This report takes into account the particular instructions and requirements of our client. It is not intended for and should not be relied upon by any third party and no responsibility is undertaken to any third party.

Job number 77337-55
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1 Introduction

Earth construction has been in use throughout the world in a range of forms (Fig 1) for thousands of years. For example, mud bricks were first used around 7000 years ago. The most common or best-documented forms are rammed earth and unfired blocks.

Having historically fallen out of favour in the developed world, earth construction remains widespread throughout developing countries, with the UNCHS estimating that as much as 40% of the world’s population live in homes built of earth.

More recently concerns over material scarcity and the high embodied carbon of modern construction materials have led to a revival in earth construction in the developed world. To date, this has been limited to a relatively small number of projects. Earth construction has, however, become a popular academic field with a large body of on-going research. In the UK this is estimated to eclipse the value of built projects per annum.

1.1 Scope

Fig 1. Earth construction typologies; those that fall within the scope of this Note are highlighted (Houben and Guillaud [1]).
This Note is intended to provide a high-level introduction to the use of unfired earth blocks for designers at Arup. It describes when earth block construction might be appropriate, and gives an overview of its limitations and merits, highlighting key design issues. References are given throughout so that more detailed information can be accessed. A library of details and list of existing Arup projects are attached as appendices.

Finally, this Note is intended to form the basis for further innovation and research into earth block construction. It is hoped that the guidance will enable unfired earth blocks to be considered a viable design option where appropriate.

The focus is on compressed blocks, with and without stabilisers, with reference made to extruded blocks and adobe construction. Rammed earth is not covered – refer to 2006 NST 10.

1.2 Definitions

Earth blocks can be formed by hand with or without moulds; they can be made by mechanical hand presses and by machines. Essential components are soil — containing gravel, clay, and sand — and water. Earth blocks are air-cured.

The terms earth, mud and soil are commonly used in earth construction to refer to graded subsoil.

Graded subsoil is soil taken from below the topsoil, with any organic material and particles larger than 5mm–6mm removed.

Adobe, mud brick and cob block are generally used as interchangeable terms to refer to hand-made blocks formed from clay, sand and water. They are shaped by hand or with the aid of a mould. Clay acts as the principal binder, with additives such as rice husks, straw or natural fibres often included to improve cohesion. They are air dried and should ideally be protected from direct sunlight and rain. Adobe construction, being an older and simpler technique, may be considered the precursor to compressed block technology.

Compressed earth blocks (CEBs) are created using a mechanised block press. A variety of presses is available, ranging from the most common single manual presses (which can be transported to individual sites) to mechanised plants. Blocks can be accurately shaped as solid, cellular or interlocking.

Stabilised soil blocks (SSBs) are generally compressed blocks with additives such as cement. They are also known as compressed stabilised earth blocks (CSEBs) and in some literature are also referred to as CEBs.

Interlocking stabilised soil blocks (ISSBs) are formed in presses that generate grooves within the blocks. Blocks may interlock vertically and or horizontally.

Stabilisation refers to methods of improving block properties such as strength and water resistance. They fall into three categories: mechanical, physical or additive stabilisation (refer to Section 3.3). In most literature, stabilisation may be taken to refer to additive stabilisation. The additives used may be chemical or natural, eg cement, lime, bitumen, natural oils or fibres.
Cob construction involves moulding and compressing a mix of clay sand, straw and water into layers, by hand or by foot, to form a monolithic structure. Cob construction is not a block form and is not covered here.

Rammed earth involves the dynamic compaction of gravel, sand, silt, clay and sometimes an organic additive or chemical admixture into formwork, typically to construct monolithic walls. Rammed earth is not covered in this Note — refer to 2006 NST 10.

![Forms of unfired earth block.](image)

**Fig 2.** Forms of unfired earth block.
1.3 Use in construction

Unfired earth blocks may be used in similar structural forms to traditional masonry, including but not limited to vaults, domes, arches, curved walls and floors.

**Watch it:** Unfired earth blocks should only be used for foundations in very dry climates on well-drained sites.

![Fig 3.](image1.jpg)  (L) Arch, Auroville Earth Institute. (R) Segmental 10.5m span vault, Deepanam School, India.

![Fig 4.](image2.jpg)  El Haj Yousif experimental school, Ethiopia, made of compressed earth blocks; regular returns provide the walls with out-of-plane stability.
Fig 5. Good Earth Trust House, Tanzania, made of curved interlocking blocks.

Fig 6. Farmhouse in Scotland constructed from earth blocks with timber cladding to provide protection and thermal insulation.

Fig 7. – Wales Institute for Sustainable Education (WISE) building, constructed from extruded earth blocks and rammed earth.
1.4 Advantages

Advantages of unfired earth block construction:

- Blocks have very low embodied carbon (they are air cured, and energy input compared to commercially or locally produced fired blocks is very low); refer to Section 1.7.
- There is little waste associated with unfired earth block construction.
- Blocks can be recycled in situ provided chemical additives have not been used.
- The thermal mass of blocks can be used as part of a passive design strategy.
- Blocks give thermal mass and acoustic insulation, inhibit condensation, and regulate the relative humidity of the atmosphere.
- Well-made stabilised blocks will typically outperform third-world homemade fired bricks in terms of strength and water permeability.
- Blocks are quick to manufacture and cure.
- Equipment needed to manufacture blocks can be inexpensive, consisting, for example, purely of simple timber moulds for adobe; refer to Section 4.2.
- Blocks may be constructed on site using site-won soil, thus reducing transport emissions and cost.
- Building with blocks can either use locally available traditional masonry skills, or provide a forum for training.

1.5 Disadvantages

Disadvantages of unfired earth block construction:

- In most quarters, unfired earth block construction is perceived as an inferior or primitive construction material that lacks durability.
- Few codes cover this form of construction, and it is generally not taught at university, meaning that designers lack the confidence to specify it.
- Unfired earth block construction is a low-strength, brittle material that cannot take tension or concentrated loads.
- Earth masonry has a lower surface hardness than many materials, making it vulnerable to damage from abrasion, accidental impact or erosion.
- Earth blocks are not suitable in freeze-thaw cycles, and in any case should be kept dry.
- Unstabilised earth becomes increasingly unstable in the presence of water.
- The dynamic behaviour of unfired earth block construction in seismic events is not well understood.
- Unfired earth block construction is susceptible to infestation by insects; for example, adobe blocks in the Americas are known to harbour the life-threatening Chagas disease; refer to Section 4.2.3.
• Contractors in the developed world lack the skills to build in earth and are increasingly averse to wet trades, whilst use of masonry is in decline.

• Insurance companies are likely to perceive unfired earth block construction as risky.

1.6 Appropriate use

Client/User
• Earth construction must be acceptable to the end user, who must be willing and able to maintain it.

Location
• Earth buildings should be located on sites that are well drained and located away from flood plains.

• Ideally there should be readily available suitable soil on site. If possible, arisings from substructure excavations should be used to avoid the need for additional excavation.

• Alternatively, soil may be imported; however, transport adds cost and carbon.

Building typology
• Load-bearing structures are unlikely to be taller than two or three storeys and may typically be one storey. Otherwise, walls become very thick and openings very small.

Block properties
• Soil properties may be improved through stabilisation. The method of stabilisation should take into account the needs of the project, local practice, cost, and availability. The indiscriminate use of cement should be avoided as this adds cost and reduces green credentials.

Detailing
• The architecture must be able to accommodate the detailing required to ensure durability.

• As with all forms of construction, seismic areas will require careful detailing and/or reinforcement.

Construction
• Block manufacture is well suited to on-site production but may also be located off-site in factories.

• Quality control is essential: block strength is dependent on the manufacture and curing process while wall strength is dependent on workmanship.
1.7 Sustainability

Unfired earth is a highly sustainable material. Where site soil is suitable to be hand manufactured into unstabilised blocks, it involves zero carbon. There is no waste and the blocks are fully recyclable at their end of life.

The decision to add cement to cement stabilise the blocks adds carbon and must be taken carefully. Refer to Section 3.3 for a detailed discussion.

1.7.1 Compressed earth


In many developing countries fired bricks are produced locally in homemade kilns. They typically consume large volumes of firewood, contributing significantly to deforestation and associated environmental degradation.

**Table 1.** Embodied carbon by volume comparison (Auroville Earth Institute [5]).

<table>
<thead>
<tr>
<th></th>
<th>Initial embodied energy (MJ/m³)</th>
<th>Embodied carbon (kgCO₂/m³)</th>
<th>Embodied carbon (kgCO₂/tonne)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CSEB (5% cement)</td>
<td>582</td>
<td>55</td>
<td>29 (1800kg/m³ assumed density)</td>
</tr>
<tr>
<td>Kiln fired brick</td>
<td>2,935</td>
<td>288</td>
<td>137 (2100kg/m³ assumed density)</td>
</tr>
<tr>
<td>Homemade fired brick</td>
<td>5,090</td>
<td>499</td>
<td>277 (1800kg/m³ assumed density)</td>
</tr>
</tbody>
</table>

1.7.2 Extruded

| Key reference | MORTON [6] |

**Fig 8.** Factory-gate embodied carbon (Morton [6]).
2 Soil

Ideally earth blocks will be constructed from site-won soil. In order to determine the suitability of a soil its properties must first be understood. These fall into four main categories:

**Table 2.** Fundamental soil properties (Houben and Guillaud [1]).

<table>
<thead>
<tr>
<th>Property</th>
<th>Definition</th>
<th>Determination method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grain or particle size distribution or texture</td>
<td>The percentage content of pebbles, gravels, sands, silts and clays</td>
<td>Sieving and particle hydrometer analysis</td>
</tr>
<tr>
<td>Plasticity</td>
<td>The ability of a soil to submit to deformation without elastic failure characterised by cracking or disintegration</td>
<td>Measurement of Atterberg limits:</td>
</tr>
<tr>
<td></td>
<td></td>
<td>LL = Liquid limit (%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>PL = Plastic limit (%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>PI = Plasticity index (%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>PI = LL - PL</td>
</tr>
<tr>
<td>Compressibility</td>
<td>The ability of the soil to be compacted to a maximum for a given energy and moisture content</td>
<td>Proctor compaction test</td>
</tr>
<tr>
<td>Cohesion</td>
<td>Ability of soil to remain together under application of tensile load.</td>
<td>Tensile strength test</td>
</tr>
</tbody>
</table>

**Table 3.** Soil particle size definition.

<table>
<thead>
<tr>
<th>Gravel</th>
<th>Sand</th>
<th>Silt</th>
<th>Clay</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt; 2mm</td>
<td>2mm – 0.063mm</td>
<td>0.063mm – 0.002mm</td>
<td>&lt; 0.002mm</td>
</tr>
</tbody>
</table>

Key references

HOUBEN and GUILLAUD [1]
Auroville Earth Institute [5]
HB195-2002 [7]
RIGASSI [8]
2.1 Water

Small amounts of water can help provide cohesion. Increasing water content serves to reduce cohesion, causing soil to become increasingly unstable.

