Section 2.2: Sustainable Building Materials & Technologies

2.2.1 Timber Frame

Historically, there are three main ways in which timber has been used to construct buildings.

- At a fairly primitive level, and where there is an abundance of timber, logs were piled up like masonry to create a solid wall. This technique has evolved into the now familiar 'log cabin' and, more recently, into 'kit' houses designed to look like log cabins but with a much more economical use of wood.
- Large section timbers (originally these were simply barked or squared-off tree trunks) were used as posts and beams that provide a structural frame when jointed together. As discussed earlier (Section 2.1.1), this offers maximum planning freedom and facilitates future adaptation or conversion. It does however require a supply of good quality, mature trees.
- As primary forests were felled and quality timber became scarce in Northern Europe and America, so posts became thinner and were placed closer together to support shallower beams. This evolved into the technique known as 'stud framing', which is now the most common form of house construction in the USA and Scandinavia. Over 60 percent of all new-build housing in Scotland is now timber framed [1]. It is an economical construction method, but has limited flexibility, as external walls are fully load bearing and roofs spaces are taken up with multi-membered, gang-nail trusses at close centres.

More recently, a system using structural insulated panels has been developed - two composite timber sheets enclosing a rigid insulation to form a load bearing wall (see Section 2.2.1c).

Of the many species of timber available, European Larch and Douglas Fir are excellent framing timbers that grow well in the UK climate. The heartwood of Larch is classified as semi-durable by the Timber Research and Development Association (TRADA), and both are naturally dense, resinous and therefore rot and insect resistant. They are far superior in quality to imported spruce/pine/fir, yet have a comparable unit price.

Oak and Sweet Chestnut are traditional UK construction timbers and are among the world's strongest and most durable hardwoods. Some of the oldest buildings in the UK are made from oak, and have lasted several centuries. Where hardwood is required in construction, it is of course important to avoid the use of tropical timbers. However, because stocks of oak have not been (and are not being) sufficiently replenished, it is not always possible to meet the demand for long, straight, large-section timbers from home-grown forests.

2.2.1a Advantages of Timber Construction

The environmental benefits of building with timber are considerable:

- Timber is the only renewable structural building material, and as such has clear advantages over non-renewable or scarce resources. Assuming that each tree felled is replanted, the resource will never run out. In addition, it is the renewable energy source of the sun that makes trees grow and produces timber.
- Timber has a low embodied energy, compared with other structural building materials. A concrete block wall will take 1.7 times as much energy to produce as a timber wall. The production process of timber is relatively simple and low-energy, as are its installation, maintenance and disposal operations. Most of the embodied energy of timber derives

from transportation, which makes UK grown timber comparatively very low in embodied energy.

- As a low energy user, timber accounts for very little pollution in its manufacture. Most of it can be attributed to motorised transport, and therefore avoided by sourcing locally. It is worth noting however, that timber can be a polluting fuel if it is not burnt in the right conditions. Chemically treated timber may emit highly toxic pollutants if burnt.
- Minimal waste is created in the production and use of timber, as there are viable end uses for virtually every part of the tree. Bark and leaves can be composted to form a mulch. Good quality timber can easily be reused or recycled, while poorer quality pieces or off-cuts can be burnt to create heat and offset fossil fuel use. Waste timber in the form of sawdust or wood chips can be burnt in efficient boilers to provide heat and power on a district scale, while plantations of fastgrowing timber such as willow can be regularly coppiced to provide biofuels for power stations. In the last resort, if timber is sent to landfill or left lying around a site, it will always biodegrade.
- Untreated timber is a healthy, inert material, which can contribute to Indoor Air Quality (IAQ). A hygroscopic material such as timber can help regulate relative humidity (RH), and maintain it within the comfort range. In general, people feel comfortable with exposed timber surfaces that are warm and smooth to the touch, unlike concrete or steel.
- Growing trees absorb carbon dioxide; therefore harvested timber is a 'carbon sink' that locks up the CO_2 absorbed by the tree until it is burnt or rots away. One kilogram of dry timber contains about 50 percent carbon, which binds in 1.8kg of CO_2. An average tree will absorb 9.1kg CO_2 in one year, equivalent to the amount emitted by a car travelling 18,300 km. [2]

  If the forests that are harvested are replanted, timber becomes a carbon-neutral material. The growing tree will take up as much CO_2 as the harvested one will eventually release. Forests also trap air pollution, prevent soil erosion, store and filter surface water, and support a multitude of plant and wildlife species.
- Buildings which use a minimum amount of energy over their lifetime are a major factor in the international strategy to reduce CO_2 emissions. Timber frame buildings are much easier to insulate to higher standards than their brick and blockwork equivalents. This is one reason why many mainstream developers are switching to timber frame, especially since the recent revisions to Part L of the Building Regulations (April 2001). A member of Buro Happold, a well known firm of structural engineers, comments, "Timber framing allows greater reduction (in wall thickness for a given U-value), leading to concerns within the house building industry that masonry construction will prove uneconomic." [3]

There are also a number of structural benefits to be gained from using timber:

- Its unique cellular structure (longitudinal fibres combined with cross sectional cells) makes timber strong in tension, compression and bending. It has a strength-to-weight ratio that is better than steel, which means timber can be used in high-performance, modern buildings, and not confined to its traditional association of low-rise, poor quality, temporary structures.
- Contrary to many people's expectations, timber performs well in fire, as it burns steadily and at a predictable rate, forming charcoal on the outer surface, which serves to insulate and protect the core. It is possible to make precise calculations on the dimensions that structural timbers need to be, in order to hold the building up for half an hour, or an hour, to allow the occupants to escape. By contrast, steel structures behave unpredictably in fires, appearing to be unaffected before failing suddenly.

- Experience in areas most affected by climatic disasters such as earthquakes and hurricanes suggests that framed buildings withstand extreme conditions better, all other things being equal. Timber frame buildings in particular are able to absorb sudden shocks without permanent damage, owing to the natural elasticity of the material.
- Timber buildings are inherently durable and easy to maintain. There are many examples in the UK of timber frame buildings from the 15th century onwards that are still standing. The oldest building in the UK is an 11th century stave church in Essex, and the oldest building in the world is the Horiuji temple in Japan, built in AD 607 out of cypress. In modern times too, timber buildings age well compared with their conventionally built equivalents. A study carried out by the Building Research Establishment on 120 timber frame houses built between 1920 and 1975, found their performance to be "similar to traditionally built dwellings of the same age and, given proper maintenance, likely to remain so for the foreseeable future" [4]. In terms of durability, records of the National House-Building Council (NHBC) show that timber frame houses tend to perform better than masonry ones [5].

2.2.1b Potential Disadvantages and Solutions

In the real world of 'green' building materials, there are no absolute rules or guidelines to follow. Even the apparently 'greenest' of materials will carry some environmental impacts, which need to be examined and minimised. These can be largely overcome however, by careful selection and good practice.

