

**Designing and evaluating  
repointing lime mortars for the  
conservation of historic buildings  
in highly exposed environments**



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# Abstract

Many historic buildings are under threat due to their severe exposure to wind, rain and high humidity. One of the main conservation challenges for historic and traditional buildings is to ensure water ingress is mitigated and moisture that has entered a wall evaporates, contributing to drier and less damp conditions. These are some of the main roles of mortar joints in a masonry: absorbing moisture from the surrounding stones and contributing to its evaporation. When mortar deteriorates or when inappropriate mortar, that traps moisture inside the wall and encourages evaporation through the porous stone, has been used, it has to be replaced by a new mortar called repointing mortar. This thesis focuses on repointing in a common UK situation of high exposure to wind and rain and masonry with low permeability, as found in the south-west of England. It aims to investigate the role of repointing mortars in the conservation of historic buildings in exposed environments: What would be the most effective mortar to repoint dense stone masonry in exposed locations? How do the environmental conditions found on-site affect these mortars? Can these repointing mortars mitigate driving-rain ingress? This thesis addresses these research questions with a multi-method and multi-scale methodological approach, from laboratory samples to test walls, to optimise, evaluate and validate twenty-three compositions of lime mortars. This work is therefore relevant to other high humidity environments and to a multitude of structures. Key scientific findings are made on the effect of specific materials in lime mortars, such as the use of wood ash, porous aggregates and quicklime, qualifying them as suitable materials to optimise repointing mortar. Wood ash contributes to increase the capillary absorption capacity of mortar while giving a potential pozzolanic activity, a positive outcome when applied under humid conditions. The thesis brings further understanding of the impact of humid environmental conditions on the properties of lime mortars, and showed that laboratory evaluation should be made on samples cured under realistic conditions if information on the early to medium-term (up to 90 days) characteristics of NHL mortar is required. Findings from experiments on test walls demonstrate that repointing mortar, by being more compacted, helps mitigate rain ingress after a short intense rainfall event. The novel pilot scoring system developed could have considerable implications for more effective and durable repointing interventions. Together, these findings have significant implications for decision-making on repair interventions for the conservation of historic buildings, especially in building resilience in a context of climate change.



*In memory of my grandfather's  
"Laboratoires Mackenzie",  
where products against moisture  
in walls have been developed.*



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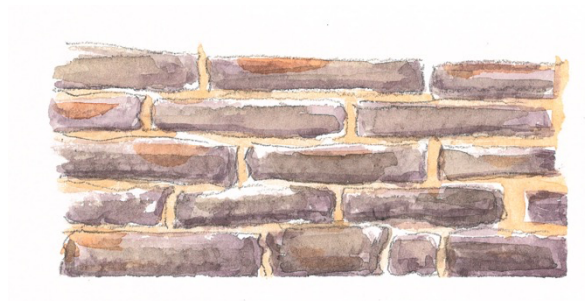
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# PART A

## Research Framework and Aims



*Details of a granite façade of a house in Brittany  
(Finistère, France) (by MF)*



# I. INTRODUCTION

---

Defining what counts as “heritage” and what is a historic monument is a complex task (Choay, 1992; Babelon & Chastel, 1994; Riegl & Boulet, 2003). Furthermore, deciding whether and why such “heritage” has been and should be preserved (Jokilehto, 2011; Germann & Schneel, 2014; Lowenthal, 2015; DeSilvey, 2017) and if so, how and what to actively conserve has always been a source of intense discussion and reflection (Viollet-le-Duc, 1854; Ruskin, 2011). The task is a large one: there are around 5.5 million traditional buildings in England (usually pre-1919) and 500,000 listed buildings in the UK alone (Historic England, 2018b), amongst which there are 911 places of worship and 1,489 buildings on the Heritage at Risk Register (Historic England, 2018c, 2018a). In finding effective and sustainable ways to deal with heritage at risk, an interdisciplinary approach that considers the history, significance and material transformation of historic buildings is necessary (Douglas-Jones *et al.*, 2016). Understanding the properties of traditional materials using scientific techniques to improve repair interventions is key and is the focus of several recent initiatives. For example, the recent UK Strategic Framework for Heritage Science shows how the heritage sector needs to deploy excellent research to “address the present needs and future requirements of heritage” (National Heritage Science Forum, 2018, p.4). Such research is needed in order to learn from the past to provide scientific answers to the conservation issues of today and prepare historic buildings to tomorrow’s challenges in a sustainable manner.

## 1.1 Context and main challenges to address

Many historic buildings are under threat due to their exposure to the challenges of climate change, including the likelihood of more intense rainfall. They are also at risk already from their severe exposure to wind, rain and high humidity, as for instance frequently found in the south-west of England (Brimblecombe & Grossi, 2007; English Heritage, 2012) or in tropical regions. When rain is driven against a building façade part of it runs off, but most is absorbed by the porous building materials. Liquid water usually enters through cracks in joints, openings and defects of roof elements (Eppell, 1981; Laycock & Wood, 2014). Large masonry structures which are composed of ashlar faces and a rubble core, as found in a multitude of traditional structures, are particularly at threat as voids found in the core of the wall and through stones can encourage liquid water to travel through the depth of the wall (Wood, 2013). Exposed buildings are a real issue since liquid water and moisture can lead to many deterioration challenges such as, salt efflorescence, bringing loss of substrate and damages to finishes as well as internal dampness which can lead to negative health effect. Liquid water is indeed one of the main agents of building deterioration (Oliver, 1997; Wendler & Charola, 2008). Control of moisture ingress and movement in a historic masonry wall has therefore an important influence on the durability of the masonry (Groot & Gunneweg, 2010) and on the overall resilience of the building to climate change.

One of the main conservation challenges for historic buildings is thus to ensure water ingress is mitigated and controlled and moisture within a wall evaporates, contributing to drier and less damp conditions. The main roles of mortar joints in masonry are to absorb moisture from the surrounding stones, by being more porous, to mitigate the ingress of moisture through the wall, and to contribute to the evaporation of moisture from the surrounding masonry (Hall *et al.*, 1984; Hughes,

1987; Maurenbrecher *et al.*, 2007). When the masonry is made of dense, low permeability stone, such as granite, as for instance found in many churches in south-west England, most of the movement of moisture occurs through the joints (Young, 2007; Hughes *et al.*, 2008). When absorbing moisture, soluble salts are brought to the surface of the joint and taken away from the valuable historic stones (Hughes, 1987). Previous repair interventions have sometimes used a hard, low-porous mortar such as cement mortar, which traps moisture inside the wall and instead encourages evaporation through the porous stone (Wedd & Westbury, 2002). This has been shown to significantly increase deterioration of the masonry (André *et al.*, 2014). To deal with situations where the surface of joints (usually finished with pointing mortar) have decayed, remedial action is needed. In these cases, inappropriate or deteriorated mortar are replaced by a new mortar called repointing mortar, to ensure mortar joints can continue to contribute to effective drying of the building (Pickles *et al.*, 2017).

Practitioners have recommended several conservation solutions to deal with internal dampness and control the ingress of rainwater through a wall. Maintenance of roof elements (such as ensuring there are no cracks in parapets and gutters are cleared) are essential and internal heating can also be used (Forster & Carter, 2011). Other masonry interventions such as rendering (covering the exterior of the wall with mortar) and grouting (injected liquid mortar in the rubble core by drilling) have also proved to be effective in some circumstances (Laycock & Wood, 2014). However, when a building is listed or of architectural significance its appearance cannot be altered and repair interventions need to be minimal and, ideally, reversible (ICOMOS, 1964; Drury & McPherson, 2008). Repointing is therefore often the only possibility for aesthetic, financial and philosophical reasons as it is less visually intrusive, cheaper and a minimal intervention.

