Development of unfired clay brick systems for sustainable construction

TSB Project no TP/5/SUS/6/I/H0192J

ABSTRACT

The project was aimed at exploiting the established advantages of unfired clay building materials, including low carbon emissions and passive environmental control, in contemporary construction. Unfired clay masonry can replace fired brick and concrete block masonry in many applications, with significant reductions in the consumption of natural resources, and in waste sent to landfill as the raw materials. These benefits are inherent in the manufacture process, but continue through the whole life cycle. This project was planned to investigate characteristics of unfired clay brick masonry, along with appropriate mortars and finishes, for use in the UK and abroad. The aim of this project was to provide technical solutions that will enable the brick industry to develop commercially viable products from unfired clay, which are more sustainable, cheaper, technically responsive and healthy compared to existing products.

The project has shown that unfired clay bricks combined with innovative mortars will provide performance required of fired clay bricks and concrete blocks in many situations, with some major benefits such as passive environmental control and, most importantly, lower cost and embodied energy. The potential applications where the project might be applied include many internal applications where fired clay bricks, concrete blocks and other construction materials are currently used. All types of projects could benefit from the potential cost savings, all habited buildings could benefit from occupant health benefits, while humidity regulation could have more specific benefits in special situations such as archiving rooms, museums, libraries, certain office environments and bathrooms. Marketing efforts of consortium partners (who between them produce most of the UK's bricks) and independent proven performance will ensure the project results will be fully exploited.

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Introduction
The project was aimed at exploiting the established advantages of unfired clay building materials, including low carbon emissions and passive environmental control, in contemporary construction. Unfired clay masonry can replace fired brick and concrete block masonry in many applications, with significant reductions in the consumption of natural resources, and in waste sent to landfill as the raw materials. These benefits are inherent in the manufacture process, but continue through the whole life cycle. This project was planned to investigate characteristics of unfired clay brick masonry, along with appropriate mortars and finishes, for use in the UK and abroad. The aim of this project was to provide technical solutions that will enable the brick industry to develop commercially viable products from unfired clay, which are more sustainable, cheaper, technically responsive and healthy compared to existing products.

Unfired clay bricks have a number of advantages over fired bricks, concrete blocks and other construction materials in many non-structural applications in a range of buildings, including:

a. significantly lower embodied energy than comparable products, with preliminary indications from DTI funded research at Dundee University indicating unfired bricks have 14% of the embodied energy of fired bricks and 25% of concrete blocks.

b. providing passive environmental control of both temperature and humidity in buildings, leading to health benefits in respect of asthma and other respiratory diseases.

c. ease of recycling as either fired or unfired bricks.

The project was planned to investigate how this new technology can be promoted with minimal changes to existing production processes and construction practices, by investigating appropriate constituent materials, block geometries, mortars and finishes.

Innovation
There have been unfired clay products on the market for many years (particularly from Germany), but there has been little research into these products and most do not conform to the established masonry standards used by the mainstream UK market. Use in Germany and in the UK has generally been limited to specialist conservation and ‘green’ construction niche markets. The technical approaches that have been adopted with these existing products are to either use very thick walls or to use a timber frame infilled with unfired clay bricks. In both these approaches, the mortar strength is not critical to the design. Neither of these approaches are considered appropriate for the UK market where very thick walls will increase material usage and decrease usable floor space, and where a timber frame infilled with bricks will slow construction and will require different trades working in the same location on site.

The technical innovation in this project was largely be associated with the development of mortars that enable unfired clay bricks to be bonded to achieve equivalent performance to that of fired bricks. This ensured that design and construction would be similar to that for fired bricks. Initial
research has shown that existing mortars from Germany are not suitable for thin-walled unfired clay brick construction but that the strength and performance of the bricks themselves should be satisfactory in many applications. A basic mortar produced by one of the consortium members (The Errol Brick Company) showed some promise with unfired clay bricks, but research established that this mortar showed poor bond strength with some types of unfired clay brick and was subject to deterioration of bond strength over time. A mortar based on sodium silicate was developed which shows good bond strength on all clay brick types investigated with no deterioration in bond strength over time. Ensuring similar performance to fired units in many applications could allow developments for fired brick within the governments drive for Modern Methods of Construction to be effectively used for unfired bricks.

Producing unfired clay products with a proven performance and the properties required for most internal applications, but at a significantly lower cost and embodied energy than fired bricks or blocks was the main aim. As a result of this project the market is expected to increase beyond the small ecobuild market to the mainstream. This is of particular importance at a time when energy costs are increasing and politicians are simultaneously promoting 'greener' technology and increases in housing stock.

**Overview of project outcomes**

The project has established the parameters for systems using unfired clay bricks that can be successfully used in place of fired bricks and concrete blocks in defined situations. Most importantly, the unfired clay brick systems should have a significantly lower cost and embodied energy, thereby moving them from the small 'green' construction market into the mainstream.

It is anticipated that existing brick manufacturing plants will be able to produce brick systems with little or no modification to their processes, with the main exception of not firing the bricks. Unfired clay masonry units have already been specified on a number of large construction projects in the UK but their further use been constrained by the lack of co-ordinated research in the field. The approach to their use has been very conservative and has failed to achieve the material's potential. This research has provided the basis for greater exploitation of proven potential benefits.

The economic benefits are largely related to the broad base of knowledge that have been obtained during the study and the potential this releases in the whole UK brick industry and its 6000 employees. It is anticipated that no major additional manufacturing plants or processes will be required and the majority of the cost savings in using this technology will therefore be passed directly to consumers. This should result in unfired UK bricks being more cost-effective and sustainable than imported or local fired bricks. As the UK brick manufacturing industry uses approximately 5.4 TWh of power each year (BDA, 2002), for every 1% of the fired brick market that is replaced with unfired bricks, the energy saving could be sufficient to power about 20,000 homes for a year (assuming 85% of the energy from processing goes into firing (BGS, 2005))
Exploitation

The project has shown that unfired clay bricks combined with innovative mortars will provide performance required of fired clay bricks and concrete blocks in many situations, with some major benefits such as passive environmental control and, most importantly, lower cost and embodied energy. The potential applications where the project might be applied include many internal applications where fired clay bricks, concrete blocks and other construction materials are currently used. All types of projects could benefit from the potential cost savings, all habited buildings could benefit from occupant health benefits, while humidity regulation could have more specific benefits in special situations such as archiving rooms, museums, libraries, certain office environments and bathrooms. Marketing efforts of consortium partners (who between them produce most of the UK’s bricks) and independent proven performance will ensure the project results will be fully exploited. In addition, there have been a number of books, marketing publications, conference papers and presentations and journal publications produced as part of this project.

Project outcomes

The project was broken down into four different work packages which will be described in more detail later in this section:

WP1. Review of other experience and quantify properties of existing unfired clay bricks
WP2. Investigation of mortars
WP3. Development of block profiles and finishes
WP4. Detailing, marketing and dissemination

The attached chart shows the planned timing of activities, which was adhered to, in spite of some management problems during the project (one of the original partners ceased trading and the original research officer emigrated to Canada during the course of the project.)
**Objectives**

- Review of other countries’ experience and study visit to Germany.
- For different unfired bricks produced by partners:
  - quantify strength and shrinkage as a function of moisture content,
  - thermal properties and hydroscopic absorption capacity to be investigated,
  - effect of different bricks on bond with one or two standard mortars to be investigated (this is included in the report for WP2)

**Review of other countries’ experience and study visit to Germany**

As part of the first project work package, which included a review of other countries’ experience with unfired clay, a study visit to Germany was completed. Since its reunification Germany has been leading Western Europe in the manufacture, construction and innovation with unfired clay building products. A wide variety of products are available, including unfired clay bricks, panel (plasterboard) products, mortars, rammed earth materials, plasters and insulation (hemp-clay) products, as shown in Figure 2. The head of the German Earth Building association indicated that the current German market for earth masonry products is approximately €50M per year and growing at 10% per year.
These materials are produced by a growing number of small and medium size enterprise factories, some of which had converted fired brick plants into making only unfired bricks products. The aim of the study visit by the project team was to view manufacturing processes, discuss German practice with local experts and view building projects. A full report on this visit can be found in Appendix 1, but the visit included a visit to a manufacturer, a meeting with the representatives from the Dachverband Lehm eV (the German earth building association) and a visit to a prominent German architect who specializes in earth masonry construction.

The visit to the manufacturer demonstrated the relative ease of converting an existing fired brick plant to produce unfired bricks or to take unfired bricks off a typical production line. In the UK this would most likely be even easier as many UK plants are less mechanized (the plant visited had only the owner and one employee). The soils used were identical to those used when fired bricks were originally produced, but the German approach is to add a large proportion (up to 10%) of organic fibre (usually sawdust / wood fibre / straw) as there is a perception that this improves performance. If a UK plant were to produce both fired and unfired products, the potential for contamination with the organic material would need to be addressed.

The visit to the Dachverband Lehm representatives was focused on the development of design and construction codes used for earth masonry. Germany has a federal governance system and these codes had been accepted by 13 of the 16 states. The construction industry in Germany is very
different to the UK as it is very tightly controlled. Dachverband Lehm intends to achieve a professional status for earth masonry by way of a specialist State Degree for Earth Building e.g. completion of a 120-hour course allows the attendants to call themselves Earth Builders. This is typical of other construction trades where builders have to have completed approved formal training before being allowed to practice. The representatives from Dachverband Lehm also indicated that the project consortium was unlikely to be able to formulate a mortar to provide sufficient bond to earth bricks so they can be used in free standing 100mm thick walls. In Germany it is typical to use earth masonry only as an infill to a timber frame, which requires different trades working together on site, thereby increasing costs and causing delays. During the course of this project the consortium was able to develop a mortar which can fulfill the original objectives – i.e. free standing walls 100mm thick can be constructed without any supporting frame. This formed part of work package 2 and is discussed in detail later.

Quality properties of different unfired bricks produced by partners

Strength and shrinkage

The full report on these tests can be found in Appendix 2.

Extensive testing was performed on unfired bricks from commercial brick plants. The majority of these materials have engineering properties of low plasticity clays as shown in Figure 3 below, but those with slightly higher plasticity do not appear to have any different performance characteristics.

![Plasticity chart for materials](image)

**Figure 3: Plasticity chart for materials**
Although engineering classification tests (Atterberg limits) indicate they behave as clays, silt sized particles dominate with only 20-40% clay sized as shown in Figure 4 below. Units with a higher clay content do generally have higher compressive strength (Figures 4 and 5).

Figure 4: Particle sizes of units

Figure 5: Compressive strength / moisture relation (strengths corrected for unit dimensions)
This graph shows that all the bricks lose strength as the moisture content increases, but the value of the strength varies considerably in the mid-range of moisture contents (between 1.5% and 3% moisture content - most likely to be found inside inhabited buildings). The decrease in strength with increase in moisture content is fairly similar for the different bricks in this mid-range, with the exception of Unit 12 which shows a smaller decrease in strength than the other units. This unit has the lowest density of all those tested by a considerable margin, and this may be the reason for the lower moisture sensitivity, although this is difficult to confirm from the available data. The effect of changes in relative humidity on strength is discussed later in this report.

Chemical tests showed organic contents of up to 2.7% which could be a cause for concern when considering fire resistance. It is recommended that further research on the influence of organic content on fire resistance be conducted, but this is beyond the scope of this research project.

There was, however, a more marked relationship between density and shrinkage where a lower density resulted in reduced shrinkage and expansion under changes in moisture content as shown in Figure 6 below. The presence of perforations appeared to have no effect on shrinkage performance. It is recommended that the density of units be reduced to reduce expansion/contraction from changes in moisture content, provided this has no effect on other performance parameters. This could be achieved through the addition of wood or straw fibres or sawdust, as common in Germany.

![Figure 6: Effect of density on shrinkage movement](image-url)
**Environmental performance**

A full report on the environmental performance, including moisture buffering capacity and thermal performance is available as Appendix 3.

Earth masonry has the ability to absorb moisture from the air at high relative humidity and release it at low relative humidity. This humidity buffering has potential to provide health benefits to occupants (particularly for respiratory diseases), but this effect was not quantified as part of this research.

An increasing clay content results in additional moisture absorption as the relative humidity increases. This moisture absorption will only occur if the relative humidity is maintained at a high level for an extended period of time, and will depend on the vapour permeability of the finish materials and the masonry units. Earth masonry units do, however, have the potential to absorb a large quantity of moisture from the air. With some 100mm thick units, over 150kg of water can be absorbed by the walls in a 4mx4mx2.4m high room as the relative humidity increases from 40% to 90%, while with fired clay bricks this would be less than 2kg. **Is this a misleading example and more typical figures given to illustrate, or should you say when this might happen in a building, eg when bathrooms or kitchens are in use?** The effect of clay content on moisture absorption capacity is shown in Figure 7.

![Figure 7: Effect of clay content on moisture absorption](image)

The strength of the masonry units decreases as the relative humidity increases, but even a relative humidity of 97.5% sustained for an extended period will not decrease strengths below 2N/mm² for all commercially available UK earth masonry units, as shown in Figure 8.
Figure 8: Effect of relative humidity on unit compressive strength

There is, on average, a 17.5% reduction in strength as the long-term relative humidity increases from 65% to 90%. The change in relative humidity from 65% to 90% will also result in wall movement, but this will be less than 1mm for a 2.4m high wall. A reduction in relative humidity from 65% to 40% will result in less than 0.5mm wall movement for a 2.4m high wall.

The thermal performance can be considered similar to that of fired masonry or blockwork, thermal calculations and details for thermal performance should be similar to those materials.

From these tests, and from monitoring movement during mortaring and rendering, it can be concluded that the critical period for both strength decrease and wall movement is during construction, unless the walls are actively wetted (through improper use or inappropriate detailing). The walls will not “turn to a pile of mud” at high humidity levels.
**Work Package 2: Investigation of mortars**

**Objectives**

- Investigate suitable mortars for use with unfired masonry.
- Investigate mechanical fixings as alternative.
- Identify relative significance of masonry characteristics to structural performance (including lateral load resistance, loadbearing capacity).
- Establish masonry properties and specifications for structural design.

**Outcomes**

The majority of the embodied energy in fired bricks comes from the firing process, and an 85% saving in manufacturing energy can be achieved if the bricks are used in an unfired form. In order for this to have a significant effect on energy usage, the unfired bricks will have to move into mainstream markets where thin (100-105mm) wall thicknesses are desirable. In order to achieve this, a significant increase in bond strength is needed.

A number of different mortars were tested with unfired clay bricks, with and without the use of a PVA bonding agent applied to the bed faces of the bricks. Clay and sand mortars used for traditional, thicker, unfired masonry walls were determined to have inadequate bond strength for thin (100mm walls). The use of lignosulphonate additive to a clay:sand mortar and a sodium silicate mortar increased the bond strength to sufficient levels.

The two most promising mortars were investigated further, looking at the effect of different mix percentages, the effect of time and environmental conditions on performance. The interface between the unfired clay bricks and mortars also requires further investigation. The future of unfired clay bricks in thin (100mm) walls appears promising.

