



TECHNICAL PAPER 32

A DATA DRIVEN APPROACH TO
UNDERSTANDING HISTORIC MORTARS IN
SCOTLAND



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Cover Image: Slate window detail at Eilean Mor.

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PREFACE

Traditional quicklime-based mortars have a long history of use in Scotland with evidence visible throughout the country on traditional buildings and structures of all types. In building conservation, the use of lime mortar of various configurations is a recognised practice; like-for-like replacement of historic material is an important part of works to ensure authenticity and accuracy. However, in more recent times, the preparation and use of traditional quicklime-based mortars in general has been increasingly superseded by hydraulic limes of various types, which have very different properties to their historic predecessors. This not only affects the performance of the masonry in its ability to handle or disperse moisture, but there is also a risk of loss of skills and familiarity with the traditional materials that make up an appropriate mortar.

Over the last twenty-five years, the Scottish Lime Centre Trust (SLCT) has gathered the results of mortar analysis from buildings of all types and dates; from the medieval to the post-war periods. With funding from Historic Environment Scotland (HES), these entries were transcribed into a database to allow for examination of the mortar composition, and for patterns and developments in the use of mortars to be ascertained. This Technical Paper is the result of this collaborative project between HES and the SLCT, delivered via an Internship between October 2015 and April 2017 (held by co-author Anne Schmidt).

Using the database, the project looked at the evidence from the different types of mortar used across Scotland in order to appreciate the extent of use, changes in composition, common mortar mix ratios, constituents, hydraulicity and regional differences. By examining these characteristics, questions on the historic composition, use and practice of lime mortars in Scotland can be better understood and answered. This can in turn inform the specification of replacement mortars to ensure that an appropriate like-for-like or modified mortar mix is used.

This Technical Paper is one of a series published by Historic Environment Scotland which aims to assist building professionals in understanding traditional lime mortars and finishes in Scotland and their relevance to conservation practice. It will add to the already published material on the development of traditional quicklime-based mortars in Scotland and how they fit into the wider suite of mortar repairs for traditional buildings. Other papers in the series look at: the micro-structure and functional performance of historic mortars; specifying traditional hot-mixed lime mortars in a modern context; a review of historic external lime finishes; a literature review of historic evidence of lime applications; and a review of evidence from more recent lime applications in Scotland.



SCOTTISH
LIME CENTRE
TRUST

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I. RESEARCH PURPOSE & SCOPE

Conservation and maintenance of our historic assets relies upon having a sound knowledge and understanding of the materials and techniques used in their construction. An awareness of how materials perform and interact with their environment is key in making appropriate conservation decisions. An understanding of original building materials: their composition; their characteristics; how they have weathered; often acts as the basis for the appropriate specification of repair materials.

The Scottish Lime Centre Trust (SLCT) was established in 1994 as a 'not for profit' organisation registered as a charity in Scotland in response to growing concern over the shortage of skills and understanding in the field of traditional building technology. SLCT's fundamental aims are to promote and encourage the appropriate repair of traditional buildings, and to conserve and develop the associated building traditions, crafts and skills through training and education. Through their Building Advisory Service, SLCT provide analysis and evaluation of building materials, for aiding repair specifications, archaeological purposes and to identify reasons for failure. Through this service, SLCT have built up a 'Mortars Archive' with information on the analysis of over 3,000 mortar samples. To the best of our knowledge, this constantly growing archive represents the largest and most comprehensive source of information on historic mortars globally. It provides an unparalleled and valuable historic record of the traditional materials used in the construction and repair of many traditional buildings and structures in Scotland.

In 2015, Historic Environment Scotland (HES) funded a collaborative project with SLCT, managed by the HES Conservation Science team, to develop our understanding of Scottish mortars using this extensive and previously undisclosed resource. This work included the digitalisation of the archive, previously held as individual analysis reports, in a purpose-built database ('SLCT Mortars Database')

and subsequent interrogation of the data, to provide us with an evidence-based and quantitative understanding of historic mortars in Scotland. The information held within the SLCT Mortars Database relates to a range of different materials including lime, cement, earth and clay, although given the focus of the Centre's work, there is an understandable bias towards lime mortars. NOTE: the SLCT also hold a database of commercially available aggregates. Analysis of this data is not within the scope of this document.

Data were interrogated in full to give an overview of the database capabilities, and based on selected data to answer specific research questions. This work aimed to address a number of questions relating to the use of lime for mortar production, specifically:

- the extent of the use of lime of different types across Scotland
- common mortar mix ratios and constituents
- hydraulicity of lime mortars in Scotland
- the influence of regional differences on mortars in Scotland.

Through interrogation of the data we have sought to validate and quantify information often cited in connection to historic mortars and generally taken as fact, but which currently lack a reliable evidence base.

This report details the process by which information on historic mortars is established (i.e. the analysis process), the breadth of information held in the database, the processes involved in data interrogation (including limitations of the data), and the conclusions that can be drawn from this.

It is hoped that this information will expand our understanding of historic mortars in Scotland and act as a valuable reference to those involved in making decisions relating to the conservation of Scotland's historic assets.

2. UNDERSTANDING LIME MORTARS

Lime has been used since prehistoric times and was once considered to be the most important building material across most of the World (Hughes and Válek, 2003). It is still used today in many countries for traditional building. Due to the development of modern construction techniques and alternative building materials, a degree of knowledge was lost prior to the 'lime revival' in the 1970s.

The widespread use of lime is undoubtedly connected to the availability of the raw materials and the simplicity of its production. The 'lime cycle' in its basic form consists of burning limestone (CaCO_3) to produce 'quicklime' (CaO) and 'slaking' with water to produce hydrated lime (Ca(OH)_2) or an aqueous lime putty (Figure 1). After mixing with aggregate, the mortar sets, and the lime returns to its original composition of Calcium Carbonate (CaCO_3). The more complex reactions involved in the production of 'hydraulic' limes, and the resultant characteristics of mortars made from them, including their ability to 'cure' in the presence of moisture, open up the possibilities for using this material across a range of climatic and environmental conditions.

Anecdotal evidence points to the prevalence of 'hot-mixed' limes (i.e. those produced using quicklime) in historic constructions, specifically for bedding of masonry and exterior finishes, indicating that the slaking of lime and mixing with aggregate would likely have been done as a one-step process. Lime putty was used for more intricate work such as plasterwork.

2.1 The history of lime in Scotland

The importance of lime in Scotland in an agricultural context is relatively well documented, and evidence indicates that the value of lime in this context was appreciated from as early as the 17th century (e.g. (Smout, 1999). Lime is considered to be among the most important innovations in farming and, through this, achieved symbolism for innovation, progressiveness and social stature (Mitchell, *forthcoming*). During the long history of lime use in Scotland there was an initial expansion of agricultural liming in lowland areas (Whyte,

1979), although lime had been produced from a much earlier time for construction of traditional mass masonry structures (Artis-Young, 2010).

The 18th century was a time of enlightenment and industrialisation in Scotland. A time of social progress expressed through writers such as Isaac Newton and David Hume (Whatley, 1997; Lenman, 2009) favouring rational thinking and scientific methods; there was a great deal of intellectual endeavour (e.g. Hume, 1976) that influenced privileged landowners and set a template for change in the latter half of the 18th and into the 19th century. These changes had an influence on agriculture and industry, promoting a more ordered and scientific approach (Whatley, 1997). There was an emphasis on improvement of one's self and society, as expressed by the preoccupation of the leading classes to reform the supposedly idle lower classes (Whatley, 1997).

Mechanisation in an industrial context was one of several aspects of improvement during this time, fuelled by a desire to increase yields through more evolved working practices. These changes can be seen in the increasingly mechanised powered mills of this time (Whatley, 1997) and this process of improvement and standardisation was mirrored in the lime industry (Mitchell, *forthcoming*).

The lime industry expanded further in the 18th century, partly due to the desire to drain and improve the marshes and bogs within Scotland, often through liming (Smout, 1999). Demand was driven by the improvers, and later agricultural institutions (like the Board of Agriculture), who promoted liming in several ways to encourage its use (Mitchell, *forthcoming*).

Additionally, the increasing urbanisation of Scotland in relation to both the spatial expansion of urban areas and the diversification of building materials used in these areas – such as the use of lime mortared stone (see Harris & McKean 2014) – played a significant role in driving demand (Whatley, 1997). One example is the 18th century construction of the New Town of Edinburgh (Lenman, 2009). This development required large quantities of building materials. This demand was matched by investment in the lime industry through large scale works such as the Charlestown limekilns in Fife which are known to have transported their lime throughout the region along the Forth and the Tay (Smout, 1999), as well as much further afield (SLCT, 2006). Such largescale limeworks could not only produce the quantity of materials required but could also ensure a greater degree of consistency in the materials produced.

There are a number of studies which consider evidence of the lime industry within individual regions in Scotland; a comprehensive study of the lime industry in Scotland as a whole, although currently unpublished, is imminent (Mitchell, forthcoming).

Skinner (1969) considers the lime industry in the Lothians, including a gazetteer of known lime works of which there were many. The article, arguably the most influential publication on lime, concludes that the lime industry took off in the mid-18th century and continued until the early 20th century. Skinner (1969) argues that this increase in production was due to the agricultural revolution as well as the urban expansion later in that century.

Nisbet (2005) looks at the evidence of the lime industry in Renfrewshire, another important area of lime production. Taking one site as an example, the evidence presented shows a more organised exploitation of limestone and coal in the area starting in the 1750s to be burned in the kilns on site (Nisbet, 2005). According to Nisbet (2005), most of the draw kilns (vertically ‘fed’ masonry-built kilns) in this area originate from the mid to late 18th century, even though clamp kilns (relatively

basic pits that were filled with lime and fuel and covered over during burning) were still used. Evidence points to a more intense lime industry starting around the same time.

Lastly, Mackay (1977) studies the evidence of a lime industry in Stirlingshire; kilns here started producing lime around 1790 on a larger scale, including both draw and clamp kilns in different locations.

While these studies only consider three areas within Scotland, all three authors show a notable increase in production in the 18th century; it is likely that a similar pattern will be established across the country as a whole.

Another important contributing factor to Scottish industrialisation was the increasing cash market supported by the foundation of the major bank houses (Whatley, 1997). This meant that increasingly, rent was paid in cash, enabling rural areas direct access to the trading market (Whatley, 1997). Lime directly contributed to this change, being one of the first agricultural resources that farmers would frequently purchase from off-farm and for which cash was required (Mitchell, *forthcoming*.)

This period also saw the improvement of many transport links and the opening up of new shipping possibilities. Overland, the roads were improved in the late 17th and 18th century, often through the investment of landowners (Saville, 1999) as well as through the improvement of military roads in the 18th century (Gordon, 1988). This was accompanied by an expansion of sea shipping from Glasgow (Whatley, 1997) and along the Forth. Canals started to be conceptualised in the early 18th century and built in the 1760s. Mainly designed for the transportation of coal to urban areas, and indeed the transport of lime (Mitchell, *forthcoming*), these were often private investments connecting different parts of the country and making transportation of heavy goods significantly easier (Haynes, 2015).



The historic limekilns at Charlestown, Fife, built by Charles 5th, Earl of Elgin on the Broomhall Estate in the 18th century. The limekilns underwent consolidation in 2018 as part of the Inner Forth Landscape Initiative.

Railways, established in the early 19th century, provided a continuation to the ever-increasing transportation network (Gordon, 1988). This now expansive network would have led to more consistent access to a wider range of materials across the country.

In conclusion, the 18th century represented a time of significant social and economic change that had a direct impact on, and an association with, the lime industry.

2.1.1 The loss & rediscovery of knowledge

After an almost universal use of lime across the UK building industry, the 19th and particularly 20th centuries saw a major decline in its use in favour of newly developed cement products.

A number of manufacturers began to produce 'natural cements' in the 18th century, including Parker's Cement (patented in 1796) and 'Calderwood Roman Cement'; the latter produced in East Kilbride, Scotland. Later came the development of early artificial cements including Edgar Dobbs in 1811, James Frost (who patented 'British Cement' in 1822), and perhaps most notably, Joseph Aspdin who patented Ordinary Portland Cement in 1824 (Aitcin, 2008).

These new materials took precedence over lime for a number of reasons, but it was perhaps the perception that these cements, which were considerably harder than lime, would be eminently more durable, combined with their decreased curing time which enabled more rapid construction and led to their popularity.

However, in the later decades of the 20th century it became apparent that cement mortars were often too strong for UK building stone, resulting in increased rates of stone deterioration and the associated need for building repair. This led to the 'lime revival', a period of increased interest and research into the traditional material and rediscovery of its benefits for conservation work (Brocklebank, 2012).

The following paragraphs provide a summary of the conclusions of much of this research that was conducted during the UK lime revival. This research was based on exploration of historical documentation and imagery, as well as scientific analysis of physical samples.

General guides on the use of lime for mortars started to appear in the 1970s and 80s. From these works, a number of conclusions about the historic use of mortars were drawn, particularly in relation to their production, suitability and practices associated with their mixing, which are now generally accepted and widely cited, although certainly in Scotland, wide scale assumptions are still to be confirmed.

Historically, lime was produced from a variety of materials including shell, marble and limestone (Ashurst, 1983), the choice constrained by availability of materials locally. Typically, lime was produced close to the building site and, as a result, there would be a degree of regional variation in the materials used across the country (Forsyth, 2008), primarily dictated by the local geology. Roman-era construction mortars were sometimes hydraulic (containing silicate components associated with clay as a raw material), but later lime mortars were typically based on non-hydraulic materials (i.e. from pure sources of CaCO_3). This started to change from the 17th century onwards, when stronger hydraulic lime mortars were more frequently specified. This was particularly true for engineering projects, such as light houses and bridges (Hughes and Válek, 2003; Henry and Stewart, 2011), and it is well known that the hydraulic lime from the Charlestown Limeworks was selected specifically for these purposes (SLCT, 2006).

