Citation for published version:

Maskell, D, Heath, A & Walker, P 2013, 'Laboratory scale testing of extruded earth masonry units', *Materials & Design*, vol. 45, pp. 359-364. <https://doi.org/10.1016/j.matdes.2012.09.008>

DOI:

[10.1016/j.matdes.2012.09.008](https://doi.org/10.1016/j.matdes.2012.09.008)

Publication date:

2013

Document Version

Peer reviewed version

[Link to publication](#)

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Laboratory Scale Testing of Extruded Earth Masonry Units

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Abstract

There has been a resurgence in use of earth as a construction material largely driven by environmental concerns. Extruded earth masonry is a method of earth brick production that utilises existing fired brick manufacturing techniques. Extruded earth has distinct physical characteristics compared to other earthen building techniques. As industrial scale extrusion trials require large volumes of material, laboratory scale material development relies on samples prepared using alternative forming methods, such as moulding and compaction, which do not reliably reproduce the full-scale manufacturing process. The paper presents a representative method of manufacturing small scale extruded earth bricks. A suitable testing methodology is proposed, with varying curing conditions investigated. The small scale bricks are compared against equivalent large scale unfired earth bricks. The small scale bricks achieved a compressive strength of 3.39MPa and with a corrected difference compared to the full scale bricks of 0.07MPa; were found to be a reliable basis for laboratory scale investigation of material performance. The relationship that describes the effect of moisture content on strength exists for both small and large scale bricks.

Keywords

Masonry; Earth Construction; Compressive Strength Testing; Size Effect

1 Introduction

Earth as a construction material is one of the oldest and the most common building materials still in use [1]. Earth architecture is commonly associated with developing countries and within the UK the heritage of earth construction largely ended during the 19th Century [2].

There has been a resurgence of construction with earth largely due to environmental concerns of high embodied energy and the global warming potential of fired bricks and cement based products [3]. While rammed earth has shown the potential for contemporary earthen architecture, greater impacts are likely to come from earth masonry where current building practices can be easily adopted.

Compressed Earth Blocks (CEB) are masonry units that are manufactured by manually or mechanically compressing earth within a mould. A growing body of research has focused on the strength and durability of CEB [4,5]. While Jayasinghe and Mallawaarachchi [4] and Oti et al. [6] showed the potential for CEB to be produced on an industrial scale, Heath et al. [7] showed the structural potential for commercially extruded bricks to remain unfired.

The manufacturing process of fired clay bricks prior to firing is also suitable, without any significant modification, for the production of unfired earth bricks. There is minimal additional capital cost of production due to an identical process being utilised and a reduced running cost due to economy of scale factors. Morton et al. [8] showed that by not firing the bricks 86% of the embodied energy of a fired brick could be saved. The commercial extrusion allows for a greater control over quality and reduced unit costs compared to CEB.

There has been limited research on the strength of unfired extruded masonry units with the exception of Heath et al. [7,9]. This is in part due to complexities of laboratory scale testing of extruded bricks. A suitable method of production and testing of extruded earth masonry units must be developed to allow for further research and development of unfired extruded earth masonry on a commercial scale.

Small scale masonry testing has been used for decades due to problems of full scale testing [10,11]. This approach is typically used to assess and investigate strengthening of existing structures as well as investigating the effects of extreme climatic events such as earthquakes. Testing at small scales is performed because of the cost and repeatability of undertaking full-scale tests [11].

This paper discusses how reduced laboratory scale brick manufacture can replicate full-scale production properties of extruded earth bricks. The focus will be on a suitable compressive strength testing methodology for small scale earth bricks, including the comparison to equivalent full scale bricks.

2 Materials and Methods

2.1 Materials

A soil used for commercial fired brick manufacturing was selected. Heath et al. [9] established that fired brick soils are also suitable for unfired clay bricks. Identical soil was used for both the full scale and small scale bricks without any modification or scaling. The soils can be described as a dark brown sandy SILT with a plasticity classification of a low plasticity clay [12]. The physical properties and particle grading was determined by the methodology provided by BS 1377-2:1990 [13], with the mineralogical content of the soil determined by XRD; shown with the plasticity and particle size distribution in Table 1.

