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Development of a Novel Binder for Mortar for Unfired Clay Bricks

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ABSTRACT

Interest in traditional unfired clay building materials has grown in the UK in recent years. Although the use of vernacular techniques has raised the profile of earthen architecture, a wider impact on modern construction is more likely to come from modern innovations such as unfired extruded clay masonry units. Traditional unfired clay walls often have basal widths of 300mm or more, providing an inherent stability through self-weight. Masonry units extracted from UK brick production lines before the firing process are typically 100mm wide, which requires good mortar-brick bond strength to meet structural robustness requirements in a typical 2.4m high wall. In testing, traditional mortars have not provided sufficient strength. This paper reports on the development of a mortar which appears to be suitable for a wide range of clay types. Results of long term tests demonstrate the suitability of this mortar for use with unfired clay masonry units.

INTRODUCTION

Unfired clay materials can provide a sustainable and healthy alternative as a replacement to conventional masonry materials, such as fired clay and concrete block, in both non-load-bearing and low rise load-bearing applications. Environmental benefits include significantly reduced embodied energy, thermal mass and regulation of humidity. Materials may be taken from sustainable resources (low grade clay and overburden) and are readily re-used, re-cycled or harmlessly disposed on end use. Materials are also entirely non-hazardous. Unfired clay materials offer potential health benefits to internal built environments, primarily through passive regulation of relative humidity. Though traditional clay masonry materials, such as adobe, clay lump and cob blocks, as well as more recently developed compressed earth blocks have been used successfully in a variety projects, more and more interest has been shown in using unfired clay bricks produced by high volume industrial brick manufacturers. The tensile strength of unfired clay materials is low and the bond between unfired clay units and traditional clay mortars is poor, therefore walls have relied on their bulk mass to ensure lateral load resistance and resilience. Consequently traditional solid walls are typically at least 250-300 mm thick. The standard size of fired clay bricks in the UK is 215 x 102.5 x 65 mm. Although the dimensions of unfired clay bricks are slightly higher they remain smaller than adobe and compressed earth block dimensions or the sizes of solid rammed earth or cob walls.

To maximise useable floor space in a project, as well as reducing material use, designers, developers and clients demand minimal wall thicknesses. Consequently the large sizes of traditional unfired clay walls are generally not acceptable for many situations. However, thin masonry walls, say 105 mm thick, cannot rely on their bulk alone to provide adequate resistance to lateral loading. Therefore, masonry bond strength is required to create a structurally robust wall that will not collapse when it experiences lateral loading. Wall thickness has a large effect on required bond strength. A 2.4 metre high vertically spanning wall at 300mm thick, even with very low bond strength (0.024 N/mm^2), can carry a uniform line load at half height of 500 N/m. In order to reduce the thickness of the wall to 105mm, while providing the same flexural capacity, the bond strength must be increased to around 0.2 N/mm^2. There are many examples of single storey 300mm thick earthen walls where the bond strength approaches zero (e.g. adobe blocks with clay mortars). The bond strength of 0.2 N/mm^2 for a 100mm thick wall is considered a reasonable target characteristic strength for unfired earth masonry.

