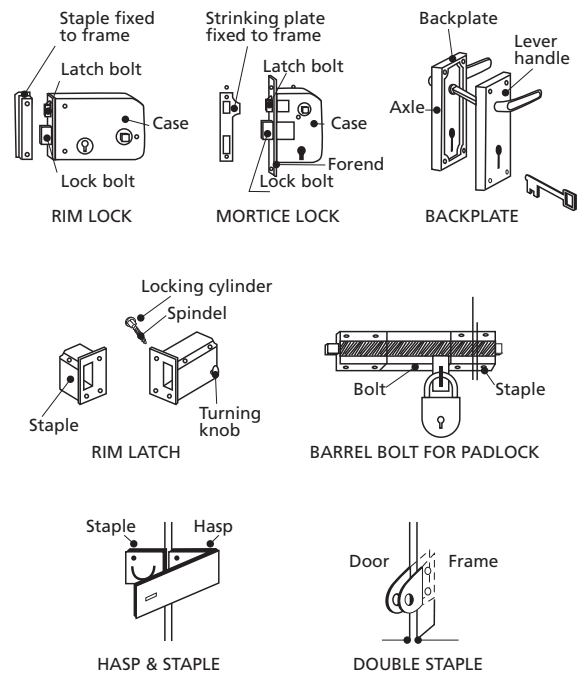


Figure 5.39 Types of locks and latches

GLASS

Glass suitable for general window glazing is made mainly from soda, lime and silica. The ingredients are heated in a furnace to about 1 500 °C, and fuse together in the molten state. Sheets are then formed by a process of drawing, floating or rolling. The ordinary glazing quality is manufactured by drawing in thicknesses ranging from 2 mm to 6 mm. It is transparent, with 90 percent light transmission. As the two surfaces are never perfectly flat or parallel, there is always some visual distortion. Plate glass is manufactured with ground and polished surfaces, and should be free of imperfections.

Glass in buildings is required to resist loads, including wind loads, impacts from people and animals, and sometimes thermal and other stresses. Generally the thickness increases with the area of the glass pane. Glass is elastic right up to its breaking point but, as it is also completely brittle, there is no permanent set or warning of impending failure. The support provided for glass will affect its strength performance. Glass should be cut to give a minimum clearance of 2 mm all around the frame to allow for thermal movements.

PLASTICS

Plastics are among the newest building materials, ranging from materials strong enough to replace metal, to foam-like products. Plastics are considered to be mainly organic materials derived from petroleum and, to a small extent, coal, which at some stage in their processing are plastic when heated.

The range of properties is so great that generalizations are difficult to make. However, plastics are usually light in weight and have a good strength-to-weight ratio, but rigidity is lower than that of virtually all other building materials, and creep is high.

Plastics have low thermal conductivity and thermal capacity, but thermal movement is high. They resist a wide range of chemicals and do not corrode, but they tend to become brittle with age.

Most plastics are combustible and may release poisonous gases in a fire. Some are highly flammable, while others are difficult to burn.

Plastics lend themselves to a wide range of manufacturing techniques, and products are available in many forms, both solid and cellular, from soft and flexible to rigid, and from transparent to opaque. Various textures and colours are available (many of which fade if used outdoors). Plastics are classified as:

- *Thermoplastics*, which always soften when heated and harden again on cooling, provided they are not overheated.
- *Thermosetting plastics*, which undergo an irreversible chemical change in which the molecular chains crosslink so that subsequently they cannot be appreciably softened by heat. Excessive heating causes charring.

Thermoplastics

Polythene is tough, waterproof and oilproof, and can be manufactured in many colours. In buildings, it is used for cold water pipes, plumbing and sanitary ware, and polythene film (translucent or black). Film should not be subjected unnecessarily to prolonged heat over 50 °C, or to direct sunlight. The translucent film will last for only 1–2 years if exposed to sunlight, but the carbon pigmentation of black film increases resistance to sunlight.

Polyvinyl chloride (PVC) will not burn and can be made in rigid or flexible form. It is used for rainwater goods, drains, pipes, ducts, electric cable insulation, etc.

Acrylics, a group of plastics containing polymethyl methacrylate, which transmit more light than glass and are easy to mould or curve into almost any shape.

Thermosetting plastics

The main uses for thermosetting plastics in buildings are as impregnants for paper fabrics, binders for particle boards, adhesives, paints and clear finishes. Phenol formaldehyde (bakelite) is used for electrical insulating accessories, and urea formaldehyde is used for particle board manufacture.