Table 1: Soil Properties

Properties	%
Physical Properties	
Liquid Limit	24.1
Plasticity Index	8.3
Linear Shrinkage	5.7
Particle Grading	
Sand	33.1
Silt	45.5
Clay	15.9
Mineral Content	
Siderite	2
Hematite	3
Smectite	3
Chlorite	6
Illite	16
Kaolinite	31
Quartz	39

2.2 Sample Preparation

2.2.1 Full Scale

Full-scale bricks were manufactured by a commercial brick manufacture following the same methodology typically used for fired bricks. Following extraction, the soil is crushed and milled to a size of 2mm in preparation of extrusion. The soil is mixed with water to approximately the plastic limit of the soil in a series of rotating augers. This soil is then extruded under a vacuum through a precisely machined die. This produces a stiff column of clay, as in Fig. 1, that is subsequently cut into single bricks.

The process of extruding earth is a different form of soil compaction that is likely to impart unique physical characteristics compared to other forms brick manufacturing and soil compaction techniques. Bricks with much higher densities than those produced by CEB are achieved [9]. In addition there is potential for particle alignment due to the friction and the tapering of the extrusion.

Figure 1: Commercial Extruder

2.2.2 Small Scale

Mohammed et al. [9] observed anisotropic effects when using scaled bricks cut from a larger bricks. In order to produce similar physical characteristics to the bricks manufactured at full scale, it was essential that a similar extrusion process be used. Scaled bricks were manufactured within a laboratory environment at The University of Bath, using a small scale vacuum extruder as shown in Fig. 2. It was unfeasible to manufacture full scale bricks using this extruder, therefore bricks at 1:3 linear scale, thus 1:27 volumetric scale were produced as shown in Fig. 3.

This machine creates a similar production process to full scale extruded bricks. Soil that has been pre-mixed with the required water content is fed in to a series of augers that help to homogenise the mixture. Under a vacuum of 50kPa the clay is effectively compacted by reducing the cross sectional area at the point of extrusion to 72 mm by 34 mm. This produces a column of soil that is then cut into 22mm thick bricks as in Fig. 3.

Figure 2: Vacuum extruder

Figure 3: Scaled brick specimens

2.3 Optimum Moisture Content

The inherent strength of earth construction is dependent on the soil type, moisture content and dry density. The dry density can be increased through increasing the amount of compaction, which is equally dependent on the soil type and the moisture content during compaction.

Compaction curves for different soil types that account for varying moisture contents during compaction are well established with the Maximum Dry Density (MDD) and Optimum Moisture Content (OMC) dependent on the soil type, but also the

compaction energy and compaction method. To optimise the inherent structural properties by achieving the MDD by extruding at the OMC is essential. A compaction curve for the extruded soil was established and shown in Fig. 4. The values shown are averages of no less than 40 bricks with a 4.7% maximum Coefficient of Variation (CV) of dry density. This was compared to the modified proctor method that is typically used for determining the OMC for rammed earth and other field compacted soils.

The modified Proctor method has proven unsuitable for the determination of OMC for extrusion. The compaction based OMC is much lower than that required for extrusion, Fig. 4. Extruding at moisture contents below the plasticity limit resulted in notable cracking in the brick surface and further more extrusion was not possible at moisture contents less than 14%. The OMC for extrusion is therefore at the plasticity limit of 16%, with all future work extruded at this moisture content unless otherwise stated.

Figure 4: Compaction curve for soil

2.4 Testing Methods

There are no British or European Standard testing methods for earth masonry. Although there are well established fired masonry testing procedures, their appropriateness must be considered. Suitable methods of testing CEB have been discussed by Walker [14] and Morel et al. [15]. The effect on compressive strength by capping, platen restraint and accelerated drying should be investigated and taken account of.

