# Masonry Construction

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# Table of Contents

## Chapter- 1

# Masonry

A mason laying mortar on top of a finished course of blocks, prior to placing the next course.

**Masonry** is the building of structures from individual units laid in and bound together by mortar; the term *masonry* can also refer to the units themselves. The common materials of masonry construction are brick, stone such as marble, granite, travertine, limestone; concrete block, glass block, stucco, and tile. Masonry is generally a highly durable form

of construction. However, the materials used, the quality of the mortar and workmanship, and the pattern in which the units are assembled can significantly affect the durability of the overall masonry construction.

Masonry units, such as brick, tile, stone, glass brick or concrete block generally conform to the requirements specified in the 2003 International Building Code (IBC) Section 2103.

## *Applications*

Masonry is commonly used for the walls of buildings, retaining walls and monuments. Brick and concrete block are the most common types of masonry in use in industrialized nations and may be either weight-bearing or a veneer. Concrete blocks, especially those with hollow cores, offer various possibilities in masonry construction. They generally provide great compressive strength, and are best suited to structures with light transverse loading when the cores remain unfilled. Filling some or all of the cores with concrete or concrete with steel reinforcement (typically rebar) offers much greater tensile and lateral strength to structures.

### Advantages

- The use of materials such as brick and stone can increase the thermal mass of a building.
- Brick typically will not require painting and so can provide a structure with reduced life-cycle costs.
- Masonry is very heat resistant and thus provides good fire protection.
- Masonry walls are more resistant to projectiles, such as debris from hurricanes tornadoes.
- Masonry structures built in compression preferably with lime mortar can have a useful life of more than 500 years as compared to 30 to 100 for structures of steel or reinforced concrete.

### Disadvantages

- Extreme weather causes degradation of masonry wall surfaces due to frost damage.
- This type of damage is common with certain types of brick, though rare with concrete blocks.
- Masonry tends to be heavy and must be built upon a strong foundation usually reinforced concrete to avoid settling and cracking.

### Structural limitations

Masonry boasts an impressive compressive strength (vertical loads) but is much lower in tensile strength (twisting or stretching) unless reinforced. The tensile strength of masonry

walls can be strengthened by thickening the wall, or by building masonry *piers* (vertical columns or ribs) at intervals. Where practical, steel reinforcements can be added.

## *Veneer masonry*

A masonry veneer wall consists of masonry units, usually clay-based bricks, installed on one or both sides of a structurally independent wall usually constructed of wood or masonry. In this context the brick masonry is primarily decorative, not structural. The brick veneer is generally connected to the structural wall by brick ties (metal strips that are attached to the structural wall, as well as the mortar joints of the brick veneer). There is typically an air gap between the brick veneer and the structural wall. As clay-based brick is usually not completely waterproof, the structural wall will often have a water-resistant surface (usually tar paper) and weep holes can be left at the base of the brick veneer to drain moisture that accumulates inside the air gap. Concrete blocks, real and cultured stones, and veneer adobe are sometimes used in a very similar veneer fashion.

Most insulated buildings that utilize concrete block, brick, adobe, stone, veneers or some combination thereof feature interior insulation in the form of fiberglass batts between wooden wall studs or in the form of rigid insulation boards covered with plaster or drywall. In most climates this insulation is much more effective on the exterior of the wall, allowing the building interior to take advantage of the aforementioned thermal mass of the masonry. This technique does, however, require some sort of weather-resistant exterior surface over the insulation and, consequently, is generally more expensive.

## *Dry set masonry*

Dry set masonry supports a rustic log bridge, where it provides a well-drained support for the log (this will increase its service life).

The strength of a masonry wall is not entirely dependent on the bond between the building material and the mortar; the friction between the interlocking blocks of masonry is often strong enough to provide a great deal of strength on its own. The blocks sometimes have grooves or other surface features added to enhance this interlocking, and some *dry set* masonry structures forgo mortar altogether.

## *Solid masonry*

Solid masonry, without steel reinforcement, tends to have very limited applications in modern wall construction. While such walls can be quite economical and suitable in some applications, susceptibility to earthquakes and collapse is a major issue. Solid unreinforced masonry walls tend to be low and thick as a consequence.

## *Brick*

Solid brickwork is made of two or more layers of bricks with the units running horizontally (called *stretcher* bricks) bound together with bricks running transverse to the wall (called "header" bricks). Each row of bricks is known as a course. The pattern of headers and stretchers employed gives rise to different **bonds** such as the common bond (with every sixth course composed of headers), the English bond, and the **Flemish bond** (with alternating stretcher and header bricks present on every course). Bonds can differ in strength and in insulating ability. Vertically staggered bonds tend to be somewhat stronger and less prone to major cracking than a non-staggered bond.

### Uniformity and rusticity

The wide selection of brick styles and types generally available in industrialized nations allow much variety in the appearance of the final product. In buildings built during the 1950s-1970s, a high degree of uniformity of brick and accuracy in masonry was typical. In the period since then this style was thought to be too sterile, so attempts were made to emulate older, rougher work. Some brick surfaces are made to look particularly rustic by including *burnt* bricks, which have a darker color or an irregular shape. Others may use antique salvage bricks, or new bricks may be artificially aged by applying various surface treatments, such as tumbling. The attempts at rusticity of the late 20th century have been carried forward by masons specializing in a free, artistic style, where the courses are intentionally *not* straight, instead weaving to form more organic impressions.

### Serpentine masonry

A crinkle-crankle wall is a brick wall that follows a serpentine path, rather than a straight line. This type of wall is more resistant to toppling than a straight wall; so much so that it may be made of a single thickness of unreinforced brick and so despite its longer length may be more economical than a straight wall.

## *Concrete block*

Concrete masonry units (CMUs) or blocks in a basement wall before burial.

Blocks of cinder concrete (*cinder blocks* or *breezeblocks*), ordinary concrete (*concrete blocks*), or hollow tile are generically known as Concrete Masonry Units (CMU)s. They usually are much larger than ordinary bricks and so are much faster to lay for a wall of a given size. Furthermore, cinder and concrete blocks typically have much lower water absorption rates than brick. They often are used as the structural core for veneered brick masonry, or are used alone for the walls of factories, garages and other industrial style buildings where such appearance is acceptable or desirable. Such blocks often receive a stucco surface for decoration. Surface-bonding cement, which contains synthetic fibers for reinforcement, is sometimes used in this application and can impart extra strength to a block wall. Surface-bonding cement is often pre-coloured and can be stained or painted thus resulting in a finished stucco-like surface.

The primary structural advantage of concrete blocks in comparison to smaller clay-based bricks is that a CMU wall can be reinforced by filling the block voids with concrete with or without steel rebar. Generally, certain voids are designated for filling and reinforcement, particularly at corners, wall-ends, and openings while other voids are left empty. This increases wall strength and stability more economically than filling and reinforcing all voids. Typically, structures made of CMUs will have the top course of blocks in the walls filled with concrete and tied together with steel reinforcement to form a bond beam. Bond beams are often a requirement of modern building codes and controls. Another type of steel reinforcement, referred to as ladder-reinforcement, can

also be embedded in horizontal mortar joints of concrete block walls. The introduction of steel reinforcement generally results in a CMU wall having much greater lateral and tensile strength than unreinforced walls.

CMUs can be manufactured to provide a variety of surface appearances. They can be colored during manufacturing or stained or painted after installation. They can be split as part of the manufacturing process, giving the blocks a rough face replicating the appearance of natural stone, such as brownstone. CMUs may also be scored, ribbed, sandblasted, polished, striated (raked or brushed), include decorative aggregates, be allowed to slump in a controlled fashion during curing, or include several of these techniques in their manufacture to provide a decorative appearance.

"Glazed concrete masonry units are manufactured by bonding a permanent colored facing (typically composed of polyester resins, silica sand and various other chemicals) to a concrete masonry unit, providing a smooth impervious surface."

Glass block or glass brick are blocks made from glass and provide a translucent to clear vision through the block.

## *A-Jacks*

A-jacks (used in erosion control walls and sea walls) are highly stable, concrete 6-pronged armor units designed to interlock into a flexible, highly permeable matrix. They can be installed either randomly or in a uniform pattern. They look like giant 3-foot versions of the metal jacks that children play with.

In the uniform placement pattern, each unit is in contact with the six adjacent units, providing high stability. They are patterned after the buckyball model.

## *Stonework*

- Stone blocks used in masonry can be dressed or rough.
- Stone masonry utilizing dressed stones is known as ashlar masonry, whereas masonry using irregularly shaped stones is known as rubble masonry. Both rubble and ashlar masonry can be laid in courses rows of even height through the careful selection or cutting of stones, but a great deal of stone masonry is uncoursed.
- Natural stone veneers over CMU, cast-in-place, or tilt-up concrete walls are widely used to give the appearance of stone masonry.
- Sometimes river rock smooth oval-shaped stones is used as a veneer.
- This type of material is not favored for solid masonry as it requires a great amount of mortar and can lack intrinsic structural strength.
- Manufactured-stone, or cultured stone, veneers are popular alternatives to natural stones.
- Attractive natural stone has become more expensive in many areas and in some areas is practically unavailable.
- Manufactured-stone veneers are typically made from concrete.

- Natural stones from quarries around the world are sampled and recreated using molds, aggregate, and colorfast pigments.
- To the casual observer there may be no visual difference between veneers of natural and manufactured stone.

## *Gabions*

Gabions are rectangular wire baskets, usually of zinc-protected steel (galvanized steel) that are filled with fractured stone of medium size. These will act as a single unit and are stacked with setbacks to form a revetment or retaining wall. They have the advantage of being both well drained and flexible, and so resistant to flood, water flow from above, frost damage, and soil flow. Their expected useful life is only as long as the wire they are composed of and if used in severe climates (such as shore-side in a salt water environment) must be made of appropriate corrosion-resistant wire.

## *Bagged concrete*

A low grade concrete may be placed in woven plastic sacks similar to that used for sandbags and then emplaced. The sacks are then watered and the emplacement then becomes a series of artificial stones that conform to one another and to adjacent soil and structures. This conformation makes them resistant to displacement. The sack becomes non-functional and eventually disintegrates. This type of masonry is frequently used to protect the entrances and exits of water conduits where a road passes over a stream or dry wash. It is also used to protect stream banks from erosion, especially where a road passes close by.

## *Masonry training*

Stonemasonry is one of the oldest professions in the history of construction. As such it is regarded as a traditional skill, and is one which is in heavy demand.

Prospective stonemasons will learn the profession through apprenticeships or a traineeship that will last 3 to 4 years. There are City & Guilds stonemasonry courses available that combine college based theory training with practical learning.

## *Passive fire protection (PFP)*

Masonry walls have an endothermic effect of its hydrates, as in chemically bound water, as well as unbound moisture from the concrete block, as well as the poured concrete if the hollow cores inside the blocks are filled.

Chapter- 2

# Brick

An old brick wall in *English bond* laid with alternating courses of *headers* and *stretchers*

Bricked Front Street along the Cane River in historic Natchitoches, Louisiana

A **brick** is a block of ceramic material used in masonry construction, usually laid using various kinds of mortar.

## *History*

The Roman Constantine Basilica in Trier, Germany, built in the 4th century with fired bricks as audience hall for Constantine I

The oldest discovered bricks, originally made from shaped mud and dating to before 7500 B.C. were found at Tell Aswad then later in the upper Tigris region and in southeast Anatolia close to Diyarbakir. Other more recent findings, dated between 7,000 and 6,395 B.C., come from Jericho and Catal Hüyük. The first sun-dried bricks were made in Mesopotamia (what is now Iraq), in the ancient city of Ur in about 4000 BC, although the arch used for drying the bricks was not actually found..

Other examples of civilizations who used mud brick include the ancient Egyptians and the Indus Valley Civilization, where it was used exclusively. In particular, it is evident from the ruins of Buhen, Mohenjo-daro and Harappa.

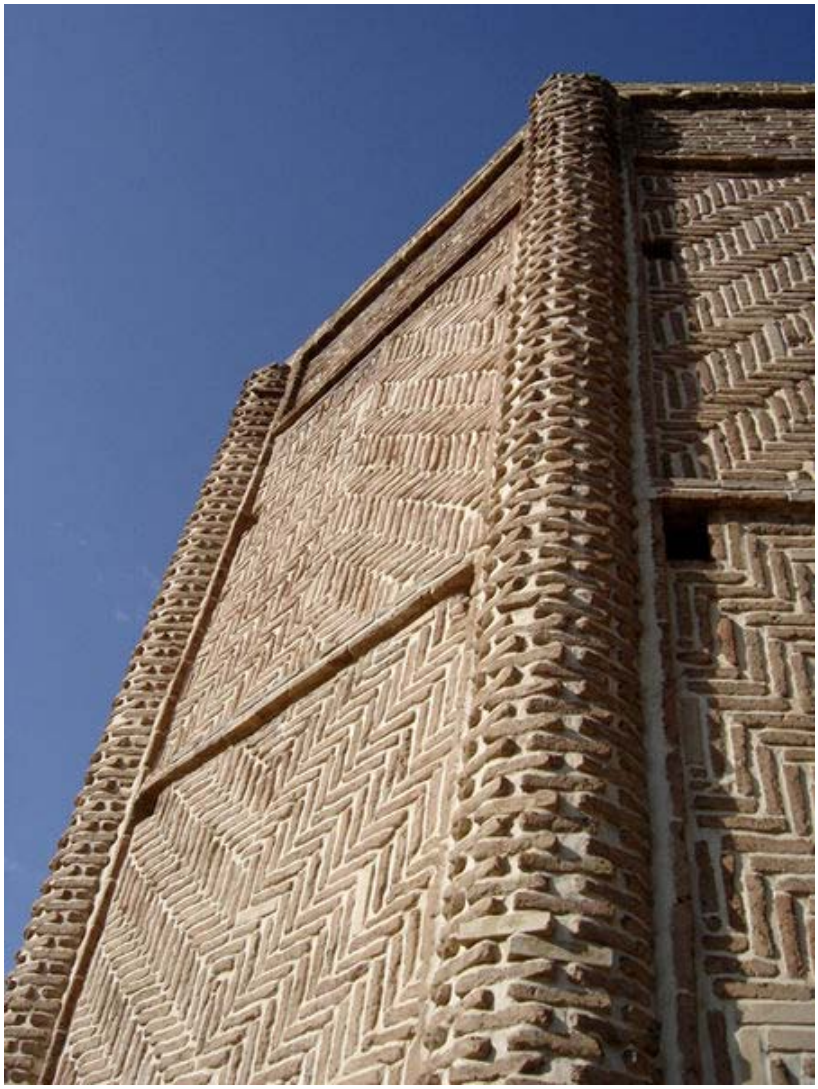
The ancient Jetavanaramaya stupa in Anuradhapura, Sri Lanka is one of the largest brick structures in the world.

The world's highest brick tower of St. Martin's Church in Landshut, Germany, completed in 1500

Malbork Castle, former Ordensburg of the Teutonic Order - biggest brick castle in the world

The Romans made use of fired bricks, and the Roman legions, which operated mobile kilns, introduced bricks to many parts of the empire. Roman bricks are often stamped with the mark of the legion that supervised their production. The use of bricks in southern and western Germany, for example, can be traced back to traditions already described by the Roman architect Vitruvius.

In pre-modern China, brick-making was the job of a lowly and unskilled artisan, but a kiln master was respected as a step above the former. Early traces of bricks were found in a ruin site in Xi'an in 2009 dated back about 3800 years ago. Before this discovery, it is widely believed that bricks appeared about 3000 years ago in the Western Zhou dynasty since the earliest bricks were found in Western Zhou ruins. These bricks are the earliest bricks discovered that were made by a fired process. Early descriptions of the production process and glazing techniques used for bricks can be found in the Song Dynasty carpenter's manual *Yingzao Fashi*, published in 1103 by the government official Li Jie, who was put in charge of overseeing public works for the central government's construction agency. The historian Timothy Brook writes of the production process in Ming Dynasty China (aided with visual illustrations from the *Tiangong Kaiwu* encyclopedic text published in 1637):



The brickwork of Shebeli Tower in Iran displays 12th century craftsmanship

...the kilnmaster had to make sure that the temperature inside the kiln stayed at a level that caused the clay to shimmer with the colour of molten gold or silver. He also had to know when to quench the kiln with water so as to produce the surface glaze. To anonymous laborers fell the less skilled stages of brick production: mixing clay and water, driving oxen over the mixture to trample it into a thick paste, scooping the paste into standardized wooden frames (to produce a brick roughly 42 cm long, 20 cm wide, and 10 cm thick), smoothing the surfaces with a wire-strung bow, removing them from the frames, printing the fronts and backs with stamps that indicated where the bricks came from and who made them, loading the kilns with fuel (likelier wood than coal), stacking the bricks in the kiln, removing them to cool while the kilns were still hot, and bundling them into pallets for transportation. It was hot, filthy work.

The idea of signing the worker's name and birth date on the brick and the place where it was made was not new to the Ming era and had little or nothing to do with vanity. As far

back as the Qin Dynasty (221 BC–206 BC), the government required blacksmiths and weapon-makers to engrave their names onto weapons in order to trace the weapons back to them, lest their weapons should prove to be of a lower quality than the standard required by the government.

In the 12th century, bricks from Northern-Western Italy were re-introduced to Northern Germany, where an independent tradition evolved. It culminated in the so-called brick Gothic, a reduced style of Gothic architecture that flourished in Northern Europe, especially in the regions around the Baltic Sea which are without natural rock resources. Brick Gothic buildings, which are built almost exclusively of bricks, are to be found in Denmark, Germany, Poland, and Russia.

During the Renaissance and the Baroque, visible brick walls were unpopular and the brickwork was often covered with plaster. It was only during the mid-18th century that visible brick walls regained some degree of popularity, as illustrated by the Dutch Quarter of Potsdam, for example.

Chile house in Hamburg, Germany

The transport in bulk of building materials such as bricks over long distances was rare before the age of canals, railways, roads and heavy goods vehicles. Before this time bricks were generally made close to their point of intended use. It has been estimated that in England in the eighteenth century carrying bricks by horse and cart for ten miles (16 km) over the poor roads then existing could more than double their price.

Bricks were often used for reasons of speed and economy, even in areas where stone was available. The buildings of the Industrial Revolution in Britain were largely constructed of brick and timber due to the demand created. During the building boom of the nineteenth century in the eastern seaboard cities of Boston and New York City, for example, locally made bricks were often used in construction in preference to the brownstones of New Jersey and Connecticut for these reasons.

The trend of building upwards for offices that emerged towards the beginning of the 19th century displaced brick in favor of cast and wrought iron and later steel and concrete. Some early 'skyscrapers' were made in masonry, and demonstrated the limitations of the material – for example, the Monadnock Building in Chicago (opened in 1896) is masonry and just seventeen stories high; the ground walls are almost 6 feet (1.8 m) thick, clearly building any higher would lead to excessive loss of internal floor space on the lower floors. Brick was revived for high structures in the 1950s following work by the Swiss Federal Institute of Technology and the Building Research Establishment in Watford, UK. This method produced eighteen-story structures with bearing walls no thicker than a single brick (150–225 mm). This potential has not been fully developed because of the ease and speed in building with other materials; in the late-20th century brick was confined to low- or medium-rise structures or as a thin decorative cladding over concrete-and-steel buildings or for internal non-load-bearing walls.

## *Methods of manufacture*

Brick making at the beginning of the 20th century.

Bricks may be made from clay, shale, soft slate, calcium silicate, concrete, or shaped from quarried stone.

Clay is the most common material, with modern clay bricks formed in one of three processes - soft mud, dry press, or extruded.

Normally, brick contains the following ingredients:

1. Silica (sand) - 50% to 60% by weight

2. Alumina (clay) - 20% to 30% by weight
3. Lime - 2 to 5% by weight
4. Iron oxide - 5 to 6% (not greater than 7%) by weight
5. Magnesia - less than 1% by weight

## Mud bricks

The soft mud method is the most common, as it is the most economical. It starts with the raw clay, preferably in a mix with 25-30% sand to reduce shrinkage. The clay is first ground and mixed with water to the desired consistency. The clay is then pressed into steel moulds with a hydraulic press. The shaped clay is then fired ("burned") at 900-1000 °C to achieve strength.

## Rail kilns

Xhosa brickmaker at kiln near Ngcobo in the former Transkei in 2007.

In modern brickworks, this is usually done in a continuously fired tunnel kiln, in which the bricks move slowly through the kiln on conveyors, rails, or kiln cars to achieve consistency for all bricks. The bricks often have added lime, ash, and organic matter to speed the burning.

## Bull's Trench Kilns

In India, brick making is typically a manual process. The most common type of brick kiln in use there are **Bull's Trench Kiln** (BTK), based on a design developed by British engineer W. Bull in the late nineteenth century.

An oval or circular trench, 6–9 meters wide, 2-2.5 meters deep, and 100–150 meters in circumference, is dug. A tall exhaust chimney is constructed in the centre. Half or more of the trench is filled with "green" (unfired) bricks which are stacked in an open lattice pattern to allow airflow. The lattice is capped with a roofing layer of finished brick.

In operation, new green bricks, along with roofing bricks, are stacked at one end of the brick pile; cooled finished bricks are removed from the other end for transport. In the middle the brick workers create a firing zone by dropping fuel (coal, [wood], oil, debris, etc.) through access holes in the roof above the trench.

West face of Roskilde Cathedral in Roskilde, Denmark.

The advantage of the BTK design is a much greater energy efficiency compared with clamp or scove kilns. Sheet metal or boards are used to route the airflow through the brick lattice so that fresh air flows first through the recently burned bricks, heating the air, then through the active burning zone. The air continues through the green brick zone (pre-heating and drying them), and finally out the chimney where the rising gases create suction which pulls air through the system. The reuse of heated air yields savings in fuel cost.

As with the rail process above, the BTK process is continuous. A half dozen laborers working around the clock can fire approximately 15,000-25,000 bricks a day. Unlike the rail process, in the BTK process the bricks do not move. Instead, the locations at which the bricks are loaded, fired, and unloaded gradually rotate through the trench.

## Dry pressed bricks

The dry press method is similar to mud brick but starts with a much thicker clay mix, so it forms more accurate, sharper-edged bricks. The greater force in pressing and the longer burn make this method more expensive.

