

Pai Lin Li Travel Award 2007

To be held at IStructE on 20 November 2008 at 18:00h

Prefabricated earth constructions in the UK and Europe

Synopsis

The study on the use of prefabricated earth construction products in the field of structural engineering consisted of visiting a number of buildings, and attending a conference and a course on the subject. These activities took place in Germany, India and Scotland, and were aimed at assessing the feasibility of constructing with earth construction materials, more particularly prefabricated low processed earth products, in Northern Europe.

Definitions

As from previous work on the subject matter [Little and Morton, 2001], earth is taken to mean naturally occurring sub soils. While the use of the term 'clay' in conjunction with 'walls', 'bricks' or 'plaster' is also often encountered within the field of earthen construction, this has been considered to be imprecise [Minke, 2006] as clay is only one of the constituents of the building material earth. The term 'loam' (closer to the German '*Lehm*') is therefore preferred by some (mostly German) authors [Minke, 2006] to refer to earth as a building material, as it consists of silt, and sometimes other aggregates as well as clay, which is merely the binder. Earth or loam can then be mixed with natural fibres, for example straw, to produce a wide variety of construction materials.

Common techniques of earth construction are:

- Mudwall (or cob): vernacular technique of monolithic walling based on the use of an earth-straw mix.
- Rammed earth (or *pisé de terre*): vernacular technique whereby earth is compacted between temporary shuttering to create dense monolithic walls.
- Earth brick masonry (or adobe): use of un-fired bricks of various composition.
- Compressed earth block masonry: use of a modern material similar to earth brick, but with higher load bearing capacity.
- Earth infill in timber frame construction (*Fachwerk* in Germany, or 'wattle and daub'): use of light earth (expanded with kaolin) or blocks of various densities as a non-structural infill.
- Earth plastering.

Some stages of the above construction techniques, traditionally performed *in situ*, have now undergone prefabrication. In Germany, it is possible to purchase ready-made earth bricks – blocks of varying density, fabric and clay boards and plasters. In Austria, rammed earth walls have successfully been prefabricated by Lehm Ton Erde Baukunst GmbH. In the UK, prefabricated earth products were until recently only available through import. Clay bricks and clay plaster mix are currently being manufactured on a small scale in the UK.

Background

It is estimated that at least 40% of the world's population lives in earth dwellings, and while there is currently a revival of earth construction in the UK and in continental Europe, mostly due to increased environmental awareness, earth is not a common engineering material in the construction industry. In the UK in particular, the use of earth in construction is marginal. Although its

profits as an industry have not been quantified, it can undoubtedly be said that, economically, it plays a negligible role.

However, in view of current national targets with respect to carbon emissions, the advantages earth offers as a construction material seem to challenge its low profile. Earth is a hygroscopic material which balances air humidity and has been shown both by Minke (2006) and Morton (2008) to regulate internal air relative humidity to between 40 and 60%, which is the optimal range for occupant health in terms of bacterial and fungal growth reduction and health of the mucous membrane. A study by Minke (2006) on the weight of moisture absorbed by different materials after an increase in relative humidity from 50 to 80% has shown that clayey loam can absorb up to 10 times more air moisture than fired brick in 48h. This is beneficial not only to the health of occupants, but also in buildings where archives or other moisture sensitive objects are stored. Earth construction can also take advantage of earth's thermal capacity, of low embodied energy, straightforward recyclability and, in some cases, reclaimability. Morton (2008) also underlines the low levels of waste that can be achieved: during manufacture, non-stabilised earth materials can be fully recycled by re-wetting and re-mixing. While it can be said that earth-based construction products and processes have low embodied energy, savings are difficult to quantify. For earth masonry, an attempt to establish comparative life-cycle analysis was made by Morton (2008). Its results are cited elsewhere in this report.

As a result of these advantages, in some developed countries, the use of earth has seen a renaissance, and behavioural knowledge has improved as a result.

While traditional earth architecture can be found in a number of countries, with impressive examples in Spain, Morocco, Mali and Yemen, recent examples are relatively few.

In Europe, it is Germany that holds the most successful market in Europe for earth construction products, with an annual turnover of £60M and a sustained growth of 20%/pa at a time when the rest of the construction industry experienced no growth [Schroeder, 2000]. Part of the innovative approach to earth architecture one finds in Germany is due to the presence of building standards for earth construction (the *Lehmbau Regeln* by Dachverband Lehm e.V., issued in 1999, the revised edition of which is due in 2008). These standards are now part of the Building Regulations in 13 of the 16 German Federal States. However, these exist partly due to Germany's long tradition of earth building. In Mediaeval Germany, earth was mostly used as an infill to timber frames. Some rammed earth German houses from this period are still standing, with examples in Meldorf and Weilburg dating back to 1795.