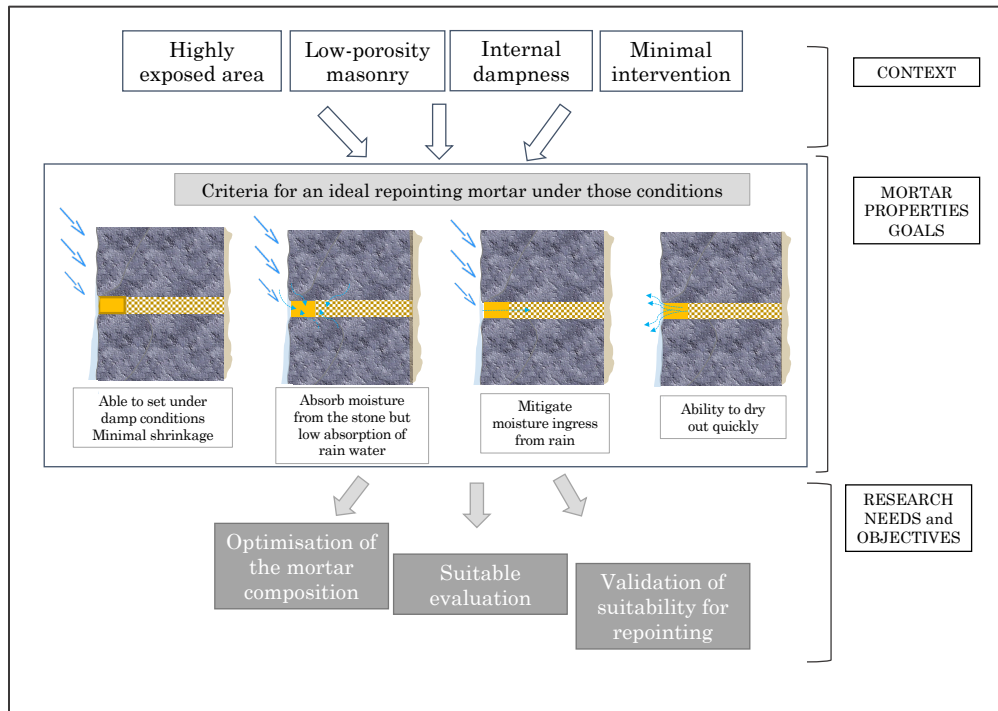


Figure 1.1. Diagram of the properties of the ideal repointing mortar in relation to a specific context; highlighting the needs for research.

Pointing and repointing mortars can be made with many combinations of binder (lime), aggregate (sand or crushed stones), and sometimes additives (Holmes & Wingate, 2002). When designing a new repointing mortar it is necessary to develop a mortar that will fit the structural and environmental requirements of a specific historic building. Although this work can be relevant to other high humidity environments and to a multitude of structures, buildings and infrastructural masonry, this thesis focuses on a common UK situation of high exposure to wind and rain and masonry with low permeability stones. In historic buildings highly exposed to driving rain, the repointing mortar used should have the following ideal properties, summarised in Figure 1.1:

- Able to set and perform under humid environmental conditions, while experiencing minimal shrinkage.
- Able to absorb moisture from the surrounding masonry unit (here mainly dense stone) while minimising absorption of water from the rain.

- Able to mitigate moisture ingress from rain
- Able to dry out quicker than the surrounding stones, minimising the risks of salt efflorescence and frost damage to the historic stones.

## 1.2 Identified research gaps

English Heritage (now Historic England) led the “Damp Towers project”, upon which this thesis builds, which began in 1989 and monitored many churches suffering from internal dampness in south-west England before, during and after repairs. The project highlighted several questions, such as: “what is the best design specification for each [remedial treatments]?” and “what is most effective at preventing moisture in these and if we can’t prevent it, what is most effective at minimising wetting and maximising drying?” (Wood, 2013, p. 10). These questions showed the need for research to design and evaluate specific repointing mortars and understanding their performance. More specifically, Hughes et al. (2008) suggested that in the investigation of a repointing mortar for granite, further evaluation focusing on the porosity and permeability, on the bond between the mortar and the stone and on durability would be necessary. They also suggested the use of hot-limes and various hydraulic limes “to optimise mortar design and behaviour” (Hughes, 2008, p. 18). Increasingly, it has been pointed out that research on the study of the influence of external factors, such as substrate, climate, environment is essential to improve understanding of the evolution and performance of lime mortars (Veiga, 2017).

Many technical and practical requirements exist for the design of repair mortars (see section 2.5.1), but little evaluation has been made of whether they mitigate water ingress, and if so how, and which specific materials should be used. In addition, the literature has highlighted that repair and repointing mortars are

sometimes designed without considering the specific environment and masonry type in which they will be used (see Table 2.7).

Several specific research gaps have been identified:

- A lack of detailed research on the composition of repointing mortar and whether it could be optimised for specific climatic contexts and deterioration problems.
- A need to define a clear method to evaluate repointing mortar; focusing on key properties, to determine whether repointing or not could be an efficient conservation solution for exposed masonry.
- A need for further study of the influence of environmental conditions on mortar development and performance.

### **1.3 Research aims and objectives**

This thesis aims to investigate the role of repointing mortars in the conservation of historic buildings in exposed environments. The thesis addresses this aim within a framework which considers the material properties of repointing mortars (lime, aggregate, and sometimes additives), workmanship, and the broader masonry context (masonry type, environmental setting). This work proposes a novel approach to the design and evaluation of repointing mortars.

Based on the identified challenges above three main research questions are posed with accompanying objectives:

**RQ 1:** What would be the most effective mortar to repoint hard stone masonry in exposed locations?

**Objective 1:** To optimise the composition of mortars suitable for repointing hard stone masonry in exposed locations using traditional materials through laboratory trials. (Study I, Study II, Study III)

**RQ 2:** How do the environmental conditions found on-site affect these mortars?

**Objective 2:** To evaluate the effect of humid environmental conditions on the development and performance of these mortars. (Study II, and Study III)

**RQ 3:** Can these repointing mortars mitigate driving-rain ingress and help a masonry dry out?

**Objective 3:** To validate whether these repointing mortars mixes effectively respond when exposed to driving-rain using test walls. (Study III)

Each objective addressed are of three axes: optimisation, evaluation and validation.

#### 1.4 Outline of the thesis and chapter summary

This thesis is divided into three parts (Table 1.1).

**Part A** presents the research context and rationale, its aims and objectives, and the methodological framework.

**Chapter I** introduces the main practical challenges, scientific research gaps and aims of the research.

**Chapter II** comprises a literature review of the relevant conservation, technical, practical and scientific literature on repointing lime mortar, which serves to introduce the historical and practical context on the use of lime, the challenges of the design of repair mortar, the technical requirements and sets the context of exposed and damp historic buildings.

**Chapter III** outlines the framework of the research, presenting the area of study and the chosen methodological approach to the research.

**Part B** combines three empirical studies that address the three objectives and axes of the research: optimisation, evaluation and validation. Some of the methodology is used throughout but each chapter also has some specific methodological differences.

**Chapter IV** (Study I) assesses the impact that varying the content of wood ash has on a range of properties of non-hydraulic and natural hydraulic lime mortars and draws conclusions about the reasons for these impacts. Biomass wood ash was added to mortars made with natural hydraulic lime (NHL) and air lime (AL) as an aggregate replacement at different concentrations: 0% (control mix), 10%, 20%, 30%, 40%, 70% and 100%.

**Chapter V** (Study II) compares realistic curing conditions (as likely found on site) of 15 °C, 85 % RH, representing an average summer climate in Devon with standard recommended laboratory conditions of 20 °C, 65 % RH, to assess what, if any, these differences in environmental conditions make to laboratory evaluations of mortar properties before repointing work begins.

**Chapter VI** (Study III) determines how various lime-based repointing mortar mixes, in a small solid and dense masonry system (granite masonry test walls), respond to drying and evaporation after an intense short rain event. It aims to determine the influence of materials, joint types, workmanship and whether repointing could mitigate moisture ingress and help masonry dry out.

**Part C** sets the results within a wider context, by discussing their implications for practical conservation and drawing conclusions from them.

**Chapter VII** builds on the discussions and conclusions presented in each study (Chapters IV, V, VI) to discuss how they have addressed the thesis objectives, research questions and aim. It also presents a comparison of approaches to grouping optimised mortars, explores the conservation philosophy of repointing and makes recommendations for future research.

**Chapter VIII** summarises the main conclusions and synthesises the issues raised in the discussion, while exploring the scientific and practical implications and contributions of the thesis.