## Extruded bricks

For extruded bricks the clay is mixed with 10-15% water (stiff extrusion) or 20-25% water (soft extrusion). This is forced through a die to create a long cable of material of the proper width and depth. This is then cut into bricks of the desired length by a wall of wires. Most structural bricks are made by this method, as it produces hard, dense bricks, and suitable dies can produce holes or other perforations. The introduction of holes reduces the volume of clay needed, and hence the cost. Hollow bricks are lighter and easier to handle, and have thermal properties different from solid bricks. The cut bricks are hardened by drying for 20 to 40 hours at 50 to 150 °C before being fired. The heat for drying is often waste heat from the kiln. European-style extruded bricks or blocks are used in single-wall construction with finishes applied inside and outside. Their many voids are a greater proportion of the volume than the solid, thin walls of fired clay. Such bricks are made in 15, 25, 30, 42 and 50-cm widths. Some models have very high thermal insulation performance suitable for zero-energy buildings.

## Calcium silicate bricks

The raw materials for calcium silicate bricks include lime mixed with quartz, crushed flint or crushed siliceous rock together with mineral colourants. The materials are mixed and left until the lime is completely hydrated, the mixture is then pressed into moulds and cured in an autoclave for two or three hours to speed the chemical hardening. The finished bricks are very accurate and uniform, although the sharp arrises need careful handling to avoid damage to brick (and brick-layer). The bricks can be made in a variety of colours, white is common but pastel shades can be achieved.

Sck bricks are common in Sweden, especially in houses built or renovated in the 1970s,, and are known as "Mexitegel" (en: Mexi[can] Bricks).

In India these are known as Fly ash bricks, manufactured using the Falg process.

Calcium silicate bricks are also manufactured in Canada and the United States, and meets the criteria set forth in ASTM C73 - 10 Standard Specification for Calcium Silicate Brick (Sand-Lime Brick). It has lower embodied energy than cement based man-made stone and clay brick.

## *Influence on fired colour*

Yellow London Stocks at Waterloo

The fired colour of clay bricks is influenced by the chemical and mineral content of raw materials, the firing temperature and the atmosphere in the kiln. For example pink coloured bricks are the result of a high iron content, white or yellow bricks have a higher lime content. Most bricks burn to various red hues, if the temperature is increased the colour moves through dark red, purple and then to brown or grey at around 1,300 °C (2,372 °F). Calcium silicate bricks have a wider range of shades and colours, depending on the colourants used. The names of bricks may reflect their origin and colour, such as London stock brick and Cambridgeshire White.

Bricks formed from concrete are usually termed blocks, and are typically pale grey in colour. They are made from a dry, small aggregate concrete which is formed in steel moulds by vibration and compaction in either an "egglayer" or static machine. The finished blocks are cured rather than fired using low-pressure steam. Concrete blocks are manufactured in a much wider range of shapes and sizes than clay bricks and are also available with a wider range of face treatments - a number of which are to simulate the appearance of clay bricks.

An impervious and ornamental surface may be laid on brick either by salt glazing, in which salt is added during the burning process, or by the use of a "slip," which is a glaze material into which the bricks are dipped. Subsequent reheating in the kiln fuses the slip into a glazed surface integral with the brick base.

Natural stone bricks are of limited modern utility, due to their enormous comparative mass, the consequent foundation needs, and the time-consuming and skilled labour needed in their construction and laying. They are very durable and considered more handsome than clay bricks by some. Only a few stones are suitable for bricks. Common materials are granite, limestone and sandstone. Other stones may be used (e.g. marble, slate, quartzite, etc.) but these tend to be limited to a particular locality.

## *Optimal dimensions, characteristics, and strength*

Loose bricks

For efficient handling and laying bricks must be small enough and light enough to be picked up by the bricklayer using one hand (leaving the other hand free for the trowel). Bricks are usually laid flat and as a result the effective limit on the width of a brick is set by the distance which can conveniently be spanned between the thumb and fingers of one hand, normally about four inches (about 100 mm). In most cases, the length of a brick is about twice its width, about eight inches (about 200 mm) or slightly more. This allows bricks to be laid *bonded* in a structure to increase its stability and strength. The wall is built using alternating courses of *stretchers*, bricks laid longways and *headers*, bricks laid crossways. The headers tie the wall together over its width.

A hastily-made wall of rough bricks without using cement or even mud in an Indian town.

A bigger brick makes for a thicker (and thus more insulating) wall. Historically, this meant that bigger bricks were necessary in colder climates, while a smaller brick was adequate, and more economical, in warmer regions. A notable illustration of this correlation is the Green Gate in Gdansk; built in 1571 of imported Dutch brick, too small for the colder climate of Gdansk, it was notorious for being a chilly and drafty residence. Nowadays this is no longer an issue, as modern walls typically incorporate specialized insulation materials.

The correct brick for a job can be picked from a choice of colour, surface texture, density, weight, absorption and pore structure, thermal characteristics, thermal and moisture movement, and fire resistance.

Face brick ("house brick") sizes, (alphabetical order)

| Standard | Imperial | Metric |
|---|---|---|
| Australia | 9 × 4⅓ × 3 in | 230 × 110 × 76 mm |
| Germany | 9 × 4¼ × 2¾ in | 240 × 115 × 71 mm |
| India | 9 × 4¼ × 2¾ in | 228 × 107 × 69 mm |
| Russia | 10 × 4¾ × 2½ in | 250 × 120 × 65 mm |
| South Africa | 8¾ × 4 × 3 in | 222 × 106 × 73 mm |
| Sweden | 10 × 4¾ × 2½ in | 250 × 120 × 62 mm |
| United Kingdom | 8½ × 4 × 2½ in | 215 × 102.5 × 65 mm |
| United States | 8 × 4 × 2¼ in | 203 × 102 × 57 mm |

In England, the length and the width of the common brick has remained fairly constant over the centuries, but the depth has varied from about two inches (about 51 mm) or smaller in earlier times to about two and a half inches (about 64 mm) more recently. In the United States, modern bricks are usually about 8 × 4 × 2 $\frac{1}{4}$ inches (203 × 102 × 57 mm). In the United Kingdom, the usual size of a modern brick is 215 × 102.5 × 65 mm (about 8 $\frac{5}{8}$ × 4 $\frac{1}{8}$ × 2 $\frac{5}{8}$ inches), which, with a nominal 10 mm ($\frac{3}{8}$ inch) mortar joint, forms a *unit size* of 225 × 112.5 × 75 mm (9 × 4 $\frac{1}{2}$ × 3 inches), for a ratio of 6:3:2.

Some brickmakers create innovative sizes and shapes for bricks used for plastering (and therefore not visible) where their inherent mechanical properties are more important than the visual ones. These bricks are usually slightly larger, but not as large as blocks and offer the following advantages:

- a slightly larger brick requires less mortar and handling (fewer bricks) which reduces cost
- ribbed exterior aids plastering
- more complex interior cavities allow improved insulation, while maintaining strength.

Blocks have a much greater range of sizes. Standard coordinating sizes in length and height (in mm) include 400×200, 450×150, 450×200, 450×225, 450×300, 600×150, 600×200, and 600×225; depths (work size, mm) include 60, 75, 90, 100, 115, 140, 150, 190, 200, 225, and 250. They are usable across this range as they are lighter than clay bricks. The density of solid clay bricks is around 2,000 kg/m³: this is reduced by frogging, hollow bricks, etc.; but aerated autoclaved concrete, even as a solid brick, can have densities in the range of 450–850 kg/m³.

Bricks may also be classified as *solid* (less than 25% perforations by volume, although the brick may be "frogged," having indentations on one of the longer faces), *perforated*

(containing a pattern of small holes through the brick removing no more than 25% of the volume), *cellular* (containing a pattern of holes removing more than 20% of the volume, but closed on one face), or *hollow* (containing a pattern of large holes removing more than 25% of the brick's volume). Blocks may be solid, cellular or hollow

The term "frog" for the indentation on one bed of the brick is a word that often excites curiosity as to its origin. The most likely explanation is that brickmakers also call the block that is placed in the mould to form the indentation a frog. Modern brickmakers usually use plastic frogs but in the past they were made of wood. When these are wet and have clay on them they resemble the amphibious kind of frog and this is where they got their name. Over time this term also came to refer to the indentation left by them.

Brick arch from a vault in Roman Bath – England

A brick section of the old Dixie Highway, United States

The compressive strength of bricks produced in the United States ranges from about 1000 lbf/in² to 15,000 lbf/in² (7 to 105 MPa or N/mm² ), varying according to the use to which the brick are to be put. In England clay bricks can have strengths of up to 100 MPa, although a common house brick is likely to show a range of 20–40 MPa.

## *Use*

Bricks are used for building and pavement. In the USA, brick pavement was found incapable of withstanding heavy traffic, but it is coming back into use as a method of traffic calming or as a decorative surface in pedestrian precincts. For example, in the early 1900s, most of the streets in the city of Grand Rapids, Michigan were paved with brick. Today, there are only about 20 blocks of brick paved streets remaining (totalling less than 0.5 percent of all the streets in the city limits).

Bricks in the metallurgy and glass industries for lining furnaces. They have various uses, especially refractory bricks such as silica, magnesia, chamotte and neutral (chromomagnesite) refractory bricks. This type of brick must have good thermal shock resistance, refractoriness under load, high melting point, and satisfactory porosity. There

is a large refractory brick industry, especially in the United Kingdom, Japan, the United States, and the Netherlands.

In the United Kingdom, bricks have been used in construction for centuries. Until recently, almost all houses were built almost entirely from bricks. Although many houses in the UK are now built using a mixture of concrete blocks and other materials, many houses are skinned with a layer of bricks on the outside for aesthetic appeal.

In the UK a redbrick university is one founded and built in the Victorian era, often as a technical college. The term is used as differentiation from older, more classics-oriented universities.

**Chapter- 3**

# Stonemasonry

Stonemason working on a fountain with pneumatic tools

An apprentice carving a block

Typical French chisels with wooden hilt, used for soft limestone

The craft of **stonemasonry** has existed since the dawn of civilization - creating buildings, structures, and sculpture using stone from the earth. These materials have been used to construct many of the long-lasting, ancient monuments, artifacts, cathedrals, and cities in a wide variety of cultures. Famous products of stonemasonry include the Taj Mahal, Cusco's Incan Wall, Easter Island's statues, the Egyptian Pyramids, Angkor Wat, Borobudur, Tihuanaco, Tenochtitlan the Iranian Persepolis, the Greek Parthenon, Stonehenge, and Chartres Cathedral.

## *Definition*


Typical Aberdeen city street showing the widespread use of local granite


19th Century Colonial Secretary's Office in Sydney, Australia constructed of typical Sydney sandstone

Stonemasonry is the craft of shaping rough pieces of rock into accurate geometrical shapes, mostly simple, but some of considerable complexity, and then arranging the resulting stones, often together with mortar, to form structures.

- **Quarrymen** split the rock, and extract the resulting blocks of stone from the ground.
- **Sawyers** cut these rough blocks into cubes, to required size with diamond-tipped saws.
- **Banker masons** are workshop based, and specialize in carving stones into intricate geometrical shapes required by a building's design. They can produce

anything from stones with simple chamfers to tracery windows, detailed mouldings and the more classical architectural building masonry. When working a stone from a sawn block, the mason ensures that the stone is bedded in the right way, so the finished work sits in the building in the same orientation as it was formed on the ground. The basic tools, methods and skills of the banker mason have existed as a trade for thousands of years.

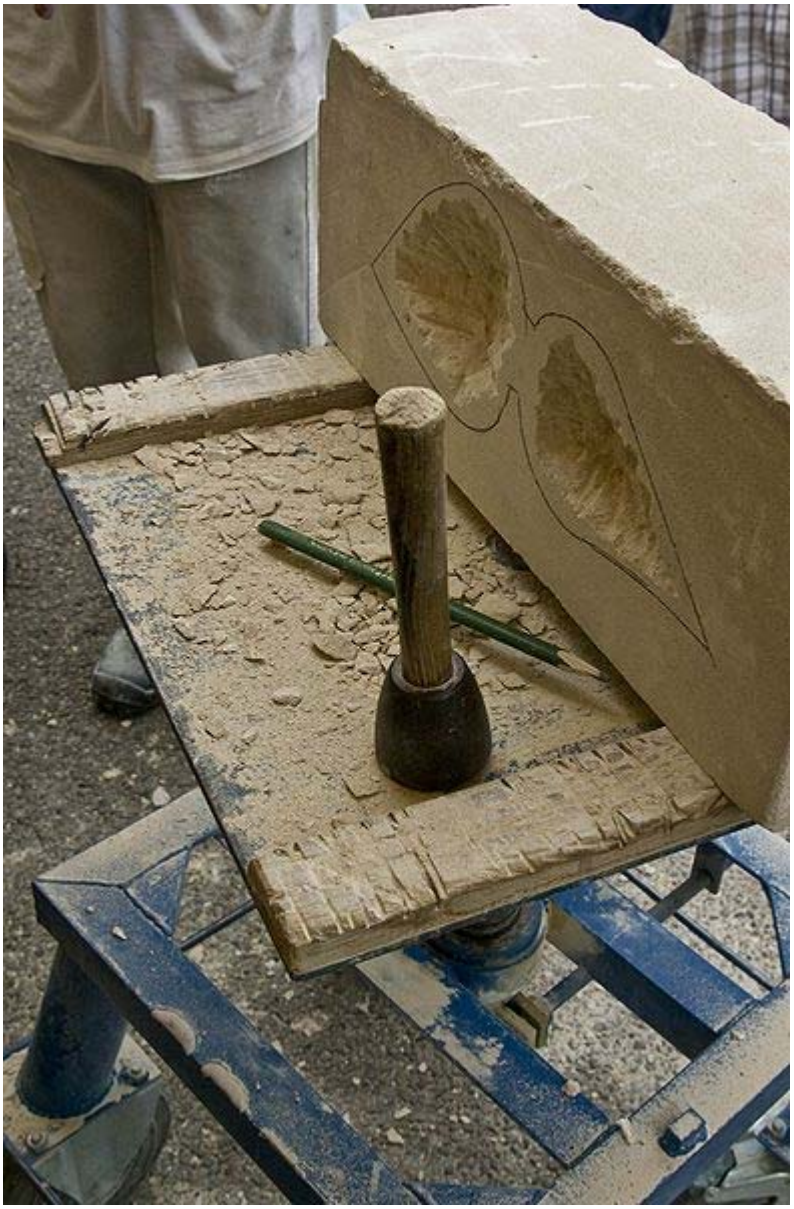
- **Carvers** cross the line from craft to art, and use their artistic ability to carve stone into foliage, figures, animals or abstract designs.
- **Fixer masons** specialize in the fixing of stones onto buildings, using lifting tackle, and traditional lime mortars and grouts. Sometimes modern cements, mastics and epoxy resins are used, usually on specialist applications such as stone cladding. Metal fixings, from simple dowels and cramps to specialised single application fixings, are also used. The precise tolerances necessary make this a highly skilled job.
- **Memorial masons** or **monumental masons** carve gravestones and inscriptions.

The modern stonemason undergoes comprehensive training, both in the classroom and in the working environment. Hands-on skill is complimented by intimate knowledge of each stone type, its application and best uses, and how to work and fix each stone in place. The mason may be skilled and competent to carry out one or all of the various branches of stonemasonry. In some areas the trend is towards specialization, in other areas towards adaptability.

### *Types of stone*

A stonemason at Eglinton Tournament bridge with a selection of tools of the trade

A stonemason's stone workbench from the 1845 Eglinton Tournament bridge construction



A modern stonemason's workbench with a block of limestone

Stonemasons use all types of natural stone: igneous, metamorphic and sedimentary; while some also use artificial stone as well.

## Igneous stones

Granite is one of the hardest stones, and requires such different techniques to sedimentary stones that it is virtually a separate trade. With great persistence, simple mouldings can and have been carved into granite, for example in many Cornish churches and the city of Aberdeen. Generally, however, it is used for purposes that require its strength and durability, such as kerbstones, countertops, flooring, and breakwaters.

Igneous stone ranges from very soft rocks such as pumice and scoria to somewhat harder rocks such as tuff and hard rocks such as obsidian, granite and basalt.

### Metamorphic

Marble has traditionally been used for carving statues, and for facing many Byzantine and Renaissance Italian buildings. The traditional home of the marble industry is the area around Carrara in Italy, from where a bright white marble is extracted in vast quantities.

Slate is a popular choice of stone for memorials and inscriptions, as its fine grain and hardness means it leaves details very sharp. Meanwhile, its tendency to split into thin plates has made it a popular roofing material.

### Sedimentary

Many of the world's most famous buildings have been built of sedimentary stone, from Durham Cathedral to St Peter's in Rome. There are two main types of sedimentary stone used in masonry work, limestones and sandstones. Examples of limestones include Bath and Portland stone. Yorkstone and Sydney sandstone are well-known sandstones.

## *Types of stonemasonry*

Types of stonemasonry are:

- Rubble Masonry

  When roughly dressed stones are laid in a mortar the result is a stone rubble masonry.

- Ashlar Masonry

  Well arranged and cut stones set in mortar.

## *Training*

Traditionally medieval stonemasons served a seven-year apprenticeship. A similar system still operates today.

Typical French chisels with wooden hilt, used for soft limestone

A French stonemason using a straightedge and chisels


A left-handed stonemason with mallet and chisel

A modern apprenticeship lasts four years. This combines on-site learning through personal experience, the experience of the tradesmen and college work where apprentices are given an overall experience of the building, hewing and theory work involved in masonry. In some areas colleges offer courses which teach not only the manual skills but also related fields such as drafting and blueprint reading or construction conservationism. Electronic Stonemasonry training resources enhance traditional delivery techniques. Hands-on workshops are a good way to learn about stonemasonry also. Those wishing to become stonemasons should have little problem working at heights, possess reasonable hand-eye co-ordination, be moderately physically fit, and have basic mathematical ability. Most of these things can be developed while learning.

### *Tools*


The foreground tool with serrated blades is a cockscomb, cock's comb or stonemason's drag, used on soft limestone

Splitting a block of marble with plug and feathers

Stonemason's mallets of plastic, beechwood and steel

Stonemasons use a wide variety of tools to handle and shape stone blocks (ashlar) and slabs into finished articles. The basic tools for shaping the stone are a mallet, chisels, and a metal straight edge. With these one can make a flat surface - the basis of all stone masonry.

Chisels come in a variety of sizes and shapes, dependent upon the function for which they are being used. There are different chisels for different materials and sizes of material being worked, for removing large amounts of material and for putting a fine finish on the stone.

Mixing mortar is normally done today with mortar mixers which usually use a rotating drum or rotating paddles to mix the mortar.

The masonry trowel is used for the application of the mortar between and around the stones as they are set into place. Filling in the gaps (joints) with mortar is referred to as pointing. Pointing in smaller joints can be accomplished using tuck pointers, pointing trowels, and margin trowels, among other tools.

At least one tool bears the name of the tradesmen that use it, and that is the Stonemason's hammer. This hammer can be used in place of a chisel in certain circumstances. The

hammer can also be used to make shims and chinks while holding a small stone in one hand and striking it with the hammer.

Stonemasons use a Lewis together with a crane or winch to hoist building stones into place.

Today power tools such as compressed-air chisels, abrasive spinners and angle grinders are much used: these save time and money, but are hazardous and require just as much skill as the hand tools that they augment. But many of the basic tools of stonemasonry have remained virtually the same throughout vast amounts of time, even thousands of years.

## *History*

Stonemasonry is one of the earliest trades in civilisation's history. During the time of the Neolithic Revolution and domestication of animals, people learned how to use fire to create quicklime, plasters, and mortars. They used these to fashion homes for themselves with mud, straw, or stone, and masonry was born.

The Ancients heavily relied on the stonemason to build the most impressive and long lasting monuments to their civilizations. The Egyptians built their pyramids, the civilizations of Central American had their step pyramids, the Persians their palaces, the Greeks their temples, and the Romans their public works and wonders. Among the famous ancient stonemasons is Sophroniscus, the father of Socrates, who was a stone-cutter.

Castle building was an entire industry for the medieval stonemasons. When the Western Roman Empire fell, building in dressed stone decreased in much of Western Europe, and there was a resulting increase in timber-based construction. Stone work experienced a resurgence in the 9th and 10th centuries in Europe, and by the 12th century religious fervour resulted in the construction of thousands of impressive churches and cathedrals in stone across Western Europe.

Medieval stonemasons' skills were in high demand, and members of the guild, gave rise to three classes of stonemasons: apprentices, journeymen, and master masons. Apprentices were indentured to their masters as the price for their training, journeymen had a higher level of skill and could go on journeys to assist their masters, and master masons were considered freemen who could travel as they wished to work on the projects of the patrons. During the Renaissance, the stonemason's guild admitted members who were not stonemasons, and eventually evolved into the Society of Freemasonry; fraternal groups which observe the traditional culture of stonemasons, but are not typically involved in modern construction projects.

A medieval stonemason would often carve a personal symbol onto their block to differentiate their work from that of other stonemasons. This also provided a simple ‘quality assurance’ system.

The Renaissance saw stonemasonry return to the prominence and sophistication of the Classical age. The rise of the Humanist philosophy gave people the ambition to create marvelous works of art. The centre stage for the Renaissance would prove to be Italy, where city-states such as Florence erected great structures, including the Cathedral of Santa Maria del Fiore, the Fountain of Neptune, and the Laurentian Library which was planned and built by Michelangelo Buonarroti, a famous stonemason of the Renaissance.

When Europeans settled the Americas, they brought the stonemasonry techniques of their respective homelands with them. Settlers used what materials were available, and in some areas stone was the material of choice. In the first waves, building mimicked that of Europe, to eventually be replaced by unique architecture later on.

In the 20th century, stonemasonry saw its most radical changes in the way the work is accomplished. Prior to the first half of the century, most heavy work was executed by draft animals or human muscle power. With the arrival of the internal combustion engine, many of these hard aspects of the trade have been made simpler and easier. Cranes and forklifts have made moving and laying heavy stones relatively easy for the stonemasons. Motor powered mortar mixers have saved much in time and energy as well. Compressed-air powered tools have made working of stone less time-intensive. Petrol and electric powered abrasive saws can cut through stone much faster and with more precision than chiseling alone. Carbide-tipped chisels can stand up to much more abuse than the steel and iron chisels made by blacksmiths of old.

Chapter- 4

# Concrete Masonry Unit

A stack of rectangular CMUs

N12 starter bars cast into concrete raft slab.

Clean out blocks to flush out debris prior to placing corefill.