Brick compressive strengths were measured by crushing specimens in their normal aspect. The load was measured with an applied constant displacement rate of 2.5 mm/min. Each brick was compressed until peak load was reached which was subsequently used to calculate the average ultimate compressive strength. This is based on the procedure for full scale fired bricks as given in BS EN 772-1 [16], with the exception of using a displacement controlled loading rather than stress controlled. Due to the smaller stress combined with a smaller cross-sectional area of the small scale earth bricks the instrumentation used to measure load allow for a greater accuracy.

2.5 Capping

Capping the irregular surface of the bricks helps to distribute the compressive force evenly and prevents local failure of overloaded higher points. The method for fired bricks requires initial grinding and capping using a cement sand mortar [16]. Grinding and cement sand mortar capping for unfired clay bricks are not suitable due to weak and moisture sensitive nature of the material. Other common methods of capping include plywood sheeting, rubber sheeting and rapid setting dental plaster. A 3mm thickness of each of these three methods of capping was compared to specimens that were uncapped.

Brick specimens were prepared as described in Sect. 2.2 at a water content of 16%. The bricks were dried within the laboratory environment for two days followed by drying for a further two days at 105°C, following which, they were then stored within the laboratory until testing.

The four methods of capping were investigated by testing a sample size of five bricks for each method at 14 days. The capping was first applied to the bricks; for the sheet materials this meant cutting the sheet to the cross sectional area of the brick. Since plaster would cause a change in moisture content of the bricks, which would in turn affect the compressive strength, a sheet of cling film was used between the plaster and the brick to prevent the movement of moisture. This prevented bonding to the brick but ensured equal load distribution.

2.6 Platen Restraint

The compression force would be typically applied to a specimen through stiff platens to evenly distribute the load. As the compression force increases the specimen would expand laterally. Friction between the specimen and the platens would effectively cause confinement of the specimen that causes an apparent increase in strength.

The effect of platen restraint decreases with increasing distance between the platens. This is dependent on the aspect ratio of the brick being tested. Correction factors that account for the aspect ratio are provided in BS EN 772-1:2011 [16] that convert the compressive strength to a normalised compressive strength.

2.7 Curing Condition

Heath et al. [9] demonstrated that there is an exponential relationship between unfired brick compressive strength and water content. Since the bricks are extruded at the PL, strength will develop with the drying of the bricks. This strength gain may be artificially increased through accelerating the drying procedure.

All of the bricks were dried within the laboratory for two days, following that the drying procedure varied. Random samples of bricks continued to be dried in the laboratory environment (average of 21.5°C at 61% relative humidity) while the drying of other bricks was accelerated. One sample of bricks was artificially dried in an oven at 60°C with another sample dried at 105°C. Commercial bricks can be dried pre-firing with 60°C representative of industrial practice in the UK. Drying at 105°C would typically lead to the complete removal of moisture from the specimen. Following two days within the ovens the specimens were removed and stored within the laboratory until testing. To investigate the development of strength through drying, bricks were tested at 7, 14 and 28 days.

The conditioning of specimens before testing should be comparable to the current methodology adopted for standard masonry units. Specimens had been conditioned following the approach of §7.3.2 and §7.3.5 of BS EN 772-1:2011 [16]. One sample of specimens were air dried while the other samples were fully immersed in distilled water for 24 hours prior to testing. These represent testing the specimens 'dry' and

'wet' conditions respectively. The method of testing by full immersion could be considered too harsh for applications where unfired bricks are likely to be used and this was the conclusion of Tingle and Santoni [17]. As saturated performance of earth masonry remains one of the greatest barriers to commercial adoption, testing under this condition will give confidence even if it is not representative of in-service conditions. BS EN 772-1:2011 [16] stipulates that a minimum sample size of six specimens be used and therefore will be adopted throughout the investigation unless otherwise stated.

3 Results and Discussion

Statistical methods of analysis were used in aid of the discussion of results. The methods are infrequently used in construction but are common in other fields have been used here.

