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# PRACTICAL APPLICATION OF SMALL-SCALE BURNING FOR TRADITIONAL LIME BINDER PRODUCTION: SKILLS DEVELOPMENT FOR CONSERVATION OF THE BUILT HERITAGE

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## Abstract

Experience has been gained in the operation of a very small-scale batch lime kiln, capable of calcining around 600kg of combined stone and fuel, as a precursor to larger scale production of several tonnes. Stone compositions were chosen to produce hydraulic lime- with important mineral transformations that can permit independent confirmation of production temperatures. Simple temperature distributions in the kiln, air flow and oxygen content of the exhaust are combined with analysis of the quicklime produced to understand the dynamics of the traditional process. Mortars were produced using a traditional hot mixing process and tested for a range of fresh and hardened properties.

## Key Words

Lime mortars, small-scale burning, built heritage, conservation

## 1 Introduction

This paper, in the main, outlines recent, largely qualitative, experience gained by the authors in operating a small-scale, vertical, batch lime kiln, as part of a research project into the production of lime mortars for the compatible repair and restoration of historic masonry buildings. Many projects have, or are currently, considering the properties and

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performance of lime-based materials for use in historic buildings and new build (e.g. recent UK Link Foresight project). Most of these materials however, are produced in relatively modern facilities with great consistency. The work presented here is part of a larger project investigating the properties of materials produced and applied using the complete chain of traditional practice from selecting limestone to mixing method and application.

The analysis of historic mortars reveals the variability of these mortars and an overwhelming abundance of local characteristics gained through the use of local materials (Hughes & Cuthbert 1999, Callebaut 2000, Leslie & Hughes 2002). In the search for more compatible repair mortars it is possible to specify that the use of original materials is the best solution, and certainly carries the greatest *authenticity* if combined with correct application method. For lime, this opens up the possibility of using the same source of limestone to produce lime specifically to repair the building in question. Large scale lime production methods are less likely to meet the criteria set here, especially with an abundance of historical small-scale sources possible in any area (Nisbet 2003), with the variability of limestone generating a variety of lime characteristics appropriate and unique to their localities.

Modern production of lime produces a very consistent product, and also in the case of hydraulic lime a hydrated and powdered one. Analysis of historic mortars, certainly those from before the advent of industrialised production during the 19$^{th}$ century, indicates not only a wider variety of lime types, but also lime textures consistent with "hot mixing", also known as dry slaking, where quicklime in lump form is mixed directly with wet aggregate to form a mortar and not through an intermediate putty stage (Gibbons 1993, Hughes et al. 2001). Using traditional practice and local materials in order to achieve authenticity and compatibility therefore places a heavy burden on mortar specifiers, as not only are modern materials not right, but they are supplied in the wrong form (dry hydrate did not exist historically). To overcome this, a return to small scale production of lime using locally sourced material is advocated. However, this is a poorly understood area in construction. It is not yet certain whether such production will satisfy the demands of conservation in any case, let alone the material quantities required. Nevertheless, the work presented here is a step towards a quantitative and controlled methodology for appropriate small-scale production.

A large scale batch "Experimental Lime Kiln" was constructed at Charlestown, Fife in Scotland in 1999. Details of this and results from limestone calcinations using the facility are presented elsewhere (Hughes et al 2002). More recently, in 2002, a considerably smaller experimental kiln was constructed to facilitate the more rapid and cost effective development of burning experience. This has been used to produce quicklime from two distinct limestone types to date. The small scale burning methods and the design of the kiln (described below) have their antecedents in publications by Wingate (1985) and the Intermediate Technology Development Group (Mason 1999). However there are some differences in approach, such as the kilns we have constructed are batch kilns, not for continuous operation and the emphasis is on burning for construction use, which does not imply a search for the best efficiency in production, but for desired material characteristics. Indeed, despite the previous discussion small scale burning of lime still continues in many parts of the world, but has disappeared from many parts of Europe and almost entirely from the UK. A notable exception includes lime production on Gottland (Sweden).

The following sections outline the construction of the small-scale kiln, the nature of the monitoring system and the method of operation. Some results are presented, though results from the testing of the materials produced are not presented here as at the time of writing they are not complete.