It should be noted, however, that Germany had a building code for earth as early as 1944, and that the pressure to shelter the homeless from the Second World War one year before the end of the war and subsequently, combined with the economy of post-war Germany (especially for the GDR), played a leading role in research on the subject and in the issuing of these standards. This process did not occur in the UK. Despite the strong link between the current *German Regulations for Building with Earth* and those from the 1950s, the current regulations reflect the existing

Chiara Perrone

MEng (Hons)

Buro Happold,
Copenhagen, Denmark

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The Pai Lin Li Travel Award, donated by the family of the late Pai Lin Li, was granted in 2007 to the author in order to spend up to 6 weeks abroad studying current practice or trends related to the use of prefabricated earth construction products in the field of structural engineering.



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levels of earth building in Germany by allowing its use in combination with timber, brick and concrete. The structure of the *Lehmbau Regeln* is based on the different stages through which earth is processed: soil classification, preparation of earth materials, manufacture of earth-based materials, use and maintenance of earth buildings and their demolition, disposal and recycling.

In the UK, unlike Germany, the construction industry is often characterised by much confusion and lack of precise understanding of earth construction techniques, which encompass only rammed earth, adobe and cob but are, in fact, numerous. Lack of information with regard to earth construction techniques applies not only to the construction industry, but also to education. Very few higher education courses about earth in construction in the UK are available to students of architecture and engineering. In Germany there is a market for earth-based construction products and there is a dedicated industry; in the UK earth construction is a small movement carried forward by a few dedicated individuals.

It therefore seemed relevant to understand why earth architecture, a very common form of construction in many countries and also a common form of construction in the UK and Europe in the past, ceased to be used in certain areas, and how it could currently be applied to construction, given that both living and construction standards are now higher than those in most of the countries where earth architecture is currently used.

The study analysed innovative practices in earth construction with particular attention to the factors which minimise the disadvantages preventing earth from being a feasible and durable construction material in the colder climates of Europe, North America, China and Japan.

The study

The study took place in three main locations: Germany, India and the UK. The starting point was a background course, both practical and theoretical, in earth construction at the Building Research Institute (*Forschungslabor für Experimentelles Bauen*) in Kassel, Germany.

Overall, the study covered theory on historical buildings and on material properties of loam, visits to buildings, both modern and ancient, attending the International Symposium on Earthen Structures (Bangalore, August 2007) and visiting a prefabricated clay brick factory in Scotland.

Limitations of earth construction

Construction needs in developing countries are entirely different to those of Europe. At the Symposium on Earthen Structures it clearly emerged that while the driver for the use of earth construction in developing countries is, foremost, the need to reduce construction costs, in Europe the main driver is the somewhat vague concept, introduced by the western world, of sustainability, and its implementation through the use of low-embodied energy and reclaimable materials. This concept did not appear, in the Symposium, to be the main justification for the use of earth construction in developing countries.

This factor lies at the root of a common divergence over the expression



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'Earthen structures', which was hotly debated: the European representatives at the conference used the expression to indicate 'pure', or 'raw' earth buildings without the addition of stabilisers (i.e. concrete), whereas most representatives from India, Brazil and Australia consider stabilised products, subjected to the addition of a percentage of cement (5% minimum), as 'earthen'. However, while the concept of low embodied energy does apply to the use of the material, its recyclability is not as straightforward, and hygroscopicity is significantly reduced.

The reasons behind stabilisation were attributed by some attendees to building regulations, which for India only apply to earth stabilised with 5% cement. There have been structural failures of earth structures in India due to poor understanding of earth's structural properties and to poor workmanship.

Stabilisation was introduced as a means to aid the predictability of the material's behaviour. Since the reasons for building in earth-based materials in India are economic and unrelated to environmental awareness, adding 5% cement was a way of keeping the construction costs low, while having some form of structural predictability.

In Germany, on the other hand, regulations only apply to un-stabilised products. The debate on stabilised materials continued at the opening meeting of EBUK (Earth Building UK), which took place in London in October 2007, a few months after the Symposium.

It was already clear before conducting the study that not many earth construction techniques are viable in continental climates. Mud or cob walls are labour intensive and therefore not economical in countries where labour costs are relatively high. Rammed earth construction is difficult in damp weather as it should be performed under cover, thus increasing construction costs, and is also labour-intensive. Earth brick fabrication also depends on weather conditions: bricks can take a long time to dry and require protection from frost damage. In addition, despite common misconceptions that earth is a good insulator, increasing earth's poor thermal insulation is essential in colder climates.