The presence of water in soil can have the following effects:

Cohesion: Films of water help to give fine grains their cohesion.
Suction: Water suction increases with a reduction in water content.
Swell: Soil volume increases with water content.
Shrinkage: Shrinkage of clay is often due to water evaporation.
Plasticity: A well-hydrated cohesive soil is able to deform without cracking after reaching its elastic limit.

2.2 Suitability

When choosing a soil there are three main options:

- Use the soil available on site, and adapt the project to the quality of the soil.
- Use another soil more suited to the requirements, but which must be brought to the site.
- Modify the local soil to improve performance, generally referred to as “stabilising” it; refer to Section 3.3.

Clay has an inherent binding strength and acts to hold the soil together. The soil must have good cohesion to be used to make blocks, as well as good grain size distribution. See Table 4 for soils suitable for block making. Soil with too much clay can be blended with sand and vice versa.

Table 4. Soil composition for block making.

<table>
<thead>
<tr>
<th>Soil Type</th>
<th>Gravel</th>
<th>Sand</th>
<th>Silt</th>
<th>Clay</th>
</tr>
</thead>
<tbody>
<tr>
<td>CEB cement stabilised [7]</td>
<td>45-70</td>
<td>10-30</td>
<td>5-25</td>
<td></td>
</tr>
<tr>
<td>CEB cement stabilised [5]</td>
<td>15</td>
<td>50</td>
<td>15</td>
<td>20</td>
</tr>
<tr>
<td>CSEB lime stabilised [5]</td>
<td>15</td>
<td>30</td>
<td>20</td>
<td>35</td>
</tr>
</tbody>
</table>
Table 5. Soil unsuited to block making (HB195-2002 [7]).

<table>
<thead>
<tr>
<th>Cement-stabilised</th>
<th>Bitumen-stabilised</th>
<th>Lime-stabilised</th>
</tr>
</thead>
<tbody>
<tr>
<td>Topsoils</td>
<td>Topsoils</td>
<td>Topsoils</td>
</tr>
<tr>
<td>Organic matter content greater than 1% to 2%</td>
<td>Highly expansive soils</td>
<td>Soils with combined clay + silt content less than 30%</td>
</tr>
<tr>
<td>Highly expansive soils</td>
<td>Alkaline soils</td>
<td>Organic matter content in excess of 20%</td>
</tr>
<tr>
<td>Soils with soluble salts in sufficient quantities to impair strength or durability (found by trial testing).</td>
<td>Soils with high organic matter and sulphate content</td>
<td>Soils with excessive sulphates.</td>
</tr>
<tr>
<td></td>
<td>Soils with mineral salt content sufficient to impair strength and durability; proposed limit 0.25%.</td>
<td></td>
</tr>
</tbody>
</table>

Adobe or mud blocks are suited to a wider range of soil types.

2.3 Suitability testing

<table>
<thead>
<tr>
<th>Key references</th>
<th>HOBEN and GUILLAUD [5] (Chapters 3 and 6)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>HB195-2002 [7] (Chapter 2 and Appendix A)</td>
</tr>
<tr>
<td></td>
<td>Technical Advice Note 2, How to make stabilised soil blocks [9]</td>
</tr>
<tr>
<td></td>
<td>MINKE [10]</td>
</tr>
</tbody>
</table>

The suitability of soil for unfired earth blocks may be determined through a variety of tests. Some may be carried out in the field with no equipment at all while others are expensive lab tests. The level of testing required will depend upon the complexity of the project. The aim typically is to determine:

1. composition (gravel/sand/silt/clay)
2. plasticity
3. optimum moisture content (see Section 3.3.1)
4. organic matter content.

Table 6 lists some of the tests available. Note that it is not intended to be exhaustive.

Watch it: With in situ field tests, experience may be needed for them to be interpreted correctly.
### Table 6. Soil suitability tests.

<table>
<thead>
<tr>
<th>In situ field tests</th>
<th>Lab tests</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensory:</td>
<td></td>
</tr>
<tr>
<td>Visual inspection, smell,</td>
<td>Composition</td>
</tr>
<tr>
<td>nibble or tongue, touch</td>
<td>Sedimentation (particle hydrometer analysis)</td>
</tr>
<tr>
<td></td>
<td>and sieve analysis</td>
</tr>
<tr>
<td>Hand washing</td>
<td>Composition</td>
</tr>
<tr>
<td></td>
<td>Linear shrinkage</td>
</tr>
<tr>
<td>Lustre</td>
<td>Composition</td>
</tr>
<tr>
<td></td>
<td>Proctor test</td>
</tr>
<tr>
<td></td>
<td>Optimum moisture content</td>
</tr>
<tr>
<td>Adhesion</td>
<td>Composition</td>
</tr>
<tr>
<td></td>
<td>Plastic limit</td>
</tr>
<tr>
<td>Sedimentation or settlement</td>
<td>Composition</td>
</tr>
<tr>
<td></td>
<td>Liquid limit</td>
</tr>
<tr>
<td>Dry strength test</td>
<td>Clay content</td>
</tr>
<tr>
<td></td>
<td>Chemical analysis</td>
</tr>
<tr>
<td>Linear shrinkage</td>
<td>Plasticity</td>
</tr>
<tr>
<td>Scratch and polish</td>
<td>Mineralogical analysis</td>
</tr>
<tr>
<td>Rolling or consistency</td>
<td>Composition</td>
</tr>
<tr>
<td>Cohesion or ribbon</td>
<td>Clay content</td>
</tr>
<tr>
<td>Drop</td>
<td>Optimum moisture content</td>
</tr>
<tr>
<td>Dilatancy or water-retention</td>
<td>Fines composition</td>
</tr>
</tbody>
</table>

Details of a low-cost, portable field laboratory/test kit for determining soil and resulting block properties can be found on the website of the BRE Centre for Innovative Construction Materials at the University of Bath: http://www.bath.ac.uk/ace/research/cicm/low-carbon-materials/low-cost-test-kit-construction-apps.html.

**Fig 9.** University of Bath low-tech soil and block testing kit.
3 Design

Compressive stresses must be kept both within safe limits and uniform by ensuring point loads are well spread. Tensile and shear stresses should be minimised with geometry and mass used to maintain stability. Generally, structural soils have limited strength reserve capacity; they are working towards their limit, and thus minor imposed environmental or building changes can result in rapidly occurring structural and material distress.

Earth blocks should be considered as a form of masonry, whose properties can be quantified and designed for. In general, strengths are lower than for industrially fired masonry. Eccentric loads should be avoided or minimised and spreader elements should be used to limit local stress: point loads from trusses should be distributed into the wall via a timber wall plate or reinforced concrete ring beam.

3.1 Codes and guidance

<table>
<thead>
<tr>
<th>Key references</th>
<th>HOUBEN and GUILLAUD [1] (Chapter 7)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>HEATH et al [4]</td>
</tr>
</tbody>
</table>

Guidance on unfired earth blocks exists in France, Australia and New Zealand, the last in particular being home to useful codes. Unfired earth blocks are not, however, currently covered by either Eurocodes or British Standards.

Having withdrawn its earth codes in the 1970s, Germany is in the process of launching a series of unfired earth codes, currently in draft version only.

Work at the University of Bath has shown that some simple calculations in EN1996 [11] can provide accurate predictions of performance of extruded, unstabilised, unfired earth blocks. This work is based upon a specific type of mortar while highlighting that moisture susceptibility is not adequately covered by the code.

Table 7. Unfired earth block design codes and specifications.