In the United States, a **concrete masonry unit (CMU)** — also called **concrete block**, **cement block** or **foundation block** — is a large rectangular brick used in construction. Concrete blocks are made from cast concrete, i.e. Portland cement and aggregate, usually sand and fine gravel for high-density blocks. Lower density blocks may use industrial wastes as an aggregate. Those that use cinders (fly ash or bottom ash) are called **cinder blocks** in the US, **breeze blocks** (*breeze* is a synonym of ash) in the UK and are also known as **besser blocks** or bricks in Australia. **Clinker blocks** use clinker as aggregate. In non-technical usage, the terms 'cinder block' and 'breeze block' are often generalized to cover all of these varieties. Lightweight blocks can also be produced using aerated concrete.

## *Sizes and structure*

Concrete blocks may be produced with hollow centres to reduce weight or improve insulation. The use of blockwork allows structures to be built in the traditional masonry style with layers (or courses) of overlapping blocks. Blocks come in many sizes. In the US, the most common size is 8 in × 8 in × 16 in (20 cm × 20 cm × 41 cm); the actual size is usually about 3/8 in (1 cm) smaller to allow for mortar joints. In Ireland and the UK, blocks are usually 440 mm × 215 mm × 100 mm excluding mortar joints (approximately 17.3 in × 8.5 in × 3.9 in). In New Zealand, blocks are usually 390 mm × 190 mm × 190 mm excluding mortar joints.

## *Uses*

Concrete block, when reinforced with concrete columns and tie beams, is a very common building material for the load-bearing walls of buildings, in what is termed "concrete

block structure" (CBS) construction. American suburban houses typically employ a concrete foundation and slab with a concrete block wall on the perimeter. Large buildings typically use copious amounts of concrete block; for even larger buildings, concrete block supplements steel I-beams. Tilt-wall construction, however, is replacing CBS for some large structures.

Wall under construction, metal door jamb and one aluminium window in position at the left. A pallet of knock out bond beam blocks on the right.

Short (three blocks high) retaining wall ready for corefill. All core will be filled.

8in.x8in.x16in. hollow-core CMUs in a basement wall prior to burial

HVAC shaft with 2 hour fire-resistance rating under construction at DuPont Canada, Mississauga, Ontario, 1986.

## Chapter- 5

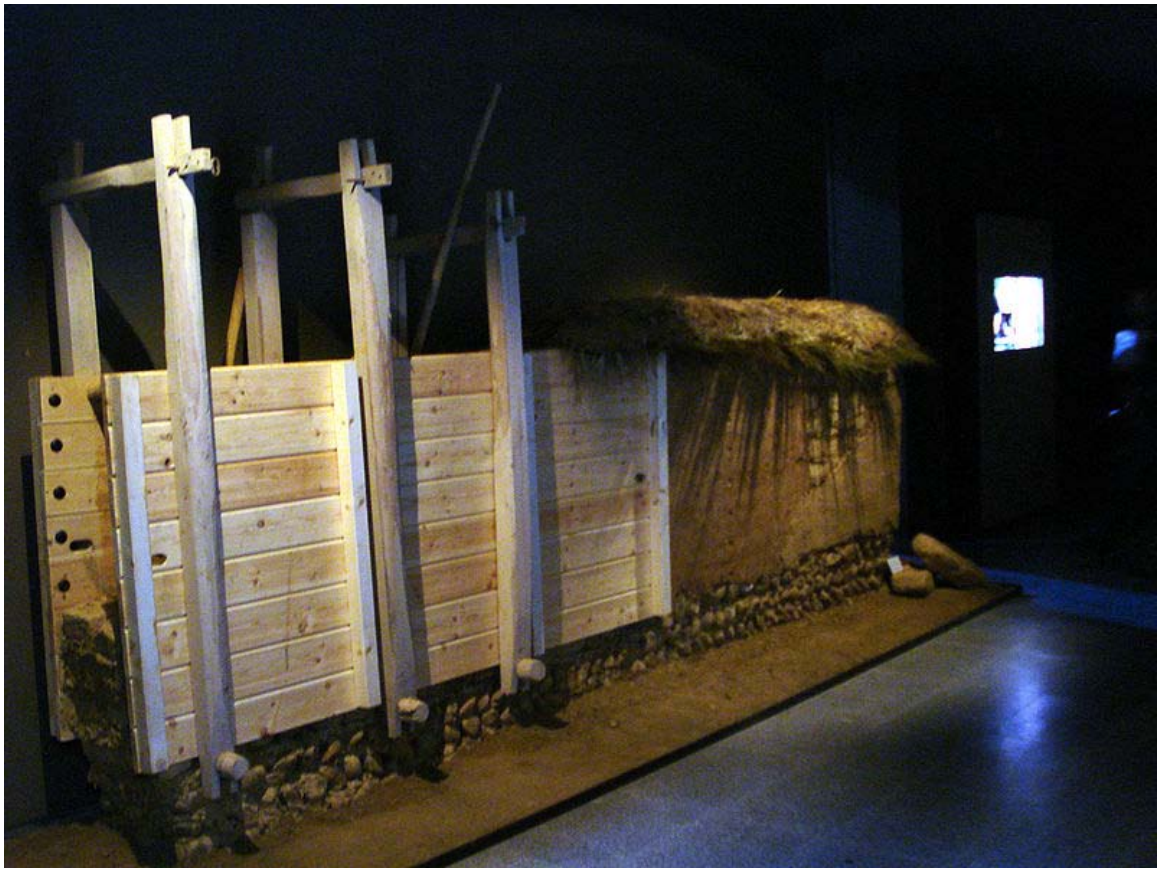
# Rammed Earth

The ruins of a Han Dynasty (202 BC - 220 AD) Chinese watchtower made of rammed earth at Dunhuang, Gansu province, the eastern end of the Silk Road

**Rammed earth**, also known as ***taipa*** (Portuguese), ***tapial*** (Spanish), ***pisé de terre*** or simply ***pisé*** (French), is a technique used in the building of walls using the raw materials of earth, chalk, lime and gravel. It is an ancient building method that has seen a revival in recent years as people seek more sustainable building materials and natural building methods. Rammed earth walls are simple to construct, incombustible, thermally massive, very strong and durable. However, they can be labour-intensive to construct without machinery (powered rammers), and, if improperly protected or maintained, they are susceptible to water damage. Traditionally, rammed earth buildings are found on every

continent except Antarctica, from the temperate and wet regions of northern Europe to semi-dry deserts, mountain areas and the tropics. The availability of useful soil and a building design appropriate for local climatic conditions are the factors which favour its use.

## *Overview of use*



Model showing construction of rammed earth wall on foundation

Building a rammed earth wall involves compressing a damp mixture of earth that has suitable proportions of sand, gravel and clay (sometimes with an added stabilizer) into an externally supported frame, creating a solid wall of earth. Historically, stabilizers such as lime or animal blood were used to stabilize the material, whilst modern construction uses lime, cement or asphalt emulsions. Some modern builders also add coloured oxides or other items such as bottles or pieces of timber to add variety to the structure.

A temporary frame (formwork) is first built, usually out of wood or plywood, to act as a mold for the desired shape and dimensions of each wall section. The frames must be sturdy and well braced, and the two opposing wall faces clamped together, to prevent bulging or deformation from the high compression forces involved. Damp material is poured in to a depth of between 10 to 25 cm (4 to 10 in), and compressed to around 50% of its original height. The compression of material is done iteratively in batches, to

gradually build up the wall to the required height dictated by the top of the frame. Compression was historically done by hand with a long ramming pole, and was very labor-intensive. Modern construction can be more efficient by employing pneumatically powered tampers.

Once the wall is complete, it is strong enough that the frames can be immediately removed. This is necessary if a surface texture (e.g. by wire brushing) is desired, since walls become too hard to work after about an hour. The walls are best constructed in warm weather so that they can dry and harden. Walls take some time to dry out completely, and may take up to two years to completely cure. Compression strength increases with increased curing time, and exposed walls should be sealed to prevent water damage.

Taipa fortifications at Paderne Castle in the Algarve, Portugal

In modern variations of the method, rammed earth walls are constructed on top of conventional footings or a reinforced concrete slab base.

## *Features and benefits*

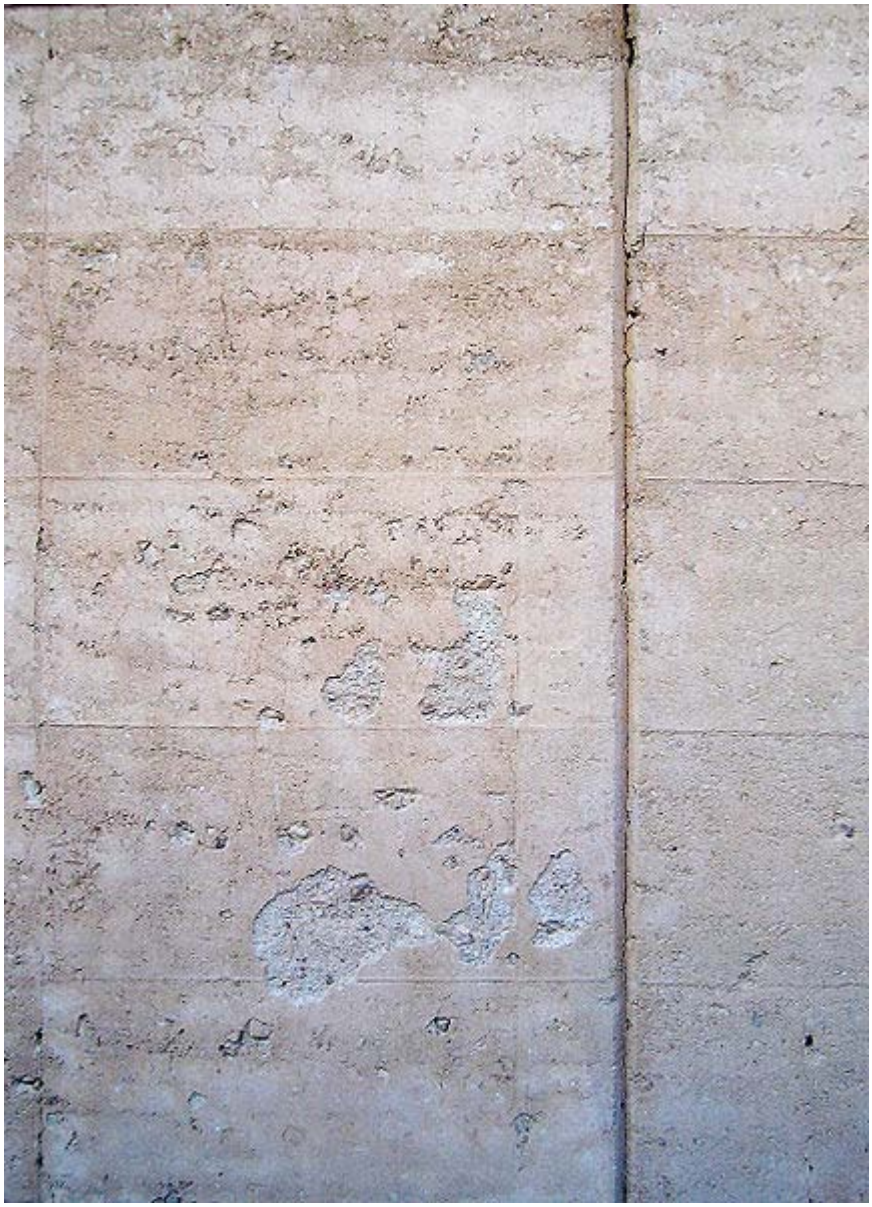
The compression strength of rammed earth can be up to 4.3 MPa (620 psi). This is less than that of a similar thickness of concrete, but more than strong enough for use in domestic buildings. Indeed, properly built rammed earth can withstand loads for thousands of years, as many still-standing ancient structures around the world attest. Rammed earth using re-bar, wood or bamboo reinforcement can prevent failure caused by earthquakes or heavy storms. Mixing cement with the soil mixture can also increase the structure's load bearing capacity, but can only be used in clay-poor mixtures. The USDA has observed that rammed earth structures last indefinitely and could be built for no more than two-thirds the cost of standard frame houses.

Rammed earth has been used around the world in a wide range of climatic conditions, from wet northern Europe to dry regions in Africa.

Soil is a widely available, low cost and sustainable resource, and utilizing it in construction has minimal environmental impact. This makes rammed earth construction highly affordable and viable for low-income builders. Unskilled labor can do most of the necessary work, and today more than 30 percent of the world's population uses earth as a building material.

While the cost of material is low, constructing rammed earth without mechanical tools can be a very time consuming project; however with a mechanical tamper and prefabricated formwork, it can take as little as two to three days to construct the walls for a 200 to 220 $m^2$ (2,200 to 2,400 sq ft) house.

One of the significant benefits of rammed earth is its excellent thermal mass; like brick or concrete construction, it can absorb heat during the day and release it at night. This can even out daily temperature variations and reduce the need for air conditioning and heating. However rammed earth, also like brick and concrete, often requires insulation in colder climates. It must also be protected from heavy rain and insulated with vapor barriers.



Rammed earth wall surface detail. Apart from the patches of damage, the surface shows regular horizontal lines from the wooden form work used in constructing the wall and subtler horizontal strata from the successive compacted layers of earth used to build the wall.

Untouched, the walls have the color and texture of natural earth. Blemishes can also be patched up using the soil mixture as a plaster and sanded smooth. Care needs to be taken to avoid moisture-impermeable finishes such as cement render, as these will impair the ability of the wall to desorb moisture, leading in turn to a loss of compressive strength.

The thickness and density of rammed earth walls, typically 30 to 35 centimetres (12 to 14 in) thick, lends itself naturally to soundproofing. Rammed earth walls are also termite-resistant, non-toxic, inherently fireproof and ultimately biodegradable.

Nails or screws can be driven easily into well-cured walls, and they can be effectively patched with the same material used to build them.

## Environmental aspects and sustainability

Rammed earth trombe wall built by the Design Build Bluff Organization

Because rammed earth structures use locally available materials, they typically have low embodied energy and generate very little waste. The soils used are typically subsoils low in clay, between 5% and 15% typically with the topsoil retained for agricultural use. Ideally, the soil removed in order to prepare the building foundation can be used, further reducing cost and energy used for transportation.

Rammed earth buildings reduce the need for lumber because the formwork used is removable and can be continually reused.

A Taipa section of the Great Wall of China

Rammed earth can effectively control humidity where unclad walls containing clay are exposed to an internal space. Humidity is held between 40% and 60% which is the ideal humidity range for asthma sufferers and the storage of susceptible items, such as books.

When cement is used in the earth mixture, sustainable benefits such as low embodied energy and humidity control will not be realized. Manufacture of the cement itself adds to the global carbon dioxide burden at a rate of 1.25 tonnes per tonne of cement produced. Partial substitution of cement with alternatives such as ground granulated blast furnace slag has not been shown to be effective and brings other sustainability questions with it.

Rammed earth can contribute to the overall energy-efficiency of buildings. The density, thickness and thermal conductivity of rammed earth makes it a particularly suitable material for passive solar heating. Warmth takes almost 12 hours to work its way through a 35-centimetre (14 in) thick wall.

The material mass and clay content of rammed earth allows the building to "breathe" more than concrete structures, avoiding condensation issues without significant heat loss.

Rammed earth housing has been shown to resolve problems with homelessness caused by otherwise high building costs, as well as to help address the ecological dilemma of deforestation and toxic building materials associated with conventional construction methods.

## *History*

Rammed earth walls form part of the entrance building for the Eden Project in Cornwall, England.

One of many pictures available of buildings of the Borough House Plantation, built in the 1820s, in Stateburg, South Carolina.

Evidence of the early use of rammed earth has been seen in Neolithic archaeological sites of the Yangshao culture and the Longshan culture in China along the Yellow River dating back to 5000 BCE. By 2000 BCE, the use of rammed earth architectural techniques was commonly used for walls and foundations in China.

In the 1800s in the United States, rammed earth was popularized by a book *Rural Economy* by S. W. Johnson. It was used to construct Borough House Plantation and Church of the Holy Cross in South Carolina, which are two National Historic Landmarks of the United States:

Constructed in 1821, the Borough House Plantation complex contains the oldest and largest collection of 'high style' pise de terre (rammed earth) buildings in the United States. Six of the 27 dependencies and portions of the main house were constructed using this ancient technique, which was introduced to this country in 1806 through the book *Rural Economy*, by S.W. Johnson.

An outstanding example of rammed earth construction in Canada is St. Thomas Anglican Church (Shanty Bay, Ontario) built between 1838 and 1841.

Church of the Holy Cross (Episcopal) Stateburg or Holy Cross Episcopal Church in Stateburg, South Carolina, built of rammed earth in 1850–1852

The 1920s through the 1940s was an active research period for rammed earth construction in the US. South Dakota State College carried out extensive research and built almost 100 weathering walls of rammed earth. Over a period of thirty years the college researched the use of paints and plasters in relation to colloids in soil. In 1945 Clemson Agricultural College of South Carolina published their results on rammed earth research in a pamphlet called "Rammed Earth Building Construction." In 1936 on a homestead near Gardendale, Alabama, the United States Department of Agriculture constructed an experimental community of rammed earth buildings with architect Thomas Hibben. The houses were built inexpensively and sold to the public, along with land sufficient for a garden and small livestock plots. The project was a success and provided valuable homes to low-income families.

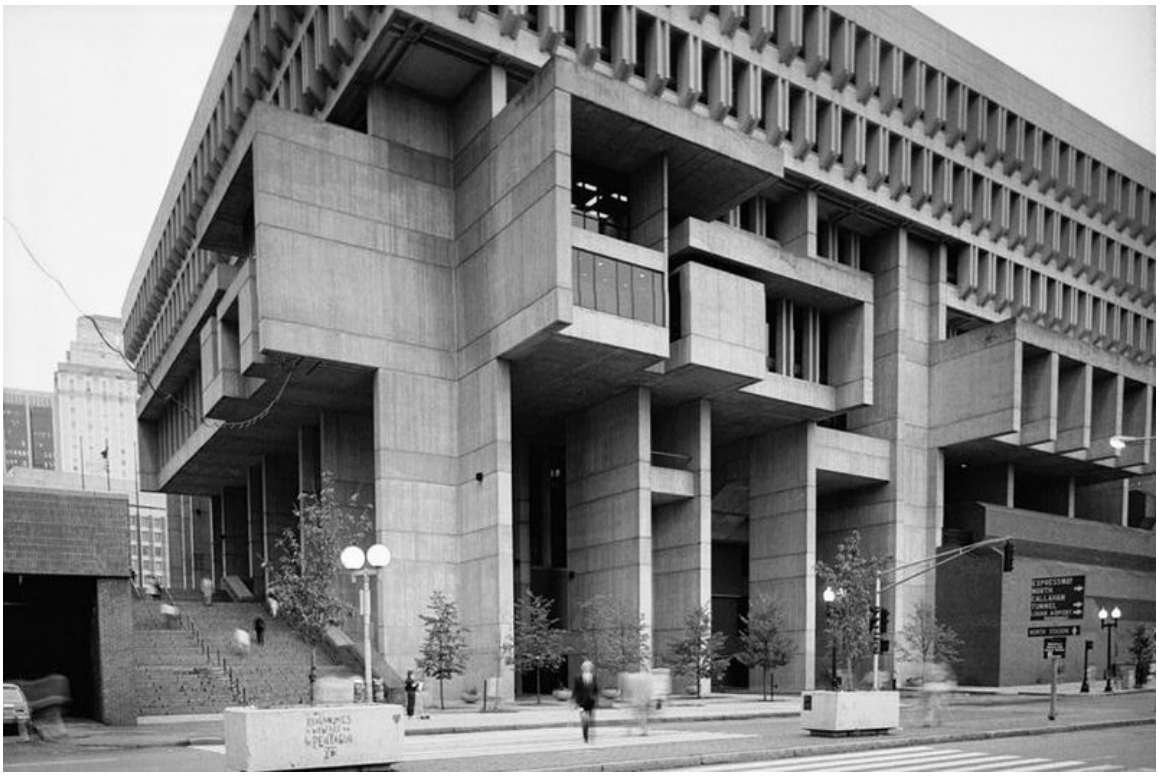
The U.S. Agency for International Development is working with undeveloped countries to improve the building science around rammed earth houses. They also financed the writing of the "Handbook of Rammed Earth" by Texas A&M University and the Texas Transportation Institute. The handbook was never available for purchase by the public until the Rammed Earth Institute International gained permission to reprint it.

Interest in rammed earth fell after World War II when the costs of modern building materials dropped. Rammed earth became viewed as substandard, and often meets opposition with many contractors, engineers, and tradesmen who are unfamiliar with earth construction techniques.

Chapter- 6

# Concrete

Outer view of the Roman Pantheon, still the largest unreinforced solid concrete dome.



A modern building: Boston City Hall (completed 1968) is largely constructed of concrete, both pre-cast and poured-in-place.

*Opus caementicium* laying bare on a tomb near Rome. In contrast to modern concrete structures, the concrete walls of Roman buildings were covered, usually with brick or stone.

Hennebique House in Bourg-la-Reine, constructed between 1894 and 1904, the first concrete building in France.

**Concrete** is a composite construction material, composed of cement (commonly Portland cement) and other cementitious materials such as fly ash and slag cement, aggregate (generally a coarse aggregate made of gravels or crushed rocks such as limestone, or granite, plus a fine aggregate such as sand), water, and chemical admixtures.

The word concrete comes from the Latin word "concretus" (meaning compact or condensed), the perfect passive participle of "concresco", from "com-" (together) and "cresco" (to grow).

Concrete solidifies and hardens after mixing with water and placement due to a chemical process known as hydration. The water reacts with the cement, which bonds the other components together, eventually creating a robust stone-like material. Concrete is used to make pavements, pipe, architectural structures, foundations, motorways/roads, bridges/overpasses, parking structures, brick/block walls and footings for gates, fences and poles.

Concrete is used more than any other man-made material in the world. As of 2006, about 7.5 cubic kilometres of concrete are made each year—more than one cubic metre for every person on Earth.

Concrete powers a US$35 billion industry, employing more than two million workers in the United States alone. More than 55,000 miles (89,000 km) of highways in the United States are paved with this material. Reinforced concrete, prestressed concrete and precast concrete are the most widely used types of concrete functional extensions in modern days.

## *History*

Concrete has been used for construction in various ancient civilizations. An analysis of ancient Egyptian pyramids has shown that concrete may have been employed in their construction.