## 2 The small-scale kiln

The small-scale kiln (Figs. 1 & 2) used is a scaled-down version of the larger Experimental Lime Kiln, located at Charlestown in Fife, Scotland, details of which are given elsewhere (Hughes et al. 2002) The smaller kiln is located at the same site. The large kiln has an internal shaft of 4.8m height and 1.8m in diameter and can hold 18-20 tonnes of material. The small kiln has a shaft of 1.5m height, around 70cm in diameter, and can hold a total of approximately 600kg of combined fuel and stone. The shaft is built of refractory bricks laid in bentonite fire clay, on a concrete base and with a rectangular fire-pit running from the front of the kiln to the rear beneath a steel grate over which stone and fuel are laid. The exterior of the kiln is built as a square using conventional concrete blocks laid in hydraulic lime mortar. The space between the shaft and the exterior skin is filled with an insulating mix of expanded vermiculite and natural hydraulic lime. The whole structure is topped with a 10cm thick concrete cap on which a removable steel plate with a hole for draught is placed, on which the chimney is positioned. Steel corner restraints are held in place by tightened plastic strapping, that can be easily renewed. These were added after the earliest burns, to counter movement in the kiln after cracking due to the elevated temperatures of operation.

*Figure 1 The small scale experimental kiln at Charlestown, Fife, Scotland. The four thermocouples can be seen at the right. The cable to the chimney stack leads to the oxygen Lambda sensor. This shows the kiln soon after lighting; the air intake flue incorporating the air velocity transmitter is yet to be fitted, once the fire has taken hold.*

The monitoring system comprises four k-type thermocouples inserted into small diameter holes cored through to the inside of the kiln shaft. Exit gas Oxygen levels are monitored by a Lambda Probe fixed in the kiln stack. This device is particularly robust as it was designed for use in automotive exhaust systems. The model used has a self heater which requires its own 12V supply (at about 1 amp) and gives an output which rises from zero or slightly negative at free air oxygen levels (22-23% $O_2$ ) to almost 1V in gases with zero oxygen. Air flow into the kiln via the input flue is monitored using a Dwyer air flow probe. This has proved to be a very versatile and reliable way of measuring input air flow on the ELK. The output is 4-20mA, and the range of airflow can be set by switches in the instrument electronics.

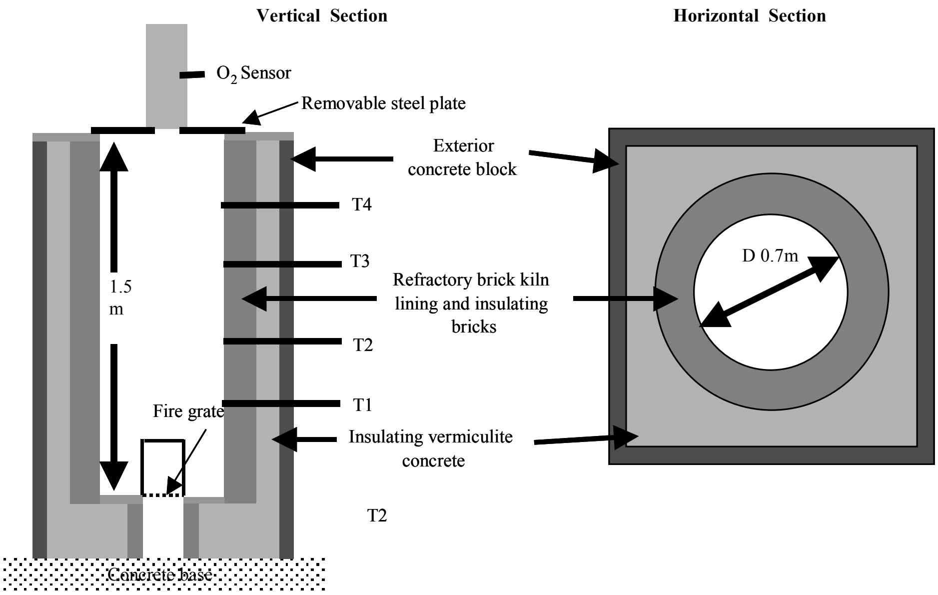


*Figure 2 Schematic sections through the small-scale kiln, showing locations of thermocouples and oxygen sensor.*

The outputs from the devices described above are fed into an ABB PR100 industrial chart recorder, that not only provides a paper chart recording of the device data, but also provides a digital output that can be linked to a computer system. The software used is SPECVIEW, which logs the incoming data once a minute, and allows the creation of onscreen data displays in numerical and graphic form. Thus the computer system allows us to continually monitor the burn and if necessary adjust the conditions by regulating the air intake. The only control we have is to either damp down the airflow, or to augment it with a blower. Factors such as temperature rise times and exit oxygen levels need to be taken into consideration.