Other limitations, or challenges, of earth construction are the lack of sound engineering design methodologies, poor seismic resistance, limited data availability on performance, uncertified products, lack of education and insufficient regulations. With the exception of poor seismic resistance, these limitations are strongly relevant to our climate and practice and provide sufficient reasons for the construction industry not to rely on the use of earth construction products.

Low loadbearing capacity

The compressive strength of earth, when used for construction purposes, depends on a number of factors such as the construction technique used. The average compressive strength for natural soil has been evaluated at 3.88N/mm², with a moisture content at test of 3.3% [Maniatidis *et al.*, 2007]. Modern unfired clay bricks available in the UK are specified by manufacturers as having a compressive strength of 3.8N/mm². Gernot Minke [2006] cites

Fig 1. Chapel of Reconciliation, Berlin. Note that there are only two openings / Fig 2. Arch cracking in historic building, Agdz, Morocco

that the tallest loadbearing rammed earth house in Europe, a six-storey residential building in Weilburg (1828), has walls withstanding a compressive force of 7.5kN/mm^2 at the bottom, where they are 750mm thick, but modern examples of rammed earth walls are closer to 3.8N/mm^2 : The Chapel of Reconciliation (see Fig 1), built in 2000, has rammed earth walls with a clay content of only 4% which, thanks to heavy compaction, can withstand up to 3.2N/mm^2 . Given the role of moisture content, these figures are only indicative, and the relatively low compressive strength has meant that earth products in Europe are currently specified as non-loadbearing materials, despite examples of multi-storey dwellings built in loadbearing earth (up to six storey in both Weilburg and Meldorf, Germany, and Shibam, Yemen).

Lack of sound engineering design methodologies

Professor Torrealba of the Pontificia Universidad Catolica del Peru, while at the Symposium on Earthen Structures, stated that the problem with earth is that 'it is not an engineering material', which could perhaps be rephrased as 'it is not a structural engineering material' in that it is a difficult material to describe in structural engineering terms.

In Germany, tests described for the purposes of earth construction relate to those usually conducted in geotechnical engineering (sieving, water content, cohesion, liquid and plastic limits) and some are simply observational tests and relate to odour, tactile qualities and visual properties. These tests, however, seem to aim at classifying the soil to understand what proportions of silt/clay/water to use and which construction method is more appropriate, more than to structural performance or behaviour.

This approach at first sight might seem inappropriate as it does not necessarily lead to a straightforward design methodology such as those that structural engineers are used to with BS codes for reinforced concrete, steel and timber. However, it is well justified if one understands that earth, even when used in construction, can and should be looked as a soil, as previously indicated by Jaquin for rammed earth walls [Jaquin, P., 2008], which behave as highly unsaturated soils. Jaquin's post doctoral work, undertaken at Durham University, looked at rammed earth as a soil, applying geotechnical engineering principles to the structural material, and showing the role suction plays in the strength of rammed earth. However, for earth masonry, it is usually suggested that structural design should follow masonry codes [Morton, 2008].

The complexity of this issue is currently being avoided in the case of earth masonry as testing procedures currently proposed in the UK for earth masonry products, are based on BS masonry codes with differences due to earth's particular characteristics [Morton, 2008]. The main difference is that when the moisture content reaches the plastic limit, and under this aspect the behaviour compared to fired earth bricks is more complex to describe, collapse occurs.

Recently, much research has investigated ways to apply physical and engineering principles to aid behavioural understanding. One example is the attempt to optimise soil grading for reduced moisture ingress and increased evaporative drying of earth materials [Hall, 2007]. The compressive strength of stabilised compressed earth materials such as stabilised rammed earth walls and compressed stabilised earth bricks can be reduced by moisture ingress caused by capillary absorption, pressure driven absorption and evap-

orative moisture loss, which are phenomena typical of the UK climate. It has been shown [Hall, 2007] that by changing solid grading characteristics through the methodology proposed by the author, capillary moisture absorption can be reduced.

The role of water in capillary forces and ionic correlation forces has also been assessed in a study by Gélard *et al.* [2007], which concludes that the amount of water needed to reach optimal cohesion and energy dissipation in earth construction cannot be quantified in absolute terms, as it is characteristic of each earth material, thus confirming that behavioural understanding is not straightforward.

Cracking

As with most materials which rely on compression and can only resist feeble tension, cracking is often observed in earth construction. Figure 2 shows some cracking due to hinge formation.

Cracking, thoroughly analysed by Jaquin (2008) for rammed earth construction, is also a problem in recent construction projects. Cracking in earth masonry in current architecture is usually a response to shrinkage of either the masonry itself or of adjacent timber in the case of earth-infill timber frames.

