Sample	IRSL Counts/second	OSL Counts/second	IRSL:OSL ratio
Errol Brick Works – fresh exposed surface	332	533	0.62
Errol Brick Works – processed (2004) clay material	339	624	0.54
Cottown Schoolhouse Interior wall – immediately beneath surface covering	5584	6139	0.91
Cottown Schoolhouse Interior wall – 4-cm deep below wall surface.	14732	11300	1.30

Table 1. Results of luminescence analysis of clay-rich materials from Errol Brick Works and from an original wall in Cottown Schoolhouse)

Notes

(1) UKCP09 climate-prediction datasets are available in various formats at the following URL: http://ukclimateprojections.defra.gov.uk (Accessed, 20 August 2011).

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THE COMPRESSIVE STRENGTH OF LIGNOSULPHONATE-STABILIZED EXTRUDED-EARTH MASONRY UNITS

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Theme 6: Research in Materials and Technology for Conservation and Contemporary Architecture
Keywords: Masonry, extruded bricks, novel stabilizers, compressive strength

Abstract

Earthen (unfired-clay) bricks offer several distinct advantages over conventional fired-clay bricks and other high-energy masonry units. Most notably, there is significantly lower-environmental impact, including carbon emissions during manufacture, than comparable products, with unfired-clay bricks having an estimated 14% of the energy of fired bricks, and 25% of concrete blocks. Earthen construction is able to provide passive-environmental controls, including the regulation of temperature and humidity, which can be utilized in unfired-clay masonry to improve internal levels of comfort.

The commercialization of unfired-clay masonry as a structural material is dependent on several factors. Modern earthen-construction methods need to fit in with demands of contemporary construction, compete commercially and provide a high-quality consistent performance. To ensure that thin-walled unfired-clay masonry can be used in a load-bearing application, it is important to consider the effect high-moisture content, due to accidental and intentional wetting, has on the strength of the material, as well as the building unit.

This paper presents initial findings from an investigation into the development of low-impact alternative stabilizers. Cement and lime are widely used in some countries, but both have an associated embodied energy and carbon emissions that may hinder the benefits of unfired clay as a mainstream building material. The use of lignosulphonate was chosen as a way of minimizing the adverse environmental impacts while improving water resilience, an essential requirement for thin-walled load-bearing masonry using earth. Unconfined-compressive strength of extruded-soil samples, which were stabilized with three types of lignosulphonate, were tested both dry and wet as a basis for comparing loss of strength due to exposure to a wet environment.

1. INTRODUCTION

Within the UK, the heritage of earthen construction largely ended during the 19th century, which is attributed to the industrialization of the construction industry (Morton, 2008, p. 17). There has been a renewal of interest in earthen construction within the past 30 years due to the increasing interest in sustainable forms of construction (Walker, 2004, p. 249).

For the beneficial effects of any sustainable form of construction to have a significant and widespread impact, then factors in addition to the embodied energy and carbon should be considered. The form of construction should also be easily adopted into current construction practice with a minimum shift in the end use by society. In this regard, any sustainable construction should be comparable to current materials with respect to durability and maintenance.

The focus of this paper is on modern earthen masonry that is commercially produced. This enables the benefits of earthen construction to be delivered to the mass market with improved quality control. Earthen bricks can be produced following the well-established manufacturing procedure as commercially produced fired bricks but without the firing. This allows the commercially produced extruded-earthen units to have about 14% of the embodied carbon of equivalent fired-clay bricks (Morton, 2008, p. 4). Based on typical figures in the Inventory of Carbon and Energy (Hammond and Jones, 2011), it can be shown that a 225-mm thick un-stabilized earthen-masonry wall has the similar embodied energy to a 100-mm thick commercially produced dense-concrete block. It is, therefore, environmentally and financially desirable to keep walls as thin as possible.

The compressive strength of extruded-earthen masonry measured at ambient temperature and humidity levels ranges from 2.8 to 5.1 MPa (Heath et al., 2009, p. 110). Therefore, there is scope for these units to be used within a 100-mm thick load-bearing wall in a two-story domestic application.

Heath et al. (2009, p. 108) developed and demonstrated the exponential relationship between compressive strength and water content for extruded unfired-clay masonry units. With increasing moisture content, the compressive strength of the units decreased. This reduction in compressive strength is critical for thin-walled load-bearing masonry. Accidental or intentional wetting would clearly create an elevated moisture content, which would significantly reduce the strength of the material, as well as the masonry that would ultimately lead to collapse.