- Two of the main drawbacks of using timber are the limitation on the length available and its tendency to distort as it dries. These have been addressed by developments in the field of timber technology, such as laminated beams ('Glulam') that allow for greater spans and loads than would be achievable using 'ordinary' timber. Various products that combine small sections or pieces of timber with a strong adhesive, such as PSL (Parallel Strand Lumber) and LVL (Laminated Strand Lumber), make efficient use of small section timber, while eliminating shrinkage, warps and twists. Prefabricated timber I-beams, made from laminated timber flanges and an Orientated Strand Board (OSB) web, can be used for rafters, studs and joists, where the structurally efficient profile can be used to span greater distances, as well as increase the insulation zone and minimise cold bridging.

Figure 1: Glulam beams forming huge spans with no internal support

Figure 2: A wooden 'I-beam'

- Energy costs involved with timber transportation can be considerable. We import 87 percent of our timber requirements, mainly from Canada, Sweden and Russia. Indeed, timber is the second most widely traded commodity in the world, second only to oil. Only 10 percent of the 6 million m^3 of sawn softwood used yearly by the UK construction industry is home-grown. Local timber production and marketing could not only save on the costs of imports (some £5 billion a year of the UK trade deficit in 1997 [6]), but also promote local industry and jobs, and reduce the environmental impact of timber even further.

- The promotion of timber as a natural healthy material is obviously undermined if it is treated with toxic chemicals that then remain locked up in its chemical structure. Conventional timber treatment uses potent biocides that can damage human DNA and RNA, and disrupt healthy enzyme functioning. One of the most common commercially available timber treatments is 'CCA', which stands for Chrome, Copper, Arsenic, and CCA can contaminate soil that it comes into contact with. Chemically treated timber will give off highly dangerous dioxins if burned, and should be disposed of as toxic waste [7].

  Problems with rot or insect attack in timber are best dealt with by prevention in the first instance, through good design and maintenance, and treatment by eliminating the source of moisture and replacing only the affected parts. The use of durable hardwoods and semi-durable softwoods, as described above, can render timber treatment unnecessary. Where preventative treatment is considered necessary, a boron compound can be used (which has a low mammalian toxicity), while various new techniques of heat treatment are being developed, in Finland for example, to make wood more resistant to rot and insect attack.

- Even with renewable resources, we need guarantees of sustainable production, involving not only replanting, but the promotion of biodiversity, soil and water quality, and the rights of local people. Old growth primary forest - thousands of years old and irreplaceable in terms of species and habitats - is still being felled, not only in tropical areas like Brazil and Indonesia, but also in Northern Europe. Most productive forests today are coniferous monocultures that induce an acidic soil, and are, ecologically speaking, deserts. In Scandinavia this type of forestry threatens more than 200 species of plants and animals with extinction [8].

Timber certification by bodies such as the Forest Stewardship Council (FSC) offers guarantees of sustainable production for consumers, as well as an acceptable future in international timber trading for producer countries. The FSC is an international non-profit organisation whose membership comprises timber traders, environmentalists, indigenous peoples' organisations, community forestry groups, forest workers unions, forestry professionals and retail companies. Its scheme for certifying timber whose production has met certain environmental standards, is widely respected, and is being extended to cover many thousands of hectares of forest worldwide. In this country, the forestry standard put forward by the government - the UK Woodland Assurance Scheme or UKWAS - has been approved by the FSC, NGOs and the Forestry Commission. This means that most timber grown in the UK is now FSC compliant.

There is another range of objections to the widespread use of timber in the building industry, centering on the prevailing unsustainable nature of timber production (notwithstanding the work of the FSC) and the many illegal abuses taking place in forest management worldwide. These objections have been raised by organisations as diverse as Friends of the Earth and the steel industry, who argue for a reduction in the use of virgin timber and the use of timber substitutes such as steel.

Arguments such as these only add weight to the need for wholesale reform in logging practices and an extension of international timber certification schemes. It is important to realise that the timber industry needs support to rebuild itself along sustainable lines, and this means continuing to provide it with a market for its product. Forests need continual thinning, mature trees need to be felled and sold, within an ecologically defined code of practice.

Sometimes it is supposed that timber is a limited and finite resource, as in the argument which goes “if everyone were to start building with timber, then there wouldn’t be enough to go round”. In fact, there is no shortage of softwood in Europe’s forests and, if anything, there may well be a problem of over-capacity. There is now more than twice as much wood in these forests as there was a hundred years ago. According to TRADA, we could double the rate of home-grown hardwood felling and still be comfortably within sustainable limits [9], and, if ultimately the solution is to plant more forests, then this can only benefit the environment as a whole.

2.2.1c Timber Products

Raw timber can be processed into many other useful products, some of which provide an end use for poorer quality or waste material. These timber products are an economic alternative to virgin timber in low-grade applications, and can also be invaluable for covering or spanning large areas. The additional processing does incur additional energy costs however, and there are health hazards associated with the synthetic, formaldehyde-based adhesives used in their manufacture.

Composite boards

Plywood and oriented strand board (OSB) contain relatively small amounts of binders, and are useful where solid timber would be extravagant or inappropriate. Care should be taken to avoid using tropical hardwood ply, which is surprisingly common and cheap.

Chipboard and MDF (medium density fibreboard) contain relatively high amounts of synthetic resins that can off-gas and cause health problems for both workers and occupants. They have poor inherent strength, and little to recommend them apart from cost.

Some timber sheet materials are bound by using the wood’s own resins, under heat and pressure. They are softboard (often called insulation board or pin board), medium board (not MDF) and hardboard. These much safer alternatives can be used where strength and rigidity are less important.

Composite beams

These use small section timbers in short lengths, glued side by side and end to end, to create large beams engineered to carry high loads and bridge long spans. Knots and other defects can be avoided, as can joints and connectors that might weaken the beam. Their embodied energy is a fraction of steel or concrete beams of equal strength. Concern over the effects of using synthetic glues has led to an increased interest in mechanical lamination (i.e. bolting).

Glulam, PSL, LVL or I-beams (see Section 2.2.1b) can be delivered in lengths up to 24 metres (12 metres for Masonite) and have a uniformity and dimensional stability which is difficult to achieve with natural timber.

Cork

An excellent insulating material - lightweight, durable and non-flammable, harvested from the Iberian cork oak without compromising the health of the tree. It is particularly useful in providing an alternative to foamed plastics in applications where a waterproof insulation is necessary.

Cellulose

A major constituent of all trees and plants that is used extensively in the building industry as an alternative to asbestos. Cellulose fibre/cement sheets provide a cheap, weatherproof material for external cladding. The fibres can also be reclaimed from various paper products

- newsprint, telephone directories - and shredded to create an insulation material, marketed in this country as 'Warmcel'. With very low embodied energy, and made from a renewable, recycled material, this is an environmental product that is difficult to beat.

2.2.1d Timber Frame Systems

Various timber frame systems have been developed, mainly by manufacturers of whole houses in kit form (where customers can pick a finished building from a catalogue), or by suppliers of prefabricated elements bolted together onsite to form a building (see the Concept Cottages case study). Other 'systems', such as those developed at the Centre for Alternative Technology and by architects associated with the Walter Segal Self Build Trust, rely on total assembly onsite.