3.1 Small Scale Test Results

All the bricks were extruded at an average moisture content of 16% and gave an average dry density of 1950kg/m³. There was no significant variation in these measurements between the different tests with the coefficient of variation (CV) for the moisture content and the density being 2.5% and 4.6% respectfully. The ultimate strength is statistically independent of these variables within the limited range of density and moisture for this phase of testing.

3.1.1 Effect of Capping

The results of the tests are provided in Table 2.

Table 2: Influence of method of capping on compressive strength

Method of Capping	Average Compressive Strength (MPa)	CV (%)
Rubber	1.50	21.7
Plywood	2.28	21.9
Plaster	3.33	13.4
Uncapped	2.62	15.1

A one-way ANOVA analysis with multiple comparisons test with a confidence interval of 95% was used to determine the statistical significance of the results. The method of capping explains 71% of the variability of results and the risk of rejecting the null hypothesis for Fishers F-Test is less 0.02%.

The use of rubber was statistically significantly different to all of the other testing methods according to Turkey HSD test and REGWQ procedure. The rubber capping gave the lowest average compressive strength. Due to the lateral expansion of the rubber under compression, lateral tension within the brick was induced and resulted in a reduced ultimate compressive strength.

Whilst capping with plaster and plywood are two quite different approaches, according to the statistical test there was no significance difference in compressive strength performance between these two capping methods and the uncapped sample. This was in agreement following the Dunett's test comparing these methods to the uncapped control method.

Applying plaster was time consuming and cumbersome, and potentially provided confinement of the brick. The plywood capping method showed a large spread of

results and was discarded. The uncapped method was chosen in preference due to the practical and statistical benefits. Any noticeable high points were filed off before testing the uncapped samples.

3.1.2 Effect of Platen Restraint

Bricks with varying heights were cut from the extruded column of soil. Following an initial two days curing at 60°C the bricks were tested uncapped at 14 days.

The results of compression tests on bricks with various aspect ratios, by changing the thickness of the brick, are given in Fig. 5. The 95% confidence interval of the average for each sample is shown in Fig. 5. These averaged results, based on a sample size of five, have been normalised to give equivalent correction factors for a unity aspect ratio. This is compared to the correction factor of 100 mm wide masonry units as provided in BS EN 772-1:2011 [16] and displayed in Fig. 5.

Figure 5: Aspect ratio correction factor

Failure of the first two aspect ratios was by crushing, whereas the two larger aspect ratios failed with the development of a distinctive shear crack forming through the width of the brick. The correction factor for 72 by 34 by 22 mm thick bricks is 0.62 whereas the full scale equivalent from BS EN 772-1:2011 [16] is 0.85. The influence of aspect factor on compressive strength is in accordance with previous findings by Walker [14]. Strength increase is observed with aspect ratios less than 1.5 and while Walker [14] comments that there is little change in strength for pressed blocks above an aspect ratio of 5 this research has shown minimal change above an aspect ratio of 2.0.

The correction factors provided in BS EN 772-1:2011 [16] are related to the aspect ratio but vary depending on the width of the brick. A brick with a smaller width results in a reduced correction factor for the same aspect ratio. Therefore, the correction factors provided in Fig. 5 should not be used to give equivalent characteristic compressive strength to that of a standard masonry unit. The values in BS EN 772-1:2011 [16] were also developed for fired bricks that have a significantly higher compressive strength and may therefore be less susceptible to crushing. Effect of Curing Condition

The effect of initial curing condition over time is shown in Fig. 6. All the specimens that were fully immersed in water, regardless of curing condition or curing time, disintegrated and are not presented. This was expected for unstabilised units, as was the case from previous research [14, 15 and 17].

Figure 6: Effect of Curing Condition

There were marginal changes in strength for the unstabilised specimens from 14 to 28 days between the different drying regimes. The variation of strength could be directly attributed to the moisture content of the brick at the time of testing as shown in Fig. 7 and in accordance with the findings of Heath et al. [9] show an exponential relationship with a coefficient of determination of 89%.

Figure 7: Effect of moisture content on compressive strength.

