# The flexural strength of earth block masonry for sustainable walling in the UK

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**Published in:**
Structural Survey

**DOI:**
10.1108/02630801111118403

**Publication date:**
2011

# Structural Survey

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# The flexural strength of earth-block masonry for sustainable walling

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**Abstract**

**Purpose** – The purpose of the paper is to explore the structural feasibility of substituting traditional thick joint mortars with earth slurry mortars modified with varying amounts of sand. Thin jointing of earth blocks would reduce the cost of sustainable earth construction.

**Design/methodology/approach** – Compressive strength of earth-block cubes was determined. Flexural strength was measured using the BRE electronic bond wrench, which enables block couplets to be tested quickly and accurately. Three samples of earth block, one from southwest England and two from East Anglia, together with nine examples of earth slurry mortar jointing were studied, including the effect of reinforcing the joint and or the block using hessian.

**Findings** – The 28-day cube characteristic compressive strengths were determined for Appley soil, Norfolk lump and Beeston soil, the last with 0 per cent sand, 25 per cent sand and with 25 per cent sand with hessian. The flexural strengths of Appley and Beeston earth slurries were determined, along with Thermalite thin jointed cement and cement mortar for comparison. The Beeston soil flexural strength increased with increasing sand content. Earth slurry with 40 per cent sand and hessian present in the joint gave the greatest strength. It is important to use blocks and slurry mortars of the same soil. Extruded and compressed earth blocks are best suited to slurry jointing.

**Originality/value** – This work successfully demonstrates the structural feasibility of carefully reducing the thickness of earth mortars when constructing sustainable earth block walling. Characteristic flexural strengths are suggested where the test results were sufficiently consistent, and of a magnitude likely to be useful in design.

**Keywords** Sustainable design, Mortars, England, Soils, Construction materials, Buildings

**Paper type** Research paper

## 1. Introduction

Unbaked earth materials are a possible replacement, where appropriate, for traditional masonry in the construction of walls of domestic scale buildings. The main unbaked earth technique that lends itself to modern construction methods is the use of earth blocks. The skills needed to manufacture, transport and lay earth blocks are similar to those associated with conventional masonry. However, as the physical properties of the earth blocks are subtly different from fired clay or concrete bricks and blocks the method of jointing of the individual units needs to take into account these differences. A further reason for examining jointing methods of earth blocks relates to the economics of earth block usage. One of the main restrictions on the rate of placing of blocks relates to the speed of laying, and the effectiveness of the resulting joint and the effect on the thickness of any walling system. To investigate the effects of using a

Structural Survey
Vol. 29 No. 1, 2011
pp. 46-62

0263-080X
DOI 10.1108/02630801111118403

range of jointing materials on the flexural strength three different categories of mortars have been examined in combination with a range of different earth blocks.

## 2. Aims

This study has three aims:

(1) To measure the 28-day cube strength of some typical earth blocks and some examples of suitable mortars.

(2) To measure the flexural strength of couplets made from various earth blocks and mortar combinations.

(3) To compare the flexural strength of these various couplets as the mortar sand content is increased and hessian is introduced to the joint.

This work will discuss earth blocks manufactured from soils obtained from two regions of England, briefly consider the soil characteristics of the two samples of earth and then present measurements of the strength of the earth blocks, and the strength of the mortars. The mortars considered will be earth slurry with and without ordinary Portland cement (OPC), earth slurry with added sand, and finally earth slurry with sand and added hessian.

The range of different mortar types that could be used with earth blocks is potentially large, traditional materials, such as lime or earthen based mortars, conventional cement based mortars and finally more recent innovations such as thin bed jointing systems. For comparison three mortars, earth, cement and thin bed systems were used, representing the range of philosophical and historical combinations of earth block and jointing compound.

Williams *et al.* (2010), discuss the wider aspects of earth block walling, such as the reasons for the decline in earth block building, the economics of earth block walling, and the thermal aspects. This establishes the case for earth block with earth mortars as a sustainable walling construction.

This paper will describe the two sources of soil used in the work, give details of the earth blocks manufactured from these soils, and then present the results of the flexural strength tests of the earth blocks, the mortars, and finally, the strengths of the block-mortar couplets produced using the earth slurry mortars.

## 3. The soils from Appley and Beeston

The two regions of the UK with the strongest tradition of earth block construction are the southwest of England and East Anglia.

Soils used to produce the blocks and slurry mortars were obtained from the block producer at Appley and from the site at Beeston.