Typically, cement can be added to improve strength and reduce water susceptibility. Using the data in the Inventory of Carbon and Energy (Hammond and Jones, 2006), it can be shown that a cement content of 5% in an earthen block will increase the embodied energy to a level similar to dense-concrete blocks, eliminating one of the environmental benefits.

There has been a growing interest in using alternative low-embodied carbon stabilizers. Lignosulphonates are natural polymers derived from lignin that binds cellulose fibers together and is typically a byproduct from the paper industry (Brandon et al., 2009, p. 12). These materials are commonly used in commercial brick manufacture to provide sufficient 'green' (wet) strength to prevent damage during handling.

The objectives of the work presented in this paper were to study, compare and report on the strength characteristics of extruded-earthen masonry. Following a review of the stabilization mechanism of lignosulphonate, an experimental program of compressive strength was completed using scaled extruded-earthen bricks made of the same brick clay with varying types of lignosulphonate.

2. STABILIZATION MATERIALS AND METHODS FOR CONSTRUCTION

Stabilization offers a method of improving the inherent properties of soil. Many of the traditional and non-traditional methods of were developed for the stabilization of unpaved roads (Tingle and Santoni, 2003, p. 72). Typically, this has focused on improving the Unconfined Compressive Strength (UCS), Californian Bearing Ratio and erosion characteristics of the roads. The outcomes of the literature concerning the use of non-traditional stabilizers for road improvement can be transferred for the possible use in building structures.

Potential mechanisms by which stabilization of the soil can occur have been summarized by Tingle and Santoni (2003, p. 74) and include:

- Encapsulation of clay minerals;
- Cation exchange;
- Chemical breakdown of the clay;
- Absorption of organic molecules into the clay interlayer.

The non-traditional additives are either byproducts of an unrelated process or, alternatively, they have been developed specifically. Lignosulphonates are byproducts that have a wide variety of uses, including acting as a plasticizer for making concrete. Lignosulphonate (C20H26O10S2) is an anionic polyelectrolyte that form salts typically with sodium, calcium and ammonium cations.

Lignosulphonate stabilizes soil by physically binding the soil's particles together with minor chemical effects (Tingle et al., 2007, p. 61-62). Individual soil particles can become coated in a thin adhesive-like film that acts to cement the particles together. Lignosulphonates are ionic and, therefore, there is the possibility for cation exchange that can alter the molecular structure of the soil. This has the potential to reduce the surface charge that can lead to flocculation, close packing and hydrophobic characteristics (Xiang et al., 2010, p. 886).

Santoni, et al. (2005, p. 34-42) tested lignosulphonate on a compacted silty-sand material. The addition of 3% lignosulphonate solution caused a 22% reduction in UCS compared to an un-stabilized sample at seven days. Lignosulphonate specimens were tested under the 'wet' conditions. In preparation, specimens were placed for 15 minutes in an inch (25.4 mm) of water. When tested in this method at seven days, the lignosulphonate stabilized specimens showed, as expected, a decrease from the dry specimens' UCS. When compared to the equivalent un-stabilized specimens tested using the 'wet' method, the lignosulphonate-stabilized specimens were on average 620% stronger and gave a UCS of 1.1 MPa.

The effect of lignosulphonate on low-plasticity soils resulted in a greater UCS (Tingle and Santoni, 2003, p. 78). An optimum concentration of 1.5% powdered lignosulphonate resulted in a UCS of 7.3 MPa, while a UCS of 4.8 MPa was achieved under 'wet'-testing conditions. Within the same test matrix performed by Tingle and Santoni (2003, p. 78), lignosulphonate stabilization achieved a 30% greater UCS than a 9% cement addition under dry conditions, and a marginal increase in strength under 'wet' testing.

Although the literature has been limited, it has shown that there is potential for lignosulphonate to be used a soil stabilizer. The potential ion-exchange mechanism warrants further research with varying types of lignosulphonate to investigate if there are any noticeable effects. The unique method of brick production by extrusion with the benefits of stabilization using byproducts may yield an unfired-masonry unit suitable for a load-bearing application without the risk of potential mechanical wetting.