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

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

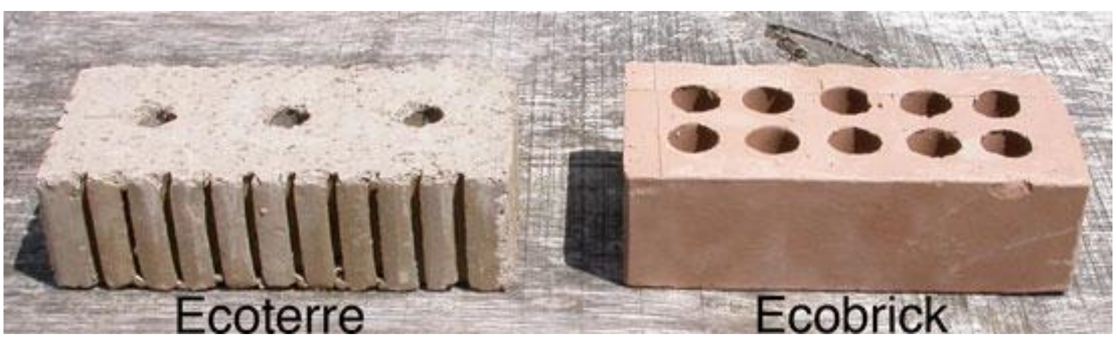

Fig. 1. Unfired Clay Bricks used in the Research

PREVIOUS WORK

A range of different mortars were assessed for bond strength on the two bricks. It was found that mortars made with sand and clay; sand and cement; and sand and lime all resulted in 28 day bond strengths below 0.01N/mm^2, insufficient for the proposed application The addition of 5% lignosulphonate to a sand and clay mortar produced an improved bond strength of 0.05N/mm^2, albeit still well below that required for thin wall construction. It was found that a proprietary lignosulphonate based mortar, marketed for use with the Ecobrick, performed poorly when used with the Ecoterre brick (similar bond strength to sand and clay alone).

In order to produce a mortar that would be suitable for all types of unfired clay brick, other binders were assessed, and sodium silicate was found to be the most promising. As sodium silicate is water soluble, it is not recommended as a cement replacement in conventional masonry. In earth masonry where the masonry units have limited water resistance, there is no requirement for a water resistant mortar and adequate performance is ensured through the use of appropriate detailing.

SODIUM SILICATE

Sodium silicate has the general chemical formulation of $Na_2O.xSiO_2$, being a mixture of varying proportions of SiO_2 and Na_2O, and it is also known as water glass. It is manufactured through the hydrothermal dissolution of silica sand in sodium hydroxide to produce a sodium silicate solution of 48% solid and a weight ratio of 2 (2 parts SiO_2 to 1 part Na_2O). The energy requirement for the production of this hydrothermal liquor is 500 MJ per tonne of output (Fawer, 1999). For comparison purposes, cement production requires about 4,400 MJ per tonne of output (International Energy Agency, 2007).

When heated, excess water is driven off from sodium silicate and a glassy material is produced. At very high temperatures, it is intumescent. These characteristics allow it to be used for passive fire protection, fire cements, automotive repairs (exhaust pipes, leaky radiators). Sodium silicate has a high pH, allowing it to be used as a buffer in detergents, and as a stabiliser in pulp and paper manufacture. It is also used in paint manufacture, as a plasticiser in the ceramics industry and as a binder and fluxing agent for welding electrodes. In construction, sodium silicate is used as a coating to significantly reduce porosity in concrete, renders and plasters through chemical combination with excess $Ca(OH)_2$ in a reaction that permanently binds the silicates with the surface of the material making it more wearable and water repellent. Soluble silicates are widely used in the production of paper and board products as an adhesive producing rigid high strength paper tubes and drums. It is this adhesive quality that led to sodium silicate being trialled in unfired clay mortars.

EXPERIMENTAL PROGRAMME

The testing of sodium silicate mortars took place in two phases. The first phase involved the establishment of the optimal formulation, and the second phase tested masonry units manufactured with the chosen formulation according to established standards, and included long term testing to establish the durability of the mortar/brick bond.

Phase 1

Sodium silicate mortars were manufactured from 3 parts building sand, 1 part crushed unfired clay (as used in brick manufacture), and varying proportions of sodium silicate solution (by volume). Water was added to produce a flow table value of between 150 and 170mm which indicates a similar workability to conventional mortars. The clay from the brick being tested was used for the crushed clay in the mortar. This was done in order to maximise the compatibility between the mortar and the brick.

In each case a number of triplets of bricks were produced using a 10mm mortar joint. The bond was then tested at 7 days following BS EN 1052-5:2005 as illustrated in Fig. 2.

