side as suggested is also specified in the Peruvian standard (RNC, 2000).

Considering the test-loading rate, it was not possible to verify its influence on the results, since it would be necessary to carry out tests with the same materials and adopt different rates. In order to avoid undesirable variables, and until data is available on the subject, the adoption of a loading rate for testing compressive strength of adobes is recommended, keeping a rate of increase in tension of 0.29 MPa/min as indicated in the PROTERRA Inter-Laboratory Program test procedure.

Excluding Laboratory A, which has been conducting trials of adobe since 1997, the other participants had no background in the preparation of samples to test the compressive strength of earthen blocks. The PROTERRA Inter-Laboratory Program provided the establishment of systematic procedure for the characterization of adobes in those laboratories. In addition, Laboratory A continues with the research in adobe using, whenever possible, the test procedures set out from the PROTERRA Inter-Laboratory Program. Laboratory D has also begun a sequence of tests of compressive strength with adobes using different types of earth, while adopting the same procedures.

Therefore, the PROTERRA Iberian-American Network intends to:

- Institutionalize the test procedure for characterizing compressive strength of adobe;
- Follow up with the inter-laboratory program, by putting forward test procedures for small adobe walls, to evaluate the behavior of adobe masonry, including the analysis by the finite-elements method.

Other laboratories are expected to adopt this procedure as well, in order to determine the compressive strength of adobes, and to collect data from different sites. This will improve the knowledge on the physical and mechanical characteristics of adobes, an ancient, but not completely understood building material.

Notes

(1) CECOVI staff members: Ariel González (coordinator), Santiago Seghesso, María Eugenia Germano and Jeronimo Silva.
(2) CEDED staff members: Célia Neves (coordinator), Ivo Oliveira, Clementino Passos and Adelson Profeta.
(3) Torino staff members: Roberto Mattoni and Gloria Pasero.
(4) UNESP staff members: Obede B. Faria (coordinator), Bruno M. de Oliveira, Margareth Tahira and Rosane Ap. G. Battistelle.
(5) Rafaela University staff members: Mirta Sánchez, Hugo Begliardo, Susana Keller, Saida Caula, Fiorela Morero and Juan Pretti.

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NOVEL MICRO-SCALE TECHNIQUES TO ESTABLISH A LIFE-CYCLE ANALYSIS OF EARTHEN-BUILT STRUCTURES IN SCOTLAND, UK

Paul Adderley, Simon J. Parkin, Dorothy A. McLaughlin, Craig Kennedy

Theme 6: Research in Materials and Technology for Conservation and Contemporary Architecture
Keywords: Micromorphology, image-analysis, luminescence dating

Abstract

The rapid changes in climate predicted for the 21st century presents a clear threat to the continued conservation and maintenance of historic vernacular buildings constructed with earth materials. With custodians of such vernacular heritage requiring a strong evidence base in order to prioritize the maintenance of such fabrics, it is clear that experimental studies considering the decay of earth materials correlated to their provenance or lifecycle in future environments is required.

This paper reports on a set of scientific initiatives designed to facilitate an evidence-based proactive approach, rather than an anecdotal and reactive approach, to the future repair and maintenance of such structures. Since climate change is manifested in different ways according to geographic location, process-led understandings are paramount. Two major techniques are used. First, thin-section micromorphology is an established technique for analysis of microscopic-structural features, as well as more extensive matrices of soils. It allows spatially-related observations to be linked to physical and chemical measurements at scales relevant to exchange processes in these materials. Second, a novel form of luminescence dating, allowing rapid on-site relative chronologies to be established, has been developed to permit temporal aspects and, hence, rates of change in the structures' lifecycle to be determined.

Using these techniques to analyze the wide range of constructional materials across a variety of regional environmental contexts in Scotland allows a multi-way comparative analysis. Sites considered include the dry internal structures of a stone-clad 18th-century merchant's house in Brechin, Angus; water-saturated earth-infill of wall from a house in Leetown, Perthshire, and exterior walling materials rich in cereal husks taken from Fladdabister, Shetland. Preliminary findings show differences in composition, internal matrix features, and relative age of these materials. This provides the basis for lifecycle analysis of these materials to be outlined in relation to climatically-related factors.