Table I shows the proportions of clay, silt and sand and Table II shows the mineralogy of the soils. Figure 1 shows the particle size distribution. It can be seen that the Appley soil contains more silt and less sand than the Beeston soil. This could explain the large difference in compressive strength between blocks made from the two soils. Table II shows that both soil samples contain a predominance of illite, which is typical across much of England. Illite is a high-potassium group of clay minerals regarded as only moderately expandable. The high-aluminium kaolinite group are only slightly expandable, but would tend to produce blocks that are more brittle than some of the more expensive clay minerals. The smectite group, which includes montmorillonite is highly expandable, but can produce blocks with high compressive strength, Smith (1982). Only the Appley sample contained small amounts of smectite. Both samples should therefore be fairly stable with moderate amounts of expansion as they absorb moisture. The mortars are made from the same material as the blocks and will therefore have similar characteristics.

Walker (1999) carefully manufactured five soil samples to avoid the changes in mineralogical and organic matter from one natural soil to another. Sand with composition 3 per cent clay, 4 per cent silt, 89 per cent sand, with 4 per cent fine gravel, was mixed with clay soil, 44 per cent clay, 4 per cent silt, 25 per cent sand, and 25 per cent fine gravel. Five different sand + clay soil compositions were then mixed and each was stabilized with 5 or 10 per cent cement. Azeredo and Morel (2009) have also studied the flexural strength of earth block-earth mortar masonry. They describe a large range of earth sample compositions, varying the content of clay, cement and lime proportions.

Two important issues arise with the work of Walker (1999) and that of Azeredo and Morel (2009):

(1) It is unwise to compare the flexural strength results from these two studies with the present work, since they are based on very different soil samples;

(2) The soil samples of Walker were stabilized with cement, while Azeredo and Morel used combinations of both cement and lime.

**Table I.**
Particle size boundaries

| Soil source | Clay (%) | Silt (%) | Sand (%) |
|---|---|---|---|
| Appley | 32.57 | 58.87 | 8.56 |
| Beeston | 27.73 | 47.9 | 24.37 |

**Table II.**
Clay mineralogy

| | Clay mineralogy (%) | | | | |
|---|---|---|---|---|---|
| Soil source | Illite | Smectite | Vermiculite | Chlorite | Kaolinite |
| Appley | 92.25 | 2.58 | 0 | 0.63 | 4.53 |
| Beeston | 93.77 | 0 | 0 | 1.63 | 4.6 |

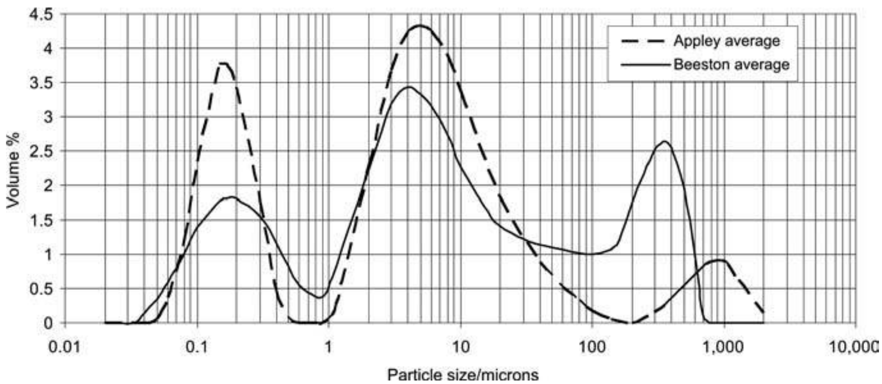


**Figure 1.**
Particle size distribution

However, in the present work the strength of natural earth sample blocks and mortars, with no addition of cement or lime to stabilise the materials, has been studied in pursuit of low cost, low energy and sustainable building materials.

## 4. The earth blocks

The earth block samples manufactured for this work reflect the areas of strongest tradition of earth block construction in the UK, namely: the southwest of England and East Anglia.

Three block types were studied, one produced from the southwest material:

(1) Appley, and two from East Anglia material.

(2) Norfolk.

(3) Beeston.

### *4.1 Southwest England*

There are at least two small manufacturers of earth blocks in the southwest. Although the tradition in this region is mainly cob, earth blocks known locally as cob blocks are seen by some as more convenient than cob itself, the blocks being ready to use and needing only traditional bricklaying skills. They are used to repair existing cob buildings as well as for other minor building.

*4.1.1 Appley blocks*. These blocks were recently used in the "Genesis project" at the Somerset College of Arts and Technology (Genesis Project, 2010). The blocks are manufactured to a standard concrete block size, 440 × 100 × 215 mm. They were purchased from The Cob Block Company based at Appley on the Devon Somerset border. The characteristics of the blocks are shown in Table III. The blocks are manufactured, by an extrusion process, using locally acquired sub soil. This process produces blocks with consistent dimensions, an important consideration when using earth slurry mortars. Uncut straw is included in the block mix. The block is largely un-screened; blocks can contain stones up to 50 mm across. Before testing, these blocks were kiln-dried until a consistent mass was obtained.