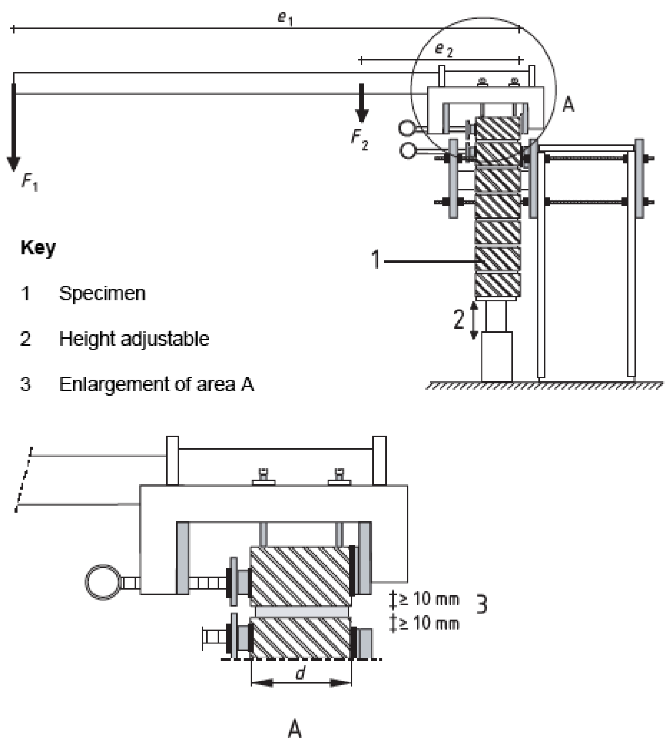

Fig. 2: Bond Wrench Mechanism per BS EN 1052-5:2005

The results of these bond wrench tests are presented in Table 1. In conventional masonry it is generally accepted as preferable for failure in tension (flexure) and shear to occur within the weaker mortar joints rather than the stronger masonry units. However, in achieving adequate flexural bond strength here, it became evident during our experiments that brick strength was often to become a controlling parameter in masonry performance. In some cases for the 'Ecobrick', it was not possible to produce a failure either in the bond or in the brick within the loading limits of the apparatus. In other cases for the 'Ecoterre', the loading produced a diagonal failure in the brick, where both the bond strength and the shear strength of the mortar exceeded that of the brick. There was found to be an evident relationship between early bond strength and concentration of sodium silicate, with a lower concentration of sodium silicate being required with the 'Ecobrick' for the bond strength and mortar strength to exceed that of the brick.

At an early stage in the research programme the manufacturers of the 'Ecobrick' went out of business, and the focus of the research concentrated on the only remaining generally available unfired clay brick, the 'Ecoterre'. Fig. 3 shows the relationship between silicate concentration and bond strength for the 'Ecoterre' brick, and this is related to the tensile strength of the brick.

As can be seen from Table 1, at three days a formulation using 14 parts sodium silicate to 60 parts sand & clay produced a mean strength in excess of that required to maintain stability in a 100mm thick wall.

Table 1: Bond Wrench Test results for Trial Mortar Formulations

Mix details Sand: clay: silicate		Age at test	Bond strength (N/mm^2)		Failure Mode
Brick	(by volume)	(days)	Mean	Characteristic	
Errol	45:15:6	7	0.05	0.03	Bond
Errol	45:15:7	7	0.07	0.03	Bond
Errol	45:15:8	7	0.16	0.06	Bond
Errol	45:15:9	7	N/A	N/A	Brick
Errol	45:15:10	7	N/A	N/A	Brick
Errol	45:15:11	7	N/A	N/A	Brick
Ecoterre	45:15:6	7	0.05	0.04	Bond
Ecoterre	45:15:7	7	0.09	0.10	Bond
Ecoterre	45:15:8	7	0.19	0.10	Bond/Mortar
Ecoterre	45:15:9	7	0.23	0.21	Mortar
Ecoterre	45:15:10	7	0.26	0.24	Brick/Mortar
Ecoterre	45:15:12	7	0.32	0.24	Brick
Errol	45:15:8	3	0.12	0.03	Mortar
Ecoterre	45:15:14	3	0.22	0.14	Brick/Mortar