3. EXPERIMENTAL MATERIALS

All the experimental bricks were produced using the same brick clay. The soil is described as a brick clay, as it is used for commercial fired-brick production. The brick clay was chosen rather than blending materials, as this is the material that is currently used for production; therefore, any stabilization method would be required to work with fundamentally the same material. The grading and Atterberg characteristics are outlined in Table 1. The soil can subsequently be described based on grading as a dark-brown slightly sandy silt with the plasticity of a low-plasticity clay. The clay mineralogy was identified by XRD as containing 39% kaolinite and 2% montmorillonite with significant amount of quartz and minimal amounts of other minerals.

For this study, sodium (Na), calcium (CA) and ammonium (Am) lignosulphonate were supplied in dry-powder form. The clay was stabilized by adding 2.5% (by dry mass) of the dry-powder lignosulphonate.

Property	
Grading (by mass)	
Fine gravel fraction (2–6 mm) (%)	5
Sand fraction (0.06–2 mm) (%)	33
Silt fraction (0.002–0.06 mm) (%)	46
Clay fraction (<0.002 mm) (%)	16
Atterberg Limits	
Liquid Limit	24
Plasticity Index	8

Table 1. Soil characteristics (credits: Daniel Maskell, Pete Walker, Andrew Heath)

Fig.1 Laboratory vacuum pug-mill extruder (credits: Daniel Maskell)

4. EXPERIMENTAL PROGRAM

The bricks were manufactured within a laboratory environment at the University of Bath. This was achieved using a vacuum pug-mill extruder able to produce bricks at 1:3 linear scale, thus 1: 27 volumetric scale as shown in Fig.1. This machine creates a similar production process as full-scale extruded bricks. Clay that has been pre-mixed with the required water content is fed in to a series of augers that help to homogenize the mixture. Under a vacuum, the clay is effectively compressed by reducing the cross-sectional area at the point of extrusion to 72 mm by 34 mm. This produces a column of clay that is then cut into 22-mm thick bricks.

Initial testing was undertaken to determine the optimum-moisture content (OMC) for the extrusion of the bricks. This was achieved by adding varying amounts of water to the clay mixture and feeding it through the extruder, then measuring the water content and dry density of the bricks that were produced. This was compared to the modified Proctor method of determining the OMC. Extruding at a moisture content less than the plasticity limit caused notable cracking in the brick surface, and extrusion was not possible at a moisture content less than 14%. The OMC for extrusion is, therefore, at the plasticity limit of 16%. It is clear from Fig.2 that the modified proctor is unsuitable for determination of OMC for extrusion. The addition of the various lignosulphonate did not change the plasticity limit and, therefore, did not change the OMC for extrusion.

Each sample was prepared by first dry mixing 2.5% of the powder lignosulphonate into the brick clay. Water was then added to achieve a mixture with moisture content of 16%. This mixture was then transferred and fed through the extruder under a vacuum of 0.5 bar. The extruded column of clay was cut to form the bricks of dimensions 72 x 34 x 22 mm, and the bricks were immediately weighed while additional samples of extruded clay were taken for moisture-content measurements.

The drying regime, curing time and testing condition were varied to independently assess the effect on stabilization mechanism. The drying procedure was varied to investigate if any stabilization effect would be facilitated or accelerated by variation in the drying regime. 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 while another was dried at 105°C. Following two days in the ovens, they were then removed and stored within the laboratory until testing. To investigate the development of strength, bricks were first tested at 14 and 28 days. Finally, testing occurred on dry and wet samples. The wet-testing regime involved fully immersing the bricks in distilled water for 24 hours prior to testing. This meant that in total, 12 different test methods were considered.

Block dimensions, dry density, uniaxial compressive strength were determined using a representative sample of six specimens for each of the 12 tests. Brick compressive strengths were measured by crushing specimens in their normal aspect without any capping. The load was measured with an applied constant-displacement rate of 2.5 mm/min. The results were averaged for each testing method and the methodology repeated for each different stabilizer. Each brick was compressed until peak load was reached.

5. RESULTS

The results of the compression test on the stabilized sample, as well as an un-stabilized sample for control is provided in Table 2, Fig.3 and Fig.4. The control sample consisted of the same brick clay with no additional stabilizer added and prepared to the same moisture content. All the bricks were extruded at an average moisture content of 15.6% and gave an average dry density of 1928 kg/m^3. There was no significant