### *4.2 East Anglia*

In East Anglia large earth blocks known as clay lumps were used from the beginning of the nineteenth century up to the First World War with a few later examples. Typical block size is 440 × 215 × 140 mm. Although small quantities of clay-lumps are produced in Norfolk using hand moulds, there are no manufacturers as such. Since clay lumps are quite heavy, between 20 and 26 kg, it was decided that testing would be made easier and quicker with smaller units.

*4.2.1 Norfolk clay-lumps*. Norfolk clay-lumps were produced from recycled earth previously used in clay-lump blocks and acquired from demolished buildings. In the clay-lump areas of East Anglia and particularly in Norfolk, clay-lump is so ubiquitous it is not uncommon to find derelict former agricultural buildings constructed of clay lump, which can be recycled. The blocks measured 447 × 185 × 140 mm, slightly smaller than normal, and weighed just less than 20 kg. Two of these blocks were cut into sections approximately 70 mm wide using an angle grinder. The sections were cut to a size that would achieve an aspect ratio of at least two, so as to give the unconfined strength, and were subjected to the test for compressive strength, BS EN 772-1 (BSI,

**Table III.**
Characteristics of earth blocks

| Block type | Mean dry mass (kg) | Mean apparent dry density (kg/m$^3$) | Dimensions (mm) | Dry tensile strength (MPa) | Dry compressive strength AFNOR XP P13-901 (2001) (MPa) | AFNOR XP P13-901 (2001) Aspect ratio | Dry compressive strength BS EN 772-1:2000 (2000) (MPa) | BS EN 772-1:2000 (2000) Aspect ratio | Number of specimens | Characteristic compressive[a] strength (MPa) | Coefficient of variation (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | 0.572 | 2.2 | 6 | 0.51 | 6.55 |
| Appley | 15.59 | 1,674 | 440 × 216 × 98 | 0.178 | 0.806 | 1.02 | | | 10 | | |
| | | | | | | | 2.078 | 0.46 | 6 | | |
| Norfolk clay lumps | 20.63 | 1,757 | 447 × 185 × 142 | | | | 1.012 | 2.03 | 6 | 0.86 | 9.07 |
| Beeston +0 per cent sand | 2.96 | 1,836 | 204 × 85 × 93 | | | | 1.595 | 2.4 | 8 | 1.33 | 9.99 |
| Beeston +25 per cent sand | 3.37 | 1,816 | 208 × 92 × 97 | | | | 1.467 | 2.26 | 4 | 1.29 | 7.25 |
| Beeston +25 per cent sand + hessian | 3.35 | 1,872 | 207 × 91 × 95 | | | | 1.826 | 2.27 | 4 | 1.51 | 10.55 |

**Note**: [a]The sand modification did not make a significant difference to the compressive strength of the blocks, but did reduce the overall shrinkage of the block

2000a). A further six clay-lumps were made into three couplets and tested for flexural strength.

*4.2.2 Beeston blocks*. About 95 earth blocks were produced to dimensions of approximately 90 × 90 × 200 mm. The soil was excavated from a site in the village of Beeston approximately seven miles northwest of the town of East Dereham. The soil is chalky boulder clay, typical of the soil used to make clay lumps in the nineteenth century and common throughout much of Norfolk and Suffolk. Uncut barley straw was added at the recommended rate of 2 per cent by weight (Harries *et al.*, 2000). The earth was spread onto a concrete surface, the straw added and then trodden into the soil, turning it periodically and re-treading until the straw and earth were completely mixed. Water was added as necessary to the point where the soil could be squeezed from under the foot when trodden. Most stones larger than 25 mm could be detected underfoot and removed by hand. This material was hand compacted into a mould and then pushed down over a block size punch to remove the wet earth block from the mould. The blocks were conditioned for several months in a heated dry space until a consistent mass was obtained (see Table III).

When making large clay-lump blocks, removing the mould from the wet clay is relatively straightforward, the weight of the earth holds the block to the ground as the mould slips over the sides. With the small blocks described previously, the weight of wet earth was insufficient to overcome the frictional resistance of the sides of the mould. The blocks were made in three batches and in the third batch, in an effort to assist extraction of the block from the mould, a hessian lining was used in the mould. It was not anticipated that the hessian wrapping would have any effect on the compressive strength of the block or on the flexural strength of the joints. This however was not the case. Hessian improved both the compressive strength of the block and the bond between the mortar and block, thus significantly improving the flexural strength of the couplets.

## 5. Practical measurement of flexural strength

British Standards Institution BS 5628 (BSI, 2005) suggests flexural strength should be determined by the wallette method. However, when developing new materials requiring multiple tests, the wallette method is expensive and cumbersome. The Building Research Establishment (BRE) has developed an electronic bond wrench known as the BRENCH. This enables multiple tests to be carried out on couplets of bricks or blocks. BRE Digests 360 (BRE, 1991), points out that the calibration between the BRENCH and the wallette method is consistently measured at 1, to within the limits of experimental variability. Design values can therefore be derived from the results of BRENCH tests, particularly for checking the safety of vertically spanning walls.