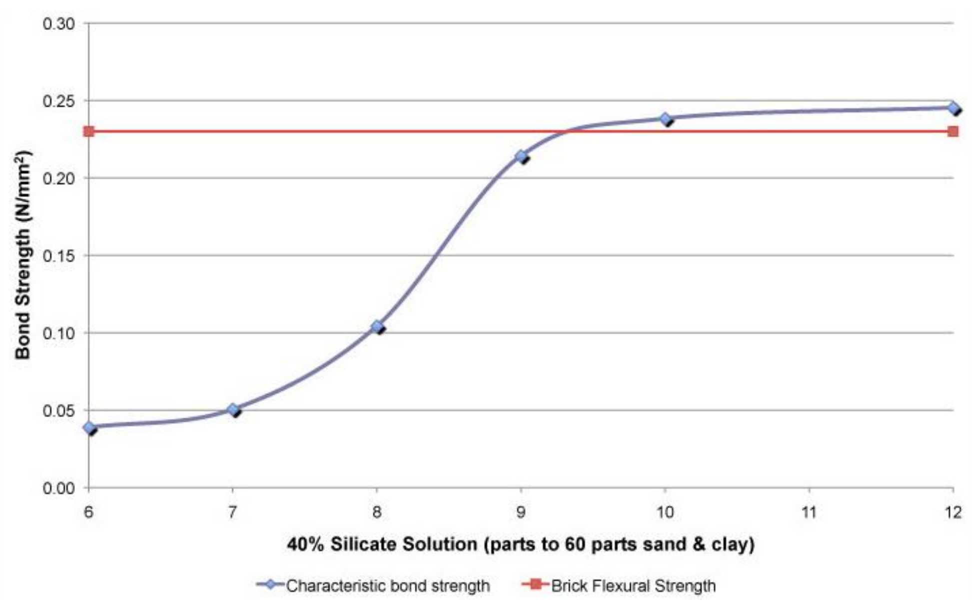

Fig. 3: Relationship between Bond Strength and Sodium Silicate Solution for 'Ecoterre' Bricks

Based on these data, it was decided to move to Phase 2 using a formulation based on 12 parts of 40% sodium silicate solution to 45 parts sand and 15 parts crushed clay. This mix required no additional water to be added to produce an acceptable flow for the purposes of brick-laying. The concentration was such that a bond greater than the shear strength of the brick could be established at an early stage in construction, thereby allowing brick-laying to proceed at an economic pace.

Phase 2

For the second phase of testing, 21 triplets of 'Ecoterre' bricks were made in order to test the bond strength at 7, 14, 28, 63, 91, 182 and 364 days according to BS EN 1052-5:2005. In addition masonry walls were constructed to test for compressive strength according to BS EN 1052-1:1999, flexural strength according to BS EN 1052-2:1999 and initial shear strength according to BS EN 1052-3:2002. A wall was also constructed of 4 bricks wide and 13 bricks high to measure shrinkage as the mortar dried out. In all cases the mortar bed was 10mm. All specimens were stored in a climate controlled chamber at 20ºC and 60% Relative Humidity (RH) in order to ensure comparability between results. This is important since the compressive strength of unfired clay bricks is particularly sensitive to moisture content (Heath, 2008). The wall testing was conducted 56 days after manufacture.

Bond Strength

The results of the bond strength data up to 182 days are presented in Fig. 4.

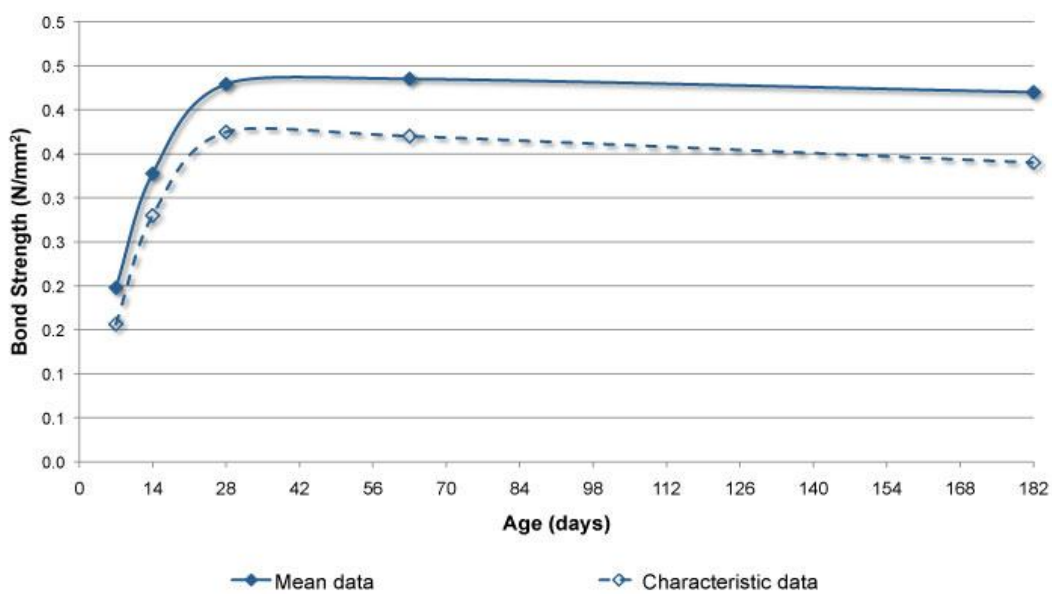

Fig. 4: Bond Strength Data for a 12 part 40% Sodium Silicate Solution to 60 parts Sand/Clay Mortar with 'Ecoterre' Bricks

In all cases from 28 days onwards, the failure was in the brick. These data show that the bond strength exceeds the required strength within 7 days of manufacture, and that by 28 days it exceeds the strength of the brick. The minor decrease in strength seen at 365 days is within experimental error and not considered to be significant.