During the Roman Empire, Roman concrete (or *opus caementicium*) was made from quicklime, pozzolana, and an aggregate of pumice. Its widespread use in many Roman structures, a key event in the history of architecture termed the Roman Architectural Revolution, freed Roman construction from the restrictions of stone and brick material and allowed for revolutionary new designs both in terms of structural complexity and dimension.


Hadrian's Pantheon in Rome is an example of Roman concrete construction.

Concrete, as the Romans knew it, was a new and revolutionary material. Laid in the shape of arches, vaults and domes, it quickly hardened into a rigid mass, free from many of the internal thrusts and strains that trouble the builders of similar structures in stone or brick.

Modern tests show that *opus caementicium* had as much compressive strength as modern Portland-cement concrete (ca. 200 kg/cm$^2$). However, due to the absence of steel reinforcement, its tensile strength was far lower and its mode of application was also different:

Modern structural concrete differs from Roman concrete in two important details. First, its mix consistency is fluid and homogeneous, allowing it to be poured into forms rather than requiring hand-layering together with the placement of aggregate, which, in Roman practice, often consisted of rubble. Second, integral reinforcing steel gives modern concrete assemblies great strength in tension, whereas Roman concrete could depend only upon the strength of the concrete bonding to resist tension.

The widespread use of concrete in many Roman structures has ensured that many survive to the present day. The Baths of Caracalla in Rome are just one example. Many Roman aqueducts and bridges have masonry cladding on a concrete core, as does the dome of the Pantheon.

Some have stated that the secret of concrete was lost for 13 centuries until 1756, when the British engineer John Smeaton pioneered the use of hydraulic lime in concrete, using pebbles and powdered brick as aggregate. However, the Canal du Midi was built using concrete in 1670. Likewise there are concrete structures in Finland that date back to the 16th century. Portland cement was first used in concrete in the early 1840s.

### Additives

Concrete additives have been used since Roman and Egyptian times, when it was discovered that adding volcanic ash to the mix allowed it to set under water. Similarly, the Romans knew that adding horse hair made concrete less liable to crack while it hardened, and adding blood made it more frost-resistant.

Recently, the use of recycled materials as concrete ingredients has been gaining popularity because of increasingly stringent environmental legislation. The most conspicuous of these is fly ash, a by-product of coal-fired power plants. This significantly reduces the amount of quarrying and landfill space required, and, as it acts as a cement replacement, reduces the amount of cement required.

In modern times, researchers have experimented with the addition of other materials to create concrete with improved properties, such as higher strength or electrical conductivity. Marconite is one example.

## *Composition*

There are many types of concrete available, created by varying the proportions of the main ingredients below. By varying the proportions of materials, or by substitution for the cemetitious and aggregate phases, the finished product can be tailored to its application with varying strength, density, or chemical and thermal resistance properties.

The *mix design* depends on the type of structure being built, how the concrete will be mixed and delivered, and how it will be placed to form this structure.

### Cement

Portland cement is the most common type of cement in general usage. It is a basic ingredient of concrete, mortar, and plaster. English masonry worker Joseph Aspdin patented Portland cement in 1824; it was named because of its similarity in colour to Portland limestone, quarried from the English Isle of Portland and used extensively in London architecture. It consists of a mixture of oxides of calcium, silicon and aluminium. Portland cement and similar materials are made by heating limestone (a source of calcium) with clay, and grinding this product (called *clinker*) with a source of sulfate (most commonly gypsum).

## Water

Combining water with a cementitious material forms a cement paste by the process of hydration. The cement paste glues the aggregate together, fills voids within it, and allows it to flow more freely.

Less water in the cement paste will yield a stronger, more durable concrete; more water will give an freer-flowing concrete with a higher slump. Impure water used to make concrete can cause problems when setting or in causing premature failure of the structure.

Hydration involves many different reactions, often occurring at the same time. As the reactions proceed, the products of the cement hydration process gradually bond together the individual sand and gravel particles, and other components of the concrete, to form a solid mass.

Reaction:

Cement chemist notation: $C_3S + H \rightarrow C\text{-}S\text{-}H + CH$
Standard notation: $Ca_3SiO_5 + H_2O \rightarrow (CaO)\cdot(SiO_2)\cdot(H_2O)(gel) + Ca(OH)_2$
Balanced: $2Ca_3SiO_5 + 7H_2O \rightarrow 3(CaO)\cdot2(SiO_2)\cdot4(H_2O)(gel) + 3Ca(OH)_2$

## Aggregates

Cement and sand ready to be mixed.

Fine and coarse aggregates make up the bulk of a concrete mixture. Sand, natural gravel and crushed stone are mainly used for this purpose. Recycled aggregates (from construction, demolition and excavation waste) are increasingly used as partial replacements of natural aggregates, while a number of manufactured aggregates, including air-cooled blast furnace slag and bottom ash are also permitted.

Decorative stones such as quartzite, small river stones or crushed glass are sometimes added to the surface of concrete for a decorative "exposed aggregate" finish, popular among landscape designers.

The presence of aggregate greatly increases the robustness of concrete over and above that of cement, which otherwise is a brittle material, and thus concrete is a true composite material.

Redistribution of aggregates after compaction often creates inhomogeneity due to the influence of vibration. As a result, gradients of strength may be significant.

## Reinforcement

Installing rebar in a floor slab during a concrete pour.

Concrete is strong in compression, as the aggregate efficiently carries the compression load. However, it is weak in tension as the cement holding the aggregate in place can crack, allowing the structure to fail. Reinforced concrete solves these problems by adding

either steel reinforcing bars, steel fibers, glass fiber, or plastic fiber to carry tensile loads. Thereafter the concrete is reinforced to withstand the tensile loads upon it.

## Chemical admixtures

*Chemical admixtures* are materials in the form of powder or fluids that are added to the concrete to give it certain characteristics not obtainable with plain concrete mixes. In normal use, admixture dosages are less than 5% by mass of cement, and are added to the concrete at the time of batching/mixing. The common types of admixtures are as follows.

- Accelerators speed up the hydration (hardening) of the concrete. Typical materials used are $CaCl_2$, $Ca(NO_3)_2$ and $NaNO_3$. However, use of chlorides may cause corrosion in steel reinforcing and is prohibited in some countries and therefore nitrates may be favoured.
- Retarders slow the hydration of concrete, and are used in large or difficult pours where partial setting before the pour is complete is undesirable. Typical polyol retarders are sugar, sucrose, sodium gluconate, glucose, citric acid, and tartaric acid.
- Air entrainments add and entrain tiny air bubbles in the concrete, which will reduce damage during freeze-thaw cycles thereby increasing the concrete's durability. However, entrained air is a trade-off with strength, as each 1% of air may result in 5% decrease in compressive strength.
- Plasticizers increase the workability of plastic or "fresh" concrete, allowing it be placed more easily, with less consolidating effort. Typical plasticizers are lignosulfonate. Plasticizers can be used to reduce the water content of a concrete while maintaining workability, and are sometimes called *water-reducers* due to this use. Such treatment improves its strength and durability characteristics. Superplasticizers (also called *high-range water-reducers*) are a class of plasticizers that have fewer deleterious effects, and can be used to increase workability more than practical with traditional plasticizers. Compounds used as superplasticizers include sulfonated naphthalene formaldehyde condensate, sulfonated melamine formaldehyde condensate, acetone formaldehyde condensate, and polycarboxylate ethers.
- Pigments can be used to change the color of concrete, for aesthetics.
- Corrosion inhibitors are used to minimize the corrosion of steel and steel bars in concrete.
- Bonding agents are used to create a bond between old and new concrete.
- Pumping aids improve pumpability, thicken the paste, and reduce separation and bleeding.

Blocks of concrete in Belo Horizonte, Brazil.

## Mineral admixtures and blended cements

There are inorganic materials that also have pozzolanic or latent hydraulic properties. These very fine-grained materials are added to the concrete mix to improve the properties of concrete (mineral admixtures), or as a replacement for Portland cement (blended cements).

- Fly ash: A by product of coal fired electric generating plants, it is used to partially replace Portland cement (by up to 60% by mass). The properties of fly ash depend on the type of coal burnt. In general, silicious fly ash is pozzolanic, while calcareous fly ash has latent hydraulic properties.

- Ground granulated blast furnace slag (GGBFS or GGBS): A by-product of steel production is used to partially replace Portland cement (by up to 80% by mass). It has latent hydraulic properties.
- Silica fume: A by-product of the production of silicon and ferrosilicon alloys. Silica fume is similar to fly ash, but has a particle size 100 times smaller. This results in a higher surface to volume ratio and a much faster pozzolanic reaction. Silica fume is used to increase strength and durability of concrete, but generally requires the use of superplasticizers for workability.
- High reactivity Metakaolin (HRM): Metakaolin produces concrete with strength and durability similar to concrete made with silica fume. While silica fume is usually dark gray or black in color, high reactivity metakaolin is usually bright white in color, making it the preferred choice for architectural concrete where appearance is important.

## *Concrete production*


Concrete plant facility (background) with concrete delivery trucks.

The processes used vary dramatically, from hand tools to heavy industry, but result in the concrete being placed where it cures into a final form. Wide range of technological factors may occur during production of concrete elements and their influence to basic characteristics may vary

When initially mixed together, Portland cement and water rapidly form a gel, formed of tangled chains of interlocking crystals. These continue to react over time, with the initially fluid gel often aiding in placement by improving workability. As the concrete sets, the chains of crystals join up, and form a rigid structure, gluing the aggregate particles in place. During curing, more of the cement reacts with the residual water (hydration).

This curing process develops physical and chemical properties. Among other qualities, mechanical strength, low moisture permeability, and chemical and volumetric stability.


Cement being mixed with sand and water to form concrete.

## Mixing concrete

Thorough mixing is essential for the production of uniform, high quality concrete. Therefore, equipment and methods should be capable of effectively mixing concrete materials containing the largest specified aggregate to produce *uniform mixtures* of the lowest slump practical for the work.

*Separate paste mixing* has shown that the mixing of cement and water into a paste before combining these materials with aggregates can increase the compressive strength of the resulting concrete. The paste is generally mixed in a *high-speed*, shear-type mixer at a w/cm (water to cement ratio) of 0.30 to 0.45 by mass. The cement paste premix may include admixtures such as accelerators or retarders, plasticizers, pigments, or silica fume. The premixed paste is then blended with aggregates and any remaining batch water, and final mixing is completed in conventional concrete mixing equipment.

High-energy mixed (HEM) concrete is produced by means of high-speed mixing of cement, water, and sand with net specific energy consumption of at least 5 kilojoules per kilogram of the mix. A plasticizer or a superplasticizer is then added to the activated mixture, which can later be mixed with aggregates in a conventional concrete mixer. In this process, sand provides dissipation of energy and creates high shear conditions on the surface of cement particles. This results in the full volume of water interacting with cement. The liquid activated mixture can be used by itself or foamed (expanded) for lightweight concrete. HEM concrete hardens in low and subzero temperature conditions and possesses an increased volume of gel, which drastically reduces capillarity in solid and porous materials.


Pouring a concrete floor for a commercial building, *slab-on-ground*.

Concrete pump.

A concrete slab ponded while curing.

## Workability

*Workability* is the ability of a fresh (plastic) concrete mix to fill the form/mold properly with the desired work (vibration) and without reducing the concrete's quality. Workability depends on water content, aggregate (shape and size distribution), cementitious content and age (level of hydration), and can be modified by adding chemical admixtures, like superplasticizer. Raising the water content or adding chemical admixtures will increase concrete workability. Excessive water will lead to increased bleeding (surface water) and/or segregation of aggregates (when the cement and aggregates start to separate), with the resulting concrete having reduced quality. The use of an aggregate with an undesirable gradation can result in a very harsh mix design with a very low slump, which cannot be readily made more workable by addition of reasonable amounts of water.

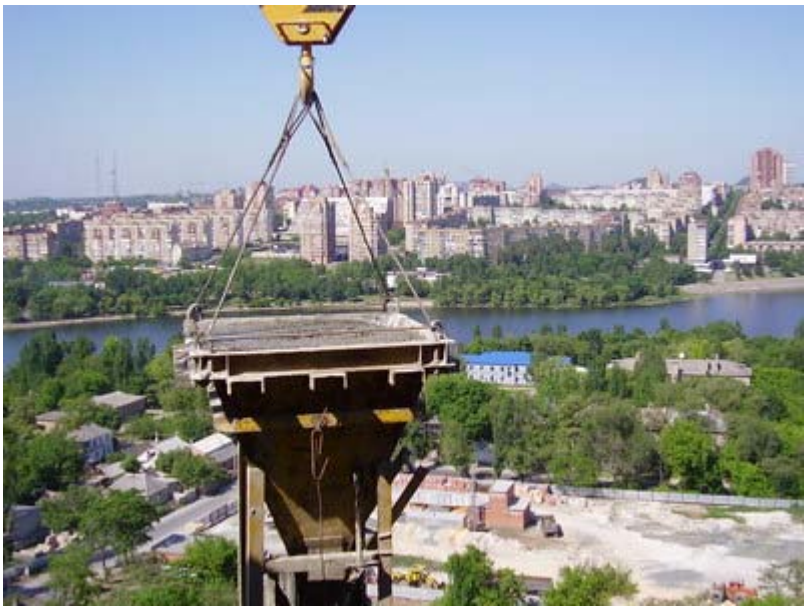
Workability can be measured by the concrete slump test, a simplistic measure of the plasticity of a fresh batch of concrete following the ASTM C 143 or EN 12350-2 test standards. Slump is normally measured by filling an "Abrams cone" with a sample from a fresh batch of concrete. The cone is placed with the wide end down onto a level, non-absorptive surface. It is then filled in three layers of equal volume, with each layer being tamped with a steel rod in order to consolidate the layer. When the cone is carefully lifted off, the enclosed material will slump a certain amount due to gravity. A relatively dry sample will slump very little, having a slump value of one or two inches (25 or 50 mm).

A relatively wet concrete sample may slump as much as eight inches. Workability can also be measured by using the Flow table test.

Slump can be increased by adding chemical admixtures such as plasticizer or superplasticizer without changing the water-cement ratio. Some other admixtures, especially air-entraining admixture, can increase the slump of a mix.

High-flow concrete, like self-consolidating concrete, is tested by other flow-measuring methods. One of these methods includes placing the cone on the narrow end and observing how the mix flows through the cone while it is gradually lifted.

After mixing, concrete is a fluid and can be pumped to where it is needed.



Concrete mixture placement

Concrete compaction

## Curing

In all but the least critical applications, care needs to be taken to properly *cure* concrete, and achieve best strength and hardness. This happens after the concrete has been placed. Cement requires a moist, controlled environment to gain strength and harden fully. The cement paste hardens over time, initially setting and becoming rigid though very weak, and gaining in strength in the weeks following. In around 3 weeks, over 90% of the final strength is typically reached, though it may continue to strengthen for decades.

Hydration and hardening of concrete during the first three days is critical. Abnormally fast drying and shrinkage due to factors such as evaporation from wind during placement may lead to increased tensile stresses at a time when it has not yet gained significant strength, resulting in greater shrinkage cracking. The early strength of the concrete can be increased by keeping it damp for a longer period during the curing process. Minimizing stress prior to curing minimizes cracking. High early-strength concrete is designed to hydrate faster, often by increased use of cement that increases shrinkage and cracking. Strength of concrete changes (increases) up to three years. It depends on cross-section dimension of elements and conditions of structure exploitation.

During this period concrete needs to be in conditions with a controlled temperature and humid atmosphere. In practice, this is achieved by spraying or ponding the concrete surface with water, thereby protecting concrete mass from ill effects of ambient conditions. The pictures to the right show two of many ways to achieve this, ponding – submerging setting concrete in water, and wrapping in plastic to contain the water in the mix.

Properly curing concrete leads to increased strength and lower permeability, and avoids cracking where the surface dries out prematurely. Care must also be taken to avoid freezing, or overheating due to the exothermic setting of cement (the Hoover Dam used pipes carrying coolant during setting to avoid damaging overheating). Improper curing can cause scaling, reduced strength, poor abrasion resistance, and cracking.

## *Properties*

Concrete has relatively high compressive strength, but significantly lower tensile strength, and as such is usually reinforced with materials that are strong in tension (often steel). The elasticity of concrete is relatively constant at low stress levels but starts decreasing at higher stress levels as matrix cracking develops. Concrete has a very low coefficient of thermal expansion, and as it matures concrete shrinks. All concrete structures will crack to some extent, due to shrinkage and tension. Concrete that is subjected to long-duration forces is prone to creep.

Tests can be made to ensure the properties of concrete correspond to specifications for the application.

## *Environmental concerns*

### Carbon dioxide emissions and climate change

The cement industry is one of two primary producers of carbon dioxide ($CO_2$), creating up to 5% of worldwide man-made emissions of this gas, of which 50% is from the chemical process, and 40% from burning fuel. The embodied carbon dioxide ($ECO_2$) of one tonne of concrete is around 100 kg/tonne. The $CO_2$ emission from the concrete production is directly proportional to the cement content used in the concrete mix. Indeed, 900 kg of $CO_2$ are emitted for the fabrication of every ton of cement. Cement manufacture contributes greenhouse gases both directly through the production of carbon dioxide when calcium carbonate is thermally decomposed, producing lime and carbon dioxide, and also through the use of energy, particularly from the combustion of fossil fuels. However, some companies have recognized the problem and are envisaging solutions to counter their $CO_2$ emissions. The principle of carbon capture and storage consists of directly capturing the $CO_2$ at the outlet of the cement kiln in order to transport it and to store the captured $CO_2$ in an adequate and deep geological formation.

### Surface runoff

Surface runoff, when water runs off impervious surfaces, such as non-porous concrete, can cause heavy soil erosion. Urban runoff tends to pick up gasoline, motor oil, heavy metals, trash and other pollutants from sidewalks, roadways and parking lots. The impervious cover in a typical urban area limits groundwater percolation and causes five times the amount of runoff generated by a typical woodland of the same size. A 2008 report by the United States National Research Council identified urban runoff as a leading source of water quality problems.

### Urban heat

Both concrete and asphalt are the primary contributors to what is known as the urban heat island effect.

Using light-colored concrete has proven effective in reflecting up to 50% more light than asphalt and reducing ambient temperature. A low albedo value, characteristic of black asphalt, absorbs a large percentage of solar heat and contributes to the warming of cities. By paving with light colored concrete, in addition to replacing asphalt with light-colored concrete, communities can lower their average temperature.

In many U.S. cities, pavement covers about 30-40% of the surface area. This directly affects the temperature of the city, and contributes to the urban heat island effect. Paving with light-colored concrete would lower temperatures of paved areas and improve nighttime visibility. The potential of energy saving within an area is also high. With lower temperatures, the demand for air conditioning decreases, saving energy.

Atlanta has tried to mitigate the heat-island effect. City officials noted that when using heat-reflecting concrete, their average city temperature decreased by 6 °F. The Design Trust for Public Space found that by slightly raising the albedo value in in New York City, beneficial effects such as energy savings could be achieved. It was concluded that this could be accomplished by the replacement of black asphalt with light-colored concrete.

However, in winter this may be a disadvantage as ice will form more easily and remain longer on the light colored surfaces as they will be colder due to less energy absorbed from the reduced amount of sunlight in winter.

### Concrete dust

Building demolition and natural disasters such as earthquakes often release a large amount of concrete dust into the local atmosphere. Concrete dust was concluded to be the major source of dangerous air pollution following the Great Hanshin earthquake.

## *Health concerns*

The presence of some substances in concrete, including useful and unwanted additives, can cause health concerns. Natural radioactive elements (K, U and Th) can be present in various concentration in concrete dwellings, depending on the source of the raw materials used. Toxic substances may also be added to the mixture for making concrete by unscrupulous makers. Dust from rubble or broken concrete upon demolition or crumbling may cause serious health concerns depending also on what had been incorporated in the concrete.

## Concrete handling/safety precautions

Handling of wet concrete must always be done with proper protective equipment. Contact with wet concrete can cause skin chemical burns due to the caustic nature of the mixture of cement and water. Indeed, the pH of fresh cement water is highly alkaline due to the presence of free potassium and sodium hydroxides in solution (pH ~ 13.5). Eyes, hands and feet must be correctly protected to avoid any direct contact with wet concrete and washed without delay if necessary.

Secondary efflorescence. Water seeping through the concrete, often in cracks, having dissolved components of concrete.

## *Damage modes*

Concrete spalling caused by the corrosion of reinforcement bars after that carbonation of cement decreased the pH below the passivation threshold for steel.

Concrete can be damaged by many processes, such as the expansion of corrosion products of the steel reinforcement bars, freezing of trapped water, fire or radiant heat, aggregate expansion, sea water effects, bacterial corrosion, leaching, erosion by fast-flowing water, physical damage and chemical damage (from carbonation, chlorides, sulfates and distillate water).

## *Concrete repair*

Concrete pavement preservation (CPP) and concrete pavement restoration (CPR) are techniques used to manage the rate of pavement deterioration on concrete streets, highways and airports. Without changing concrete grade, this non-overlay method is used to repair isolated areas of distress. CPP and CPR techniques include slab stabilization, full- and partial-depth repair, dowel bar retrofit, cross stitching longitudinal cracks or joints, diamond grinding and joint and crack resealing. CPR methods, developed over the last 40 years, are utilized in lieu of short-lived asphalt overlays and bituminous patches to repair roads. These methods are often less expensivethan an asphalt overlay but last three times longer and provide a greener solution.

CPR techniques can be used to address specific problems or bring a pavement back to its original quality. When repairing a road, design data, construction data, traffic data, environmental data, previous CPR activities and pavement condition, must all be taken into account. Pavements repaired using CPR methods usually last 15 years. The methods are described below.

- Slab stabilization restores support to concrete slabs by filling small voids that develop underneath the concrete slab at joints, cracks or the pavement edge.
- Full-depth repairs fixes cracked slabs and joint deterioration by removing at least a portion of the existing slab and replacing it with new concrete.
- Partial-depth repairs corrects surface distress and joint-crack deterioration in the upper third of the concrete slab. Placing a partial-depth repair involves removing the deteriorated concrete, cleaning the patch area and placing new concrete.
- Dowel bar retrofit consists of cutting slots in the pavement across the joint or crack, cleaning the slots, placing the dowel bars and backfilling the slots with new concrete. Dowel bar retrofits link slabs together at transverse cracks and joints so that the load is evenly distributed across the crack or joint.
- Cross-stitching longitudinal cracks or joints repairs low-severity longitudinal cracks. This method adds reinforcing steel to hold the crack together tightly.
- Diamond grinding, by removing faulting, slab warping, studded tire wear and unevenness resulting from patches, diamond grinding creates a smooth, uniform pavement profile. Diamond grinding reduces road noise by providing a longitudinal texture, which is quieter than transverse textures. The longitudinal texture also enhances surface texture and skid resistance in polished pavements.
- Joint and crack sealing minimizes the infiltration of surface water and incompressible material into the joint system. Minimizing water entering the joint reduces sub-grade softening, slows pumping and erosion of the sub-base fines, and may limit dowel-bar corrosion caused by de-icing chemicals.