Couplets of joined earth blocks representing the chosen range of jointing systems were subjected to a BRENCH test.

## 6. Structure of this study

The experimental work and the results are divided into five sections.

(1) The measurement of the physical and strength characteristics of the five types of earth blocks, Appley, Norfolk, Beeston, Beeston with sand, and Beeston with sand and hessian.

(2) The measurement of the physical and strength characteristics of the various types of mortars. For convenience the mortars are numbered mortar type 1 through to mortar type 9.
(3) The measurement of the flexural strength of mortars 1 to 5 when used with Appley blocks.
(4) The measurement of the flexural strength of mortars 6 to 8 when used with Beeston blocks. Here the effect of adding sand to the Beeston earth slurry was studied.
(5) The measurement of the flexural strength of mortar 9 when used with Beeston blocks. Mortar 9 had 40 per cent by weight of added sand and hessian reinforcement.

These results are now presented in detail.

*6.1 The earth block characteristics*
Table III shows the properties of the various earth blocks used in this study. There are strength results for five different blocks:

(1) Appley.
(2) Norfolk.
(3) Beeston with no sand.
(4) Beeston with 25 per cent sand.
(5) Beeston with 25 per cent sand and hessian.

Interpreting the results of compressive tests on masonry units can be very misleading. A unit strength of 1.5 MPa can seem quite low particularly when compared to conventional masonry where strengths typically range from 2.8 to 10 MPa for aerated or concrete blocks. It is important to distinguish between unit strength and characteristic strength. Unit strength refers to the masonry unit. BS EN 772-1 (BSI, 2000a) requires the masonry units to be tested in the aspect in which they are laid. Characteristic strength is the strength of the masonry formed from the bricks or blocks with the mortar acting together. To determine the characteristic strength, a design engineer will need to take account of the strength of the mortar, as well as the aspect ratio of the block. The characteristic strength of masonry is generally less than the strength of the units themselves. There are two reasons for this:

(1) The mortar can have a weakening effect. The more frequent the bed joints, the greater will be the weakening effect. For blockwork, and particularly unstabilised earth blocks, this is normally small or negligible since the mortar will be comprised of the same material as the block.
(2) Tests on the units do not give a correct indication of the strength of the unit within a wall unless the aspect ratio is 2.

If a series of specimens of identical material were tested with different aspect ratios, the strengths obtained from the tests would vary as a function of aspect ratio (see Table III). It must be clear that the material is not changing; it is the nature of the test, which is providing the different answers. Units with a low aspect ratio will record higher compressive strengths than those with high ratios because the platens of the testing machine restrain the top and bottom faces of the specimen against expansion. This introduces a state of tri-axial compression in the material close to the ends of the specimen and hence enhances its strength. The shorter the specimen, the greater is the effect on the overall strength. The unconfined (or unrestrained) strength of a masonry unit can be determined by testing specimens with an aspect ratio of 2. For conventional masonry BS 5628 (2005) provides tables to convert the unit strength and mortar strength to a characteristic strength for design purposes.

The absence of similar tables for earth masonry complicates the design process in the UK. One possible solution is to test the blocks on edge to give the unconfined strength.

*6.2 Comparisons between earth slurry mortars and cement based mortar mix C1*

Mortar mix C1 is defined in BS 8221-2 (BSI, 2000b) and in this work is called mortar type 5. It is a cement mortar of moderate compressive strength, frequently used with soft bricks or stones. The mix proportions are 1:3:12 by volume (OPC/hydrate lime/coarse sand). Weak cement mortars have in the past been used with earth blocks in the belief that they provide improved compressive and flexural strength. A cube of mortar type 5 achieved a compressive strength of 2.7 MPa at 28 days. It was used with Appley blocks to provide a comparison with Appley earth slurry. A cube of Appley slurry achieved a compressive strength of 1.03 MPa at 28 days. Mortar type 5 achieved a mean flexural strength of 0.012 MPa. This compared with 0.021 MPa for mortar type 3 (Appley slurry) using the same Appley blocks. The important conclusion is that the earth slurry mortar achieved a flexural strength 75 per cent higher than the C1 cement mortar.

*6.3 Flexural bond strength of mortar type 1 to 5*

The purpose of this first sequence of mortar studies was to compare unmodified slurry mortars with more commonly used mortars with known properties. Both Appley and Beeston soils were converted to slurry and used without sand or other modification. The other mortars were Thermalite proprietary thin joint mortar and mortar mix C1 to BS 8221-2 (BSI, 2000b). Beeston slurry mortar was also used with 10 per cent OPC, as mortar type 4 which is mentioned later, to see if the addition of cement improved the flexural bond strength.