<table>
<thead>
<tr>
<th>Country</th>
<th>Title</th>
<th>Pages</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MIDDLETON and SCHNEIDER [12]</td>
<td>65</td>
<td>Bulletin 5 is the de facto standard for earth construction in Australia and is accepted by many local authorities. There are no provisions for earthquake loads in Bulletin 5.</td>
</tr>
<tr>
<td></td>
<td>ARS680-682:1996 [16]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Country</td>
<td>Code</td>
<td>Language/Description</td>
<td></td>
</tr>
<tr>
<td>----------</td>
<td>-------------------------------------------</td>
<td>-------------------------------------------------------------------------------------</td>
<td></td>
</tr>
<tr>
<td>France</td>
<td><strong>DTC2001 [18]</strong></td>
<td>No English version found.</td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>DTC2101 [19]</strong></td>
<td>No English version found.</td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>DTC2102 [20]</strong></td>
<td>No English version found.</td>
<td></td>
</tr>
<tr>
<td>Germany</td>
<td><strong>DIN18945 [21]</strong></td>
<td>No English version found.</td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>DIN18958 [22]</strong></td>
<td>No English version found.</td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>DIN18946 [23]</strong></td>
<td>No English version found.</td>
<td></td>
</tr>
<tr>
<td>India</td>
<td><strong>IS1725:1982 [26]</strong></td>
<td>10 Specification for soil-cement blocks used in general building construction.</td>
<td></td>
</tr>
<tr>
<td>New Zealand</td>
<td><strong>NZS4297:1998 [28]</strong></td>
<td>62 Specifies design criteria, methodologies and performance aspects for earth wall buildings and is intended for use by structural engineers.</td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>NZS4298:1998 [29]</strong></td>
<td>90 Provides methods and details for the design and construction of earth walled buildings not requiring specific engineering design.</td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>NZS4299:1998 [30]</strong></td>
<td>130 Defines the material and workmanship requirements to produce earth walls which, when designed in accordance with NZS4297 or NZS4299, will comply with the requirements of the New Zealand Building Code; covers adobe, rammed earth and pressed brick.</td>
<td></td>
</tr>
<tr>
<td>USA</td>
<td><strong>ASTM E2392/E2392M - 10e1 [32]</strong></td>
<td>10 Specification and some guidance.</td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>IBC: 2009 Section 2109.3 [33]</strong></td>
<td>4 Specification and some guidance.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>New Mexico earthen buildings code [34]</td>
<td>13 Specification and some guidance.</td>
<td></td>
</tr>
</tbody>
</table>

Earth codes are also available in Peru and the Ivory Coast.
3.2 Structural properties

Table 8 gives the key structural properties from a range of sources as listed along the top. It is intended to give the user an idea of the range of values for various structural properties that might be achieved for a given block type. It may be necessary to improve the block properties; this process is called stabilisation (refer to Section 2.3).

Table 8. Typical structural properties.

<table>
<thead>
<tr>
<th>Block Type</th>
<th>Standards</th>
<th>Test results (Houben and Guillaud, 1994)</th>
<th>Developing world manufacturers</th>
<th>Arup Case studies</th>
<th>Commercial Manufacturers</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Auroville Class A</td>
<td>CSEB</td>
<td>CSEB</td>
<td>CSEB</td>
<td>CSEB</td>
</tr>
<tr>
<td>Block dimensions (mm)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>mm</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>mm</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Volume (m3)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Block weight (kg)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Block density (kg/m3)</td>
<td>1900 - 2200</td>
<td>1700 - 2000</td>
<td>&gt; 1600</td>
<td>1700 - 2200</td>
<td>&gt; 2200</td>
</tr>
<tr>
<td>28 Day dry compressive strength (MPa)</td>
<td>5-7</td>
<td>2.5</td>
<td>&gt;2.5</td>
<td>&lt;2</td>
<td>2 - 5</td>
</tr>
<tr>
<td>28 Day wet compressive strength (MPa)</td>
<td>2-3</td>
<td>1-2</td>
<td>&gt;1.5</td>
<td>0 - 0.5</td>
<td>&gt;2</td>
</tr>
<tr>
<td>28 Day bending strength (MPa)</td>
<td>0.5 - 1</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Water absorption (%)</td>
<td>5 - 10</td>
<td>10 - 20</td>
<td>&lt;15</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Cement content (%)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Notes: (1) - Kenya standard specification (2) - Uganda standard specification (3) - Blocks immersed in water for 24h (4) - Assumption (5) - Tested after 14 days only
3.2.1 Compressive strength

Compressive strength increases with dry density and can be improved through compaction. Adobe blocks will typically have compressive strengths at the lower end of the unfired block range as a result.

Compressive strength increases with time from the point of manufacture as the blocks “cure”.

**Watch it:** The strength of unstabilised extruded earth blocks reduces exponentially with moisture content (Heath et al [4]).

![Compressive strength with moisture content](image)

**Fig 10.** Compressive strength of unstabilised extruded earth blocks with varying water content.

3.2.2 Bending strength

Bending strength depends mainly on the clay content. Montmorillonite has a higher bending strength than kaolinite (Minke [35]).

**Table 9.** Bending strength (*HB195-2002* [7]).

<table>
<thead>
<tr>
<th>Block type</th>
<th>Bending strength</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adobe</td>
<td>0 – 0.5MPa</td>
</tr>
<tr>
<td>CEB</td>
<td>0.4 – 4.0MPa</td>
</tr>
</tbody>
</table>

Previous Arup projects where CEBs were used have assumed a value of 0.2MPa. As an approximate rule of thumb, compressive strength may be expected to be five to eight times the bending strength (Rigassi [8]).
3.2.3 Tensile strength

Tensile strength should be taken as zero. Structures should be designed to avoid tension.

3.2.4 Shear strength

Shear strength should be taken as zero unless proven otherwise by testing.

The frictional component of shear capacity should be calculated using the relevant coefficient of friction, which for dry, horizontal beds should be taken to have a maximum value of 0.2 (*HB195-2002* [7]).

3.2.5 Elastic modulus

Earth block masonry is brittle. Where it is, however, assumed to have linear elastic properties and in the absence of test data, Young’s modulus may be taken as $E=200\text{MPa}$ (*HB195-2002* [7]).

3.3 Stabilisation

<table>
<thead>
<tr>
<th>Key references</th>
<th>HOUBEN and GUILLAUD [1] (Chapter 4)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MORTON [6]</td>
</tr>
<tr>
<td></td>
<td>MINKE [10]</td>
</tr>
<tr>
<td></td>
<td>MUKERJI [37]</td>
</tr>
<tr>
<td></td>
<td>DAVIS and LAMBERT [38]</td>
</tr>
</tbody>
</table>

Often it may be necessary to improve block properties. The aim of stabilisation is to achieve:

- improved cohesion
- improved compressive, tensile or shear strength
- reduced porosity and in turn susceptibility to shrinkage and swell
- improved waterproofing, resistance to erosion or abrasion.

Soil stabilisation is not an exact science, and there is no miracle stabiliser that can be applied indiscriminately. The method of stabilisation falls into one of three categories, namely:

1. mechanical
2. physical
3. additive.

Each method may in turn have one of six effects, namely raising density, reinforcement, linking, binding, waterproofing and water repellent treatment (Houben and Guillaud [1]).

A wide range of stabilisers are used in earth block construction. Table 10 lists a small selection with a summary of their effects.
### Table 10. Stabilisation matrix (Morton [6], Minke [10], and Mukerji [37]).

<table>
<thead>
<tr>
<th>Soil type</th>
<th>Physical</th>
<th>Mechanical</th>
<th>Chemical additive</th>
<th>Natural additive</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Compressive strength</td>
<td>Tensile strength</td>
<td>Water erosion</td>
<td>Cohesion</td>
</tr>
<tr>
<td>Physical</td>
<td>Compression</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Mechanical</td>
<td>Optimisation of grain fraction</td>
<td>x</td>
<td>X</td>
<td>x</td>
</tr>
<tr>
<td>Chemical additive</td>
<td>Cement (low levels can cause a reduction)</td>
<td>x</td>
<td>X</td>
<td>x</td>
</tr>
<tr>
<td></td>
<td>Lime</td>
<td>x</td>
<td>X</td>
<td>x</td>
</tr>
<tr>
<td></td>
<td>Bitumen (high levels can cause a reduction)</td>
<td>x</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Natural additive</td>
<td>Animal products (dung, urine, animal glues, fats, oils)</td>
<td>x</td>
<td>X</td>
<td>x</td>
</tr>
<tr>
<td></td>
<td>Plant saps</td>
<td>x</td>
<td></td>
<td>x</td>
</tr>
<tr>
<td></td>
<td>Starches</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td></td>
<td>Lignosulfates</td>
<td>x</td>
<td></td>
<td>x</td>
</tr>
<tr>
<td></td>
<td>Gypsum</td>
<td>x</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fibres</td>
<td>Reduction</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td></td>
<td>Ashes</td>
<td>x</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Tannins</td>
<td>x</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Gum Arabic</td>
<td>x</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
3.3.1 Mechanical stabilisation

Mechanical stabilisation increases the density of the blocks, often through the use of a press. This reduces the maximum pore size and increases compressive strength and resistance to water as a result.

Optimum moisture content is defined as the water content at which a specified compactive force will result in the maximum dry weight of a given soil.

The optimum moisture content is usually 2-3% less than the plastic limit of the soil. In the absence of soil test data an optimum moisture content of 10% may be assumed for clayey sands.

![Graph showing relative strength and moulding moisture content](image)

**Fig 11.** Optimum moisture content for various compaction methods for an example soil (Houben and Guillaud [1]).

3.3.2 Physical stabilisation

Physical stabilisation is where the mix is improved by using optimum amounts of silt, clay, sand and gravel. The aim is to reduce the voids ratio and increase contacts between the grains. This can dramatically improve compressive strength and resistance to water erosion (Minke [10]).

3.3.3 Additive stabilisation

Note that most literature is referring to additive stabilisation when using the term “stabilised”.

Additive stabilisation can be natural or chemical. This Note refers in detail only to Portland cement, being the most common method. A wide range of chemical and natural additives is used to improve block quality (see Table 10). More recent additions not listed in the table include geopolymers and enzyme stabilisers.
3.3.4 Cement

Watch it: Indiscriminate use of cement stabilisation should be avoided; it adds cost and carbon and reduces hygroscopicity.

Watch it: Cement changes the properties of earth bricks significantly, becoming the principle binder rather than increasing the properties which already exist in the clay; at low levels cement can reduce the compressive strength of a block.

Cement improves water resistance and durability as well as compressive strength. Some soils require just 3% while in other soils this will cause a reduction in compressive strength. Good results are achieved with between 6–12% cement.

