STRUCTURAL EVALUATION OF A NOVEL SOLUTION FOR SUSTAINABLE MASONRY CONSTRUCTION

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To reduce its environmental impact masonry construction requires novel innovative solutions. The work presented in this paper forms part of a larger PhD project investigating the potential use of fired clay brick masonry with hemp-lime biocomposite insulation. Hemp-lime is a low carbon insulation material, utilising renewably sourced hemp shiv with a lime based binder, that can provide levels of thermal insulation suitable for modern building requirements. Due to its low structural strength and stiffness hemp-lime is generally used in non-loadbearing applications. In the proposed application hemp-lime is cast as an internal insulating layer against an external 102.5 mm thick fired clay brickwork structural facing. This paper presents the results of investigations into the structural interaction between the hemp-lime and brickwork. Although the hemp-lime is considered non-structural, its potential indirect structural restraint to buckling of the brickwork has been explored experimentally. Some enhancement in capacity has been observed, however this benefit has been found to be variable. The experimental results of four large scale wall tests are reported together with discussion and conclusions from the study to date. The contribution of ties between the wall and hemp-lime has been studied. Recommendations for further work are also explored.

Keywords: Sustainability, brick, hemp-lime, structural testing.

INTRODUCTION
The usage of fired-clay brick masonry is widespread throughout the United Kingdom. However, over the past ten years there has been a steady decrease of 53\% in brick production in the UK\textsuperscript{(1)}. This is exacerbated by the close relationship between the industry and the mortgage market, as seen during the financial troubles of 2008 where the number of bricks produced in the UK reduced by 22\% compared to the 2007 levels\textsuperscript{(1)}. It is therefore desirable to investigate innovative solutions to allow a continued application of brick masonry in construction.

Current clay brick masonry comes with two associated disadvantages; low thermal resistance and high levels of embodied CO\textsubscript{2}\textsuperscript{(2)}. A common solution to the first problem is to construct a cavity wall, with an internal skin of either concrete blocks or a timber frame. The cavity is then at least partially filled with a (often) synthetic insulation layer. This improves the thermal resistance at the cost of even higher embodied CO\textsubscript{2} for the wall construction. With the ever increasing requirements for the thermal resistance of walls and consequently thicker
insulation, this embodied CO₂ value will increase. The role of the external brick masonry skin is reduced to that of supporting its own weight and providing a weather-proof facing.

It is necessary to provide a solution that supplies high levels of thermal resistance, while reducing or eliminating embodied CO₂ in the material. The brick masonry then must retain its durability and strength and perform in an efficient structural manner. In order to provide good thermal resistance hemp-lime was chosen as the insulation. Hemp-lime is a modern material with very low levels of embodied carbon, due to conversion of atmospheric CO₂ by the hemp plant during photosynthesis, as well as providing good thermal resistance \(^{(3)}\). It is formed from renewable hemp-shiv, the woody core of the plant stem, and a lime based binder. The dry constituents are mixed with water and the resulting blend can be erected using conventional formwork. The plant component and its internal structure means that while its embodied CO₂ is very low (estimated to be \(-110\text{kg/m}^3\) by Bevan et al.\(^{(4)}\)) its structural strength and stiffness are also low. For these reasons it has not been fully characterised or is generally used structurally.

This research considers a half brick thick (102.5 mm) wall of fired clay masonry tied, at regular intervals, to a bulk of hemp lime 250 mm thick (see figure 1). In the proposed structure the brick masonry provides structural strength while the hemp-lime acts as a restraint for the masonry and provides thermal resistance. This paper reports on the testing of the structural properties. This work forms part of a larger project; of which previously published results are used for comparative purposes in this paper.

EXPERIMENTAL PROGRAMME

The hypothesis of all testing undertaken was that hemp-lime could provide some resistance to the lateral movement of masonry under eccentric loading. This resistance was initially explored in the paper by Molesworth and Walker\(^{(5)}\), however two primary problems were identified:
1. The importance of producing buckling behaviour and hence lateral displacement in the masonry; 
2. A requirement for a stronger tie with a greater pull-out resistance from the hemp-lime.

These two requirements led to the development of a new tie. Previous walls\(^{(5)}\) had used a standard metal wall tie commonly used in construction in the UK. The tie was attached to a plate placed vertically in the hemp to provide bearing resistance. This tie resulted in an uneven transfer of load due to the bending of the plate. To improve the pull-out resistance it was decided that the load must be spread more evenly into the hemp-lime matrix. For this reason a wire mesh embedded in the mortar joints in the wall, as shown in figure 2, was chosen, allowing a large area of direct load transfer through the numerous strands of wire.

To evaluate the strength of the tie pull-out testing was undertaken. Specimens of each tie were embedded in a large block of hemp lime, sized to minimise edge effects from the support arrangement. The ties were pulled out of the hemp at a steady rate of displacement and applied loads were measured. The results, shown in figure 3 clearly indicate that while the strength of the rectangular mesh is variable, it is at least 2 times stronger than the more traditional wall ties used in early specimens and resulted in the highest pull-out resistance of the three meshes tested. For this reason and for the good stiffness shown in the pull-out, the rectangular mesh was taken forward for use in the principal test specimens.

