CHARACTERISATION OF EARTHEN ELEMENTS.
A COMPARISON BETWEEN EARTH BLOCK
MASONRY, RAMMED EARTH AND COB

Lorenzo Miccoli¹, Urs Müller²

ABSTRACT

Earth represents one of the oldest construction materials, which are still utilized both in developed and developing countries. While research on stone and brick masonry has recently benefited from significant advances, knowledge on the material properties and failure mechanisms of earthen building construction is limited and fragmented. In this paper a comparison of the mechanical performance of structural elements built in adobe (earth block) masonry, rammed earth and cob is presented. Earth can be processed in many ways, the three construction techniques, however, represent the most important typologies, which constitute totally different properties based on differences in their granulometry, moisture state during preparation, homogeneity, structural performance, additive or stabiliser. In order to gain better knowledge on the structural behaviour an extensive compression and diagonal compression (shear) tests campaign was performed. During diagonal compression experiments, a technique based on a photogrammetric system was applied in order to monitor deformation. First compression results show brittle mechanical behaviour in the case of adobe masonry and rammed earth elements, whereas cob exhibits a very different stress-strain pattern: cob can deform beyond the elastic range with a gradual drop in capacity. This behaviour is strongly influenced by the presence of fibres. Despite its low compressive strength, cob thus presents a relatively good performance within the earthen material range as far as shear behaviour is concerned. This parameter, together with its long post-peak plastic phase, is relevant if its use in seismic areas is considered. The study is part of our work in the framework of the ongoing project NIKER funded by the European Commission dealing with improving immovable Cultural Heritage assets against the risk of earthquakes.

Keywords: Earthen materials, Compression test, Diagonal compression test

1. INTRODUCTION

It is estimated that 30 to 40% of the world population currently lives or works in structures built in or with earth. Earth structures require high maintenance as they are prone to erosion under rainfall, spalling and cross-sectional reduction when salts are transported by capillary action, and are also susceptible to cracking both under low tensile and low compressive stresses. When these dwellings are located in regions with high earthquake risk, their intrinsically low resistance to dynamic actions is further worsened by such durability issues. A number of construction and repair practices negatively affect earthen buildings and make them susceptible to high damage even under low seismic forces [1]. Lack of continuity at corners and at wall junctions, the presence of heavy roofs that are not supported by ring beams, and also that roofs are often not connected to walls are some typical recurring examples. Some countries where the population, particularly the rural one, still inhabits earthen building have been affected by highly destructive earthquakes, for instance Turkey (Erzinkan 1992), Iran (Bam 2003), Peru (Pisco 2007), Chile (Concepción 2010). Although damage to dwellings and their collapse is usually the cause of human losses, earthquakes are as well devastating to the built cultural heritage in these regions. As a matter of fact, it is often overlooked that a considerable amount

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of heritage sites, of which many are endangered, are built in earth. Some vernacular earthen building
techniques are no longer in practice, and the knowledge of how to build in such materials has been
lost. Earthen techniques considerably differ as far as material composition and construction methods
are concerned. While some guidelines and standards for building with earthen materials do exist as
ASTM E2392 / E2393 M [2], IS13827 [3] and NTE E.080 Adobe [4], these often lack design charts.
Moreover, values specified do not take the high variability of earthen materials in terms of mechanical
properties into consideration, which is dependent on a number of parameters affecting physical and
chemical bonds at microstructural level, e.g. granulometry or fibre content [5], compaction and
moisture content.
Newly introduced seismic regulations for countries where earthen buildings are still present within the
built environment (Morocco, Pakistan) are often based on those of developed countries and exclude
earth as a building material. When seismic regulations for earthen buildings do exist (New Zealand),
these tend to group all earthen materials into one. In addition, they are relevant to new-build and not to
existing historic structures. Repair and retrofitting of earthen structures are often carried out without
being recorded and when based on elastic stiffness design, additional elements introduced are being
found to be too stiff in comparison with earthen materials. Observation in most recent earthquakes and
in shaking table tests suggests that the introduction of concrete [6] or steel elements [7] as well as
retrofitting with steel mesh and cement plaster [6] negatively affects the behaviour of earthen
structures under seismic loading: stiffer elements attract more load and pound the original earthen
building elements to the ground. Thus even simple repair measures which might have been introduced
with the original intent of improving the behaviour of the building under static loads might harm the
structure under dynamic loads. Numerical modelling provides an effective tool by means of which the
behaviour of earthen buildings and typical damage typologies under seismic loading can be
understood further, and by means of which retrofitting proposals can be assessed before being
adopted, but sufficient material characterisation to use as input to numerical models is currently
missing. While some models for earthen structures can be built, their correlation to real-life situations
or experiments as a means of validation has yet to be thoroughly analysed.