In soil determined to be suitable for block making, and where the need for stabilisation has been identified, one way to determine the cement content is from a shrinkage test (see Table 11). Although widely quoted, linear shrinkage could be considered a crude and arbitrary way to determine cement content. Alternatives include trial and testing.
Table 11. Shrinkage test to determine cement content (Davis and Lambert [38]).

<table>
<thead>
<tr>
<th>Gap</th>
<th>Mix ratio</th>
<th>Soil</th>
<th>Cement</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Less than 15mm</td>
<td>Too much sand — add clay</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15 - 30mm</td>
<td>16</td>
<td>1</td>
<td>6.3%</td>
<td></td>
</tr>
<tr>
<td>30 - 45mm</td>
<td>14</td>
<td>1</td>
<td>7.1%</td>
<td></td>
</tr>
<tr>
<td>45 - 60mm</td>
<td>12</td>
<td>1</td>
<td>8.3%</td>
<td></td>
</tr>
<tr>
<td>More than 60mm</td>
<td>Too much clay — add sand</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

3.4 Rules of thumb for non-seismic load-bearing construction

Key references
HB195-2002 [7]
MIDDLETON and SCHNEIDER [12]

Table 12. Minimum wall thickness (HB195-2002 [7]).

<table>
<thead>
<tr>
<th>Minimum wall thickness (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>External</td>
</tr>
<tr>
<td>Internal</td>
</tr>
<tr>
<td>200</td>
</tr>
<tr>
<td>125</td>
</tr>
</tbody>
</table>

Table 13. Maximum slenderness (HB195-2002 [7]).

<table>
<thead>
<tr>
<th>Maximum slenderness</th>
<th>Compressed block</th>
<th>Adobe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clear height</td>
<td>Lateral restraint at top and bottom</td>
<td>≤ 10t</td>
</tr>
<tr>
<td>Freestanding</td>
<td>≤ 18t</td>
<td>≤ 14t</td>
</tr>
<tr>
<td>Clear length</td>
<td>≤ 30t</td>
<td>≤ 20t</td>
</tr>
</tbody>
</table>

3.4.1 Openings
The total length of openings in a wall should be less than 35% of its overall length.
The minimum distance between an opening and a corner should be 1m.

3.4.2 Other
Vertical joint spacing 3m–6m
Pier width ≥ t or 650mm (whichever is greater)
Lintel support ≥ 250mm
3.5 Detailed design calculations

Key references

<table>
<thead>
<tr>
<th>Reference</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>HB195-2002</td>
<td>[7]</td>
</tr>
<tr>
<td>NZS4297:1998</td>
<td>[28]</td>
</tr>
</tbody>
</table>

3.6 Durability

In order to achieve durability, it is important that the limitations of unfired earth block construction are understood and considered by both the architect and the engineer. If used correctly there is no reason why they cannot satisfy the typical 50-year design life. Methods of damage include:

Water: loss of cohesion – earth construction is soluble in water

- splitting due to freeze/thaw cycles
- salt deposits which may break down the clay matrix

Impact: from people, animals, etc

Vegetation: undermining of wall

- plant growth on the surface as a result of damp facilitating infestation from rodents and insects.

3.6.1 Detailing

**Fig 14.** Pajule School, Uganda — interlocking stabilised soil blocks protected by veranda with stone and cement base render; openings and corners also protected with render.

The overarching principle is to protect against water. Earth masonry should never be allowed to sit in water. The “hat and shoes” approach should be followed — the parts of a wall most vulnerable to water are the top and the bottom. Refer to Appendix A: Case studies and Appendix B: Typical details.
Orientation

Walls facing the prevailing wind direction are at greater risk from wind-driven rain and should be well protected. Consider orientating gable ends away as they tend to be more exposed.

Surroundings

A veranda or covered walkway provides additional protection, and should be designed to drain away from the wall.

Vegetation should be kept away from walls.

Drainage

Water must not be allowed to pool at the base of a wall.

The surrounding area should be well drained and graded to prevent surface water collecting. Consider that hard surfaces cause more splashing.

Gutters and pipes carrying water should be located away from walls if possible in case of leaks. Alternatively they should be checked regularly to ensure speedy repair as part of a maintenance regime (refer to Section 4.7).

Foundations

Earth blocks should only be considered for foundations for very dry, well-drained sites. In this case the blocks should always be stabilised.

Damp-proof course

Earth masonry must be isolated from groundwater and so a damp-proof course should always be included, even when the masonry is located on top of a concrete or fired earth brick foundation.

The damp-proof course should be continuous with the slab protection and generally at least 150mm above ground level.

The material chosen should be flexible in order to accommodate shrinkage of the wall. Suitable materials include bitumen-coated aluminium, copper and copper alloys, lead and zinc, or heavy-duty plastic sheeting.

Base protection

The base of a wall is especially prone to water erosion by splash, standing or pore water. To this end the base of the wall may either be raised up on a base course or protected by a wearing layer.

A base course could consist of fired brick or concrete.

A wearing layer could consist of a stone/cement render as employed at Pajule School, Uganda. Refer to Appendix A: Case studies.
Table 14. Base course height (Houben and Guillaud [1]).

<table>
<thead>
<tr>
<th>Climate</th>
<th>Base course height</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry regions</td>
<td>0.25m</td>
</tr>
<tr>
<td>Average rainfall</td>
<td>0.4m</td>
</tr>
<tr>
<td>Heavy rainfall</td>
<td>0.6m</td>
</tr>
<tr>
<td>Area susceptible to flooding</td>
<td>Above predicted flood height</td>
</tr>
</tbody>
</table>

The height of the base course may also depend upon the roof overhang provided.

Roof overhang

Roof overhangs should normally be provided to prevent water impacting on and running down the face of the wall. The length of projection required will vary according to the climate. In areas with extreme weather where wind-driven rain may impact the wall at shallow angles, roof overhangs become less effective. In this case additional measures such as surface protection should be provided.

Table 15. Suggested roof overhangs.

<table>
<thead>
<tr>
<th>Category</th>
<th>Roof projection</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full protection Terrain category 1 [12]</td>
<td>H</td>
</tr>
<tr>
<td>Full protection Terrain category 2 [12]</td>
<td>0.75H</td>
</tr>
<tr>
<td>Full protection Terrain category 3 [12]</td>
<td>0.5H</td>
</tr>
<tr>
<td>Excellent protection against rainfall in most regions [7]</td>
<td>0.33H</td>
</tr>
<tr>
<td>Minimum [7]</td>
<td>400mm</td>
</tr>
</tbody>
</table>

H = height of earth wall measured from base course to roof eaves; H might be reduced if the base of the wall is protected by a wearing layer.

AS1170.2-1989: Category 1: Exposed open terrain with few or no obstructions (natural or man-made objects that generate turbulent wind flow, such as trees, forest, isolated structures and closely spaced buildings) and water surfaces. Category 2: Water surfaces, open terrain, grassland with few, well-scattered obstructions having heights generally from 1.5m–10m. Category 3: Terrain with numerous closely spaced obstructions 3m–5m high, such as areas of suburban housing.

Surface protection

The requirement for a protective coat or finish may depend on several factors:

1. climate
2. architectural detailing and aesthetic requirements
3. building use
4. acceptable level of maintenance.

Surface protection may be applied internally and externally. It is vital that it is vapour permeable. Refer to Section 3.8.1 for more information.

Internal walls around “wet areas” such as sinks should be protected against splashback. Showers and other areas subject to high volumes of water should be constructed of other materials.
Clients and architects may wish to expose the blocks. In this case washes may be applied. These tend to be less robust and should only be used in conjunction with base protection and roof overhangs.

Methods of surface protection include but are not limited to:

- **Cladding:** (eg, timber rain screen or external leaf of fired brick) In climates where buildings must be heated, the external surface will need to be insulated and clad to provide inherent weather protection.

- **Render:** Refer to Section 3.8.1.

- **Paint/distemper/wash/slurry:** These are typically less robust and may require more regular re-application.

### Corner details

The stability of earth masonry structures depends largely on the stability of their corners. Consider that corners and openings are especially prone to impact damage.

Corners may be strengthened by substituting a harder material, such as stone or burnt brick, for the earth blocks. Alternatively surface protection may be applied.

### 3.6.2 Maintenance

Refer to Section 4.7.

### 3.7 Seismic

#### 3.7.1 Introduction

Design guidance for unfired earth block structures is lacking compared to modern construction materials. This is especially true for seismic design (see Section 3.7.2).

In the absence of definitive guidance this part of the Note gives an overview of the issues. Further, but incomplete, information may be found in Appendix D.

**Watch it:** Earth masonry is a low-strength, brittle material.

**Watch it:** Unfired earth structures are susceptible to damage from even low-intensity seismic action due to their heavy weight, low tensile strength and poor resistance to shear loading. During earthquakes, unfired earth structures are liable to fail abruptly; typical failure mechanisms are illustrated in Fig 15. Their vulnerability can be compounded by poor workmanship and lack of maintenance.
There is a large quantity of existing earth structures, typically adobe, in seismic areas, with several research projects examining how these structures might be retrofitted or built more robustly in the future. Refer to Appendix D.

Watch it: In structures with limited ductility, the system as a whole, or the primary lateral load-resisting components, are not considered to be capable of sustaining the inelastic displacements that are expected in fully ductile structures, without significant loss of strength or reduction in energy-dissipating capacity.