Tek-Haus

This is a lightweight, modular system using Structural Insulated Panels (SIPs) and offering excellent insulation and air tightness. Its promoters are seeking to respond to the post-Egan demand for reducing onsite construction time and minimising defects. The panels have a core of 'Kingspan Therma' rigid urethane foam, which is 'zero ODP' (zero Ozone Depleting Potential, meaning that the blowing agents do not damage the ozone layer) and the outer layers are formed of Oriented Strand Board. External wall U-values of 0.18 W/m^2K can be achieved, which is twice as good as the 2002 Building Regulations standard.

It is unfortunate that the polyurethane insulation comes from a non-renewable and scarce resource, is polluting in its manufacture and is difficult to recycle. It is claimed however that its durability and performance characteristics more than compensate for the negative environmental impacts. "The choice of insulating material is relatively insignificant compared to achieving optimal thermal resistance. The most important design issue is to ensure longevity of performance over the lifetime of the material." [10]

The promoters claim that this system is ideal for light commercial and residential buildings. A $150m^2$ house can be erected in 2-3 days (not including foundations and finishes). Walls can be thinner for a given U-value, because of the efficiency of the insulation, giving up to 13 percent more floor space.

A research and demonstration project called 'LightWeight, AirTight, LowHeat', sponsored by XCO2 Conisbee and Kingspan Insulation, was seeking to construct and monitor a pair of 'TekHaus' houses for Longhurst Housing Group in Nottinghamshire. Early computer modelling showed a predicted heating energy demand of 39 $kWh/m^2/yr$. An ultra low-energy version with additional external insulation and an MVHR system had a predicted 18 $kWh/m^2/yr$ heating demand [11].

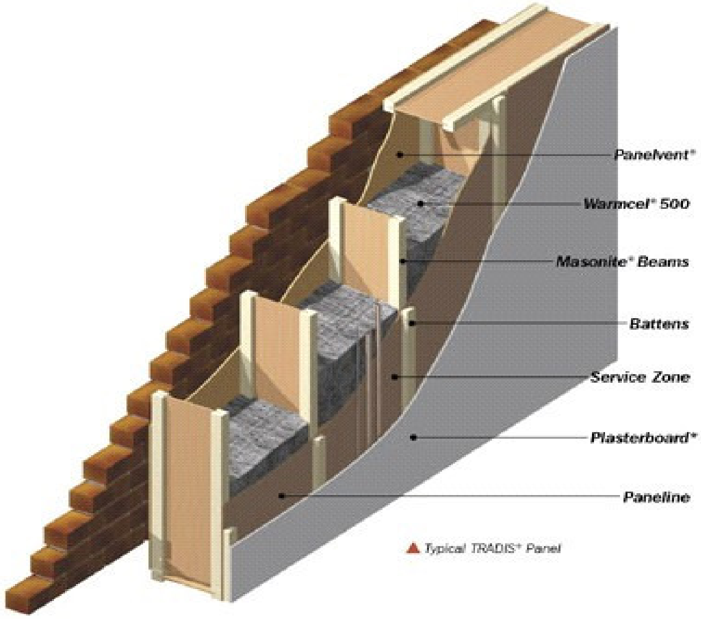
The Tradis system

This has been launched by Fillcrete, who are suppliers of Warmcel insulation and Masonite I-beams, which form the basis of the prefabricated panel. It offers similar U-values as the Tek-Haus system but with a breathing construction, as shown in Figure 3. The beams have a web of structural hardboard (Masonite) that, at only 8mm thick, minimises cold bridging. The system is designed to minimise energy costs, and to use materials from recycled or sustainable sources. Awarded Millennium Product status by the Design Council, the main components of the Tradis system are BBA approved.

Tradis claims a new record in reducing onsite labour time, with the erection in Liverpool of 10 houses for CDS Housing in 4 days with a team of only 3 people. The construction method allows the roof space to be used as an extra 'room-in-the-roof', or extra room height can be proided with a 'cathedral roof'.

Prefabricated timber panels do not depend exclusively on a timber frame. In a two-storey extension to Waseley Hills High School, Tradis panels were used with steel frames and prefabricated concrete floors [12]. Fillcrete have also launched a timber frame design software package called ‘Timeframe’, which can convert “a design created in brick and block or standard timber frame to a Masonite-based design in a couple of mouse clicks” and promises to reduce typical design times by 80 percent [13]. It will also produce manufacturing drawings and cutting lists simultaneously and automatically.

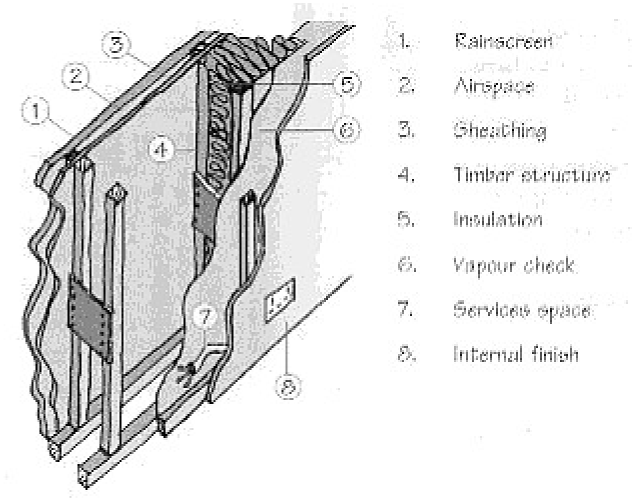
Figure 3: The Tradis construction system, here with a brick outer skin [14]



The Centre for Alternative Technology timber frame wall

The timber frame system developed over the last 15 years at C.A.T. evolved from their attempts to create very low-energy, low-impact buildings, based on the self-build method proposed by the late Walter Segal. Using a post and beam timber frame, high levels of insulation (300-400mm) are achieved by using a ‘spaced-stud’ infill wall construction, and by hanging ceiling joists from rafters. Conventional plastic vapour barriers, whose failure can result in completely destroyed timber structures, are rejected in favour of ‘breathing’ construction. This uses different levels of vapour resistivity to ensure a controlled passage of moisture through the building fabric, avoiding the risk of interstitial condensation. Reasonable levels of air-tightness result from care in detailing and gap-filling onsite. Chemically treated timber is completely avoided - an approach justified by the use of durable and semi-durable timbers, careful detailing and regular maintenance.

Figure 4: The Centre for Alternative Technology timber frame wall [15]



2.2.2 Cement Free Construction

Cement is the second most widely used material in the world, second only to water, and the amount used globally is equivalent to 1 ton/person/year. It is manufactured by heating together limestone, silica and alumina, and grinding the resulting clinker with 5 percent gypsum. It has considerable performance advantages of quick setting times, high compressive strength, heat storage (thermal mass) and durability.