Testing was conducted on lignosulphonate mortars and sodium silicate mortars at different concentrations and using different additives. It would appear that although lignosulphonate mortars produce high bond strengths with some brick types at early stages, the bond becomes more variable and weaker with age, such that within one year the bond is below the required level. I don’t think you can quite say that it’s too specific – it depends what the ‘required level’ is, which will vary.

Sodium silicate based mortars bond with all types of unfired clay bricks tested to date, and the bond appears to be proportional to the amount of sodium silicate in the mix. It would appear that bond strength up to 1 year does not deteriorate with time. In order to obtain good early bond strength it is considered that the maximum silicate solution concentration commensurate with acceptable mortar flow should be used.

The full details of these tests are given in Appendix 5. In addition to the results available in Appendix 5, some long term tests (up to 365 days) were performed and demonstrated there is no deterioration in strength during this period (Note: 365 day test results will be available in Mid July and will be included in the final report). Because of a temporary failure of the humidity control system in the storage facility the samples dried out slightly at 90 days.
where the humidity dropped to 45% relative humidity, while the rest of the results are for 60% relative humidity. It was possible to correct the results at 90 days by using the correlation between brick flexural strength and relative humidity, and this is shown in Figure 9, along with the brick flexural strength.

As shown, the slight changes in strength after 56 days can be attributed to variation in test results, and are not considered significant for long term performance.

This graph shows a gradual decline in bond strength over time, can you be clearer why this will not be a problem in the long term – it would worry me

Figure 9: Bond strength development over time

Given the success of the sodium silicate mortars it was concluded that it was not necessary to investigate mechanical fixings, as these were likely to be more expensive to produce and more time consuming to fix than the use of conventional mortar this is a bit overstated – remember the German panels screwed to timber frames, very quick and easy alternative to plasterboard and avoiding all the problems of mortared construction. In some situations dry fixing would be cheaper and easier than mortared masonry. Better to re-write saying something like ‘given the success of sodium silicate mortars and the experience gained in Germany, it was concluded that the research should focus on mortared construction as it is likely to be the key initial market as it requires no new plant for its production, Mechanically fixed dry materials have the potential to be quick and easy to install in some situations, but would require more market and manufacturer development.

Testing of the performance of masonry units to BSEN 1052 was conducted using Ecoterre bricks and 8% sodium silicate mortar. A full report of these tests is made in Appendix 6. The tests conducted on unfired clay brick
masonry walls bonded with sodium silicate mortar clearly show that the mortar is fit for purpose and the walls have sufficient strength to resist typical lateral loads on non-structural walls. The high levels of shrinkage (associated with the moisture necessarily used to make the mortar) create particular problems which need to be allowed for in construction planning. As the majority of this shrinkage occurs during the first day after construction it is not considered a major limitation.
Objectives

- Different block sizes and profiles will be investigated. The costs and benefits of producing the modified profiles must be compared to those of standard bricks.
- Different finishes will be investigated with suitable combinations of blocks and mortars. Recent changes in construction practice (e.g. moving from traditional plasters to plasterboards) will be considered.

Block sizes and profiles

As a result of the success of Work Package 2, with the evident performance enhancement that could be gained from the use of sodium silicate mortars, it was decided not to proceed with the investigation into different block sizes and profiles as these did not appear to be important in the understanding of earth masonry behaviour. Since it had been demonstrated that standard size and profile bricks could be made to perform satisfactorily, this can easily be extended to non standard shapes and sizes which may be chosen for marketing or constructability. A larger unit would require less mortar per unit area (which would reduce costs and time of construction), but because of the high density of the units, a standard blockwork-sized unit (450mmx225mmx100mm) would have a mass of approximately 20kg which could make handling difficult. How does that compare to a conc. block, surely comparable, there are earth blocks that size on the market including uk eg naterra and german ones.

Finishes

Twelve different clays were tested along with various possible additives, to assess the technical potential for developing mass-produced clay plasters. Three of the clays showed excellent potential, with a further five showing good potential if processed further. The key factors are clay type and grading, with a very fine grading required for a finish plaster. Good quality finish coats were produced, which could also be painted if desired. The range in colours for unpainted finishes is illustrated in Figure 10.
An undercoat was straightforward to produce, with fibre added. Various additives were tested. Few significantly improved performance and some reduced it. Starch and seaweed could have potential but would need more specific experimentation.

25% of the samples of dry ground clays currently produced by the industrial partners showed very good potential for use as clay plasters, with the simple addition of fine sand. This is likely to be simple and economic to produce commercially and could be distributed dry-bagged. A further 42% of the clays showed good potential for use, if the clays can be ground finer than the samples received. The results were thought very promising.

The design of a specific commercial product could look to refine mix proportions to suit the individual characteristics of a particular clay, but it should be relatively straightforward to produce a high quality commercial product that would compete well on cost with clay plasters that are currently imported.
Objectives

- Detailing appropriate for unfired masonry
- Marketing of products
- Dissemination

Detailing

Appropriate detailing is necessary to ensure earth masonry buildings perform well over a long time period. Water is the greatest danger to earth masonry and active wetting is required to reduce performance to unacceptable levels. Appropriate detailing can significantly reduce the occurrence of active wetting through accidental events (such as floors being washed or washing machines leaking). As mentioned earlier, the units will perform adequately structurally even at a relative humidity of 97.5% over a sustained period of time. As mechanical wetting cannot be guaranteed against in extreme situations (for example from firefighting), it is not currently recommended that 100mm thick earth masonry walls be used in structural applications.

Because of the wide range of potential uses, a full list of appropriate details cannot be supplied as part of this report, but some main aspects are:

- A short fired brick or blockwork plinth should be used at every floor level to protect against water flooding.
- A longer bearing length should be used for lintels above door and window openings to reduce disperse stresses in the earth masonry.

A comprehensive list of details is presented in Tom Morton’s book (full reference in the publications section), produced by one of the partners during this project. Reproducing those in this document would affect the marketing of the partner and is therefore undesirable. Thank you, but you could include one or two as an advert. If you want to choose them I will email them.

Marketing and dissemination

Marketing and dissemination was undertaken throughout the project by all partners. Some partners, in particular the larger manufacturers have large marketing departments. A major marketing activity is the annual Ecobuild trade fair held annually in Earls court and a number partners funded displays at least once during the project.

During the course of the project a UK Earth Building Association (EBUK) was launched with partners from the project consortium being elected both chair and secretary of the association.

One book, three journal publications and five conference papers were produced and presented during the course of the project, and are summarized in the section below. A generic earth masonry factsheet (Appendix 7) was written for public dissemination. Extensive product literature is also available.
Further publications and dissemination activities are planned.

Publications by partners during the project

Books

Journal papers
Heath, A, Walker, P, Fourie, C and Lawrence, M, 2009, Compressive strength of extruded unfired clay masonry units. *Construction Materials* Accepted for publication: Accepted 21/01/2009


Conference papers and presentations


Factsheets and product literature

Lime Technology Sumatec: [www.limetechnology.co.uk/pages/sumatec.php](http://www.limetechnology.co.uk/pages/sumatec.php)
Conclusions and recommendations

The project was aimed at exploiting the established advantages of unfired clay building materials, including low carbon emissions and passive environmental control, in contemporary construction. Unfired clay masonry can replace fired brick and concrete block masonry in many applications, with significant reductions in the consumption of natural resources, and in waste sent to landfill as the raw materials. These benefits are inherent in the manufacture process, but continue through the whole life cycle. This project was planned to investigate characteristics of unfired clay brick masonry, along with appropriate mortars and finishes, for use in the UK and abroad. The aim of this project was to provide technical solutions that will enable the brick industry to develop commercially viable products from unfired clay, which are more sustainable, cheaper, technically responsive and healthy compared to existing products.

The project has shown that unfired clay bricks combined with innovative mortars will provide performance required of fired clay bricks and concrete blocks in many situations, with some major benefits such as passive environmental control and, most importantly, lower cost and embodied energy. The potential applications where the project might be applied include many internal applications where fired clay bricks, concrete blocks and other construction materials are currently used. All types of projects could benefit from the potential cost savings, all habited buildings could benefit from occupant health benefits, while humidity regulation could have more specific benefits in special situations such as archiving rooms, museums, libraries, certain office environments and bathrooms. Marketing efforts of consortium partners (who between them produce most of the UK’s bricks) and independent proven performance will ensure the project results will be fully exploited.

Although this project has resulted in significant advances in the development of earth masonry, there are a number of areas for further research:

1) Development of UK sourced earth renders, possibly with additives. Currently most earth renders are imported from Germany at considerable cost, and UK brick clays mixed with sand show promise as an alternative to the German materials.

2) Structural use of earth masonry. The 100mm thick walls investigated as part of this research are probably more suited for non-load bearing applications but thicker walls have potential for structural applications if suitably protected from external and internal wetting. The strength of commercially produced earth masonry units is typically higher than for other forms of earth construction (such as rammed earth and cob) which have been used in load-bearing applications.

3) Quantifying and modelling the effect of earth masonry on building environmental performance, especially with regard to buffering of internal humidity.
Appendix 1 - Report on study visit to Germany (20th - 23rd May 2007)

DTI Technology Programme Project
‘Development of unfired clay brick systems for sustainable construction’

Report on study visit to Germany (20th - 23rd May 2007)

Compiled by: Pete Walker, Andrew Heath, Tom Morton, Lex Harrison, Ali Arasteh and Emma Challoner

Background

As part of the first project work package, which includes a review of other countries’ experience with unfired clay, a study visit to Germany was completed. Since its reunification Germany has been leading Western Europe in the manufacture, construction and innovation with unfired clay building products. A wide variety of products are available, including unfired clay bricks, panel (plasterboard) products, mortars, rammed earth materials, plasters and insulation (hemp-clay) products. These materials are produced by a growing number of small and medium size enterprise factories. The aim of the study visit by the project team was to view manufacturing processes, discuss German practise with local experts and view building projects.

The itinerary for the study visit was:

May 20th  Team arrive at Frankfurt airport, travel by car to Reinheim
May 21st  Visit the Ziegelwerk Grün factory in Reinheim to view and discuss manufacturing of unfired clay blocks and panels. Travel to Weimar.
May 22nd Meet Dr Horst Schroeder and Stephan Jörchel of Bauhaus University. Travel to Kassel.
May 23rd Meet Prof. Gernot Minke, Kassel University. Return to UK.

Study team members:

Ali Arasteh  Brick Development Association
Emma Challoner  Errol Brick Co.
Lex Harrison  Ibstock Brick
Andrew Heath  University of Bath
Tom Morton  arc Architects
Pete Walker  University of Bath

Apologies were received from Ian Pritchett (Lime Technology) and Ian Walker (Hanson). Abdelfattah Abbaker was unable to travel due to delays in receiving a travel Visa from the German embassy in London. Comments in this report have been compiled from notes and contributions from all study team members.
1. Visit to Ziegelwerk Grün, Reinheim

The study team was met by Stephan Jörchel (Bauhaus University/ Dachverband Lehm e.v.) who acted as an interpreter. The team met with Philipp Liebig, the owner of Ziegelwerk Grün.

- Fired clay units were produced in the factory until some six years ago, when the entire production was changed to unfired units. The factory now employs just one worker at present! There has been little investment required in new plant for the change to unfired clay production (some new dies for the extrusion process).

- Present production is around 5000 tonnes/year, making it a medium-sized producer of unfired clay materials in the German market (Claytec are the largest).

- Product includes ‘perforated bricks’ (figure 1), clay panels (25mm thick by 240 mm wide by 600mm long) (figure 2), hemp-clay mix (figure 3), clay mortars and plasters.

Figure 1. Ziegelwerk Grün perforated unfired clay block
The clay panels are mechanically fixed (screwed) onto vertical timber studs and a hemp shiv + clay binder mix infill is placed between the skins of the wall (figure 2). The clay panels can have heating water pipes readily embedded in them in order to provide ‘warm walls’ (figure 3).
4). The cost of the clay panels is around three times that of gypsum plasterboard. The clay boards are finished with clay plasters (figure 5), requiring different skills from that using gypsum plasters. The speed of construction seemed much faster using clay board than masonry.

Figure 4. Water pipes inside clay panels

Figure 5. Clay plasters over panels and pipes
• Production control for the product was considered low compared with typical practice in fired clay brick production in the UK. No real production was seen but it appeared that a lot of rule of thumb and feel factors were applied to the production.

• Drying/curing is achieved in open sided outdoor huts, minimising energy. Since the factory has switched entirely to unfired clay products, there is no kiln exhaust heat for this process. The clay products are extruded at around 25% m.c. and are packaged at around 2~5% following drying. Drying times vary with weather conditions.

• Clay products from this factory were not intended for load bearing masonry construction, but used compositely as infill with timber framed buildings (traditional practice in Germany). Blocks and bricks are placed between studs (around 600 mm centres or closer) rather than as a skin tied into a stud wall (as used in recent projects in the UK).

• Though solid clay bricks were produced, they are not used as intended or proposed in the UK.

• Straw, straw dust and other plant based material were added to the clay materials to reduce density and drying shrinkage and improve mechanical resistance.

• Following drying product was stacked on palettes, shrunk wrapped in plastic and stacked outdoors otherwise unprotected (figure 6).

Figure 6. Outdoor storage of unfired clay blocks
2. Meeting with Dr. Horst Schroeder and Stephan Jörchel (Bauhaus University/Dachverband Lehm eV)

Dr. Horst Schroeder and Stephan Jörchel both work at the Bauhaus University in Weimar and work for the Dachverband Lehm eV (the German earth building association). The Dachverband Lehm eV has played a key role in promoting earth building in Germany in recent years, offering approved training courses and publishing a German earth building standard.

- Dr Schroeder in turn described his work and activities within the University and the Dachverband Lehm eV.

- Current German market for earth masonry products is €50M p/yr growing 10% p/yr. Growth areas are rammed earth and earth plasters. Health benefits are the main attractions. It represents 1% (approx) of concrete and fired clay projects value. Much interest from Europe but also Emirates and S Korea.

- There are some 2.5 – 3 million structures, mainly houses, in Germany where some form of earth construction has been used.

- The first draft of the unfired clay 'standard', Lehmbau Reglen (LR), was accepted by the Supreme State Building Authority (SSBA) in 1999 and was recommended to the Federal Building Standards (FBS) for implementation; to date 13 of 16 federal states have accepted this. In Germany at least two options are available for producing a standard: DIN and Federal Building Standards (FBS, 16 in the country). LR covers the design and construction of earth masonry – as a nationally excepted regional code; it has as much authority as a DIN code.

- The third revision of the standard is now ready and has been submitted to the SSBA for approval.

- Having a standard has been key to clients gaining insurance and financing (mortgages).

- It is expected that in time this will turn into a European Standard. However, there are currently too many formal lines and requirements for the LR to become a Euro code. The way forward has been identified but resources do not allow this at present. Italy, Switzerland, Portugal & Spain, as well as the UK, all very interested in creating a standard.