2. AIMS AND OBJECTIVES

In comparison to recent advances in research on stone and brick masonry, knowledge on the material
properties and failure mechanisms of earthen materials is limited and scattered [8]. The current paper
focuses on the determination of material parameters and the behaviour of earthen panels and other test
specimens under different loading conditions. The entire experimental program was performed in the
laboratories of BAM, Germany. The types of wall segments considered in the experiments consist of one
leaf adobe masonry with earthen mortar and of monolithic rammed earth and cob walls (Tab. 1).
Investigations were carried out at micro and macrostructural levels in order to acquire the mechanical
behaviour of constituent materials as well as that of the structural elements (panels). The goal of the
experiments is to acquire a basic knowledge of the mechanical properties of different earthen materials.

3. EXPERIMENTAL PROGRAM

3.1. Materials

<table>
<thead>
<tr>
<th>Type of application</th>
<th>Material</th>
<th>Specifications</th>
<th>Mass density ρ [kg/m³]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Masonry panel</td>
<td>Earth block</td>
<td>Solid blocks produced by a mechanized hand moulding procedure (no compression, plastic consistency); size (240 x 115 x 72) mm</td>
<td>1863 1870</td>
</tr>
<tr>
<td></td>
<td>Earthen mortar</td>
<td>Shrinkage 2 %, particle size up to 4 mm. Sand particle</td>
<td>1885</td>
</tr>
<tr>
<td>Rammed earth panel</td>
<td>Rammed earth</td>
<td>Shrinkage 0.5 %, particle size range 0-16 mm, panels produced with soil moist material</td>
<td>2190</td>
</tr>
<tr>
<td>Cob panel</td>
<td>Cob</td>
<td>Earth, water and straw fibres of 200 to 300 mm in length</td>
<td>1475</td>
</tr>
</tbody>
</table>
Earthen materials for the experiments are sourced from a local manufacturer of prefabricated earthen building products. Material specifications, mineralogy and granulometric properties for the different wall construction typologies are listed in Tabs. 1, 2 and 3. Though certain material properties are specified by the manufacturer, detailed parameters required for the structural characterisation of the constituent materials were determined in the BAM laboratories. Earth blocks, earth mortar and rammed earth are ready-made products from the manufacturer. Cob, however, was prepared at the BAM premises with soil from the manufacturer of the other earthen products and straw fibres mixed to a mass of plastic consistency. Mixing was performed in a concrete mixer. After mixing, \( (700 \times 700 \times 1000) \) mm high panels were built following traditional cob building practice. After drying of the small walls, the test specimens were cut out by means of a saw.

### Table 2
Mineralogy properties of earthen materials. Quantities: +++ = high, ++ = medium, + = low

<table>
<thead>
<tr>
<th>Material</th>
<th>Grain constituents</th>
<th>Clay fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Quartz</td>
<td>Feldspar</td>
</tr>
<tr>
<td>Earthen block</td>
<td>+++</td>
<td>+</td>
</tr>
<tr>
<td>Earthen mortar</td>
<td>+++</td>
<td>+</td>
</tr>
<tr>
<td>Rammed earth</td>
<td>++</td>
<td>+</td>
</tr>
<tr>
<td>Cob</td>
<td>+++</td>
<td>+</td>
</tr>
</tbody>
</table>