## *Concrete recycling*

Concrete recycling is an increasingly common method of disposing of concrete structures. Concrete debris was once routinely shipped to landfills for disposal, but recycling is increasing due to improved environmental awareness, governmental laws, and economic benefits.

Concrete, which must be free of trash, wood, paper and other such materials, is collected from demolition sites and put through a crushing machine, often along with asphalt, bricks, and rocks.

Reinforced concrete contains rebar and other metallic reinforcements, which are removed with magnets and recycled elsewhere. The remaining aggregate chunks are sorted by size. Larger chunks may go through the crusher again. Smaller pieces of concrete are used as gravel for new construction projects. Aggregate base gravel is laid down as the lowest layer in a road, with fresh concrete or asphalt placed over it. Crushed recycled concrete can sometimes be used as the dry aggregate for brand new concrete if it is free of

contaminants, though the use of recycled concrete limits strength and is not allowed in many jurisdictions. On March 3, 1983, a government funded research team (the VIRL research.codep) approximated that almost 17% of worldwide landfill was by-products of concrete based waste.

Recycling concrete provides environmental benefits, conserving landfill space and use as aggregate reduces the need for gravel mining.

## *World records*

The world record for the largest concrete pour in a single project is the Three Gorges Dam in Hubei Province, China by the Three Gorges Corporation. The amount of concrete used in the construction of the dam is estimated at 16 million cubic meters over 17 years. The previous record was 3.2 million cubic meters held by Itaipu hydropower station in Brazil.

### Concrete pumping

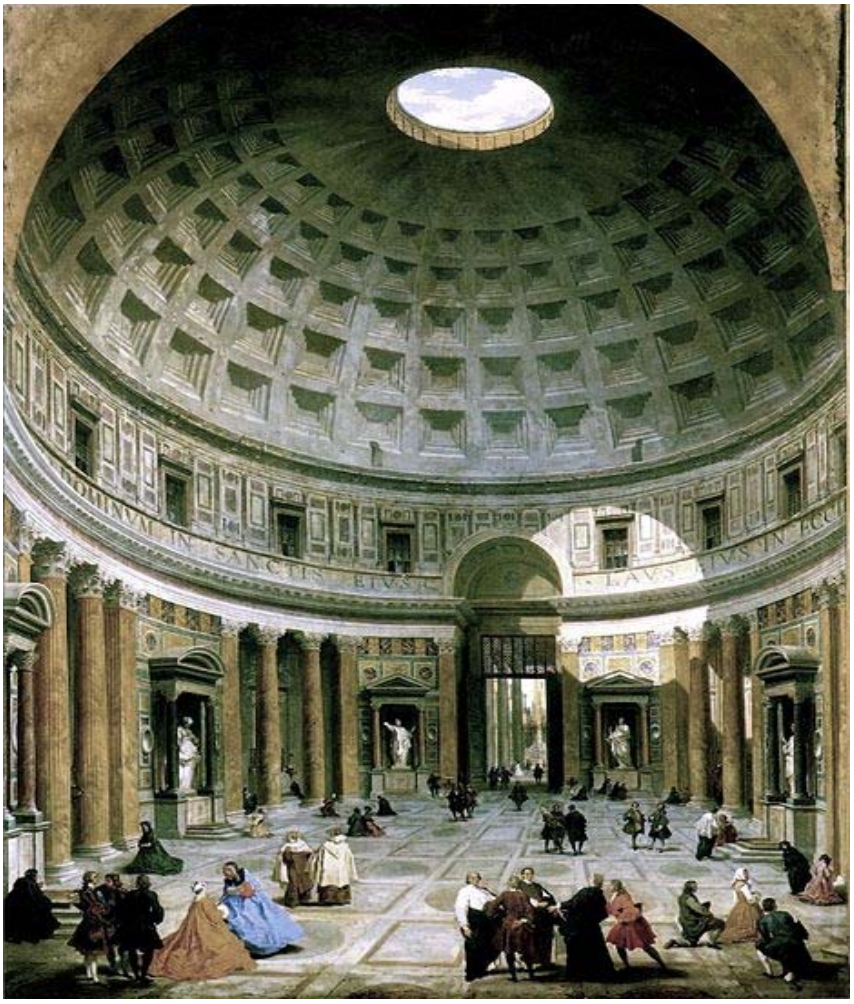
The world record was set at on 7 August 2009 during the construction of the Parbati Hydroelectric Project, near the village of Suind, Himachal Pradesh, India, when the concrete mix was pumped through a vertical height of 715 m (2,346 ft).

### Continuous pours

The world record for largest continuously poured concrete raft was achieved in August 2007 in Abu Dhabi by contracting firm, Al Habtoor-CCC Joint Venture. The pour (a part of the foundation for the Abu Dhabi's Landmark Tower) was 16,000 cubic meters of concrete poured within a two day period. The previous record (close to 10,500 cubic meters) was held by Dubai Contracting Company and achieved March 23, 2007.

The world record for largest continuously poured concrete floor was completed November 8, 1997, in Louisville, Kentucky by design-build firm, EXXCEL Project Management. The monolithic placement consisted of 225,000 square feet (20,900 $m^2$) of concrete placed within a 30 hour period, finished to a flatness tolerance of $F_F$ 54.60 and a levelness tolerance of $F_L$ 43.83. This surpassed the previous record by 50% in total volume and 7.5% in total area.

The record for the largest continuously placed underwater concrete pour was completed October 18, 2010, in New Orleans, Louisiana by contractor, C.J. Mahan Construction Company, LLC, out of Grove City, Ohio. The placement consisted of 10,224 cubic yards of concrete placed in a 58 hour period using two concrete pumps and two dedicated concrete batch plants. Upon curing, this placement will allow the 50,180 square foot cofferdam to be dewatered approximately 26 feet below sea level to allow the construction of the IHNC GIWW Sill & Monolith Project to be completed in the dry.



The interior of the Pantheon in the 18th century, painted by Giovanni Paolo Pannini.

## *Use of concrete in infrastructure*

### Mass concrete structures

These include gravity dams such as the Hoover Dam, the Itaipu Dam, and the Three Gorges Dam and large breakwaters. Concrete that is poured all at once in one block (so that there are no weak points where the concrete is "welded" together) is used for tornado shelters.

### Reinforced concrete structures

Reinforced concrete contains steel reinforcing that is designed and placed in the structure at specific positions to cater for all the stress conditions that the structure is required to accommodate.

## Prestressed concrete structures

**Prestressed concrete** is a form of reinforced concrete that builds in compressive stresses during construction to oppose those found when in use. This can greatly reduce the weight of beams or slabs, by better distributing the stresses in the structure to make optimal use of the reinforcement. For example a horizontal beam will tend to sag down. If the reinforcement along the bottom of the beam is prestressed, it can counteract this.

In pre-tensioned concrete, the prestressing is achieved by using steel or polymer tendons or bars that are subjected to a tensile force prior to casting, or for post-tensioned concrete, after casting.

## Concrete textures

When one thinks of concrete, the image of a dull, gray concrete wall often comes to mind. With the use of form liner, concrete can be cast and molded into different textures and used for decorative concrete applications. Sound/retaining walls, bridges, office buildings and more serve as the optimal canvases for concrete art. For example, the Pima Freeway/Loop 101 retaining and sound walls in Scottsdale, Arizona, feature desert flora and fauna, a 67-foot (20 m) lizard and 40-foot (12 m) cacti along the 8-mile (13 km) stretch. The project, titled "The Path Most Traveled," is one example of how concrete can be shaped using elastomeric form liner.

40-foot cacti decorate a sound/retaining wall in Scottsdale, AZ.

## *Building with concrete*

Concrete is one of the most durable building materials. It provides superior fire resistance compared with wooden construction, can gain strength over time. Structures made of concrete can have a long service life. Concrete is the most widely used construction material in the world with annual consumption estimated at between 21 and 31 billion tonnes.

### Environmentally sustainable

With its 100-year service life, concrete conserves resources by reducing the need for reconstruction. Its ingredients are cement and readily available natural materials: water, aggregate (sand and gravel or crushed stone). Concrete does not require any $CO_2$ absorbing trees to be cut down. The land required to extract the materials needed to make concrete is only a fraction of that used to harvest forests for lumber.

The Baths of Caracalla, Rome, Italy, in 2003.

Concrete absorbs $CO_2$ throughout its lifetime through carbonation, helping reduce its carbon footprint. A recent study indicates that in countries with the most favorable recycling practices, it is realistic to assume that approximately 86% of the concrete is carbonated after 100 years. During this time, the concrete will absorb approximately 57%

of the $CO_2$ emitted during the original calcination. About 50% of the $CO_2$ is absorbed within a short time after concrete is crushed during recycling operations.

Concrete consists of between 7% and 15% cement, its only energy-intensive ingredient. A study comparing the $CO_2$ emissions of several different building materials for construction of residential and commercial buildings found that concrete accounted for 147 kg of $CO_2$ per 1000 kg used, metals accounted for 3000 kg of $CO_2$ and wood accounted for 127 kg of $CO_2$. The quantity of $CO_2$ generated during the cement manufacturing process can be reduced by changing the raw materials used in its manufacture.

A new environmentally friendly blend of cement known as Portland-limestone cement (PLC) is gaining ground all over the world. It contains up to 15% limestone, rather than the 5% in regular Portland cement and results in 10% less $CO_2$ emissions from production with no impact on product performance. Concrete made with PLC performs similarly to concrete made with regular cement and thus PLC-based concrete can be widely used as a replacement. In Europe, PLC-based concrete has replaced about 40% of general use concrete. In Canada, PLC will be included in the National Building Code in 2010. The approval of PLC is still under consideration in the United States.

## Energy efficiency

Energy requirements for transportation of concrete are low because it is produced locally from local resources, typically manufactured within 100 kilometers of the job site. Once in place, concrete offers significant energy efficiency over the lifetime of a building. Concrete walls leak air far less than those made of wood-frames. Air leakage accounts for a large percentage of energy loss from a home. The thermal mass properties of concrete increase the efficiency of both residential and commercial buildings. By storing and releasing the energy needed for heating or cooling, concrete's thermal mass delivers year-round benefits by reducing temperature swings inside and minimizing heating and cooling costs. While insulation reduces energy loss through the building envelope, thermal mass uses walls to store and release energy. Modern concrete wall systems use both insulation and thermal mass to create an energy-efficient building. Insulating Concrete Forms (ICFs) are hollow blocks or panels made of either insulating foam or rastra that are stacked to form the shape of the walls of a building and then filled with reinforced concrete to create the structure.

Models of Porsche automobiles, made out of concrete, part of an exhibition, "Best of Austria," in the Lentos Museum in Linz, Austria in 2009.

## Fire safety and quality of life

Concrete buildings are more resistant to fire than those constructed using wood or steel frames. Since concrete does not burn and stops fire from spreading, it offers total fire protection for occupants and their property. Concrete reduces the risk of structural collapse and is an effective fire shield, providing safe means of escape for occupants and protection for firefighters. Furthermore, it does not produce any smoke or toxic gases and does not drip molten particles, which can spread fire. Neither heat, flames nor the water used to extinguish a fire seriously affect the structure of concrete walls and floors making repairs after a fire a relatively simple task.

A study was conducted in Sweden by Olle Lundberg on the cost of fire damage associated with larger fires in multi-unit buildings, based on statistics from the insurance association in Sweden (Försäkringsförbundet). The study was limited to buildings with an insured value greater than €150,000. It covered 125 fires that occurred between 1995 and 2004, about 10% of the fires in multi-family homes, but 56% of the major fires. The results showed that:

- the average insurance payout per fire, per unit in wood frame buildings was around five times that of fires in concrete buildings (approximately €50,000 compared with €10,000)

- a major fire is more than 11 times more likely to develop in a wood-frame house than in one built using concrete
- among the burned houses, 50% of those made with wood had to be demolished, whereas only 9% of the concrete ones were beyond repair
- the fire spread to neighbouring apartments in only three of the 55 fires in concrete houses
- of those 55 fires, 45 were in attics and roofing

Options for non-combustible construction include floors, ceilings and roofs made of cast-in-place and hollow-core precast concrete. For walls, concrete masonry technology and Insulating Concrete Forms (ICFs) are additional options. ICFs are hollow blocks or panels made of fire-proof insulating foam that are stacked to form the shape of the walls of a building and then filled with reinforced concrete to create the structure.

"Fire-wall" tests, in which ICF walls were subjected to a continuous gas flame with a temperature of more than 1000°C for as long as 4 hours showed no significant breaks in the concrete layer or dangerous transmission of heat. In comparison, wood frame walls normally collapse in an hour or less under these conditions. Concrete provides stable compartmentation in large industrial and multi-storey buildings so a fire starting in one section does not spread to others.

Using concrete to construct buildings offers the best possible protection and safety in fires:

- it does not burn or add to fire load
- it has high resistance to fire, preventing it from spreading thus reduces resulting environmental pollution
- it does not produce any smoke, toxic gases or drip molten particles
- it reduces the risk of structural collapse
- it provides safe means of escape for occupants and access for firefighters as it is an effective fire shield
- it is not affected by the water used to put out a fire
- it is easy to repair after a fire and thus helps residents and businesses recover sooner
- it resists extreme fire conditions, making it ideal for storage facilities with a high fire load
- it provides complete fire protection so there is normally no need for additional measures

Recycled crushed concrete being loaded into a semi-dump truck to be used as granular fill.

Concrete also provides the best resistance of any building material to high winds, hurricanes, tornadoes due to its lateral stiffness that results in minimal horizontal movement. When properly designed for ductility, it also provides superior resistance to seismic events. It does not rust, rot or sustain growth of mold and stands up well to the freeze – thaw cycle. As a result of all these benefits, insurance for concrete homes is often 15 to 25 percent lower than for comparable wood frame homes.

Concrete buildings also have excellent indoor air quality with no off-gassing, toxicity and release of volatile organic compounds so they are generally healthier to live in than those made of wood or steel. As it is practically inert and waterproof, concrete does not need volatile organic-based preservatives, special coatings or sealers. Concrete can be easily cleaned with organic, non-toxic substances. Its sound insulating properties make buildings and homes a quiet and comfortable living environment. After accounting for sound passing through windows, a concrete home is about two-thirds quieter than a comparable wood-frame home.

Due to the long life of concrete structures, their impacts on the environment are negligible. Once built, they have minimal maintenance requirements and as a result

minimal social disruption. Using concrete reduces construction waste as it is used on an as-required basis, thereby minimizing the waste put into landfills.

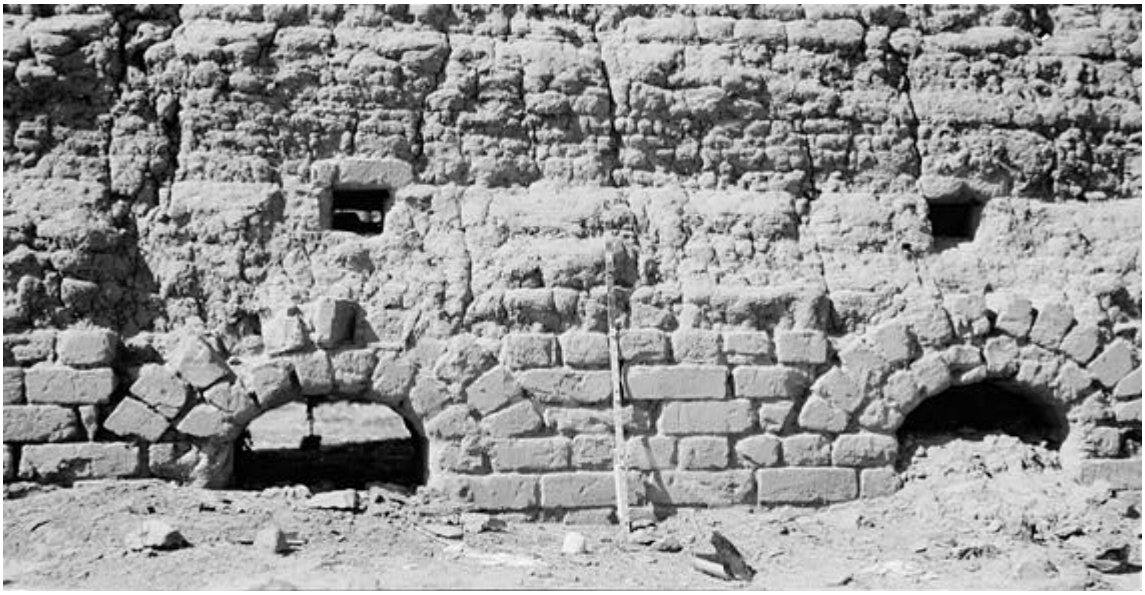
## Recycling and recyclable

A nearly inert material, concrete is suitable as a medium for recycling waste and industrial byproducts. Fly ash, slag and silica fume are used in making concrete, which helps reduce embodied energy, carbon footprint and quantity of landfill materials. The process of making cement also uses waste materials. Tires have high energy content and can supplement coal as fuel in the kiln. Industrial byproducts such as ash from coal combustion, fly ash from power stations as well as mill scale and foundry sand from steel casting provide the silica, calcium, alumina and iron needed for making cement. Even kiln dust, a solid waste generated by cement manufacturing, is often recycled back into the kiln as a raw material. Old concrete that has reached the end of its service life can be recycled and reused as granular fill for road beds.

## Chapter- 7

# Adobe

Renewal of the surface coating of an adobe wall in Chamisal, New Mexico



Detail of adobe kilns in Arizona

**Adobe** is a natural building material made from sand, clay, water, and some kind of fibrous or organic material (sticks, straw, and/or manure), which the builders shape into bricks using frames and dry in the sun. Adobe buildings are similar to cob and mudbrick buildings. Adobe structures are extremely durable and account for some of the oldest existing buildings in the world. In hot climates, compared with wooden buildings, adobe buildings offer significant advantages due to their greater thermal mass, but they are known to be particularly susceptible to earthquake damage.

Buildings made of sun-dried earth are common in the West Asia, North Africa, West Africa, South America, southwestern North America, and Spain (usually in the Mudéjar style) East Europe and East Anglia, particularly Norfolk known as 'clay lump'. Adobe had been in use by indigenous peoples of the Americas in the Southwestern United States, Mesoamerica, and the Andean region of South America for several thousand years, although often substantial amounts of stone are used in the walls of Pueblo buildings. (Also, the Pueblo people built their adobe structures with handfuls or basketfuls of adobe, until the Spanish introduced them to the making of bricks.) Adobe brickmaking was used in Spain already in the Late Bronze Age and Iron Age, from the eighth century B.C. on. Its wide use can be attributed to its simplicity of design and make, and the cheapness thereby in creating it.

A distinction is sometimes made between the smaller *adobes*, which are about the size of ordinary baked bricks, and the larger *adobines*, some of which may be one to two yards (2 m) long.

## *Etymology*

Church at San Pedro de Atacama, Chile.

The word *adobe* has existed for around 4000 years with little change in either pronunciation or meaning: the word can be traced from the Middle Egyptian (c. 2000 BC) word *dj-b-t* "mud [*i.e.*, sun-dried] brick." As Middle Egyptian evolved into Late Egyptian, Demotic, and finally Coptic (c. 600 BC), *dj-b-t* became *tobe* "[mud] brick." This evolved into Arabic *al-tub* (الطّوب *al* "the" + *tub* "brick") "[mud] brick," which was assimilated into Old Spanish as *adobe*, still with the meaning "mud brick." English borrowed the word from Spanish in the early 18th century.

Adobe style in Santa Fe, New Mexico

In more modern English usage, the term "adobe" has come to include a style of architecture that is popular in the desert climates of North America, especially in New Mexico. (Compare with stucco).

## *Composition*

An adobe brick is a composite material made of clay mixed with water and an organic material such as straw or dung. The soil composition typically contains clay and sand. Straw is useful in binding the brick together and allowing the brick to dry evenly. Dung offers the same advantage and is also added to repel insects. The mixture is roughly half sand (50%), one-third clay (35%), and one-sixth straw (15%).

## *Adobe bricks*

Adobe bricks near a construction site in Milyanfan, Kyrgyzstan

Bricks are made in an open frame, 25 cm (10 in) by 36 cm (14 in) being a reasonable size, but any convenient size is acceptable. The mixture is molded by the frame, and then the frame is removed quickly. After drying a few hours, the bricks are turned on edge to finish drying. Slow drying in shade reduces cracking.

The same mixture to make bricks, without the straw, is used for mortar and often for plaster on interior and exterior walls. Some ancient cultures used lime-based cement for the plaster to protect against rain damage.

The brick's thickness is preferred partially due to its thermal capabilities, and partially due to the stability of a thicker brick versus a more standard size brick. Depending on the form that the mixture is pressed into, adobe can encompass nearly any shape or size, provided drying time is even and the mixture includes reinforcement for larger bricks. Reinforcement can include manure, straw, cement, rebar or wooden posts. Experience has shown that straw, cement, or manure added to a standard adobe mixture can all produce a stronger, more crack-resistant brick. A general testing is done on the soil content first. To do so, a sample of the soil is mixed into a clear container with some water, creating an almost completely saturated liquid. After the jar is sealed the container

is shaken vigorously for at least one minute. It is then allowed to sit on a flat surface for a day or so until the soil has settled into layers or remains in suspension. Heavier particles settle out first so gravel will be on the bottom, sand above, silt above that and very fine clay and organic matter will stay in suspension for days. After the water has cleared percentages of the various particles can be determined. Fifty to 60 percent sand and 35 to 40 percent clay will yield strong bricks. The New Mexico US Extension Service recommends a mix of not more than 1/3 clay, not less than 1/2 sand, and never more than 1/3 silt. The largest structure ever made from adobe (bricks) was the Bam Citadel, which suffered serious damage (up to 80%) by an earthquake on December 26, 2003. Other large adobe structures are the Huaca del Sol in Peru, with 100 million signed bricks, the ciudellas of Chan Chan and Tambo Colorado, both in Peru.