1. INTRODUCTION

The present paper outlines several techniques developed to help enable two complementary research projects on Scottish earthen structures that are being undertaken by the authors. The background to these projects spans two major themes. First is the need to understand processes of building decay in a manner relevant for the understanding of conservation needs and the development of conservation practices for historic earthen-built structures in Scotland. The number of past academic studies on such buildings is small and encompasses a wide array of approaches, including field observations of specific buildings (e.g. Walker, McGregor, and Little, 1996), ethnography and folklore (Fenton, 2008), and actualistic experimentation using trial walls, such as that reported by Morton (2011). Second is the overarching issue of climate change and the response of different types of earthen-built structures to such changes. In doing so, conservation needs and priorities for both scheduled (protected) buildings and those that are not subject to legislation can be identified and prioritized. The two research projects are in their earliest phases of development. They span the investigation of building histories, experimental examination of earthen-building materials subjected to predicted future climatic conditions, and development of practitioner-relevant advice.

2. HISTORIC AND GEOGRAPHIC CONTEXT

2.1 Earth buildings in Scotland

There has been a great variety in the use of earth as a structural element in Scotland's past buildings, reflecting the diversity of building types found historically in the Scottish landscape and the range of functions for which they were constructed. Clays were essential to the construction of great prehistoric stone-built monuments, such as Maes Howe in Orkney, whereas the Roman-built Antonine Wall was composed of expertly cut and laid turf. These are examples of well-known structures that are now designated World Heritage sites. The vast majority of Scotland's historic earthen buildings were, however, of the vernacular type, with people utilizing the products of their local landscapes to build functional homes, byres and walls without employing formal architectural conventions. This is not to say that earthen building was necessarily reserved for the lower elements of society, a notion that was perpetuated from the 18th century through the diatribe of 'improvement,' which frequently denunciated earth buildings as being temporary or 'backward'. Indeed, in Medieval England, successive archbishops of Canterbury were happy for earth to be used in the construction of ancillary structures at Lambeth Palace (Dyer, 2008). Improvement ideology and the associated physical and social reorganizations that took hold from the 18th century precipitated a drastic downturn in the employment of earthen-building practices in Scotland and, ultimately, the loss of a vernacular tradition whose geographically widespread history was far longer and more significant than would appear if the number of remaining examples was reflective of their original quantity.

Given the long history of earthen building in Scotland, the majority of such vernacular earthen-built structures have since returned from whence they came as a result of abandonment, decay and their inherent 'recyclability'. The consequent invisibility of these structures somewhat belies their previous ubiquity as a result. There is no doubt, though, that the use of unfired earth and turf as everyday building materials stretches back over millennia in Scotland, and archaeological evidence can be used with historic and ethnographic corroboration so as to testify to the continuity of the earthen-building tradition from the Neolithic (or earlier) through to the 20th century (Loveday, 2006).

2.2 Construction methods in Scotland

A range of construction techniques using earth have been employed throughout Scotland's history. A number of the known surviving examples of historic earthen-walled buildings can be said to be of a similar type to the 'cob' buildings that still abound in Devon in the south of England, the walls of which are constructed through the laying down of successive 'lifts' of clay-rich earth intermixed with straw and gravel. A