Insights were gained in relation to the suitability of limes for different purposes and the 'modification' of mortars to provide or enhance specific qualities and characteristics. It is often cited that quicklime was used for external finishes and bedding mortars, whereas lime putty was more suitable for internal work (e.g. Henry and Stewart, 2011; Ashurst, 1983).

There is also much evidence for the use of a variety of historic additives. Pozzolans, such as brick dust and wood ash, as well as hair and straw, were added to enhance strength, and tallow or fat was often used for waterproofing (Artis-Young, 2014; Ashurst, 1983; Henry and Stewart, 2011).

There is often much discussion around historic mortar mix ratios; Vitruvius is cited as being the first source to specify a 1:3 ratio of lime to aggregate for mortar production (e.g. Hughes, 2003). The historic use of quicklime (quicklime approximately doubles in volume upon slaking) means such a mortar would be binder rich – often considered favourable as it produces a more workable material.

It is clear from the literature that practices today are different. Natural hydraulic lime (NHL) in the form of lime hydrate (powdered lime) is often used in modern conservation works. This typically has

a higher hydraulicity than historic counterparts (Brocklebank, 2012), due to the more refined production methods of today. The increasing popularity of hydrated limes in recent decades appears to have led to some confusion around appropriate mortar mixes for repair work, the use of the 1:3 (binder:aggregate) ratio as a modern mix leading to leaner (binder poor) mortars. In cases where an inappropriate mortar is used, issues of incompatibility between mortar and the adjacent stone can arise.

It should be noted that the focus of UK lime production is not on construction. The steel and agriculture industries, which demand pure limes mean that UK limes are lacking the qualities they had historically, i.e. those imparted by so-called ‘impurities’. The majority of limes commercially available to the UK conservation sector are now imported from Central Europe.

2.2 Compatibility of materials

The revelation of the damage caused by the use of inappropriate materials for repair to historic fabric led to an interest in the compatibility of materials.

Developing an understanding of historic mortars with a view to producing suitable, ‘matching’ repair mortars became an important step in making conservation decisions. Indeed, this was acknowledged as sufficiently important to be included in the HES ‘best practice’ guidance (Historic Environment Scotland, 2015 (and earlier iterations)).

In response to this need to better understand historic building fabric, SLCT (in parallel with others on an international level) developed a bespoke method of analysis of lime mortars.

A range of techniques are employed to address specific questions relating to the materials and to establish their physical and chemical properties (Table 1, Figure 1). A full description of the process can be found in Leslie and Gibbons (2000).

This method of standard analysis can be supplemented with other techniques, such as petrographic analysis, which provides another layer

of information of the mortars’ history, including, for example, evidence of moisture penetration and binder leaching, or the presence of cementitious components and associated pore blocking.

Table 1 - Techniques used by SLCT in the standard analysis of mortar samples.

PROCESS		INFORMATION ACQUIRED	INFORMS
1	visual analysis	colour	composition of binder & aggregate
		strength & hydraulicity	
		granular additives	
		carbonate aggregate	mortar production methods
		lime inclusions	
2	reaction with Phenolphthalein	carbonation	carbonation state of mortar
3	binder dissolution	binder reactivity	composition of binder
		solution colour	composition of binder use of additives
		reaction residue	
4	aggregate analysis	aggregate grading	mortar production methods
		mineralogical assessment	provenance of raw materials
5	calculations	binder & aggregate content	mortar mix ratios



Deterioration of stonework adjacent to incompatible cement based mortar.

Despite the apparently simple formulation of lime mortars (binder, aggregate, water), there is an infinite number of variations that can be created by altering raw materials, mix proportions, and water content. This research aims to identify trends in the

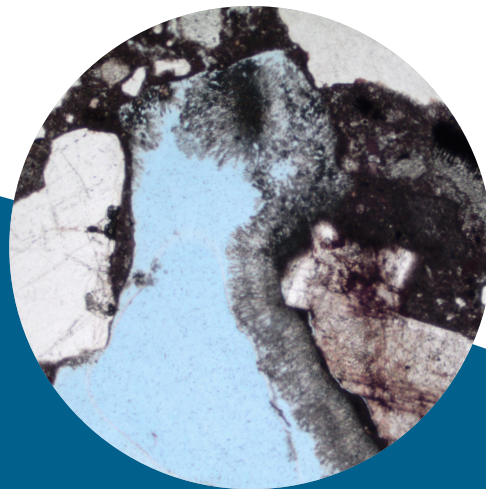
way limes were produced, and used for specific functions in Scotland, to further our understanding of historic building materials, and to aid in the appropriate future repair of historic fabric through raw material choice and mix design.



Figure 1 - Different stages of the standard analysis process. 1. visual analysis, 2. colour analysis, 3. testing with Phenolphthalein indicator, 4. pink staining on uncarbonated lime sample for reaction with Phenolphthalein indicator, 5. reaction with Hydrochloric Acid (binder dissolution), 6. Residual aggregate, ready for grading.



Lime mortar in hand specimen (macro scale).



Lime mortar in thin section showing pore blocking by recrystallisation of binder (microscale).

3. RESEARCH METHODOLOGY

The results detailed in this report are founded on the interrogation of the SLCT Mortars Database. This chapter provides information on the extent of, and context in which data were input and extracted from the database, and subsequently analysed. The limitations of the mortar analysis process, data entry, and final data analysis and interpretation is discussed, so the information presented, and conclusions drawn, can be understood within a fuller context.

This research report is based on data gathered from SLCT mortar analysis between September 1994 and June 2016. Prior to digitisation of the SLCT Mortars Archive, mortar analysis results were held as discrete information within Microsoft Word or PDF reports. Legacy data from over 20 years' worth of mortar analysis reports was manually entered into the database providing a number of benefits:

- ability to quickly and easily access results summaries from historic reports
- ability to interrogate data to identify trends in mortar characteristics
- an understanding of the geographical spread of mortar analysis and the representativeness (and strength) of conclusions drawn from the data.

The SLCT Mortars Database was designed using Microsoft Access. Fields were selected based on the information held in analysis reports, and a bespoke 'front end' was created to provide a quick and easy means of searching of data according to a number of site, sample and analysis-related fields. Database design was continuously reviewed and optimised throughout the projects primarily to enable enhanced search functions, aimed at addressing specific research questions.

Due to the evolution and refining of the SLCT sample documentation and mortar analysis procedure over time, variations in depth of sample information within the reports were evident; not all database entries have information against each field. Gaps identified were typically associated with building types and construction dates, so where possible, additional desk-based research was conducted to retrieve the missing information.

The extent of analysis of samples in the SLCT Mortars Archive was based on the needs and budgets of projects (and clients); no supplementary analysis was carried out for the purposes of this research. The data extracted for interrogation relates to the standard SLCT mortar analysis process as detailed in Table 1, unless otherwise stated.

The SLCT Mortars Database is an add-on to the existing 'SLCT Sands and Aggregates Database', the digitisation of which was funded by Historic Scotland in 2007. The linking of the two datasets allows for automatic matching of aggregate between the analysed samples and known commercially available aggregate products from across the UK using set criteria (grading and colour) and tolerances. This automatic data-based approach to matching gives a greater degree of assurance in identification of suitable aggregates for repair mortars by removing the potential for human error in the comparison process; the availability of the matching aggregate is dependent on the currency of the information in the Sands and Aggregates Database; information on commercially available matching aggregate is not included in the scope of this report.

3.1 Data interrogation

Data were extracted from the system in two ways. For basic information, database queries and searches were run in the database itself. Where more complex analysis of data was required, for example to cross-correlate a number of site or mortar characteristics, raw data were exported to Microsoft Excel, and interrogated therein via the use of Pivot tables. Data were interrogated to identify large-scale trends (e.g. geographically, or historically).

As such, individual building and/or client information is not identified in this report. Database entries were analysed based on a number of factors including building type, building location, mortar date, mortar function and binder type. This approach allowed specific research questions to be considered, these include:

- Was quicklime the most common binder type in historic times?
- Is binder type linked to the time of construction?
- How has popularity of binder types changed over time?
- How does mortar composition vary geographically?

Given the extent of Scotland's historic built environment, an estimated 455,000 pre-1919 dwellings (Historic Scotland, 2011), it is acknowledged that the ~3,000 samples analysed by SLCT represent only a small proportion of the country's historic construction materials. That being said, the SLCT Mortars Database is believed to be the largest historic mortars archive; a unique resource that provides a means of exploring and answering some long-standing questions. This report does not intend to mislead by claiming trends presented here to be absolute, but intends

to provide some insights into traditional Scottish lime mortars by comparing mortars analysed with one another, and giving an overview of the evidence gathered through their analysis.

3.2 Assumptions & limitations

This research makes a number of assumptions around the information held in the SLCT Mortars Database and in the criteria set for data interrogation. Additionally, there are some limitations to the data, as touched upon in previous sections. This section highlights these assumptions and limitations.

This research assumes that:

1. Where samples were provided directly by clients (rather than via trained consultants), information provided on building age, mortar date and mortar function is accurate.
2. Samples are representative: due to the commercial nature of analysis, repeated analysis is typically not viable, it is therefore assumed that accurate results are achieved first time. This relies on the sample provided being representative of its type, and there being no error in the analysis process. Where trends are presented, these are based on averages of multiple samples, but do not include duplicate results for individual samples.
3. Where multiple samples have been taken from the same building, it is assumed that these do not influence overall trends.
4. There has been no human error in the initial mortar analysis process that has provided the information for this study, and that considerations/factors applicable to more subjective areas of analysis (e.g. assessment of hydraulicity) have been applied consistently.

5. There has been no human error in transferring information from the Mortars Archive to the Mortars Database.

6. For the purpose of this report, 'historic' mortars are those dated as pre-1919; mortars dated from after this date are considered to be 'modern'. Mortars dated from 1900-1919 (inclusive) are herein termed 'early 20th century' mortars; 20th century mortars dating from after 1919 are termed 'later 20th century mortars'.

7. When multiple dates were provided by clients (indicating multiple phases of work to a building) the mortar was dated as the latest date; this cautious approach was intended to avoid incorrect allocation of the term 'historic' to mortars that are in fact post-1919.

In relation to point three, there are many cases where there are multiple samples associated with a single project ('project' typically, but not always, referring to a building). This research assumes that the inclusion of multiple samples from the same project does not constitute duplication of data; it is assumed that these were of sufficient difference (e.g. in appearance, or location within the building) to warrant the analysis of multiple samples.

In the case of Scottish historic samples, there are samples from 476 projects, with the average

number of samples per project being two; in the majority of cases, these are of differing functions (e.g. bedding mortar and pointing mortar samples).

For the purposes of this report, it is assumed that the presence of multiple samples from the same building does not skew trends associated with geography as no single project represents more than 2% of all samples in this dataset; there are only 5 projects that contribute more than 1% each.

On a regional level, there are only a few instances where a single project contributes more than 10% of samples in the region. However, there is a clear bias in central region (see explanation of data interrogation on a regional basis in Sections 4.2 and 5.2), where there are a significant number of samples (from 12 different projects) associated with Stirling Castle. Although this provides strong evidence in relation to historic mortars at this site, it weakens conclusions drawn for Central region overall.

Limitations of the data include:

- The number of samples within some of the datasets is small. As such, any results taken from these are not as reliable as for larger datasets. Nevertheless, the SLCT Mortars Database presents the largest of its kind in the United Kingdom, meaning that any results are the most accurate of their kind, and as can be at the time of production of this report.



The SLCT mortars database

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- Due to a small sample set, data relating to mortars from before the 17th century were combined and presented as ‘pre-17th century’ mortars; this small sample set is unlikely to be as reliable as datasets for other centuries.
 - As analysis was conducted by a number of staff from different disciplines, the extent and range of information provided during the analysis process varies (e.g. the level of detail provided in relation to aggregate composition, identification of certain additives etc.) in line with this.
 - The assessment of hydraulicity of historic mortars, although guided by observations, can be considered subjective. In the absence of quantitative chemical analysis, such as X-ray diffraction, there remains a degree of uncertainty around hydraulicity levels recorded during the standard mortar analysis process.
 - In relation to the point, there are some queries around the identification of less common mortar constituents, specifically gypsum. Almost all of the samples containing gypsum are prior to the beginning of 2006. Since this time, no gypsum has been identified. This is likely due to the fact that gypsum is difficult to identify in small quantities, particularly as it looks very similar to common clay, as well as the variation in skill and expertise of the analyst. As a result, reliability of conclusions drawn in relation to the use of gypsum are of reduced confidence.
 - Due to the nature of ashlar mortar samples which are often thin and fragile, samples received by SLCT analysts typically do not meet the requirements for analysis. Furthermore, the presence of linseed oil in many historic ashlar mortar samples, and the resultant reaction with hydrochloric acid used for binder dissolution, renders them unsuitable for standard mortar analysis. As a result, data presented on ashlar mortars may not be a true representation given the low sample numbers.
 - Whilst there is information on the presence of additives and pigments within the database, the primary aim of the SLCT standard mortar analysis procedure is to establish binder types, aggregate types and mix ratios of mortars samples. As a result, additives are likely to be identified only where they are present in sufficient quantity as to appear in hand specimen and/or impact the reactions during, and results of, binder dissolution (e.g. solution colour change in the case of brick dust). As such, values relating to the presence of additives and pigments are likely to be significantly lower than in reality.
 - The recent growing interest in earth and clay building materials has brought an increased level of awareness of their potential presence when analysing mortars*. Only a small proportion of entries in the SLCT Mortars Database relate to earth or clay mortars; it is not clear if this is a true representation of their occurrence, or due to a sampling bias.
*It should be noted that identification of earth and/or clay would be captured at various stages of the SLCT analysis process.
 - Trends associated with ‘historic’ mortars are likely to relate to the ‘best’ mortars of these times. Very old mortars will only remain if they have the sufficient strength and durability; weaker, less durable mortars would have likely been replaced at some point in time already. However, it should be noted that replacement mortars (depending on the time of the work) can still be ‘historic’.
 - Data relating to ‘modern’ mortars is biased towards poor quality or incompatible mortars. Based on samples in the SLCT Mortars Database, mortars less than 70-80 years old are typically only analysed to identify reasons for failure. As such, the late 20th and 21st century datasets are negatively skewed towards failed mortars.