### Table 3
Granulometric properties of the used earthen materials (mass-%)

<table>
<thead>
<tr>
<th>Material</th>
<th>Gravel and Sand &gt; 0.063 mm</th>
<th>Silt = 0.002-0.063 mm</th>
<th>Clay &lt; 0.002 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Earthen block</td>
<td>43</td>
<td>45</td>
<td>12</td>
</tr>
<tr>
<td>Earthen mortar</td>
<td>55</td>
<td>37</td>
<td>14</td>
</tr>
<tr>
<td>Rammed earth</td>
<td>64</td>
<td>25</td>
<td>11</td>
</tr>
<tr>
<td>Cob</td>
<td>18</td>
<td>61</td>
<td>21</td>
</tr>
</tbody>
</table>

### 3.2. Manufacturing process
For the static compressive experiments, wall segments of size \( 500 \times 520 \times 110 \) mm were produced made of 6 earthen unit courses, in accordance with EN 1052-1: 1998 [9]. However, the courses were connected by 20 to 25 mm joints, and thus thicker than recommended by the standard, since large joint widths are often observed in historic earth block masonry. Earth block masonry specimens were built without pre-wetting the earth blocks for compression tests. For the shear tests specimen with non-wetted as well as wetted blocks were built. Monolithic panels were built in the same size. Rammed earth walls were produced with formwork, whereas cob wall segments were cut from bulk specimen, which are built in typical cob style with raw earth, water and straw fibres (200 to 300 mm long). After drying, segments of \( 420 \times 420 \times 115 \) mm in size were cut from the bulk specimens, thus preserving the original texture of the cob. After production, the panels were stored in a climate room at 23°C and 50 % RH with the aim of equilibrating the moisture content of the walls. Specimens were removed from the climate room shortly before the strength testing took place.

### 4. COMPRESSION TEST

#### 4.1. Test setup
Compression tests were performed using a universal testing machine. Prior to the tests, two I-girders were attached to the lower and upper side of the wall segments in order to introduce the compression forces into the specimens. Accurate parallelisation of the girders was achieved by using a low strength cement mortar joint between the girders and the wall segment. Tests were performed with the levelled specimens, where the smaller sides of the wall segments were parallel to the chosen loading plates of the testing machine. For each wall type, 4 to 5 specimens were tested. Compressive tests were carried
out under displacement control. The loading speed was adjusted in a way that the failure point was reached after 20 to 30 minutes. Deformations were monitored by LVDTs parallel and perpendicular to the loading direction on both sides of the panel specimen.

4.2. Test results

The setup and the results of the tests are shown in Fig. 1. For earth block masonry wall panels the strength values ranged between 2.8 and 3.5 MPa. The displacement was in the range 0.5 to 1% with usually an abrupt failure. Failure patterns of the panels are depicted in Fig. 1, failure was visible by vertical or diagonal cracks. Sometimes cone shaped failure pattern could be observed. Rammed earth panels reached the highest compressive strength of all three types of earth constructions. The values ranged between 3.4 and 4 MPa. The deformations of the panels were similar to those of earth block masonry. Failure was abrupt after maximum stress was reached.

![Fig. 1 Earth block masonry, rammed earth and cob specimens under compression. Examples of failure modes (cracks marked in yellow lines)](image)

The failure pattern showed cone shaped cracking pattern, at least one side, sometimes on both sides. Cob showed a completely different behaviour under compressive load than the other two construction types. Maximum strength ranged from 1.4 to 1.7 MPa. Deformations measured were high reaching up to 6 % of vertical strain [10]. Due to the content of straw the material showed a ductile behaviour under compressive load with no distinctive maximum yielding point. Crack patterns after the tests were almost randomly and only in one sample a cone shaped failure was indicated.

4.3. Evaluation and comparison of results

Results obtained from the compression tests are given Tab. 4, where $E_{1/3}$ is Young’s modulus measured at 1/3 maximum load, as well as for the vertical (normal) strain $\varepsilon_{1/3}$. The stress-strain envelope for earth block masonry shown in Fig. 2 exhibits a short phase of post-peak strain softening under compression, due to its brittle behaviour under monaxial load. Rammed earth shows a brittle behaviour, in some (but not all and not markedly) cases with a hardening phase present in the first part of the stress-strain envelope. The compressive stress-strain envelope of cob shows its deformation beyond the elastic range with a gradual drop in capacity, presenting a ductile behaviour after its elastic