Guidance on the design of masonry structures in areas of seismicity is provided by the New Mexico City Building Code [34] and EN1998 [40], covering reinforced and confined masonry design. Both are written with engineering quality brick in mind and require minimum compressive strengths of 5MPa and 6MPa respectively — greater than most unfired earth blocks. In any case the applicability of this guidance to unfired earth blocks is untested.
3.7.3 Design approach

The design approach in seismic areas is:

1. Determine the seismic hazard.
2. Do local seismic codes exist? If so, are they up to date? If not, understand what is required by local building control to deviate from them.
3. Understand client and building use requirements for performance of the structure in a seismic event.

Passive design

A commonly stated approach is to “passively” design out as much of the risk as possible (Blondet et al [39]). This includes, but is not limited to:

- suitable site selection
- use of uniform brick sizes
- providing symmetry on plan
- minimising the height of centre of gravity
- provision of regular crosswalls
- detailing walls, floor and roofs so that they are well tied and work together in a seismic event; floors should behave as diaphragms sharing load between walls
- ensuring appropriate workmanship, paying particular attention to mortar bond strength
- consideration of maintenance.

Active design

Active measures typically require greater design input, build complexity, and cost:

- reinforced masonry
- confined masonry.

Refer to Appendix D for further information.
3.8 Specification

3.8.1 Render

Watch it: Impermeable surface finishes should be avoided for unstabilised walls. It is vital that water is allowed to move freely into and out of earth construction. This includes sand and cement renders/plasters and many types of paint. Water, which will inevitably find its way into the wall via small cracks, then becomes trapped leading to degradation and failure of the surface finish and/or the wall.

- Renders may be stabilised with a similar list of products as for the blocks themselves.
- Shrinkage can be controlled by fibre additives.
- Single coats should be avoided. Render should be applied in two or preferably three coats.

![Render application](https://via.placeholder.com/150)

**Fig 17.** Render is best applied in three layers (Houben and Guillaud [1]).

3.8.2 Mortar

Watch its: High cement content can mean that the mortar is the most expensive part of the wall!

- Wall panel flexural properties are governed by bond strength.
- Bond strength is especially important in seismic areas where it plays a big role in a structure’s ability to withstand seismic loads.
- Mortar should be compatible with the blocks, ie it should have similar or lower compressive strength and erosion resistance. Sand/cement mortars are likely to be unsuitable. The Good Earth Trust advises that damaged blocks may be crushed and mixed with additional cement to form the mortar for ISSB construction.
- Stabilised mortar must be used with stabilised bricks. The stabiliser content should be increased by 1.5–2 times relative to the blocks with which it is used (Houben and Guillaud [1]).

- Mortar beds should be limited to 10mm at most, as thicker beds act to weaken the wall. For pressed blocks, mortar beds may be as thin as 2mm–3mm.

- Hand-shaped adobe blocks may require mortar beds thicker than 10mm so as to accommodate any unevenness.

### Commercially extruded blocks

Heath et al [4] states that conventional cement or lime-based mortars do not provide sufficient bond strength to be used in load-bearing construction using unstabilised extruded blocks. It instead recommends that sodium silicate-based mortars should be used. Cheaper versions of the widely-used but expensive fire-proof sodium silicate mortars are being developed specifically for earth masonry.

The manufacturer Ibstock Brick recommends that for non load-bearing applications moderately hydraulic lime mortar or alternatively clay mortars should be used to lay their blocks. Lime Technology recommends the use of sodium silicate mortar where blocks are laid on edge, requiring a stronger bond. Where blocks are laid flat, a hydraulic lime mortar is sufficient.

### 3.9 Other properties

Earth block construction provides thermal mass and acoustic insulation, inhibits condensation, and regulates the relative humidity of the atmosphere.

**Watch it:** Passive environmental control can be reduced by cement stabilisation which reduces hygroscopicity (Modern Earth Masonry).

#### 3.9.1 Humidity

<table>
<thead>
<tr>
<th>Key references</th>
<th>MORTON [6]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MINKE [10]</td>
</tr>
</tbody>
</table>

Earth buildings are proven to generate healthy indoor climates through regulation of relative humidity and removal of airborne pollutants. Earth is a hygroscopic material, meaning that it is able to absorb and release water as a gas from the air. This enables it to passively regulate relative humidity, potentially reducing the reliance on mechanical systems. Hygroscopicity can also eliminate the need for vapour control membranes and design out the risk of condensation.

Unfired clay can absorb and desorb indoor humidity faster than any other building material, and will regulate relative interior humidity between 40%–70%, the level at which the likelihood of airborne infectious bacteria and viruses surviving is the lowest. It also prevents building materials from emitting toxins such as formaldehyde, and helps prevent the occurrence of mould. There is also evidence of how clay plaster can treat pollutants and neutralise indoor odours.
Fig 18. The weight of moisture absorbed by different materials after an increase in relative humidity from 50%–80%: RH (Minke [10]).

3.9.2 Thermal

<table>
<thead>
<tr>
<th>Key references</th>
<th>HOUBEN and GUILLAUD [1]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MORTON [6]</td>
</tr>
<tr>
<td></td>
<td>MIDDLETON and SCHNEIDER [12]</td>
</tr>
</tbody>
</table>

The specific heat of soil is between 800–1000 (J/kgK). Earth masonry therefore gives good thermal mass.

**Watch it:** Insulation properties are generally not as good as sometimes perceived.

The thermal conductivity varies with dry density and moisture content. Empirical observations indicate that a 1% increase in moisture content can result in a 15% increase in thermal conductivity (Houben and Guillaud [1]).

Fig 19. Insulating properties of earth (Houben and Guillaud [1]).

Where earth construction is used in heated buildings, it is recommended that external insulation is used. This can act to protect the earth wall from the weather while utilising the properties of the earth to help regulate the internal temperature and humidity.
Table 16. Thermal conductivity and resulting U-values (Houben and Guillaud [1]).

<table>
<thead>
<tr>
<th>Construction</th>
<th>Density</th>
<th>Conductivity</th>
<th>U-value for given wall thickness based upon lower bound</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>W/m°C</td>
<td>W/m²K 150mm</td>
</tr>
<tr>
<td>Compressed block; 30MPa compression</td>
<td>&gt; 2200</td>
<td>0.93 - 1.04</td>
<td>6.20</td>
</tr>
<tr>
<td>Compressed block; 2-4MPa compression</td>
<td>1700 - 2200</td>
<td>0.81 - 0.93</td>
<td>5.40</td>
</tr>
<tr>
<td>Adobe</td>
<td>1200 - 1700</td>
<td>0.46 - 0.81</td>
<td>3.07</td>
</tr>
</tbody>
</table>

3.9.3 Fire

Earth blocks generally perform well in fire, although high fibre content may reduce this. They are, however, vulnerable to being damaged by water during firefighting. Walls may be oversized or provided with surface protection.

In the German standard DIN4102, Part 1 [42], loam is said to be non-combustible, even with straw content, provided the density is greater than 1700kg/m³.

Table 17. Pilot fire rating tests (Middleton and Schneider [12]).

<table>
<thead>
<tr>
<th>Construction type</th>
<th>Wall thickness</th>
<th>Fire rating (AS1530: Part 4, 1975)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adobe block</td>
<td>250mm</td>
<td>4hrs</td>
</tr>
<tr>
<td>Cimva ram (compressed) block</td>
<td>150mm</td>
<td>2hrs</td>
</tr>
</tbody>
</table>

3.9.4 Electromagnetic radiation

Earth is relatively good for insulation against electromagnetic radiation. In tests, a 240mm earth masonry wall created a reduction of 24dB at 2GHz frequency, in comparison to a 7dB reduction in a similar stone masonry wall (Minke [10]).

3.9.5 Acoustics

Table 18. Acoustic attenuation (Houben and Guillaud [1]).

<table>
<thead>
<tr>
<th>Construction</th>
<th>Density</th>
<th>Acoustic attenuation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>200mm, 500Hz</td>
</tr>
<tr>
<td>Compressed block; 30MPa compression</td>
<td>&gt; 2200</td>
<td>40</td>
</tr>
<tr>
<td>Compressed block; 2-4MPa compression</td>
<td>1700 - 2200</td>
<td>40</td>
</tr>
</tbody>
</table>

Limited testing carried out in Australia indicates that 250mm of adobe block with render on both faces can achieve an airborne sound transmission rating of 50dBA (Middleton and Schneider [12]).
4 Construction

Block quality is determined by soil selection/preparation, correct application of stabilisation, compression, and curing. Each step requires an understanding of the material and is highly susceptible to poor workmanship. Several organisations around the world advocate and provide training in the use of earth blocks. Refer to Appendix C.

4.1 Soil preparation

The steps for soil preparation are:

1. Dry the soil, otherwise steps 2 and 3 will be severely slowed down.
2. Crush the soil.
3. Pass soil through a 5mm or 6mm sieve to remove larger stones; see Fig 21 for an example of a sieve frame.
4. Depending upon the grading of particles in the soil, additional clay/sand/gravel may be blended in.
5. If required, mix stabiliser until mixture is all the same colour. This is generally done by volume. It is best done in relatively small batches to ensure consistency and thorough mixing.
6. Water should be mixed gradually and thoroughly by hand. The amount required is likely to vary, but 10%–15% by volume may be used as a starting point. Dropped from shoulder height, the mixture should break into two or three pieces. If it crumbles it is too dry. If it is too wet it will remain as one piece. Concrete mixers are not suited to soil mixing as the soil will stick within the sides and not mix properly.
7. Mixing time should be at least eight minutes.

Key references

- T4T [43]
- ANDABATI [44]
- Technical Advice Note 2, How to make stabilised soil blocks [9]
- PEREZ-PENA [45]
- GUILLAUD et al [46]
8. “Holdback time” between mixing and block production should be kept below one hour at the most where soil is cement-stabilised, as strength can reduce. Where lime is used, strength may increase with holdback time.

9. Each block should be marked with the date on which it was manufactured. This allows identification in case subsequent block test results are below those required.