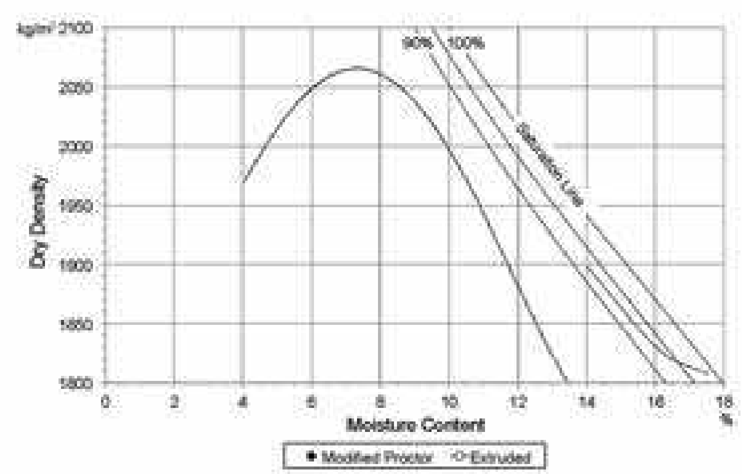

Fig.2 OMC of clay soil (credits: Daniel Maskell, Pete Walker, Andrew Heath)

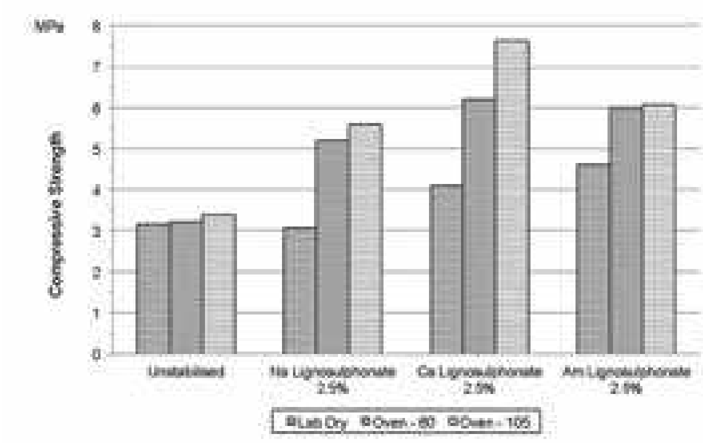

Fig.3 14-day compressive strengths (credits: Daniel Maskell, Pete Walker, Andrew Heath)

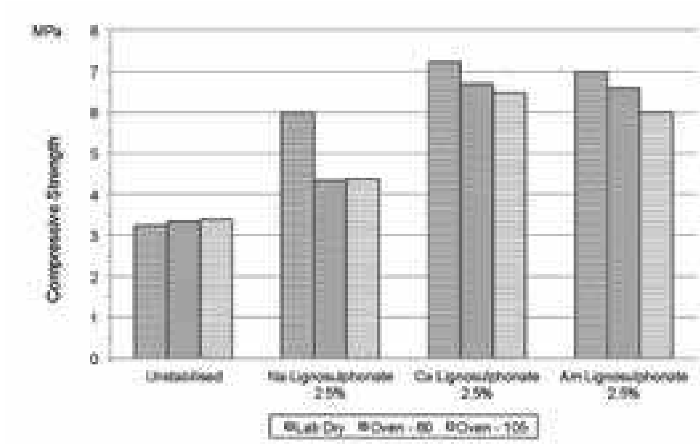

Fig.4 28-day compressive strengths (credits: Daniel Maskell, Pete Walker, Andrew Heath)

variation in these measurements between the different tests, therefore, assumed to be constant in terms of the contribution to strength gain. The effect of stabilizer type, drying regime and curing time can be independently analyzed.

5.1 Effect of lignosulphonate type

The effect of stabilizer type was evaluated by testing three different types of lignosulphonate. The results show that the addition of any lignosulphonate-based stabilizer will not have a detrimental effect but can significantly improve the dry compressive strength of the bricks. All of the bricks, including those stabilized, that were tested under the wet regime disintegrated and, therefore, were not tested.

Calcium lignosulphonate was the most effective stabilizer, and achieved the maximum compressive strength of 7.65 MPa when oven dried at 105°C, representing a 126% increase over the equivalent un-stabilized samples. The improved performance of calcium over sodium and ammonium may be due to the process of cation exchange. The monovalent sodium cation (Na+) is present, along with water molecules, within the double layer of certain clay minerals. Therefore, cation exchange would be limited. The higher-valence calcium cation (Ca2+) preferentially will exchange with the cations present within the clay structure. Ammonia ions (NH4+) may also exchange with some of the metal cations present in clay and adhere to the negative edges of the particles. Cation exchange has the effect of a reduction in the size of the double layer, as well as leading to increased flocculation (Prusinski and Bhattacharja, 1999).