Exposed wall core at Melrose Abbey,
Scotland's first Cistercian monastery, founded
in 1136.

4. EXPLORING THE SLCT DATABASE

This chapter provides an overview of the SLCT Mortars Database. The type and scale of information held in the database is discussed, and figures relating to the database as a whole are presented. This information is aimed at providing a complete picture of the dataset, and an indication of where the strengths and weakness lie with regards to representativeness.

4.1 Data overview

In total, there are 3,407 mortar analysis records held in the SLCT Mortars Database. Samples have been taken (or received) from 23 different countries; 95% of samples were taken from buildings in the British Isles, with 82% (2,781) originating from Scotland. Of the samples from outside the UK and Ireland, the largest sample set is from the USA; at 26 samples, this relates to just 0.76% of the entries in the SLCT Mortars Database. There are very few samples from European countries that have a known history of using lime mortars (e.g. Germany); there are similar mortar analysis services in these countries.

Buildings from which samples have been taken have been categorised according to their function/use; a list of categories (from which a selection can be made) was established based on the most commonly occurring building types within the

mortar analysis reports; buildings which did not fit into any of these categories are classed as 'other'.

Accounting for 32% of all samples 'dwellings' are the most common type (Figure 2); defined as any building that is lived in, regardless of its size. Religious buildings (including churches, cathedrals and synagogues) and civic buildings (including libraries, town halls and schools) are the second and third most common building types respectively, followed by ruins (of any type). Perhaps surprisingly, 'monuments' (scheduled or unscheduled) account for less than 100 entries in the database. Buildings classed as 'composite' are those which fall within two or more categories, for example, a shop with flat above (commercial and dwelling). Approximately 10% of samples provided for analysis were from a building with an unknown or unspecified function.

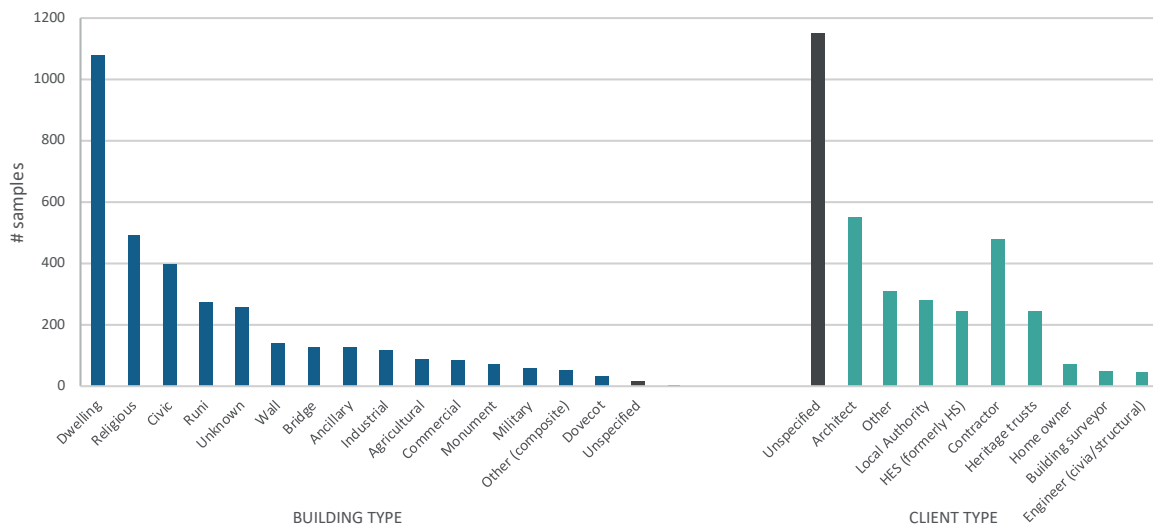


Figure 2 - Mortar samples per building type (left) and client type (right).

As part of the commercial analysis service, SLCT hold client details against all records. Although these details were not used in this research, access was granted to the client type. This provides interesting information on the types of profession taking informed conservation decisions in relation to mortar repair. In terms of large-scale Estate management, both HES and the Scottish local authorities have taken advantage of the information provided by mortar analysis. Architects are the largest group of professionals to use this service; given their frequent leading role in conservation projects, and involvement in design and specification of materials, this is as expected.

The binder type of mortars was assessed as part of the analysis process. Table 2 shows the simplified binder types identified, and the proportion of database entries in each. Mortars stated as 'quicklime', 'lime hydrate' or 'lime putty' consist predominantly of the stated binder type; it should be noted that the term 'hydrate' here refers to the physical form of the binder (i.e. powdered lime formed by slaking quicklime) and is not indicative of the hydraulicity. 'Cementitious' identifies all

samples in which the binder is exclusively cement (of any type). The term 'hybrid' refers to any mortar that had a combination of main binder types; this includes a number of combinations as shown in Table 2. Samples in which the binder type was not clearly identified in analysis reports have been categorised as 'unspecified'.

The most common binder type is quicklime, accounting for over half of all samples in the database. Lime hydrate and lime putty follow in similar proportions, with cement and composite mortars accounting for a relatively low proportion of the dataset. These trends across the complete dataset are mirrored in the isolated figures for Scottish samples.

Information on mortar function is provided by clients on submission of samples for analysis, or established by SLCT consultants when samples were obtained from site. Samples can be assigned more than one function to cover scenarios where the same material fulfils more than one function (e.g. where the 'bedding' and 'pointing' mortar are clearly the same material), or where a sample provided has multiple components (harling with limewash coating).

Table 2 - Proportion of samples by binder type; figures are presented for the entire dataset, and separately for Scottish samples.

	ALL SAMPLES		SCOTTISH SAMPLES	
	Count	Percentage	Count	Percentage
Quicklime	1773	52%	1519	55%
Lime putty	421	12%	331	12%
Lime hydrate	403	12%	308	11%
Lime (not specified)	265	8%	192	7%
Hybrid mix	291	9%	225	8%
Cement lime hybrid	214	6%	173	6%
Clay-lime hybrid	18	1%	16	1%
Earth lime hybrid	2	0%	2	0%
Lime gypsum hybrid	56	2%	34	1%
Lime organic hybrid	1	0%	-	-
Cementitious	153	4%	128	5%
Other	24	1%	14	1%
Not specified	77	2%	64	2%
TOTAL	3,407	-	2,781	-

Information presented in this report relates to the primary mortar function only to avoid duplication when presenting data (Table 3). The 'other' category includes, but is not limited to, samples of wall core mortar, mortar for 'bedding' floor slabs, floor coverings/screeds, roofing mortars; these mortar functions were not common enough to justify having separate categories for data interrogation.

The majority of samples analysed by SLCT are bedding and pointing mortars; together, mortars of these types constitute over half of all database entries. There is also a significant proportion of harling, plaster and render samples. There are very few limewash samples; this is to be expected given the nature of this material, i.e. the thinnest, outermost (and sacrificial) skin of a building.

Table 3 - Breakdown of database entries by mortar function.

MORTAR FUNCTION	ALL SAMPLES		SCOTTISH SAMPLES	
	#	%	#	%
Bedding	1181	35%	982	35%
Pointing	805	24%	700	25%
Harling	305	9%	284	10%
Plaster	267	8%	185	7%
Render	228	7%	127	5%
Ashlar Pointing	90	3%	84	3%
Limewash	9	0%	7	0%
Roughcast	9	0%	4	0%
Other	107	3%	76	3%
Unknown	406	12%	332	12%

Table 4 - Sample number per date category.

CENTURY	ALL SAMPLES		SCOTTISH SAMPLES	
	#	%	#	%
Pre 17th century	141	4%	126	5%
17th century	89	3%	69	2%
18th century	211	6%	175	6%
19th century	441	13%	352	13%
20th century	243	7%	199	7%
21st century	158	5%	107	4%
Unknown date	2,124	62%	1753	63%

Dates assigned to mortar samples in the database vary in precision, from exact dates, where details of construction phases is known, to approximate figures where there is a degree of uncertainty. For the purposes of this research, dates were grouped into centuries. Mortar samples in the database range from the 5th-7th century to the 21st century. 1,283 mortar samples in the database are of known date.

Greatest confidence can be gleaned from analysis of largest datasets. There are significant sample numbers for the 18th to 21st centuries. The small pre-17th century sample set is unlikely to be as reliable as the larger datasets for other centuries. Table 4 shows the proportion of database entries associated with each century; a total of 763 samples are known to be historic Scottish mortars (i.e. have sufficient date information); this includes early 20th century samples.

4.2 Geographic distribution of samples

This research aims to address a number of factors relating to the geography of Scottish mortars; how mortars vary compositionally across Scotland, and what impact local climates might have had on chosen materials and methods. The influence of geology (and therefore geography) on the composition of mortars is widely understood, but evidence-based verification, and indeed quantification, of these regional distinctions is lacking. Understanding the spread of database

entries across the different regions of Scotland gives an indication of the confidence with which statements on regional variations in mortar properties can be made.

The SLCT Mortars Database holds sample location information in the form of addresses. As the system is not currently held within a GIS-enabled platform, the most obvious way of geographical analysis is using the local authority area (LAA) search function. Assessing mortars for regional trends via geo-political boundaries comes with significant limitations on the conclusions that can be drawn, as it is insufficiently complex to allow for the distinction between different geological, topographical and climatic regions, which undoubtedly have influence over what is required and what is achievable in terms of mortar requirements and design. In an attempt to work around this limitation, LAAs have been grouped into 7 distinct regions that are considered to be more reflective of the geological and climatic divisions seen across Scotland; this is discussed in Section 5.2.

Figure 3 shows the distribution of database entries across LAAs. Most of these areas are represented in the database, but there are significant variations in dataset size. City of Edinburgh, Highland, East Lothian, Fife, Perth and Kinross, and Stirling are the most well represented areas in relation to numbers of historic mortar samples.

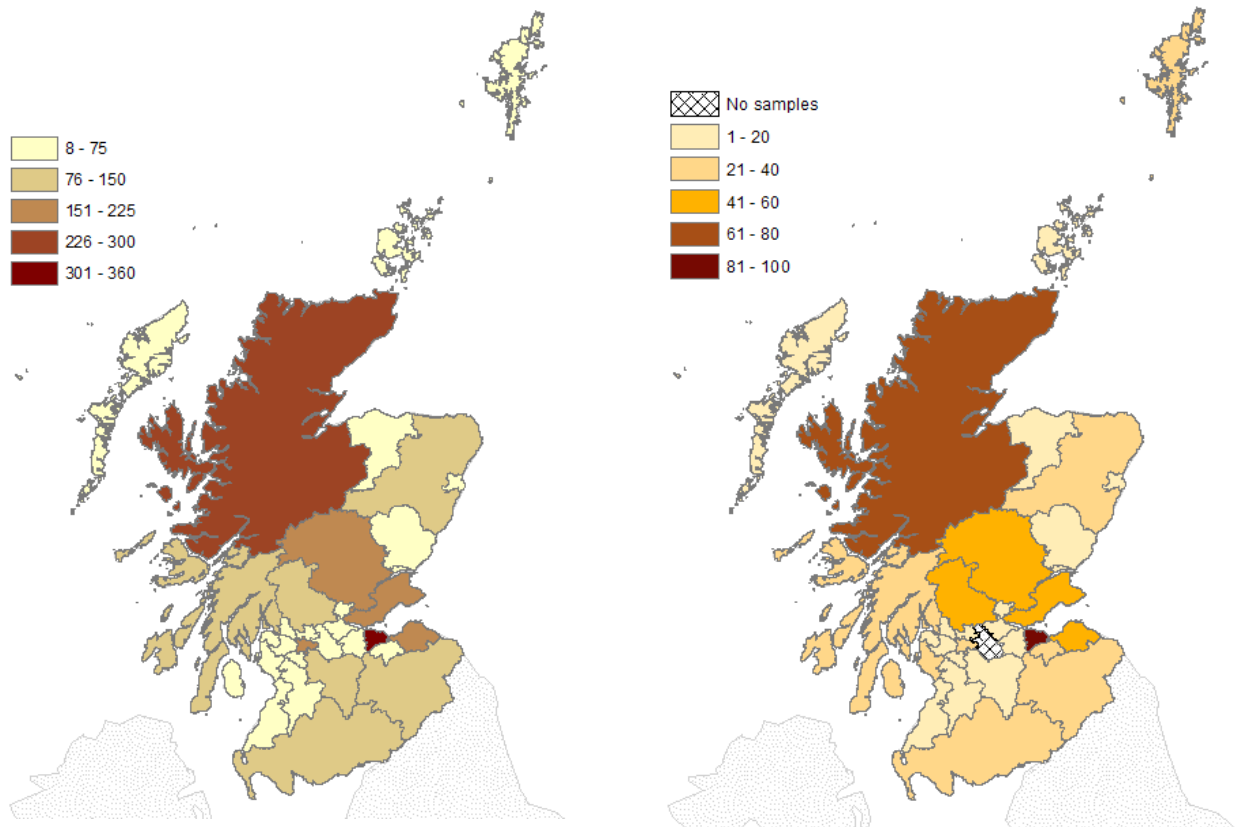


Figure 3 - Geographical distribution of database samples; map on left relates to all samples, map to right relates to historic mortar samples only.