Table 1.1. Structure of the thesis

PART A	Chapter I	<b>Introduction</b> - Research background, gaps and aims
	Chapter II	<b>Literature review</b> - Lime mortar and repointing: historical context, technical requirements and conservation of damp historic buildings
	Chapter III	<b>Framework and methodology</b>
PART B	Chapter IV	<b>Study I</b> - The effect of wood ash on the properties and durability of lime mortar for repointing damp historic buildings
	Chapter V	<b>Study II</b> - A comparison of standard and realistic curing conditions of natural hydraulic lime repointing mortar for damp masonry: impact on laboratory evaluation
	Chapter VI	<b>Study III</b> - Drying out traditional masonry - Response of lime-mortar joints in granite test walls after intense rainfall, before and after repointing
PART C	Chapter VII	<b>Discussion</b>
	Chapter VII	<b>Conclusions</b>



## II. LITERATURE REVIEW

### **Lime mortar and repointing: historical context, technical requirements and conservation of damp historic buildings**

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This chapter reviews the relevant conservation, technical, practical and scientific literature in order to set the context for repointing lime mortars for dense highly exposed masonry. Section 2.1 gives the historical context of the “invention” and development of lime mortars over the centuries, and section 2.2 explains the technology of lime and which materials to choose from for lime mortars for conservation. Section 2.3 explores the issues historic buildings face when exposed to high rainfall, with a focus on the south-west of England, and what has been proposed in the literature as causes and solutions for conservation. The following sections 2.4 and 2.5, respectively give a definition of repointing mortar, its role and function and review the requirements and the design of a selection of repair mortars. Section 2.6 summarises the review of the literature and its implications.

#### **2.1 Learning from the past: historical context of the use of lime mortar**

##### ***2.1.1 Historic development and uses of lime mortars***

The earliest occurrence of the calcination of lime to be used as plaster is identified around 12,000 BC, during the Palaeolithic period, in the Middle East (Gourdin & Kingery, 1975; Kingery *et al.*, 1988). The review by Hughes (Hughes & Válek, 2003) gives a good account of research on the earliest uses of lime technology, mainly as plaster, but sometimes found for construction, in the Pottery Neolithic (6,400 BC – 4,500 BC) in Mesopotamia and Egypt. The use of lime as a binder starts

to be seen across the world, including in China around 1700 BC and mainly by the Greeks (Coutelas, 2009; Carran *et al.*, 2012).

It is generally agreed that the Romans extended and mastered the use of lime mortars, called “opus caementitium”, and developed the use of hydraulicity in their mortar (Davey, 1961; Malinowski, 1981; Dix, 1982; A Moropoulou, A. Bakolas, *et al.*, 2005). Traditional lime mortar is made of a binder (lime), and aggregate (usually sand), with sometimes also additives, mixed with water. The Romans were able to select specific materials for their quality (A Moropoulou, A. Bakolas, *et al.*, 2005), making the production of lime mortar one of their key technological innovations (Dessales, 2017). Davey (1961) explains that in England, sand and coarse materials were selected by the Romans for their size and grading for use as aggregates in particular work. Vitruvius in his *Ten Books of Architecture* (1960) and Pliny in his *36<sup>th</sup> book on Natural History* produced some of the first written sources on the technology of lime calcination, the choice of materials for mortar and the methods of mixing (Vitruvius, 1960; Pliny & Eichholz, 1989). The concepts they established, mainly that the hardest lime was the whitest and purest lime (Sickels, 1987), were followed by architects such as Palladio (1570) and De l’Orme (1626).

A wide number of publications since the mid 1970s’ focuses on the characterisation of historic mortars over time (Furlan & Bissegger, 1975; A Moropoulou, A. Bakolas, *et al.*, 2005), and specifically from the Greek, Hellenistic (Moropoulou *et al.*, 2000) and Roman periods (Sánchez-Moral *et al.*, 2005; Pavía & Caro, 2008; Izzo *et al.*, 2016; Ontiveros-Ortega *et al.*, 2016), but also medieval (Sapin, 1991; Hughes & Cuthbert, 2000) and Renaissance mortars (Dotter, 2010; Borges *et al.*, 2014). These studies focus mainly on determining the compositions of those ancient mortars, but also on the reasons for their alterations (Malinowski, 1981; Hees *et al.*, 2004), causes of damage and decay (Dotter, 2010; Borges *et al.*, 2014). A

few studies used the information to develop compatible restoration mortars (Sapin, 1991; Hughes & Cuthbert, 2000). Over time methodologies to analyse historic mortars have been developed (Holmström, 1981; Leslie & Hughes, 2002; Middendorf *et al.*, 2005; Elsen, 2006), and there is a new considerable amount of literature on historic mortars.

In France and England, the 18<sup>th</sup> and 19<sup>th</sup> centuries saw the publications of essential treatises on construction and building materials. 1756 – 1855 was a time of experimentation and discussion to recreate the hydraulic limes of the Romans (Sickels, 1987). Some of these treatises gave general principles about architectural styles, concepts and materials, such as the “Cours d’Architecture” by Jean-François Blondel (1777) and the “Traité sur l’Art de Bâtir” by Jean-Baptiste Rondelet (1803) and some were more specific such as George R. Burnell’s “Rudimentary Treatise on Limes, Cements, Mortars, etc.” and Valentin Biston’s “Manuel théorique et pratique du chaffournier” (1836). In all of them, lime calcination is detailed along with methods to mix lime with sand and recipes of a range of mortars are compared and given. Sickels (1987) and Coutelas (2009) both give a detailed account of the “re-invention” of hydraulic limes. Important work was carried out by John Smeaton who wanted to develop a mortar that would survive in harsh salty and wet environment forced by the Eddystone Lighthouse in 1756 (Smeaton, 1793). He was the first to understand that the hydraulicity of limes is due to their clay content (Sickels, 1987).

### ***2.1.2 Lime revival and reasons to use lime for repair***

As the timetable of significant dates in mortar development in England in the English Heritage practical guide on “Mortars, Renders and Plasters” states (Henry & Stewart, 2012), the decline in the use of lime in mortar occurred between 1920 and 1945. In the 1970-90’s, conservation work saw a revival in the use of lime

mortar, mainly started by the restoration of Wells Cathedral in 1974, where mortar design, based on practical experiment, used non-hydraulic lime putty for the conservation of fragile limestone sculptures (Henry, 2018). In 1981, the ICCROM symposium on “Mortars, Cements and Grouts used in the Conservation of Historic Buildings” was the first attempt to establish a strategy based on scientific methods for the investigation of historic mortars and the design of repair mortars. The symposium expressed the clear need for research in the field (Holmström, 1981). Establishing analytical standard methods became necessary (Cliver, 1974; Rota Rossi-Doria, 1986; Teutonico, 1988), and research towards designing repair mortar for conservation started, based on historic mortars (Sapin, 1991) or with the needs of a specific site in mind (Teutonico *et al.*, 1993). Interestingly, lime became widely used in cement mortar to give workability and prevent cracking (Vernon, 1970; Cliver, 1974), while it was also soon agreed that cement mortar alone was not compatible with historic permeable stones, being too impermeable and could cause decay to the masonry (Rota Rossi-Doria, 1986; Teutonico *et al.*, 1993; Gibbons, 1995; Mack & Speweik, 1999).