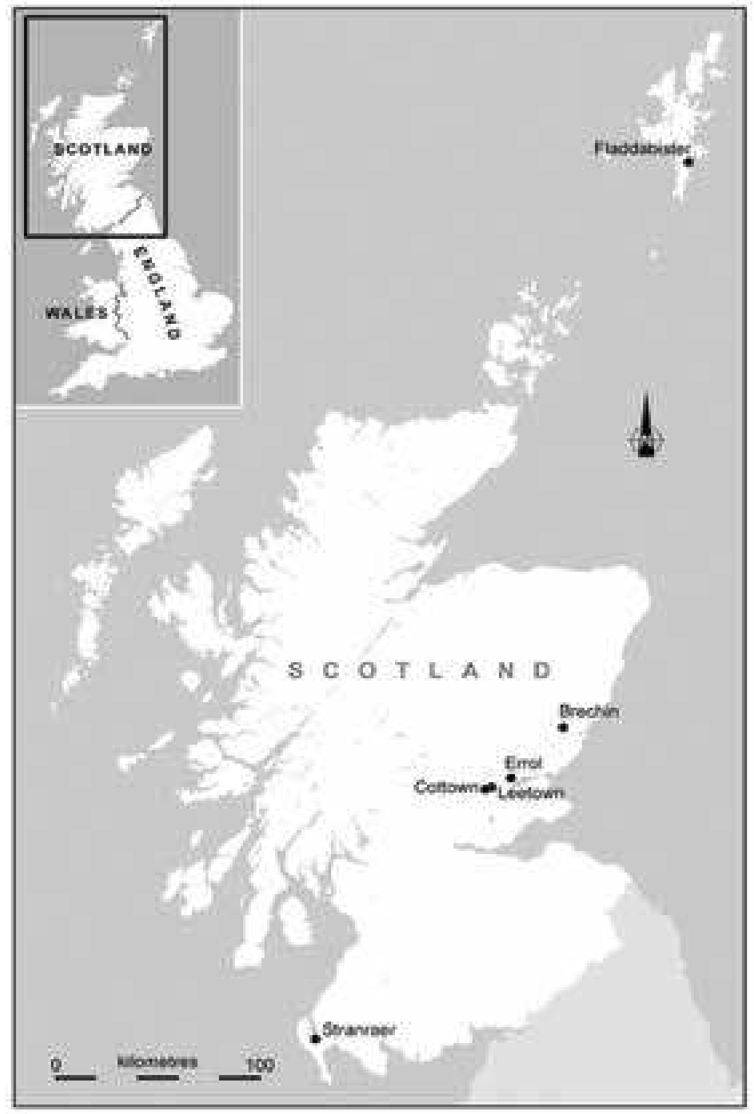

Fig.1 Map of Scotland showing location of sites mentioned in paper. The three sites in close proximity, Cottown, Errol and Leetown, are all located on the Carse of Gowrie, an area rich in marine-derived hydrous-mica clay deposits (credits: Paul Adderley, 2012)

diverse range of additional substances, differing from building to building and dependent on what was available at the time of construction, could be added to this basic mix of ingredients so as to augment the key elements. This is corroborated by the samples taken from Brechin and Fladdabister, which contain hair and cereal husks, respectively. Mass earthen-walled structures are typically referred to in Scotland as being 'mudwall' or 'claywall', although it is likely that since-forgotten regional terminologies once reflected the localized variations on this general theme (Walker, 1979). 'Clay and bool' walls (known as 'Auchenhalrig work') are an example of a local variation on the solid clay wall, incorporating larger, rounded stones into the earthen mix, and found only in Morayshire in northeast Scotland. Structures built with mass earthen walls, which also include those that used formwork in a method similar to pisé, are of primary importance to the wider project to which this piece is associated. Nevertheless, it is essential to note that there was a vast array of different structures that

could be raised using earth or turf as an essential component.

In addition, earthen mixes were commonly applied to wooden skeletons in a variety of forms such as on the exterior of wattle work or between upright timbers (Walker et al., 1996). Earth was used as an infill in the dry-stone walls of the blackhouses of the Western Isles, whilst clay was applied at the wallheads for waterproofing. The blackhouse can be seen as a relative of the turf-walled farmhouses of the North Atlantic building tradition, and can still be found in Iceland. Although turf structures were deemed the lowliest type by 18th and 19th century Improvers, this notion undermines the skill with which turf has been employed as a building material in Scotland's history. The range of turf cuts and variations in the way it was incorporated as a structural element in a range of building types serves to demonstrate a high level of craftsmanship (Walker et al., 2006).

2.3 Geographic spread

It would be difficult to underestimate the extent to which earthen-built structures were formerly spread across the Scottish landscape. It must be noted, however, that enclaves with a greater concentration of surviving earthen buildings would seem to correlate with local geological and geographic circumstances that determine the increased suitability of clays, for example, to mass earthen-construction techniques. Indeed, many past studies have focused on sites such as Cottown and Errol in the Carse of Gowrie. Some areas are relatively undocumented with the Rhins of Galloway near Stranraer in southwest Scotland having evidence of a rich, yet relatively unstudied, history of earthen-built construction.

2.4 Climate

Scotland is associated with a maritime-climate regime typified presently by frequent (i.e. intra-daily or weekly) changes between mild warm and dry conditions to mild warm and damp conditions. With detailed historical climate records extending to 1757, climate changes relative to long-term mean values can be evaluated throughout Scotland. Until the mid-20th century, mean annual precipitation varied little compared to the long-term mean, but from the 1970s has increased markedly (Smith, 1995). This annual countrywide increase in rainfall is marked by significant localized shifts in weather patterns with some regions experiencing pronounced seasonal shifts (Mayes, 1994). Comparison of 30-year monthly climate normals, e.g. 1941-1970 vs. 1961-1990, provides evidence of winters having become wetter coupled with dryer summer periods, with the greatest contrast seen in northern central regions.