## *Thermal properties*

An adobe wall can serve as a significant heat reservoir due to the thermal properties inherent in the massive walls typical in adobe construction. In desert and other climates typified by hot days and cool nights, the high thermal mass of adobe levels out the heat transfer through the wall to the living space. The massive walls require a large and relatively long input of heat from the sun (radiation) and from the surrounding air (convection) before they warm through to the interior and begin to transfer heat to the living space. After the sun sets and the temperature drops, the warm wall will then continue to transfer heat to the interior for several hours due to the time lag effect. Thus a well-planned adobe wall of the appropriate thickness is very effective at controlling inside temperature through the wide daily fluctuations typical of desert climates, a factor which has contributed to its longevity as a building material. In addition, the exterior of an adobe wall can be covered with glass to increase heat collection. In a passive solar home, this is called a Trombe wall.

## *Adobe wall construction*

The citadel of Bam, or Arg-é Bam, in Kerman province of Iran: The world's largest adobe structure, dating to at least 500 BC.

When building an adobe structure, the ground should be compressed because the weight of adobe bricks is significantly greater than a frame house and may cause cracking in the wall. The footing is dug and compressed once again. Footing depth depends on the region and its ground frost level. The footing and stem wall are commonly 24" and 14", much larger than a frame house because of the weight of the walls. Adobe bricks are laid by

course. Each course is laid the whole length of the wall, overlapping at the corners on a layer of adobe mortar. Adobe walls usually never rise above 2 stories because they're load bearing and have low structural strength. When placing window and door openings, a lintel is placed on top of the opening to support the bricks above. Within the last courses of brick, bond beams are laid across the top of the bricks to provide a horizontal bearing plate for the roof to distribute the weight more evenly along the wall. To protect the interior and exterior adobe wall, finishes can be applied, such as mud plaster, whitewash or stucco. These finishes protect the adobe wall from water damage, but need to be reapplied periodically, or the walls can be finished with other nontraditional plasters providing longer protection.

## *Adobe roof*

The traditional adobe roof has been generally constructed using a mixture of soil/clay, water, sand, and other available organic materials. The mixture was then formed and pressed into wood forms producing rows of dried earth bricks that would then be laid across a support structure of wood and plastered into place with more adobe. For a deeper understanding of adobe, one might examine a cob building. Cob, a close cousin to adobe, contains proportioned amounts of soil, clay, water, manure, and straw. This is blended, but not formed like adobe. Cob is spread and piled around a frame and allowed to air dry for several months before habitation. Adobe, then, can be described as dried bricks of cob, stacked and mortared together with more adobe mixture to create a thick wall and/or roof.

### Roof materials

Depending on the materials available, a roof can be assembled using lengths of wood or metal to create a frame work to begin layering adobe bricks. Depending on the thickness of the adobe bricks, the frame work has been performed using a steel framing and a layering of a metal fencing or wiring over the framework to allow an even load as masses of adobe are spread across the metal fencing like cob and allowed to air dry accordingly. This method was demonstrated with an adobe blend heavily impregnated with cement to allow even drying and prevent major cracking.

### Traditional adobe roof

More traditional adobe roofs were often flatter than the familiar steeped roof as the native climate yielded more sun and heat than mass amounts of snow or rain that would find use in precipitous roofs. Cement may be introduced to prevent moisture from penetrating the composite of mud and organic matter. Vigas are beams across the roof that support the roof.

### Raising a traditional adobe roof

To raise a flattened adobe roof, beams of wood or metal should be assembled and span the extent of the building. The ends of the beams should then be fixed to the tops of the

walls using the builder's preferred choice of attachments. Taking into account the material the beams and walls are made from, choosing the attachments may prove difficult. In combination to the bricks and adobe mortar that are laid across the beams creates an even load-bearing pressure that can last for many years depending on attrition.

Once the beams are laid across the building, it is then time to begin the placing of adobe bricks to create the roof. An adobe roof is often laid with bricks slightly larger in width to ensure a larger expanse is covered when placing the bricks onto the beams. This wider shape also provides the future homeowner with thermal protection enough to stabilize an even temperature through out the year. Following each individual brick should be a layer of adobe mortar, recommended to be at least an inch thick to make certain there is ample strength between the brick's edges and also to provide a relative moisture barrier during the seasons where the arid climate does produce rain.

## Attributes

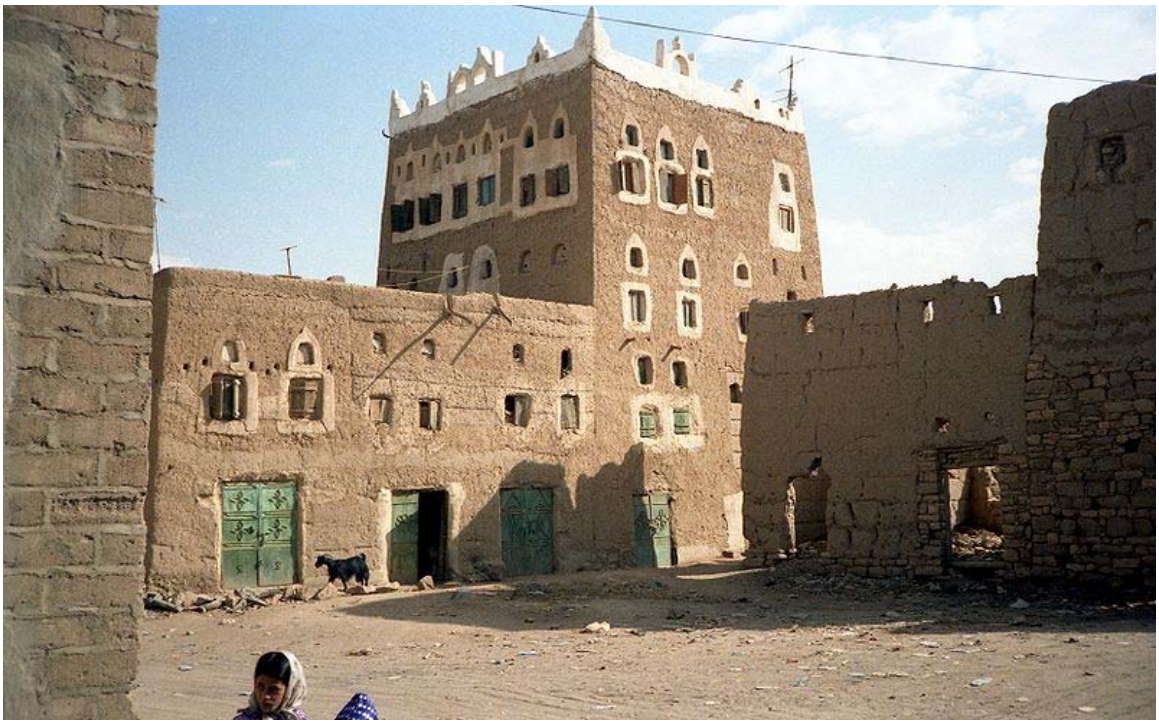
Depending on the materials, Adobe roofs can be inherently fire-proof, which is a valuable attribute when the fireplace is kept lit during the cold nights. The construction of the chimney can also greatly influence the construction of the roof supports, creating an extra need for care in choosing the right materials. The builders can make an adobe chimney by stacking simple adobe bricks in a similar fashion as the surrounding walls.

## *Around the world*

Still in production today, Romania's Danube Delta

Mixing mud and straw in brick frames

Community effort

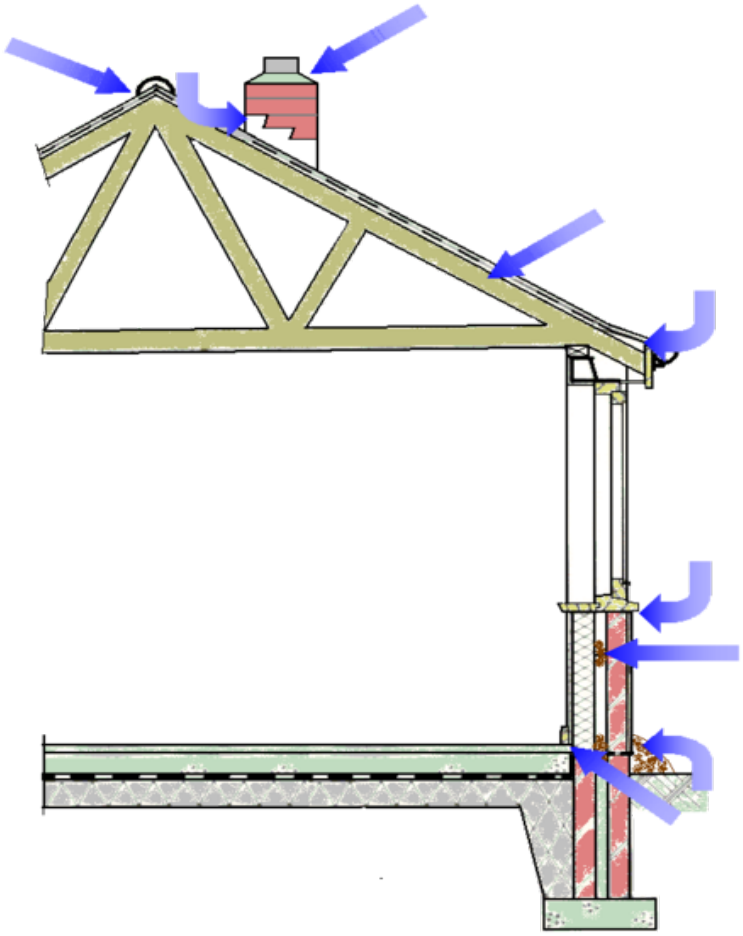


House in Sa'dah, Yemen

Chapter- 8

# Damp (structural) and Damp Proofing

## Damp



Detail showing some of the causes of damp penetration

**Structural dampness** refers to the presence of unwanted moisture in the structure of a building, either the result of intrusion from outside or condensation from within the structure. A high proportion of damp problems in buildings are caused by the "big three," condensation, rain penetration, and rising damp, although other causes of dampness such as pipe leakage and construction moisture should not be overlooked.

## Symptoms

Dampness tends to cause secondary damage to a building. The unwanted moisture enables the growth of various fungi in wood, causing rot. Plaster and paint deteriorate and wallpaper loosens. Stains, from the water, salts and from mold, mar surfaces. Externally, mortar may crumble and salt stains may appear on the walls. Steel & iron fasteners rust. It may also cause respiratory illness in occupants. In extreme cases, mortar or plaster may fall away from the affected wall.

A 2009 World Health Organisation report entitled "Children Living in Homes With Problems of Damp" stated that:

*"Excess moisture leads – on almost all indoor materials – to growth of microbes such as moulds, fungi and bacteria, which subsequently emit spores, cells, fragments and volatile organic compounds into the indoor air. Moreover, dampness initiates chemical and/or biological degradation of materials, which also causes pollution of the indoor air. Exposure to microbial contaminants is clinically associated with respiratory symptoms, allergies, asthma and immunological reactions. Dampness has therefore been suggested to be a strong and consistent indicator of risk for asthma and respiratory symptoms such as cough and wheeze."*

## Identification

A wide range of instruments and techniques can be used to investigate the causes of moisture in building materials. When used correctly, they can provide a valuable aid to investigation. The competence and experience of the person undertaking the damp investigations is of greater importance than the kit he or she carries.

Processes for diagnosing rising Damp in buildings is set out in BRE Digest 245.

All of the above should be considered during any assessment for damp related defects in buildings.

## Prevention and treatment

Most forms of dampness can be prevented by thoughtful building design and careful construction. In the UK, well built modern houses include a synthetic damp-proof course (DPC), about 15 cm above ground level, to act as a barrier through which water cannot pass. Slate or "engineering bricks" with a low porosity were often used for the first few courses above ground level, and these can in theory help minimise the problem.

There are many approaches to the treatment of dampness in existing buildings. Key to the selection of an appropriate treatment is a correct diagnosis of the types of dampness affecting a building. Details of possible treatments for specific types of dampness are covered in the sections below.

The cause of the dampness must first be eliminated, by providing better drainage or fixing leaking pipes. BRE Digest 245 describes several methods of treating rising damp, including the use of land-drains and the insertion of physical and chemical damp-proof courses. Then, any affected plaster or mortar must be removed, and the wall treated, before replacing the plaster and repainting.

The major damp treatment authorities within the U.K. are The British Wood Preserving and Damp-proofing Association (BWPDA) and The Property Care Association.

## *Condensation*

Condensation comes from water vapour within the building. Common sources may include cooking, bathing etc. The moisture in the air condenses on cold surfaces. Buildings with poorly insulated walls are very prone to this problem. It often causes damage similar to damp in a building and often appears in similar places. This is because it occurs in the "dead air" pockets that accumulate in both horizontal and vertical corners (i.e. out of circulating air patterns).

In the United Kingdom, condensation problems are particularly common between October and March - to the extent that this period is often referred to as the "condensation season."

### Identification of condensation

If it is suspected that the problem is condensation, then a room should be sealed off with a dehumidifier left running for the recommended time and then further instrument tests made. If the dampness has disappeared, then condensation is very likely the problem.

Alternatively Humiditect cards or dataloggers (measuring air humidity, air temperature, and surface temperature) can be used as tools for diagnosing a condensation problem.

### Treatment

Typical remedies for condensation include increasing background heat and ventilation, improving the insulation of cold surfaces and reducing moisture generation (e.g. by avoiding the drying of clothes indoors).

## *Rain Penetration*

Rain Penetration (also known as "penetrating damp") is a common form of dampness in buildings. It can occur through walls, roofs, or through openings (e.g. window reveals).

Water will often penetrate the outer envelope of a building and appear inside. Common defects include.

- Roof defects such as faulty flashing, cracked or missing slates or tiles.
- Faults in the brickwork or masonry such as missing or cracked pointing. Porous bricks or stones.
- Missing or defective mastic around windows and doors.
- Blocked weep holes.
- Missing or defective trays in cavity walls.

### Walls

Rain penetration is most often associated with single-skin walls, but can also occur through cavity walls - e.g. by tracking across wall ties.

## *Rising dampness*

Rising damp is the common term for the slow upward movement of water in the low parts of walls and other ground-supported structures by capillary action. It could be identified by a characteristic "tide mark" on the lower section of affected walls, but this could be caused by damp ingression rather than rising damp. This tide mark is caused by soluble salts (particularly nitrates and chlorides) contained in the groundwater. Due to the effects of evaporation these salts accumulate at the "peak" of the rising damp.

According to Jurin's Law the maximum height of rise is inversely proportional to the capillary radius. Taking a typical pore radius for building materials of 1 μm, Jurin's Law would give a maximum rise of about 15 m, however, due to the effects of evaporation, in practice the rise would be considerably lower.

A "physical model" of rising damp was developed by Christopher Hall and William D Hoff in their paper "Rising damp: capillary rise dynamics in walls". The analysis is based on experimentally well established properties of porous building materials and the physics of evaporation from building surfaces. They state that model can be used to predict the height to which damp will rise in a wall, based on factors such as wall thickness, the sorptivity of the wall structure and the effect of evaporation. Further work has confirmed experimentally the importance of mortar properties in determining the height to which damp will rise in walls. BRE Digest 245 lists several factors that can influence the height of the rise including rate of evaporation from the wall, pore sizes of the masonry, salt content of the materials and the soil, groundwater and degree of saturation, and use of heating within the property. The effect of seasonal variations in evaporation rate on the height of moisture rise have been comprehensively described.

A number of people have expressed the view that rising damp is a myth. A former chairman of the construction arm of the Royal Institution of Chartered Surveyors (RICS), Stephen Boniface, has said that ‘true rising damp’ is a myth and chemically injected damp-proof courses (DPC) are ‘a complete waste of money’. Konrad Fisher's article "The

Fraud of Rising Damp" points out that the historic city hall in Bamberg stands in the river Regnitz and its bridge remains dry without any chemical, mechanical or electronic damp-proof course. In fact, evidence would suggest that not all walls are capable of supporting rising damp, so this finding is not particularly surprising. These views are not reflected by the views the UK Building Research establishment (BRE). Indeed, Part C of the Building Regulations for England and Wales specifically calls for the inclusion of a damp-proof course in all new properties.

A review of data and publications commissioned by the Property Care Association and carried out by the University of Portsmouth concluded that "Rising damp is an age-old and ubiquitous problem." It also noted that "Records on observation and descriptions on this phenomenon date back to early times. It was identified as a public health issue in the second half of the 19th Century."

## Diagnosis

The first step in assessing damp is to check for standing water. Removing water with good drainage will remove any form of dampness. Once done, and dampness remains, the next step is to look for the presence of a damp-proof course. If a damp-proof course is present, it is likely to be functioning, as the materials from which damp proof courses are manufactured tend to have a long lifespan. However, it should be acknowledged that there are cases where existing damp proof courses fail for one reason or another.

One method that is often used to determine if the source of dampness is rising damp (rather than other forms of dampness) is to look for the presence of salts - in particular a tell tale "salt band" or "tide mark" at the peak of the damp's rise. Although this is a useful indicator, it is not completely reliable as salts can enter the fabric of the wall in other ways - e.g. unwashed sea sand or gravel used in the construction of the wall.

If there is no damp-proof course and rising damp is suspected (tide mark, moisture confined to lower section of wall etc...) then a number of diagnostic techniques can be used to determine the source of damoness. BRE Digest 245 states that the most satisfactory approach is to obtain samples of mortar in the affected wall using a drill and then analysing these samples do determine their moisture and salt content. The fact that this technique is destructive to the wall finish often makes it unacceptable to homeowners. It is for this reason that electrical moisture meters are often used when surveying for rising damp. These instruments are unable to accurately measure the moisture content of masonry (they were developed for use on timber), however the patterns of readings that they provide can provide a useful indication of the source of dampness.

## Treatment

In many cases, damp is caused by "bridging" of a damp-proof course that is otherwise working effectively. For example a flower bed next to an affected wall might result in soil being piled up against the wall above the level of the DPC. In this example, moisture

from the ground would be able to ingress through the wall from the soil. Such a damp problem could be rectified by simply lowering the flower bed to below DPC level.

Where a rising damp problem is caused by a lack of a damp-proof course (common in buildings over approximately 100 years old) or by a failed damp-proof course (comparatively rare) there are a wide range of possible solutions available. These include:

- Replacement physical damp proof course
- Injection of a liquid or cream chemical damp proof course (DPC Injection)
- Porous tubes
- Electrical-osmotic systems
- Land drainage

BRE Digest 245 suggests that with the exception of replacement physical DPCs, only methods of treatment with third party accreditation (E.g. British Board of Agreement Certificate) should be considered. It then goes on to state that the only method of currently satisfying this requirement is DPC injection and that "this is the only method which BRE considers suitable where insertion of a physical DPC is not possible." The Royal Institute of Chartered Surveryors (RICS) publication "Remedying Damp" is more cautious about reliance on third party accredititation, casting doubt upon the validity of the test methods employed, arguing that trials are usually conducted using "specially built masonry panels - which do not match up in many respects to walls found in real properties," and that "if a DPC were proved *to not* work in a specially built masonry panel, this would be the more significant result." The MOAT No 39 test employed by the British Board of Agreement (BBA) in the UK is dismissed as "quite a clever test idea but in the author's opinion not actually replicating a real wall." Furthermore, the point is made that "BBA testing is paid for by manufacturers, and the results are not thought to be publicly available."

## Replastering

Replastering will often be carried out as part of a rising damp treatment. Where plaster has become severely damaged by ground salts there is little argument about the need to replaster. However there is considerable debate about:

1. The extent of replastering required
2. The use of hard sand:cement renders to replaster as part of a rising damp treatment

BS6576:2005 states that "the function of the new plaster is to prevent hygroscopic salts that might be present in the wall from migrating through to its surface, while still allowing the wall to dry." However, writing in the RICS publication "Remedying Damp", Ralph Burkinshaw claims that, "the plaster is really there for *two* main reasons." He accepts the need for replastering when significant amounts of ground salts have built up in the existing plaster, however he then goes on to say that replastering is often carried out to make up for an unreliable chemical DPC. He also suggests that damp-proofers

have an incentive to carry out more replastering than is strictly necessary as it allows them to finish the job without having to wait for walls to dry out, resulting in faster payment.

Although the sand:cement renders typically installed as part of a rising damp treatment are very effective at holding back damp and ground salts, they have a number of disadvantages. These include an incompatibility with the soft bricks and mortars encountered in older buildings and a lack of insulation properties compared with more traditional plasters, resulting in an increased risk of condensation. Replastering is also one of the most expensive parts of a rising damp treatment.

Porous renders to German WTA specification 2-2-91 can be used as an alternative to dense sand-cement renders. These have a minimum porosity of 40% of total volume. Salts crystallise in these pores rather than on the plaster surface, avoiding decorative spoiling. Such plasters offer a better solution than dense sand-cement renders when used on moderately salt-contaminated walls as their porous nature gives them insulation properties, resulting in a warmer surface temperature and making condensation problems less likely to occur. However, when used on heavily salt contaminated walls they may need to be replaced frequently as they lose effectiveness once all the pores have become filled with crystallised salt.

## Rising Dampness References by Victorians

The issue of rising damp has been a concern since Victorian times. Indeed the Public Heath Act of 1875 introduced the requirement for a damp-proof course in walls to prevent rising damp. An entry in the British medical Journal from 1872 describes the phenomonen as follows:

*"Even if the rising damp be arrested by what is technically called an impervious damp-proof course, it will be frequently found that this is built in the wall too near the ground line, so that the heavy rain besplatters the ground and splashes above it. As time rolls on the surface of the ground also becomes elevated, and this damp course is soon lost to sight. Attempts have been made to remedy this evil of porous bricks by the substitution of the hard blue bricks of Staffordshire; and then it may often be noticed that the wet has only struck, sailor-like, across the mortar-joints and chequered the inside walls like a tartan plaid."*

The architect, Thomas Worthington, described rising damp in his 1892 essay, "The Dwellings of the Poor: And Weekly Wage-Earners in and Around Towns":

*"It should be bourne in mind that damp walls absorb much more heat than dry ones and that they are frequent agents in causing rheumatism, kidney disease and colds. Rising damp from the ground may be prevented by most simple means. Six inches of good Portland cement concrete should cover the whole site of the dwelling, and concrete never less than nine inches thick should underlie all walls. A damp course should disconnect the whole of the foundations from the superstructure. This preventative may consist of a*

*double layer of thick slates bedded in cement, or of patent perforated stone-ware blocks or of three-quarters of an inch of best asphalt."*

# Damp proofing

A damp proofing barrier

**Damp proofing** in construction is a type of waterproofing applied to building foundation walls to prevent moisture from passing through the walls into interior spaces. A **damp-proof course** (often abbreviated to DPC) is a horizontal barrier in a wall designed to resist moisture rising through the structure by capillary action - a phenomenon known as rising damp. A **damp-proof membrane** (DPM) performs a similar function for a solid floor. Moisture resistance is not necessarily absolute: it is usually defined by a specific test method, limits, and engineering tolerances.