## **2.2 Materials of lime mortars**

### ***2.2.1 Lime technology and classification***

Lime is produced by burning limestones in a kiln to a temperature of 800°C to 1000°C, depending on the clay content of the limestones. Pure limestones ( $\text{CaCO}_3$ ) without clay, will result in non-hydraulic lime, or air lime; clay-containing limestones will produce hydraulic lime or water lime (Snow & Torney, 2014). The main difference between air lime and hydraulic lime is, as their qualification indicates, air lime only sets through carbonation whereas hydraulic lime also needs moisture in the air to set and therefore have the capacity to cure under humid

environmental conditions (Fig. 2.1). In conservation, the general advice is that if hydraulic lime were to be used, natural hydraulic limes (NHL) should be used (Henry & Stewart, 2012). Vicat, was the first to come up with a classification of limes into five categories based on their clay content (Vicat, 1818; Sickels, 1987):

- 'Rich' limes contained 1 - 6% of clay - being non-hydraulic lime
- 'Poor' limes had 3 - 15% of clay
- Feebly hydraulic limes contained 8 - 12% of clay
- Hydraulic limes had 20 - 30% of clay with half of that being silica
- Eminently hydraulic limes amount of silica was 11 - 25% of clay

This classification was used by Cowper (1927) and eventually adopted as the British Standard BS EN 459-1 (1995, 2010) with the following classification:

- Air lime or non-hydraulic lime: “lime which combines and hardens with carbon dioxide present in the air”, “air lime is divided into two sub-families, calcium lime (CL) and dolomitic lime (DL)” (British Standard Institution, 2010, p. 5),
- Natural hydraulic lime (NHL): “lime with hydraulic properties produced by burning of more or less argillaceous or siliceous limestones” (British Standard Institution, 2010, p. 18),
- Formulated Lime (FL): “lime with hydraulic properties consisting of air lime and/or natural hydraulic lime (NHL) with added hydraulic and/or pozzolanic material” (British Standard Institution, 2010, p. 18),
- Hydraulic Lime (HL): “a binder consisting of lime and other materials such as cement, blast furnace slag, fly ash, limestone filler” (British Standard Institution, 2010, p. 19).

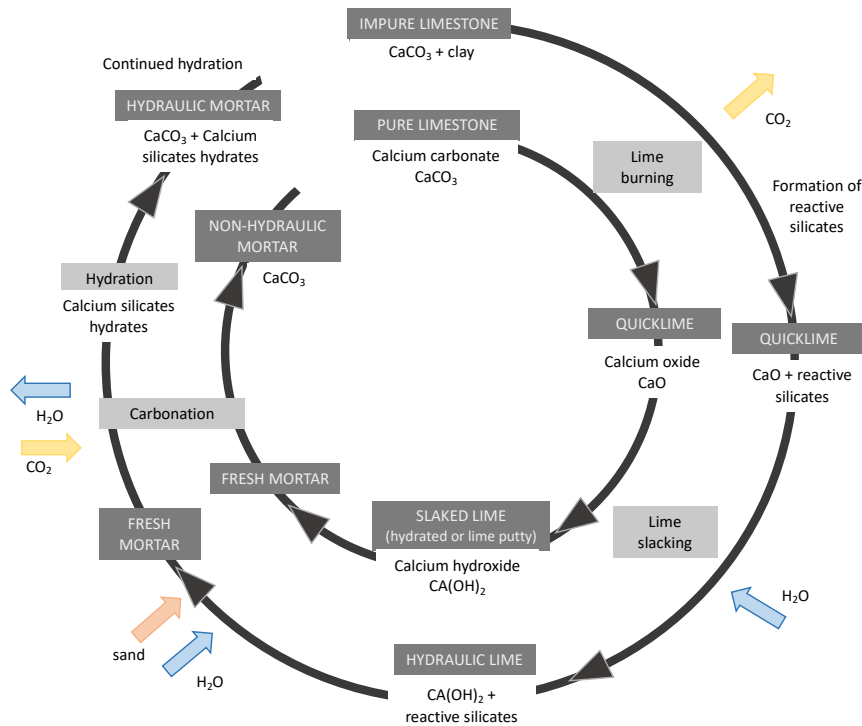


Figure 2.1. Simplified lime cycles for non-hydraulic and NHL limes. (after (Gibbons, 2003; Henry & Stewart, 2012; Snow & Torney, 2014)

The lime cycles diagram (Fig. 2.1), as initially drawn by Gibbons (2003), and seen in many other publications since (Henry & Stewart, 2012; Snow & Torney, 2014), gives a good explanation of the chemical process involved in the production of lime mortars. The lime cycle for non-hydraulic and hydraulic lime is different as their setting process and mineral content differ.

Calcination of pure limestones in the form of calcium carbonate ( $\text{CaCO}_3$ ) results in calcium oxide ( $\text{CaO}$ ), also called “quicklime”. Slaking of quicklime or adding water, results in a highly exothermic reaction and produces calcium hydroxide ( $\text{Ca(OH)}_2$ ), also called Portlandite. Slaking produces hydrated lime, or if there is excess water, lime putty. When mixed with sand, the lime forms a mortar. During setting, the calcium hydroxide reacts with carbon dioxide ( $\text{CO}_2$ ) from the atmosphere to form calcium carbonate ( $\text{CaCO}_3$ ), usually in the form of calcite. This process is called carbonation, through which lime returns to its original chemical composition (Snow

& Torney, 2014). Carbonation has been shown to change the pore size distribution of air lime, as the carbonate crystals form around the aggregate, creating a large number of small pores ( $< 0.03 \mu\text{m}$ ) (Lawrence *et al.*, 2007).

When burned, impure clay-containing limestones form calcium oxide (CaO) with silicate (C<sub>2</sub>S) and alumina (Al<sub>2</sub>O<sub>3</sub>), called reactive materials (Torraca, 2009). Setting occurs through a two-phase process: first, a ‘hydraulic set’, using moisture from the air, resulting mainly in the formation of calcium silicate hydrates (C–S–H) and calcium aluminate hydrates (C–A–H) and, second, carbonation (Forster, 2004). Formations of these hydrates gives NHLs their hydraulicity, which means that they can set under humid conditions (Allen *et al.*, 2003). This initial setting also gives them an early strength gain, essential for resisting extreme environmental conditions (Kalagri *et al.*, 2014), while still remaining permeable through the creation of interconnected pores (Banfill & Forster, 1999).

### ***2.2.2 Which lime for conservation?***

Nowadays, because they are breathable and permeable, modern lime binders are considered a compatible conservation material for historic masonry units (Hansen *et al.*, 2008).

Slaked non-hydraulic lime is usually used in the form of lime putty. Studies have shown that repair mortar should use lime putty more than a year old, as the aging reduces the particle size and changes the shape of the crystals of calcium hydroxide which increase the plasticity, density and workability of the lime (Elert *et al.*, 2002; Hansen *et al.*, 2008). Slow slaking, or storing slaked lime for an extended period of time, also has an impact on the particle formation and structure of the lime putty (Balksten & Steenari, 2010) and improves the degree of carbonation (Cazalla *et al.*, 2000).

Historically, it seems that quicklime was used directly with sand, and slowly left to slake (De L’Orme, 1626) or added to the mix of slaked lime and sand (Rondelet, 1803; Pollio & Morgan, 1960). In recent years, experiments have been done to re-evaluate using quicklime, non-hydraulic or hydraulic, as it could be a more authentic method to make mortar and could produce a mortar with better durability, adhesion and workability (Forster, 2004; Artis, 2018; Henry, 2018). When used directly with sand, it is called “hot lime” or “hot lime mix” as it generates an exothermic reaction in contact with water or moisture of the sand. This reaction seems to be beneficial for the bond created between binder and aggregate, improving porosity and adhesion. However, in harsh environmental conditions hot lime mixes can fail (Artis, 2018).

In conservation using pozzolan to give hydraulicity to the non-hydraulic lime mortar instead of using modern NHL is often preferred as it gives mortar a lower strength than the surrounding masonry (Henry & Stewart, 2012) and is also a more traditional method. Indeed, the Romans mastered the use of pozzolans to give non-hydraulic lime mortar some hydraulicity, mainly by the addition of ceramics, giving durability and good quality (Pavía & Caro, 2008).

Current NHLs are classified according to their strength gain over time (British Standard Institution, 2010) (Table 2.1). However, it has been shown that NHLs from different manufacturers have different characteristics of strength over time and cannot necessarily correspond to this table (Gulotta *et al.*, 2013; Figueiredo *et al.*, 2016).