5. UNDERSTANDING HISTORIC MORTARS

This chapter provides a high-level overview of the characteristics of Scottish historic mortars. In many cases, the interrogation of data provides the evidence to support statements that have been made for some time based on anecdotal evidence. It also allows for quantification of these statements, providing a better understanding of the strength and extent of long-served assumptions and anecdotal evidence. This data analysis was not restricted to samples of a specific mortar function unless indicated in the text.

5.1 National overview of Scottish historic mortars

5.1.1 National overview: binders

Analysis of information gathered from historic mortar samples from Scotland (for which a binder type was established; n=752) verifies commonly stated assumptions about the use of particular binders; quicklime was by far the most commonly used binder with 64% of mortars found to comprise of this binder type, this is followed by lime putty at 12% (Figure 4). A range of other binders were also used including lime hydrate, hybrid binder mixes and predominantly cementitious binders. Variations in use of these materials, geographically and over time, is discussed in later sections.

As expected, the binder type varies with mortar function (Table 5); whilst quicklime is dominant in bedding, pointing and harling mortars, lime putty is more prevalent in ashlar pointing. There is a relatively even balance between these two binder types in the case of historic plasters.

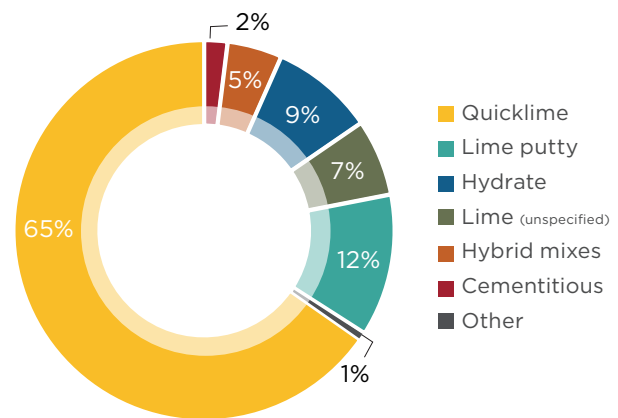


Figure 4 - Traditionally used binder types in Scottish pre-1919 mortar samples.

Approximately 12% of historic Scottish samples did not have hydraulicity identified during the analysis process, either because this was not possible (i.e. in non-lime samples) or was not applicable (where there was insufficient binder remaining to make an assessment); a probable hydraulicity was established for 648 historic Scottish samples.

Table 5 - Frequency of use of particular binders in relation to specific mortar functions (historic mortars only).

	MORTAR FUNCTION				
	Pointing	Bedding	Harling & Render	Plaster	Ashlar pointing
# Samples	126	352	108	70	29
Quicklime	69%	76%	70%	38%	18%
Lime putty	6%	9%	5%	32%	54%
Hydrate	12%	8%	10%	1%	7%
Lime (unspecified)	5%	5%	9%	6%	11%
Hybrid mix	6%	2%	4%	15%	7%
Cementitious	2%	1%	3%	0%	4%
Other	0%	0%	0%	7%	0%

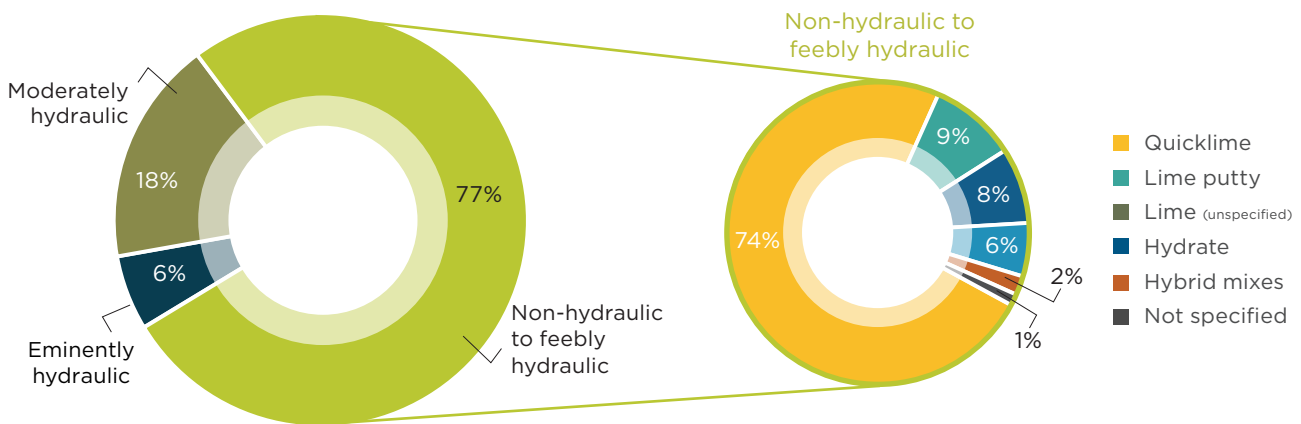


Figure 5 - Binder types and hydraulicity of Scottish historic mortars (n=648).

It is evident that non-hydraulic to feebly-hydraulic quicklime was the most commonly used binder (56%), followed by moderately hydraulic quicklime (14%). Following this are other non-hydraulic to feeble-hydraulic binders (hydrates, putty, hybrid mixes) (Figure 5).

These general trends are as expected, given the raw materials available for the production of mortars historically. The production of moderately and eminently hydraulic limes requires the availability of chemically 'impure' limestone, i.e. those with a proportion of silicate minerals. The chemistry of Scottish limestones varies, and whilst there are areas where the limestone is sufficiently 'impure' as to produce hydraulic limes, this is not the majority. The relatively small proportion of cementitious and hybrid mixes perhaps indicates an aversion to experimentation, or perhaps simply that the materials produced from traditional methods met the needs of the buildings at that time. A greater understanding of variations in practice can be gained through the identification of geographic trends in binders, aggregates and additives as detailed in later sections.

5.1.2 National overview: aggregates

For analysis of data relating to aggregate type, the presence of particular aggregate types within samples has been assessed as either:

- 'major' - where there are large grains that have been identified through visual and microscopic

examination of hand specimens, and/or significant quantities of a particular aggregate types amongst the aggregate retained after acid dissolution of the mortar binder

- 'minor' - where there are lower quantities of a particular aggregate type, that have only been identifiable through the microscope examination of aggregate retained after acid dissolution of the mortar binder.

Assuming aggregates are sourced locally, a rock type can be expected to form a major component of the aggregate from locations close to its source, but it can also be present as minor components of aggregate used farther afield; as rock weathers and is transported (e.g. by rivers), grains are said to increase in 'maturity', becoming smaller and more rounded as a result of the continuous abrasion as they travel. The ratios of coarse to fine grains of aggregate is referred to as its 'grading'. A mixture of grain sizes such as that shown in Figure 6a is preferable in the production of a mortar, particularly for bedding and pointing; this is referred to as 'well graded'.

There is no specific relationship between primary aggregate composition and mortar function, indicating that, historically, there was no specific 'selection' of aggregate; certainly prior to developed trades route, this would not have been expected.

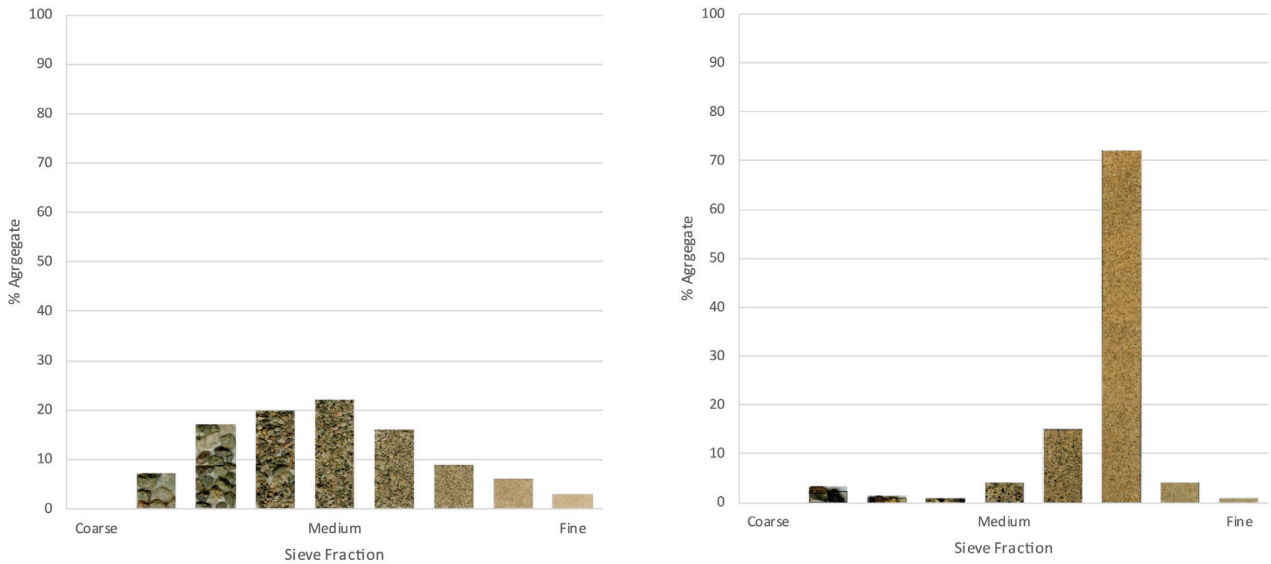


Figure 6 - Sandgraphs showing aggregate that is well graded (left) and poorly graded (right).

Table 6 shows the percentage of samples of each function that contain the indicated rock type as a primary component of the aggregate. Whilst the proportions vary slightly, the order of frequency of occurrence of different aggregate types in mortars for different function is fairly consistent. Sandstone, granite, basalt (or similar igneous rocks) and schist (or other similar metamorphic rocks) remain the most commonly identified rock types regardless of function.

The importance of grading aggregate is now well established (e.g. Gibbons and Leslie, 1999). Appropriate grading is vital to the success of a mortar; it promotes timely curing of mortars, ensures sufficient strength development, prevents shrinkage, and therefore moderates water absorption. Prior to this understanding, aggregate was used 'as dug' and grading was, at times, relatively poor.

Table 7 shows the proportion of historic Scottish mortar samples of each aggregate grading classification for a number of mortar functions.

As expected, ashlar mortars were typically very poorly graded. This is a desirable property which promotes a degree of workability in ashlar mortars beyond what is required for other pointing mortars. Modern counterparts typically use very fine, poorly graded quartz sand, or in some cases chalk dust to achieved the desired levels of workability. There is a similar tendency towards poor grading for plaster mortars, but to a lesser extent.

Pointing mortars were predominantly moderately to well graded, as were harling mortars. Overall, bedding mortars show a greater level of variability ranging from well graded to poorly graded. However, in a small number of cases, where bedding and pointing mortars from the same building/structure were analysed, a difference in the grading of the two was identified in less than 30% of cases.

This lack of correlation in either composition or grading with mortar function indicates that there was little more (if anything) to the selection of aggregate, other than what was locally available.

Table 6 - Aggregate composition and mortar function.

	MORTAR FUNCTION			
	Pointing	Bedding	Harling & Render	Plaster
# Samples	77	258	77	56
Sandstone	47%	16%	47%	39%
Limestone	-	1%	1%	-
Granite	12%	4%	34%	29%
Basic igneous*	34%	13%	42%	32%
Argillaceous sedimentary**	8%	3%	5%	4%
Schist	17%	8%	23%	20%
Slate	-	1%	-	4%
Gneiss	-	-	1%	-

*'Basic' refers to basalt and similar igneous rocks. **'Argillaceous' refers to fine-grained clay-rich sedimentary rocks such as shales, siltstones and mudstones.

Table 7 - Proportion of pre-1919 Scottish samples of each aggregate grading classification for a number of mortar functions.

	MORTAR FUNCTION				
	Pointing	Bedding	Harling & Render	Plaster	Ashlar pointing
# Samples	52	157	50	32	3
Very well graded	-	3%	8%	-	-
Well graded	37%	32%	44%	16%	-
Moderately graded	31%	27%	30%	22%	-
Poorly graded	13%	31%	14%	34%	33%
Very poorly graded	19%	8%	4%	28%	67%

NOTE: grading requirements of plaster and ashlar mortars is different to that of their mortar types. The use of poorly graded aggregate in these mortars is not a negative attribute.

5.1.3 National overview: practice

This section focuses on three main areas with the aim of analysing the practice(s) of historic mortar production in Scotland:

- 1) Burning methods: inferred from the presence of contaminants from the burning process.
- 2) Additives: the inclusion of additives to give desirable properties to mortars.
- 3) Mix ratios: to assess the understanding of materials.

Burning methods: both coal and wood have been identified in historic mortar samples from Scotland. It is assumed that both these materials were used as fuel in the burning process, although it is also recognised that coal dust and wood ash have a pozzolanic effect (Ashurst, 1983; Fusade et al., 2019) (therefore aiding the setting of the mortar) and therefore might have been an intentional 'contaminant'. Seventy per cent of samples have identifiable fragments of coal; such common contamination is likely due to the layering of coal within the kiln, which is believed to have been common practice; only 12% of samples have traces of wood. Fuel type was identified for a total of 549 Scottish historic mortar samples. Although there are cases where both fuel types have been identified together, with 86% of samples having just one, this is not commonplace.