![Figure 2: Wire mesh tie, as used in structural testing, undergoing pull-out strength testing.](image-url)
METHODOLOGY

Four single leaf walls were constructed, by an experienced bricklayer, using standard clay facing bricks (Berkley Red Multi units supplied by Ibstock Brick Ltd). These units were tested using the method outlined in BS EN 772-1:2000(6) adjusted to cap the bricks with thin plywood. The unit strength, as calculated using the above standard, and adjusted for use in BS EN 1996-1-1(7), was 58 MPa. The bricks were laid in a proprietary pre-mixed 1:1:6 cement, lime, sand mortar. This was specified to be a class III mortar at 28 days, with an expected strength of approximately 8 MPa. The mortar was tested at 28 days according to the method given in BS EN 1015-11:1999(8), the compressive strength achieved was 15.1 MPa. The compressive strength of the masonry was tested using the method set out in BS EN 1052-1:1999(9) the average strength being 23.1 MPa.

The wall was constructed in a stretcher bond to 23 courses high, by two bricks wide, giving dimensions of 1730 mm (high) by 440 mm by 102.5 mm. Ties were embedded every fourth course. The walls were then left for seven days to cure. After seven days the brick masonry was placed on its lower support and braced for stability. Hemp-lime was formed to a thickness of 250 mm behind the brickwork, up to the 22nd course, to allow movement of the machine head during testing (figure 4). The entire structure was then left for 28 days before testing. The hemp-lime was mixed to a ratio of 2:1 binder to shiv by mass with a target density of 330 kg/m³. The mixture is placed into formwork by hand, tamping the edges to ensure a good surface. In practice up to 300 mm of hemp-lime would be used to ensure a good U-value for the wall however 250 mm was the thickest that it could be formed for practical reasons within the laboratory.
Loading was applied to the walls through steel rollers resting on steel plates at the top and bottom of the masonry. Vertical loading was applied only to the masonry and not the hemp-lime. The eccentricity of load varied from 0 to 0.2t (t = thickness of brick skin) as each test required and is detailed in table 1. For all tests a vertical plate was used to restrain the hemp-lime as a simulation of the restraint that would be present from surrounding material in a larger wall. Test C contained an extra restraint clamping the sides of the hemp-lime in an attempt to further simulate this effect. Both clamps can be seen in figure 5, which shows the vertical clamp in the form of the threaded bar, and the extra restraint of the plywood, hiding the hemp-lime.

Wall D was tested without hemp-lime by clamping the free end of the ties to a rigid support. This was done to understand whether the ties themselves could restrain the brickwork and increase the capacity of the masonry.
Figure 5: Wall C Showing restraint of the hemp-lime.

### Table 1: Summary of walls tested.

<table>
<thead>
<tr>
<th>Wall</th>
<th>Load Eccentricity</th>
<th>Hemp-lime Thickness (mm)</th>
<th>Restraint</th>
<th>Dry Density (kg/m³)</th>
<th>Strength (MPa)</th>
<th>Maximum Load (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Concentric</td>
<td>0</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>869</td>
</tr>
<tr>
<td>B</td>
<td>0.2t</td>
<td>250</td>
<td>Vertical</td>
<td>320</td>
<td>0.309</td>
<td>325</td>
</tr>
<tr>
<td>C</td>
<td>0.2t</td>
<td>Vertical and side clamp</td>
<td>338</td>
<td>0.317</td>
<td>435</td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>0</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>525</td>
<td></td>
</tr>
</tbody>
</table>

**ANALYSIS**

Figure 6 below suggests that there was no significant restraint provided by the hemp-lime in either of the walls tested with hemp-lime, as no improvement in strength or stiffness compared to the unrestrained walls. It is unlikely that the increase in mortar strength observed in walls A-D had a marked effect on the overall strength of the masonry when compared to walls 9-12 from Molesworth and Walker\(^5\) (plotted as the range bounded by the horizontal dotted lines). Those walls were loaded at the same eccentricity under the same support conditions and contained a mix of hemp-lime restrained walls. And fully unrestrained plain brick specimens.
Figure 6: Graph of load versus displacement for walls A-D. Previously presented results\(^{(5)}\) lie in the range marked by the horizontal dotted lines.