- The present Standard is based on now withdrawn DIN standards. DIN Standards on earth masonry were withdrawn through lack of interest in ‘traditional’ construction and the advent of new construction materials after WWII.
• Not all earth product/masonry producers support the Standard; some prefer not to have one in order to allow themselves greater flexibility!

• Some discussions pursued regarding the European Standards: The present document, although a standard, is considered a low level document. It will be extremely difficult to turn this kind of document into a European Standard (CEN Standard).

• There are numerous issues concerning CEN standardization not least of which is the CE marking. With such a variation in material properties associated with ‘earth’ masonry and unfired clay products it is difficult to see how a pan European status of free trade can be achieved. It is quite likely that Earth masonry remains a national product.

• Dachverband Lehm intends to achieve a professional status for earth masonry by way of a specialist State Degree for Earth Building e.g. completion of a 120-hour course allows the attendants to call themselves Earth Builders.

• The issue of fire resistance was discussed and apparently fire tests of 250mm thick walls achieve 90 minutes resistance. This needs to be properly investigated e.g. unfired clay masonry response to high heat in respect of possible material change to vitreous and heat induced deflection when the unfired material undergoes a drying process.

• Pete Walker described the current research work at the University of Bath for the benefit of Dr Schroeder: Unlike the German/European large format units UK work on unfired clay is on 220mm x 105mm x 70mm units. At present mortar seems to be an issue; bond strengths of 0.02 to 0.03 N/mm² are insignificant in engineering terms. Dr Schroeder has no experience of use of bio polymers in mortars and he thinks use of such materials will diminish the natural cleanliness associated with earth masonry. Geogrids (perforated or woven polymer sheets) can be used to provide reinforcement.

• Consideration needs to be made as to whether earth building should be:
  
  A. Small groups of users e.g., cob builders, earth ships, etc. (Based on vernacular tradition)
  
  B. Large scale industrial manufacture for the wider construction industry

• Individual projects vary so an engineer or architect must justify a design where no codes exist by using precedents and testing – possibly doing testing where appropriate.

• Fachkraft Lembau – new development to produce a course & qualifications in earth building. (German trades people must be
qualified by the Chambers of Trade, e.g. bricklayers must be qualified). Future plans are to provide courses in English.

- Domestic flooding – structural walls can be detailed to channel water away.
- Possibility of developing a UK Earth Building Federation?

3. Meeting with Prof. Gernot Minke (University of Kassel)

- Visited Gernot Minke’s own house consisting of four unfired brick domes covered with earth and green roofs (figures 7-8). Entirely build with earth masonry, except the foundations, with some remarkable dome structures.

![Gernot Minke’s domed unfired clay brick house (interior)](image_url)

Figure 7 Gernot Minke’s domed unfired clay brick house (interior)
• Visited labs – 25+ years worth of experiments including structural analysis of earth building forms, metal parabolic arch building templates, structural models, earth building products and various test equipment for pull apart tests, material analysis and abrasion tests (Figures 9-11).

Figure 8 Gernot Minke’s house (exterior)

Figure 9 Models of clay domed houses
• Visited live project area with various test structures and outdoor ‘earth building school’. Various structural forms were seen including domes, Nubian Arches and a straw bale house (figures 12-16).
Figure 12. Unfired clay brick dome building protected with bonded FRP sheets

Figure 13. Test structure
Figure 14. Experimental structure

Don’t show this – it looks very dodgy, why not choose another one from my book of a more sexy or normal building
4. Further comments from team members:

Ali Arasteh:

- All in the entire trip was well worth it. It brought to light the way the Germans consider use of ‘new’ materials which is quite different to the UK approach. They seem to be more willing in trying new techniques and experimenting with new materials. However even in Germany the production and use of earth masonry products seemed to be on an ad hoc basis; for example the reluctance of some manufacturers to support the Lehmbau Reglen is indicative of lack of interest in standardising the approach.

- The approach in the UK should be on a more technical rather than purely architectural and environmental basis in order to provide a reasonable chance of commercial success for earth masonry. Unless the vast benefits of earth building are highlighted through well planned advertising campaigns and well structured educational packages I just cannot see a major developer opting for this in favour of what he is used to.

Emma Challoner:

- Waterproofing is/will be a major question from clients

- The need to come up with a suitable clay plaster is important

- The word is natural so why use plastic mesh? Isn't the Hessian enough?

- I personally do feel that the campaign to use earth materials needs to start at the colleges and universities and I don't mean a brief talk and information sheet on the subject. The government needs to give incentives such as VAT relief.

Lex Harrison:

- I was surprised at how different the German approach to contemporary earth building is compared to the UK. The main German market seems to be following vernacular tradition rather than developing unfired clay as contemporary ecological building material.

- For the UK market to thrive, earth building will need to be adapted to mainstream construction practice e.g. single-skin walls. Earth building schemes using thick walls and/or vernacular techniques are few and far between and do not adapt easily to standard construction practice. Such schemes will not generate a sufficient market to encourage large scale manufacturers to produce the products required.
• Development of a UK standard is essential as few designers seem willing to take the risk associated with ‘unproven technology’

Tom Morton:

• It was useful to see the small-scale mass producer of earth masonry products and the buildings of Minke. It would have been good to see the large Claytec factory and more buildings, but this was not absolutely necessary to the project. The Claytec factory would have given a clearer impression of the industrial potential of the material, in terms of scale of production and sophistication of product, however, and been a better model for Ibstock and the BDA. Other buildings might have been less idiosyncratic than Minke's house and given a better illustration of applications in everyday construction.

• What was critical was that we met with the two people who have the greatest knowledge about the development of the sector and technical research in Germany.

• It was useful to confirm that the technical problems we have been addressing of bond strength in thin walls, has not been addressed already in Germany.

• It was clear through our discussions, that the German situation, although informative, is quite different in two important respects:

  a) The German use has grown from the conservation and adaptation of a much greater surviving stock of earth buildings, ~3m. In the UK the surviving earth heritage is smaller and less well recognized and it only survives as a living tradition on one small area, the southwest. Consequentially, the German approach is founded on a gradual development of traditional methods, knowledge and skills for new uses, whereas in the UK there is more of a clean slate from which to develop a contemporary approach to the use of the same materials in construction.

  b) The German construction industry is much more highly regulated in terms of trades and training and in order to gain acceptance the Dachverband has developed training for earth building as a recognized trade. This inevitably tends to promote earth building as a craft requiring specialist knowledge in the use of generic materials, whereas in the UK the recognized lack of specialist skills and unregulated construction industry mean that it is more appropriate to develop products rather than people, products that can be used by non-specialist labour, without specialist tools.

• These differences mean that the building culture and construction industry in which earth construction has developed in Germany is not
an exact model for development in the UK, though it is important in high-
lighting the issues and potential. The UK suits a more free approach, focusing on more rapid development of products for the mass market, products that can be used flexibly with a variety of different building systems and methods of procurement. In this way products can be introduced that do not depend on specialist skills, which are not available. The exception is clay plastering, where the need for specialist training on a small scale cannot be avoided.

- There is potential to arrange an English language version of the Dachverband's training course for people already involved in earth construction in the UK. Funding would need to be found for translation, etc. Around 16 would be needed. This would be for specialists who could spread high quality work developing the market through showcase projects. Perhaps more pressing is the need to develop training in clay plastering in the UK, though this would require a demonstrable market.

- The Dachverband see the merit of a European wide earth construction standard, as there are currently several nations trying to develop their own standards independently and the German standard has been translated into several languages, though they think the time is not yet right. A standard would require considerable work, including extensive testing and the potential to collaborate on this, with European funding, was discussed. Minke might also collaborate.

- The Dachverband stressed the need to create a national association in the UK to coordinate development of the sector, represent the industry to government and develop collaboration with national associations from other countries. This was discussed in the group.

Pete Walker:

- Visit to the Ziegelwerk Grun factory was very informative to see how easily a fired clay producer can adapt to manufacture of unfired product with little investment.

- The visit confirmed the differences in approach between Germany and UK construction. The technical challenge the DTi project is tackling has not been answered in German practice. No easy answers!

- For future development of earth building in the UK establishment of a national trade association for earth building is essential. The Dachverband Lehm eV has been essential to development of earth building in Germany and production of the earth building standards, which have supported this development through training, regulations and financial aspects.

- Manufacture of clay panel boards and clay plasters in the UK would seem to have considerable potential.
There are clear cultural and structural differences between the German and UK construction industries. It seems apparent that the renewed craft tradition in earth building has greatly assisted the growth of the material in Germany. Without this tradition, development of earth building in the UK will be different.

22 June 2007
Confidential

Report on the testing of unfired clay bricks

for

Technology Strategy Board
Project TP/5/SUS/6/I/H0192J

by

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Prof. Pete Walker
Abdelfattah Abbaker
Dr Mike Lawrence

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Department of Architecture & Civil Engineering
University of Bath
Bath
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January 2008
1. Introduction

This report presents experimental results from the testing of unfired clay bricks manufactured and supplied by the industrial partners for the Technology Strategy Board (TSB) project TP/5/SUS/6/1/H0192J - Development of unfired clay brick systems for sustainable construction.

The industrial partners on the project are:
- Brick Development Association
- Ibstock Brick Limited
- Hanson Building Products
- Lime Technologies Limited
- ARC-Architects
- The Errol Brick Company Limited

1.1 Scope

Because some of the industrial partners are competitors and between them retain the majority of the brick manufacturing market in the UK, all bricks have been identified through a number rather than a source or manufacturer.

The test results provided in this report relate only to unfired brick properties, and do not include walling systems (mortars, renders, fixing etc). These will be described in subsequent reports.

All unfired bricks were produced by commercial brick manufacturing plants and were either extruded or moulded and dried either naturally or artificially to less than 3% moisture content without firing.

As only a nominal number of bricks were supplied from certain sources, comprehensive testing was only performed on some bricks. In all, 18 different brick types were provided. At the time of testing, two different bricks were commercially available as unfired bricks, the Ecobrick from the Errol Brick Company and the Ecoterre produced by Ibstock. Both are shown in Figure 1.1.
Figure 1.1: Errol Ecobrick (top) and Ibstock Ecoterre (bottom)

2. Source material properties

The source materials were evaluated in terms of their Atterberg limits, particle size distributions and chemical properties, tested according to BS EN 1377-2:1990 and BS EN 1377-3:1990. The Atterberg limits are summarised in Table 2.1 and Figure 2.1.
Table 2.1: Atterberg limits

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<th>Unit Code</th>
<th>Liquid limit (%)</th>
<th>Plastic limit (%)</th>
<th>Plasticity index (%)</th>
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<th>Linear shrinkage (%)</th>
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Figure 2.1: Plasticity chart

As shown above, the majority of the materials used in the manufacture of the units can be defined as low plasticity clays, although there are some intermediate plasticity clays present. None were considered high, very high or extremely high plasticity and none were defined as silts. The Atterberg limits provide information on how the materials will behave and do not necessarily provide information on the particle size distribution which is summarised in Table 2.2 and Figure 2.2.
Table 2.2: Particle size distribution

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<tr>
<th>Unit Code</th>
<th>Clay (%) &lt;0.002mm</th>
<th>Silt (%) 0.002-0.6mm</th>
<th>Sand (%) 0.6-2.0mm</th>
<th>Fine gravel (%) 2mm-6mm</th>
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Figure 2.2: Particle size distribution

As shown above, although the Atterberg limits indicate the materials will behave as clays, the majority have more silt than clay sized particles with averages of approximately 30% clay, 40% silt and the remaining 30% sand and fine gravel.

The results of chemical testing are presented in Table 2.2
Table 2.2: Chemical test results

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<th>Unit code</th>
<th>Organic content (%)</th>
<th>pH</th>
<th>Acid soluble SO4 (%)</th>
<th>Water soluble SO4 (g/l)</th>
<th>Water soluble chloride (mg/l)</th>
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Key: DNT – Did not test, U/S unable to sample

As shown, there is a large variation in organic content, but the other chemical properties are fairly consistent with low sulphate and chloride contents.

The variation in organic content is a cause for concern as those with higher organic contents may be considered combustible and may require fire testing.

3. Dimensions, mass and density

Block dimensions were determined according to BS EN 772-16:2000 – ‘Methods of test for masonry units – Determination of dimensions’. The mean and standard deviation of the gross dimensions are provided in Table 3.1 (any holes or frogs are not included in the table as they will assist in identifying individual sources). The results are from measuring six different units. The bricks were stored at a controlled 20°C and 60% RH for at least three weeks before measuring.
Table 3.1 : Unit dimensions

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<td>1.24</td>
<td>0.60</td>
</tr>
<tr>
<td>2</td>
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<td>224.1</td>
<td>107.2</td>
<td>66.5</td>
<td>0.12</td>
<td>0.08</td>
<td>0.17</td>
</tr>
<tr>
<td>3</td>
<td>Extruded</td>
<td>222.7</td>
<td>105.6</td>
<td>67.5</td>
<td>0.14</td>
<td>0.22</td>
<td>0.48</td>
</tr>
<tr>
<td>4</td>
<td>Extruded</td>
<td>223.6</td>
<td>107.0</td>
<td>67.3</td>
<td>0.13</td>
<td>0.05</td>
<td>0.10</td>
</tr>
<tr>
<td>5</td>
<td>Moulded</td>
<td>220.0</td>
<td>103.0</td>
<td>63.0</td>
<td>0.62</td>
<td>0.05</td>
<td>1.06</td>
</tr>
<tr>
<td>6</td>
<td>Extruded</td>
<td>227.4</td>
<td>106.9</td>
<td>67.8</td>
<td>0.00</td>
<td>0.23</td>
<td>0.05</td>
</tr>
<tr>
<td>7</td>
<td>Moulded</td>
<td>214.2</td>
<td>101.7</td>
<td>62.9</td>
<td>0.17</td>
<td>0.32</td>
<td>0.31</td>
</tr>
<tr>
<td>8</td>
<td>Extruded</td>
<td>225.0</td>
<td>107.0</td>
<td>75.8</td>
<td>0.21</td>
<td>0.05</td>
<td>0.13</td>
</tr>
<tr>
<td>9</td>
<td>Moulded</td>
<td>215.8</td>
<td>101.6</td>
<td>62.9</td>
<td>0.51</td>
<td>0.33</td>
<td>0.47</td>
</tr>
<tr>
<td>10</td>
<td>Moulded</td>
<td>220.9</td>
<td>105.8</td>
<td>66.3</td>
<td>0.77</td>
<td>0.23</td>
<td>0.66</td>
</tr>
<tr>
<td>11</td>
<td>Extruded</td>
<td>226.5</td>
<td>106.8</td>
<td>66.2</td>
<td>1.30</td>
<td>0.42</td>
<td>0.16</td>
</tr>
<tr>
<td>12</td>
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<td>222.8</td>
<td>105.6</td>
<td>66.9</td>
<td>0.23</td>
<td>0.21</td>
<td>0.88</td>
</tr>
<tr>
<td>13</td>
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<td>225.2</td>
<td>107.6</td>
<td>67.0</td>
<td>0.27</td>
<td>0.15</td>
<td>0.71</td>
</tr>
<tr>
<td>14</td>
<td>Extruded</td>
<td>222.6</td>
<td>105.2</td>
<td>65.9</td>
<td>0.49</td>
<td>0.45</td>
<td>0.25</td>
</tr>
<tr>
<td>15</td>
<td>Extruded</td>
<td>218.8</td>
<td>105.1</td>
<td>66.5</td>
<td>0.37</td>
<td>0.28</td>
<td>0.93</td>
</tr>
<tr>
<td>16</td>
<td>Extruded</td>
<td>215.4</td>
<td>103.4</td>
<td>64.4</td>
<td>0.29</td>
<td>1.15</td>
<td>0.51</td>
</tr>
<tr>
<td>17</td>
<td>Extruded</td>
<td>227.0</td>
<td>108.2</td>
<td>68.6</td>
<td>0.29</td>
<td>0.18</td>
<td>0.36</td>
</tr>
<tr>
<td>18</td>
<td>Extruded</td>
<td>227.9</td>
<td>108.4</td>
<td>67.8</td>
<td>0.08</td>
<td>0.12</td>
<td>0.15</td>
</tr>
</tbody>
</table>

As illustrated, there is considerable variation in unfired unit sizes which illustrates the different shrinkage expected during firing. Although it is not always true, the moulded units are generally smaller than the extruded units, but the variability in size of the extruded units from a particular source is slightly lower. The variability in size is less than would be expected from the equivalent fired units as there is no distortion from firing.