Cement also carries a heavy environmental price however, mainly in the form of high energy use and CO_2 emissions. Cement kilns are maintained at temperatures of 1500ºC, and in addition to the energy required for this, CO_2 is also released by the chemical reaction which takes place in the kiln. In the UK, the cement industry is the biggest CO_2 producer after the electricity generating industry, and in some developing countries cement production can account for up to two thirds of total energy use. Globally, cement production is responsible for 8-10 percent of all CO_2 emissions - almost as much as the international aviation industry. In addition, heavy metals are emitted during the firing process, and other associated atmospheric pollutants include SO_2, NO_2 and dust. Pollution to watercourses can occur, with the highly alkaline wash-out water being toxic to fish.

Partly to cut fuel bills and presented as an environmental improvement, many cement producers now use Secondary Liquid Fuels (SLFs) to heat their kilns. These fuels are the (often hazardous) waste products from other industries, such as old tyres and industrial solvents. Known as 'co-incineration', this practice is covered by permits issued by the Environment Agency, but cement kilns are not covered by the stringent EU Waste Incineration Standards that apply to municipal incinerators. The Environment Protection Agency in the USA states that cement kilns burning chemical waste are the highest emitters of dioxins.

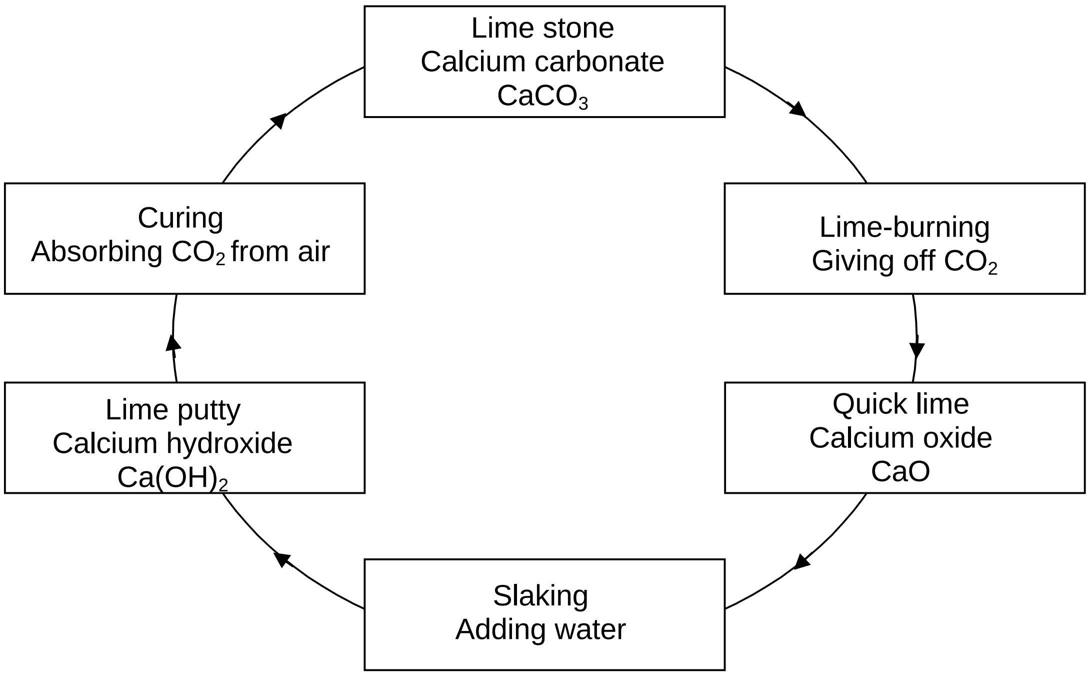
Cement products are not easy to dispose of, although some can be recycled to lower grade uses. It has been reported in the USA that concrete is the largest and most visible component of C&D (construction and demolition) waste, comprising approximately 67 percent of the total. Cement-based mortars also restrict the reuse of components such as bricks and blocks.

In 2002, the Batelle Institute published a report on behalf of the World Council for Sustainable Development, entitled 'Towards a Sustainable Cement Industry'. The cement industry responded by publishing the 'Cement Sustainability Initiative' [16], which pledges improvements in several areas including climate change and emissions. It is clear nevertheless that, from an environmental agenda, we need to limit our use of cement and explore the viability of alternative materials.

Lime

The traditional alternative to cement is lime, which was widely used before cement became popular in the mid 19th century. Although it is made with the same basic ingredients as cement, the necessary kiln temperature is much lower (800ºC) and the chemical by-product of CO_2 is reabsorbed as the lime hardens and reverts to limestone (calcium carbonate). Indeed, there is something very satisfying in the cyclical nature of its manufacture and use (see Figure 5).

Figure 5: The Lime Cycle



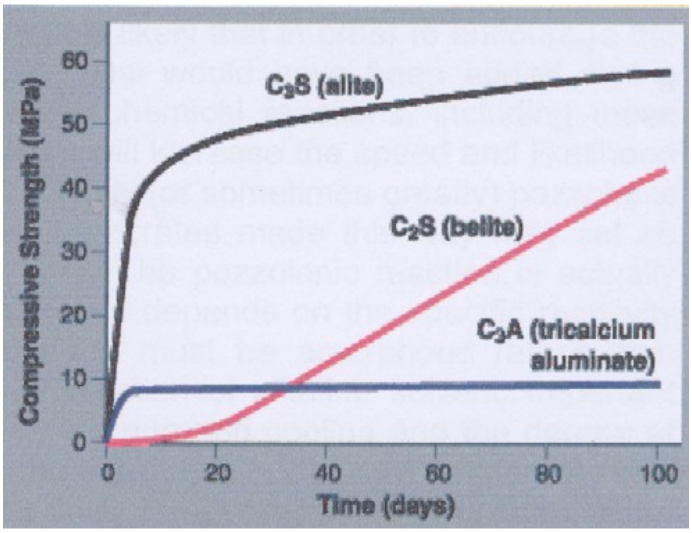
Pure lime, in its hydrated form of lime putty, was the basis for all mortars and renders. Although it needs a long preparation and slow drying time, and protection from frost and dry heat throughout its curing, it is a soft, elastic and breathable material that allows component reuse. It is not compatible with modern fast-track construction, but is appropriate for use in historic buildings and conservation work.

There is one form of lime however that is relatively quick setting and can be used as a practical alternative to cement within the time and budget constraints of a contemporary building project. Hydraulic lime, made from a limestone which contains certain impurities of silica and alumina, lends itself very well to new build work. Although it absorbs on curing only 50 percent of the CO_2 released chemically, it takes less energy to produce than pure lime, because there is less CO_2 to 'disassociate', or burn off [17].

Lime is less dense than cement, so although it is more expensive, less will be needed to make a standard mortar mix. To produce 1m^3 of mortar requires 240kg of cement (1:6) or 200kg of lime (1:3). There is no doubt that cement is the stronger and faster-setting material (see Figure 6), but it also is often used in strengths that are unnecessarily high.

Although building workers may need training initially in the correct use and handling of a 'new' product, lime does offer a more sustainable alternative to cement, particularly with regard to CO_2 reduction and facilitating component reuse/recycling.