The five mortar types considered here are:

(1) *Mortar type 1: Thermalite thin joint cement.* This proprietary product was used as a yardstick by which the other mortars could be measured. It is supplied as a dry powder to which water is added at the rate of 1 kg bag of mortar to 5.75L of water and whisked for two to three minutes. It should stand for five minutes and then a short final re-mix will create folds in the mortar, which are indicative of correct consistency.

(2) *Mortar type 2: Beeston earth slurry.* This was prepared by desiccating the soil for 24 hours, whisking, using an electric drill, for approximately four minutes, and then pouring the slurry through a 5 mm sieve. The slurry was produced to the same consistency as the Thermalite Thin Joint cement. It was used without the addition of sand.

(3) *Mortar type 3: Appley earth slurry.* This was prepared in the same way as the Beeston slurry and also passed through a 5 mm sieve. It was used at the same consistency as the Thermalite proprietary product.

(4) *Mortar type 4*: Beeston earth slurry plus 10 per cent OPC.
(5) *Mortar type 5: Mix C1*. The mix is 1:3:12 by volume cement/lime/sand mortar, BS 8221-2 (2000). Coarse sand was used in the mix.

*6.3.1 Failure modes of mortars 1 to 5*. Three failure modes were observed with mortars types 1 to 5, and they were classified as follows:

(1) *Failure mode A*. This occurred mainly in the set using Thermalite Thin Joint cement mortar. The mortar joint being stronger than the block the joint failed by splitting the block some 5 to 10 mm below or above the joint. With the Thermalite proprietary cement, the blocks sometimes failed in compression as well as flexure, as the back plate of the BRENCH jaw crushed the back of the block. A partial failure within the block also occurred in some samples where chalk fragments or straw were close to the surface.
(2) *Failure mode B*. This occurred at the interface between the block and the mortar. This was the most common mode of failure indicating a weak bond between the mortar and the block.
(3) *Failure mode C*. This was a flexural failure within the thickness of the joint. This occurred where the bond between the mortar and the joint was strong. It was usually combined with failure modes A or B.

*6.3.2 Flexural strengths of mortar types 1 to 5*. The results of the flexural studies on these mortars are shown in Table IV. Both the mean and characteristic flexural strengths are reported. Here the earth slurries were used without sand modification and as a result suffered extensive shrinkage cracks within the bed joints. This had the effect of reducing contact between the mortar and the blocks. This was judged to have resulted in the lower flexural strengths achieved in this first series compared with the later measurements using sand modified slurries. It was also found that the particle size was too large to achieve a thin joint. The material had been passed through a 5 mm sieve and as a result the thickness of the joint averaged approximately 9 mm. This may also have contributed to high shrinkage and reduction in flexural bond strength.

*6.3.3 Effect of using proprietary thin joint mortar with earth blocks (mortar type 1)*. Thermalite thin joint cement mortar had a 28-day cube strength of 10.7 MPa. A set of ten couplets was prepared. These achieved a mean flexural strength of 0.057 MPa. Failure mode tended to be type A. That is the failure occurred within the block rather than the joint indicating that the flexural limit of the block had been reached. A higher flexural strength would only have been attainable with a stronger block. The relatively low coefficient of variation indicates a high degree of consistency.

Where maximum flexural strength is required, Thermalite thin joint cement will give a flexural strength roughly equivalent to that of the earth block. It may not however be advisable in practice to use a mortar many times stronger than the block. Thermal and moisture induced movements in the wall could result in serious cracking within the block if the mortar is excessively strong.

*6.3.4 Effect of mixing earth blocks and earth mortars from disparate sources*. Appley blocks were used with both Appley slurry (mortar type 3) and Beeston slurry (mortar type 2). Where Appley blocks were used with Appley slurry, the adhesion was improved by a factor of three compared to the same blocks with Beeston slurry. The combination of Appley blocks and Beeston slurry produced very weak adhesion. Some

**Table IV.**
Characteristics of mortars 1 to 5

| Mortar type | Block type | Number of couplets | Flexural strength Mean (MPa) | Characteristic (Mpa) | Coefficient of variation (%) | Mode of failure |
|---|---|---|---|---|---|---|
| Thermalite thin joint cement | Appley | 10 | 0.057 | 0.041 | 16.5 | Block failure combined in just two samples with partial interface failure |
| Beeston earth slurry | Appley | 7 | 0.007 | 0.005 | 18.2 | Interface failure in all cases |
| Appley earth slurry | Appley | 10 | 0.021 | 0.011 | 27.3 | Mainly interface failure combined with partial block failure indicating improved bond |
| Beeston earth slurry plus 10 per cent OPC | Appley | 9 | 0.016 | 0.007 | 32.7 | Interface failure in all cases |
| Cement mortar mix C1 | Appley | 10 | 0.012 | 0.007 | 24.7 | Interface failure in all cases |

couplets came apart during the preparation for testing. The question then arose as to whether the lack of adhesion resulted from incompatibility of the two soils or whether there is some inherent weakness in the Beeston slurry.