The average mass of the units, water content and density after storing at 20°C and 60% RH are presented in Table 3.2. The net density was calculated after subtraction of the volume of voids which were measured according to BS EN 772-16:2000.
### Table 3.2: Unit mass, ambient moisture content and densities

<table>
<thead>
<tr>
<th>Unit code</th>
<th>Mass at ambient moisture content (kg)</th>
<th>Ambient moisture content (%)</th>
<th>Gross bulk density (kg/m³)</th>
<th>Net bulk density (kg/m³)</th>
<th>Net dry density (kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.88</td>
<td>1.68</td>
<td>1933</td>
<td>1933</td>
<td>1902</td>
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<td>2</td>
<td>2.77</td>
<td>1.87</td>
<td>1737</td>
<td>2149</td>
<td>2109</td>
</tr>
<tr>
<td>3</td>
<td>2.53</td>
<td>1.79</td>
<td>1595</td>
<td>2008</td>
<td>1972</td>
</tr>
<tr>
<td>4</td>
<td>2.48</td>
<td>1.83</td>
<td>1539</td>
<td>1978</td>
<td>1943</td>
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<tr>
<td>5</td>
<td>2.28</td>
<td>2.39</td>
<td>1598</td>
<td>1738</td>
<td>1698</td>
</tr>
<tr>
<td>6</td>
<td>2.68</td>
<td>1.81</td>
<td>1629</td>
<td>2027</td>
<td>1991</td>
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<tr>
<td>7</td>
<td>2.22</td>
<td>1.29</td>
<td>1620</td>
<td>1796</td>
<td>1774</td>
</tr>
<tr>
<td>8</td>
<td>2.78</td>
<td>2.04</td>
<td>1523</td>
<td>1968</td>
<td>1928</td>
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<tr>
<td>9</td>
<td>2.26</td>
<td>1.72</td>
<td>1638</td>
<td>1816</td>
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<td>11</td>
<td>3.09</td>
<td>1.64</td>
<td>1932</td>
<td>2055</td>
<td>2021</td>
</tr>
<tr>
<td>12</td>
<td>2.03</td>
<td>2.09</td>
<td>1290</td>
<td>1631</td>
<td>1597</td>
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<tr>
<td>13</td>
<td>2.64</td>
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<td>3.57</td>
<td>2.77</td>
<td>2135</td>
<td>2135</td>
<td>2077</td>
</tr>
</tbody>
</table>

As expected, there is considerable variation in the mass of the units (from just over 2kg to just over 3.5kg), largely due to the presence of holes and frogs. The ambient moisture content varies from approximately 1.3% to 2.8%, and this appears to be best related to the linear shrinkage of the material where soils with a low linear shrinkage have a low ambient moisture content, as illustrated in Figure 3.1. This is most likely related to clay mineralogy.

![Figure 3.1: Relationship between linear shrinkage and ambient moisture content](image)

Figure 3.1: Relationship between linear shrinkage and ambient moisture content
The net density shows considerable variation (dry density between approximately 1600 kg/m$^3$ and 2100 kg/m$^3$), but as some bricks have added organic material, this is not unexpected. There is no significant difference in the density between the extruded and moulded units, and no significant effect of source material properties on density.

4 Compressive strength

The compressive strength of the blocks was determined following, as much as possible, the provisions of BS EN 772-1:2000 ‘Methods of test for masonry units. Determination of compressive strength’. The uni-axial compressive strength (maximum load divided by cross-sectional area) is geometrically corrected to provide a normalised compressive strength value. For bricks with dimensions in the order of those presented here, this requires the measured compressive strength to be multiplied by approximately 0.85 to get the normalised value. This is similar to the value used for platen restrained earth blocks in earth design codes in New Zealand and Australia and is considered appropriate for initial evaluation of brick compressive strengths. This was used for both the net and gross compressive strengths, although the net compressive strength will, in reality, be influenced by the geometry of any voids.

The blocks were tested at varying, pre-prepared, moisture contents, varying between oven dry (dried at 105°C and cooled) to 2% above the ambient moisture content. The blocks were not capped as this would influence the moisture content (and therefore compressive strength) of the units. Instead, the bricks were placed between plywood platens and loaded. This is considered appropriate for these units as there is no warping from firing and the units have a far lower stiffness than fired units. Although not an ideal method for the reasons mentioned above, the frogged units had to be capped on the frogged side with dental plaster which was allowed to dry for 3 weeks before testing.

The units were not soaked before testing as they would disintegrate. The test results for compressive strength at ambient moisture content are outlined in Table 4.1 below.
Table 4.1: Compressive strength at ambient moisture content

<table>
<thead>
<tr>
<th>Unit code</th>
<th>Compressive strength not corrected for dimensions</th>
<th>Compressive strength corrected for dimensions</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Gross (N/mm²)</td>
<td>Net (N/mm²)</td>
</tr>
<tr>
<td>1</td>
<td>3.57</td>
<td>3.57</td>
</tr>
<tr>
<td>2</td>
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<td>4</td>
<td>1.97</td>
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<tr>
<td>18</td>
<td>6.16</td>
<td>6.16</td>
</tr>
</tbody>
</table>

The net compressive strengths provide information on the strength of the actual material, although because of different perforation patterns and densities, it is difficult to draw definitive comparisons between strength and material properties. While there appears to be no relationship between strength, density and quantity of perforations, there is an general relationship with increasing net strength with increasing clay content, within the range of materials tested as illustrated in Figure 4.1.

![Figure 4.1: Relationship between clay content and net compressive strength (corrected for dimensions) at ambient moisture content](image-url)
For this figure, Unit 18 was not included with the rest of the data as the strength far exceeds that of the other units and does not fit the general trend illustrated. This unit may have been treated with a stabiliser such as lignosulphonate during the manufacturing process which is intended to provide increased “green” strength before firing. This practice is widespread in the brick manufacturing industry and the lignosulphonate usually burns off during firing.

The effect of moisture content on the compressive strength of selected unfired bricks is illustrated in Figure 4.2 for eight of the units which were subjected to comprehensive testing. The graph also contains logarithmic best-fit curves for all the data.

![Figure 4.2: Relationships between moisture content and net compressive strength (corrected for dimensions)](image)

This graph shows that all the bricks lose strength as the moisture content increases, but the value of the strength varies considerably in the mid-range of moisture contents (between 1.5% and 3% moisture content - most likely to be found inside inhabited buildings). The decrease in strength with increase in moisture content is fairly similar for the different bricks in this mid-range, with the exception of Unit 12 which shows a smaller decrease in strength than the other units. This unit has the lowest density of all those tested by a considerable margin, and this may be the reason for the lower moisture sensitivity, although this is difficult to confirm from the available data.

5 Moisture driven expansion and contraction

The expansion and contraction of the units under changes in moisture conditions was examined for a number of different units. The units were subjected to a nominal 2% increase in moisture content above the ambient moisture content and sealed in a polythene bag at this moisture content for 3 days to ensure equilibrium, and then allowed to dry under conditions of 20°C and 60% RH. The initial expansion after wetting was measured and then the contraction under drying was measured over a
period of three weeks at which point most had returned to their original conditions. The expansion was only measured in the longitudinal (length) direction, as illustrated in Figure 5.1.

In addition to the standard bricks, Unit 18 (extruded solid) had ten 25mm diameter holes drilled through it to determine whether perforations reduced shrinkage. The results for Unit 18 as a solid or with perforations are illustrated in Figures 5.2 and 5.3 below. These are typical of the results for the other bricks.
Figure 5.2: Effect of moisture content on expansion and contraction

As shown, the relationship between moisture content and length change is largely linear within the range tested. The samples do not fully recover at the end of the three week period although they appear to have achieved a steady state condition and any further contraction is likely to be very slow. The change in length and change in moisture content for the different units is summarised in Table 5.1 below.
Table 5.1: Change in length with change in moisture content

<table>
<thead>
<tr>
<th>Unit code</th>
<th>Length change (%) / moisture content change(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
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</tr>
<tr>
<td>3</td>
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</tr>
<tr>
<td>4</td>
<td>0.043</td>
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</tr>
<tr>
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<td>0.077</td>
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<tr>
<td>7</td>
<td>0.032</td>
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<tr>
<td>8</td>
<td>0.058</td>
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<td>DNT</td>
</tr>
<tr>
<td>11</td>
<td>0.043</td>
</tr>
<tr>
<td>12</td>
<td>0.038</td>
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<tr>
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</tr>
<tr>
<td>14</td>
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<tr>
<td>15</td>
<td>0.081</td>
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<tr>
<td>18</td>
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</tr>
</tbody>
</table>

Key: DNT = Did not test

As with many other properties, there is considerable variation in shrinkage with changes in moisture content. There is, however, a general trend where decreasing the net density of the material results in decreased shrinkage, as illustrated in Figure 5.4. This indicates shrinkage problems may be overcome by producing a less dense unit.

![Figure 5.4: Relationship between shrinkage and net dry density](image-url)
6 Conclusions and recommendations

Extensive testing was performed on unfired bricks from commercial brick plants. This section presents conclusions and recommendations relating to this testing. These recommendations relate only to the brick properties and do not consider mortars, renders or other ancillary components.

The majority of these materials have engineering properties of low plasticity clays, but those with slightly higher plasticity do not appear to have any different performance characteristics. Materials with a higher linear shrinkage generally have a higher ambient moisture content, but this is mainly of academic rather than practical interest and is most likely related to clay mineralogy.

Although they behave as clays, silt sized particles dominate with only 20-40% clay sized. Units with a higher clay content do, however, appear to have higher compressive strength without detrimentally affecting performance in other areas. It is recommended that materials with a clay content of 25%-40% be used for unfired bricks.

Chemical tests showed organic contents of up to 2.7% which could be a cause for concern when considering fire resistance. It is recommended that further research on the influence of organic content on fire resistance be conducted, but this is beyond the scope of this research project.

All bricks showed a strength decrease with increases in moisture content, but although it is difficult to draw definitive relationships, the strength decrease was lowest for the least dense unit. There was, however, a more marked relationship between density and shrinkage where a lower density resulted in reduced shrinkage and expansion under changes in moisture content. The presence of perforations appeared to have no effect on shrinkage performance. It is recommended that the density of units be reduced to reduce expansion/contraction from changes in moisture content, provided this has no effect on other performance parameters. This could be achieved through the addition of wood or straw fibres or sawdust, as common in Germany.

Further research into mortars, renders and ancillary building components is required to fully develop unfired brick building systems.
Appendix 3 - Effect of environmental conditions on performance

Confidential

Effect of environmental conditions on performance

for

Technology Strategy Board
Project TP/5/SUS/6/I/H0192J

by

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April 2009
Introduction

Earth masonry has the ability to absorb moisture from the air at high relative humidity and release it at low relative humidity. There is considerable empirical evidence that the use of earth masonry regulates both temperature (through thermal mass) and humidity (through breathable wall construction and moisture buffering) which should lead to reduced energy demand when compared to existing highly processed materials (for example concrete blockwork and gypsum plasterboard). Because of a lack of research into this topic, the reduced energy demand has never been effectively quantified and designers have been forced to operate on a mainly empirical basis when including these materials in construction. Neither the brick properties that influence this behaviour, nor the effect of this behaviour on other aspects of performance (especially structural performance and shrinkage / swelling) have been quantified.

Previous studies

While some empirical studies have involved humidity measurements in earth buildings which have demonstrated but not quantified the ability to control humidity (e.g. Morton et al. 2005, Morton 2006, Minke 2006), others have provided rather unhelpful statements which demonstrate the fundamental lack of understanding of performance: “Regarding the balance of the indoor air humidity, the inhabitants confirmed an observation, which is mentioned very often in connection with unfired loam constructions: due to the excellent sorption ability of the unfired loam, the mirror in the bathroom does not steam up, even after a long hot shower.” (Kunze and Macho, 2007).

While there have been attempts to quantify moisture buffering provided by earth masonry, this has generally been for museum archives and similar applications (Padfield, 1998; Padfield and Larsen, 2004), and in these cases have been to determine whether or not mechanical humidity control is required. These specific applications have a low number of air exchanges, and a constant humidity is required. Padfield (1998) did investigate a number of materials, and earthen materials provided the most promise as a moisture buffering material in building construction.

In addition to potentially limiting ventilation demand, humidity buffering has potential to improve occupant health by limiting humidity variability, as demonstrated by the following statement: “The incidence of absenteeism or respiratory infections was found to be lower among people working or living in environments with mid-range versus low or high relative humidities.” (Arundel et. al. 1986). Based on data from the International Study of Asthma and Allergies in Childhood, researchers concluded that high average indoor humidity and a low minimum indoor humidity (low humidity buffering capacity) resulted in increased asthma symptoms (Weiland et al, 2004). As the UK has the highest incidence of asthma in Western Europe, any reduction in asthma through appropriate use of building materials would have a significant economic benefit.
Scope and objectives

Quantifying the effect of earth masonry on occupant health and quantifying the reduced energy demand from earth masonry is beyond the scope of this project report and is an aspect requiring further investigation.

This report is concerned with quantifying the effect of changes in relative humidity on brick moisture content (and therefore the ability of earth masonry to absorb moisture from the air). This can also be used to calculate the effect of changes in humidity on brick strength and movement likely from changes in humidity. There is a perception amongst some in the construction industry that at high humidity levels earth masonry will “turn into a pile of mud” and one intention is to disprove this.