Durability

An easily noticeable aspect of earth architecture is often damage to the external façades of buildings, and the difference between façades treated with forms of plaster or other protective coatings, and untreated façades. This does not occur in arid climates.

Figure 3 shows damage to a rammed earth wall at the Eden Project in Cornwall (2001). While the erosion is not necessarily due to climatic conditions, as it looks like the wall has been picked at, the wall is of recent construction and erosion due to rain is likely to cause further damage if the overhang does not provide sufficient protection.

The effects of climatic conditions such as rainfall on unprotected earth can be seen in Fig 4, which shows the effect of rainfall on two houses in the same region (Bangalore, Karnataka) in approximately the same time lag (20 years) but built of different materials.

While the climate of Karnataka is clearly different from that of Northern Europe, as the rainfall is concentrated in the monsoon seasons, erosion on external façades is, likewise, a considerable drawback to the use of earth architecture in Northern Europe. Maintenance costs in the UK are relatively high, and while in some countries such as Australia it is sufficient to provide long enough overhangs, Northern Europe is characterised by driving rain which, through capillary action, might affect compressive strength.

Stabilisation

Erosion, as shown in Fig 4, can be limited thanks to 'stabilisation', provided by the addition of 5% volume of cement. Buildings made of stabilised mud blocks (SMB), perhaps more precisely defined when referred to as 'soil-cement' blocks, such as those shown in Fig 4 (to the right), are very common in Bangalore City: it is estimated that there are more than 4000, the majority of which are 2-3



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Fig 3. Rammed earth wall, Eden Project, Cornwall / Fig 4. Comparison between durability for unstabilised earth masonry (left) and masonry stabilised with 5% cement (right), of approximately the same age (20 years) in Southern India. Note that the wall to the right is not protected by an overhang

storey high load bearing masonry houses.

Through the Pai Lin Li travel award, it was possible to see the production of SMBs on site (Fig 5).

Buildings of higher quality than those shown in Fig 5 were observed in Auroville, home to the UNESCO Chair of Earthen Architecture. The Auroville Building Centre's Earth Unit researches, develops, promotes and transfers earth-based technologies.

Despite being the home to the Chair of Earthen Architecture, what emerges upon visiting Auroville is that the good aesthetic quality of the local work is achieved through stabilisation, and that unstabilised earth buildings are hardly present.

Using stabilisation as a means to improve durability might be widely accepted in India, but often conflicts with the ideas of low embodied energy and reusability that determine the use of earth construction in the first place.

While studies have shown that unprotected rammed earth walls are relatively durable in Southern Europe [Bui and Morel, 2007], and rammed earth walls have also been constructed unprotected in the UK (Fig 3), there is a tendency to protect earth masonry materials in externally exposed situations in UK climatic conditions [Morton, 2008], and plastering is often used as a form of protection.

Thermal performance

While solid earth walls are well suited to hot arid climates in which the high thermal mass of the walls dampens the effects of heat during the day and *vice versa*, in cooler and damper climates such as in the UK, reliance on thermal mass alone may not prove sufficient during cold periods, as common earth masonry products are relatively dense (1900kg/m^3) and therefore have high thermal conductivity (1W/m K for a low moisture content; Morton, 2008)

The effects of using low density additives such as pumice, recycled glass, poly-foam waste and kenaf fibres have been investigated [Maniatidis *et al.*, 2007]. Results show that while the addition of lightweight additives is successful in reducing density and therefore increasing thermal insulation, this compro-

mises the aesthetic qualities and possibly the fire resistance of the material. Thus the preferred solution to the necessity of insulating rammed earth walls is the incorporation of separate thermal insulating layers. Since build up of excessive moisture in rammed earth walls can lead to catastrophic failure, vapour permeability needs to be maintained, and not all materials are suitable for insulation unless a vented air gap between the wall and the insulation is provided. Incorporating insulation within rammed earth walls is, however, not straightforward, due to the effects of compaction on the insulating layer.

While the role of thermal insulation, even for temperature ranges as limited as $0\text{-}30^\circ\text{C}$, has been shown to be just as important when earth masonry is used [Heathcote, 2007], incorporating insulation to earth masonry is more feasible via layered construction. Morton (2008) suggests that the earth masonry should form the inner skin of the wall, while insulation should be applied externally. This approach has been implemented at Kirk Park, Dalguise, Perthshire [Morton, 2008].

Openings

When earth is used as a structural material, a characteristic of most buildings is the limited number and size of openings. In historical structures, openings have been observed, but often these are achieved through the use of arches such as those shown in Fig 2, and it is unclear to the author how else openings could be achieved, unless arches or timber or concrete lintels are used. While in the case of load-bearing domes this issue can be circumvented by the use of skylights, as shown in Fig 6, even recent and innovative examples of earth architecture tend to show little openings (see Fig 7 and Fig 1).