<table>
<thead>
<tr>
<th></th>
<th>Compressive strength [MPa]</th>
<th>Tensile strength [MPa]</th>
<th>Young’s modulus $E_{1/3}$ [MPa]</th>
<th>Vertical strain $\varepsilon_{1/3}$ [%]</th>
<th>Poisson ratio [-]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>STD</td>
<td>Mean</td>
<td>STD</td>
<td>Mean</td>
</tr>
<tr>
<td>Earth block</td>
<td>5.10</td>
<td>0.31</td>
<td>0.50</td>
<td>0.14</td>
<td>2197</td>
</tr>
<tr>
<td>Mortar</td>
<td>3.16</td>
<td>0.44</td>
<td>0.30</td>
<td>0.08</td>
<td>1067</td>
</tr>
<tr>
<td>Earth block masonry</td>
<td>3.28</td>
<td>0.40</td>
<td>nd</td>
<td>nd</td>
<td>803</td>
</tr>
<tr>
<td>Rammed earth</td>
<td>3.73</td>
<td>0.23</td>
<td>nd</td>
<td>nd</td>
<td>4143</td>
</tr>
<tr>
<td>Cob</td>
<td>1.59</td>
<td>0.03</td>
<td>0.32</td>
<td>0.06</td>
<td>651</td>
</tr>
</tbody>
</table>
The distinctive maximum strain could visible be observed before and after the test. There was a strict dependency between the components and the observed material behaviour. In this context it is interesting to make a comparison with results obtained by Quagliarini et al. [5], who studied the compressive failure behaviour of adobe blocks which differed constituents. Their results showed that the addition of straw increased the ductility of the material considerably, while the introduction of sand, particularly in high amounts, tended to significantly lower its compressive strength. This difference in behavioural pattern was similar to that observed for the different earthen materials investigated, thus giving an indication of the effect of constitutive materials on compressive stress-strain behaviour of materials resulting from different construction techniques.

5. DIAGONAL COMPRESSION TEST

5.1. Test setup
Diagonal compression tests were performed in compression mode following ASTM E 519-10 [11]. According to the test, to induce shear forces wall segments were turned by 45° around the middle axis with one diagonal of the wall segment being perpendicular to the loading plates of the testing machine. The stress was introduced by loading shoes. Particular attention was directed to the problem of the load distribution along the corners in order to avoid an excessive concentration of compression stresses at these surfaces. The loading shoes, placed between the jack and the corner, was designed according to the standard and failure of the panels never occurred due to excessive compression stress at the corners. Six to eight specimens were tested for each wall construction type. The load was applied at a rate of 130 N/s. The test consisted in monotonic loading up to failure.

Displacement transducers were used for measuring strain and placed according to the standard, one pair on the front and one pair on the back side of the panel. For selected specimen additionally a photogrammetric camera system (ARAMIS) was measuring the two-dimensional deformation during the test. For this a frame of ca. 35 × 25 cm of the center of the panel was observed. Prior to the test the specimen were plastered with a thin white earthen render and sprayed with a marker. The deformation of the samples was measured by stereographic recording of the movement of the singular marker points and additionally by one set of LVDTs placed on the back side of the panel.
The test is usually used for block masonry but was used in this study for the pseudo monolithic building elements rammed earth and cob. In monolithic materials the diagonal test should introduce compression forces until horizontal strain creates a vertical crack. As could be seen in the results, this is true for the beginning of the failure. The actual failure, however, revealed for all earthen materials a strong shear component.

5.2. Test results
As mentioned before masonry panels were prepared with wetted and with non-wetted blocks. Past and current practice is actually not to wet earth blocks for building-up earthen masonry. However, earth blocks show generally high water absorption and suck out moisture from the fresh mortar, which influences the bond between the two wall components greatly. This naturally has also a big influence on the shear strength of the masonry. As a comparison, therefore 2 sets of sample panels were prepared, one set with non-wetted and another set with wetted blocks.

Masonry panels with non-wetted blocks showed very low shear strength values, which were in the range of 0.08 and 0.11 MPa. The stress strain curves usually showed one or several yielding points.