The behaviour of wall A is significant. Loading was applied to the wall through rollers in a similar manner to the other walls. The load was applied concentrically. The wall began to fail exhibiting vertical cracking without significant lateral deformation until the point at which structural stability was lost and the wall fell sideways. This behaviour is evident in the plateau then sudden drop in load visible in figure 6. The other walls, which failed through buckling and show no plateau in the load/deflection plots. Most significantly the 19.1 MPa strength achieved was close to the range of results from the smaller masonry wall strength tests. The small walls, which were four courses high by 1.5 bricks wide achieved strengths ranging from 22 MPa to 24 MPa. Increasing the slenderness ratio (eff. height/eff. thickness) from approximately 3 to 16.8 lead to a reduction of strength of only approximately 10%. In comparison guidance given in EC6 specifies a design reduction of approximately 20% for a slenderness of 17. This result is corroborated by work collated by Hendry\(^{(10)}\) which showed that there was no significant loss in strength in a masonry specimens with slenderness ratio less than 33.

Wall A also shows that no wall tested under eccentric loading from either A-D in this paper or previously\(^{(5)}\) achieved full section capacity. While wall D shows increased capacity over that of walls B and C they should not be directly compared, as wall D was restrained as shown in figure 7. The behaviour of B and C is comparable to those walls previously presented\(^{(5)}\). The support structure to which the ties were clamped for testing of wall D (figure 7) failed before full section capacity could be achieved. Wall D still does go some way to show that the ties could restrain the brickwork and enable enhanced load capacity of the masonry.
Of the walls presented here, only C exhibited indication of increased strength and ductility using hemp-lime as a restraint. It can be seen on figure 6 that wall C achieved a higher load and stiffness than wall B and any other hemp-lime wall loaded at 20% eccentricity previously presented\(^5\). While conclusions are difficult to draw from this single result, it is worth noting that the behaviour of wall C is significantly different to those walls that preceded it. The sole difference between walls B and C was the restraint applied to the hemp lime under test. While the hemp-lime in wall B was restrained from significant horizontal movement at the top and bottom it was still free to bend in the centre. In a real situation, where over-loading of a wall is only likely to occur in specific locations, the surrounding materials, both within the masonry and the hemp-lime, will likely have a significant effect on the strength of the over-loaded section. It is difficult in a laboratory setting, due to restrictions of testing apparatus and laboratory space, to simulate a continuous wall in a test, the clamping and restraint applied to wall C does however go to providing a solution. The strength of wall C provides some evidence that this clamping method improves the capacity of the masonry however more results are needed to provide good statistical rigour.

An observation made during testing is again easily illustrated by wall C. Figure 8 shows a comparison between the wall pre failure on the left and post failure on the right. This increase in deformation appeared rapidly at the point of buckling, resulting in the large majority of the final deformation occurring in a couple of seconds. In the walls where hemp-lime is not present this results in the collapse of the specimen, however where hemp-lime is present the behaviour seen in figure 8 is observed. The hemp-lime is able to restrain the deformation of
the brickwork, but only after substantial movement of the masonry has occurred and significant vertical capacity has been lost.

The horizontal load applied to the hemp-lime is proportional to the vertical load being applied to the masonry. In the pull out tests undertaken as preliminary experiments the load was applied to the ties (and hence the hemp lime) in a slow and controlled manner. During loading of the masonry the tie deformations achieved during the pull-out tests are only reached during buckling of the wall. The rapid increase in strain and associated load will affect the strength of the tie to some degree. Further testing needs to be undertaken to check whether hemp-lime and tie exhibit better structural properties under rapid loading (as is common with more ‘traditional’ materials), or if it weakens when the masonry buckles. If it can be constructed in a way such that the tie can take much higher loads at lower deformation then it should be possible to provide significantly more restraint to the masonry.

CONCLUSIONS AND RECOMMENDATIONS
While some restraint can be seen from the hemp-lime it is difficult to conclude whether this could prove to be a practical solution. The behaviour of the brickwork in these tests closely correlates with behaviour previously collated by Hendry et al.\(^{(10)}\). This contrasts with the design methods used when considering slender brickwork in EC6\(^{(7)}\). Walls under eccentric loading did, however, correlate with calculated values taken from the code.

The ties used are able to restrain the brickwork against horizontal movement as shown by wall D, however this load is not then transferred into the hemp-lime resulting in walls that fail at close to the capacity of plain brick walls. Wall C shows greater restraint than those walls presented in previous papers \(^{(5)}\), but only if the hemp-lime is significantly restrained in
movement itself. The ties are also subjected to significantly different loading conditions in the hemp-lime when compared to the situation present during the pull-out tests.

As a structural material hemp-lime has little compressive strength or stiffness, however it is the variability of the material that causes the most problems. The sensitivity of the structural properties to the density of the material is too high, and relying on its structural capability is not currently recommended in this situation.

Recommendations for further work are as follows:

- Improve the understanding of the structural properties of hemp-lime, and work to improve its consistency of performance. This will also improve the load transfer between the wall ties and the hemp-lime.
- Study the behaviour of the tie at the point of buckling, and develop a method that prevents the masonry from reaching this point. So removing the issues surrounding short impulse loading.
- Test larger samples loaded under point loads. Load only part of the brickwork and hemp-lime to failure and compare to the results of the smaller walls to understand the full effect of the presence of surrounding material.

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