Past evidence of climate change is a useful test of climate models. A range of different climate predictions have been made using modeled data for northern Europe over the last decade. The latest sets of scenarios modeled by the HAD CM3

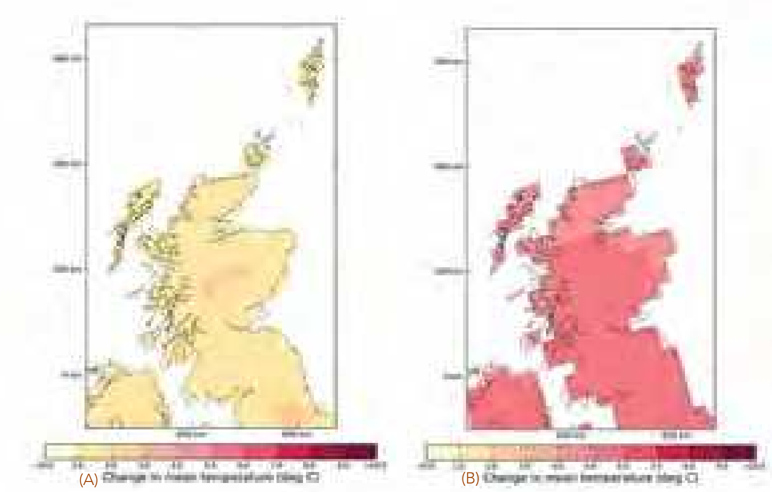

Fig.2 UK Climate Prediction (UKCP09) projections for the increase in temperatures for Scotland and northern Britain over the course of this century with continued "high emissions" of greenhouse gases. Scenarios for the 2020s (A) and 2080s (B) are shown. The 'high emissions' scenario shown would be of the greatest threat to historic earthen buildings. The data is based on HAD CM3 climate-model predictions (1) (credits: © UK Climate Projections, 2009)

model are widely accepted and form the basis for the most recent IPCC report (Metz, Davidson, Bosch, Dave, and Meyer, 2007). For Scotland and northern Britain, these predictions have been mapped at a resolution of 25 km^2 resulting in a series of possible outcomes.

The interaction of different weather events (rain, frost, dry weather) with earthen structures in northern Europe has many determining factors. While external forces, such as raindrop impact and frost-induced cracking, are obvious, internal surfaces of closed but unheated building structures are subject to more subtle effects. A recent study by Lankester and Brimblecombe (2011) measured thermo-hygrometric climates within a historic house in southern Britain, and has proposed a series of dose response, or so called 'damage' functions for assessing the fate of the coverings of internal walls. While a basis for such functions to be modeled in respect of earthen-built structures exists, their development and application requires suitable techniques for deriving starting parameters and model validation.

3. SUSTAINABILITY OF SCOTTISH EARTHEN BUILDINGS

The sustainability of existing earthen-built properties in Scotland depends upon adequate responses to the issues raised by climate change. These include increased flooding, water movement through the earthen matrix of walls, and more rapid changes between wet and dry conditions. This coupled with general increases in air temperatures will lead to changes in the rate and nature of movement of water and soluble salts in earthen-built structures. To understand these processes requires the pore-geometry of the sediments to

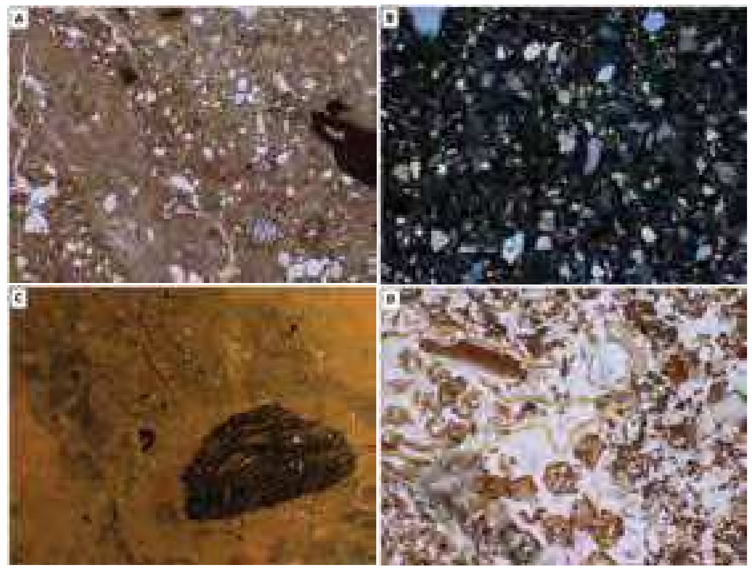

Fig.3 Photomicrographs taken using different illumination techniques; plane-polarized (PPL) and oblique-incident illumination (OIL), (A) Cereal straw used as an organic amendment within an earthen-built school house wall, Cottown, Perth and Kinross (PPL), (B) Highly organic materials and mixed mineral component, sand-rich turf-built walls, Newtonmore, Inverness-shire (XPL), (C) Charred wood fragments within mud-wall construction, Leetown, Perth and Kinross, (OIL), (D) Open structure and organic materials with wall material, Newtonmore, Inverness-shire (PPL) (credits: Paul Adderley, 2012)