# 3 Kiln Operation

## 3.1 Stone selection

Two stone types were used; Blue Lias limestone from Somerset, England and the local Charlestown Limestone. The Blue Lias stone is a calcareous mudstone, or marl, of consistent fine grained texture. It was historically used for lime production and at the time of writing was being produced by one producer in England on a commercial scale. The Charlestown stone, used historically for the production of lime in Scotland is a complex dolomitic biomicrite that contains appreciable amounts of clay (Pickard 1994). Both stones are hydraulic, containing sufficient amounts of silica to produce hydraulic components, such as $C_2S$ and $C_3S$ on burning. The commercial production of Blue Lias lime is for natural hydraulic lime. The Charlestown limestone, though not used for production for over 50 years is known as a moderately hydraulic material. Both stones contrast in texture and composition.

## 3.2 Loading and lighting

The kiln is loaded in a simple manner by hand. First of all, a layer of wood is placed across the grate and the bottom of the shaft and then a quantity of solid fuel is spread over this. This bottom layer is intended to catch light to start the firing cycle. The solid fuel used throughout has been a 1:1 mixture by weight of pet coke and anthracite (Columbian Red). These fuels are essentially smokeless and have a low ash content.
After this, stone and fuel are weighed out in predetermined quantities and “mixed” in a container in batches of approximately 120kg. It is important to note that in this project,

as is considered traditional in Scotland, coal is used, and it is mixed throughout the load, not layered. Unlike wood firing this means that once lit the kiln can be left relatively unattended, and has no need for continuous stoking. The batches of stone and fuel are then lifted onto the top of the kiln using a forklift and tipped into the shaft. Table 1 gives an example of the record of one burn using the Blue Lias stone.

*Table 1 Example loading pattern, for burn using Blue Lias stone*

| | Stone | Coke | Anthracite |
|---|---|---|---|
| **Load 5** | 71 | 4.9 | 4.9 |
| **Load 4** | 110 | 7.2 | 7.6 |
| **Load 3** | 110 | 7.6 | 7.2 |
| **Load 2** | 110 | 7.6 | 7.6 |
| **Load 1** | 110 | 7.6 | 7.6 |
| **Bottom Layer** | wood | 5.3 | 4.2 |
| **Total** | 511 | 40.2 | 39.1 |
| **Fuel content** | | | 13.4 wt.% |

On the very top of the fill bricks are placed to simulate an insulating layer of stone (Figure 3). Experience of earlier burns revealed that the top layer of stone would not calcine properly, such are the inefficiencies of a traditional batch kiln. The bricks have proven to reduce this effect in later burns.

Lighting is simple; a fire is started using wood underneath the grate and maintained until it is certain that the fuel above the grate has lit. This can be confirmed as temperatures inside the kiln begin to rise and from a glow detected above the grate.

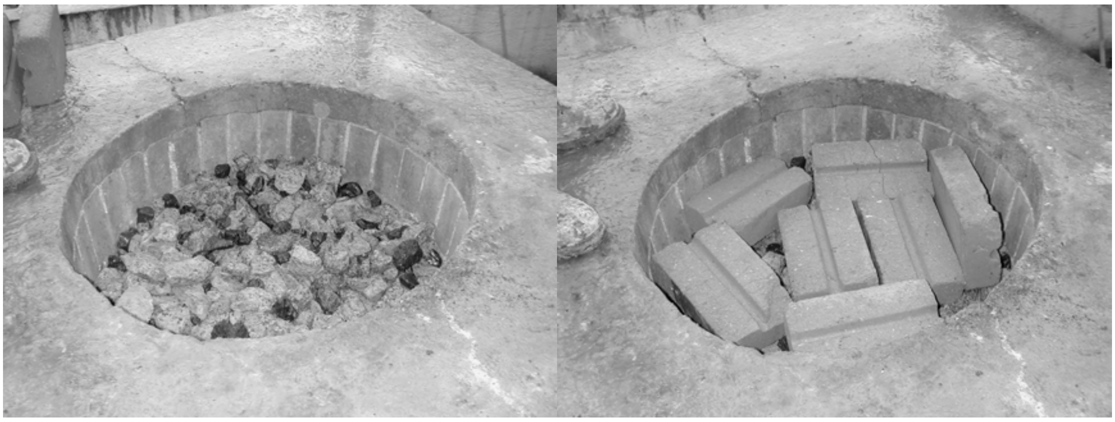

*Figure 3. Loading of the kiln. Left- the stone with fuel mixed through. Right- top layer of "insulating" bricks to reduce heat loss from top stone layer. Diameter of kiln 70cm.*

## 3.3 Firing Cycle

Once the kiln is alight, close attention is paid to the development of the initial temperature profile. The oxygen also shows an initial drop in level as the fire establishes. Then at some time up to 5 hours the oxygen levels rise, indicating more free burning and the beginnings of temperature rise in the kiln. Once burning has established it is important to control the air flow into the kiln, principally by reducing the draught to slow the burning rate down, otherwise the fuel will burn through too quickly, and the stone will not get a sufficient residence time above the calcination temperature. Reducing the air flow results in more efficient and slower burning, and a low exit oxygen content.