Additives: despite the emphasis that is often placed on the use of additives, there is little evidence within the database to suggest that this was common practice. However, it must be considered that identification of additives is not the primary aim of SLCT standard mortar analysis. Hair and gypsum are the most commonly identified additives, and as expected are prevalent in plasters. Hair and gypsum were identified in 44% and 14% of plasters; these same additives were evident in only 1-4% of bedding, pointing and harling mortars.

The most prevalent of additives is brick dust; presumed to be used for its widely recognised pozzolanic properties. Overall, 14% of mortars were found to contain brick dust. With the exceptions of limewash and ashlar mortar in which the use of brick dust was rare, use was fairly consistent across all mortar types.

Mix ratios: the binder:aggregate ratios established via standard lime mortar analysis are calculated based on the weight of samples before and after acid digestion, but considering that quicklime expands (in volume) by approximately 60-100% upon slaking (conversion of CaO to CaCO_3), quicklime mortars would have been considerably more binder rich than hydrates and putty that have been found to have the same ratio by weight.



One of many draw holes of the historic Charlestown limekilns.

As part of the SLCT mortar analysis, approximate volume weights, based on the relative bulk density of the raw materials, are calculated to give a better, and more easily understood, representation of the mortar mix.

A binder:aggregate ratio of 1:3 is typically cited as being an appropriate specification for modern mortars; this is based on the void ratio of the ‘average’ well graded sand (typically around 33%) and assumes that filling all voids provides a suitable, cohesive mortar (Leslie and Gibbons, 1999).

There is often discussion around the lack of consistency of this with historic mortars (Lynch, 2007) and the misinterpretation of 1:3 historic specifications, due to the lack of consideration of raw binder type. A quicklime mix specified at a 1:3 binder:aggregate ratio would typically produce a mortar with a ratio of between 1:1½ and 1:2 (Lynch, 2007); indeed a more binder-rich mix such as this would be required for poorly graded aggregates,

as are found in some historic samples (Table 7), which can have a void ratio of up to 60% (Snow and Torney, 2013), therefore demanding a greater quantity of binder to produce a workable mix.

Interrogation of the database shows that this assumed ‘typical’ mix ratio was a rarely used mix ratio in historic mortars, with ‘fatter’, more binder rich mixes being the majority. Seventy-five per cent of quicklime mortars were found to have a binder:aggregate ratio of 1:1 or less (i.e. binder rich), with the majority of hydrates falling into this category too (Figure 7).

It should be noted that, in the absence of petrographic analysis, it is not possible to establish what impact binder dissolution and reprecipitation has had on mortar samples in this dataset. This research assumes that mix ratios calculated during analysis are reflective of those originally produced, however in reality, there is likely to be a degree of error, particularly in relation to very binder-poor (due to binder dissolution) or very-rich (due to binder reprecipitation) mortars.

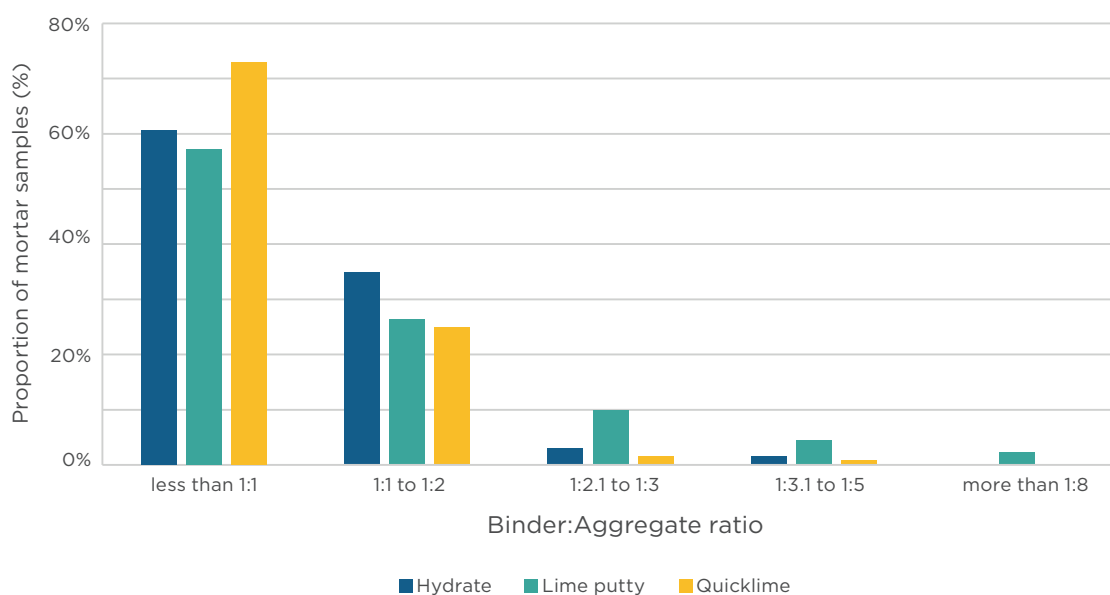


Figure 7 - Typical mix ratios (by volume) of Scottish historic lime mortars (n=648).

5.2 Regional trends in Scottish historic mortars

The following sections detail variations in mortar constituents and perceived practices across 7 different regions within Scotland. Figure 8 indicates the extent of these regions, which have been identified based on climatic information from the MET office. Regional borders typically coincide with LAA boundaries, with a few exceptions to enable more appropriate grouping in relation to climate data.

A total of 2,774 Scottish samples, 763 of which are historic mortars, had sufficient location information to assign them to a 'region'. Table 8 shows the distribution of the samples within these regions.



Figure 8 - Map showing the extent and location of different 'regions' used in data interrogation and identification of trends.

Table 8 - Strength of regional datasets.

REGION	# DATABASE ENTRIES	
	ALL SAMPLES	HISTORIC SAMPLES
Centre	376	112
East Coast	466	125
Highlands	411	108
Islands	101	50
Lothians & Borders	719	206
South West	253	53
Strathclyde	448	109
Grand Total	2,774	763

5.2.1 Regional trends: binders

The use of quicklime for the production of historic mortars was widespread. Quicklime was the binder of choice for upwards of 75% of bedding and pointing mortars across most parts of the country (bedding n=334, pointing n=118). The use of other (non-quicklime) binders/mix types varies considerable between regions (Figure 9).

Amongst the non-quicklime binders, there is notable variation in the use of different materials, or mix types in bedding and pointing mortars. The use of putty is relatively consistent across the country, with the exception of the Highlands and Islands.

The use of lime hydrate is consistent across most of the regions, with the exception of the Islands (which have no instances of hydrate bedding or pointing mortars) and the Lothians & Borders, (where levels are higher than other areas). The timing of adoption of this material in place of the more traditional quicklime and putty binders may have varied from region to region, in line with the accessibility of materials and the exchange of knowledge, which could both be related to trade routes.

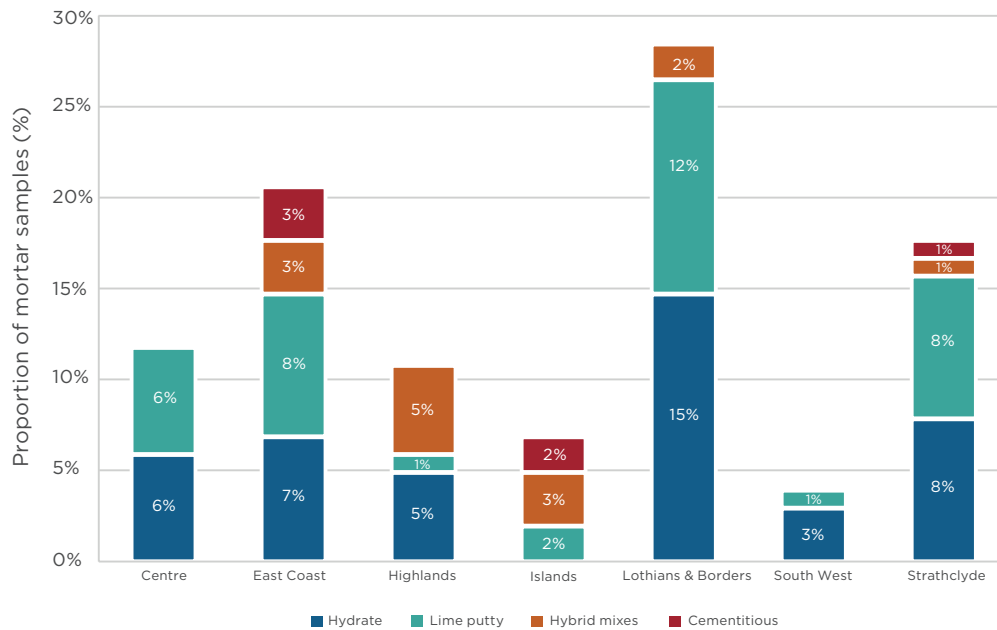


Figure 9 - Regional variations in proportion of bedding and pointing mortar samples with non-quicklime binders.

Whilst the data shows an apparent increase in instances of hydrate mortars from the 18th century (see Section 6.1), these samples account for a small proportion of this dataset. As a result, a confident analysis of geographic trends associated with the uptake of hydrates in specific regions cannot be made. Additionally, sample numbers for early 20th century (pre-1919) mortars are too low to comment on whether or not this rise continued beyond the 19th century, although anecdotal evidence on the specifications of modern lime mortars for conservation work would tend to indicate that this increase was exponential beyond the 20th century.

A number of regions have evidence of the availability of a variety of materials for binder use, but the Highlands and Islands show higher proportions of hybrid and cementitious mixes than other regions. This might mark a heightened degree of experimentation in these regions, perhaps due to the additional demands associated with the more extreme climate and the resultant stresses (e.g. increased moisture exposure, more problematic curing conditions) imposed on the buildings and structures, combined with the limited availability of lime sources in an igneous and metamorphic geological complex.

Figure 10 shows the proportions of lime mortars

of each hydraulicity classification across different areas of the country. The variations in hydraulicity between regions highlights the diversity in the raw materials used in different areas; a direct reflection of the geology.

Non-hydraulic to feebly hydraulic limes form the majority in all regions, with the more hydraulic mortars rarely exceeding 30% of a region total.

Eminently hydraulic limes are seen across the country, with the exception of the Islands, but despite this apparent wide geographical spread (Figure 11), the instances of its use are very low; at most, 8% of samples within a region are eminently hydraulic, but on a national scale this averages at 6%. Within this there are a number of more local 'hot-spots' where the proportion exceeds 10%. This includes Aberdeen City, where there are many deposits of 'low grade' metamorphic limestone from the Dalradian Series in which there is a notable proportion of silica, and Fife, which is world renowned for its Charlestown Main limestone of Carboniferous age, which has a clayey matrix and argillaceous transitional beds (Robertson *et al.*, 1947), the chemistry of which lends itself to the production of a more hydraulic lime.

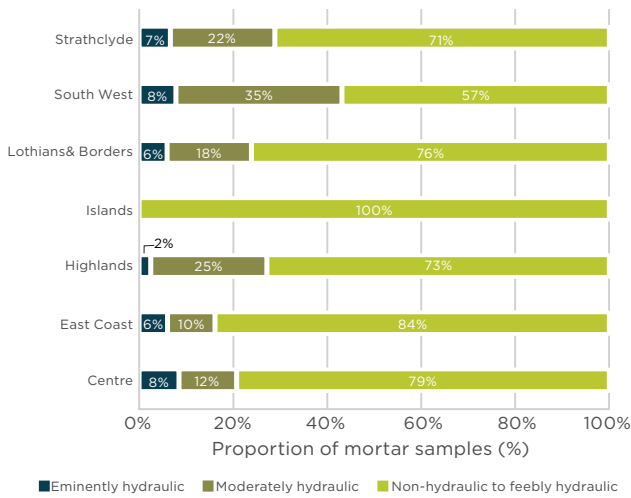


Figure 10 -Proportion of lime mortars (all functions) of differing hydraulicity across the regions (n=648).

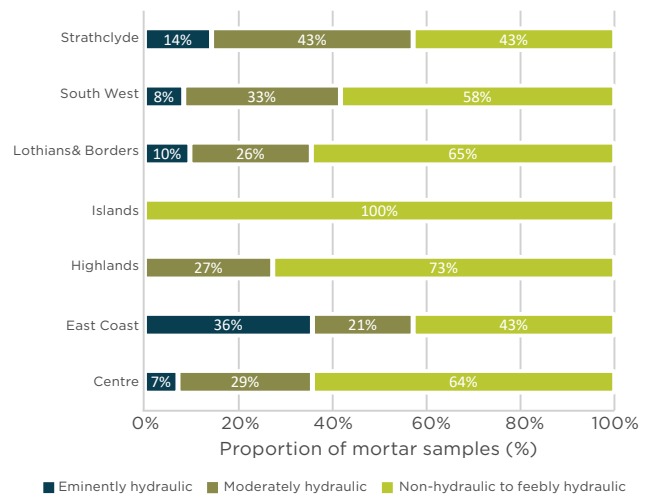


Figure 12 -Proportion of pointing mortars of differing hydraulicity across the regions (n=107).