Initial shear strength

The data from the initial shear strength test are presented in Fig. 5.

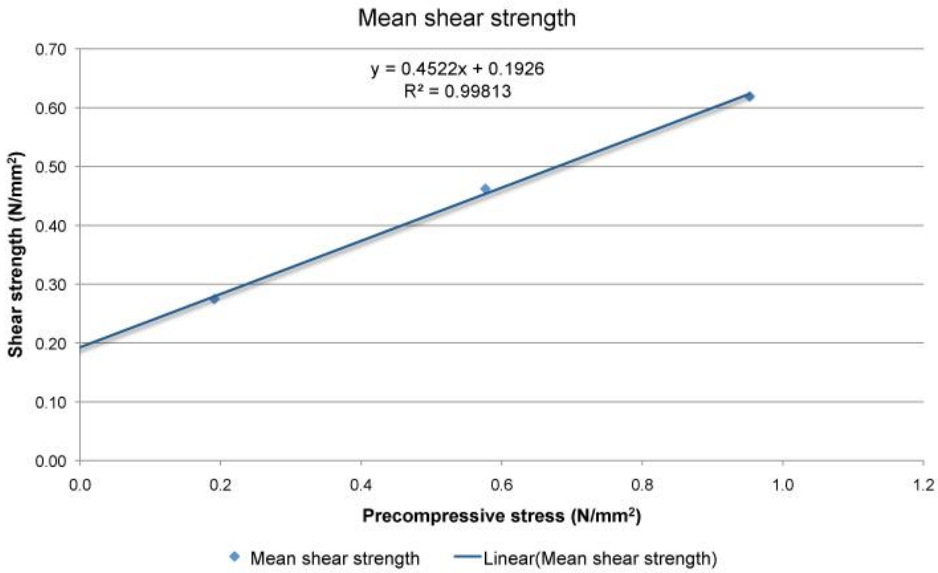

Fig. 5: Mean Shear Strength of a 12 part 40% Sodium Silicate Solution to 60 parts Sand/Clay Mortar with 'Ecoterre' Bricks

The mode of failure was generally A3 (shear failure in the unit), at higher pre-compressions some failures were A4 (crushing or splitting failure in the units). In no case did the bond fail. Mean shear strength by the graphical method was 0.193 N/mm^2

Compressive strength

Fig. 6 shows the test set-up. Strain gauges were positioned on both sides of the wall to measure deformations in the wall. Loading was applied at 0.15 N/mm^2.min which produced a failure in around 24 minutes (the standard calls for a failure time of between 15 and 30 minutes). Typically the mode of failure was a vertical split through the narrow face of the wallette. The test results are shown in Table 2.

The characteristic compressive strength of the masonry walls is 2.07 N/mm^2. This is similar to the characteristic compressive strength of the bricks. The compressive strength of the mortar was measured at 9.48 N/mm^2.

The mode of failure indicates that the bricks were the weakest element of the composite since the failure does not follow either the line of the bond or of the mortar.

Fig. 6: Set-up for Compressive Tests according to BS EN 1052-1:1999

Table 2: Results of Compression Tests

Specimen #	**Density (kg/m^3)**	**Strength (N/mm^2)**
1	2020	2.42
2	2050	2.52
3	2020	2.47
4	2030	2.49
5	2030	2.62
6	2040	2.40
Mean	**2030**	**2.49**
Std. deviation	**10**	**0.08**

Flexural strength

Fig. 7 shows the set-up for the vertical flexural test, and Table 3 shows the results of the flexural tests. As with the compressive tests, failure occurs in the bricks rather than in the mortar or at the brick/mortar interface. The test results are shown in Table 2. In both orientations, failure occurred in the bricks rather than in the mortar or at the mortar/brick interface. Once again the limiting strength is the brick. This again demonstrates that the mortar is not the weakest link in the flexural strength of unfired clay masonry walls.