## *Background*

Rising damp can occur for various reasons - the failure of an existing damp proof course, bridging due to the raising of external ground or internal floor levels, or in older buildings, the complete absence of a damp proof course.

Brick, stone and mortar are porous allowing damp from the ground to rise by capillary action, carrying with it ground salts including chlorides and nitrates. These salts from the ground can absorb moisture from the atmosphere leading to wall dampness in conditions of high relative humidity. Also they can ruin decorations and break down internal plaster.

A Roman damp-proof course at Hardknott Roman Fort

Damp-proof courses have been used since ancient times. The Romans used a horizontal course of slate inserted in a wall to act as an impervious barrier.

Building standards in many countries require most new buildings to incorporate a DPC/DPM at the time of construction. This may consist of a thin strip of plastic, a course of engineering brick or slate, or a layer of bitumen.

## *Materials*

Materials widely used for damp proofing include:

- Flexible materials like hot bitumen, plastic sheets, bituminous felts, sheets of lead, copper, etc.
- Semi-rigid materials like mastic asphalt
- Rigid materials like impervious bricks, stones, slates, cement mortar or cement concrete painted with bitumen, etc.
- Stones
- Mortar with waterproofing compounds
- Coarse sand layers under floors
- Continuous plastic sheets under floors

## Construction

A DPC is usually a thick plastic strip bedded into the mortar between two courses of bricks or blocks. It can often be seen as a thin plastic line in the mortar near ground level.

A DPM is usually a thick polythene sheet laid under the floor slab, to allow the slab to dry out and keep out groundwater. It is often laid on a bed of sand, to prevent the sharp edges of the hardcore damaging it.

To create a continuous barrier, pieces of DPC or DPM are welded together. In addition, the DPC is welded to the DPM around the outside edges of the ground floor, completely sealing the inside of the building from the damp ground under it.

In a cavity wall, there is usually a DPC in both the outer and inner wall. In the outer wall it is normally 150-200mm above ground level (the height of 2-3 brick courses). This allows rain to form puddles and splash up off the ground, without saturating the wall above DPC level. The wall below the DPC may become saturated in rainy weather. The DPC in the inner wall is usually below floor level, (under a suspended timber floor structure), or, with a solid concrete floor, it is usually found immediately above the floor slab so that it can be linked to the DPM under the floor slab. This enables installation of skirting boards above floor level without fear of puncturing it. Alternatively, instead of fitting separate inner and outer DPCs, it is common in commercial housebuilding to use a one-piece length of rigid plastic, (albeit an angled section), which fits neatly across the cavity and slots into both walls (a cavity tray). This method requires the need for weep vents to enable rainwater ingress to drain from the cavities otherwise rising dampness could occur from above the DPC.

## Remedial DPC

In old buildings there may be a DPC made from lead. The DPM may be non-existent, leading to damp problems, or it may rely on an impermeable floor finish such as ceramic tiles to keep most of the damp out.

Where a DPC is absent or inadequate, there are various means of retrofitting one. A common method in masonry walls is to drill holes into the wall at regular intervals and inject a penetrating liquid (e.g. silicone) into the holes. The chemical is absorbed into the

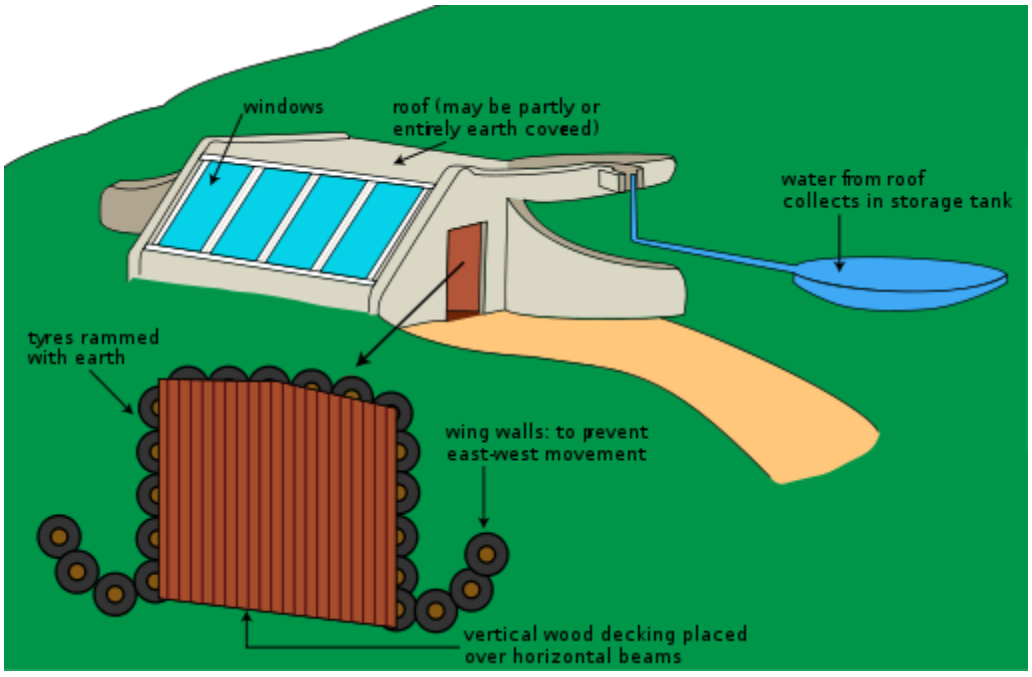
masonry, where it cures to form a waterproof barrier. More recently, damp-proofing creams have been introduced which are faster to install and do not require specialist pumping equipment. Whether in liquid or cream form, the effectiveness of chemical damp-proofing products depends on a number of factors including product strength, the types of active ingredients in the formulation, the delivery system (e.g. solvents and surfactants), and the suitability of the system for the substrate that it is being injected into. Some forms of the chemical are odour-free; others have a strong odour.

Damp proofing remedies include:

- Silane diffusion: Utilising a concentrated thixotropic silane / silicone ‘cream’
- Siliconate transfusion: A gravity fed system with no wastage via hidden voids
- Siliconate injection: Recommended occasionally for single brick walls

## Chapter- 9

# Earthship




The design used with most earthships. A large series of windows characterise the earthsheltered building and the use of tires

A somewhat customized earthship built at Rio Arriba County, New Mexico, USA and shot from the side

the exterior of a very modern Earthship

An **Earthship** is a type of passive solar house made of natural and recycled materials. Designed and marketed by **Earthship Biotecture** of Taos, New Mexico, the homes are primarily constructed to work autonomously and are generally made of earth-filled tires, using thermal mass construction to naturally regulate indoor temperature. They also

usually have their own special natural ventilation system. Earthships are generally Off-the-grid homes, minimizing their reliance on public utilities and fossil fuels.

The original Earthships' designs were at first very experimental, but with practice and evolution the houses began looking attractive.

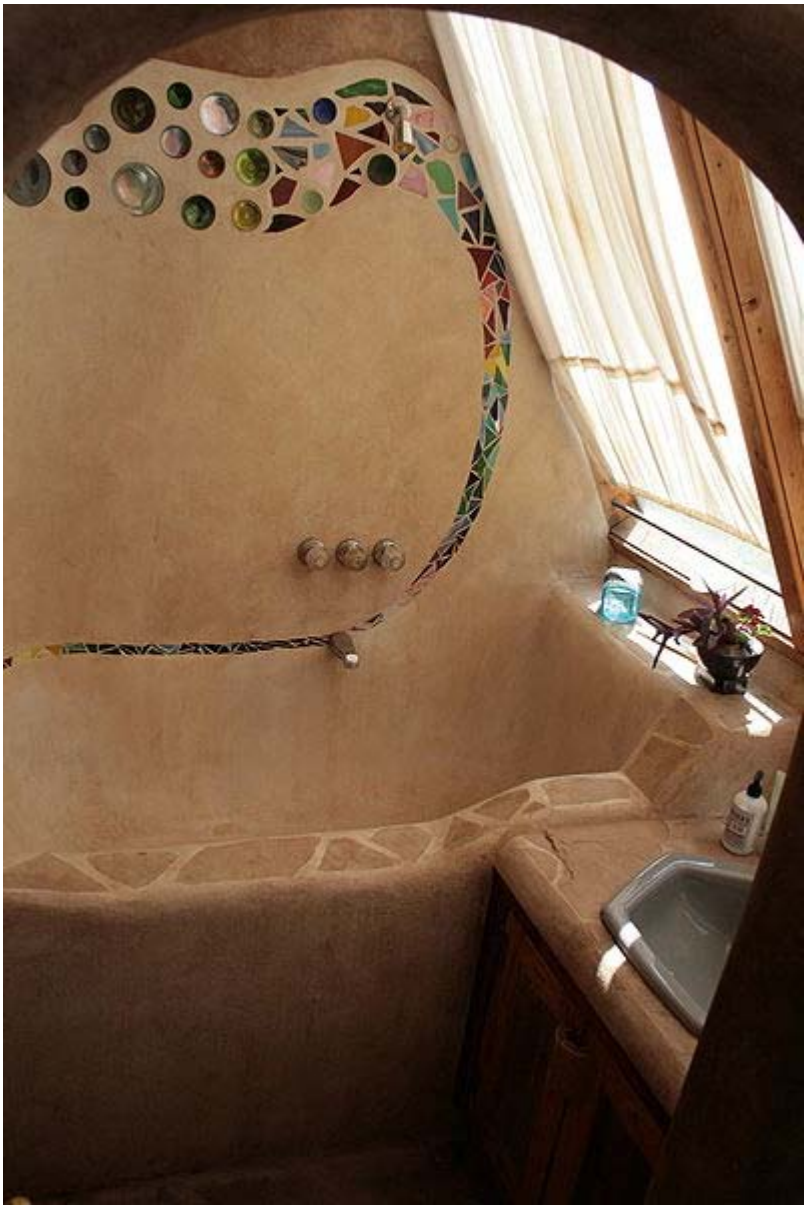
Earthships are built to utilize the available local resources, especially energy from the Sun. For example, windows on sun-facing walls admit lighting and heating, and the buildings are often horseshoe-shaped to maximize natural light and solar-gain during winter months. The thick, dense inner walls provide thermal mass that naturally regulates the interior temperature during both cold and hot outside temperatures.

Internal, non-load-bearing walls are often made of a honeycomb of recycled cans joined by concrete and are referred to as tin can walls. These walls are usually thickly plastered with stucco.

The roof of an Earthship is heavily insulated – often with earth or adobe – for added energy efficiency.

## *History*

a bottle wall of an Earthship bathroom



an Earthship bathroom

The Earthship, as it exists today, began to take shape in the 1970s. Mike Reynolds, founder of Earthship Biotecture, a company that specializes in designing and building Earthships, wanted to create a home that would do three things; first, it would be sustainable, using material indigenous to the entire planet as well as recycled materials wherever possible. Second, the homes would rely on natural energy sources and be independent from the "grid", therefore being less susceptible to natural disasters and free from the electrical and water lines that Reynolds considered unsightly and wasteful. Finally, it would be economically feasible for the average person with no specialized construction skills to be able to create.

Eventually, Reynolds' vision took the form of the common U-shaped earth-filled tire homes seen today. As a concept, the Earthship was not limited to tires – any dense material with a potential for thermal mass, such as concrete, adobe, or stone could theoretically be used to create an Earthship. However, the earth-rammed tire version of the Earthship is now the most common design, and is usually the only structure referred to as “Earthship”.

Earthships are made of Earth-rammed tires, bottles and cans

Unlike other materials, rammed-earth tires are more accessible to the average person. Scrap tires are ubiquitous around the world and easy to come by; there are an estimated 2 billion tires throughout the United States. As of 1996, as many as 253 million scrap tires were being generated each year in the United States, with 70% being reclaimed by the scrap tire market (leaving perhaps 75 million scrap tires available for reuse as whole tires). In addition to the availability of scrap tires, the method by which they are converted into usable "bricks", the ramming of the earth, is simple and affordable.

The earth-rammed tires of an Earthship are usually assembled by teams of two people working together as part of a larger construction team. One member of the two person team shovels dirt, which usually comes from the building site, placing it into the tire one scoop at a time. The second member, who stands on the tire, uses a sledge hammer to pack the dirt in. The second person moves in a circle around the tire to keep the dirt even and avoid warping the tire. These rammed earth tires in an Earthship are made in place

because, when properly made, they weigh as much as 300 pounds and can be very difficult to relocate.

Additional benefits of the rammed earth tire are its great load-bearing capacity and its resistance to fire.

A fully rammed tire, which is about 2 feet 8 inches wide, is massive enough to surpass conventional requirements for structural load distribution to the earth. Because the tire is full of soil, it does not burn when exposed to fire. In 1996 after a fire swept through many conventional homes in New Mexico, an Earthship discovered in the aftermath was relatively unharmed. Only the south-facing wall and the roof had burned away, compared to the total destruction of the conventional homes.

Currently, Earthships are in use in almost every state in the United States, as well as many countries in Europe. The use of insulation on the outside of tire walls, which was not common in early designs, is improving the viability of Earthships in every climate without compromising their durability. In the year 2000, Mike Reynolds, in partnership with Daren Howarth, launched Earthship Biotecture Europe, an organization that aims to explore and evolve the concept of the Earthship within a European context. Two more directors were appointed to Earthship Biotecture Europe in July 2006 – Kevan Trott and Kirsten Jacobsen.

## *Europe*

Brighton Earthship, UK

In 2000, Michael Reynolds and his team came to build the first residential earthship in Boingt (Belgium). While water, power module, solar panels and the team where on their way to Europe, the mayor of Boingt put his veto on the building permit. So Josephine, the woman who wanted to build the earthship, and Michael Reynolds decided to do a demonstration model in her back yard at her residence in Strombeek (Belgium). This was the beginning of a series of trips of Reynolds which led to a series of earthships in the UK, France and the Netherlands.

In 2004, the very first Earthship in the UK was opened at Kinghorn Loch in Fife, Scotland. It was built by volunteers of the SCI charity. In 2005, the first earthship in England was established in Stanmer Park, Brighton with the Low Carbon Trust.

Earthship biotecture has now finalized plans for a planning application to build on a valuable development site overlooking the Brighton Marina in the UK. The application follows the successful six-month feasibility study funded by the UK Environment Agency and the Energy Savings Trust. The application calls for sixteen one, two, and three-bedroom earthship homes on this site. The homes are all designed according to basic earthship principles developed in the United States. 15,000 tires will be recycled to construct these homes (the UK burns approximately 40 million tires each year). The plans include the enhancement of habitats on the site for lizards that already live there, which is the reasoning behind entitling the project "The Lizard". This will be the first development of its kind in Europe, and successful development in Brighton may help to pave the way for similar projects around the UK and other places.

The first official Earthship home in mainland Europe with official planning commission approval was built in a small French village called Ger. The home, which is owned by Kevan and Gillian Trott, was built in April 2007 by Kevan, Mike Reynolds and an Earthship Crew from Taos. The design was modified for a European climate and is seen as the first of many for the European arena. It is currently used as a holiday home for eco-tourists.

The first official earthship district (23 earthships) in Europe is currently being developed in Olst (the Netherlands). Building will start in summer 2011.

## *Africa*

The first earthship was built by Angel and Yvonne Kamp from 1996 to 1998. They rammed a total of 1,500 tires for the walls. The earthship, near Hermanus, is located in a 60 hectare private nature reserve which is part of a 500000ha area enclosed in a game fence and borders the Walker Bay Nature Reserve.

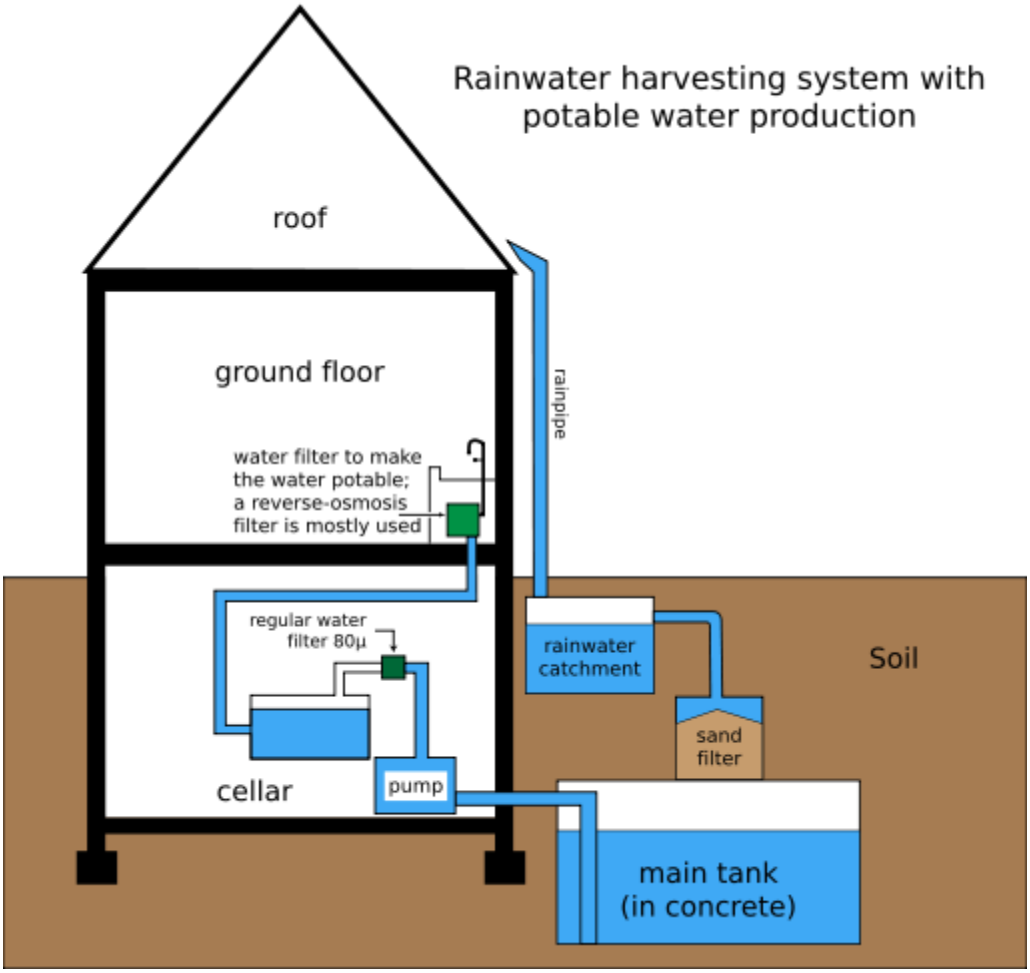
Two new projects are also in early development in Africa, an information and training centre in Orania, South Africa and a residential house in Swaziland.

## *Systems*

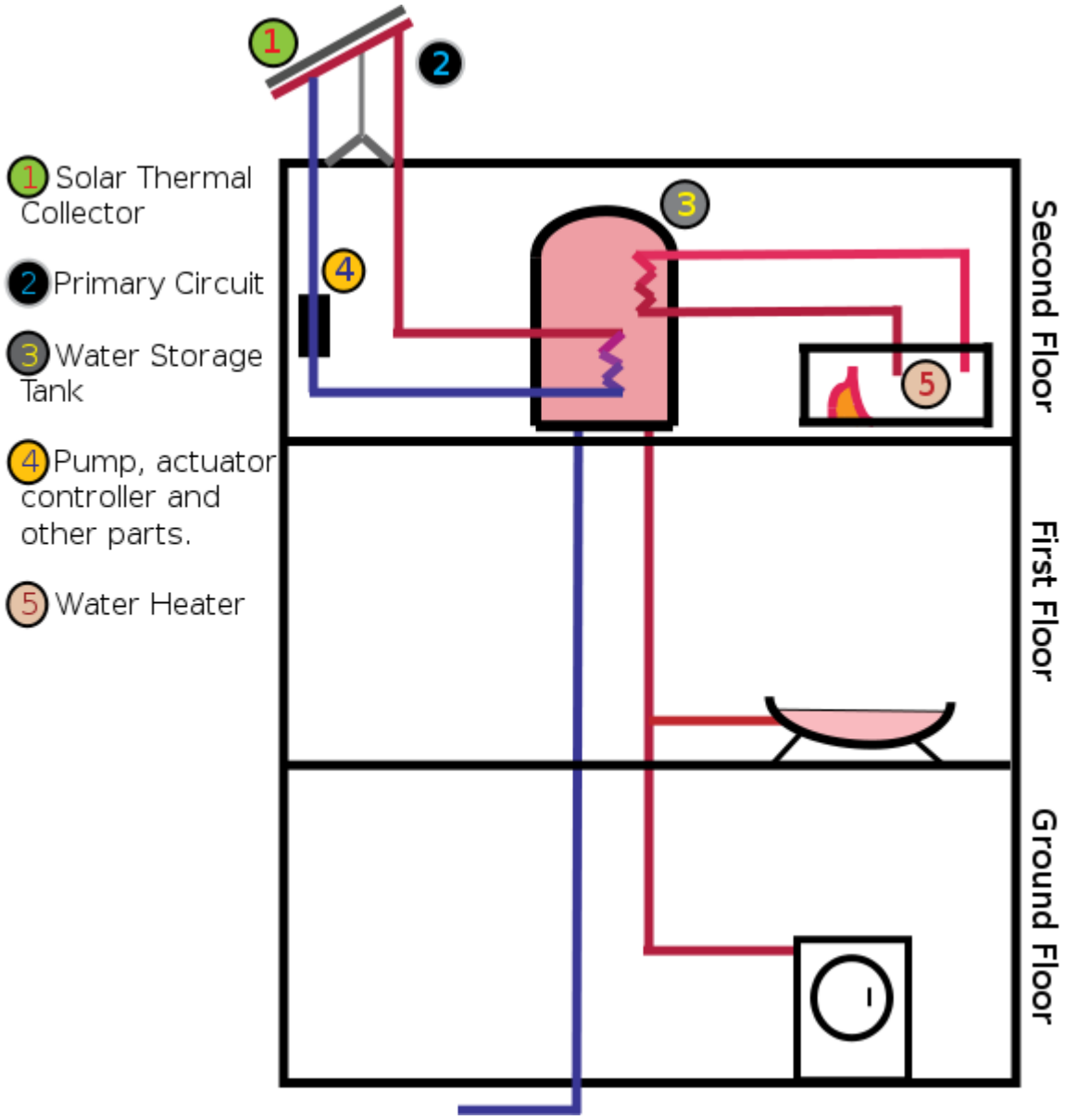
The Earthship was designed as a structure that would exist in harmony with its environment and be freed from the constraints of modern shelters which rely on centralized utilities. It is important that the Earthship create its own utilities as well as use readily available and sustainable materials. In order to be entirely self-sufficient the Earthship needs to be able to handle the three systems of water, electricity, and climate. While these systems are not exclusive to Earthships, a properly designed Earthship must have these systems.