While this characteristic does not represent an issue for architecture in Southern India (see Fig 8), at latitudes where most activities take place outdoors and there is a necessity to keep the sun out, in Northern Europe there is a strong tendency, especially in more recent architecture, to have a higher surface area of windows.

Few buildings visited during the study had spacious rooms with high levels of light. One example was a house on the outskirts of Kassel where this was



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Fig 5. On-site production of Stabilised Mud Blocks (left) and masonry work (right), Bangalore / Fig 6. Unfired loam brick dome, Building Research Institute, Kassel / Fig 7. (left) Youth Centre in Spandau, Germany. (right) Exterior, 32.5m rammed earth walls. Note the lack of openings Fig 8. Interior of an earthen dwelling in village of 9ne Gunte, 40km from Bangalore, India

achieved by combining the use of unfired clay blocks to that of some elements of reinforced concrete: beams supporting vaults.

The Vikas community building (Fig 9), which comprises 13 apartments on three floors, also shows the use of reinforced concrete elements in combination with that of (stabilised) earth blocks.

Interestingly, there are a number of examples of buildings that, despite being described as ‘Cob’, or ‘earth’, from a structural perspective are supported by materials other than earth, most often timber. An example is the Cob Visitor Facility at the Eden Project [Abey and Smallcombe, 2007]. Structural features of the building are blockwork plinths with strip foundations for the ground-works, and timber rafters to resist wind loading.

While in historic structures one can notice that openings are achieved through the use of timber lintels, concrete has also been used to allow for large window openings [Rauch, 2007]. The combination of reinforced concrete and earth blocks, which is common in developing countries (see Fig 10), does seem to provide a compromise between structure and services.

The same principle, that of using earth blocks as an infill to the structural frame, is in fact an established vernacular form of construction. Referred to as ‘*Fachwerk*’ in Germany and ‘wattle and daub’ in the UK, it is a traditional form of construction in most Western European countries. It is also found in Turkey, Syria and the Balkans. Fig 11 shows some examples of infill to timber frame under construction.

Lack of standards

The lack of British Standards is often seen as a strong impediment to the use of earth construction, and the innovative approach towards earth architecture than can be found in Germany is often attributed to the presence of the *Lehmbau Regeln*.

However, as Morton (2008) explains, compliance in the UK can be demon-

strated through self-certification or compliance with European documents such as the *Lehmbau Regeln*. The study has not investigated this particular aspect further.

The Chapel of Reconciliation (Fig 1), one of the most striking examples of contemporary earth architecture, despite being built in Germany, is an example of a building which underwent a particular approval process, as it was the first time that the municipal authorities and structural engineers in Berlin had encountered the proposed technique.

The Chapel (*Kapelle der Versöhnung, Bernauer Straße, Berlin*), a monument to mark 10 years since the fall of the Berlin Wall, stands on the location of a Neo-Gothic church which was demolished in 1985 in order to keep the firing lines open on the no man’s land strip lying between the two walls.

The leaflet describing the project to visitors of the chapel explains that the municipal authorities ‘imposed structural safety standards seven times higher than for conventional buildings’. This statement is, in terms of structural engineering, imprecise, but it does show that though Germany does have standards for loam construction and though it is considered to be open to loam construction, in practice engineers are still sometimes required to prove structural soundness to a higher degree.

In the case of the Chapel, it seems that this was carried out by *Technische Universität Berlin*, which provided on-site supervision and scientific support. 390t of soil was collected from around the city, and processed in 3 months. The wall contains fragments of broken brick from the former church and gravel. The advantage of this coarse grain mixture with a clay content of only 4% and a minimal moisture content of 8.1%, is that shrinkage was limited to 0.15%. The compressive strength of 3.2kN/m² was achieved thanks to intensive compaction. Although the wall is 60cm thick, it is not thick enough for the required U-value to be achieved (Minke states that for the correct U-value to be achieved in Germany, most rammed earth walls would need to be 1.60m thick if no insula-



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Fig 9. The Vikas Community, an example of Stabilised Earth Masonry, Auroville / Fig 10. Combination of RC frame and earth blocks (Agdz, Morocco) Fig 11. Top left: Light earth (expanded kaolin), provides the advantage of improving thermal insulation in comparison to denser earth blocks, and is less prone to result in cracking. bottom left: Unfired, non-stabilised dense loam bricks used with clay mortar. Right: Light earth and unfired brick masonry infills to timber frame. For light earth, the procedure requires the use of shuttering on both sides / Fig 12. Some CLAYTEC products: loam for plaster (top), fibre loam board (bottom left) and earth blocks of different densities (bottom right)

tion is provided). A worker on site confirmed that the building is not heated and that in the winter it is very cold. The building would not be suitable as a dwelling. Moreover, the cost of the chapel was relatively high, at €4350/m².