The thermal properties of the masonry units will also be investigated.

Hygrothermal testing

A number of masonry units supplied were tested according to BS EN 112571:2000 (Hygrothermal performance of building materials and products - Determination of hygroscopic sorption properties). This involved measuring the moisture contents of samples of masonry units at different relative humidity levels. For the testing performed, the relative humidity was increased from 0% (oven dry state) to 100%, and down again to 0%. Testing was at a temperature of 23°C according to the standard. As the full range of humidity is unlikely to be achieved in practice, only values above 30% RH are presented and were used in fitting to a model.

The model used in this case was that originally proposed by Hansen (1986) which although it has some shortcomings, is a simple model which represents behaviour across the range of interest. Although there is hysteresis in the wetting and drying during testing, this was ignored and a bit-fit to the Hansen equation is used for comparative purposes. The results of the testing are summarized in Figure 1 below.

As shown, the earth masonry units have the ability to absorb significantly more moisture from the air than the blockwork or fired masonry units.
Figure 1: Isotherms for different units at 23°C

Figure 2: Effect of clay content on moisture absorption

As shown in Figure 2, an increasing clay content results in additional moisture absorption as the relative humidity increases from 40% to 90%. Heath et al. (2008) showed that the clay content was also the most important parameter in determining brick strength. The water contents at 100% relative humidity are significantly below those used in the production of the units (typically over 15%).
In a room that is 4mx4mx2.4m high, the maximum amount of moisture in the air will be approximately 768g (about 20g/m³ of water vapour in the air at 23°C). If 100mm thick earth masonry walls surround the room, these walls will be able to absorb 76.8kg (100 times the available moisture) for every 1% of moisture absorption (assuming the density of the masonry units is 2000kg/m³). Therefore with some 100mm thick units, over 150kg of water can be absorbed by the walls in a 4mx4mx2.4m high room as the relative humidity increases from 40% to 90%, while with fired clay bricks this would be less than 2kg.

In reality there will be a steady supply of available moisture from occupants, air leakage / ventilation and other activities (e.g. cooking), but this demonstrates why earth masonry is so effective in buffering humidity in buildings. This moisture absorption will only occur if the relative humidity is maintained at a high level for an extended period of time, and will depend on the vapour permeability of the finish materials and the masonry units.

**Effect on strength**

The effect of changes in humidity on strength can be seen in Figure 3 below. This was determined using the isotherms from Figure 1 in this document and the strength / moisture content relations for the same units (Heath *et al.*, 2008). The percentage strength change under specified humidity changes are illustrated in Figure 4 below. It should be noted that long term monitoring of an earth brick house by Morton *et al.* (2005) revealed the long-term (20 day average) relative humidity remained between 40% and 65% throughout the year. The 20 day average is fairly important as this is approximately the time required for the units to achieve equilibrium moisture after a change in relative humidity.

![Figure 3: Effect of relative humidity changes on compressive strength](image-url)
As shown, the decrease in strength as the relative humidity moves from 65% to 90% over a sustained period is on average 17.5%, while the corresponding strength increase when the relative humidity decreases from 65% to 40% is about 9%. All the bricks retained some degree of strength at relative humidity levels up to 97.5%, with all commercially available UK unfired bricks having strengths of at least $2\text{N/mm}^2$ at 97.5% relative humidity. There appears to be little correlation between material properties and strength at high humidity, but the sample with the lowest clay content (20.3%) did have the lowest strength at all humidity levels.

**Movement as a result of humidity changes**

The movement as a result of changes in moisture content for different masonry units was determined by Heath *et al.* (2008), and these results along with the data in Figure 1 can be used to calculate the movement as a result of changes in humidity, as illustrated in Figure 5. These are for a “standard” wall height of 2.4 m.

![Figure 4: Percentage change in strength for specified humidity changes](image-url)
In all cases the vertical movement was very small - less than 1mm expansion if the relative humidity increased from 65% to 90%, and less than 0.5mm contraction if the relative humidity decreased from 65% to 40%. These values are calculated assuming there is no restraint at all (i.e. the wall is not even tied along the edges), and any restraint will decrease the amount of movement.

There is no defined relation between material properties and moisture movement, but the unit with the lowest moisture movement (Unit H) was also the unit with lowest clay content and lowest strength. The beneficial effect of higher clay contents in terms of strength and moisture absorption appear to offset the slight decrease in humidity-driven expansion and contraction. In mass earth construction techniques (e.g. rammed earth and cob) where the individual units are not dried before construction, large shrinkage may occur during drying with high clay contents. This highlights the importance of adequately drying the units before installation as any excess moisture may result in shrinkage post construction as the units stabilize to their equilibrium moisture contents.

**Thermal properties**

Earth masonry can contribute to thermal mass in a building which will help to buffer temperature changes and reduce energy use. Preliminary indications are that thermal mass may be included in a future revision of Part L of the building regulations (Conservation of fuel and power). While the absorption of moisture from the air may contribute to thermal mass, this had never been proved and it is conservative to ignore this aspect.

Walker et al (2005) investigated the thermal properties of rammed earth and concluded it was similar to other dense building products such as fired bricks, blockwork or concrete where it is highly dependent on density. As the density
of extruded earth masonry units is similar to fired clay bricks, the thermal properties are expected to be similar. The table proposed by Walker et al (2005) for the thermal conductivity of rammed earth is therefore considered appropriate for commercially produced earth masonry. The actual heat flow through walls with earth masonry also depends on the perforation pattern and the table below should only be used for solid units. The average net density of the units tested as part of this research was 1965kg/m³.

<table>
<thead>
<tr>
<th>Dry density (kg/m³)</th>
<th>Thermal conductivity (W/mK)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1400</td>
<td>0.60</td>
</tr>
<tr>
<td>1600</td>
<td>0.80</td>
</tr>
<tr>
<td>1800</td>
<td>1.00</td>
</tr>
<tr>
<td>1900</td>
<td>1.30</td>
</tr>
<tr>
<td>2000</td>
<td>1.60</td>
</tr>
</tbody>
</table>

As the thermal performance can be considered similar to that of fired masonry or blockwork, thermal calculations and details for thermal performance should be similar to those materials.

**Conclusions**

Earth masonry has the ability to absorb moisture from the air at high relative humidity and release it at low relative humidity. An increasing clay content results in additional moisture absorption as the relative humidity increases. This moisture absorption will only occur if the relative humidity is maintained at a high level for an extended period of time, and will depend on the vapour permeability of the finish materials and the masonry units. Earth masonry units do, however, have the potential to absorb a large quantity of moisture from the air. With some 100mm thick units, over 150kg of water can be absorbed by the walls in a 4mx4mx2.4m high room as the relative humidity increases from 40% to 90%, while with fired clay bricks this would be less than 2kg.

The strength of the masonry units decreases as the relative humidity increases, but even a relative humidity of 97.5% sustained for an extended period will not decrease strengths below 2N/mm² for all commercially available UK earth masonry units. There is, on average, a 17.5% reduction in strength as the long-term relative humidity increases from 65% to 90%. The change in relative humidity from 65% to 90% will also result in wall movement, but this will be less than 1mm for a 2.4m high wall. A reduction in relative humidity from 65% to 40% will result in less than 0.5mm wall movement for a 2.4m high wall.

The thermal performance can be considered similar to that of fired masonry or blockwork, thermal calculations and details for thermal performance should be similar to those materials.

From these tests, and from monitoring movement during mortaring and rendering (in separate reports), it can be concluded that the critical period for both strength decrease and wall movement is during construction, unless the
walls are actively wetted (through improper use or inappropriate detailing). The walls will not “turn to a pile of mud” at high humidity levels.

**References**


Mortars for thin unfired clay masonry walls

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Abstract

Interest in traditional unfired clay building materials, including cob, mud block, and rammed earth, has grown in the UK in recent years. Though the use of traditional vernacular techniques, such as cob, has raised the profile of earthen architecture, wider impact on modern construction is more likely from modern innovations such as unfired extruded masonry units. This paper summarises modern developments in the UK in use of unfired clay building materials, focussing in particular on unfired clay bricks. Results of on-going research at the University of Bath are summarised. The largest bricks manufacturers in the UK (accounting for approximately 70% of the bricks produced) are working with the University of Bath to develop unfired clay masonry systems. The paper examines bonding properties of a range of mortars with a number of commercially available unfired clay bricks. The materials used for the unfired masonry are largely the same as those used for fired clay bricks as commercial brick manufacturers would prefer to use existing materials and manufacturing plants for the mass production of unfired clay masonry. The significance of interim experimental findings are summarised, and details of the ongoing research programme are described.
INTRODUCTION

Traditional earth construction techniques, including cob, mud-block, wattle and daub, and rammed earth, has a long and largely successful history in the UK [Pearson, 1992]. There are an estimated 500,000 occupied earth buildings in the UK, most built before the twentieth century [Little and Morton, 2001]. Although earth buildings are distributed throughout the country with many regional variations, there are regional concentrations, such as cob in the South West and clay lump (mud block) in East Anglia. Earth is primarily used for wall, and occasionally, floor construction. Walls are thick solid construction, in contrast to modern masonry walls, which are generally comprised of two thin leaves with an insulated cavity between. The thermal insulating qualities of traditional earth walls in general do not meet the requirements of modern building regulations in the UK, although the poor insulating qualities are, to some extent, offset by their high thermal mass and hygrothermal properties.

Unfired clay materials provide a sustainable and healthy alternative as a replacement to conventional masonry materials, such as fired clay and concrete block, in both non-load-bearing and low rise load-bearing applications. Environmental benefits include significantly reduced embodied energy, thermal mass and regulation of humidity. Materials may be taken from sustainable resources (low grade clay and overburden) and are readily re-used, re-cycled or harmlessly disposed on end use. Materials are also entirely non-hazardous. Unfired clay materials offer potential health benefits to internal built environments, primarily through passive regulation of relative humidity. Though traditional clay masonry materials, such as adobe, clay lump and cob blocks, as well as more recently developed compressed earth blocks have been used successfully in a variety projects, more and more interest has been shown in using unfired clay bricks produced by high volume industrial brick manufacturers. The tensile strength of unfired clay materials is low and the bond between unfired clay units and traditional clay mortars is poor, therefore walls have relied on their bulk mass to ensure lateral load resistance and resilience. Consequently traditional solid walls are typically at least 225-300 mm thick. The standard size of fired clay bricks in the UK is 215 x 102.5 x 65 mm. Although the dimensions of unfired clay bricks are slightly higher they remain smaller than adobe and compressed earth block dimensions or the sizes of solid rammed earth or cob walls.

The bond strength of masonry is required to create a stable wall that will not collapse if it experiences lateral loading. Wall thickness has a large effect on required bond strength. A 2.4 metre high vertically spanning wall at 300mm thick, even with very low bond strength (0.024 N/mm²), can carry a uniformly distributed lateral load of 500 N/m². In order to reduce the thickness of the wall to 105mm, while providing the same flexural capacity, the bond strength must be increased to around 0.2 N/mm². There are many examples of single story 300mm thick earthen walls where the bond strength approaches zero (e.g. adobe blocks with clay mortars). The bond strength of 0.2 N/mm² for a 100mm thick wall is considered a reasonable target characteristic strength for unfired earth masonry.

The University of Bath is the lead partner in a two-year UK Government Technology Strategy Board (TSB) funded project to investigate and develop unfired clay masonry. Industrial partners include Ibstock Brick, Hanson, Errol
Brick Co., The Brick Development Association, Lime Technology, and arc Architects.

The test results provided in this paper build on previously published work [Walker et al, 2008] and relate to the bond strength characteristics of a range of different mortars with two commercially available unfired clay bricks. These two are shown in Figure 1.

![Commercially available unfired clay bricks](image)

**Figure 1. Commercially available unfired clay bricks**

**MATERIALS AND METHODS**

Previous work examined the bond strength of six different mortar mixes at 28 days, and the results are summarised in Table 1. There is no apparent correlation between mortar compressive strength and bond strength for the different mortars. The cement:sand mortar has the highest compressive strength but a very low bond strength with the unfired clay bricks when no bonding agent is used. With the exception of the sand:cement mortar the compressive strengths for the mortars were below that of the brick which is normally desirable in masonry. For all bricks the use of PVA bonding agent increased bond strength, however its use is not considered suitable for general use.

![Table 1: Phase 1 mortar test results](table)

<table>
<thead>
<tr>
<th>Mix</th>
<th>Mortar description</th>
<th>Average mortar compressive strength (N/mm²)</th>
<th>Average bond strength (without PVA) (N/mm²)</th>
<th>Average bond strength (with PVA) (N/mm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3:2 (sand:clay)</td>
<td>2.0</td>
<td>0.002</td>
<td>0.012</td>
</tr>
<tr>
<td>2</td>
<td>3:1 (sand:clay)</td>
<td>2.5</td>
<td>0.009</td>
<td>0.11</td>
</tr>
<tr>
<td>3</td>
<td>3:1 (sand:cement)</td>
<td>11.0</td>
<td>0.002</td>
<td>0.35</td>
</tr>
<tr>
<td>4</td>
<td>3:1 (sand:clay) + 5% lignosulphonate</td>
<td>3.3</td>
<td>0.052</td>
<td>0.52</td>
</tr>
<tr>
<td>5</td>
<td>‘Eco-brick’ brick proprietary mortar</td>
<td>2.2</td>
<td>0.26</td>
<td>N/A</td>
</tr>
<tr>
<td>6</td>
<td>Sodium silicate mortar</td>
<td>3.2</td>
<td>0.47</td>
<td>N/A</td>
</tr>
</tbody>
</table>

All of the joints, with exception of the sodium silicate mortars, exhibited an interface failure when no bonding agent was used. This changed to a majority
of joints exhibiting failure within the mortar joint after the interface strength had been increased with the bonding agent. Failure of the sodium silicate mortared joints was through the face of the bricks rather than along the interface or mortar; bond strength was therefore limited by brick strength, indicating that sodium silicate mortar mix used is perhaps too strong for these bricks.

MIXES 4 AND 5 HAD 5% SODIUM LIGNOSULPHONATE, AT 55% CONCENTRATION, ADDED TO THE CLAY, SAND AND WATER. LIGNOSULPHONATE (OR LIGNOSULFONATE) IS A LIGNIN BASED BY-PRODUCT OF THE PAPER PRODUCTION INDUSTRY AND IS COMMONLY USED AS A BINDER IN A VARIETY OF APPLICATIONS, AND IS ALSO USED IN THE CONSTRUCTION INDUSTRY AS A CONCRETE PLASTICISER. IT HAS PREVIOUSLY BEEN USED AS A MORTAR ADDITIVE FOR A LIMITED NUMBER OF CONSTRUCTION PROJECTS IN THE UK.