Table 2.1 Classification of NHLs according to strength gain (after BS EN 456-1:2015)

Type of natural hydraulic lime	Compressive strength (MPa)		Traditional terminology
	7 days	28 days	
NHL 2		$\geq 2$ to $\leq 7$	Feebly hydraulic
NHL 3.5		$\geq 3.5$ to $\leq 10$	Moderately hydraulic
NHL 5	2	$\geq 5$ to $\leq 15$	Eminently hydraulic

Mix reference	Non-hydraulic lime*	Natural hydraulic lime			Brick dust as pozzolanic additive ‡	Aggregate	Masonry type	Internal walls	External walls sheltered	Moderate exposure	Severe and marine exposure
		NHL 2†	NHL 3.5†	NHL 5†							
A	1					1-2	Highly durable stones and bricks of low permeability	B, C, D, E	B, C, D, E	B, C, D, E, F	G
B	1					2.5-3					
C	1				0.25-0.5	2.5-3	Average durability and permeability stones and bricks	B, C, D	B, C, D	B, C, D, E	C, D, E, F
D		1				2.5-3.5					
E			1			2.5-3.5	Lower durability or decayed, friable stones or under-fired bricks	B	B	B, C, D	C, D
F				1		2.5-3.5					
G				1	0.5	2.5-3	Very fine jointed ashlar (including gauged brickwork)	A	A	A	A

Table 2.2. Determination of lime binder according to masonry type and exposure (after (Mack & Speweik, 1999)).

Because of their different properties: air lime and NHLs are used for different masonry types and under different environmental contexts. Pure lime mortars are often defined as not being suitable for extreme, wet climates as they do not have the adequate durability (Teutonico *et al.*, 1993). The SPAB pamphlet “The need for old buildings to breathe” (Hughes, 1987) determines which lime binder to use based on the durability and permeability of the masonry and its type of exposure (Table 2.2). For low permeability stones in severe exposure conditions, it recommends NHL 5 with pozzolan and aggregate in a 1:0.5:3 ratio. Mack and Speweick propose a similar table but with different choices of lime binder (Table 2.3). For granite and severe exposure, they suggest the use of Portland cement, lime putty and sand in a 1:0.25:3 ratio (Mack & Speweik, 1999). However, nowadays, the use of NHL 5 and particularly Portland cement is generally not recommended in conservation practice. Other practical guides (Henry & Stewart, 2012) also recommend the use of NHL 3.5 or 5 or non-hydraulic lime with pozzolanic additions for tough masonry (very durable stone), under very exposed conditions. Figure 2.2 represents an idealised view of generally accepted ideas of which mortar types to use under which environmental conditions and with which masonry type. It presents only binder types that are nowadays generally acceptable in conservation practice and therefore omits cement mortar.

Table 2.3. Determination of lime binder according to masonry type and exposure (after (Hughes, 1987)).

Mortar Types (Measured by volume)				Suggested Mortar Types for Different Exposure			
Designation	Cement	Hydrated Lime or Lime Putty	Sand	Masonry Material	Exposure		
					Sheltered	Moderate	Severe
M	1	1/4	3 – ¼	Very Durable granite, hard-covered brick, etc.	O	N	S
S	1	½	4 – 4 ½	Moderately durable limestone, durable stone, molded brick	K	O	N
N	1	1	5 – 6				
O	1	2	8 – 9	Minimally durable soft hand-made brick	L	K	O
K	1	3	10 – 12				
L	0	1	2 ¼ - 3				

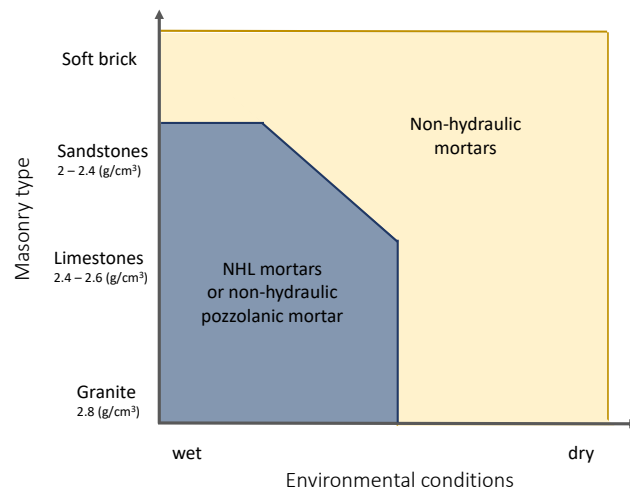


Figure 2.2. Schematic representation of which binder to use when taking into account both the masonry type and the environmental conditions. The stone types are ordered by bulk density from Siegesmund & Dürrast (2014)

### 2.2.3 Which aggregates?

Much could be said about aggregate types. Henry & Stewart’s practical guide (2012) and Schnabel (2008) both give good example of sands suitable to use. The Romans knew how to choose aggregates based on their intuitive knowledge and experience (Moropoulou, Bakolas, *et al.*, 2005), and used a highly diverse range of mortar compositions (Moropoulou *et al.*, 2000). Studies have shown careful consideration of the choice of aggregate is essential (Lanas & Alvarez, 2003; Arizzi

& Cultrone, 2013; Scannell *et al.*, 2014; Szemerey-Kiss & Török, 2017) as well as variation in grain size within one aggregate type (Stefanidou & Papayianni, 2005; Isebaert *et al.*, 2016) as both impact the mechanical and structural properties of lime mortar. For instance, limestone and calcitic aggregates have been shown to contribute to the strength of lime mortars (Lanas & Alvarez, 2003; Lawrence *et al.*, 2013) and to improve the carbonation (Arizzi & Cultrone, 2013).

#### 2.2.4 Which additives?

Natural pozzolans can be added in fine powder to non-hydraulic lime mortar to increase durability and to give a hydraulic set (Gibbons, 2010; Stefanidou, 2016). Their use as well as the use of organic additives (Ventol *et al.*, 2011; Centauro *et al.*, 2017; Thirumalini *et al.*, 2017) has been a growing field of research for repair lime mortar made of both non-hydraulic and natural hydraulic limes. Indeed, in all studies natural and organic additives are shown to optimise the properties of both hydraulic and non-hydraulic lime mortars, such as enhancing the strength and resisting water. Table 2.4 gives an overview of the range of organic and inorganic traditional additives that can be found in lime mortars. Amongst this, wood ash has been identified to be suitable for buildings in wet environment (Smeaton, 1793) and could help improve the general properties such as the porosity and strength (Mendel Goodman, 1998)

Table 2.4. Summary of the range of additives that can be found both in historic and repair lime mortars

<b>Additives used</b>	<b>References</b>
Natural pozzolan	(Veiga <i>et al.</i> , 2009; Stefanidou, 2016)
Brick powder, ceramic dust	(Baronio & Binda, 1997; Ulukaya <i>et al.</i> , 1997; Silva <i>et al.</i> , 2009; Matias <i>et al.</i> , 2014; Navrátilová & Rovnaníková, 2016)
Wood ash	(Mendel Goodman, 1998; Naik <i>et al.</i> , 2001)
Rice husk ash, sticky rice	(Cizer <i>et al.</i> , 2006; Wei <i>et al.</i> , 2012)
Herbs, cactus	(Ventol <i>et al.</i> , 2011; Thirumalini <i>et al.</i> , 2017)
Blood	(Fang <i>et al.</i> , 2015)f
Animal glue	(Ventol <i>et al.</i> , 2011)

## 2.3 The problem of highly exposed historic buildings and proposed conservation solutions

### 2.3.1 Causes of rain ingress and internal dampness

Highly exposed historic buildings are subject to high intensity rainfall and especially wind driven rain (WDR). WDR is defined by Blocken and Carmeliet (2004) as ‘rain with a horizontal velocity component given by the wind’. As explained by BS 8104 (British Standard Institution, 1992, p. 3), the “quantity of rain falling [...] on a wall, depends on both the intensity of the rainfall and the wind speed”. A large part of the west of the UK including the south-west of England, is in severe to very severe areas of exposure to WDR (Fig. 2.3 and 2.4). There are also many historic buildings located in these areas (Historic England, 2018). Combining pressure and a large amount of rain, WDR events are seen as one of the most common sources of moisture affecting the durability and performance of buildings and leading to deterioration (Briggen *et al.*, 2009).