The conclusion here is that both Appley and Beeston slurries work well when used with blocks of the same material. Mixing the two produced very poor results with recorded strengths approximately 66 per cent below that attainable with the same block-mortar combination.

*6.3.5 Effect of adding cement to slurry mortar*. Appley blocks were used with Beeston slurry (mortar type 2) and with Beeston slurry combined with 10 per cent OPC (mortar type 4). Adding 10 per cent cement improved performance by over 120 per cent.

The conclusion here is that moderate amounts of cement can improve flexural strength.

*6.4 Flexural bond strength of mortar types 6 to 8*

In this second sequence, Beeston slurry mortar was modified with varying amounts of sand and used with Beeston blocks and Norfolk clay lumps made from similar soil. The slurries were produced by wet sieving through a 2 mm mesh. The sand was also passed through a 2 mm mesh. The mortars were:

- Mortar type 6: Beeston slurry unmodified, identical to mortar type 2.
- Mortar type 7: Beeston slurry modified with 20 per cent sand (by mass).
- Mortar type 8: Beeston slurry modified with 40 per cent sand (by mass).

The results obtained for the flexural strengths of the mortars type 6 to 8 are shown in Table V.

In this sequence of mortar studies, a further ten couplets were prepared using Beeston slurry (mortar type 6, identical to mortar type 2) with Beeston blocks. These produced results around 70 per cent better than those obtained using the Appley combination.

Although the flexural strength of the unmodified Appley slurry had been better than a C1 cement mortar, the unmodified slurry had cracked extensively and it was thought this may have reduced surface contact and therefore flexural strength. The second set of tests would involve slurry mortars modified with varying amounts of sand with an unmodified set as a comparison.

In the previous sequence of studies, section 6.3, the thickness of the joints at approximately 9 mm was almost the same as conventional mortar. This would require large amounts of slurry mortar and would reduce the possible cost savings.

*6.4.1 Effect of adding sand*. The addition of sand virtually eliminated shrinkage cracking in the bed joint. The mean flexural strength increased from 0.036 MPa with no sand to 0.060 MPa with 20 per cent sand and 0.095 MPa with 40 per cent sand. This pattern was repeated with couplets of full-size Norfolk clay lumps, with a flexural strength of 0.014 with 0 per cent sand, 0.024 with 20 per cent sand and 0.030 with 40 per cent sand.

Each soil type will have an optimum clay percentage. If visible shrinkage cracks develop in the mortar, flexural bond strength will be adversely affected. Slurry mortar should be modified to the point where shrinkage cracks are eliminated. The more finely

**Table V.** Characteristics of mortars 6 to 8

| Mortar type | Block type | Bedding surface | Number of couplets | Flexural strength Mean (MPa) | Characteristic (Mpa) | Coefficient of variation (%) | Mode of failure |
|---|---|---|---|---|---|---|---|
| Beeston slurry unmodified | Beeston | Base to base | 5 | 0.036 | 0.032 | 6.5 | Mainly interface some block failure over straw |
| Beeston slurry unmodified | Beeston with hessian wrap | Hessian | 5 | 0.096 | 0.072 | 15.2 | Interface between slurry and non-Hessian wrapped block |
| Beeston slurry plus 20 per cent sand | Beeston | Side to side | 5 | 0.048 | 0.02 | 35 | Interface with block failure over straw or chalk fragments |
| Beeston slurry plus 20 per cent sand | Beeston | Base to base | 3 | 0.06 | 0.030[a] | 30.7[a] | Interface with block failure over straw or chalk fragments |
| Beeston slurry plus 20 per cent sand | Beeston with hessian wrap | Hessian | 2 | 0.129 | 0.063[a] | 31.2[a] | Interface between hessian and slurry |
| Beeston slurry plus 40 per cent sand | Beeston | Side to side | 5 | 0.051 | 0.027 | 28.8 | Interface with block failure over straw or chalk fragments |
| Beeston slurry plus 40 per cent sand | Beeston | Base to base | 5 | 0.095 | 0.074 | 13.5 | Interface with block failure over straw or chalk fragments |

**Note**: [a]Where the number of couplets tested is less than 5, the characteristic strength and coefficient of variation should not be regarded as reliable indicators of performance sieve material produced mortar joints of approximately 3 to 5 mm. This may also have contributed to an increase in flexural strength.