Cation exchange would be particularly prevalent with the montmorillonite fraction but limited with kaolinite. Considering the percentage weight of these minerals, cation exchange of the whole sample may be dominated by kaolinite and, therefore, limited. Bell (1996) comments that "very small amounts of certain clay minerals may exert a large influence on the physical properties". The alternative source of strength increase may be due to the adhesive properties of the lignosulphonate. If only the anionic lignosulphonate is involved in the adhesion process, then the strength increase would be uniform. If the cation is involved in the process, then it may be reasonable to assume that varying the cation will vary the adhesion and, hence, compressive strength. Alternatively, the cation present may cause a change in pH of the water that may lead to slightly different reactions to occur that cause the variation in compressive strength.

5.2 Effect of drying regime

Testing all the samples of lignosulphonate stabilised clay, but accelerating the drying, evaluated the effect of drying regime on performance. A sample was cured within the laboratory environment and acted as a control to compare the drying regime. The compressive strength of the unstabilised sample showed a negligible increase in compressive strength. However the accelerated drying of the lignosulphonate stabilisers showed a increase in strength at 14 days but a decrease at 14 days. The increase in temperature from 60°C

Curing Regime	Age	Moisture condition at testing	Unstabilised		Na Lignosulphonate 2,5%		Ca Lignosulphonate 2,5%		Am Lignosulphonate 2,5%	
			UCS MPa	MC %	UCS MPa	MC %	UCS MPa	MC %	UCS MPa	MC %
Lab Dry	14 Days	Dry	3.17	2,23	3.08	3.19	4.11	3.09	4.62	2.89
	28 Days	Dry	3.24	1.84	6.01	1.67	7.23	2.05	7.00	1.84
Oven - 60	14 Days	Dry	3.19	1,27	5.21	1.46	6.19	1.61	6.00	1.10
	28 Days	Dry	3.33	1.35	4.34	1.36	6.69	1.61	6.57	1.22
Oven - 105	14 Days	Dry	3.39	1.44	5.59	1.14	7.65	1.11	6.07	0.69
	28 Days	Dry	3.39	1.42	4.38	1.28	6.45	1.42	6.01	1.35

Table 2. Compressive strength and moisture content at testing (credits: Daniel Maskell, Pete Walker, Andrew Heath)

to 105°C resulted in an increase in compressive strength for all 14 day samples. This was most noticeable with the calcium lignosulphonate that resulted in a 24% increase in strength from the 60°C to 105°C. Increased drying temperature over the first few days resulted in a decrease of testing moisture content at 14 days. By 28 days the stabilised samples left to dry in the laboratory environment achieved a greater strength than those subject to accelerated drying. There appears to be a time dependent effect related to the effect of the initial acceleration of drying.

5.3 Effect of time curing

The effect moisture content on the strength, and how this varies over time and with different drying regimes should be considered. There were marginal changes in strength for the un-stabilized samples from 14 to 28 days. This suggests that these samples achieved equilibrium-moisture content by 14 days. The lignosulphonate-stabilized samples' change in strength was dependent on the initial drying regime.

The effectiveness of lignosulphonate for increasing dry-compressive strength may be related to the rate of drying. The rate of drying would increase due to an increased hydraulic gradient due to a higher-surface temperature than core temperature of the brick, causing water to move through the pores at a greater rate. This movement would allow the dissolved lignosulphonate salt to move through the brick enabling cation exchange and coating of the particles with the adhesive. If this effect was accelerated, then it might be expected that the 14-day strength would be greater as more lignosulphonate adhesive would precipitate out of solution. By 28 days the laboratory-dried sample would have lost more moisture giving the gain in strength. The slower drying rate would have meant that the movement of the dissolved salt could happen over a greater amount of time allowing for more reactions to occur, which results in strength gain. There is a significant increase in moisture content for the lignosulphonate samples dried at 105°C, which would account for the general decrease in strength. The effectiveness of lignosulphonate to stabilize extruded-unfired earth is potentially dependent on moisture content and, therefore, dependent on drying regime and curing time.