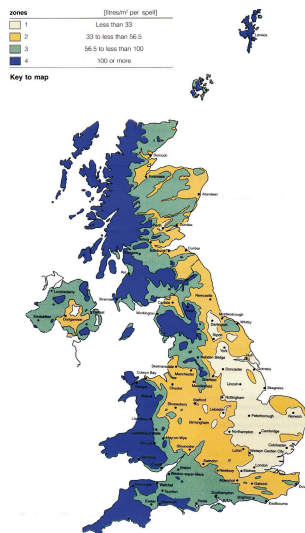


Figure 2.3. Wind driven-rain map of the UK ((Gething, 2010) from (Lacy & Building Research Establishment, 1977))  
Exposure zones: green: severe, blue: very severe

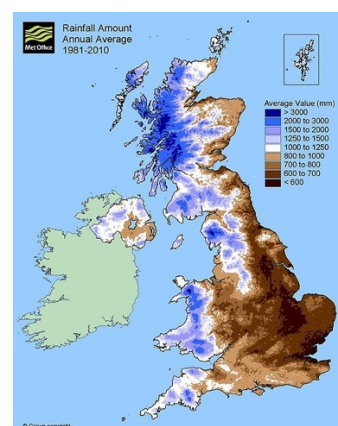


Figure 2.4. Annual rainfall in the UK (Met Office, 2018)

One of the key problems caused by WDR and general water ingress in many historic properties is internal dampness (Oliver, 1997). Internal dampness is most commonly caused by three factors: shrinkage of the pointing mortar or cracks in the masonry (Forster, 2010), which allows ingress of moisture; bad specification of the mortar or application of cement, often having incompatible properties with the historic masonry; and/or poor workmanship during construction or restoration, especially when removing the old mortar (Young, 2007; Laycock & Wood, 2014). Internal dampness can often lead to biological growth and negative health outcome (Oliver, 1997).

In a context of climate change it has been shown that historic buildings are already being affected by an increase in extremes of wetting and drying and increasing frequency of intense rainfall (English Heritage, 2012), the latter being identified as one of the main threats to historic buildings (Brimblecombe & Grossi, 2007). When driving rain hits a building façade, even when a masonry wall is of considerable thickness (as found in historic church towers for instance) (English Heritage, 2013), it will enter the wall face through mortar joints, cracks and at the interface between stone and mortar as demonstrated by Wood and Laycock in their test walls' experiment (Laycock & Wood, 2014), or through openings (Eppell, 1981).

Observations from practitioners (such as conservation officers and craftsmen) and scientific research have both identified that rainwater and moisture ingress through the joints are often caused by failure of weathered original pointing mortar or previous inappropriate interventions (Young, 2007; Rirsch & Zhang, 2010). Wrong specification of mortar, such as the use of cement mortar for repointing, has indeed been shown to increase weathering damage and stone surface recession (André *et al.*, 2014) and to trap moisture in the wall as it is less permeable than the surrounding stones (Speweik, 1997). Cement has however often been recommended

for repointing because it is more durable and on the basis that it would resist soluble salt and will not be itself a source of harmful soluble salt for the rest of the masonry (Duffy *et al.*, 1993; Manita & Triantafyllou, 2011). The opposite approach has however now been demonstrated and even cement gauged with lime has been shown to have negative effects on strength, durability and permeability of lime mortars (Teutonico *et al.*, 1993). The SPAB publication (Wedd & Westbury, 2002) gives a clear explanation of how strong cement pointing traps moisture inside the wall, due to the impermeability of the mortar (Fig. 2.5). With hard inappropriate mortar in the joint, moisture has to evaporate from the surface of the masonry (stones or bricks) bringing harmful soluble salts. It results in salt weathering and loss of substrate of the historical and valuable masonry units (stones or bricks) (Goudie & Viles, 1997; Young, 2007).

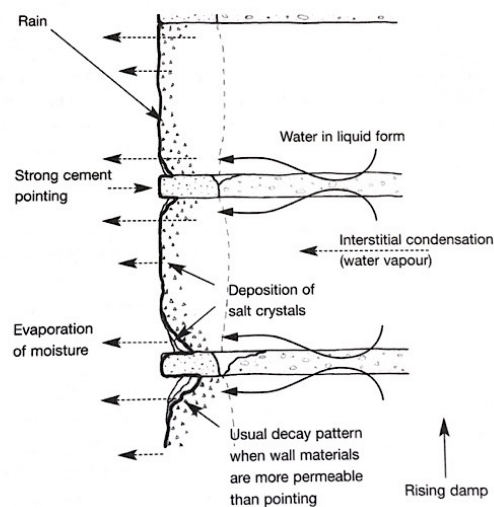


Figure 2.5 Schematic representation of the damaging effect of cement pointing on the movement of moisture through a masonry wall (after (Wedd & Westbury, 2002), drawing Nicola Westbury)

### 2.3.2 Consequences of rainfall and dampness

Water has been shown to be one of the main agents of building materials' deterioration leading to chemical and physical weathering (Collepari, 1990), surface erosion (Erkal *et al.*, 2012), biological growth (Pender *et al.*, 2014), frost

damage and salt efflorescence (Oliver, 1997; Siegesmund & Dürrast, 2014) and damp internal conditions (Oliver, 1997; Abuku *et al.*, 2009). In most building material failures, water has been identified as the key factor in the deterioration of porous building materials (Wendler & Charola, 2008).

Lime mortar has been shown in particular to be at risk from moisture and salt (Hees *et al.*, 2004). Indeed, climate conditions have also been found to change the porosity distribution and permeability of lime mortars (Dotter, 2010) as variations in temperature and relative humidity produce different reactions with lime, such as mineral transformation of portlandite ( $\text{Ca(OH)}_2$ ) into calcite ( $\text{CaCO}_3$ ) that will have important effects on the internal development and structure of lime mortar (Lanas & Alvarez, 2003; Grilo *et al.*, 2014).

It is clear that control of moisture ingress and movement in a historic masonry wall is therefore linked to the durability and resilience of the masonry (Groot & Gunneweg, 2010), especially under severely wet climatic conditions. Overall, mitigating the degradation of historic fabric should preserve the significance and architectural, historical and use value of exposed historic buildings and is thus an important goal of conservation.

### ***2.3.3 The specificity of traditional masonry***

A typical traditional wall often comprises two skins of stonework with a core filled with rubble, loose stones and mortar. The outside stonework can be dressed in ashlar which characterised by regular stones and a surface dressing of good quality or can be courses of rubble, being often a mix of irregular stones and bricks (Brunskill, 1978).

The 15 years “Damp Towers” research project commissioned by English Heritage to investigate and monitor damp churches and undertake testing on various test walls has highlighted several conservation issues due to large masonry.

For instance, over time, the core of a large masonry becomes increasingly eroded through wash-out or because of poor construction, creating voids that easily conducts liquid water to the inside even though the walls may be four metres thick (Laycock & Wood, 2014). Large masonry wall, as found in church towers, are therefore often subject to internal dampness as it takes a long time for inside moisture to travel back outside and evaporate (Wood, 2013). In addition, the research observed that churches were often damper after conservation work was done because of bad specification of the conservation interventions (Wood, 2013). No report has yet been written, but positive outcomes about rendering and grouting in helping a church tower to dry out have been shown. Recommendations included research into more effective repointing mortars in dealing with large amount of moisture ingress, in addition to repoint to at least twice the depth of a normal repointing mortar and to improve the internal ventilation (English Heritage, 2013).

#### ***2.3.4 Learning from practice: conservation solutions to internal dampness problems***

When dealing with historic buildings highly exposed to rainfall and suffering from interior dampness problems, conservation officers first recommend maintenance of the building features, such as the drainage system, and roof elements (Oliver, 1997; Forster & Carter, 2011). When this has been ensured but interior dampness is still present, conservation work on the external part of the masonry is considered, such as rendering (covering the exterior of the wall with mortar), grouting (injected liquid mortar in the rubble core by drilling) or repointing (replacing the mortar in the first few inches of the joints) (Henry & Stewart, 2012) (Fig. 2.6).