be characterized at an appropriate scale; in this paper, we outline an approach using soil thin-section micro-morphology. Furthermore, given the need to establish rates of change, chronological assessment through either relative or absolute dating is a key parameter. An approach to rapid relative dating of mineral materials is described.

4. MICROMORPHOLOGY AND IMAGE ANALYSIS

4.1 Characterization of materials through micro-morphology analysis

The use of microscopic analysis of materials from historic earthen-built structures is a particularly important analysis tool for investigation of historic earthen structures. When combined with complementary analyses, such as electron microprobe or X-ray elemental analyses, spatial relationships between the different components (clay, gravel, organic materials) can be identified and measured. Investigations from buildings in Scottish contexts have so far revealed a wide variety of fabrics and organic additions.

4.2 Spatial descriptions of porosity

Comprehending the porosity characteristics of the materials used in earthen-built structures is essential if process-based models and understandings of water and salt movement are to be advanced (Grossi et al., 2011). The description of water movement, i.e. percolation, in porous media, such as soil, requires knowledge of the relationship between soil-water content and the pressure head of the water moving through the pore space. Many models of percolation in porous media have been developed that are based on capillary behavior, i.e. how does water move through an unsaturated capillary pore during wetting or drying? Such simple models, typically, assume the pore spaces in the media are a uniform set of capillaries running in parallel. Soil materials are, however, inherently more complex and the porosity of the soil materials can be better described as a network of pores connected by "throats" or constrictions between them (Kodešová, 2009; Fig. 4A). The geometry of the network, i.e. the size of capillaries and the minimum size of these throats, is a key determinant in the rate of water percolation.

Direct measurement to characterize these networks by methods, such as mercury porosimetry, are common on solid materials, such as stone, but are more problematic when applied to softer materials, such as soils (e.g. Fiès and Bruand, 1990). Artifacts in measurement emerge due to the need to dry the sample prior to analysis, which may lead to clay-drying cracks. The intrusion of mercury may also result in very high pressures deforming the soil fabric. If water and soluble-salt movement in earthen-building materials is to be modeled through deriving rates of percolation, the size, distribution and arrangement of pores and throats must be established. Image analysis of thin-section materials allows their characterization in two dimensions and the development of such models.

4.3 Quantitative analysis of porosity through mathematical morphology

Quantitative analysis of materials seen in soil thin sections through image-processing techniques has become well established in soil science. Quantification of the relative contribution of different components of the fabric of an earthen wall can be readily achieved, but image processing is essential to quantifying and characterizing the porosity of the material (Whalley et al., 2005). While porosity can be simply measured by the area of the thin section covered by pores, if transport processes are to be considered then an assessment that measures throats is required. One method is to use a mathematical analysis using "closing" and "opening" functions in a repeated sequence until the throat closes (Fig. 4D). By keeping the mathematical operators applied constant, the method can be applied to different images; the number of iterations of opening and closing required to close all the throats in an image provides a robust measure of the pore geometry.

5. MEASUREMENT OF THE STORED-DOSE LUMINESENCE CHARACTERISTCS OF EARTHEN–BUILDING MATERIALS

Luminescence dating is a recently established method in geomorphology and cultural-heritage studies. It is based on the fact that there is a constant flux of naturally occurring ionizing