## *Water*

A botanical cell for greywater treatment featuring interior banana trees




A domestic rainwater harvesting system




Schematic of an active solar heating system

## Collection

Earthships are designed to catch and use water from the local environment without bringing in water from a centralized source. Water used in an Earthship is harvested from rain, snow and condensation. As water collects on the roof it is channeled through a silt-catching device and into a cistern. The cisterns are positioned so they gravity-feed a WOM (water organization module), that filters out bacteria and contaminants, and makes it suitable for drinking. The WOM consists of filters and a DC-pump that are screwed into a panel. Water is then pushed into a conventional pressure tank to create common household water pressure. Water collected in this fashion is used for any household

activity except flushing toilets the conventional way. Rather, the water used for flushing toilets has been used at least once already: frequently it is filtered waste-water from sinks and showers, and described as "Greywater".

## Greywater

Greywater, water that has been used and is unsuitable for drinking, is used within the Earthship for a multitude of purposes once it is reclaimed. First, before the greywater can be reused, it is channeled through a grease and particle filter/digester and into a 30”-60" deep rubber-lined botanical cell, a miniature living machine, within the Earthship. This filter with imbedded plants can potentially also be used to produce food (by using a fruit tree, ...). Oxygenation, filtration, transpiration, and bacteria-encounter all take place within the cell and help to cleanse the water (Reynolds 2000). Within the botanical cell, filtration is achieved by passing the water through a mixture of gravel and plant roots. Because of the nature of plants, oxygen is added to the water as it filters, while nitrogen is removed. Water taken up through the plants and transpired at their tops helps to humidify the air. In the cell, bacteria will naturally grow and help to cleanse the water.

Water from the low end of the botanical cell is then directed through a peat-moss filter and collected in a reservoir or well. This reclaimed water is then passed once more through a greywater board and used to flush conventional toilets.

Often, any greywater that is made at earthships is not polluted enough to justify treatment (its "pollution" being usually just soap, which is often not environmentally damaging). At earthships, the use of plants placed at outlets of fixtures is then practiced to regain the water and the nutrients lost (from the soaps, etc.).. Usually, a single plant is placed directly in front of the pipe, but mini drain-fields are also sometimes used. The pipe is made large enough (5,08 cm) so that the formation of underground gas (from the greywater) is avoided. This is done with kitchen and bathroom sinks, and even showers, washing machines, and dishwashing machines. The plants are usually placed indoors with the sinks and outdoors with the washing/dishwashing machines and shower (to avoid indoor "floods"). Also, with the latter, larger drain-fields are used instead of a mere plant being placed before an outlet.

## Black water

Black water, water that has been used in a toilet, was usually not created within many of the earliest earthships as the use of conventional toilets was discouraged. Instead, in the early days composting toilets were advocated, which use no water at all. However, with the new greywater treatment system design (used in Nautilus, Helios, ...) created by Michael Reynolds, flush toilets have now found a place in the earthship and the general water system has been redesigned according to the new "6-step process".

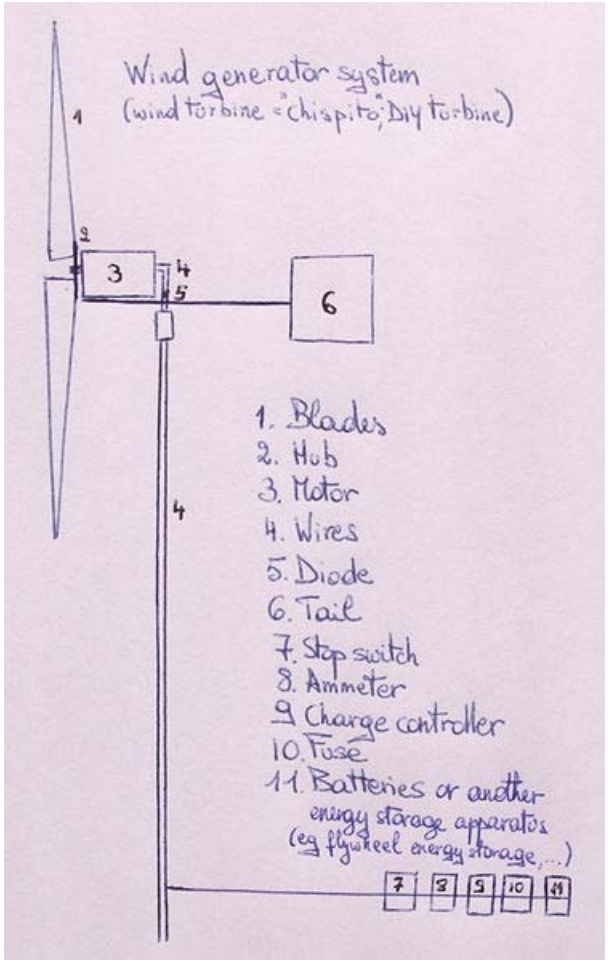
Now, when the newly included flush-toilets are used, blackwater is not reused within the Earthship. Instead, blackwater is sent to a solar-enhanced septic tank with leach-field and planter cells (the whole being often referred to as the “incubator”). The solar-enhanced

septic tank is a regular septic tank which is heated by the sun and glazed with an equator-facing window. The incubator stores the sun's heat in its concrete mass, and is insulated, to help the anaerobic process. Water from the incubator is channeled out to an exterior leach field and then to landscaping "planter cells" (spaces surrounded by concrete in which plants have been put). The cells are similar to the botanical cell used in greywater treatment and are usually placed just before and under the windows of the earthship.

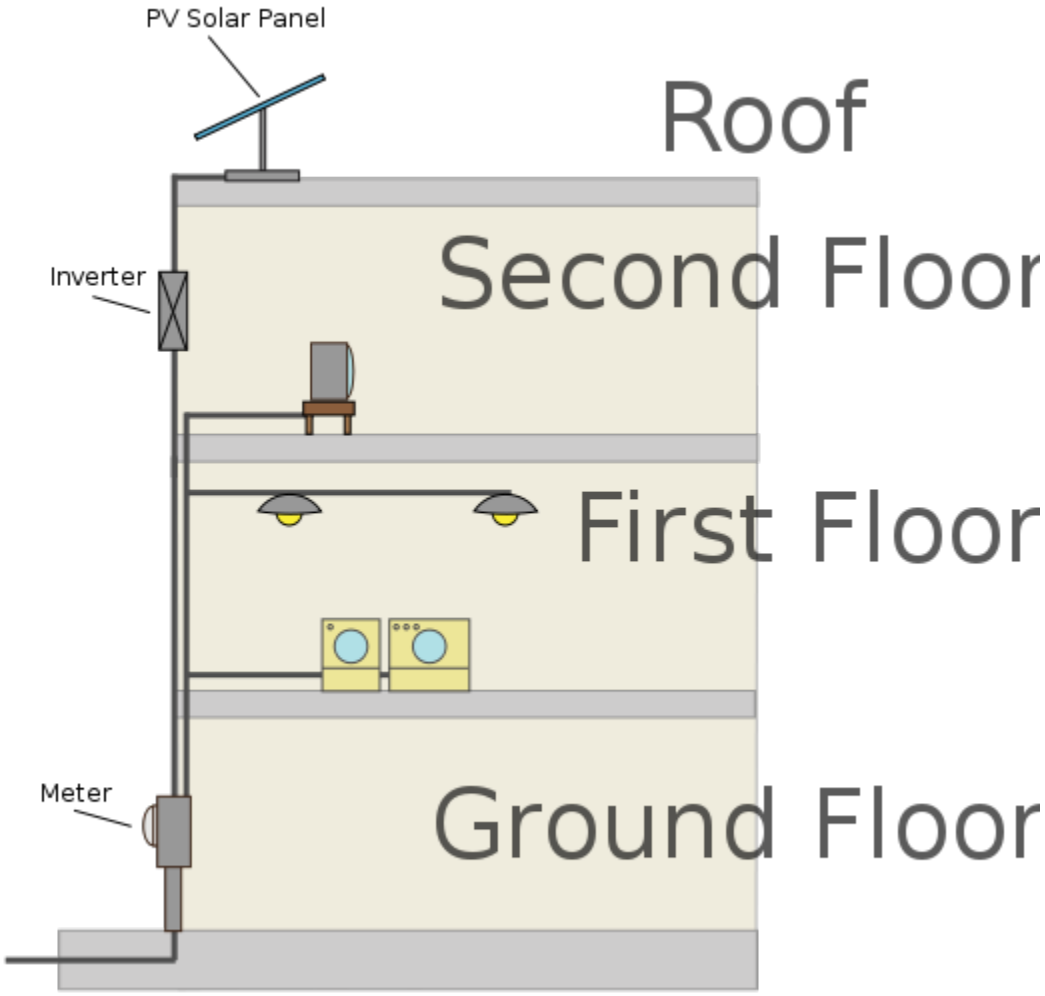
In cases where it is not possible to use flush-toilets operating on water, dry solar toilets are now advocated, instead of *regular* composting toilets. If this is the case, obviously no black water is formed and the use of an incubator is thus (usually) not necessary. Instead, regular "planters" (plants used for sucking up water/nutrients) are then used. When using regular planters as well, no chemical soaps or detergents can be used.

The space where the WOM (water organization module), graywater pump panel, pressure tank, (first set of) batteries, and POM (power organising module) are stored is in a small room referred to as the "systems package".

## *Electricity*




Parts of DIY Wind turbine




A PV-solar system

Earthships are designed to collect and store their own energy from a variety of sources. The majority of electrical energy is harvested from the sun and wind. Photovoltaic panels and windturbines located on or near the Earthship generate DC energy that is then stored in several types of deep-cycle batteries. The space in which the batteries are kept is usually a special, purpose-built room placed on the roof. Additional energy, if required, can be obtained from gasoline-powered generators or by integrating with the city grid.

In an Earthship, a Power Organizing Module is used to take stored energy from batteries and invert it for AC use. The Power Organizing Module is a prefabricated system provided by Earthship Biotecture that is simply attached to a wall on the interior of the Earthship and wired in a conventional manner. It includes the necessary equipment such as circuit breakers and converters. The energy run through the Power Organizing Module

can be used to run any house-hold appliance including washing machines, computers, kitchen appliances, print machines, vacuums, etc. Generally, none of the electrical energy in an Earthship is used for heating or cooling.

## *Climate*

The interior climate of an Earthship is stabilized and made comfortable by taking advantage of many phenomena. Mainly, the Earthship tries to take advantage of the properties of thermal mass and passive solar heating and cooling. Examples are large front windows with integrated shades, trombe walls and other technologies such as skylights or Track Rack solar trackers (dualling as an energy generation device and passive solar source.

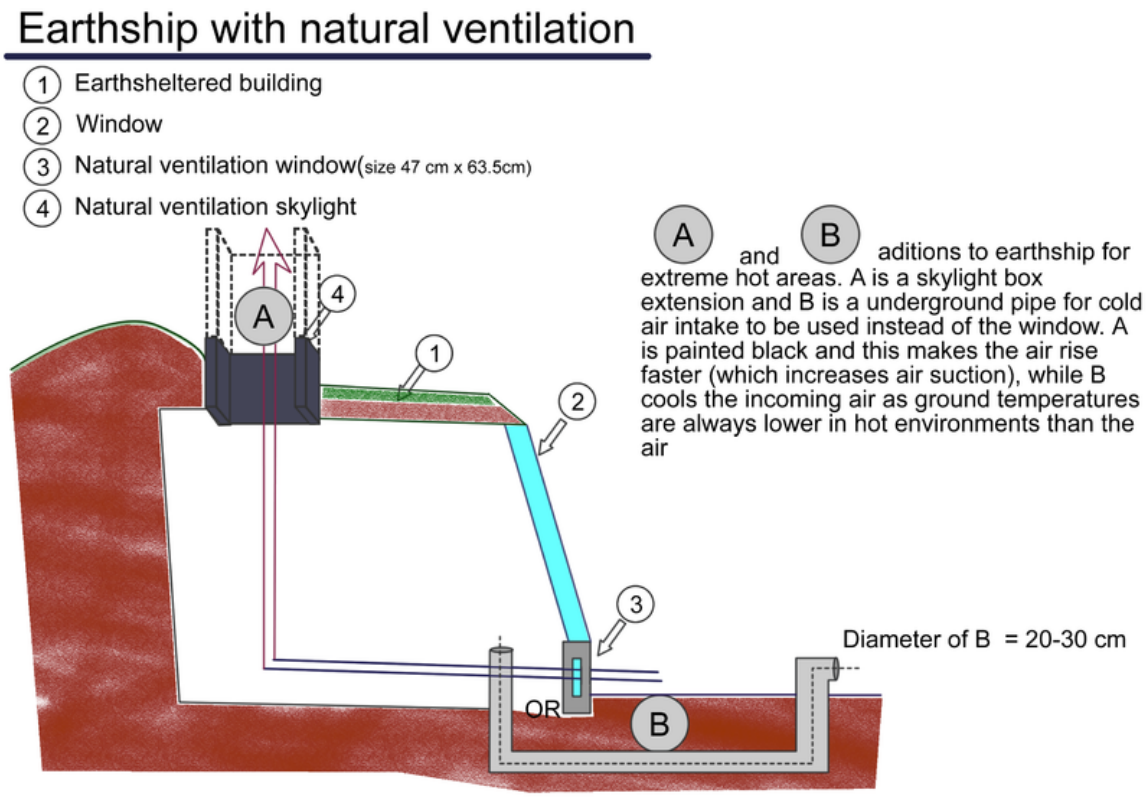
The load-bearing walls of an Earthship, which are made from steel-belted tires rammed with earth, serve two purposes. First, they hold up the roof, and second, they provide a dense thermal mass that will soak up heat during the day and radiate heat during the night, keeping the interior climate relatively comfortable all day.

In addition to high thermal mass, some Earthships may be earth-sheltered. The benefits of earth-sheltering are twofold because it adds to the thermal mass and, if the Earthship is buried deep enough, allows the structure to take advantage of the Earth's stable temperature.

The Earthship is designed in such a way that the sun provides heating, ventilation, and lighting. To take advantage of the sun, an Earthship is positioned so that its principal wall, which is nonstructural and made mostly of glass sheets, faces directly towards the equator. This positioning allows for optimum solar exposure.

To allow the sun to heat the mass of the Earthship, the solar-orientated wall is angled so that it is perpendicular to light from the winter sun. This allows for maximum exposure in the winter, when heat is wanted, and lesser exposure in the summer, when heat is to be avoided. Some Earthships, especially those built in colder climates, use insulated shading on the solar-orientated wall to reduce heat loss during the night (Reynolds 2000).

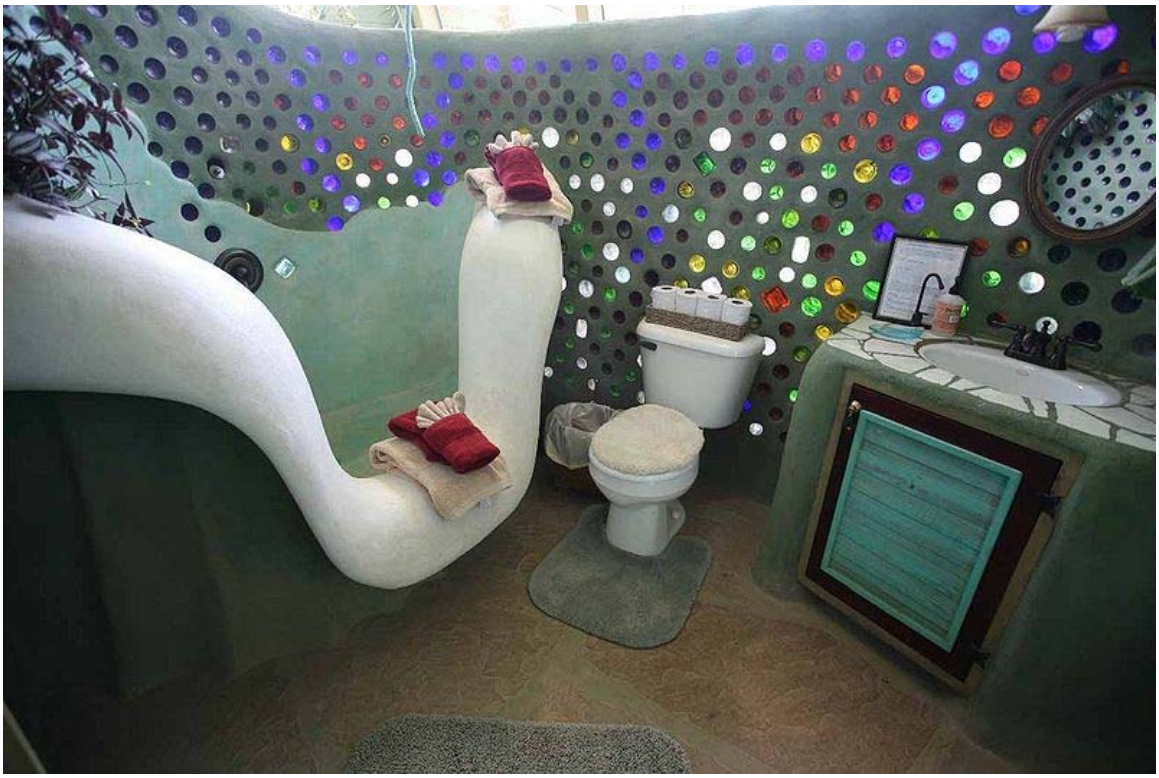
## Natural ventilation




The ventilation system of an earthship

The earthships usually use their own natural ventilation system. It consists of cold(er) air coming in from a front ("hopper") window, especially made for this purpose and flowing out through (one of) the skylights that are placed on the earthship. As the hot air rises, the system creates a steady airflow - of cooler air coming in, and warmer air blowing out.

## *Heating problems*



Bottle walls are used in earthships such as this earthship bathroom, located in Phoenix Earthship, Taos, NM, USA

Earthships rely on a balance between the solar heat gain and the ability of the tire walls and subsoil to transport and store heat. The design intends to require little if any auxiliary heat. Some earthships have suffered from over-heating and some from over-cooling.

Some earthships appear to have serious problems with heat loss. In these cases heat appears to be leaking into the ground constantly during the heating season and being lost. This situation may have arisen from the mistaken belief that ground-coupled structures (building in thermal contact with the ground) do not require insulation. The situation may also be due to large climatic differences between the sunny, arid, and warm Southwest (of the USA) where earthships were first built and the cloudier, cooler, and wetter climates where some are now being built. Malcolm Wells, an architect and authority on earth-sheltered design, recommends R-value 10 insulation between deep soils and heated spaces. Wells's insulation recommendations increase as the depth of the soil decreases.

In very limited and specific situations, uncommon during the heating season, thermal mass can marginally increase the apparent R-value of a building assembly such as a wall. Generally speaking thermal mass and R-value are distinct thermodynamic properties and should not be equated. Thermal performance problems apparently seen in some earthship

designs may have occurred because of thermal mass being erroneously equated to R-value. The R-value of soil is about 1 per foot.

## *Potential advantages*

- Having an earth-bermed home with windows facing the sun is a good idea in any climate where heating is required.
- Collecting rainwater that falls on the roof reduces the runoff impact of the building and may reduce water and even sewer service fees.
- Having a combination of photovoltaic cells and wind generation is a prudent way to provide electricity in many situations.
- Using curved modules as horizontal arches to resist earth loads is a sound structural design.
- On-site processing of runoff water, grey water, and black water using plant beds reduces the environmental impact of the building.
- Rubber tires make a wind- and puncture- resistant wall. They may be safe from outgassing when plastered semi-airtight.
- Rubber tires are usually free and it may be possible to be paid to take them. It also is beneficial to keep them out of landfills or prevent them from being illegally burnt.
- Potential to eliminate utility bills.
- The structure is highly moldable to different aesthetic tastes.

## *Potential disadvantages*

- The sloped glazing may be hard to keep watertight and in warm climates allows excessive solar gain in summer. In colder climates, the glazing itself, which has far poorer insulating properties than any other component, will obviously be the major conduit of heat loss in winter. New designs call for vertical windows with an overhang.
- Uninsulated ground-coupled thermal mass presents a large potential for heat loss, especially in climates with a heating season. This varies to a degree with soil type and moisture content.
- Rubber-tire walls tend to lack structural stiffness and may require perpendicular stiffening ribs.
- Most solar photovoltaic systems suffer from poor efficiency and some wind systems only generate in periods of high wind velocity.
- The novel design may diminish resale value or make buyers more difficult to find.
- The intimate ground contact inherent in this approach may increase hazards due to soil gases including Radon, and those due to water intrusion.
- Packing or ramming dirt into the inside of tires is a very labor-intensive process.
- Many Earthship builders are drawn to this system by its apparently low environmental impact. However, this is only valid if the design is highly thermally efficient. Earthship designs may require substantial thermal analysis and redesign to be adapted to non-Southwest USA climate.

- Earthships built with concrete, sand bags, or adobe and with better solar and heat control perform better.
- Earthships are usually built in areas of extremely low population density, so unless they are entirely self-sufficient, a significant amount of fossil fuels could have to be expended in their construction because of the transportation of materials and workers. They can be built anywhere, however, and this can mitigate certain issues dealing with fossil fuels and transportation.

## *Images of Earthships*

an unfinished Earthship

an unfinished Earthship

an unfinished Earthship