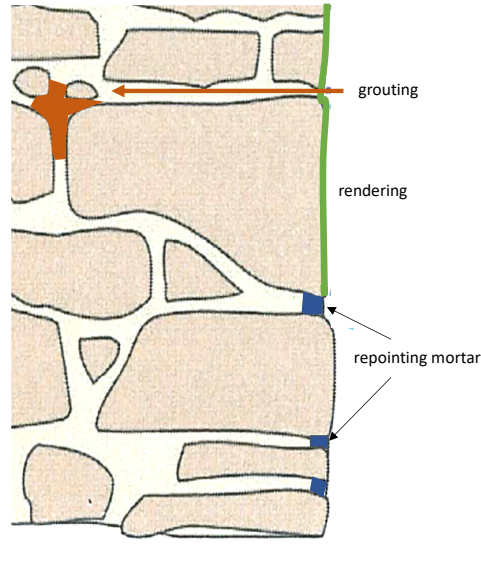


Figure 2.6 Diagram of the different mortar types for conservation intervention on external masonry (by the author)

Previous research has shown that a render often helps to hold most of the water until the rain stops when evaporation will allow the masonry to dry out (Wood, 2012). In severe conditions, the application of a render made with air-lime mortar and pozzolan has shown to be suitable (Veiga *et al.*, 2010). Grouting has the advantages of filling the voids inside the core of a large masonry wall, which will prevent ingress of liquid water through the inside of the building. However, grouting can be destructive of the external layer of the masonry and render can be visually intrusive, therefore repointing has two clear advantages: firstly, it is far less disruptive than rendering and grouting, since it ensures a minimal intervention to the historic masonry, secondly, it is less costly (Wood, 2012). Table 2.5 presents the advantages and disadvantages of each remedial treatment.

Table 2.5 Comparison of the different mortar types for conservation intervention on external masonry with pros and cons

<b>Masonry conservation intervention</b>	<b>advantages</b>	<b>disadvantages</b>
<i>Grouting</i>	Fill in difficult to access voids and can limit water ingress.	Can be difficult to operate and require drilling into historic masonry.
<i>Rendering</i>	Hold moisture before it goes into the masonry and helps evaporation.	Visually disruptive if no render was already in place. Used a lot of material and time which can be costly.
<i>Repointing</i>	Respect minimal intervention requirements for conservation.	Often needs to be paired with other intervention such as internal heating and carefully designed to be fully effective.

Careful repointing is thus one of the remedies against the ingress of water and internal dampness (Oliver, 1997; Young, 2007). In addition, repointing meets some key conservation principles. Indeed, it is recommended that conservation interventions for repair retain the heritage values of a site by respecting the appearance and ensuring minimal intervention to the original fabric, as well as achieving long-term stability and sustainability (ICOMOS, 1964; Drury & McPherson, 2008; Forster, 2010). However, the Venice Charter clearly states that repair should be clearly distinguishable from the original fabric. This is not possible in the case of repointing mortar which is usually required to be compatible visually with the masonry, that is, not clearly noticeable (Hughes & Válek, 2003; Forster, 2010).

### ***2.3.5 Conservation practices in line with sustainability***

Beyond the debate about what makes a building worth preserving, where its values and significance lie (Babelon & Chastel, 1994; Riegl & Boulet, 2003), discussions on managing heritage in a context of climate change are occurring. The idea of “managing the rate of decay” seems to be the coming conservation approach

(DeSilvey, 2017). This means conserving without curing or erasing decay, but slowly letting buildings adapt and transform as the environment affects them. In a sense, conservation is not about deciding whether to preserve or destroy, neither about fixing a building in place (Germann & Schneel, 2014). This goes somehow along Ruskin’s idea, who advocated to “watch an old building with an anxious care” and against any strong intervention on the fabric, as buildings “belong partly to those who built them, and partly to all the generation of mankind who are to follow us” (Ruskin, 2011, p. 104).

Besides, in a context of climate change where environmental sustainability and the use of more green energy are encouraged, the use of more sustainable materials is necessary. First of all, lime, which consumed less energy to be produced than cement or concrete, is a good sustainable material (Sickels-Taves & Allsopp, 2005), along with being a historical and traditional one. Besides, reuse of materials from masonry or waste, for instance, sand, ash, ceramic or brick can be encouraged (Elinwa & Mahmood, 2002; Kavas & Olgun, 2008; Jiménez *et al.*, 2013; Xu *et al.*, 2016). Replacing sand by ash for instance, is highly beneficial in a context of green specification and maintenance (Forster *et al.*, 2011). Finally, if repairs are done appropriately and therefore more durable, less is spent and more buildings can be repaired, conserved or simply managed.

## **2.4 Repointing with lime mortars: role and function**

### ***2.4.1 Definition of repointing***

Another way to classify mortar, instead of according to binder types, is by purposes of application: e.g. coating (external: render or internal: plaster), masonry (bedding, pointing, grouting) or adhesive (for tiles or floor panels). Pointing and repointing mortar fits into the category of masonry mortar, as defined by the RILEM

classification (TC-167COM) given by Hughes and Valek (2003). Bedding mortar serves to assemble stone masonry together, with vertical (perpends) and horizontal (beds) joints, and pointing mortar refers to the surface of the joint (Fig. 2.7). When a masonry wall is built, it often happens that the bedding and pointing mortars are the same. Over time, when the surface of the joints weather or when the wrong mortar has been used in previous conservation interventions, it is necessary to remove the defective mortar and to replace it with fresh mortar that will harden. This repair intervention is called repointing (ASTM, 2012). In conservation, pointing and repointing are sometimes employed to design the same mortar, which is then a repointing one as the original mortar would have decayed. Pointing is then the general term for “surface joint”.

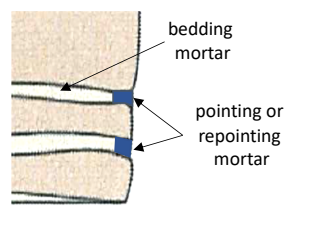


Figure 2.7. Localisation of bedding, pointing and repointing mortars (by the author)

The general definition of repointing is the process of filling the external part of an existing masonry mortar joint with a new mortar that may differ in composition from the existing bedding mortar, as defined by Maurenbrecher (2012) and Historic England (Pickles *et al.*, 2017) (Fig. 2.7). Several practical guides to repointing have been published over time (Table 2.6), comprising explanation of material choices, description of best workmanship - mixing, application and reasons for repointing. Other guides to repointing are often included into general technical notes on repair mortars.

It is often said that repointing, or restoration, mortar is a ‘sacrificial’ material (Pavía, 2005; Torney *et al.*, 2015). On one hand this is because salt deposition and

frost will cause faster decay of the mortar than of the stone (Wedd & Westbury, 2002), and on the other hand because it is easier to repair than building stone. However, careful repointing done by skilled practitioners should be durable for many years, contributing to the preservation of the entire building (Mack & Speweik, 1999; Maurenbrecher *et al.*, 2007; Pender *et al.*, 2014).

Table 2.6. Summary on specific literature about repointing available

<b>References</b>	<b>Publisher</b>	<b>Audience</b>
Repointing mortar joints in historic masonry buildings (Mack & Speweik, 1999)	Stone World	Practical guide for US contractors
Repointing mortars for older masonry (Maurenbrecher & Rousseau, 2000)	The Canadian Architect	Technical notes for Canadian contractors
Repointing stone and brick walling (Wedd & Westbury, 2002)	SPAB	Short practical guide UK contractors
Standard Guide for Repointing (Tuckpointing) Historic Masonry (ASTM, 2012)	ASTM E2260-03	Technical American standard
RILEM TC 203-RHM: Repair mortars for historic masonry. Requirements for repointing mortars for historic masonry (Maurenbrecher, 2012)	RILEM	Scientific and technical publication
Repointing Brick and Stone Walls - Guidelines for Best-Practice (Pickles <i>et al.</i> , 2017)	Historic England	Practical guide for UK contractors

#### **2.4.2 Functional role of mortar joints and repointing in masonry**

Repointing has essentially two effects: it impacts on the appearance of the overall building and contributes to its overall durability. Figure 2.8 illustrates the ideal pathways movement of moisture out of mortar joints. One of the primary functions of mortar in a solid masonry wall is to manage the movement of moisture, in particular to mitigate the penetration and accumulation of rainwater within the wall (Maurenbrecher *et al.*, 2007). Once it has entered, moisture should leave a masonry by evaporation to help it dry out (Hall *et al.*, 1984; Hughes, 1987). For this

reason, mortar joints should be more permeable than the surrounding masonry units to draw moisture out of the wall (Rirsch & Zhang, 2010; Maurenbrecher, 2012) and permit evaporation of moisture (Hughes, 1987). The use of lime mortar is therefore essential as it is indeed able to easily absorb moisture (Gibbons, 2003). During evaporation harmful soluble salts are brought to the surface of the joints, as shown in Figure 2.8, and therefore taken away from the masonry which contains important historic stones (Holmes & Wingate, 2002).