In most cases, epoxy resins are provided in two parts: a resin and a curing agent. They are extremely tough and stable, and adhere well to most materials. Silicone resins are water-repellent and used for waterproofing in masonry. Note that fluid plastics can be very toxic.

Plastics used for seepage protection in dams

Seepage from dams is a common problem. Occasionally, site conditions and the lack of local clay may require the use of synthetic liners, also called geomembranes, to line the dam and overcome the problem of seepage. If the correct product is selected and good installation procedures are used, only normal maintenance will be needed during the service life of the dam.

Three types of lining material are available: low-density plastic sheeting; woven polyethylene fabric; and high density polyethylene (HDPE) sheeting. All of these products are susceptible to degradation by introduced chemicals. The most suitable product for a specific job depends on a number of factors. These include: site conditions, cost, resistance to sunlight, strength, resistance to puncturing and the method of joining.

Low-density plastic sheeting

Commonly referred to as ‘builder’s plastic’, these sheets are normally black or orange in colour. Low-density plastic sheeting is manufactured in various thicknesses, with the recommended thickness being 0.2–0.3 mm. This sheeting punctures easily, as it is relatively thin. It is suitable for use on low slopes (less than 2:1, i.e. 2 metres horizontal to 1 metre vertical) and on sites free of sticks, small stones and abrasive materials. Extreme care needs to be taken during installation. Low-density plastic breaks down quickly in sunlight if it is not covered with soil.

Woven polyethylene fabric

This has a polyethylene coating on both sides, and is blue or green in colour. Woven polyethylene fabrics are generally the most suitable as dam liners in temperate countries, and are sold according to weight, not thickness. Fabric weight of about 250 grams per square metre is normally selected for farm dams. Heavier grades are required where puncturing is a concern. Although polyethylene fabrics are not UV resistant, their life expectancy can be increased to 15–20 years with soil cover.

It is normal practice to cover these fabrics with at least a 300 mm layer of soil. Owing to the need to provide this cover, sites with steep batters (greater than 2:1) are not suitable. For woven polyethylene fabrics used as dam liners, the batter slopes of the embankment and excavations should not exceed 2:1, although a gentler slope is preferable to ensure that any soil cover stays on the liner.

High-density polyethylene (HDPE) sheeting

High-density polyethylene sheeting, which is black in colour, does not require soil cover, but it is the most expensive of lining materials. Installation is generally undertaken using fusion-weld joining equipment. Thicknesses range from 0.4 mm to 2.5 mm. It is suitable for sites where puncturing of cheaper products cannot be avoided, or where steep slopes (steeper than 2:1) preclude the use of other products.

HDPE is the most widely used geomembrane, and offers the most cost-effective liner for large, exposed, lining projects. This product has been used in landfills, wastewater treatment lagoons, animal waste lagoons, mining applications and water storage. It has the following advantages:

- soil covering is not required;
- it has high overall chemical resistance and is resistant to ozone and UV;
- it is cost effective for large projects;
- it is suitable for potable water.

Plastic components used with dam liners

In the process of lining dams, there may be needed one or more additional components that will ensure the longevity of the earth dam. These components include:

(a) Geosynthetics:

These are synthetic materials made from polymers (geomembranes are also classified under geosynthetics). When these materials are used together with dam liners (geomembranes), the service life of the earth dam is extended. The geosynthetics commonly used together with dam liners include:

1. *Geonets:* These are open grid-like materials formed by a continuous extrusion of parallel sets of polymeric ribs intersecting at a constant acute angle. They are used in the design of drainage systems, particularly on slopes and are a viable alternative to the common sand and gravel systems.
2. *Geocells:* These are constructed from polymeric strips, which are joined together to form a 3-dimensional network. They are used to stabilize the side slopes of dams and other earth structures. This usually involves filling the cells with soil.
3. *Geogrids:* These are stiff or flexible polymer grid-like sheets with large uniformly distributed apertures. These apertures allow direct contact between soil particles on either side of the sheet. Their main use is to reinforce unstable soils.

Combination of two or more of the geosynthetics, e.g. geogrid and geomembrane, are referred to as

geocomposites. Several combinations are possible and this area has attracted interest of many research establishments. The main uses of geocomposites embrace the entire range of uses of the geosynthetics discussed above, e.g. reinforcement, drainage, liquid barrier, etc.

(b) Degradable erosion mats:

These are made of flexible erosion control blankets that are used to keep soil and seeds stable until vegetation completely covers the dam catchment. As they are made of organic materials, they eventually breakdown and become part of the soil.

RUBBER

Rubbers are similar to thermosetting plastics. In the manufacturing process, a number of substances are mixed with latex, a natural polymer. Carbon black is added to increase strength in tension and to improve wearing properties.