Figure 6: Setting times and strengths for Ordinary Portland Cement (alite) and hydraulic lime (belite) [18]



2.2.3 Secondary Materials

These are industrial by-products that are often available in large quantities and are difficult to dispose of. If they can be used to replace a virgin resource (e.g. cement in a concrete mix), this would reduce mineral extraction, energy costs and the environmental impact of disposal. The Government, in trying to discourage the use of primary aggregates, has imposed a tax on all newly quarried materials and has published a target of a 25 percent increase in the use of secondary aggregates by 2006, based on 1997 levels. As far as the construction industry is concerned, there are three main sources of secondary materials:

Recycled industrial gypsum

Used in the manufacture of most makes of plasterboard to replace natural gypsum. Usually this comes from spent flue gas desulphurisation kits (FGD gypsum) used in power station chimneys to extract pollutants from the exhaust gases. There is also phospho-gypsum, which is a by-product of artificial fertiliser manufacture.

Ground Granulated Blastfurnace Slag (GGBS)

A by-product of steel manufacture, which can be used to replace between 30 and 60 percent of the cement component of concrete. It has been in use since the 1920s, is covered by a British Standard, and was used in the construction of the Humber Bridge and Channel Tunnel. GGBS cement is also resistant to sulphur attack.

Pulverised Fuel Ash (PFA)

Comes from coal-fired electricity generation, and is the residue left once the coal has been burned. In common with GGBS, it is a pozzolan, which means that it causes other materials to harden. Both PFA and GGBS have greater durability and strength than Ordinary Portland Cement (OPC) mixes, and show a reduced risk of shrinking and cracking. Longer curing times can be a problem however, especially for PFA cement.

In a holistic assessment of the environmental impact of using secondary materials, it is important to realise that they are themselves products of polluting processes in non-sustainable industries. This should be set against their environmental benefits. There are also potential health hazards associated with the use of these products. Concrete blocks made with GGBS cement have been found to contain high levels of dioxins. Heavy metals left over from the original incineration process may leach from secondary materials in cement powder and products. It has been suggested that industrial gypsum may contain heavy metals and radioactive particles, particularly phosphogypsum from European sources [19].

2.2.4 New Technologies

Some new technologies are emerging that could provide radical and environmentally positive alternatives to cement.

Geopolymers

These use naturally occurring silico-aluminates, found in pure clays such as kaolin, to chemically integrate other minerals. Reductions in CO_2 emissions of 80 percent are achievable, with kiln operating temperatures of 600-750ºC. Geopolymers have already been produced commercially as specialist quick-setting, fire resistant cements, but they remain prohibitively expensive for the mass market. Their use in binding hazardous and toxic wastes has also been explored (e.g. they can achieve good chemical bonds with heavy metals and mine tailings are encapsulated more securely than in their original ore) as well as low-level nuclear waste neutralisation in Eastern bloc countries.

Eco-cement

This is a magnesium based product currently being developed in Tasmania. Still in the preproduction phase, it promises to be cheaper and more durable than Portland cement. It is recyclable, CO_2 neutral and contains a high proportion of 'mineral waste' such as PFA, GGBS, sewerage ash or rice husk ash. With low-temperature firing, production energy savings of 25 percent are forecast. It too is deemed suitable for 'immobilising' hazardous wastes.

2.2.5 Building with Earth

Earth is one of the most abundant and locally available materials that it is possible to build with. Over 70 percent of the Earth's landmass is either pure clay or laterite - clay with some iron content. Earth building is one of the cheapest and lowest-impact construction methods, and over one third of the world's population currently live in homes built from earth.

Earth has been used in houses, temples and famous structures such as the Great Wall of China and the Tower of Babel, in every continent and climatic zone. There is archaeological evidence to show the existence of entire cities built of earth, such as Jericho and Babylon, some 10,000 years old. The Romans introduced rammed earth into Southern France; the Moors brought adobe into Southern Spain. In the South West of England, the tradition of cob building is undergoing something of a revival. The Scottish Executive is looking at ways of reviving Scotland's 'rich heritage of earth construction' [20].

Earth, or the sub-soil used for construction to be more exact, is a very low-energy and non-polluting material, as long as transportation is kept to a minimum. In many cases, suitable material can be excavated from the site itself. Traditionally, earth buildings were built with human and animal energy alone, and on demolition the building simply reverted to earth. Thick earth walls provided good thermal mass that offered some thermal comfort as well as shelter. The provision of all these benefits, without the high environmental impact of most modern building materials, makes earth construction one of the techniques favoured by modern eco-designers and builders. They must always be protected from undue weathering however, by a raised plinth wall, overhanging roof and breathable renders or cladding.

There are various ways in which earth can be used in buildings:

Rammed earth

Also known by the French term *'pisé de terre'*, this technique makes use of moist, loose earth mechanically compacted between shuttering, or formwork in layers. The forms are then moved along or upwards, to construct a whole wall.

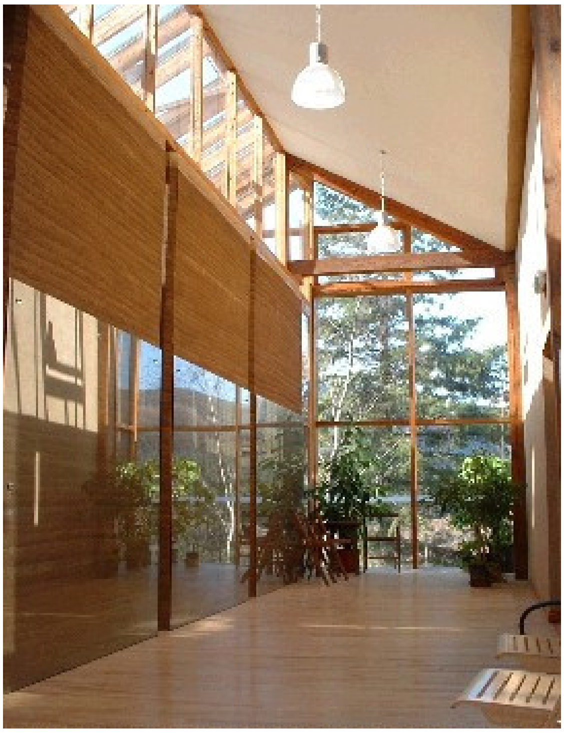
The exact composition of the soil and the right amount of water are critical for the success of this method. The clay content should be between 15 percent and 30 percent: not enough and the mix will crumble and collapse; too much and it will shrink and crack on drying. Rammed earth walls are often stabilised with cement or lime, and here the earth becomes simply the filler or aggregate. This can be done so routinely, without examining or taking advantage of the characteristics of a particular soil sample, that it becomes known as 'brown concrete' and loses its environmental advantages.

In the UK climate, rammed earth walls will suffer if they are used externally and not protected with render (see Figures 7 and 8). They can be used as striking internal features, but are labour-intensive to build and require care, commitment and understanding from the workforce. Soil samples need to be laboratory tested for satisfactory results.

Rammed earth replicates the geological processes that form sedimentary rock. Over a period of time, which can be up to two years, a rammed earth wall will dry out and become as durable as sandstone, with significant loadbearing capacity.