*6.4.2 Effect of block shape*. In cross-section, Beeston blocks were almost square with their sides only a few mm less than the base. The base of the block was generally flat while the sides tapered in slightly due to the method of drying. It was not anticipated that the bedding aspect would affect the results. However, as can be seen in Table V, blocks bedded base-to-base performed significantly better than those bedded side to side. This is most pronounced with mortar type 8. It is believed that this is partly related to the un-even surface of the side bedded blocks, which may have required a slightly thicker joint and partly due to the taper on the side, which may have induced a degree of torsion over the surface when tested.

For slurry-jointed masonry, the earth blocks must be dimensionally regular and consistent. Where the blocks were un-even due to the method of production, lower flexural strength resulted.

Extruded blocks and compressed earth blocks would be best suited to slurry jointing.

*6.4.3 Effect of hessian*. A greater influence resulted from blocks with a hessian wrap. With mortar types 6 and 7, the hessian wrap doubled the flexural strength of the couplet. Where the hessian covered only one block in the couplet, failure occurred at the interface with the non-hessian covered block. Where both blocks were hessian wrapped, failure occurred within the joint between the hessian and the slurry mortar.

Without the influence of hessian, failure was generally at the interface between the block and the joint. But where straw or chalk fragments were close to the surface of the block failure occurred within the block also. Hessian wrapped blocks improved the flexural strength of the joint dramatically. With type 6 mortar, the mean flexural strength improved from 0.036 to 0.096 MPa. A similar improvement was demonstrated with type 7 mortar. With handmade blocks the hessian wrap can be achieved by lining the mould. With extruded and other mechanised block production techniques, it would be less easily accomplished.

The use of hessian as a wrapping to earth blocks increased the flexural strength of the couplet by over 200 per cent.

*6.5 Flexural bond strength of mortar type 9*

In the third and final sequence of mortar studies, it was decided to use the best of the slurries with hessian reinforcement within the joint, to see if the results obtained with hessian wrapped blocks could be repeated. For handmade blocks, lining the mould with hessian is straightforward. However, if block production is ever to become commercially viable, it must become mechanised. Mechanised block production would make it almost impossible to incorporate a hessian wrap to the block. The only other way of incorporating hessian would be as a bed joint reinforcement.

Slurry was poured onto the lower block, the hessian pushed into the slurry and a further covering of slurry was provided before bedding the top block.

The results shown in Table VI for mortar type 9 with hessian indicate that a significant improvement in flexural strength can be obtained with hessian as a bed joint reinforcement.

All blocks were laid in the same aspect top to bottom. The tops of the blocks are particularly un-even and this will have influenced the consistency of the results.

Nevertheless, the coefficient of variation was comparable with earlier results using hessian wrapped blocks.

The mean flexural strength of 0.107 MPa was exceeded only by the small sample of hessian wrapped blocks. The characteristic flexural strength of 0.065 MPa was exceeded only by the type 8 mortar (Beeston slurry with 40 per cent sand) with blocks bedded base to base giving a consistent joint thickness. The coefficient of variation at 24 per cent is within the expected range of masonry tested with the BRENCH (BRE, 1991).

## 7. Discussion

Earth slurry mortars, modified with appropriate amounts of sand, will provide a flexural strength greater than can be achieved using thick joint mortars. Not only will the cost savings in terms of reduced labour be available, but it should also be possible to reduce the overall wall thickness. However, both the earth block and the slurry mortar must be made from the same soil. It must also be remembered that each soil will potentially produce different results. It would therefore be wrong to extrapolate these results beyond the soils tested in this work.

For slurry mortar to become a practical option, the earth blocks must be dimensionally regular. Compressed earth blocks and extruded blocks should both be suitable for use with slurry mortars.

Hessian can be included as a bed joint reinforcement or as a wrapping to the earth block and can improve the flexural strength by a factor of between two and three.

For conventional thin joint masonry, the claimed savings in labour costs vary between 35 per cent (Langdon, 2007) and almost 50 per cent (Howes, 2001).

Establishing flexural bond strength of a magnitude and consistency likely to be useful when designing walls to resist lateral (wind) loading, will enable significant savings to be made in the wall thickness. For two-storey dwellings, the compressive strength of earth block masonry has never been in doubt. The applied compressive stress under factored loads is likely to be around 0.2 MPa or approximately 60kN per linear metre with 300 mm thick walls. For external walls, and particularly those with limited pre-compression, for example with lightweight roofs and short span floors; the ultimate controlling stress will be wind induced flexural stress.

If zero flexural strength is assumed together with a fairly typical wind load in eastern and south-eastern England of 0.7kN/m$^2$, the pre-compression available from the mass of a wall 360 mm thick, together with roof load, is likely to produce zero flexural stress.