After forming, the product is vulcanized by heating under pressure, usually with sulphur present. This process increases the rubber's strength and elasticity. Ebonite is a fully vulcanized, hard rubber.

Modified and synthetic rubbers (elastomers) are increasingly being used for building products. Unlike natural rubbers, they often have good resistance to oil and solvents. One such rubber, butyl, is extremely tough, has good weather resistance, excellent resistance to acids and very low permeability to air. Synthetic rubber fillers and nail washers are used with metal roofing.

BITUMINOUS PRODUCTS

These include bitumen (asphalt in the United States), coal tar and pitch. They are usually dark brown or black and, in general, they are durable materials that are resistant to many chemicals. They resist the passage of water and water vapour, especially if they have been applied hot.

Bitumen occurs naturally as rock asphalt or lake asphalt, or can be distilled from petroleum. It is used for road paving, paint, damp-proof membranes, joint filler, stabilizer in soil blocks, etc.

PAINTS

Paint preserves, protects and decorates surfaces, and enables them to be cleaned easily. All paints contain a binder that hardens. Other ingredients found in various paints include: pigments, strainers, extenders, driers, hardeners, thinners, solvents and gelling agents. Some water-thinned paints contain emulsifiers.

Owing to the cost involved, few buildings in rural areas are painted. When paint can be afforded, priority should be given to painting surfaces likely to rust, rot or decay because of exposure to rain or dampness, and to rooms such as a kitchen or a dairy, where hygiene demands easily cleaned surfaces. White and other light

colours reflect more light than dark colours, and can be used in a sitting room or a workshop to make the room lighter.

Painting

Adequate preparation of the surface to be painted is essential. The surface should be smooth (not shiny, because this would not give good adhesion), clean, dry and stable. Old, loose paint should be brushed off before a new coat is applied. Most commercial paints are supplied with directions for use, which should be read carefully before the work is started. The paint film is usually built up in two or more coats;

Priming paints are used for the first coat, to seal and protect the surface and to give a smooth surface for subsequent coats. They are produced for application to wood, metal and plaster.

Undercoating paints are sometimes used to obscure the primer, as a further protective coating and to provide the correct surface for the finishing paint.

Finishing paints are produced in a wide range of colours and finishes (e.g. matt, semi-matt or gloss). Some commonly used types of paint for farm structures are detailed below, but many others are manufactured with special properties, making them water- and chemical-resistant, heat-resistant, fire-retardant, anti-condensation, fungicidal or insecticidal, for example.

Estimation of quantities of paint required

The volume of paint required for a particular paint job can be determined from knowledge of the following:

1. Surface area of the surface(s) to be painted.
2. Spreading rate of the paint being used.
3. The number of coats needed.

Spreading rates

The spreading rate of paint is the area that a specific volume of paint will cover at a specified film thickness. Two standard measurements are used to describe the film thickness of a coating: mils and microns. A micron is a metric system measurement equal to 0.001 millimetres.

The spreading rate in microns may be calculated as follows:

Any liquid will cover 1 000 square metres per litre at 1 micron wet. Therefore, a 100 percent volume/solids material will cover 1 000 m² per litre dry when applied at 1 micron wet and, because it is 100 percent solids, it will yield a 1 micron-thick dry film. However, if a coating is less than 100 percent solids, then the dry film thickness will be thinner because the volatile portion of the volume will evaporate and leave the film, thereby reducing the dried film volume or thickness.

Assuming a material has 42 percent volume of solids, the area that it will cover when a dry film thickness of 38.1 microns is required may be calculated as follows:

1 000 m² / litre × 0.42 = 420 m² / litre at 1 micron thickness.

Assuming 38.1 microns dry is desired, then:

$$420 \text{ m}^2 / \text{litre} / 38.1 = 11.0 \text{ m}^2 / \text{litre}$$

A coating with 42 percent volume solids, applied at 11.0 m² / litre, will produce a dry film that is 38.1 microns thick.

Example 5.4

The living room walls require painting, excluding the ceiling. The walls are 3 metres high, with a total of 18 metres of wall length. The total door and window area is 3 m². If a spreading rate of 11 square metres per litre is used, and only two coats of paint are required, work out how much paint is needed.

To work out how much paint is needed:

- Take the surface area = (3×18) - 3 = 51 m²
- The spreading rate is 11 m² / litre
- The number of coats needed = 2
- The required litres of paint = (51m² / 11m² / litres) × 2 coats = 9 litres in total (i.e. a 10-litre pail)

Oil- and resin-based paints

Oil paints are based on naturally drying oils (e.g. linseed oil). They are being gradually replaced by alkyd and emulsion paints.