Figure 7: Rammed earth wall at Eden Centre, Cornwall, showing erosion and damage from splashback

Figure 8: Entrance lobby of the Environmental Information Centre, C.A.T.
Rammed earth walls on the left-hand side support the roof beam, with a protective glass shield.



Cob

Sub-soil mixed with straw and water, and then pounded or trodden until it reaches a suitable consistency. It is built up in horizontal layers on a stone or brick plinth, compacted by being trodden down, and trimmed when dry with an adze or spade, to form freestanding mass walls. Hundreds of Devonshire cob houses are still standing today, the oldest dating back to C15th.

Adobe

Sun-dried earth blocks that can be made from most types of sub-soil. Traditionally, the earth was trodden to a paste, often by animals, then mixed with chopped straw, pushed or thrown into moulds and left to dry in the sun. The blocks were then laid and bonded with a mud and lime mortar, rendered with a mud and dung mix, and/or limewashed.

Mud bricks have the advantage of being simple to make, and therefore appropriate for unskilled labour. They can be produced all at once, or in small batches, as and when time permits. The quality can be checked, and any suspect bricks rejected, before they are assembled into a wall.

Compressed earth blocks

Earth blocks made harder and more durable by compaction. Small amounts of lime or cement (5-10 percent) may be added to the earth as a stabiliser, and bitumen can be added as a water repellent. The mix is compressed in a machine, such as a Cinva Ram, designed to exert a large amount of pressure on the earth in the mould. Blocks are thus produced in standard sizes and can perform as well as fired or baked bricks or blocks, in terms of load bearing capacity, longevity of life and freedom from maintenance.

Clay plasters

A blend of clay, fine sand and organic fibres that can be supplied pre-mixed in different colours for use internally. They can be applied to ordinary gypsum plasterboard, although the manufacturers recommend the use of a clay/reed board as a substrate, and can be reworked indefinitely by the addition of a fine water spray. They are compatible with a ‘breathing’ construction, have a rough ‘rustic’ texture compared to gypsum plaster, and being self-coloured, do not need decorating.

Green roofs

These can be created for low pitched roofs (<20º) using turf or seeded topsoil on top of a waterproof membrane. The membrane, laid loose over decked-out rafters, is usually a tough, durable, high-energy plastic or synthetic rubber sheet, and its use does tend to undermine the environmental claims made for turf roofs. It is essential though for weatherproofing and durability. Increasingly, designers are using sedum instead of grass, because it is very shallow-rooting, drought tolerant and therefore needs a minimal thickness of compost (25mm-50mm).

The earth itself is not a good insulator (too shallow and often wet), so high levels of insulation should still be used between or underneath the rafters. The main function of the turf is to weigh down the membrane, protect it from UV light, and look attractive, with bulbs and wild flowers.

Figure 9: Turf roof with daffodils on a semi-underground food store at C.A.T.

Earth sheltered construction

This is quite different from buildings made from earth, and usually involves structures that are in effect tanked and reinforced concrete shells built underground (see Figure 10). The surrounding earth acts as a huge thermal store and reduces energy usage, assuming it is fairly dry and well drained. These buildings are usually long and thin in plan, as shown in Figure 11, but even where the 'front' wall is highly glazed, back areas tend to be dark and permanently artificially lit.

Although this technique involves using relatively high-impact materials, such as concrete, steel or plastic foam insulation, it should deliver high energy savings in use. Neither Hockerton Housing Project nor the Berm House have space heating systems fitted. Monitoring of the Berm House by the then Department of Energy showed virtually no diurnal temperature change in the main rooms, "which is very unusual" [21]. Minimum air temperatures were 17-18ºC and had changed by less than 1ºC in all months from 1987-1995, "with the exception of one very wet September" [Ibid]. Hockerton Housing Project estimate their energy use as one tenth that of a comparable conventional house - 8 kWh instead of 80 kWh [22].

Figure 10: Cross section through the Berm House

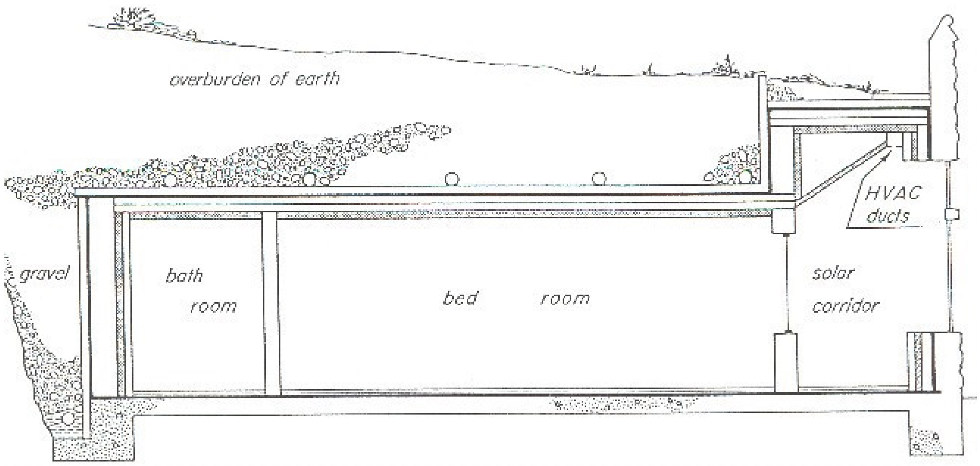
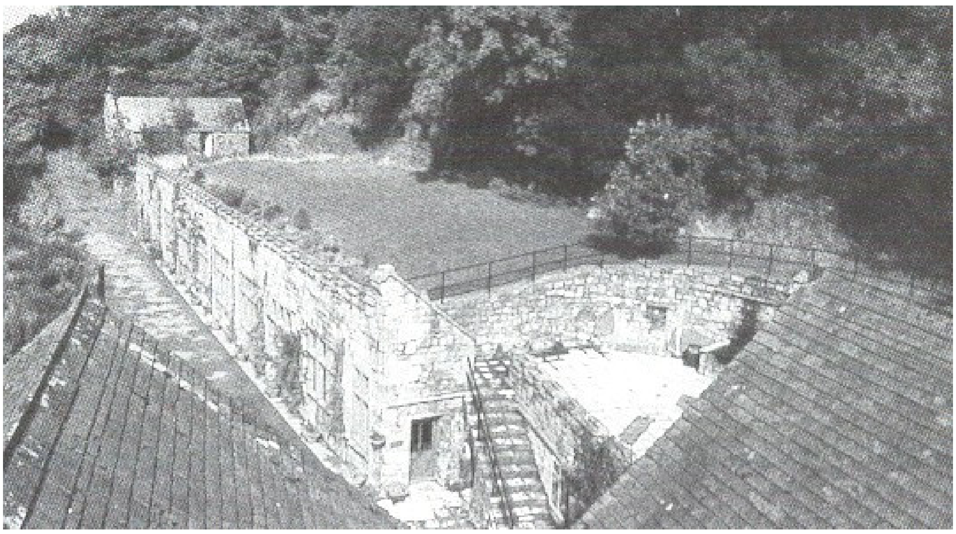