Table 3: Results of Flexural Tests

	Flexural tests (vertical)		**Flexural tests (horizontal)**	
	Flexural Strength f_{xi} N/mm^2	**Density kg/m^3**	**Flexural Strength f_{xi} N/mm^2**	**Density kg/m^3**
Panel 1	0.59	2035	0.39	2047
Panel 2	0.54	2052	-	-
Panel 3	0.49	2029	0.44	2060
Panel 4	0.56	2040	-	-
Panel 5	0.67	2049	0.41	2025
Panel 6	0.56	2033	0.44	2061
Mean	**0.57**	**2039**	**0.42**	**2048**
Std dev.iation	**0.06**	**9**	**0.03**	**0.02**

Fig. 7: Set-up for Flexural Tests (Vertical) according to BS EN 1052-2:1999

Shrinkage tests

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

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

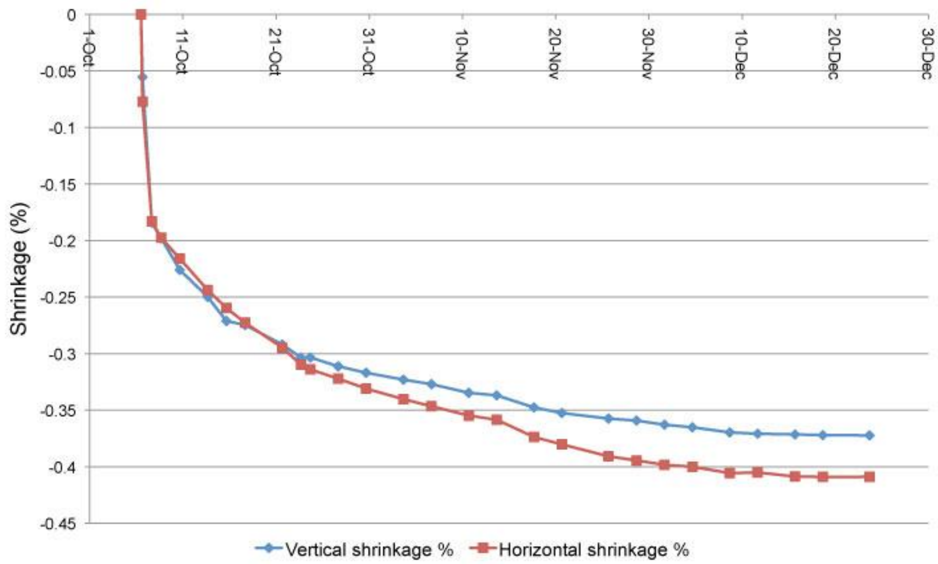

Fig. 8: Shrinkage Data for 'Ecoterre' Sample Walls held at 60% RH and 20ºC from Date of Manufacture

CONCLUSIONS

The tests conducted on unfired clay brick masonry walls bonded with sodium silicate mortar clearly show that the mortar is fit for purpose and has significantly lower embodied energy than conventional cement mortars. The high levels of shrinkage, associated with moisture necessarily used to make the mortar, has the potential to create particular problems which need to be allowed for in construction planning. However, as most shrinkage occurs during the first day, much of the shrinkage is allowed for in subsequent day’s work.

This research has demonstrated that it is possible to construct thin masonry walls from unfired clay bricks which have adequate structural performance. The benefits that accrue from this are numerous and significant:

- Unfired clay bricks offer the potential for passive regulation of relative humidity, thereby improving the internal environmental conditions
- The manufacture of 'standard sized' unfired clay bricks using fired clay brick production lines offers efficiency and cost savings
- The use of thin wall construction increases the available space within a building, reducing the construction cost per square metre compared with traditional adobe or rammed earth construction.
- The use of unfired clay masonry walls in place of concrete block or brick walls contributes towards reductions in the carbon footprint of construction
- The use of sodium silicate mortars instead of cement based mortars further reduces the carbon footprint of construction

Although unfired clay bricks are used for external walls in Germany, it is likely that the main application in the UK will be for internal non load-bearing walls, where advantage can be taken of the low carbon cost of this method of construction, its thermal mass, its ability to regulate relative humidity and its sound insulation qualities. Care needs to be taken to minimise the risk of inundation and of exposure to rainfall through appropriate detailing.

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