Prefabrication

CLAYTEC is a leading manufacturer of earth construction products in Germany, producing and selling its products throughout Germany and Europe:

- Earth plasters in a variety of different colours and components (some plasters are high-finish plasters with fine grains, some are coarser and contain fibres). These can be purchased ready mixed, or in powdered form (Fig 12, left) to mix with water.
- *Lehmbauplatten*. These are boards which, in section, resemble some forms of vernacular construction, and consist of woven fibres of various types and diameters and clay (Fig 12, centre). The boards are produced in different thicknesses and are a quick and effective means of finishing walls whilst balancing indoor humidity.
- Earth bricks and blocks in different sizes and densities (Fig 12, right).

As made clear by Herr Schultz, who owns an outlet of CLAYTEC products in Berlin, these products are relatively expensive compared to their 'standard' equivalents. The fibre clay boards, for instance, cost €15-22 per metre square.

Although Germany is seen as the country in Europe with the highest turnover in this industry, Herr Schultz explained that there are only few architects that are able to use the products properly (20 – 30 in Berlin) and it is mostly for 'environmentally aware clients' who are prepared to pay the extra costs.

Herr Schultz also pointed out that although the earth bricks are sold in different densities (700, 1200 and 1500 kg/m³) none of them are of low enough density to be used independently from other insulating materials such as rock wool or similar.

The author obtained samples of a wide range of its products (Fig 12). However, it seems that CLAYTEC's selling point is that it has developed building systems, not just products, which makes the company very successful in the German building market, despite the relatively high costs of its products. One tangible advantage is a manual (in German), which can be ordered online directly from the CLAYTEC website, explaining diagrammatically how each product is used. Nothing of the kind is currently published in the UK by manufacturers of similar products.

In view of the limitations of earth construction, it would appear that the use of earth blocks and light earth infill in timber frame construction (Fig 11) might

be a way of re-introducing earth construction to the UK. Prefabrication provides the advantages of lower and more predictable construction times and higher quality control. It also seems to limit the possible disadvantages of using earth, and using infill to timber frames which is easily adaptable to the timber frame industry in areas where it is already established (i.e. Scotland).

At the time that the proposal for the study was written, there were no established producers of earth construction materials in the UK. Materials were sometimes produced on site, which complicates quality control and can cause delays in construction times. Pre-fabricated blocks and panels, the alternative solution, were either made offsite by specialist manufacturers (the panels still are) or imported from abroad. Specialist manufacturers are relatively expensive and importing from Germany and Austria, not always a justifiable option, is inefficient and disproportionately expensive.

Currently, mass produced masonry products from the UK are the Eco-Brick by the Errol Brick Company, the production of which was witnessed by the author during this study, Ecoterre by Ibstock, Naterra by Akristos and Sumatec by Lime Technology. The latter three only entered the market very recently. This seems to indicate that mass production, which results in cheaper materials with lower embodied energy and therefore lower environmental impact, has been deemed as feasible and is currently implemented to a larger scale than it was at the time the proposal to the current Pai Lin Li study was made.

As explained by Peter Walker who represented Tom Morton at the Symposium for Earthen Structures, the development of contemporary earth construction in the UK might find an answer in earth masonry, which has the potential to break out of the niche of eco-building to make significant savings in CO₂ emissions and waste production. The fact that the fire brick industry in the UK is declining is another strong factor in the development of unfired earth bricks, as existing fired brick factories can easily be converted into unfired brick factories.

The Errol Brick Company Ltd is one manufacturer which has implemented the addition of un-fired brick production (Fig 13) to that of fired brick manufacturing process, and is one of the few producers of unfired earth bricks (Fig 14) in the UK. Its Eco bricks are designed to be fully reusable and can be bought as part of a brick and earth mortar system, the only system of the kind manufactured in commercial form in the UK at the time of writing. The size of the brick is a nominal 225 × 110 × 68 (mm) and is designed to fit between timber wall studding as a non load-bearing component, thus offering the builder the ability to construct a breathable wall system which balances humidity, through hygroscopicity, if the walls are finished with a clay plaster.