![Comparison between the three earthen materials under compression, stress-strain envelope](image)
where the blocks began to slide gradually and until friction set in and increased stress again until final failure. Masonry panels with wetted blocks showed much higher shear strength values than with non-wetted blocks. For the three tests strength values 0.25 and 0.4 MPa were reached, which is two to three times higher than in the case of non-wetted blocks. The stress-strain curve of two of the three specimens showed a distinctive yielding point, when elasticity of the samples was exceeded and first cracks appeared. Stress was then increasing until the sample failed. The maximum deformation values were approximately the same for both sets of panels. This type of stress-strain response can be linked to the actual failure mode of the specimen. The sample specimen yields the stress until a first vertical crack appears by exceeding the maximum elastic horizontal strain. The crack ran not only along joints but also through blocks. At the second yielding point the sample failed by sliding of the blocks along the joints until complete collapse. This failure pattern could also be observed on rammed earth panels (Fig. 3). Rammed earth panels yielded the highest results for shear strength of all three different construction types. Values ranged between 0.65 and 0.85 MPa. The maximum strain was much higher than with earth block masonry and usually between 1 and 2% before complete failure.

Almost all the panel specimen safe for one showed a distinctive yielding point after the elastic range on the stress-strain curves. Observation from video footage showed the development of failure:

- No visible changes in the elastic range of the strain;
- Appearance of a vertical crack close to the first yielding point;
- Development of a system of small parallel running vertical cracks with an increase in load; the systems usually run diagonal from one end of the upper loading shoe to the other end of the lower one;
- Combination of the single shear cracks to one coherent crack running diagonally through the sample at the maximum load; sometimes the diagonal shear crack run partially through the vertical crack;
- Collapse of the sample.

![Fig. 3 Earth block masonry, rammed earth and cob specimens under diagonal compression](image)

![Fig. 4 Results from photogrammetric analysis by ARAMIS and the corresponding stress-strain curve showing the deformation of two rammed earth panels. Yellow, red and white colours indicate cracking. Note the diagonal deformation in the elastic range which is parallel to the rammed earth layers](image)
It is noteworthy that even though a first vertical crack appeared in the panels an increase in load was still possible. Not in every sample the vertical crack was combined with the diagonal crack system. In two of the seven samples tested both cracks appeared to be independent. It is probably safe to say that the final failure was not caused by compression but mostly by shear failure as in the earth block masonry wall panels. The photogrammetric analysis by the ARAMIS 3D system essentially confirmed the findings from the stress-strain curves and the analysis of the failure mode. Fig. 4 shows exemplarily the results of one of the rammed earth panels tested.

Though only a section of the entire panel was visualized the development of cracks on the stress-strain curve followed the scheme as described above. Interesting was the appearance of a diagonal deformation (in Fig. 4 indicated by red lines) in the elastic range of the curve. The direction of the deformation was in the layering of the rammed earth. Some of these deformations became cracks by increasing the load to the maximum value. Even though cob wall panels (Fig. 5) revealed the lowest strength values in the compression tests, the results from the diagonal compression (shear) experiments where much better than that of the earth block masonry panels and only slightly below the values for rammed earth panels. The strength figures ranged from 0.40 to 0.65 MPa (Fig. 6). The maximum strain was, as in the compression tests, the highest of the three earth construction techniques ranging from 2 to 5%.

![Load vs. Shear strain graph](image)

**Fig. 5** Results from the photogrammetric analysis (ARAMIS) and the corresponding load-strain curve showing the deformation of two cob panels. Yellow, red and white colors indicate cracking

A first yielding point on the stress-strain curve, as observed for the masonry and rammed earth panels could not be recognised on the curves of the cob specimen (Fig. 5). The typical course was an elastic range with a low shear modulus followed by a plastic-type deformation of the sample specimen. Typical vertical cracks due to the compression load as observed with the other two construction types were not identifiable here. Usually the specimens collapsed after reaching maximum load by shear failure. Cracks were always running diagonally from one end of the upper loading shoe to the other end of the lower shoe (Fig. 3). The results by ARAMIS showed that majority of the cracking occurred not in the end of the elastic range but on the way to the plateau of the maximum load (Fig. 5). However, when the maximum load was reached cracking was prominent and failure followed suit, even though deformation was still possible since the specimen parts were still held together by strings of straw fibre.