![Fig 21. (L) Hold back time vs compressive strength (Houben and Guillaud [1]); (R) sieve frame with fine mesh reinforced by coarse mesh behind.]

### 4.2 Manufacture

Within Europe, Germany currently has the best-developed unfired clay manufacturing sector.

#### 4.2.1 Block dimensions

Examples of block dimensions may be found in Table 8.

**Watch it:** CEB dimensions tend to vary between different press manufacturers.

Where block moulds are to be fabricated for the project it is worth considering the size and weight of block that can reasonably be man handled.

Where blocks are to be used as “headers” they should satisfy the rule: \( l = 2b + m \), where:

\[
\begin{align*}
    l &= \text{block length} \\
    b &= \text{block breadth} \\
    m &= \text{mortar width}.
\end{align*}
\]

#### 4.2.2 Adobe

From *HB195-2002* [7], the two main types of mould used for adobe production are:
**Slop-moulding**: A relatively wet mix is poured into a mould and left for 24–48 hours. Moulds are then lifted away from the partially dry bricks. Soil mixture should be wet enough to pour into the moulds, requiring no kneading or only nominal compaction.

**Slip-forming** A relatively stiff mix is pushed into a mould and compacted into corners using hand kneading or tamping. The mould is then removed immediately. The wet soil mix should be sufficiently stiff to prevent slumping. The method is preferable where rapid drying is likely.

**Watch it**: Cracks within and between adobe blocks can harbour the life-threatening Chagas disease, also known as the “kissing bug” or *Chinche* in Spanish. The disease affects up to 11M people across the Americas. Local communities are often aware of this, contributing to reduced acceptance of earth construction.

The cracks that harbour Chagas can be eliminated through use of a block press, whereby the blocks technically cease to be “adobe” and instead become “CEBs”. As such, earth blocks should be compressed wherever there is risk of Chagas disease.

### 4.2.3 Compressed earth blocks

**Watch it**: Blocks must be removed carefully from the press, taking care to not damage the edge.

The Cinva ram, developed in 1952 in Columbia, is widely credited as the first manual block press.

**Table 19. Compressed block manufacture matrix.**

<table>
<thead>
<tr>
<th>Process</th>
<th>Example</th>
<th>Compaction applied</th>
<th>Blocks /day</th>
<th>Technology</th>
<th>Manufacture EC0</th>
<th>Labour</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hand mould — adobe</td>
<td></td>
<td>Minimal</td>
<td>Zero</td>
<td>Zero</td>
<td>Zero</td>
<td>Intensive</td>
</tr>
<tr>
<td>Mechanical hand press</td>
<td>Cinva ram, Makiga, T4T</td>
<td>~2MPa</td>
<td>200 - 400</td>
<td>Basic</td>
<td>Zero</td>
<td>Medium</td>
</tr>
<tr>
<td>Hydraulic hand press</td>
<td></td>
<td>~10MPa</td>
<td>Medium</td>
<td>Zero</td>
<td>Medium</td>
<td>Medium</td>
</tr>
<tr>
<td>Mechanised press</td>
<td></td>
<td></td>
<td>Advanced</td>
<td>Electricity or combustion engine</td>
<td>Mechanised</td>
<td></td>
</tr>
<tr>
<td>Mechanised hydraulic press</td>
<td>Hydraform</td>
<td>1000 - 3000</td>
<td>Advanced</td>
<td>Electricity or combustion engine</td>
<td>Mechanised</td>
<td></td>
</tr>
</tbody>
</table>
4.2.4 Interlocking compressed earth blocks

<table>
<thead>
<tr>
<th>Key references</th>
<th>T4T [43]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ANDABATI [44]</td>
</tr>
<tr>
<td></td>
<td>PEREZ-PENA [45]</td>
</tr>
</tbody>
</table>

The use of interlocking compressed earth blocks is being championed in East Africa by Makiga, T4T, the Good Earth Trust, and HYT, among others. Refer to Appendix C: Organisations for more information. Their experience suggests that mortar may be limited to every fourth bed as a result of the interlock. Advantages include:

- much less mortar required, as multiple layers may be dry-stacked; exceptions to this rule include their use in the construction of water tanks, in which case mortar should be used in every bed joint
- accuracy and speed of construction increased, as the interlock guides mason.

4.2.5 Extrusion

<table>
<thead>
<tr>
<th>Key references</th>
<th>HEATH et al [4]</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>HEATH et al [47]</td>
</tr>
<tr>
<td></td>
<td>OTI et al [48]</td>
</tr>
</tbody>
</table>

Extrusion is the process through which conventional fired bricks are manufactured, and represents the most likely method through which unfired blocks would be mass-produced in the UK.

Recycled clay or waste clay is extruded through the same machines used for fired bricks, which serve to compact them. Blocks are then dried (but not fired) using waste heat from the main brick kilns.

Several UK brick manufacturers have experimented with mass production. A complete list is offered below. Ibstock is the only company to currently advertise them. It reports that initial enquiries are often stalled by the absence of design codes and the perceived difficulty in obtaining insurance.

1. **Ibstock**
2. **Hanson**
3. **Lime Technology — Sumatec — product discontinued**
4. **Errol Brick — Ecobrick — has ceased trading at time of writing.**

Ibstock blocks have been tested for use with Fisher fixings.

Blocks may or may not be stabilised: Ibstock blocks are unstabilised and are recommended for “internal non load-bearing” use.
4.3 Curing

This section covers the steps required to cure stabilised blocks. The requirements for curing adobe blocks may be relaxed (*HB195-2002* [7]).

- Like concrete, earth construction gains strength with age.
- It is important that earth blocks are not allowed to dry out too quickly as this may cause cracking.
- Blocks should be protected against rain and sun.
- Curing requires time and storage space.
- Curing should be located close to the press to reduce the carrying distance and minimise the risk of damage to uncured blocks.
- Blocks should be raised up or placed on plastic sheet to prevent loss of moisture to the ground.
- Blocks should be covered over with plastic sheet or cloth to prevent evaporation and protect against rain.
- Blocks should be kept damp for several days by sprinkling with a watering can or similar.
- Blocks may initially be stored flat before being stacked into piles.
- Blocks stabilised with cement should ideally be cured for a minimum of 14 days, ideally 30 days. Blocks stabilised with lime should ideally be cured for at least 30 days.

![Image](image-url)

**Fig 22.** Blocks laid flat initially and then stacked.

![Image](image-url)

**Fig 23.** The effect of curing conditions on cement-stabilised blocks (Houben *and* Guillaud [1]).
4.4 Block property testing

| Key references | HOBEN and GUILLAUD [1]  
|                | MORTON [6] (Appendix B)  
|                | HB195-2002 [7]  
|                | Technical Advice Note 2, How to make stabilised soil blocks [9]  
|                | NZS4298:1998 [29]  
|                | T4T [43] |

Laboratory tests can be performed to determine just about any characteristic providing that the facility is well equipped. Where blocks are manufactured on site it will often be necessary to test the blocks in situ in a low-tech environment so as to verify the design assumptions made. In situ testing may include but not be limited to:

- water absorption
- compressive strength
- three-point bending test
- water-immersion durability test
- robustness drop test
- scratch test
- impact test.

Details of a low-cost, portable field laboratory/test kit for determining soil and resulting block properties can be found on the website of the BRE Centre for Innovative Construction Materials at the University of Bath.

**Fig 24.** Rudimentary block tests: (L) drop test; (C) bending test; (R) durability test (T4T machine operation manual [43]).

4.5 Construction

| Key references | HOBEN and GUILLAUD [1]  
|                | HB195-2002 [7]  
|                | GUILLAUD et al [46] |

While experience of earth masonry among contractors in the UK is currently very low, this rarely presents a problem when building walls. However, clay plastering often requires specialist training (Morton [6]). Several contractors in the UK specialise in clay plaster. Refer to Appendix C: Organisations.
4.5.1 Block laying

Bond strength is greatly affected by workmanship.

Walls should be fully bonded at returns and corners, as for good masonry construction. All vertical joints in consecutive courses should be greater than a quarter of a block length apart.

**Fig 25.** Stretcher bond plan and elevation showing fully bonded corner and internal wall detail.

**Fig 26.** Examples of wall bond patterns (Guillaud *et al* [46]).

Horizontal and vertical bed joints should be compressed to ensure a decent bond is achieved. Slushed joints, where the mortar is placed into the vertical joint between two blocks after the block is laid, should be avoided as they will give a poor bond. This substantially reduces the wall’s compressive strength, bending strength and shear strength (Houben and Guillaud [1]).

All blocks should be cleaned and wetted before applying mortar.

When laying the horizontal mortar bed, do not spread it out more than three to five blocks in advance so that it does not dry out. Mortar should be soft and
plastic. Excessively wet mortar should be avoided as it causes shrinkage and microfissuration and does not adhere well (Houben *and* Guillaud [1]).

![Fig 27. Vertical mortar applied to block so that it may be compressed as the block is laid (Houben *and* Guillaud [1]).](image)

**4.5.2 Render**

Where renders exist, and if they are determined to be appropriate, local practices should be utilised. Poorly applied renders are likely to fail unacceptably fast.

1. Finish mortar joints so that beds are not flush with wall face.
2. Roughen (key) the surface of the blocks with a sharp implement.
3. Brush any loose dirt from the wall.
4. Wet the surface generously before application.
5. Apply quickly and evenly, avoid over-trowelling; over-trowelling, or compression of the surface, causes water to be drawn to the surface where it evaporates, and is likely to cause cracking.
6. Shade, and keep render wet, in order to control the rate of drying: duration will depend on the climate.