The clay:sand mortars used without a bonding agent and with thick (300mm) walls in traditional earth masonry construction have low bond strengths. These materials cannot be used in thin (100mm) wall without a substantial reduction in load carrying capacity. In order to produce a similar structural capacity under lateral loading for a 100mm thick wall, the bond strength must be increased to 0.20 N/mm². The lignosulphonate, used with PVA bonding agent, and the sodium silicate mortar achieved this value and these were considered the most promising mortars for further investigation. The use of a synthetic PVA bonding agent is not necessarily ideal, and alternative natural adhesives are to be investigated further. The use of any bonding agent will slow the construction process and increase costs unless this could be applied as part of the brick manufacture process.

The proprietary sodium silicate mortar has been designed for use with fireproof bricks and is costly (about 5x the cost of a pre-packed lime mortar) It was therefore not considered to be appropriate for further investigation. The second phase of tests therefore investigated lime mortars, lignosulphonate based mortars and sand/clay/sodium silicate solution mortars. Sodium silicate is a material which has a low carbon footprint (60kg CO₂ per tonne of product), and is economical in use (€600 per tonne of dry powder, equivalent to €36 per tonne of mortar at 6% silicate concentration). All mortar mixes were mixed with sufficient water to provide a mortar flow value of between 150 and 170mm according to BS EN 1015-3:1999. Bond strength was tested on six specimens of each mix after a number of different times in accordance with BS EN 1052-5:2005.

RESULTS OF BOND TESTS
The experimental mortar mixes are summarised in Table 2. Three different forms of failure were seen:

1. Interface failure, where the bond between mortar and brick was weaker than tensile strength of either the mortar or the brick. (Bond)

2. Failure within the mortar, where the bond between mortar and brick is stronger than the tensile strength of the brick. (Mortar)

3. Failure within the brick, where both the bond between mortar and brick and the tensile strength of the mortar are stronger than the tensile strength of the brick. (Brick)
Table 2: Experimental mortar mixes

<table>
<thead>
<tr>
<th>Specimen #</th>
<th>Brick</th>
<th>Mortar mix details (by volume)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Ecoterre</td>
<td>Proprietary Pre-formulated lime - Basecoat®</td>
</tr>
<tr>
<td>2</td>
<td>Ecoterre</td>
<td>1:2:25 NHL3.5 lime mortar</td>
</tr>
<tr>
<td>3</td>
<td>Errol</td>
<td>3:1 sand:clay with 5% lignosulphonate</td>
</tr>
<tr>
<td>4</td>
<td>Ecoterre</td>
<td>3:1 sand:clay with 5% lignosulphonate</td>
</tr>
<tr>
<td>5</td>
<td>Ecoterre</td>
<td>3:1 sand:clay with 10% lignosulphonate</td>
</tr>
<tr>
<td>6</td>
<td>Ecoterre</td>
<td>3:1 sand:clay with 10% lignosulphonate</td>
</tr>
<tr>
<td>7</td>
<td>Errol</td>
<td>45:15:6 sand:clay:silicate solution</td>
</tr>
<tr>
<td>8</td>
<td>Errol</td>
<td>45:15:7 sand:clay:silicate solution</td>
</tr>
<tr>
<td>9</td>
<td>Errol</td>
<td>45:15:8 sand:clay:silicate solution</td>
</tr>
<tr>
<td>10</td>
<td>Errol</td>
<td>45:15:9 sand:clay:silicate solution</td>
</tr>
<tr>
<td>11</td>
<td>Errol</td>
<td>45:15:10 sand:clay:silicate solution</td>
</tr>
<tr>
<td>12</td>
<td>Errol</td>
<td>45:15:11 sand:clay:silicate solution</td>
</tr>
<tr>
<td>13</td>
<td>Ecoterre</td>
<td>45:15:7 sand:clay:silicate solution</td>
</tr>
<tr>
<td>14</td>
<td>Ecoterre</td>
<td>45:15:8 sand:clay:silicate solution</td>
</tr>
<tr>
<td>15</td>
<td>Ecoterre</td>
<td>45:15:8 sand:clay:silicate solution</td>
</tr>
<tr>
<td>16</td>
<td>Ecoterre</td>
<td>45:15:10 sand:clay:silicate solution</td>
</tr>
<tr>
<td>17</td>
<td>Ecoterre</td>
<td>45:15:11 sand:clay:silicate solution</td>
</tr>
<tr>
<td>18</td>
<td>Ecoterre</td>
<td>45:15:12 sand:clay:silicate solution</td>
</tr>
<tr>
<td>19</td>
<td>Ecoterre</td>
<td>45:15:10 sand:clay:silicate in 5% sugar solution</td>
</tr>
</tbody>
</table>

The average and characteristic bond strengths resulting from the tests conducted are shown in Table 3.
Table 3: Bond wrench results (data from six specimens for each test)

<table>
<thead>
<tr>
<th>Test #</th>
<th>Mix details</th>
<th>Age at test (days)</th>
<th>Bond strength (N/mm²)</th>
<th>Failure Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Ecoterre PFL</td>
<td>7</td>
<td>0.11 0.01</td>
<td>Bond</td>
</tr>
<tr>
<td>2</td>
<td>Ecoterre PFL</td>
<td>28</td>
<td>0.14 0.08</td>
<td>Bond</td>
</tr>
<tr>
<td>3</td>
<td>Ecoterre NHL3.5</td>
<td>28</td>
<td>0.02 0.01</td>
<td>Bond</td>
</tr>
<tr>
<td>4</td>
<td>Errol 5% Ligno</td>
<td>7</td>
<td>0.34 0.28</td>
<td>Bond</td>
</tr>
<tr>
<td>5</td>
<td>Errol 5% Ligno</td>
<td>28</td>
<td>0.25 0.12</td>
<td>Bond</td>
</tr>
<tr>
<td>6</td>
<td>Errol 5% Ligno</td>
<td>396</td>
<td>0.16 0.05</td>
<td>Bond</td>
</tr>
<tr>
<td>7</td>
<td>Ecoterre 5% Ligno</td>
<td>28</td>
<td>0.04 0.01</td>
<td>Bond</td>
</tr>
<tr>
<td>8</td>
<td>Ecoterre 10% Ligno</td>
<td>28</td>
<td>0.16 0.05</td>
<td>Bond</td>
</tr>
<tr>
<td>9</td>
<td>Ecoterre 15% Ligno</td>
<td>28</td>
<td>0.07 0.02</td>
<td>Bond</td>
</tr>
<tr>
<td>10</td>
<td>Errol 60:6 silicate</td>
<td>7</td>
<td>0.05 0.03</td>
<td>Bond</td>
</tr>
<tr>
<td>11</td>
<td>Errol 60:7 silicate</td>
<td>7</td>
<td>0.07 0.03</td>
<td>Bond</td>
</tr>
<tr>
<td>12</td>
<td>Errol 60:8 silicate</td>
<td>7</td>
<td>0.16 0.06</td>
<td>Bond</td>
</tr>
<tr>
<td>13</td>
<td>Errol 60:9 silicate</td>
<td>7</td>
<td>N/A N/A</td>
<td>Brick</td>
</tr>
<tr>
<td>14</td>
<td>Errol 60:10 silicate</td>
<td>7</td>
<td>N/A N/A</td>
<td>Brick</td>
</tr>
<tr>
<td>15</td>
<td>Errol 60:11 silicate</td>
<td>7</td>
<td>N/A N/A</td>
<td>Brick</td>
</tr>
<tr>
<td>16</td>
<td>Ecoterre 60:10 silicate/sugar</td>
<td>7</td>
<td>0.17 0.13</td>
<td>Bond/mortar</td>
</tr>
<tr>
<td>17</td>
<td>Ecoterre 60:10 silicate/sugar</td>
<td>28</td>
<td>0.12 0.05</td>
<td>Bond</td>
</tr>
<tr>
<td>18</td>
<td>Ecoterre 60:7 silicate</td>
<td>7</td>
<td>0.05 0.01</td>
<td>Bond</td>
</tr>
<tr>
<td>19</td>
<td>Ecoterre 60:8 silicate</td>
<td>7</td>
<td>0.11 0.06</td>
<td>Bond/mortar</td>
</tr>
<tr>
<td>20</td>
<td>Ecoterre 60:9 silicate</td>
<td>7</td>
<td>0.14 0.06</td>
<td>Mortar</td>
</tr>
<tr>
<td>21</td>
<td>Ecoterre 60:10 silicate</td>
<td>7</td>
<td>0.17 0.09</td>
<td>Mortar</td>
</tr>
<tr>
<td>22</td>
<td>Ecoterre 60:11 silicate</td>
<td>7</td>
<td>0.15 0.08</td>
<td>Mortar</td>
</tr>
<tr>
<td>23</td>
<td>Ecoterre 60:12 silicate</td>
<td>7</td>
<td>0.15 0.10</td>
<td>Mortar</td>
</tr>
</tbody>
</table>

Pre-formulated Lime Mortars

Pre-formulated lime mortars used with Ecoterre bricks achieve 80% of their 28 day bond strength within 7 days, but even at 28 days the bond strength is 30% below desired levels. Failure occurs at the interface between brick and mortar, and it is considered that these types of mortars are inappropriate for use with unfired clay bricks in thin walls.

Lime Mortars

Since hydraulic lime mortars take more than 7 days to set, the bond was only tested at 28 days. At this time the bond was found to be only 10% of the required level. These mortars performed even worse than the pre-formulated lime mortars, and are also considered to be inappropriate for use with unfired clay bricks in thin walls.

Lignosulphonate Mortars
The lignosulphonate mortar adheres much better to the Errol brick than it does to the Ecoterre brick, and the bond with the Ecoterre brick is inadequate at 28 days. Specimens made with Errol bricks are of sufficient age to allow long term tests to be conducted, and data up to 396 days are presented in Figure 2. It would appear that although lignosulphonate mortars produce high bond strengths with some brick types at early stages, the bond becomes more variable and weaker with age, such that within one year the bond is below the required level.

![Figure 2: Bond strength for lignosulphonate mortars up to 396 days](image)

The nature of the bond formed by lignosulphonate mortars with unfired clay bricks is unclear. Scanning electron microscope (SEM) images reveal the growth of a fine (~2.5µm diameter) web of material (Figure 3).

![Figure 3](image)
Figure 3: SEM image of Lignosulphonate mortar at 28 days (x100)

Energy dispersive X-Ray analysis (EDX) of these filaments shows a material which is high in silica content with small amounts of calcium, iron and potassium. This may be indicative of a chemical reaction between the lignosulphonate and the clays in the aggregate. Lignosulphonate mortars are considered to be problematic when used with unfired clay brick thin walls for two reasons:

1. Variable bond strength according to the type of clay in the bricks;
2. Loss of long term bond strength.

**Sodium Silicate Mortars**

Sodium silicate based mortars bond with all types of unfired clay bricks tested to date, and the bond appears to be proportional to the amount of sodium silicate in the mix (Figure 4). It would appear that bond strength up to 63 days does not deteriorate with time. In order to obtain good early bond strength it is considered that the maximum silicate solution concentration commensurate with acceptable mortar flow should be used. A further phase of research has therefore been initiated to evaluate the bond strength of sodium silicate mortars over extended time periods. This programme will also evaluate compressive strength, flexural strength and vapour permeability of the mortars as well as movement characteristics of the masonry.

CONCLUSION

The majority of the embodied energy in fired bricks comes from the firing process, and an 85% saving in manufacturing energy can be achieved if the bricks are used in an unfired form. In order for this to have a significant effect on energy usage, the unfired bricks will have to move into mainstream
markets where thin (100-105mm) wall thicknesses are desirable. In order to achieve this, a significant increase in bond strength is needed. Sodium silicate based mortars have been shown to perform more consistently and to a higher level of performance than other mortar types. In addition these mortars have a low carbon footprint and are environmentally benign, which makes them attractive for use in low carbon construction. These mortars are the subject of ongoing research, looking at the effect of time and environmental conditions on performance and the nature of the bond between brick and mortar. The use of sodium silicate mortars with thin (100mm) walls appears promising.

Acknowledgements

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References


**Appendix 5 - Masonry test results**

**Introduction**

In order to establish the performance of clay brick masonry bonded with sodium silicate mortars, a series of tests were conducted using British Standard tests. Tests were for compressive strength (BSEN 1052-1:1999), flexural strength (BSEN 1052-2:1999), and initial shear strength (BSEN 1052-3:2002). In addition to these tests, three sample walls were maintained at a constant 60% RH and shrinkage from the time of manufacture was measured over an 8 week period, until no further significant movement was detected.

Tests on structural performance were conducted at 56 days when it was considered that the moisture content in the mortar had equilibrated with the bricks and shrinkage had ceased. Bond wrench tests had shown that the bond strength of the mortar at 56 days exceeded that of the tensile strength of the bricks.

**Sample manufacture**

Sample walls were built using Ecoterre bricks by a professional bricklayer using a mortar made (by weight) with 8.44 parts building sand, 3.04 parts crushed Ecoterre bricks (sieved to <2mm), 1 part sodium silicate and 2.39 parts water.

3 walls measuring 4 bricks wide x 13 bricks high were built for shrinkage tests, 6 walls measuring 2 bricks wide x 5 bricks high, for compressive tests (BSEN 1052-1:1999), 6 walls measuring 2 bricks wide x 10 bricks high and 6 walls measuring 4 bricks wide x 4 bricks high, for flexural tests (BSEN 1052-2:1999), and 9 triplets for initial shear strength (BSEN 1052-3:2002).

Sample walls were stored in a climate control room at 20ºC and 60%RH until testing, which was carried out at 56 days to the appropriate British Standard.

**Test results**

**Compression tests (BSEN 1052-1:1999)**

Figure 1 shows the test set-up. Strain gauges were positioned on both sides of the wall to measure deformations in the wall. Loading was applied at 0.15 N/mm².min which produced a failure in around 24 minutes (the standard calls for a failure time of between 15 and 30 minutes). Typically the mode of failure was a vertical split through the narrow face of the wallette (Figure 2). The test results are shown in Table 1.
Figure 10: Test set up for compression tests

Figure 11: Typical mode of failure for compressive tests
Table 1: Results of compression tests

<table>
<thead>
<tr>
<th>Specimen #</th>
<th>Density (N/mm²)</th>
<th>Failure Stress (N/mm²)</th>
<th>Modulus of Elasticity (N/mm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.02</td>
<td>2.42</td>
<td>1272</td>
</tr>
<tr>
<td>2</td>
<td>2.05</td>
<td>2.52</td>
<td>1738</td>
</tr>
<tr>
<td>3</td>
<td>2.02</td>
<td>2.47</td>
<td>2255</td>
</tr>
<tr>
<td>4</td>
<td>2.03</td>
<td>2.49</td>
<td>2867</td>
</tr>
<tr>
<td>5</td>
<td>2.03</td>
<td>2.62</td>
<td>2940</td>
</tr>
<tr>
<td>6</td>
<td>2.04</td>
<td>2.40</td>
<td>1806</td>
</tr>
<tr>
<td>Mean</td>
<td>2.03</td>
<td>2.49</td>
<td>2146</td>
</tr>
<tr>
<td>sd</td>
<td>0.01</td>
<td>0.08</td>
<td>665</td>
</tr>
</tbody>
</table>

The characteristic compressive strength of the masonry walls is 2.07 N/mm². This is similar to the characteristic compressive strength of the bricks. The compressive strength of the mortar was measured at 9.48 N/mm².