6. CONCLUSIONS

Although the exact type of lignosulphonate varies, it has shown that lignosulphonate will not have a detrimental effect on the compressive strength and, in most cases, leads to significant dry-strength increase when compared to un-stabilized samples. Maximum strength increase was achieved with calcium lignosulphonate that was dried for two days at 105°C and tested at 14 days. The greatest improvement of strength at 28 days was achieved when the curing period did not involve elevated temperatures. There is clearly scope for further research to optimize the drying regime to possibly achieve further strength gains. In addition, there is scope for further research into optimum stabilizer quantity. Considering the mechanisms involved, it is likely that calcium lignosulphonate will remain the stabilizer that gives the greatest strength improvement. The long-term performance of lignosulphonate-stabilized earth, and the relationship to moisture content remains unknown and should be investigated.

All of the bricks that were fully immersed in water were unable to be tested as they had completely disintegrated. An increase in concentration of stabilizer may provide enough adhesion; however, solubility of the material remains a concern. The method of testing by full immersion could be considered to harsh and was the conclusion of Tingle and Santoni (2003). As saturated performance of earthen masonry remains one of the greatest barriers to commercial adoption, then it will be required to meet this testing method.

This work has shown that there is significant potential for strength increased with lignosulphonate. Lignosulphonate was shown to be ineffective at stabilizing against elevated-moisture contents. Earthen bricks are targeted for domestic application where an increase in strength is not required compared to moisture resilience. Therefore, stabilizing earthen masonry with lignosulphonate has been shown to be ineffective.

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THE FEASIBILITY OF USING SCIENTIFIC TECHNIQUES TO ASSESS REPAIR-MATERIAL SUITABILITY IN EARTHEN BUILDING CONSERVATION

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Theme 6: Research in Materials and Technology for Conservation and Contemporary Architecture
Keywords: Earth, sacrificiality, wychert, compatibility

Abstract

The application of scientific techniques to conservation work has in recent years grown as a discipline, driven by a desire within the field of building conservation to better understand historic building materials. Wide ranges of historic materials are now analyzed to determine behavior and performance characteristics, which has led to advancements in the implementation of conservation work. However, the area of earthen building conservation has not yet been investigated in great detail; there is at present a large lacuna on how to select earthen repair materials, especially in terms of sacrificiality of interventions. This study directly addresses this fact by carrying out laboratory analysis of earthen materials in order to assess the feasibility of using repair materials to specify conservation work.

A case study from Buckinghamshire in England was chosen; a wychert-cob ecclesiastical building that had recently undergone repair and conservation. An identical program of material classification and performance tests was carried out on two sample materials from the building; one historic and one repair material. Through the study of laboratory results, the material characteristics and mechanical behavior of the two earthen materials were compared, and a critical analysis of the compatibility of the historic and repair material carried out. The findings of the study concluded that the repair material was unsuitable for use in this case, being incompatible with the original material. The achievement of the work was twofold; firstly it serves as verification for using these techniques to obtain comparable results that can be used to appraise material sacrificiality, and secondly it demonstrates that earthen materials are of a complexity whereby compatibility cannot be assumed using basic techniques. Work such as this highlights the need for analytical investigations in earthen building conservation, in order to ensure appropriate repair materials and techniques are used.

1. INTRODUCTION

There is currently very little scientific basis behind the methods used for repairing earthen structures, with factors, such as availability of materials and traditional building techniques, usually taking precedence. It is particularly rare for analytical investigations to be undertaken on repair and historic materials, and subsequently there is at present no standardized protocol to follow in order to understand whether a soil (adobe, rammed earth, etc.) will behave sacrificially when inserted in the historic fabric. Failure to consider this vital aspect of conservation work is in direct contradiction to the guidelines set out by the ICOMOS Charters, used to guide the selection and detailing of repair work. This work addresses this issue at a fundamental level by undertaking such an investigation on the material used to repair a historic cob earthen building in England.

Cob is a material consisting of unbaked soil, mixed to quite a wet consistency and placed directly onto the wall. Walls are built without the use of shuttering and, as such, rely on self-consolidation for strength. Following their construction, cob walls consolidate through drying and by virtue of their own weight (Ashurst and Ashurst, 1988). As the material dries the necessary cohesion to produce a hard, strong, monolithic body is achieved. Their strength is, therefore, dependent on the proportion of materials used, the thorough mixing of those materials, and the compaction of the mix through treading.

For the purposes of conservation, comparative analytical studies require work to be carried out on both new and historic material, with an approach to testing that encompasses investigation into the interaction of these materials. Furthermore, any intervention and associated technical specification must take account of the principles that guide conservation work, and that consider important factors, such as reversibility of the work and authenticity of the historic structure in question, as