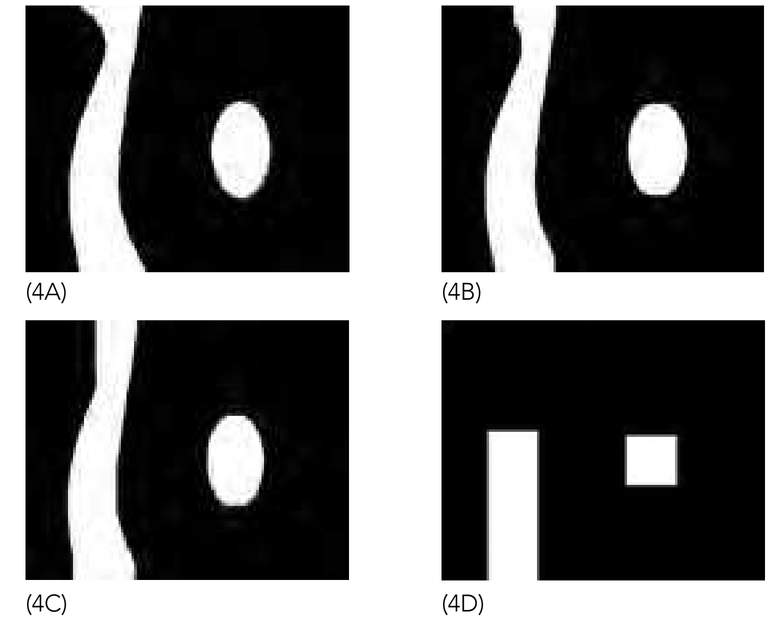

Fig.4 Starting with a schematic pore network of an open pore and closed pore (A), sequential application of mathematical-morphology opening and closing functions (B, C) allows quantification of the step when the 'throat' of the open pore closes (D) (credits: Paul Adderley, 2012)

radiation in the environment, and that many silicates can act as a dosimeter of this radiation. This stored dose can be released by heat or light. This means that the amount of luminescence emitted from a sample (e.g. quartz) is proportional to the accumulated dose since it was last exposed to either heat (e.g. pottery) or light (soils, sediments). If both the background-dose rate and the stored dose are known, a date since firing (pottery) or last exposed at the ground surface (soils) can be calculated. Among many factors, however, the results are conditioned by the nature of the sediment or fired material examined. By accepting that the measurement of stored luminescence in unfired clays and other silicates is conditioned by the material itself (mineralogy, bulk density), it is possible to examine the use of a novel portable instrument to rapidly examine stored-dose measurements. Using examples from the Carse of Gowrie it is illustrated how such data can be interpreted.

5.1 Instrument

The SUERC portable luminescence-reader instrument was developed by Sanderson and Murphy (2010). It is designed to prioritize conventional dating measurements by allowing an assessment of mineralogical properties and sensitivities. It measures both infra-red (λ 880 nm) stimulated luminescence (IRSL) and blue-light (λ 470 nm) luminescence (OSL) stimulated luminescence. The greater the OSL count, the greater the age of sediment since last resetting by light or heat. Changes of the IRSL:OSL ratio are a possible proxy of mineralogical differences. To test the use of such an instrument for earthen-built structures, materials from an internal rammed-earth wall at Cottown Schoolhouse (Morton, 2011) and from the local clay source at Errol have been examined.

Fig.5 Portable luminescence-measurement apparatus comprising sample chamber with attached photomultiplier, control box, and laptop PC; sample in foreground (credits: Paul Adderley, 2012)

5.2 Measurements

Luminescence measurements are reported in Table 1. From historical records, the processed clay material at Errol was last exposed in c. 2004, and the interior matrix of the Cottown schoolhouse is likely to date from AD 1745. It is clear that both IRSL and OSL measurements reflect these periods. It is also clear that the action of processing a bulk-clay body from brick-making is sufficient to reset the luminescence. This suggests that if similar manipulation of earthen materials occurs during vernacular construction, the luminescence signal will be reset. This would suggest that full luminescence dating of such structures is possible. The contrast in materials from the wall in Cottown Schoolhouse is presumably due to past exposure of the surface during interior decoration; however the IRSL:OSL ratio may suggest mineralogical differences due to surface treatments.

6. CONCLUSION

We have successfully developed and demonstrated, using a small set of case studies, methods for laboratory-based field sampling and monitoring initiatives. These methods are presently being integrated into a wider set of site-based and experimental studies assessing climatically related processes of decay in historic earthen-built structures found across Scotland. By establishing quantitative methods, rates of decay and modeled 'damage' functions can be established. The use of the portable OSL system has provided valuable information that may help direct sampling for detailed chronological assessment, for example, the dating of building repairs. These data may also direct sampling for assessment of mineralogy and for thin sections of structures. Through the latter, the initial composition of the matrix of the earthen structure, as well any repair materials can be characterized. Combined, these analytical tools allow a deeper process-led assessment of the life-cycle of earthen-built structures.

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

Daniel Maskell, Peter Walker, Andrew Heath

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