The mode of failure indicates that the bricks were the weakest part of the composite since the failure does not follow either the line of the bond or of the mortar. This demonstrates that the mortar is not the weakest link in the compression strength of unfired clay masonry walls.

**Flexural tests (BSEN 1052-2:1999)**

Figures 3 and 4 show the test set up for the flexural tests.

Figure 12: Set-up for flexural tests (horizontal) according to BSEN 1052-2:1999.
Figure 13: Set-up for flexural tests (vertical) according to BSEN 1052-2:1999.

The mode of failure of the wallettes is shown in figures 5 and 6.

Figure 14: Mode of failure for flexural tests (horizontal) according to BSEN 1052-2:1999
As with the compressive tests, failure occurs in the bricks rather than in the mortar or at the brick/mortar interface. The test results are shown in Table 2. In both orientations, failure occurred in the bricks rather than in the mortar or at the mortar/brick interface. Once again the limiting strength is the brick. This again demonstrates that the mortar is not the weakest link in the flexural strength of unfired clay masonry walls.
Table 2: Results of flexural tests

<table>
<thead>
<tr>
<th>Panel</th>
<th>Flexural Strength $f_{n}$ N/mm²</th>
<th>Flexural Strength $F_{x}$ N/mm²</th>
<th>Flexural Density kg/mm²</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.589</td>
<td>2.035</td>
<td>0.388</td>
</tr>
<tr>
<td>2</td>
<td>0.538</td>
<td>2.052</td>
<td>0.441</td>
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<tr>
<td>3</td>
<td>0.488</td>
<td>2.029</td>
<td>0.435</td>
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<tr>
<td>4</td>
<td>0.560</td>
<td>2.040</td>
<td>0.408</td>
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<tr>
<td>5</td>
<td>0.669</td>
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<td>0.408</td>
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<tr>
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<tr>
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<td>0.567</td>
<td>2.039</td>
<td>0.418</td>
</tr>
<tr>
<td>sd</td>
<td>0.060</td>
<td>0.009</td>
<td>0.025</td>
</tr>
</tbody>
</table>

Initial shear strength tests (BS EN 1052-3:2002)

Results from the initial shear strength tests are shown in Table 3. Failure modes were either A3 (shear failure in the unit) or A4 (crushing or splitting failure in the units). In both cases these are failures in the bricks rather than in the mortar or in the mortar/brick interface.

Table 3: Shear strength test results

<table>
<thead>
<tr>
<th>Precompressive Stress (N/mm²)</th>
<th>Shear Strength (N/mm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1912</td>
<td>0.2748</td>
</tr>
<tr>
<td>0.5768</td>
<td>0.4620</td>
</tr>
<tr>
<td>0.9528</td>
<td>0.6191</td>
</tr>
</tbody>
</table>

These data can be represented on a graph with a linear regression of $y=0.4522x + 0.1926$ (Figure 7). This gives a mean shear strength of 0.1926 N/mm² (characteristic 0.1541N/mm²), and a mean internal friction angle of 24.3° (characteristic 19.9°). The bond strength expected from these data is given as $2c \sin\phi/(\tan\phi(1+\sin\phi))$ where $\phi$ is the internal friction angle and $c$ is the shear strength. This gives a mean bond strength of 0.25N/mm² (characteristic 0.22N/mm²), compared with 0.43N/mm² mean bond strength (0.37 N/mm² characteristic) at the same age.

The shear and bond wrench tests are testing different aspects of behaviour and the theoretical models that provide a link between the two are contradicted by experimental test results. This is one reason for the recent introduction of the bond wrench as a European standard where previously the shear strength test was used as a governing criteria for design.
**Shrinkage tests**

The shrinkage specimen walls had targets affixed to them across eight joints vertically and four joints horizontally, and movements were measured periodically using a DEMEC gauge, taking measurements in pairs of four joints vertically and two horizontally (Figure 8).
The resultant data were averaged over three walls and are shown in Figure 9.

Figure 18: Shrinkage data for sample walls held at 60%RH and 20°C from date of manufacture

It can be seen that there is a sharp initial shrinkage which gradually slows down over a period of about 6 weeks. Total shrinkage is around 0.4% horizontally, and slightly less vertically. By the 56 days, when the masonry tests were conducted, shrinkage appeared to have finished. A 0.4% shrinkage would result in a shrinkage crack of just under 10mm in a 2.4m high unfired clay brick masonry wall. This is considerably larger shrinkage than would be expected from a fired brick wall, and due allowance would need to be made in the construction planning in order to accommodate this.

**Conclusions**

The tests conducted on unfired clay brick masonry walls bonded with sodium silicate mortar clearly show that the mortar is fit for purpose. The high levels of shrinkage (associated with the moisture necessarily used to make the mortar) create particular problems which need to be allowed for in construction planning.

**References**

Appendix 6 – Clay plaster research

CLAY PLASTER RESEARCH

Report

Tom Morton, Arc Architects
Becky Little, Little & Davie Construction

SUMMARY & CONCLUSIONS

Summary

Twelve different clays were tested along with various possible additives, to assess the technical potential for developing mass-produced clay plasters.

Three of the clays showed excellent potential, with a further five showing good potential if processed further. The key factors are clay type and grading, with a very fine grading required for a finish plaster.

Good quality finish coats were produced, which could also be painted. An undercoat was straightforward to produce, with fibre added.

Various additives were tested. Few significantly improved performance and some reduced it. Starch and seaweed could have potential but would need more specific experimentation.

Conclusions

25% of the samples of dry ground clays currently produced by the industrial partners showed very good potential for used as clay plasters, with the simple addition of fine sand. This is likely to be simple and economic to produce commercially and could be distributed dry-bagged. Fibres could be added to make undercoats and special additives perhaps used for a high performance plaster, for example, in areas of higher abrasion risk.

A further 42% of the clays showed good potential for use, if the clays can be ground finer than the samples.

The results were thought very promising. The design of a specific commercial product could look to refine mix proportions to suit the individual characteristics of a particular clay, but it should be relatively straightforward to produce a high quality commercial product.
1. INTRODUCTION

1.1 Background

Plasters are a key finish to earth masonry, combining compatibility of physical properties with continuity of benign environmental characteristics.

Clay plasters can also be applied to substrates other than earth masonry. In Germany the use of clay plasters led the growth of the commercial unfired clay materials sector, with applications particularly in refurbishment of existing buildings to achieve an attractive finish and improve indoor air quality.

Requiring a low level of energy to manufacture, clay plasters are potentially a good low-carbon finish for buildings. Currently imported German products are expensive, but if production can be developed in the UK, clay plasters could be more affordable and play a similar role.

Currently there are no clay plasters mass-produced in the UK, though they are produced on a small-scale craft basis. There is little understanding of the factors that would affect industrialised production.

1.2 Aims

The aim of the research was to assess the technical potential of a range of UK brick clays to be used to mass-produce clay plasters and highlight any key issues that would affect developing production and use.

1.3 Methodology

This work followed on from the materials understanding already gathered on mortars, and developed the knowledge base to inform the capabilities of industrial partners to produce other key components of a clay masonry system. Samples of different clays were supplied by the brick company partners.

There were five work stages.

1. Review of available information. Review published information, interview key people with experience of using clay plasters to date in UK
2. Make clay plaster with a range of clays currently used in brick manufacture and assess their characteristics; workability, adhesion, shrinkage, dusting, etc.
3. Make clay plasters with a range of additives and assess improvement of qualities
4. Lab test of cure times for a standard plaster in varying environmental conditions and on different substrates
5. Write summary report
Fig. 1: The range of colours in the sample clays

Fig. 2: Large particles made it difficult to achieve a good finish with some of the clays.

Fig. 3: Finer grained clays achieved a better finish
2. **RESULTS**

2.1 **Summary**

2.1.1 **Clays**

Samples of twelve different clays were received from the industrial partners and tested as a 1:1 mix with fine sand and then with different proportions of sand.

All the samples showed good adhesion properties. Five of the samples did not have good working qualities, being either too lean, heavy or coarse. These relate to the clay mineral and degree of grinding.

Of the other seven, three clays made good mixes having good workability, producing a good finish, low shrinkage, being visually attractive, good adhesion and no dusting.

The remaining four were generally marred by not being fine enough. Coarse grains would tear the finished surface when floated. Some of these were sand particles, but others were clay particles that dispersed when left to soak for five minutes. The other clays could be improved by finer grinding.

Of the three good clays, Hanson’s buff Redbank Blend F was the best. Ibstock’s red Shortwood was also selected for further testing in different proportions and with additives.

*Texture*

1:1 mixes generally produced a fine finish, but were more susceptible to shrinkage. 1:2 mixes were slightly more open textured, but were better graded.

*Colour*

The tested clays finished to their natural colour, ranging between brown, red, buff and grey. The colour of the sand had a minor effect on the colour. What the tests did not produce was a large variation in colour, as seen in some imported products. These rely on a white base clay, with added pigments.

2.1.2 **Undercoat**

An undercoat, using fibre, was made, which worked well.

2.1.2 **Plasterboard Base**

A primer paint was made, using 0.5% starch with 1:1 clay: sand, which worked well.

2.1.3 **Paint finish**

A sample was painted with white NBT Trade Emulsion, achieving a good finish.
2.1.4 Fibres

Several fibres were tested as additives. Small hemp fibres worked well, but commercial supply may be problematic. Straw was problematic and would need to be processed very fine. Paper pulp reduced workability.

2.1.5 Starches

The addition of hydrated starch (methyl cellulose) has the potential to strengthen and reduce dusting of a plaster, but needs to be controlled as even small amounts (2%) increase the water content needed to make a workable mix, and therefore increase drying times and shrinkage. Mixes with approximately 0.2% starch content would be worth further research.

The benefit was marginal on these two good clays, but might be more marked on clays with less good basic properties.

2.1.6 Casein

Casein had no benefits and reduced working qualities.

2.1.7 Seaweed

Seaweed subtly improved working qualities, but would need further research.

2.2 Clay Test Record

Eleven different clays were supplied by the industrial partners, as representative of a range of clays that are currently available as dry ground material suitable for processing into a dry powdered clay plaster. The clays varied in colour between grey, buff and red/brown.

2.2.1 Chesterton Etruria Marl

Project Ref: I1
Supplier: Ibstock
Colour: brown
Texture: quite coarse
Description: a North Staffordshire clay from Newcastle-Under-Lyme, produced with a hammer mill, giving a fairly fine grind.

Assessment: A test mix was prepared, at proportions of 1:1, clay: fine sand, 45ml. Clay: 45ml sand : 25ml water. The mix seemed very wet at first, but fattened over 5 minutes, so 2.5ml more water was added. The mix felt grainy and very sticky. A second test was carried out with less water, 21.5ml, and this was improved, sticky but still grainy.

Conclusion: Poor potential. This material seemed to have an overly reactive clay content, and an overly coarse grading for commercial use as clay plaster.
2.2.2 Alms Red

Project Ref: I2
Supplier: Ibstock
Colour: red
Texture: very coarse
Description: a red-burning marl from Cattybrook, dry ground

Assessment: A test mix was prepared, at proportions of 1:1, clay: fine sand, 45ml. Clay: 45ml sand : 27ml water. The mix felt grainy, but nice and sticky.

Conclusion: Poor Potential. This material seemed to have overly coarse grading for commercial use as clay plaster, though its stickiness suggested it could be good if ground finer.

2.2.3 MH Tilley Bulring

Project Ref: I3
Supplier: Hanson
Colour: grey
Texture: quite coarse
Description:

Assessment: A test mix was prepared, at proportions of 1:1, clay: fine sand, 45ml. Clay: 45ml sand : 25ml water. The mix felt grainy, but had good working qualities. A second mix was prepared with 27ml water and left to stand for 1 hour, which much improved the texture.

Conclusion: Good potential. Some soaking dispersed clay particles, creating a plaster with good working qualities.

2.2.4 Claughton Clay

Project Ref: I4
Supplier: Hanson
Colour: dark grey
Texture: very coarse
Description:

Assessment: A test mix was prepared, at proportions of 1:1, clay: fine sand, 45ml. Clay: 45ml sand : 25ml water. The mix was sloppy, not fattening up when left to stand and had poor working qualities.

Conclusion: No potential. This poor performance of the material related to the clay mineral type and grading.

2.2.5 Red Shortwood

Project Ref: I5
Supplier: Ibstock
Colour: red
Texture: coarse. 0.3 gravel, 37% sand, 38% silt, 25% clay
Description: Fine Red clay from Cattybrook

Assessment: A test mix was prepared, at proportions of 1:1, clay: fine sand, 45ml. Clay: 45ml sand : 27.5ml water. The mix had good working qualities and smelled metallic. A second mix was prepared with 26.5ml water and left to stand for 1 hour, which much improved the texture.

Conclusion: Very good potential. Some soaking dispersed clay particles, creating a plaster with very good working qualities.

2.2.6 Dalton

Project Ref: I6
Supplier: Hanson
Colour: grey
Texture: very coarse
Description:

Assessment: The material was assessed as being too coarse in its dry state to merit testing.

Conclusion: No potential due to grading.

2.2.7 Dalton/Huncote

Project Ref: I7
Supplier: Hanson
Colour: grey
Texture: very coarse.
Description:

Assessment: A test mix was prepared, at proportions of 1:1, clay: fine sand, 45ml. Clay: 45ml sand: 20ml water. The mix was sloppy and did not fatten up. It was grainy and heavy to work with.

Conclusion: Poor potential. It was thought the clay fraction was probably too small.

2.2.8 Buff

Project Ref: I8
Supplier: Ibstock
Colour: grey
Texture: very coarse. 1 gravel, 16% sand, 51% silt, 32% clay
Description: A fireclay from Throkley at Gateshead

Assessment: A test mix was prepared, at proportions of 1:1, clay: fine sand, 45ml. Clay: 45ml sand : 25ml water. The mix grainy but had good working qualities. A second mix was prepared with 25.5ml water and left to stand for 1 hour, which did not improve the texture.
Conclusion: Little potential. Soaking did not disperse clay particles, with good working qualities hindered by poor grading.

2.2.9 Redbank Blend D

Project Ref: H1
Supplier: Hanson
Colour: red
Texture: fine. 37% sand, 38% silt, 25% clay
Description: clay from Redbank

Assessment: A test mix was prepared, at proportions of 1:1, clay: fine sand, 45ml. Clay: 45ml sand : 20ml water. The mix was too wet. A second mix was prepared with 17ml water and was better, but heavy and with poor working qualities.

Conclusion: Little potential, probably associated with the clay type.