### 5.3 Evaluation and comparison of results

Results obtained for diagonal compression tests and calculated according to ASTM E519-10 [11] are given below in Tab. 5, where \( G_{1/3} \) is the shear modulus of elasticity measured at 1/3 maximum load, as well as for the shear strain \( \gamma_{1/3} \). The maximum shear strength of the specimens was calculated from the maximum load. Fig. 6 shows a comparison of the behaviour between earth block masonry, rammed earth and cob in terms of results for diagonal compression loads. As in the case under vertical compression, cob presented a marked and significant post-peak strain phase before failure, with a gradual drop in capacity. Rammed earth, as in compressive test, shows a hardening phase at the
beginning with failure starting from compaction planes. It is important to remark that earth block masonry samples, which were manufactured without wetting the earth blocks showed insufficient bonding between mortar and blocks. This might have caused micro damages when handling and preparing the specimen for the test. This also had certainly a strong influence in the low shear strength values exhibited by the masonry specimen.

Table 5 Results from diagonal compression tests in comparison (W = earth block, wetted; STD = standard deviation)

<table>
<thead>
<tr>
<th></th>
<th>Shear strength $\tau_u$ [MPa]</th>
<th>Shear modulus $G_{1/3}$ [MPa]</th>
<th>Shear strain $\gamma_{1/3}$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>STD</td>
<td>Mean</td>
</tr>
<tr>
<td>Earth block masonry</td>
<td>0.09</td>
<td>0.01</td>
<td>41</td>
</tr>
<tr>
<td>Earth block masonry (W)</td>
<td>0.34</td>
<td>0.06</td>
<td>660</td>
</tr>
<tr>
<td>Rammed earth</td>
<td>0.71</td>
<td>0.11</td>
<td>2326</td>
</tr>
<tr>
<td>Cob</td>
<td>0.50</td>
<td>0.10</td>
<td>420</td>
</tr>
</tbody>
</table>

Fig. 6 Comparison between earth block masonry, rammed earth and cob under diagonal compression, envelope of stress-strain curves. Note the difference in results with earth block masonry, when wetted and dry blocks were used.

6. CONCLUSIONS

This part presents an analysis of the mechanical properties of traditional earthen construction materials, based on results obtained from compressive and shear tests. Basic parameters concerning seismic behaviour were determined, including shear strength, shear modulus and elastic modulus. The compressive tests on wall panels were carried out with displacement control, and it was thus possible to determine post peak strain performance. Diagonal compression test were performed under force control. In terms of compressive strength, the maximum value of 3.73 MPa was obtained for the rammed earth specimens, whereas the compressive strength of earth block masonry and cob was found to be 88% and 43%, respectively, of that of rammed earth.

In the second part of the research program, diagonal compression testing was carried out, yielding a maximum shear strength value of 0.71 MPa for the rammed earth specimens, 0.50 for cob and a significantly lower value for earth block masonry. For earth block masonry the construction technique is essential for performance. With the same materials but with dry and wetted earth blocks prior to laying the wall panels yielded different results in the shear tests (Tab. 5). Moistening the blocks prevents early water reduction in the mortar, thus improving the bond between mortar and earth block and enabling the increase of the shear strength of a masonry wall two to three times. On the other hand, for historical buildings the masonry often shows a poor bond between block and mortar, indicating that blocks were not wetted and therefore a low value for shear strength has to be anticipated.

A general conclusion which can be drawn is that cob, which exhibits lower compressive resistance, shows relatively ductile post peak behaviour when compared with the brittle behaviour of the earth block masonry and rammed earth specimens: cob can deform beyond the elastic range with a gradual drop in capacity. This behaviour is strongly influenced by the presence of fibres. Despite its low compressive strength, cob thus presents a relatively good performance within the earthen material
range as far as shear behaviour is concerned. This parameter, together with its long post peak plastic
phase, is relevant if its utilisation in seismic areas is considered. Buildings in these areas are bound to
be subjected to lateral displacements and the ability of a building to deform without collapsing is
essential for saving human lives and the repair of a structure.

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