Figure 11: The Berm House, Caer Llan Field Study & Conference Centre, Monmouth

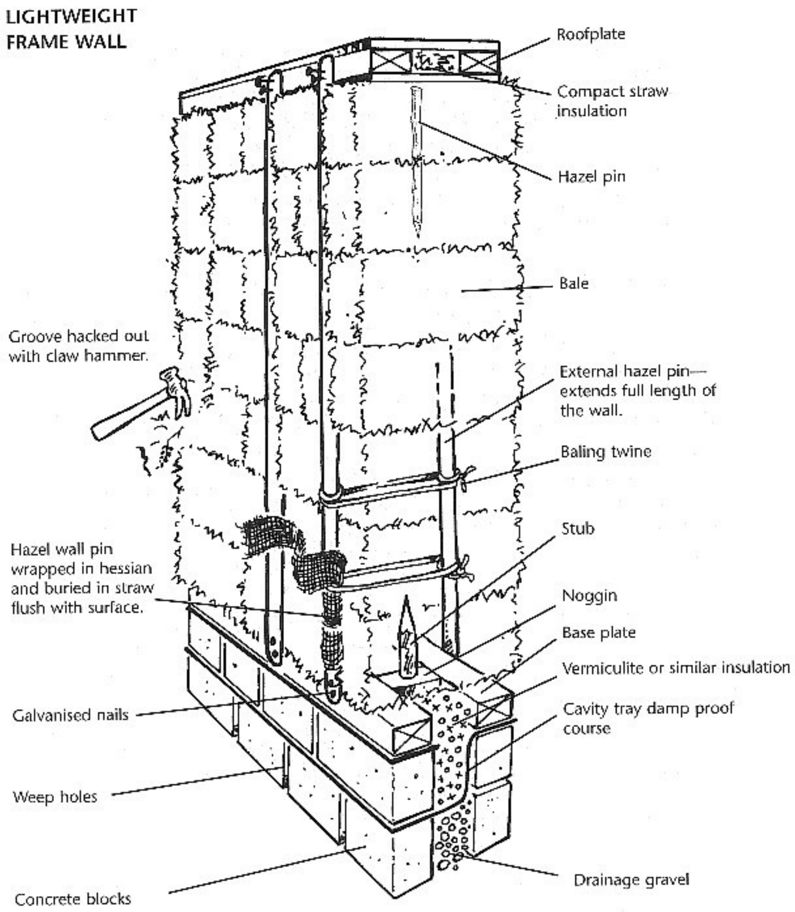


2.2.6 Straw Bale Buildings

Straw is a renewable material, cheap and often locally available, which requires minimal processing and energy use. Its use in buildings solves a waste disposal problem and its construction can be easily understood and carried out by self-builders. It can be used to construct external walls with a U-value of half the current Building Regulations standard.

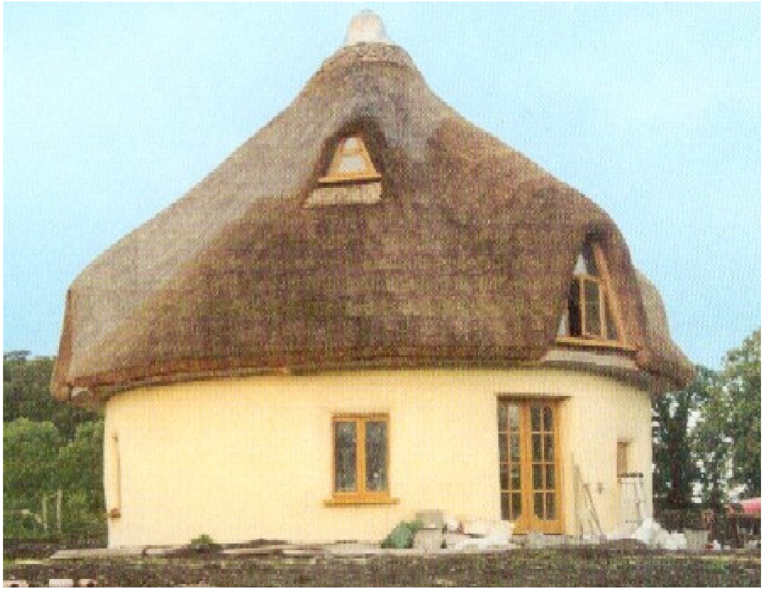
Walls made of straw bales can be fully loadbearing, or bales can be used as an infill between timber frames. The bales are stacked like giant building blocks, with staggered joints, and pinned to the foundation and to each other with coppiced hazel rods (see Figure 12). The walls are then plastered inside and out, ideally with a lime render.

Figure 12: Straw bale wall on block plinth with hazel pins [21]



According to Barbara Jones, “working with straw is unlike working with any other material. It is simple, flexible, imprecise, organic…it lends itself well to curved and circular shapes…it’s also a very forgiving material (and) doesn’t require absolute precision” [23].

Figure 13: Straw bale house with thatched roof in Ireland. Photo Barbara Jones



Straw bale building is cost-effective, with savings compared to brick-and-block construction of over £4,000 on a normal 3-bedroomed house, and even more if self-build labour is used. In addition, straw bale houses are cheap to run, with potential savings of 75 percent on normal home energy demands [Ibid]. The Canada Mortgage & Housing Corporation have published a survey showing that straw bale houses use an average of 21 percent less space heating than conventional homes [24].

To date in the UK, several straw bale buildings have received planning permission, including an architect's house and office in Islington, a three storey building in Ireland, a 95m^2 farm dwelling in South Wales, and a dance studio in Hertfordshire. "No straw bale building in the UK or Ireland has ever been refused planning permission or building regulation approval on the grounds of it being made of straw, or on the question of durability" [23].

There is no reason why a well built and maintained straw bale house should not last at least 100 years. There are a dozen or so straw bale houses in the USA nearing their century, and showing no signs of decay. Rodents can be kept out by keeping the render in good repair and avoiding any gaps or cavities.

Fire-proofing is partly provided by the two-coat, half-inch thick render which surrounds the straw. In addition, the high silica content of straw (3-14 percent) inhibits the spread of fire, and there is very little free oxygen in a compressed bale to support a flame. Fire tests carried out in New Mexico found that a 450mm thick bale, plastered both sides, survived fire penetration for more than two hours, and even an unplastered bale survived for 34 minutes.

The main danger to the integrity of a straw bale building is damp. If bales get wet at any time, during construction or occupation, then they must be cut out and replaced or they will eventually rot away. Like earth buildings, details such as a high plinth wall and overhanging eaves are essential for protection against excessive weathering. "The key to durability is good design, good quality work, and maintenance" [23].

2.2.7 Biocomposites

This is a term used to describe a mix of materials which can be poured in-situ like concrete, or pre-fabricated as (interlocking) blocks. It consists of a vegetable or plant-based fibre, such as straw, wood or hemp, mixed with a mineral binder; principally lime or clay. Typically it is used as an infill material, with some insulating properties, installed between or around a structural frame. With the right composition and material quality, it could be used as a structural, loadbearing element. In any case, it offers an alternative to conventional cement / concrete technology.