The complete cycle in the small kiln takes a little over 24 hours. However, the quicklime in the kiln is usually cool enough to handle after 48 hours (about 40-60$^{o}$C). This is beneficial also to prevent air slaking of the quicklime.

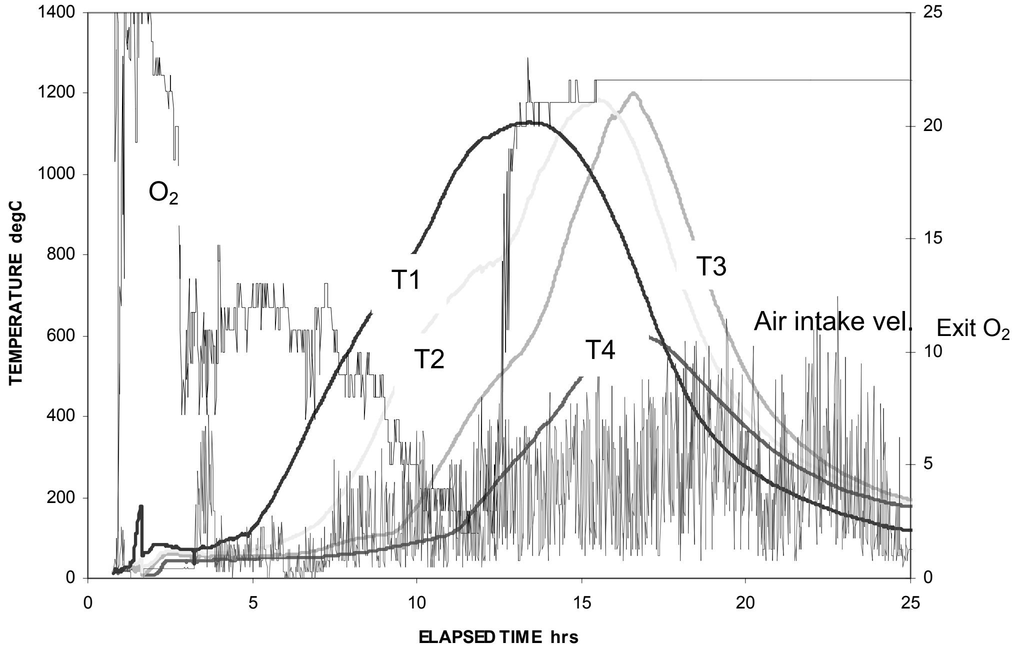


*Figure 4  Example log of burn conditions in small scale experimental lime kiln for Blue Lias stone.T1=lowest thermocouple  T4=highest thermocouple*