2.2.10 Redbank Blend F

Project Ref: H2
Supplier: Hanson
Colour: buff
Texture: fine, a few lumps. 37% sand, 38% silt, 25% clay
Description: clay from Redbank

Assessment: A test mix was prepared, at proportions of 1:1.4, clay: fine sand, 45g. Clay: 68g sand : 22ml water. The mix had excellent working qualities. A second mix was prepared at proportions of 1:2, clay: fine sand, 48g. clay: 96g sand : 30ml water. This was wetter, but also had excellent qualities.

Conclusion: Very good potential.

2.2.11 Lower Oxford Clay

Project Ref: H3
Supplier: Hanson
Colour: brown/ grey
Texture: very coarse
Description:

Assessment: A test mix was prepared, at proportions of 1:1, clay: fine sand, 45ml. Clay: 45ml sand : 22.5ml water. The mix was coarse, but rich. A second mix was prepared with 25ml water and left to stand for an hour. This showed no improvement.

Conclusion: Little potential, due to clay type and grading.
2.2.12 Ball Clay

Project Ref: H4  
Supplier: Hanson  
Colour: light grey  
Texture: very coarse  
Description:

Assessment: A test mix was prepared, at proportions of 1:1, clay: fine sand, 45ml. Clay: 45ml sand : 25ml water. The mix was very coarse, but made a good sample.

Conclusion: Some potential, though the clay would need to be ground finer.

2.3 Additive Test Record

Ten different tests of additives were undertaken, with two additional control tests.

2.3.1 Test 1: RBBF Control

Mix: 100g clay: 200g sand: 50g water  
Water added after 30 mins: 2ml  
Clay: Red Bank Blend F

Assessment: Very quick and easy to mix, fattened slightly over 30 minutes. Easy to finish and apply.

2.3.2 Test 2: Starch Paste

Mix: 100g clay: 200g sand: 93g water: 0.7g starch paste  
Water added after 30 mins: 1ml  
Clay: Red Bank Blend F

Assessment: Mix thickened rapidly, but was heavy. In applying, it was moussey, slimy and difficult to finish.

2.3.3 Test 3: Starch Paste

Mix: 100g clay: 200g sand: 78g water: 0.35g starch paste  
Water added after 30 mins: 1ml  
Clay: Red Bank Blend F

Assessment: The mix was more workable than Test 2, but still not as easy as Test 1. It was still difficult to finish.

2.3.4 Test 4: Starch Powder

Mix: 100g clay: 200g sand: 67g water: 0.35g starch powder  
Water added after 30 mins: 1ml  
Clay: Red Bank Blend F

Assessment: This mix had much less thickening than the starch paste and worked up more like Mix 1. It applied well, being slightly richer than Test 1.
2.3.5 Test 5: Methyl Cellulose

Mix: 100g clay: 200g sand: 70g water: 0.35g methyl cellulose
Water added after 30 mins: 1ml
Clay: Red Bank Blend F

Assessment: This mixed up well, like the starch powder Test 4. In applying, it was slimier and stickier, similar to Test 3.

2.3.6 Test 6: Red Control

Mix: 100g clay: 200g sand: 60g water
Water added after 30 mins: 0
Clay: Red

Assessment: This was much leaner than the RBBF mix, lacking adhesion, but producing a nice finish.

2.3.7 Test 7: Starch Paste

Mix: 100g clay: 200g sand: 88g water: 0.35g starch paste
Water added after 30 mins: 1ml
Clay: Red

Assessment: Mix was stickier than Test 6, but more workable. The mix was too wet, but achieved a nice finish.

2.3.8 Test 8: Casein

Mix: 100g clay: 200g sand: 140g water: 15g starch casein
Water added after 30 mins: 0ml
Clay: Red Bank Blend F

Assessment: The mix has a very sticky and grainy texture and it was difficult to mix in the water. It was very difficult to apply and achieve a decent finish.

2.3.9 Test 9: Casein

Mix: 100g clay: 200g sand: 67g water: 3g casein
Water added after 30 mins: 1ml
Clay: Red Bank Blend F

Assessment: This was still hard to mix in water. In applying, it was lumpy and gelatinous, but easy to finish.

2.3.10 Test 10: Alginate Extract

Mix: 100g clay: 200g sand: 50g water: 1g alginate extract
Water added after 30 mins: 0ml
Clay: Red Bank Blend F

Assessment: There was no discernable difference to Test 1 in mixing or application.
2.3.11 Test 11: Alginate Extract

Mix: 100g clay: 200g sand: 50g water: 5g alginate extract
Water added after 30 mins: 0ml
Clay: Red Bank Blend F

Assessment: The additive stiffened the mix slightly, but less difference than with the starches. In application, it was slightly richer than control Test 1 and lovely to use.

2.4 Abrasion Tests

Five samples of clay plaster were prepared for abrasions tests using the Red Bank Blend F. These were made at 25mm thick in order to allow the abrasion rate to be determined. Finishing coat plasters are normally 1-3mm thick and so the shrinkage was greatly exaggerated in these samples. As a result some of the samples cracked severely and could not be tested.

In general, all abrasion results were poor in comparison with gypsum plasters. This was expected and the plasters are thought to have adequate abrasion resistance for general use.

The purpose of the tests was to gain comparative data on the performance of different mixes and in this respect they were useful. Only one of the additives showed an enhanced resistance to abrasion, though this was marginal and accompanied by increased shrinkage.

It is concluded that such additives are now beneficial to a well-graded clay plaster. They are likely to be of more benefit to a poorly graded plaster, with low clay content, where they would provide a more significant improvement by increasing binding strength.

2.4.1 Test 1: Control

Mix: 1 clay: 2 sand, with 350ml water per 2kg dry mix
Initial shrinkage: no central shrinkage cracks, linear ~0.5%
Abrasion rate: 28.6 kg/m³
Assessment: This simple mix performs well.

2.4.2 Test 2: Alginate (seaweed extract)

Mix: 1 clay: 2 sand, with 350ml water & 60ml alginate per 2kg dry mix
Initial shrinkage: 1 central crack ~ 40mm long, 1mm wide, linear ~2%
Abrasion rate: 27.7kg/m³
Assessment: Possible marginal benefit. The alginate additive increased shrinkage, approximately quadrupling it, but marginally improved abrasion resistance by about 3%.
2.4.3 Test 3: Starch Paste

Mix: 1 clay: 2 sand, with 640ml water & 1.5g starch paste per 2kg dry mix
Initial shrinkage: several severe central cracks full length, 5mm wide, linear ~5%
Abrasion rate: Too cracked to test
Assessment: Failure. The starch additive, and associated increase water content required to make it workable, severely increased shrinkage

2.4.4 Test 4: Methyl Cellulose

Mix: 1 clay: 2 sand, with 440ml water & 2.5g starch paste per 2kg dry mix
Initial shrinkage: two large central cracks, 70mm long, 2mm wide, linear ~3%
Abrasion rate: Too cracked to test
Assessment: Failure. The methyl cellulose additive, and associated increase water content required to make it workable, significantly increased shrinkage

2.4.5 Test 5: Starch Powder

Mix: 1 clay: 2 sand, with 370ml water & 2.5g starch paste per 2kg dry mix
Initial shrinkage: one small central crack ~10mm long, 0.5mm wide, linear ~1%
Abrasion rate: 34.3 kg/m3
Assessment: No benefit. The starch additive did not require increased water content to make it workable. However, the additive marginally increased shrinkage and reduced abrasion resistance by about 20%.
Appendix 7 – Factsheet for earth masonry construction

What is modern earth masonry?
Also known as unfired clay brickwork—/masonry or adobe, earth masonry is constructed using earth materials (possibly with some additives). Earth masonry is not “fired” like conventional bricks, but the masonry units are air dried after manufacture to reduce shrinkage and improve strength. In some traditional forms of earth construction (e.g. cob or rammed earth), monolithic (solid) walls are constructed, but earth masonry is similar to other masonry systems where there the units (“bricks”) are bonded together with mortar and possibly covered with a finishing system (paint or render).

Traditional forms of earth masonry (cob blocks, adobes and mudbricks) are generally made by hand and as a result, have variable dimensions and other properties. Traditional earth masonry has thick walls (often over 300mm thick) as the mortar provides low bond strength and the thick walls have sufficient mass to keep themselves stable against lateral loads in dwellings.

Because of the environmental and financial cost of using materials in construction, it is preferable to reduce the wall thickness to approximately 100mm for internal partitions (the standard thickness for fired clay bricks and concrete blockwork). Thinner walls also reduce the structural loading and increase available space inside buildings.

Modern earth masonry uses earth masonry units manufactured to accurate tolerances using a commercial extrusion or pressing system to provide a consistent, high quality product. This enables rapid, cost effective, 100mm thick walls with low environmental impact to be constructed. In most cases, modern earth masonry units are produced in commercial fired brick manufacturing plants using similar materials to fired bricks, but without putting the earth masonry through the firing process. This significantly reduces the energy used in manufacture and previous research has indicated unfired bricks have 14% of the embodied energy of fired bricks and 25% of the embodied
energy of concrete blocks. In Germany, some fired brick plants have moved to making only modern earth masonry and associated products.

**Control of internal environment**
Earth masonry has been shown to provide passive environmental control in buildings through buffering of the temperature in the building (through the provision of thermal mass), and through buffering relative humidity by absorbing moisture from the air at high humidity, and releasing it at low humidity. Buffering of temperature and humidity will normally reduce the energy required to operate buildings. To enable buffering of relative humidity, a specialist vapour-permeable render and paint are required. Gypsum plasterboard and non-permeable paints should not be used with earth masonry as they could lead to premature failure through build-up of water in the masonry.

The amount of moisture that will be absorbed by the walls in a 4mx4mx2.4m high room with a 100mm wall thickness is illustrated in the figure below. As shown, the earth masonry can absorb significantly more moisture from the air than either concrete blockwork or fired brick masonry without impairing its durability. Better state that this isn't a problem.

![Figure 20 - Moisture buffering capacity of earth masonry](image)

Empirical evidence has show that earth masonry can buffer humidity to medium humidity levels (40-65% relative humidity), but further research is required to confirm and model this effect. If this is confirmed, it could have positive implications for occupant health: “The incidence of absenteeism or respiratory infections was found to be lower among people working or living in environments with mid-range versus low or high relative humidities.” (Arundel et. al. Indirect health effects of relative humidity in indoor environments. Environ Health Perspect. March; 65 pp 351–361 (1986)).

**Strength of modern earth masonry**
The compressive strength of earth masonry is much more complicated than for blockwork or fired clay bricks and no single strength value can be assigned. The strength of modern earth masonry is dependent on the material properties, the dimensions of the wall and the water content. The material property that influences the masonry strength more than any other is the clay content in the masonry units.
As the water content in the masonry units is increased, the strength decreases and it is therefore important to keep the masonry dry once constructed through appropriate detailing, such as provision of a fired masonry or blockwork plinth to prevent accidental wetting from spills. Further information on detailing is available in the books listed at the end of this factsheet. The water content will normally be highest during construction (from application of wet mortar and render), and will then stabilise to a lower level (stronger masonry) during use.

After construction and in the absence of any accidental wetting (through appropriate detailing), the water content will be controlled by the relative humidity in the air, resulting in the relationship in the figure below. It is worth noting that the humidity must be maintained at the level for a considerable period of time (a number of weeks) before the water content will stabilise throughout the masonry. Boiling a kettle or having a shower will have negligible effect on the strength of the masonry.

![Figure 21 - Effect of relative humidity on strength](image)

As shown in the figure, even in the extreme range likely to be experienced (30% to 97.5% relative humidity), there is only a small change in strength. Long-term monitoring of a house constructed with modern earth masonry in Dalguise, Scotland showed that the relative humidity in the house remained between 40% and 65% throughout the year, even in the bathroom where a shower was used. Under this change in relative humidity the strength will change by approximately 12% for the earth masonry with high clay content, and only 8% for the low clay content.

The strength of earth masonry is normally lower than fired clay bricks or concrete blockwork, and 100mm thick earth masonry walls are currently not recommended for high load structural applications. Increasing the wall thickness will open the possibility for structural use of earth masonry.

**Mortars for modern earth masonry**

As the wall thickness decreases, the mortar must bond more to the masonry units to provide sufficient structural strength against lateral loads (pushing horizontally against the wall). The effect of wall thickness on required bond strength can be determined by a structural engineer, but it can be calculated that a 300mm thick wall with almost no bond strength (traditional earth masonry) can support the same load as a 100mm thick wall with a bond strength of approximately 0.2N/mm². The bond strength of different mortars with modern earth masonry is shown in the figure below.
This figure includes clay/sand and lime mortars used for traditional earth masonry and a cement/sand mortar used with fired bricks.

Figure 22 - Bond strength with different mortars

As shown, the mortars used for traditional earth masonry do not provide the bond strength required to construct 100mm thin walls using modern earth masonry. The use of a preformulated sodium silicate/clay/sand mix does, however, provide the required strength and provides a bond strength similar to cement mortars with fired bricks. The preformulated sodium silicate mortar has less than 10% of the embodied CO$_2$ than typical cement based mortars but does not perform as well at high water contents. These high water contents can be avoided through appropriate detailing.

An alternative to a sodium silicate based mortars is to tie 100mm thick modern earth masonry to a timber or other frame to provide the required lateral load capacity. This will provide the environmental benefits of earth masonry (thermal mass and humidity buffering) to a timber framed building.

Bricks, blockwork or earth masonry – which is best?

There is no simple answer to which is best as the different materials are suited to different applications. — That's way too weak!! Try 'There is strong evidence that in many internal walls, earth masonry will be preferable to concrete blockwork or fired brickwork, because of its low carbon emissions and health benefits. Concrete and fired brickwork are more likely to be suitable for loadbearing and fireproof walls. Some point to consider are:

- Earth masonry generally has much lower embodied energy and is easier to recycle and dispose of at end of use than blockwork or fired clay masonry.
- Earth masonry has the ability to absorb more moisture from the air than blockwork or fired brick masonry, and therefore provides better passive humidity control.
- Earth masonry does not have the same moisture resistance as blockwork or fired clay masonry, and detailing should ensure it is kept dry during and after construction.
Earth masonry generally has a lower strength than blockwork or fired clay masonry, and it is currently not recommended to use thin-walled earth masonry in high-load structural applications. It will also not support as high a load from fixings as fired clay bricks and concrete blockwork.
Further information

Books


Trade associations
UK earth building association: [http://www.arc-architects.com/research/EBUK.htm](http://www.arc-architects.com/research/EBUK.htm)

German earth building association: [http://www.dachverband-lehm.de/index_gb.html](http://www.dachverband-lehm.de/index_gb.html)


Research leader
BRE / University of Bath Centre for Innovative Construction Materials: [http://www.bath.ac.uk/bre/](http://www.bath.ac.uk/bre/)

Research partners
Arc Architects - [http://www.arc-architects.com](http://www.arc-architects.com)


Ibstock Brick Ltd: [http://www.ibstock.com/](http://www.ibstock.com/)

Lime Technology Ltd: [http://www.limetechnology.co.uk](http://www.limetechnology.co.uk)

Research publications