The environmental advantages are in the use of renewable fibres which give tensile strength to the mix. Often these fibres are also a waste product and, as a filler in the mix, can substitute for the use of virgin aggregate. Since the dangers of asbestos products have become widely known, asbestos has been largely replaced with cellulose fibres in building sheets and tiles. Bulkier fibres, with a hollow core such as straw, can provide increased insulation, although whether these walls will ever reach acceptable thermal standards without excessive thickness, is a moot point. The binders also carry substantially less environmental impact than cement.

Hemp / lime

A French product called Isochanvre uses a mixture of hydraulic lime and *chenovette* (the cellulose that is left when the hemp fibres are removed), as a ‘constructive insulation’. Mixed with water, it can be used for infill walls between timber frames, and is installed by compacting the material between shuttering, in the same way as for rammed earth. It can also be used for floors in place of concrete or a cement screed. Claimed to be resistant to attack by fire, rot, or insects, and naturally breathable with superior thermal and acoustic properties, Isochanvre is being marketed as the ultimate ecological building material. It is potentially an excellent use of a renewable waste product. It is also used without the lime as loose fill insulation.

Some unresolved issues remain however, such as the rather mysterious process of mineralisation, which apparently changes the vegetable fibres to minerals over time, so that the structure “petrifies”. There is also the question of just how good an insulator any compacted material can be. Its conductivity is 1.2 for a built-in wall and 0.64 for loose fill. If the wall is thick enough it will give a reasonable level of insulation; a 225mm wall gives a 0.23W/m^{2}K U-value.

Inspired by the use of hemp in French buildings, Ralph Carpenter of Modece Architects has designed an experimental scheme for Suffolk Housing Society. This consists of four terraced houses, externally identical, two built with hemp/lime around a timber frame, and two conventionally built control houses (brick and block with 100mm cavity insulation). The hemp homes also have hemp/lime floors, cast directly onto the hardcore without a damp proof membrane. Figures 14 and 15 show external and internal views of the hemp homes.

Figure 14: External view of hemp/lime houses in Haverhill, Suffolk

Figure 15: Internal wall finish in hemp/lime house

Monitoring by the Building Research Establishment (BRE) will produce a comparative assessment of energy consumption, moisture resistance and overall stability. Initial results from monitoring during the first half of 2002 show that: [25]

- Overall, the performance of the hemp/lime structure and its likely durability was found to be at least equal to traditional construction.
- The thermal performance of the hemp homes ensured there was no higher heating use than in the control houses even though the temperatures in the hemp houses were consistently 1-2ºC higher than in the controls.
- Acoustically, the hemp houses performed less well than the control houses, but were still adequate and met the required standard.
- Both forms of construction appeared to give complete protection against water penetration. After a 96-hour spray test, there was no evidence of water penetration through the complete thickness of the hemp walls. The hemp houses were considered to generate less condensation internally.
- On balance, there was little difference in the waste produced during construction.
- The estimated true cost of hemp construction was £526/m^2, compared with £478/m^2 for the control houses.

Professor Tom Woolley, Professor of Architecture and Director of the Centre for Green Building Research at Queens University Belfast, thinks that it may be possible to use hemp grown in the UK that has not been through the 'secret' mineralisation process. He has conducted tests on hemp/lime blocks made with Hemcore horse bedding and left out in the Irish rain for 12 months. These have shown no sign of deterioration. In addition, he has looked at compressive strengths for various hemp/lime mixes, and obtained results which are 'surprisingly high'. Experiments using hemp and clay instead of lime have also had positive results [26].

Woodwool / lime

This composite uses fine wood shavings, made by passing softwood logs under a giant 'cheese grater'. Similar shavings are sometimes used as a packaging material for delicate objects. When mixed with hydraulic lime (NHL 5) and water in a cement mixer for up to 20 minutes, an aerated foamy mixture results which can be poured directly into shuttering and left to self-settle. A ratio of 1 part lime : 4-5 parts woodwool seems to give best results. This is not a commercially available product, but has been used experimentally at a small scheme of six eco-houses at Bishops Castle, Shropshire (see Figure 16).

Figure 16: The curved wall of a stair well, at a house in Bishops Castle, with three lifts of woodwool/lime visible, cast round a timber frame, and shuttering for the final lift in place. Photo, Pat Borer.

Research is under way at the University of Bangor to determine the properties of this product:

- U-values of various density blocks
- Fire resistance
- Effects of variations in humidity
- Chemical effects
- Reducing the friability of blocks
- Properties of blocks made of different timber species
- Properties of blocks made with varying ratios/various particle sizes
- Effects of moisture content of timber on blocks

Compression tests on sample blocks have given a figure for loadbearing capacity of $0.86N/mm^2$. While this is much lower than, say, a Celcon aerated concrete block with $2.8N/mm^2$, it is still encouraging in terms of its structural potential.

Light earth

According to the German standard DIN 18951, an earth mix can be called lightweight if it has a density of less than $1200kg/m^3$. Typically, straw, hemp, reed or wood fibres are combined with a rich clay slurry, and poured or tamped between shuttering. Naturally or artificially foamed minerals, such as pumice, expanded clay, glass or perlite can also be used, as can foamed plant matter such as cork. The growing interest in this class of materials has largely been in an attempt to improve the insulating properties of external earth walls, so that they meet the building regulations in different European countries. The more porous the mixture, the lighter it is and the greater is its thermal insulation [27].

A new technique for installing lightweight loam (as it is called in Germany) has been developed by Gernot Minke and used in three houses in Kassel, Germany. An elastic cotton hose is filled with the earth mix, either manually or with an electric pump, and cut to length as convenient. The hose acts as a sort of reinforcement and makes handling a lot easier. When stacked on top of one another the earth oozes out to cover the fabric and bind the coils together. They can be left untreated internally (see Figure 17), or rendered externally.

Figure 17: Interior wall made from 'light earth' filled hoses

A new company in Germany has marketed a technique of 'blowing' or pumping lightweight loam straight into a timber frame. High compaction rates are achieved and it is immediately stable. At a thickness of150mm it is half the cost of earth blocks, with a density of 600-700 kg/m^3. This technique can also be used to retrofit insulation into existing timber frame buildings.

In this country, cob is a form of light earth construction, though using more earth than straw, while straw/clay proper has recently been used for a small domestic building by Gaia Architects in Scotland.

New possibilities

Other potential candidates for use in biocomposite materials include RPMS (Recycled Paper Mill Sludge) and fibres made from MSW (Municipal Solid Waste) [28]. RPMS is produced in large quantities (200,000 tonnes per year from one large paper manufacturer alone) and is currently disposed of by combustion or landfill. It is interesting in that it has an evenly balanced plant (cellulose) and mineral (clay) content, and so may be able to act as both binder and fibre.

The ash from burning RPMS is being used, together with GGBS, at the University of Glamorgan to make a quick setting cement substitute called WSA cement, for use in pre-cast blocks. The blocks have been shown to meet BS 6073 strength tests and BBA approval is being sought. [29]

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