**4.6 Health and safety**

As a breathable dust, clay presents a small but significant hazard to human health, causing silicosis and other respiratory diseases. Sources of clay can include dry clay mortar or block mixes, and dust created during transportation or from cutting/drilling operations. In the context of earth blocks and adobe, the risk is small and easily managed by sensible storing of dry materials and minimising the amount of post-drying cutting.

Care should be taken with lifting or carrying heavy loads. Individual blocks will not usually exceed the limit in manual handling regulations, but the risks in a given situation should be assessed. Blocks are sometimes sized to suit the carrier.
4.7 Maintenance

Careful detailing of earth construction will aid its durability but will not negate the need for a maintenance regime. It is vital that this considered at the design stage and is communicated to the client.

Future maintenance will require finding skilled contractors to identify the cause and severity of defects, and specify and undertake correct and adequate repairs.

1. Who is responsible?
2. How often is maintenance required?
3. How will it be funded?

Render/plaster can act as a superficial layer which is repaired or replaced. Rain, sun, impacts, abrasion, and insects will gradually damage the render. When this happens, the render should then be repaired (for minor decay) or replaced (for major damage).

Potential durability problems, such as leaking downpipes or overflowing gutters, which impinge water onto earth walls, should always be corrected as quickly as possible (HB195-2002 [7]).
References


[17] CENTER FOR THE DEVELOPMENT OF INDUSTRY.  


[22] DEUTSCHES INSTITUT FÜR NORMUNG. DIN18958. (Draft standard on earth masonry mortar.) DIN, 2012


[34] STATE OF NEW MEXICO. New Mexico earthen buildings code. New Mexico, 2003.


Appendix A

Case studies
A1 Introduction

This appendix gives an overview of previous Arup projects where unfired earth blocks have been used. Additional information and photos may be found in Arup Projects and Asset Bank.
## A2 Case study summary

<table>
<thead>
<tr>
<th>Name and Arup Projects link</th>
<th>Location</th>
<th>Job No.</th>
<th>Start Date</th>
<th>Contact for additional info</th>
<th>Client</th>
<th>Collaborators</th>
</tr>
</thead>
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<td>Uganda</td>
<td>126359-00</td>
<td>2010</td>
<td>Timothy Hoggins</td>
<td>Care and Share Foundation</td>
<td>EFOD</td>
</tr>
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<td>Druk White Lotus School</td>
<td>India</td>
<td>55792-00</td>
<td>1998</td>
<td></td>
<td>Drukpa Trust</td>
<td></td>
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<tr>
<td>Malawi schools</td>
<td>Malawi</td>
<td>126346-00</td>
<td>2008</td>
<td>Adrian Campbell</td>
<td>William J Clinton Foundation</td>
<td>John McAslan and Partners</td>
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<tr>
<td>Pajule Secondary School</td>
<td>Uganda</td>
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<td>2011</td>
<td>Hugh Gray</td>
<td></td>
<td>Good Earth Trust and Makere University</td>
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<tr>
<td>Sabre sustainable KG schools</td>
<td>Ghana</td>
<td>126351-00</td>
<td>2008</td>
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<td>The Sabre Charitable Trust</td>
<td>Davis Langdon</td>
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<tr>
<td>Shalom International School</td>
<td>Uganda</td>
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<td>2011</td>
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<td>TESO Educational Support Scheme</td>
<td>EFOD</td>
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<td>Salt Peter Trust</td>
<td>EFOD</td>
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<td>Tanzania schools and health centre</td>
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<td>1997</td>
<td>Isobel Byrne-Hill</td>
<td>Health Projects Abroad</td>
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<tr>
<td>Rainwater-harvesting tank</td>
<td>Tanzania</td>
<td>No Arup Involvement</td>
<td></td>
<td>Good Earth Trust</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
A3  CASSO Orphanage, Uganda

Key data

- double interlocking stabilised soil blocks (ISSBs)
- imported murram
- reinforced concrete ring-beam at roof level to provide a structural tie during a seismic event
- piers formed from ISSBs at regular intervals to provide lateral restraint
- load-bearing single-storey construction.

Watch its

- Local practice typically means that mortar is over-applied. A timber guide was developed on site to limit the amount used.

Note: Murram is an East African word for Laterite, which typically consists of a gravelly, clayey soil, rich in iron. Mined commercially on various scales in East Africa, it is used in construction for road surfaces in particular.

Fig A28. Load-bearing ISSBs with concrete ring beam and timber roof trusses.
Fig A29. Construction of ISSB wall using timber mortar guide.

Fig A30. Typical section.
Fig A31. Pier details.

Fig A32. Pier construction stages.
A4.1 External wall

Fig A33. Internal mud leaf of external wall.

Key data

- hand-moulded mud brick/adobe, site-won soil
- mud mortar
- used as internal leaf, tied to external stone wall with concrete tie block giving improved thermal performance and durability compared to traditional mud walling.
- high seismicity.
Fig A34. Section through internal and external wall.
A4.2 Internal wall

Fig A35. Internal mud leaf partition.

**Key data** (where different from external wall)

- internal non load-bearing partition wall – infill for timber frame.

**Watch its**

- Where blocks are used as solid infill panels, consideration must be given to the interaction between the blocks and the structural frame. If it is assumed they do not contribute to frame stiffness, movement joints should be detailed accordingly.

- Buildability will be improved if the sizes of the block and the timber frame are compatible.
Key data

- compressed stabilised soil blocks, Cinva–ram block press, site-won soil
- 290mm×140mm×100mm
- load-bearing single-storey
- reinforced concrete floor slab with fired brick foundation
- Damp-proof course and termite nib.
Fig A37. Ring beam detail.

Fig A38. Wall details.
Fig A39. Base detail.
A6  Pajule Secondary School, Uganda

Fig A40. Classroom block.

Key data

- double interlocking stabilised soil blocks with mortar in every fourth bed typically, site-won soil
- 290mm×140mm×115mm
- large roof overhang – building surrounded by a veranda
- 600mm high stone cladding at base
- concealed reinforced concrete ring beam formed through modified block type.

Watch it

- Block production was slowed by wet soil, which must be dried before it can be sieved.
Fig A41. Ring beam detail.

Fig A42. Foundation detail with external hardstanding.
A6.1 Concealed ring beam

The structural engineers from Arup’s Dublin office who lead the design came up with a modification to the wide double interlocking block which eliminates the need for timber shuttering and at the same time conceals the concrete ring beam. They inserted a 75mm × 50mm timber block into the press to increase the depth of the interlock from 12mm to 62mm. Inverting one of these blocks and placing another on the top gives a 150mm × 75mm void which was used to conceal a small but effective concrete tie beam.
Fig A44. Modified concealed ring beam (L) and the standard approach (R).

Fig A45. Modifications to a standard block to accommodate a hidden ring beam.
A7 Sabre Sustainable KG schools, Ghana

A7.1 Classroom

Fig A46. Classroom.

Key data

- stabilised soil blocks, hand press sourced locally, site-won soil
- 300mmx180mmx150mm
- cement: soil = 1:16, determined by shrinkage test carried out in accordance with Engineering in Emergencies
- one-third of cement replaced with pozzolana, a sustainable cement substitute
- 10mm mortar bed with two 6mm bars in each bed tied into reinforced concrete columns
- located in a seismic zone; non load-bearing low-level walls to keep mass down; lightweight bamboo cladding above
- reinforced concrete moment frame carries vertical load
- cement-stabilised earth render applied inside and out
- large roof overhangs on two sides
- blocks sit on a reinforced concrete strip footing with heavy-duty plastic damp-proof membrane and termite nib.
Fig A47. Low-level SSB walls.

Fig A48. Reinforced concrete columns with starter bars for SSB walls.
Fig A49. Low-level SSB walls with bed reinforcement and render.

Fig A50. Wall section.
Fig A51. Wall elevation.
Fig A52. Double interlocking blocks.

Fig A53. Interlocking load-bearing blocks with reinforced concrete ring beam at roof level.
Key data

- double ISSBs
- imported murrum
- single-storey load-bearing construction
- reinforced concrete ring beam at roof level to provide a structural tie during a seismic event.

Fig A54. Foundation and slab detail.
Fig A55. Double ISSB block dimensions.

Fig A56. Corner detail.

Fig A57. Internal wall to external wall.
Fig A58. Internal wall to internal wall.

Fig A59. Pier details.
Soroti Medical Centre, Uganda

Key data

- single interlocking blocks
- cement: imported murram = 1:10 and 1:8
- 265mm×140mm×120mm
- reinforced hollow concrete block columns with reinforced concrete ring beam
- infill panels
- two 50 000L rainwater harvesting tanks with a 5m diameter constructed from curved double interlocking stabilised soil blocks.

Watch it

- It was originally intended that the murram for the blocks would be taken from on-site excavation for a septic and water tank. With construction of the main structure occurring during the middle of the dry season, the ground was baked solid. This delayed excavation of the tanks until later in the programme, requiring the murram to be imported from a local quarry in order to make the blocks.

Fig A60. Cellular concrete block columns with reinforced concrete ring beam and timber roof trusses; infill interlocking stabilised soil block walls between.
Fig A61. Reinforced cellular concrete block columns and single interlocking stabilised soil blocks.

Fig A62. Rainwater harvesting tank.
A10 Tanzania schools and health centre

Key data

- compressed stabilised soil blocks, site-won soil
- 300mm×100mm×100mm
- single storey load-bearing construction
- reinforced concrete ring beam at roof level, mass concrete strip footings.

Fig A63. Block wall construction with reinforced concrete ring beam.
A11 Rainwater-harvesting tank, Good Earth Trust, Tanzania

Key data

- curved double interlocking stabilised soil blocks, site-won soil
- mortar in every layer
- can be built above or below ground or a combination of both
- if suitable, excavated earth may be used to construct blocks for tank and associated buildings
- damp-proof membrane wrapped around tank when located beneath ground level
- internal surface rendered with waterproof cement; render is applied to chicken mesh which is first tacked onto the blocks in order to prevent cracking

Watch it

- Watch out for fake waterproof cement. It is likely to be cheaper and weigh less than the labelled amount. A water droplet should sink into the cement; if it is fake, it will float on the top.