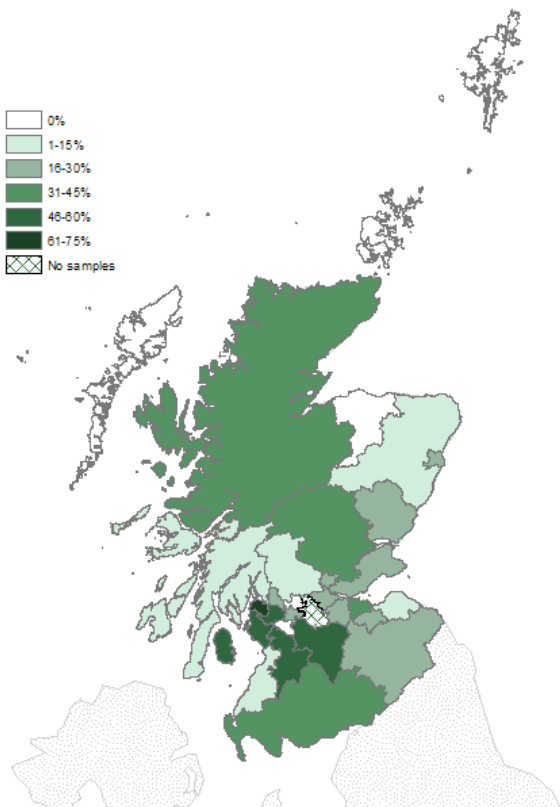


Figure 11 -Occurrence of moderately and eminently hydraulic historic limes across Scotland by Local Authority Area. Dark green indicates highest proportion of samples showing this level of hydraulicity. Note the absence of hydraulic limes in the Islands. Hatching within North Lanarkshire areas indicates an absence of any samples rather than a lack of hydraulic mortars.

Interestingly, lime mortar samples from the Islands are exclusively non-hydraulic to feebly hydraulic. This fits with the common conception that island (and coastal) sites often used shells in the production of lime; marine brachiopods and bivalves typically have calcite (calcium carbonate) shells and as such would burn to produce non-hydraulic lime. Such improvisation was essential in areas dominated by igneous and metamorphic geology; this could be the driver for the aforementioned experimentation and move away from single-binder mortars.

The identification of shelly material within binder material is sometimes possible through petrographic analysis of mortars. However, this costly analysis does not form part of the standard SLCT mortar analysis procedure and, as such, this hypothesis cannot be verified or quantified using the data available at this time.

The trends in hydraulicity vary somewhat depending on the mortar function (Table 9). Bedding mortars are very reflective of this overall distribution, which is, in part, due to the fact that this category of mortar makes up half of this dataset, but it is also likely to be because these mortars, which by their nature, are protected from the elements, are perhaps more likely to be ‘unmodified’ by experimental practice.

Table 9 - National averages in relation to hydraulicity of mortars of differing function.

		BINDER HYDRAULICITY			
		Non hydraulic to feebly hydraulic	Moderately hydraulic	Eminently hydraulic	# samples
MORTAR FUNCTION	Bedding	77%	18%	4%	325
	Pointing	63%	26%	11%	107
	Ashlar Pointing	80%	13%	7%	15
	Harling	89%	7%	4%	83
	Plaster	88%	12%	-	43

Conversely, pointing mortars display a greater tendency (albeit still a minority) towards stronger hydraulicities (Figure 12), which could be linked to a greater variation in practice to achieve specific desirable performance criteria, although in the limited cases where bedding and pointing mortars were sampled from the same building, this is only evident in 10%.

In relation to pointing mortars, the prominence in use of stronger hydraulicity binders is seen only in some areas, with the East Coast and Strathclyde regions showing a majority of samples to have moderate to high (eminent) hydraulicity (Figure 12). Given the high exposure of pointing mortars relative to bedding mortars, this difference could be a reflection of the needs imposed by climatic conditions, with hydraulic components assisting with the setting in colder (East) and wetter (South West and Strathclyde) climates; considerations that commonly inform specifications of today.

The vast majority of mortars of other functions (harling, plaster and ashlar pointing) are composed of low hydraulicity lime, but sample set numbers for these types are much lower, creating a lower level of confidence in any conclusions drawn.

5.2.2 Regional trends: aggregates

The grading of aggregates used in the production of mortars today will vary depending the function of the mortar and the colour, texture and finish required. However, historically, it is likely that the composition of mortars would have remained relatively consistent within an area; in the absence of good transportation links and trade routes, local beaches, rivers and quarries provided the only readily available source of raw materials.

As expected, the prominence of specific aggregate types is well aligned with the regional geology (Table 10).

Sandstone and basalt (or similar igneous rock) aggregates are geographically widespread; in almost all regions, these aggregate types are found either as major or minor constituents in the majority of samples. Given the prominence of these rock types in Scottish geology, this is not surprising.

Granite aggregate is most prevalent in the Highlands, Islands and East Coast regions, and metamorphic rocks are common in central areas, the Islands, the Highlands and the East Coast; these are rocks typical of the Moine and Dalradian series formed during the Caeldonian Orogeny.

Gneiss is evident as a minor aggregate constituent in the Islands and Strathclyde. This rock type only forms a major component of aggregate in the Highlands. It is perhaps surprising that such a geologically prominent stone (Lewisian Gneiss) was not used more widely as aggregate in the Western Isles and Highlands.

Sandstone, basalt and schist appear more frequently in mortar samples from the Highlands and Islands region; probably because the more easily weathered rock types are likely to form a higher proportion of river and beach sands in this area.

There is only a small proportion of historic Scottish mortar samples in the database for which aggregate provenance was stated at the time of analysis (77 in total). Due to the small sample size, the confidence in conclusions drawn from this dataset is questionable, however, there are a few interesting results worth noting:

1. Mortar from the Islands exclusively used beach sand.

Despite the availability of other aggregate sources (e.g. river beds, dunes), the ease of access to,

and extraction of beach sand from Island sites made this the most viable source of aggregate for mortars. Overall, 33% of Islands samples were found to contain shell.

2. High proportions of samples from the East Coast region consisted of beach sand.

Eighty-five per cent of East Coast samples in this dataset consisted of sand from a beach environment, with the remaining being aggregate from a fluvial source (i.e. river). Overall, 16% of East Coast samples were found to contain shell.

3. Crushed rock (as opposed to sand) was only found in the Highland and Lothians & Borders region.

The historic samples found to contain crushed rock aggregate relate to just three different buildings/ structures. The production of crushed rock would require a considerable amount of effort (relative to the use of sand), and it might have been assumed that such methods would only have been employed where there were no alternative sources of aggregate.

Table 10 - Occurrence of different aggregate types in mortars across the regions (n=501).

		REGION						
		Central	S'clyde	East Coast	Highland	Lothian & Borders	Islands	South West
AGGREGATE TYPE	Sandstone	63%	64%	36%	45%	61%	63%	66%
	Limestone	2%	-	3%	1%	4%	-	5%
	Granite	27%	16%	42%	55%	6%	44%	11%
	Basic igneous	58%	71%	62%	41%	63%	53%	63%
	Argillaceous sedimentary	15%	20%	15%	3%	42%	6%	45%
	Schist	65%	22%	48%	59%	8%	64%	21%
	Slate	7%	7%	1%	7%	3%	-	3%
	Gneiss	-	4%	-	12%	-	18%	-

However, all three of these locations are at, or relatively close to, the coast. This suggests that there was a specific reason for the use of crushed rock. It might be assumed that this would be for aesthetic reasons, but given that the samples in question are bedding mortars, as well as pointing, this is unlikely to be the case. It is not possible to ascertain anything further from the data held in the database.

5.2.3 Regional trends: practice

Burning methods: the use of wood and coal together appears to be more prominent in some regions than others.

The South West, Lothians & Borders and the Highlands have higher instances of combined fuel use. Whilst the use of wood in the Highlands might be expected (due to a lack of sedimentary geology), the presence of coal in the Carboniferous Limestone Series in the Lothians & Borders, and the abundance of the Carboniferous Coal Measures towards the South West of the country suggest that this is not a likely explanation.

The exclusive use of wood is consistently low across all regions, with no examples at all of this practice in the Islands or Strathclyde regions. The proportion of samples using both fuel sources is higher than expected (14%) in Strathclyde, a region that has no shortage of coal, again suggesting that there may be other explanations.

It is possible that the source of this 'contamination' was from kiln construction, or from the use of tools and/or equipment, or that there was a specific reason for the inclusion of wood. A more likely explanation is that this was used because the incorporation of wood offers a 'cleaner' burn, or lowers the temperature and reduced the proportion of clinker (over burnt limestone) in the resultant lime.

Additives: the use of brick dust varies somewhat across the regions. Its use is relatively consistent across most of the mainland, and as such there is no strong indication that climatic conditions played a role in its consideration.



Oyster shell pinnings in mortar joints - Elcho Castle, Perthshire.



Tightly pinned mortar joints in whinstone masonry - Collinsburgh, Fife.

Use of brick dust is lower in the Highlands and Islands regions as well as the East Coast, which (particularly in relation to Highlands and Islands) is perhaps where climate conditions would be more likely to demand the use of pozzolans to enable setting of mortars in harsher conditions.

It may be the case that the natural hydraulic components of limes in these (possibly clays from the low grade pelitic and semi-pelitic material of the Moine Supergroup) was sufficient to achieve the required durability.

It is possible that certain practices were employed (e.g. the use of hot mortars) to provide added durability in areas where the only limestone sources produced limes of low hydraulicity.

Mix Ratios: to identify any genuine variations in mix ratios used across the regions, any variability associated with mortar function or binder type must be eliminated, as such, the dataset used to establish the following is restricted to historic Scottish quicklime bedding mortars (n=265); due to low sample numbers, conclusions cannot be drawn in relation to the Islands region.

There is little evidence to indicate that there was any notable variation in mix ratios used for bedding mortars across the country. Lothian & Borders region appears to have a slightly stronger tendency towards binder rich mixes, and Strathclyde region appears to go the other way, but with relatively low samples numbers, it is difficult to assess whether such variations are significant and genuine on a bigger scale or simply down to the range of samples in the database.

Lime mortar joints in red sandstone masonry at Fort George
© Historic Environment Scotland



6. EVOLUTION OF SCOTTISH MORTARS

This chapter looks in more detail at mortars from specific time periods. Using data captured on mortar dating, it is possible to chart changes in the properties of mortars over time and develop a greater understanding of the changing use of raw materials and practice. Once again, this analysis provides quantified evidence for some long-served assumptions around evolving building attitudes and practices.

The following section relates to Scottish mortar samples for which mortar date was specified at the time of analysis; conclusions are drawn based on a maximum of 1,011 samples (i.e. those with specified mortar dates). This data analysis was not restricted to samples of a specific mortar function, unless indicated in the text.

6.1 Binder evolution

Interrogation of data associated with Scottish historic mortars, for which binder type was specified (n=746), supports long-standing anecdotal evidence on the use of raw materials for binders.

Quicklime was predominant up to the 20th century, the chosen binder for 60% or more of mortars (Figure 13). Despite this long-served dominance, there was a notable decline in use of quicklime from as early as the 17th century. Parallel to this was the increased use of lime hydrate and lime putty from the 18th century. Accounting for only

5% of 18th century mortars, there was more than a two-fold increase in the use of lime hydrates in the 19th century, which levelled off and remained static in the early 20th century.

The introduction and rapid adoption of cementitious mortars is also evidenced in this dataset; at first a low level appearance in the 19th century (accounting for 3% of mortars), rapidly rising to 12% in the early 20th century. It is interesting to note that instances of hybrid mixes are highest in the 18th century. The ratio of hybrid mixes to cementitious mixes declines from the 18th century onwards (Figure 14). It is possible that this marks an initial period of experimentation (the addition of cement to lime mortars) with what was a new and relatively little understood material, which phased out as confidence in this material grew, and practice moved away from using it in combination with lime.

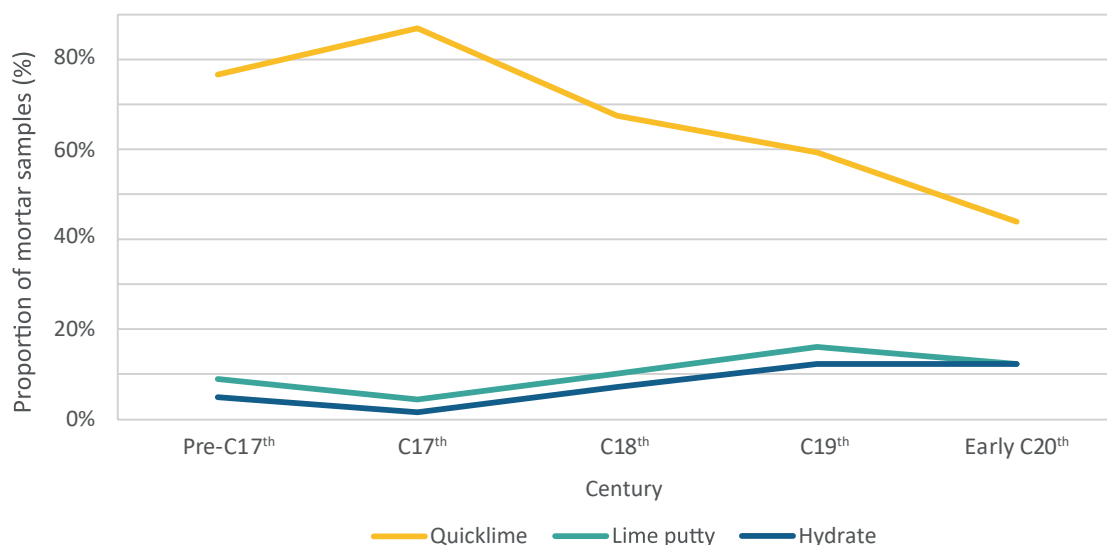


Figure 13 - Changes in the use of lime binders as (raw materials in Scottish lime mortars) over time.