Alkyd paints are oil-based paints, modified by the addition of synthetic resins to improve durability, flexibility, drying and gloss. They are quite expensive.

Synthetic resin paints contain substantial proportions of thermosetting resins, such as acrylics, polyurethane or epoxides, and are often packed in two parts. They have excellent strength, adhesion and durability, but are very expensive.

Bituminous paints are used to protect steelwork and iron sheeting from rust, and to protect wood from decay. They are black or dark in colour, and tend to crack in hot sunlight. They can be overpainted with ordinary paint only after a suitable sealer has been applied.

Varnishes are either oil/resin or spirit-based and used mainly to protect wood with a transparent finish, but protection is inferior to opaque finishes. Spirit-based varnish is used only for interior surfaces.

Water-based paints

Non-washable distemper consists of chalk powder, mixed with animal glue dissolved in hot water. It is cheap, but easily rubbed or washed off, and therefore suitable only for whitening ceilings.

Washable distemper (water paint) consists of drying oil or casein, emulsified in water with the addition of pigments and extenders. Hardening is slow but, after a month, it can withstand moderate scrubbing. It weathers fairly well outdoors and is reasonably cheap.

Whitewash (limewash) consists of lime mixed with water. It can be used on all types of wall, including earth walls, and is cheap, but its lack of water resistance and poor weathering properties make it inferior to emulsion

paint for outdoor surfaces. However, the addition of tallow or cement gives some degree of durability for external use. Whitewash can be made in the following way:

- Mix 8 litres (9 kg) of quicklime with about 18 litres of boiling water, adding the water slowly and stirring constantly until a thin paste results.
- Add 2 litres of salt and stir thoroughly.
- Add water to bring the whitewash to a suitable consistency.
- If external quality is required, add a handful of cement per 10 litres of whitewash just before use.

In *emulsion paints*, the pigments and binder (vinyl, acrylic, urethane or styrene polymers) are dispersed as small globules in water. They harden quickly, are quite tough and weather-resistant, and the cost is moderate. Although they adhere well to most supports, because they are permeable an oil-based primer may be required to seal porous exterior surfaces.

Cement-based paints are often used for exteriors, and are quite inexpensive. They contain white portland cement, pigments (if other colours are desired) and water-repellents, and are sold in powder form. Water is added just before use to obtain a suitable consistency. Paint that has thickened must not be thinned further. It adheres well to brickwork, concrete and renderings, but not to timber, metal or other types of paint. Surfaces should be dampened before painting.

Cement slurries make economical surface coatings on masonry and concrete, but earth walls that shrink and swell will cause the coating to peel off. Slurries are mixtures of cement and/or lime, clean fine sand and enough water to make a thick liquid. A good slurry can be made using 1 part cement, 1 part lime and up to 4 parts sand. It is applied on the dampened surface with a large brush or a used bag, hence the name 'bag washing'.

REVIEW QUESTIONS

1. (a) Explain how the following factors affect construction material choice:
 - (i) resource utilization in the choice of construction materials;
 - (ii) social costs and shadow prices.
 (b) Define the following for cement:
 - (i) hydration;
 - (ii) setting.
 (c) Briefly describe the Pozzolana as a building material.
2. (a) Outline three disadvantages of soil as a construction material.
 (b) During the bar shrinkage test the following results were obtained:
 - Length of wet bar = 600 mm
 - Length of dry bar = 420 mm
 Find the shrinkage ratio and state the conclusion that may be drawn from this result.
 (c) Briefly describe how burnt (soil) bricks are made.
3. (a) Name five methods for seasoning wood.
 (b) Briefly outline the Bethel full-cell process of timber preservation.
4. Briefly describe: geonets, geocells and degradable erosion mats.
5. The tensile strength of blue gum timber is 50 MPa at a moisture content of 12 percent. If the strength determined in its green state was 42 MPa, and its fibre saturation point occurs at a moisture content of 25 °C, find the strength of this timber at a moisture content of 8 percent. If the density of the wood was 1.4 g/cm³ at moisture content of 12 percent, find the density at a moisture content of 8 percent.
6. (a) Briefly describe glass as a building material.
 (b) Briefly describe three main types of paint.
 - (i) Assuming paint has 42 percent volume of solids, find the area that 1 litre will cover when a dry film thickness of 38.1 microns is required.
 - (ii) The walls of a room are 3 metres high, with a total of 30 metres of wall length. The total door and window area is 3 square metres. If the spreading rate is 11 square metres per litre, and only two coats of paint are required, work out how much paint is needed.

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