Fig A64. Soil block water tank set into the ground - Good Earth Ttrust.
Fig A65. Internal surface render detail showing chicken mesh tacked onto top of soil block walls with waterproof cement render on top - Good Earth Trust.
Appendix B
Details
B1 Introduction

This Appendix includes a limited selection of unfired earth block details. Additional details may be found in the Reference documents listed in the main text.
B2 Water protection

B2.1 Roof overhang and base protection (Andabati [44])

B2.2 Roof overhang, base protection and drainage (HB195-2002 [7])
B2.3 Permeable surface protection (Schofield and Smallcombe [58])

Where walls are unstabilised (no added cement) surface coatings must be permeable.

Watch it: Earth walls should sit on top of a damp-proof membrane.
**B2.4  Base protection and raised base course** (Houben and Guillaud,[1])

![Diagram](image1.png)

**B2.5  Base detailing** *(HB195-2002 [7])*  

**Watch it:** The drainage channel should align with the roof eaves.

**Watch it:** Consider the effect on the design assumptions for the foundations if it is chosen to locate a drainage channel immediately alongside.

![Diagram](image2.png)
B2.6  **Base detailing to avoid trapping water** (Baker [59])

Ledges that trap water should be avoided or detailed to ensure water drains freely.

---

B2.7  **Damp-proof course** (Baker [59])

A damp-proof course that is continuous beneath slab and wall should be included to prevent water damage via capillary action.

---

B2.8  **Damp-proof course** (Middleton and Schneider [12])
B3  Hydraform proprietary details

B3.1  Typical section (Hydraform [60])

Caution: Detail suggests a base course of 7MPa unfired earth blocks. This should only be employed where site is very well drained; better to instead construct the base course from fired brick, stone or concrete.

B3.2  Roof detail (Hydraform [60])
B4 Adobe wall cyclone bolts

B4.1 Typical section (Middleton and Schneider [12])

B4.2 Top plate detailing (Middleton and Schneider [12])
B5  Contemporary design in temperate climates

B5.1  Base detail (Morton [6])

Plastered half brick thick, earth masonry forms the inner lining of an external timber framed wall. The earth brick is isolated from rising damp and internal flood risk.

B5.2  Window head (Morton [6])

Exposed, brick thick earth masonry forms the inner lining of an external timber framed wall.
B5.3 Window head (Morton [6])

Plastered, half brick thick, earth masonry forms the inner lining of an external timber-framed wall. When using timber lintels it is important they have the correct moisture content.

Exposed earth brick wall; the lintel could be timber, concrete or steel.
B5.4 Window jamb (Morton [6])
Plastered, half brick thick, earth masonry forms the inner lining of an external timber-framed wall.

B5.5 Internal partition head (Morton [6])
Lateral restraint at the head allows a thinner wall. The details allow for some settlement of the new wall away from the existing structure.

B5.6 Timber framed partition (Morton [6])
Mortared earth masonry is used as infill, with a plastered finish.
B5.7 Door jamb (Morton [6])

B5.8 Door jamb (Morton [6])
Appendix C
Organisations
<table>
<thead>
<tr>
<th>Name</th>
<th>Location</th>
<th>Website</th>
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<td>Kickstart</td>
<td>East Africa</td>
<td><a href="http://www.kickstart.org/">http://www.kickstart.org/</a></td>
<td>Earth related documents can be downloaded free of charge</td>
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<tr>
<td>Earth Building UK</td>
<td>UK</td>
<td><a href="http://www.ebuk.uk.com/">http://www.ebuk.uk.com/</a></td>
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<td>Makiga</td>
<td>Kenya</td>
<td><a href="http://www.makiga-engineering.com">www.makiga-engineering.com</a></td>
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<td>T4T</td>
<td>Uganda</td>
<td><a href="http://t4tafrica.co/index.html">http://t4tafrica.co/index.html</a></td>
<td>ISSBs</td>
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<tr>
<td>Good earth trust</td>
<td>UK, Uganda, Kenya, Tanzania</td>
<td><a href="http://www.goodearthtrust.org.uk">www.goodearthtrust.org.uk</a></td>
<td>ISSBs</td>
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<tr>
<td>Hydraform</td>
<td>South Africa</td>
<td><a href="http://www.hydroform.com">http://www.hydroform.com</a></td>
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<tr>
<td>Limetecnology</td>
<td>UK</td>
<td><a href="http://limetech.info/upload/documents/Sumatec/LT_S_1ISH_Sumatec%20Info%20SheetSm.pdf">http://limetech.info/upload/documents/Sumatec/LT_S_1ISH_Sumatec%20Info%20SheetSm.pdf</a></td>
<td>Sumatec blocks have been discontinued</td>
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<tr>
<td>Claytec</td>
<td>Germany</td>
<td><a href="http://www.claytec.com">www.claytec.com</a></td>
<td>Site is in German. Produce a wide range of earth construction products</td>
</tr>
<tr>
<td>Gate International</td>
<td>UK</td>
<td><a href="http://www.gate-international.org/index.html">http://www.gate-international.org/index.html</a></td>
<td>NGO - has shut down, website still running - good documents available for download</td>
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<tr>
<td>Papercrete</td>
<td></td>
<td><a href="http://www.papercrete.co.uk/home.html">http://www.papercrete.co.uk/home.html</a></td>
<td>Sell plans for Cinva ram</td>
</tr>
<tr>
<td>Appro Techno</td>
<td>Belgium</td>
<td><a href="http://www.approtechno.com">www.approtechno.com</a></td>
<td>Manual, semi-motorised and motorised presses, various shapes also mixers and sorters</td>
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<tr>
<td>S &amp; S Cob Blocks</td>
<td>UK</td>
<td><a href="http://www.cobbblocks.co.uk/index.php">http://www.cobbblocks.co.uk/index.php</a></td>
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</table>
Appendix D

Seismic
This appendix should be treated as a work in progress.

D1.1 Active measures

Reinforced masonry

<table>
<thead>
<tr>
<th>Wall reinforcement scheme</th>
<th>Type of building</th>
<th>Construction complexity</th>
<th>Cost</th>
<th>Seismic safety</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>New</td>
<td>Existing</td>
<td>Simple</td>
<td>Moderate</td>
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<tr>
<td>Internal cane reinforcement</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>External cane and rope mesh</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>External bamboo and internal wire mesh</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Welded wire Mesh</td>
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<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Polymer Mesh</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Used car tire straps</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Polypropylene band</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Integral masonry system</td>
<td>X</td>
<td>X</td>
<td>X</td>
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</tbody>
</table>

Reinforcement may be categorised as either integral/internal or external. Where integral steel reinforcement is provided, horizontal bars are located in mortar beds or sometimes within grooves in the blocks, with vertical bars running in cavities or holes through the blocks that are filled with mortar.

Cyclic load tests have been carried out into various external reinforcement techniques as detailed in the key references above. Experimental test details may also be found on Quake Safe Adobe.

Internally reinforced interlocking blocks piloted by Auroville Earth Institute have been approved for use in parts of India and Iran.
Watch it: When subject to seismic load, the bond between the mortar and reinforcement deteriorates. Consequently high tensile stresses and yielding in rebar cannot be developed, preventing ductile behaviour and energy dissipation.

Watch it: In order to achieve a ductile behaviour of masonry, it is necessary that the shear strength of the wall is greater than the bending strength to ensure bending failure. Therefore increased amount of vertical reinforcement at the edges of the wall may not improve its resistance, particularly with weak masonry units. Thus the minimum percentage of reinforcement, either vertical or horizontal, depends on the strength of the masonry units.

More information can be found at City University’s Reinforced brick/masonry and Masonry adobe websites.
Confined masonry

<table>
<thead>
<tr>
<th>Key References</th>
<th>1. BREZV [53]</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>2. MELI et al [54]</td>
</tr>
<tr>
<td></td>
<td>3. SCHACHER [55]</td>
</tr>
<tr>
<td></td>
<td>4. BLONDET [56]</td>
</tr>
<tr>
<td></td>
<td>5. TOTTEN [56]</td>
</tr>
</tbody>
</table>

Watch it: Most of the guidance on confined masonry is written for cement blocks or fired clay bricks. Its suitability to low-strength unfired blocks is unproven.

Confinement is provided by vertical and horizontal reinforced concrete elements, enabling the masonry to act as a panel. The vertical elements or practical columns may be toothed into the wall, whereby the blocks are laid first and then used as permanent formwork for the practical column.

Confined masonry may also have reinforcement running vertically and in horizontal bed planes.

Fig 68. Confined masonry house (Blondet [56]).

Watch it: Compared to externally reinforced masonry there is less information available concerning dynamic behaviour and the level of ductility achievable.

Confined masonry is, however, widely recognised to perform significantly better than unreinforced masonry in a seismic event.
D1.2 Non-structural infill panels

Where walls are non load-bearing and do not contribute to the stability system, consideration must still be given to their stability in a seismic event.

Watch it: Consider that during a seismic event, restraint provided by the primary structure may impose loads for which the wall is not designed.

D1.3 Interlocking blocks

The seismic performance of interlocking blocks is not well understood and requires further work. The comparative performance of interlocking vs non-interlocking blocks would be of particular interest.

Watch it: Practitioners in East Africa do not account for seismic resistance beyond provision of some basic tying.

Details of limited testing on a small room (4m×4m) can be found on Hydraform’s website: Auroville Earth Institute has conducted some research on reinforced interlocking blocks.