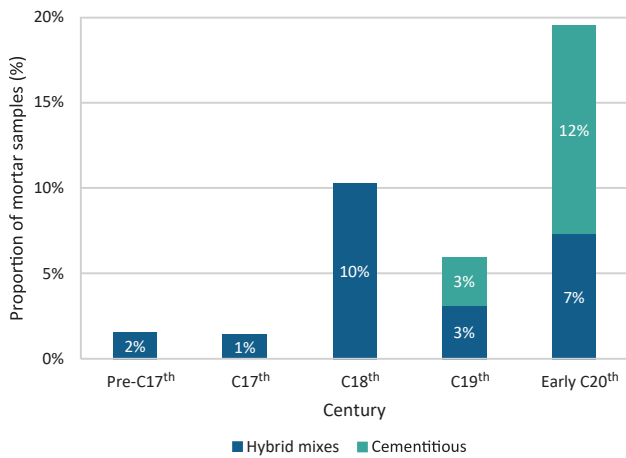


Figure 14 - The prominence of hybrid mixes and cementitious mixes by century.

Data interrogation relating to samples, for which mortar date and hydraulicity were both established (n=799), shows that the vast majority of historic mortars were made using non-feeblely hydraulic lime (Figure 15); proportions vary between centuries but are typically between 60% and 80%. After the 19th century, there is a clear downward trend with non-feeblely hydraulic limes accounting for just 45% of mortars by the 21st century. In line with this, there is an increase in the use of moderately and eminently hydraulic limes over this same period. The occurrence of eminently hydraulic limes more than doubles from the 19th to 21st century, albeit still only accounting for 25% of samples.

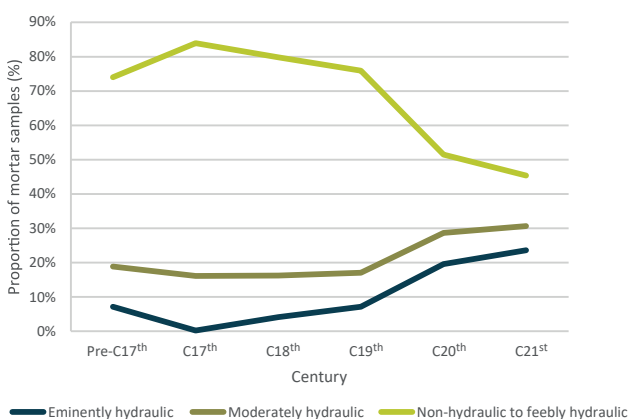


Figure 15 - Variations in hydraulicity of Scottish mortars over time (n=813).

There is a clear change in the 19th century, with an increase in hydraulicity of mortars used. Figure 19 clearly shows that the turning point in this transition was in the 19th and early 20th centuries, consistent with the development of Portland Cement.

6.2 Aggregate evolution

This section draws attention to trends specifically around additives/contaminants and aggregate grading, where these have been identified. Where properties were found to be consistent across the centuries (i.e. there are no evident trends or correlations), as is the case for primary aggregate composition, these properties have not been discussed.

As aggregate grading is inextricably linked to mortar function, bedding mortars were analysed in isolation in an attempt to identify evolution in aggregates associated with their grading; this related to 223 database entries.

Although there are no trends in the proportion of aggregates of a specified grading classification (e.g. well, or poorly graded) over time, a more in-depth look at the breakdown of grain sizes within samples does reveal some interesting trends. Taking an average of grading across all samples of a century enables comparison of average grading over time.

As can be seen from Figure 16, there is a gradual shift in the grading of aggregate in bedding mortars. Early mortars tend to be coarser with a more even grain size distribution; later mortars see a shift towards medium-fine grain sizes and significantly lower proportions of coarse grains. This is likely to indicate evolving practice, specifically the screening out of large particles, associated with increased knowledge of material properties; these changes to aggregate grading would likely have resulted in more workable mortars.

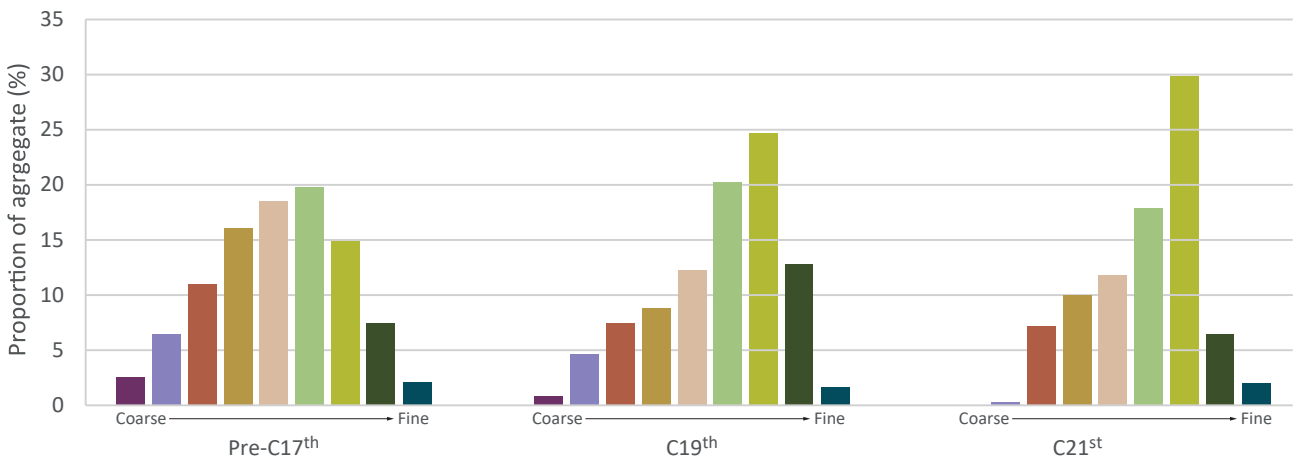


Figure 16 - Evolution in aggregate grading over time. Bar charts show average aggregate grading for bedding mortars or different centuries. Coloured bars indicate different sieve fractions which reflects aggregate grain size from coarse to fine (left to right).

6.3 Evolving practice

Burning methods: interesting and parallel trends in the occurrence of coal and the use of quicklime are evident (Figure 17).

The proportion of mortars containing coal (whether this be intentional use as a pozzolan, or an unintentional contaminant from the burning process) undergoes a relatively steep decline after the 18th century. By the 21st century, only 25% of mortars were found to include coal fragments. Indeed, due to the close link between these two materials, coal is often used as confirmation of binder identification in analysis of quicklime mortars.

The decline in the use of quicklime is earlier and more pronounced than the decline in coal contamination. This suggests that any changes in

production methods that led to the production of ‘cleaner’ lime came later relative to the transition in material/binder use; consistently high proportions of coal containing quicklime mortars also support this.

The sustained level of quicklime mortars with coal contaminants might suggest that there was little change/improvement in the burning stage of lime production in Scotland, but more so in the later refining stages of the production process (e.g. slaking to produce hydrate).

Additives: as with coal, there was a steep decline in the use of brick in mortar mixes from the 17th century.

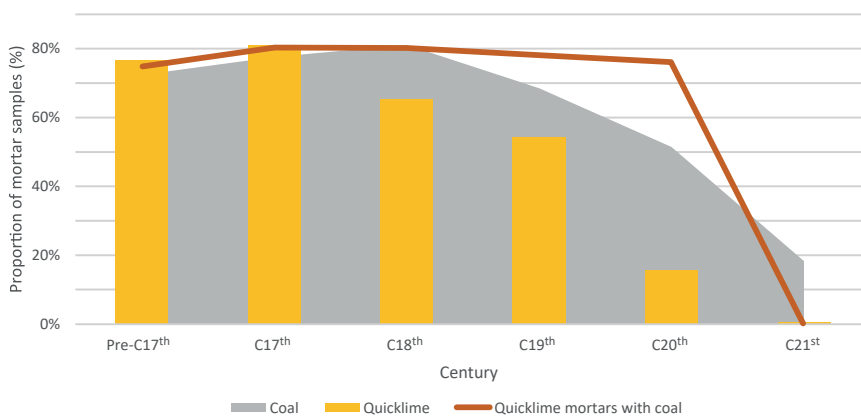


Figure 17 - Relationship between quicklime use and occurrence of coal in mortars.

It is somewhat surprising to see such a high proportion of pre-17th and 17th century samples containing brick, given that brick use was not used on a large scale until the mid-18th century (Jenkins, 2014).

The introduction of brick as a more common building material coincides with a decline in its use as an additive; it is not immediately apparent if the two are linked. It is possible that natural pozzolans were phased out at this time in concurrence with the development of other ‘modern’ building materials such as early cementitious products.

Mix Ratio: as the mix ratio is intrinsically linked to the desired properties and therefore function of a mortar, it would not be clear if trends based on analysis of samples across the entire dataset (i.e. all mortar functions and binder types) were an

indication of evolving practices or an artefact of the data associated with variations in proportions of samples types across the centuries. Therefore, this section focuses in on a single binder type and mortar function to establish how this practice evolved over time; namely, Scottish quicklime bedding mortars of known date (n=265).

Data show that until the 18th century, mixes tended to be very binder rich, with the vast majority of mortars having a binder:aggregate ratio (by volume) of less than 1:1. After the 18th century, there was a considerable shift towards leaner mixes, and by the 20th century, a greater proportion of mortars were significantly more aggregate rich (Figure 18).

Considered in conjunction with many of the other trends identified in this report, this marks a gradual shift in practice/mortar production. Aggregate ratios are generally higher for mortars made with lime hydrate (as opposed to quicklime or putty) and based on the findings of section 6.1, this shift in mix ratio was preceded by an increase in the use of lime hydrate.

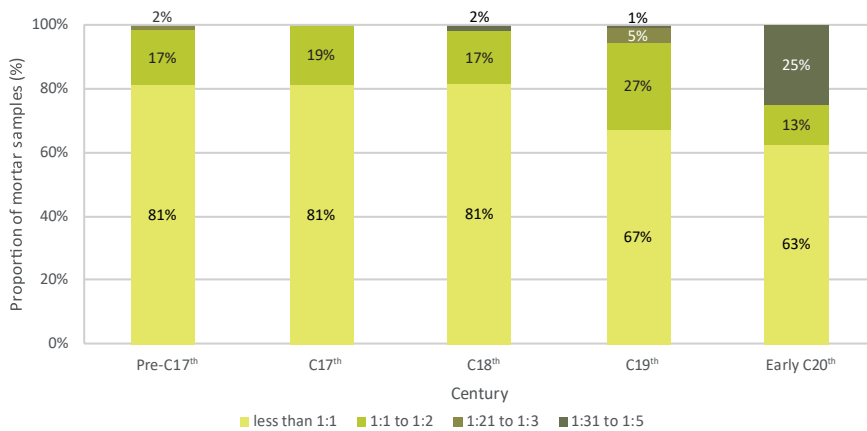


Figure 18 - Typical mix ratios (by volume) of binder:aggregate by century.



7. MODERN MORTARS

Mortar analysis services provided by SLCT are not restricted to traditional materials. Some samples in the database relate to ‘modern’ repairs on traditional buildings and these samples provide an interesting comparison to what was used historically. This chapter explores this dataset.

Examination of data relating to more recent mortars (20th and 21st centuries) shows that trends in binder selection evident from earlier centuries continued, and the use of quicklime further declined in the 20th and 21st centuries. Of the later 20th century mortars (n=137), just 7% are quicklime mortars and in the 21st century dataset (n=105) only 1% of samples were found to be quicklime. Quicklimes gave rise to lime hydrate mortars, the occurrence of which rises sharply from 12% in the early 20th century to 45% in the 21st century; indeed, modern lime mortars from recent years submitted for analysis have been almost exclusively hydrates.

There is also a notable change in the hydraulicity of binders in modern lime mortars. The 2010’s marked a turning point in the use of limes, moving to more strongly hydraulic hydrate mixes (Figure 19). Additionally, the shift towards more aggregate rich mixes seen after the 18th century continued into the 20th century (Figure 20).

However, there appears to have been a return to slightly more binder rich mixes in more recent

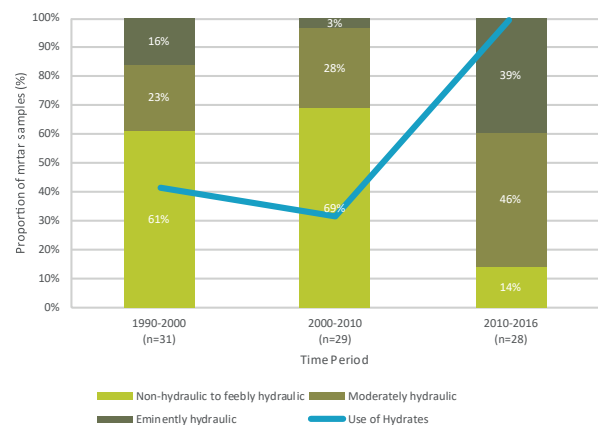


Figure 19 - Recent changes in binder use.

decades (for bedding and pointing mortars), as well as to well graded aggregates. One might speculate that this is associated with an increased level of understanding of traditional practices, however, as has been shown above, this does not extend to the binder choice; it is possible that this disparity is associated with the availability of materials, or perceptions of what is required in today’s changing climate.

A disused lime quarry in Charlestown, Fife.



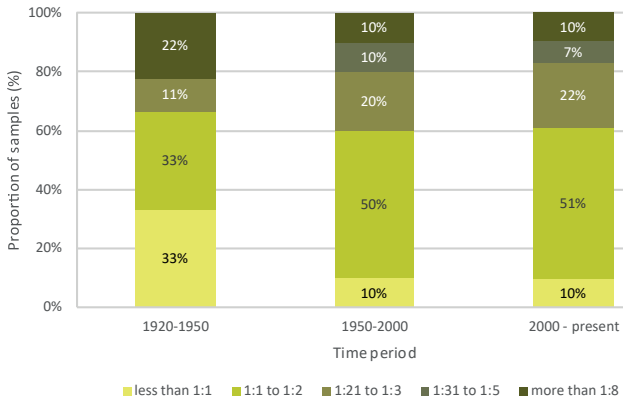


Figure 20 - Changes in binder:aggregate ratio in 20th century bedding and pointing mortars (n=64) showing a reduction in very aggregate-rich mortars in more recent decades.