The brick is composed of post glacial alluvial clay, sand and sawdust from



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Fig 13. Different stages of the production of unfired clay bricks. Note the extrusion at the middle, one of the stages with highest energy consumption. These stages are the same as for fired clay bricks, with the difference that while fired bricks are fired in the kiln, unfired bricks are oven-dried, thus resulting in energy savings, as shown in Fig 14 / Fig 14. Unfired clay bricks after oven-drying

local sources. The mortar supplied by Errol Brick consists of ground dry clay and organic binder produced in the UK. These materials are mixed with water in the following proportions: Mix ratio 3ltr sand, 1ltr clay, 0.025ltr binder, water to suit. Binder must be added before the water.

It is claimed that the embodied energy of a tonne of unfired earth bricks is 123.5kWh and 22kg CO₂ at the factory gate. Although accurate comparable figures are difficult to obtain, this amounts to 14% of the embodied energy and carbon production of fired bricks (Morton, 2007), a significant saving if one considers increasing energy costs and taxation due to these costs and due to the production of CO₂. Other advantages over fired bricks used for the same purposes are their excellent sustainability credentials of low energy input, low waste production and reusability. Their use also provides thermal mass and acoustic insulation, and they are hygroscopic and thus inhibit condensation by regulating the relative humidity of the atmosphere. As a finish, unfired clay brickwork can be finished with a variety of 'breathable' materials including clay and lime plasters, clay boards, some paints and limewashes. If paint is used, it should only be high vapour permeable paint.

The price of bricks from Errol bricks is currently the same for fired and unfired bricks. The reason is that while the Errol Brick Company had to purchase no new equipment for the production of the bricks, it did invest in equipment for the manufacture of the mortar and in testing for the development and certification of the bricks.

Ibstock Bricks, located in England, make a product similar to Errol's Eco Brick called 'Ecoterre', an earth brick which is also intended for most internal non load-bearing applications, but it does not produce clay mortar. The earth bricks are manufactured in two sizes: 220 × 105 × 67mm (weighing 3kg) and 220 × 105 × 133mm (weighing 6kg) and have the following characteristics:

Code	EC 3590
Configuration	Vertically perforated
Compressive strength	3.8 N/mm ²
Density	1940kg/m ³

Ibstock specifies two types of mortar to be used in conjunction with the bricks: clay mortar by Construction Resources and Lime Mortar (also known as Limetec) by Lime Technology Ltd which should be moderately hydraulic lime mortar. Interestingly, for undercoats, CLAYTEC products, which are produced in and imported from Germany, are specified.

The importance of mortar has been explained by Heath *et al.* (2007): in order for the energy savings that unfired clay bricks can implement, these would need to be used in mainstream markets, where thin wall thicknesses (typically 100–150mm) are preferred. A significant increase in the bond strength of unfired earth masonry is thus required. The authors identified two promising mortars: Lignosulphate and Activ 7, for use with unfired earth bricks.

Discussion

The study aimed at answering one key question: whether earth is an economically viable and durable construction material in countries where workmanship is relatively expensive and the climate can be wet and cold. The analysis of the advantages of the use of the material in terms of energy savings, health (thanks to its effect on relative humidity) and more generally building services goes beyond the scope of this report.

While there is a trend towards the vernacular in Europe, this is not the case in developing countries. The only reason earth is used in these countries is that it is cheaper to do so: it was observed that in India any reasonably wealthy family would refuse to live in earth dwellings. In one village seen during the study, the richest family in town, which produced silk, was the only family to own a concrete house.

Some aspects of earth construction which are usually seen as disadvantages, such as difficulties in obtaining a 'clean' finish and the inability to hang objects off walls, are minor issues which can easily be resolved, and the same can be said for erosion. However, a number of issues related to earth construction remain, and these are to do with the fact that earth is not a 'typical' engineering material, as its properties vary greatly, especially with variation in moisture content, and are difficult to quantify, especially if few tests are taken. In addition, earth cannot withstand tensile forces.

In colder climates such as that of the UK, there are even further limitations to its use: insulation is required, and despite some indication in the literature that 'light' earth with density as low as 1500kg/m³ can be used instead, studies

have shown that insulation is indeed required [Heathcote, 2007], and some earth construction techniques have been proven particularly difficult to combine with insulation [Maniatidis *et al.*, 2007]. It has been shown that openings for windows are difficult to achieve in a straightforward manner and the use of reinforced concrete or timber frames are recommended in conjunction with earth whenever walls are load bearing [Rauch, 2007].

Hygroscopicity, a word often used by building services engineers and supporters of earth construction in the UK and abroad, is not necessarily always effective enough to justify the use of earth construction: the Youth Centre in Spandau (Fig 7), has a 32m rammed earth wall which is claimed to 'subdivide the building and serves to conserve thermal energy and balance air humidity' [Minke, 2006]. However, despite being a strong feature, the building is mostly light-weight, and the ability of the wall to 'conserve thermal energy and balance air humidity' is arguable, given the small wall surface volume ratio. This raises a point about earth architecture: while its use is often justified as a means of balancing indoor humidity, this can only be applied to spaces where wall surface volume ratios are relatively high.