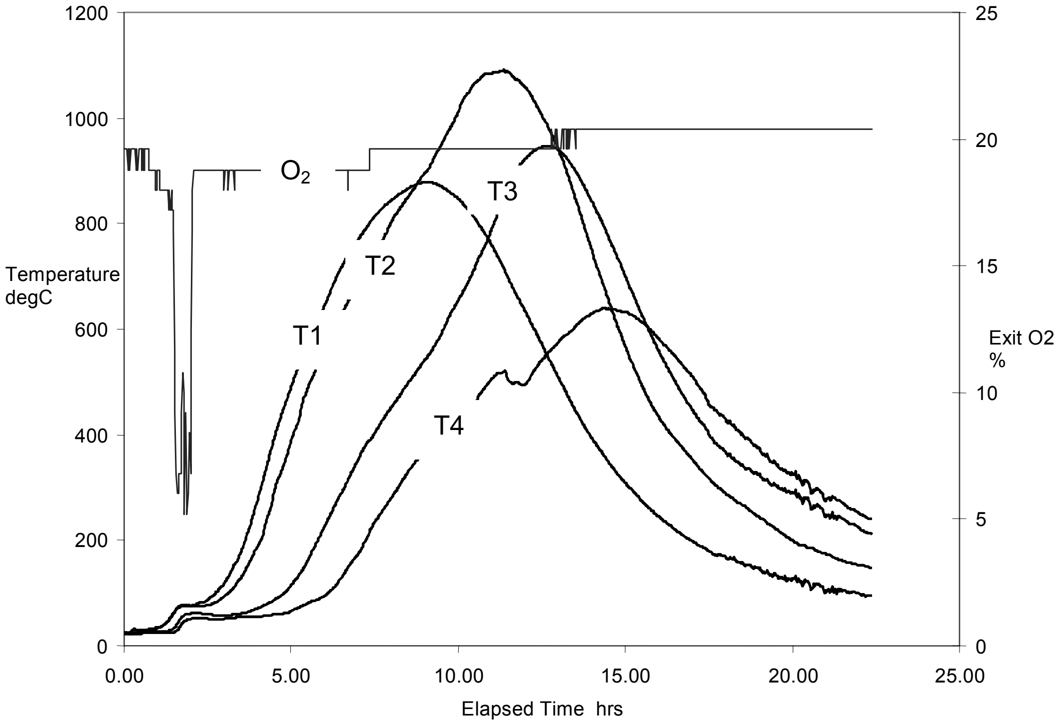


*Figure 5  Example log of burn conditions in small scale experimental lime kiln for Charlestown limestone.T1=lowest thermocouple  T4=highest thermocouple. Note no air velocity data due to technical difficulties.*

Figure 4 gives an example of the evolution of recorded conditions within the kiln. The pattern of thermal evolution is predictable, but it can be seen that the air flow and oxygen levels in the exit gasses are the most variable.  The residence times over

800°C for this burn are between 4-5 hours, and the highest temperature recorded is 1200°C. The draught for this burn was carefully controlled and resulted in sufficient residence times. This can be compared with the data from an earlier burn in Figure 5 below. In this example, air intake was not so well controlled, resulting in lower maximum temperatures and reduced residence times.

### 3.4 Unloading and assessment of degree of calcination

The kiln is unloaded by hand, firstly by removing the air intake flue and breaking through the temporary block, tile and mortar seal of the unloading "door" above the grate (Figure 6). All of the contents of the kiln are then weighed and compared with the weight of the material loaded. This is a method essentially the same as that advocated in Mason (1999) for estimating the degree of calcination, except for this project the small quantities involved allow the weighing of the complete kiln fill.

If the loss on ignition figure of the stone is known from laboratory determination an estimation of the degree of calcination achieved in the firing can be arrived at. The theoretical weight loss can be calculated and the actual weight loss determined and compared. From this the efficiency of the process can also be determined. This calculation takes the fuel use into consideration. The best estimates for efficiency previously using the large Experimental Lime Kiln are 45%.

For the burn relating to Figure 4 above the degree of conversion was found to be 100%. Indeed the residence times indicate not only 100% calcination to be likely, but the maximum temperature reached of 1200°C suggests the formation of hydraulic components. In an earlier burn (not shown here) the temperature peaked at 1350°C. Subsequent analysis of the material confirmed the presence of C3S (alite) in the lime (Livesey & Sagar pers comm.) For the burn relating to Figure 5, however, the residence time above calcination temperature was quite short, and the maximum temperature was lower. This was confirmed as a large proportion of the stone remained unburnt, with a considerable amount of core. This occurred despite an identical fuel content to the burn depicted in Figure 4. The difference was in the degree of control of the air intake. The burn in Figure 5 was too rapid and the fuel burnt through too quickly.

*Figure 6 Unloading the kiln. Left- first sign of fresh quicklime in kiln just above fire grate. Right- removing the quicklime by hand.*

## 4 Discussion and Conclusions

Once the kiln is unloaded it has been found that a highly usable, but inherently variable material has been produced. The emphasis in the work presented here is to establish a simple methodology for small-scale burning and the experimental analysis of the process. This has been achieved, with full recording of kiln conditions demonstrated to be possible. Some important lessons are being learnt; namely that draught control is extremely important for the quality of the material produced. This is, of course, nothing new, but we are able to demonstrate, with a degree of quantification, the conditions that should be achieved in the kiln. Recording also allows us to develop a methodology for doing this and for active control relatively quickly.

The practical output is relatively clear and simple, but the theoretical impact is more difficult to assess at this early stage. The elements of theory important in this context relate less to the practice of lime production and more to the relationship of the materials produced to the questions posed about material authenticity and compatibility. There is no question that material can be produced using “traditional” methods, and this also in a modern context of quantification, close monitoring and materials analysis. However, this paper explicitly does not cover the issue of compatibility and performance in use. Such an analysis requires comparison and assessment of the materials within a context of use with Historic Buildings.

The materials produced through small-scale burning are being investigated for their composition (chemical and mineralogical) and also for their properties in mortars. In accordance with the approach taken in this project the mortars are being produced using dry-slaking or “hot” mix methods. These types of mortars have yet to be investigated at length scientifically, but are known to work in practice quite well. Difficulties arise with comparisons with modern produced materials, in terms of proportioning and mixing, and issues surrounding the fresh properties of the mortars.

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