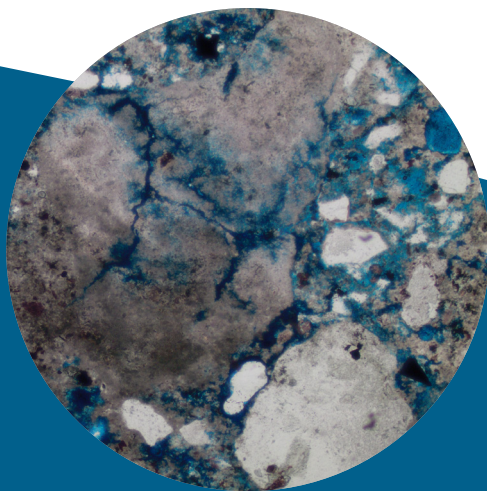
It should be noted that this small dataset has significant gaps which, if filled, would provide increased confidence in these conclusions and a better understanding of how modern practices evolved, and when the sharing of knowledge and skills development from recent decades took effect.

Interesting trends can also be seen in the evolution of surface coatings (harling and renders); the

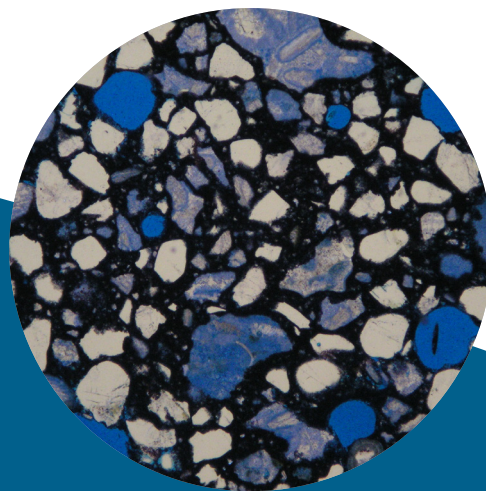
database holds information on coat thickness for 97 samples (63 historic and 34 modern). Whilst a notable variation in total coat thickness (up to 10 mm) was evident amongst both historic and modern samples, at the individual-layer scale modern renders, are overall marginally thicker by 1-2 mm.

On average, historic harling and renders have a total thickness of 11 mm, while modern equivalents are 15 mm thick. In general, historic samples had two coats, while modern renders almost always consist of three coats. This additional layer, combined with thicker individual layers results in modern renders being up to 11 mm thicker; effectively, in some cases, modern renders can be twice as thick as historic counterparts.

The presence of limewash was noted in just 30% of historic samples. From documentation and photography, it is generally recognised that the use of limewash was wider spread than this figure suggests. This relatively low value is the result of the sacrificial nature of the thin coating, which in the absence of repeated reapplication, could not be expected to remain in place indefinitely.



Thin section of historic lime harling from Stirling Castle showing an open texture with interconnected pores. Field of view = 2.5 mm.



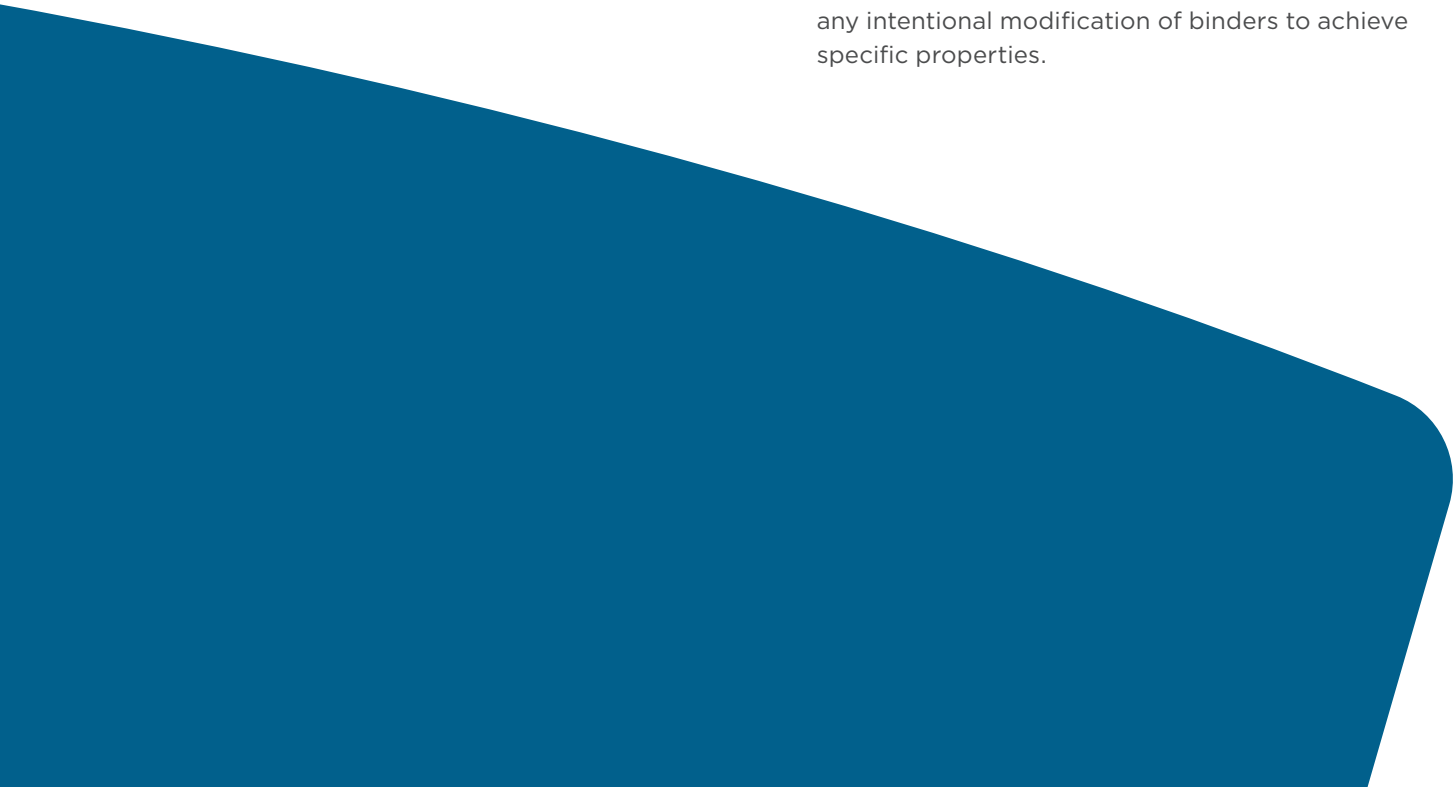
Thin section of modern surface coating showing dense matrix with isolated pores. Field of view = 2.5 mm.

8. CONCLUSIONS

The interrogation of the SLCT Mortars Database, as presented throughout this document, has provided some concrete evidence for many long-standing but previously anecdotal assessments of the use of lime mortars in Scotland.

Perhaps of most interest has been the quantification of historic quicklime use across Scotland. This work has confirmed that quicklime was almost exclusively used until the 18th century, at which point it saw a sharp decline. There were significant changes in the selection of binders over time, with some notable changes in aggregates and additives also.

The main findings associated with the evolution of the physical properties of mortars are that:

- Quicklime was the dominant binder for historic bedding and pointing mortars, and harling; lime putty was more typical in the case of ashlar pointing mortars, and there was a more even balance in the use of lime putty and quicklime for historic plasters.
 - There was a sharp decline in the use of quicklime in the 18th century paired with an increase in the use of lime hydrates.
 - Scottish historic mortars were predominantly non-hydraulic to feebly hydraulic, with areas of higher hydraulicity attributable to local geology.
 - There was an overall reduction in the presence of coal contaminants in the 19th century, although contaminant levels remained high in quicklime mortars. This indicates that refinements to achieve cleaner mortar production methods were associated with the production of other binders, rather than a refinement in the production of quicklime itself.
 - There was a decline in the use of brick dust as an additive from the 17th century.
 - In general, there is little evidence to suggest that historic practice varied to any great extent to accommodate demands of regional climates. Whilst there are areas which have higher proportions of more hydraulic mortars, this seems more consistent with geology (and availability of lime sources) than any intentional modification of binders to achieve specific properties.
- 

- There was a gradual shift away from very coarse aggregates, indicating some degree of aggregate processing (e.g. screening out of large particles); this related to grain size only, and not to composition.

- There was a shift towards leaner, binder-poor mortar mixes in more recent centuries (paired with the shift to lime hydrate binders).

Further to these tangible factors, several intangible conclusions are also evident.

This data interrogation has identified a gradual turning point in the use of mortars between the 18th and 19th centuries, with traditional methods and materials giving way to more contemporary approaches. This is strong evidence of a change in knowledge and skills; traditional practice giving rise to experimentation and the adoption of new materials, followed by refinement of practices.

There have been positive shifts in the use of lime binders and aggregates in very recent years, likely attributable to a number of factors including an increased understanding of the properties of historic lime mortars (through services such as the SLCT advisory services), and acknowledgement of the changing climate and the stresses this imposes on traditionally built buildings and structures.

However, there are also changes that have shifted the focus away from what was practiced historically, such as the availability and promotion of commercially available limes. The predominance of non- to feebly hydraulic binders in historic mortars raises the question of the suitability of currently available limes for the production of repair mortars. It is recognised in the sector that even the lower strength hydraulic (NHL 2) limes are inherently stronger than their historic counterparts, albeit via anecdotal evidence due to the challenges associated with testing mechanical properties of historic mortars (e.g. Válek and Veiga, 2005).

However, it is equally recognised that the use of non-hydraulic limes, whilst successful in some environments, is challenging in the current Scottish climate, and that hydraulic limes are more resistant to deterioration associated with binder leaching (Banfill *et al.*, 2016).

The quantification of the components in historic mortars fills a previous gap in our knowledge, and the greater level of certainty of the materials and methods used in production of historic mortars gained here might, in the appropriate circumstances, provide some useful insight in relation to the specification of repair materials.

However, whilst we can gain considerable insight into the materials and methods of the past through such interrogation of data, given the increasing demands and stresses imposed on traditionally built structures, for example by increasing precipitation levels and more frequent extreme weather events, replication of original mortars is often not an appropriate course of action.

Furthermore, the changes that historic mortars have undergone through time as a result of natural weathering and deterioration mean that the mortars we analyse today are not the same as what was used originally, rather a naturally 'modified' version. As such, the results of historic mortar analysis and indeed the trends reported in this research should not be taken out of context; standard mortar analysis reveal the 'contemporary' properties of historic mortars and this alone does not provide a sound specification for repair materials (Hughes and Válek, 2003).

An holistic evaluation of the building or structure is essential in establishing a repair specification (e.g. Frew, 2007; Snow and Torney, 2013). It must be recognised that, in some cases, requirements will have changed, and will continue to change, and this must be considered in the approaches taken in caring for and conserving our historic assets.

8.1 Further work

This research has identified a number of gaps in the evidence base that must be filled to further develop our understanding of the evolution of historic lime mortars. Areas which could be developed further, subject to an available evidence base are:

- Using petrographic analysis of mortars to establish the extent of different practices around their production and use, such as cold versus hot use of quicklime mortars.
- Verify data-based evidence around mix ratios, particularly in relation to binder-rich mortars, through petrographic analysis; petrographic examination of mortars in thin section would help establish the authenticity of these mix ratios by revealing the extent to which binder dissolution and reprecipitation has played a role in their calculated binder content.
- Assess the validity of conclusions drawn in relation to hydraulicity, via verification of hydraulicity using X-Ray Diffraction analysis to quantify the presence of hydraulic components in a sub-set of samples.
- Understanding evolution in the management of historic assets through client type.

Interrogation of the SLCT Mortars Database and the associated findings presented in this report relate to analysis conducted over approximately two decades.

Data show gradual change in client type over time. Relative to the first decade, the second decade has seen a proportionate decrease in analysis requests from architects, and an increase from contractors. This might indicate a transition of conservation work from the specialist to the more mainstream and a greater range of trades (e.g. roofing specialists) incorporating conservation work into their remit.

Whilst these clients are adopting good practice in seeking guidance from experienced professionals through the SLCT advisory service, there are other areas where there is concern around declining skills levels and the impact that apparent 'mainstreaming' (particularly in relation to materials) might have in the longer-term (e.g. Torney *et al.*, 2012).

A scientist analysing a mortar sample
© Historic Environment Scotland



- Future work to incorporate the data from the SLCT Mortars Database onto a GIS platform would allow for a more detailed analysis of mortar trends in relation to geology, topography and geography, and enable a more detailed analysis of production and practice associated with specific locations and/or features, such as an assessment of urban versus rural or coastal versus inland practice, and studies on the impact or influence of historic quarries or other specific material sources (e.g. by cross-referencing with British Geological Survey datasets).
- Comparison of the evolution of mortars in Scotland with those from other countries. This could be established by conducting a similar exercise using similar datasets (e.g. those held by testing facilities in other countries).
- Associated with the previous point, the use of data from across the UK, and further afield, to conduct a more in-depth analysis of the variations in mortar properties between different regions, so as to understand the impact that regional climate played in the evolution of mortars and the advancements of practices on a wider scale.
- The use of current climate projections to inform the testing of lime mortars with a view to understanding how our historic assets will continue to deteriorate in the light of the ever-changing climate, and how we can best use traditional materials to increase resilience of these otherwise vulnerable buildings and structures.





Following the consolidation of the limekilns in 2018 as part of the Inner Forth Landscape Initiative, this important part of Scotland's lime burning heritage can now be enjoyed by the public.

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