Both the scarcity of skilled workmanship and its relatively high cost are other significant issues.

Although the revival of earth architecture in the UK has seen the use of *in situ* rammed earth as the leading contender, the existence of published guidelines [Walker, 2005] has also highlighted its limitations which are considerable: insulation cannot be easily applied; compressive strength, even after compaction, is rarely higher than 3.8N/mm²; construction times are long and rely on weather conditions and its compressive strength can be reduced due to capillary action, pressure driven capillary action and evaporative moisture loss [Gelard *et al.*, 2007]. In more general terms, rammed earth requires specialist processes and specialist testing, as does cob.

Most of these disadvantages can be overcome through the prefabrication of both rammed earth walls and bricks. While the former are not currently available for sale in the UK, the latter have now been available on the market for about a year, and their use in conjunction with timber-framed buildings, which are also seeing a revival in Northern Europe, seems feasible. Their cost is no higher than that of fired bricks, the skills required to construct unfired-masonry walls are not considerably different from those required for fired masonry. For the moment, these need not be used as load-bearing members, thus minimising construction risks. Unfired bricks are currently available in Scotland from the Errol Brick Company and in England from Ibstock Brick, and can be used either with earth mortar or with lime mortar. The indigenous manufacture of these products has therefore been proven feasible, but is yet not mass production. A publication giving detailed practical guidance on contemporary construction using this material and providing numerous technical details in the form of illustrations has recently been published by IHS BRE Press (Morton 2008).

Currently, as an engineering material, it is an issue to specify earth as a construction material if intended as a structural material. Although regulations are said to be the main reason why earth construction in the UK is not 'mainstream', and despite the turnover of earth construction in Germany (£60M/year), the projects visited in Germany during the study do not seem to indicate particular differences in terms of structure: in Germany, as the Chapel of Reconciliation shows, authorities are also uncomfortable with the use of earth as a construction material, and although there are indeed a number of high-finish buildings all over Europe, whether in the UK or outside, they are small in number. Each is a unique project often carried out over a long period, especially in the case of rammed earth, and often with a strong sculptural value.

Most of these issues emerged at the opening meeting (London, 2007) for the formation of an Earth Building organisation in the UK (EBUK), organised by Pete Walker of the University of Bath and BRE, and Tom Morton of Arc Architects. The meeting helped in understanding who within the construction industry felt the need to introduce a UK earth building institution. While a number of academics, artists, conservation architects and manufacturers were present, there were no engineers working for consultancy firms, apart from the author.

It was agreed at the meeting that the association should be interested in all aspects of earth construction, with the potential for collaboration across sectors, and it was suggested that it would be informative to be able to quantify the value of earth construction as an industry, so that growth could be recorded.

It was also noted that the translation of the German *Lehmbau Regeln*

(Earth construction standards) could be a worthwhile step towards development of a UK standard.

Conclusions

Most of the disadvantages of earth construction can be overcome by prefabricating both rammed earth walls and unfired bricks. While the former are not currently available for sale in the UK, the latter are now available on the market, and their use in conjunction with timber- or concrete-frame buildings, seems feasible. Their cost is no higher than that of fired bricks, the skills required to construct unfired masonry walls are not considerably different from those required for fired masonry, and insulation can be applied without significant practical complications.

Other frame-infill materials that could be used in the UK are light-earth (expanded kaolin) and earth blocks or bricks with lower density than those currently produced in the UK.

The highest positive impact of the use of earth in construction is on humidity regulation, internal comfort and environmental issues, and not on

structural efficiency. The use of earth which at present appears more viable in the UK market (unfired earth bricks or rammed earth infill to timber or reinforced concrete frame) is currently not structural. A widening in the extent of the use of earth as a structural material does not currently seem likely, unless structural engineers start to understand the material through other disciplines, such as geotechnical engineering, and stop slavishly relying on building standards. Nevertheless, currently, the structural engineer can play an important role in the holistic design of a building by understanding this material, its behaviour and perhaps, more importantly, its limitations.



The author completed an MEng degree in Structural Engineering with Architecture at the University of Edinburgh in 2006. Since then, she has intermittently worked for Buro Happold, who also sponsored part of her studies through the Happold Trust. She is currently working in Buro Happold's Copenhagen office, working on Massar, a Children's Discovery Centre in Damascus, Syria, in close cooperation with Henning Larsen Architects.

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