Figs. 6 and 7 suggests that the specimens that were dried at 105°C achieved equilibrium moisture content by 14 days as evident by no further change in moisture content or strength. Whereas the other samples are still drying out by 28 days and hence increasing in strength. The difference in strength is marginal and can be attributed to the hysteresis in wetting and drying observed for unsaturated soils.

3.2 Large Scale Test Results

The large scale bricks were extruded at an average moisture content of 16% and gave an average dry density of 2100kg/m³. The bricks were tested uncapped in the

normal aspect ratio, with varying curing conditions. The average results of six tests are compared to the equivalent small scale bricks are presented in Table 3. The large scale samples that were submerged disintegrated and the results omitted. This indicates increased size is probably insufficient to provide resilience against saturation.

Table 3: Compressive Strengths of Bricks

Days Since Extrusion	Initial Curing Condition (°C)	Small Scale UCS (MPa)	Large scale UCS (MPa)
7	20	-	1.13
7	60	-	3.83
7	105	-	5.34
14	20	3.17	2.02
14	60	3.19	3.19
14	105	3.39	3.69
28	20	3.24	2.75
28	60	3.33	3.06
28	105	3.39	3.05

There is a similar change in strength for the large scale bricks over time. By 28 Days only those bricks with an initial accelerated drying obtained a similar compressive strength. The average 28 day strength of the small scale bricks was 10% greater than the average 28 day strength of the accelerated drying full scale bricks, with 17.6% strength difference between the non accelerated drying bricks. There is a statistically significant difference between the results of the 28 Day testing and suggest that there is a related size effect of the brick unit.

Fig. 8 shows the change in strength and moisture content over time, with the moisture content moving towards an equilibrium. Where the original drying of the bricks was accelerated, it appears that by 28 days the samples had reached average equilibrium moisture content of 1.7% while the 28 day moisture content 20°C initial curing appears to require further drying to reach stability.

Figure 8: Change in Moisture Content and Strength over Time (UCS=compressive strength and M.C. =moisture content for each of the curing temperatures).

There is a significant difference in moisture content measurements for the 28 days test of samples. The exponential relationship that describes the change in strength for varying moisture content for the large scale bricks, as shown in Fig. 9, has a coefficient of determination (R^2) of 92%. Using the same model to describe the small scale bricks gives a coefficient of correlation of 0.94. This indicates that 89% of the variation in strength can be attributed to the change in moisture content and not the size effects of the testing of the brick.

Accounting for the difference in moisture content and factoring the strengths accordingly results in an average difference in strength between the two scale of bricks at 28 days of 0.07 MPa. Therefore although the size of the bricks may lead to a different drying profile there is negligible effect if the samples are tested at a specified moisture content of after equilibrium is achieved.

Figure 9: Effect of moisture content on compressive strength.

4 Conclusion

This research has demonstrated the suitable method of representative manufacture and testing methodologies of small scale extruded earth bricks. Although there is a difference between the compressive strength of the full size and scaled bricks, this can be attributed to the moisture content.

Small scale testing can be conducted without any capping of the specimens. There is a platen restraint effect due to the relative dimensions of the bricks. This has been quantified and can be used for the calculation of equivalent characteristic compressive strengths.

Initial drying of the bricks at either 60 or 105°C helps the moisture content to reach equilibrium and gives stable compressive strength results after 14 days. The same exponential relationship between moisture content and compressive strength exists for the small and large scale bricks. This may allow for non-destructive compressive strength testing of existing earth masonry structures. The exponential relationship could be developed based on manufacturing and testing of small scale bricks. A moisture content sample can be taken from the existing structure and used to give a compressive strength.

The dry compressive strength of the large scale units is suitable for loadbearing masonry walls. All the bricks tested irrespective of curing condition or size disintegrated when fully submerged in water. It has been recognised that for the

adoption of structural unfired earth masonry further research into moisture susceptibility is required.

The findings of this research will allow further testing on suitable stabilisers to address the water resilience. This work can be done on a small scale that would allow continued research an optimisation while accounting for the inherent properties of the bricks.

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