With flexural strength of 0.065 MPa (Mortar type 9 with hessian bed joint reinforcement) and the same design moment, the wall thickness could be reduced to 300 mm. With a flexural strength of 0.07 MPa (Mortar type 8 with Beeston block) the wall thickness could be further reduced to around 290 mm. This represents a 20 per cent reduction in wall thickness. In very simple terms this means 20 per cent less blocks and mortar and 20 per cent less labour.

## 8. Conclusions

This study of earth masonry had three aims, which have been met:

(1) The 28-day cube strength of some typical earth blocks made from soils found in Somerset and in East Anglia have been measured, along with the strengths of suitable mortars made from these soils.

**Table VI.**
Characteristics of mortar 9

| Mortar type | Block type | Bed joint reinforcement | Number of couplets | Flexural strength Mean (MPa) | Characteristic (MPa) | Coefficient of variation (%) | Mode of failure |
|---|---|---|---|---|---|---|---|
| Beeston slurry plus 40 per cent sand | Beeston | Hessian | 10 | 0.107 | 0.065 | 24 | Interface between top block and slurry or joint failure between slurry and Hessian |

(2) The flexural strength of couplets made from various earth blocks and mortar combinations has been reported. The greatest strength was achieved when the mortar was made with the same soil as the block.
(3) Measurements of the flexural strength of various block-mortar couplets as the mortar sand content was increased and as hessian was introduced to the slurry joint, indicated that the greatest strength occurred when the sand was at 40 per cent and hessian was present in the joint.

Finally, this study has highlighted four important issues regarding earth block masonry.

(1) Thermalite thin joint cement will give a flexural strength roughly equivalent to that of the earth block. It is unwise to use a mortar many times stronger than the block. Thermal and moisture induced movements in the wall could result in serious cracking within the block if the mortar is excessively strong.
(2) Both Appley and Beeston slurries work well when used with blocks of the same material. Mixing the two produced very poor results with recorded strengths approximately 66 per cent below that attainable with the same block-mortar combination.
(3) Each soil type will have an optimum clay percentage. If visible shrinkage cracks develop in the mortar, flexural bond strength will be adversely affected. The more finely sieved material produced mortar joints of approximately 3 to 5 mm, which may have contributed to an increase in flexural strength.
(4) For slurry-jointed masonry, the earth blocks must be dimensionally regular and consistent. Where the blocks were un-even due to the method of production, lower flexural strength resulted. Extruded blocks and compressed earth blocks would be best suited to slurry jointing.



### References

AFNOR XP P13-901 (2001), *Compressed Earth Blocks for Walls and Partitions: Definitions, Specifications, Test Methods, Conditions of Acceptance*, Association Française de Normalisation, Saint-Denis La Plaine Cedex.

Azeredo, G. and Morel, J.C. (2009), "Tensile strength of earth mortars and its influence on earth masonry behaviour", *Proceedings 11th International Conference on Non-conventional Materials and Technologies (NOCMAT2009), September 6-9, Bath.*

BRE (1991), *Digest 360: Testing Bond Strength of Masonry*, Building Research Establishment (BRE), Watford.

BSI (2000a), *BS EN 772-1: 2000: Methods of Test for Masonry Units-Part 1: Determination of Compressive Strength*, British Standards Institution, London.

BSI (2000b), *BS 8221-2: 2000: Code of Practice For Cleaning and Surface Repair of Buildings, Surface Repair of Natural Stones, Brick and Terracotta*, British Standards Institution, London.

BSI (2005), *BS 5628-1: 2005: Code of Practice for the Use of Masonry: Part 1: Structural Use of Un-reinforced Masonry*, British Standards Institution, London.

Genesis Project (2010), *Genesis Project*, available at: www.genesisproject.com/index.php?view=virtual-tour&c id=11 (accessed 15 April).

Harries, R., Clark, D. and Watson, L. (2000), "A rational return to earth as a contemporary building material", *Terra 2000, 8th International Conference on the Study and Conservation of Earthen Architecture, Torquay, Devon, UK, May 2000*, James and James, London, pp. 319-21.

Howes, P. Chartered Surveyors (2001), *A Report on Speed Trials for Thin Joint Mortar*, Marley Building Materials, Birmingham.

Langdon, D. (2007), *Spon's Architects' and Builders' Price Book*, Taylor and Francis, London.

Smith, E.W. (1982), *Adobe Bricks in New Mexico*, Circular 188, New Mexico Bureau of Mines and Mineral Resources, Socorro.

Walker, P. (1999), "Bond characteristics of earth block masonry", *Journal of Materials in Civil Engineering*, Vol. 11 No. 3, pp. 249-56.

Williams, C., Goodhew, S.M., Griffiths, R. and Watson, L. (2010), "The feasibility of earth block masonry for building sustainable walling in the UK", *Journal of Building Appraisal*, Vol. 6 No. 2, pp. 99-108.



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