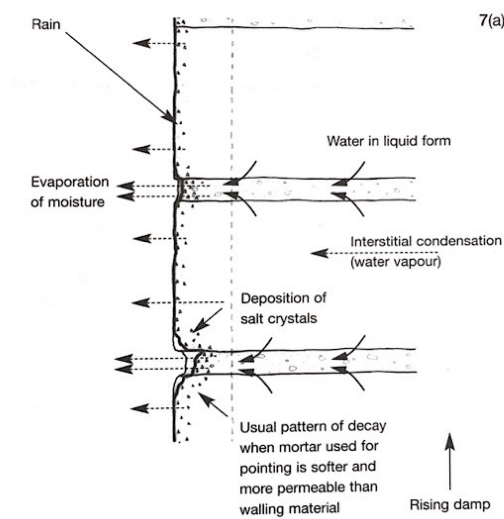


Figure 2.8 Schematic representation of the ideal pathways of moisture out of mortar joints (after (Wedd & Westbury, 2002), drawing Nicola Westbury)).

Many studies have concluded that pointing mortar is an important contributor reducing water penetration (Hughes, 2012) and could often solve problems of dampness by assuring good water resistance (Young, 2007). When done correctly, some practical guide mention that repointing intervention is the most significant repair to assist waterproofing of a wall and physically stabilising the stones in the masonry (Mack & Speweik, 1999). However, practical surveys have also shown that excessive water absorption leads to the pointing and bedding mortars absorbing more water than they can lose by evaporation (Young, 2007). For repointing mortar to effectively contribute to mitigate rain ingress and improve evaporation, the right balance in composition needs to be found. In this sense, as Forster (2010) concludes,

the performance of the pointing mortar is critically important in ensuring the durability of the entire masonry.

### 2.4.3 The importance of workmanship

The success and good performance of mortar has long been identified as fully dependent on good workmanship, as explained in the practical guides listed above (Table 2.6) and by expert masons. Most of the steps of best-practice workmanship to repoint a masonry wall are detailed below (Table 2.7):

Table 2.7. Summary of best-practice for repointing mortar

<i>Steps</i>	<i>Explanations</i>
Preparation of fresh mortar mixes	Mixing carefully measured materials together with water to obtain an homogenous workable fresh mortar, using a paddle mixer or mortar mill, and a trowel to check that the desired consistency is obtained (Mack & Speweik, 1999; Maurenbrecher, 2012). Left to rest and remix 10 minutes if necessary (Burns, 2018).
Preparing the joints	Clearing the joints from the previous mortars using masonry chisels or other tools, leaving a square-cut joint. The joints must be dampened before application of new mortar so that suction from the surrounding masonry is reduced (Pickles <i>et al.</i> , 2017).
Filling the joints	Using pointing tools, making sure the joints are carefully filled and good compaction and pressure are given to the mortar to prevent voids (Burns, 2018).
Finishing the joints	Finishing the joints for aesthetic and to ensure resistivity to water (Kenneth, 1995) while they start to harden but are still damp. Flush finishing is the most common one but others exist (Ashurst & Dimes, 1998).
Protection and maintenance	Protection from wind, rain, strong sunlight and frost is essential during repointing (Pickles <i>et al.</i> , 2017). After completion, protection of the joints with a damp cloth is preferable to avoid early shrinkage cracks (Burns, 2018).

Rondelet, a leading French architectural theoretician, pointed out in his *Art de Bâtir* in 1803 that the good performance of Roman mortar results from good workmanship and care as well as the use of good and appropriate materials (Rondelet, 1803). Indeed, research has shown that the amount of lime used in the mix influences the porosity: porosity, especially capillary pores, increases when the water:lime ratio increases but it also decrease the strength of the mortar (Arandigoyen *et al.*, 2005). Figure 2.9 illustrates how workmanship contributes with other factors to the performance of masonry. It has also been shown that good workmanship, following the steps listed in Table 2.7, can significantly influence the water resistance of joints (Newman, 1989; Ashurst & Dimes, 1998; Groot & Gunneweg, 2010).

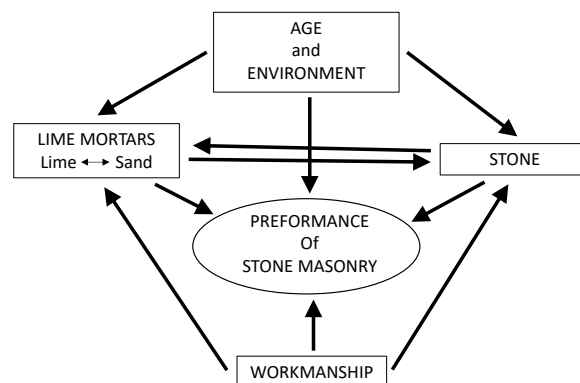


Figure 2.9. Stone and lime mortar interaction and influencing factors (after (Hughes & Válek, 2003) after Bartos & Lawson, 1996).

## 2.5 Design of repair and repointing mortar: technical requirements for conservation

### 2.5.1 Design framework and methodologies developed

The design of repair mortar usually follows one of three main approaches (Hees, 2012): the identical reproduction of the original historic mortar; the production of a new mortar mix based on the characteristics of the existing mortar,

such as permeability and porosity (Sapin, 1991; Gibbons, 2003); or the creation of a completely new mix, compatible with the existing masonry and designed for a specific conservation purpose.

In conservation of historic buildings, it is often the case that a new repair mortar is created, for two main reasons. Firstly, the performance requirements of the repair mortar may be significantly different than those of the original mortar (Teutonico *et al.*, 1993), for instance the climate has changed or the masonry has decayed faster due to previous wrong interventions so that the mortar needs to respond to the current circumstances of the building (Wedd & Westbury, 2002). Secondly, the original mortar cannot always be reproduced (Gibbons, 1995), due to the non-availability of the same raw materials – i.e. lime not being produced anymore, sand quarry close or the material currently available have different properties (Moropoulou *et al.*, 2005). Another important factor is the impossibility of accurately characterising the original mortar. This may be because the physical composition of mortars modifies over time as they interact with the environment (Leslie & Hughes, 2002); or because of the complexity of the historic mortars produced at variable firing temperatures leading to variations in hydraulicity (Forster, 2004). In addition, historically, repointing or pointing mortar were often made with a different material than the bedding mortar and were also replaced over time, so that the original pointing mortar may not be available anymore, e.g. in Roman Gaul (Coutelas, 2009).

In general, research emphasizes that the design of repair mortars should be based upon practical experience and historical sources (Bear and Miller, 2018) and that decisions should be made based on knowledge of the materials to which they are applied (Rota Rossi-Doria, 1986), as well as the nature and conditions of the masonry (Teutonico *et al.*, 1993). A “design process” has to be adopted (Moropoulou *et al.*, 2005). However, not all research adopts the same approach to designing repair

mortars and various parameters have been considered. For instance, Veiga (2001) proposes a methodology with the following steps:

- Determination of the physical and mechanical characteristics of the original mortars,
- Preparation of mortar with similar composition and appearance to the original ones,
- Testing to verify similarity,
- Repetition of 1 to 3 until fundamental characteristics and adequate performance are achieved,
- Experimental application in-situ,
- Correction of new composition if necessary,
- Corrections of application specification.

The cycle methodology proposed does not however mention the specificity of the masonry or the environment or how to evaluate what performance is required.

Because mortar can never be fully replicated, Forster (2010) recommends a “performance-based approach” which aims at using both the performance and characteristics of the existing mortar and of the masonry to guide the design of a new mortar, aiming at a desired performance. Additionally, Forster and Carter (2011) discuss the use of durability classes (based on strength) as a tool to make decisions on the type of NHL to use, refining the classification so that the selection process should involve the location of the building and its surrounding climate. While developing a framework for decision-making on the use of NHL (Fig. 2.10), they emphasize that the decision making-process towards the composition of a new mortar should be based on many parameters, including: a survey of the masonry conditions, the surrounding climate and the durability classes.

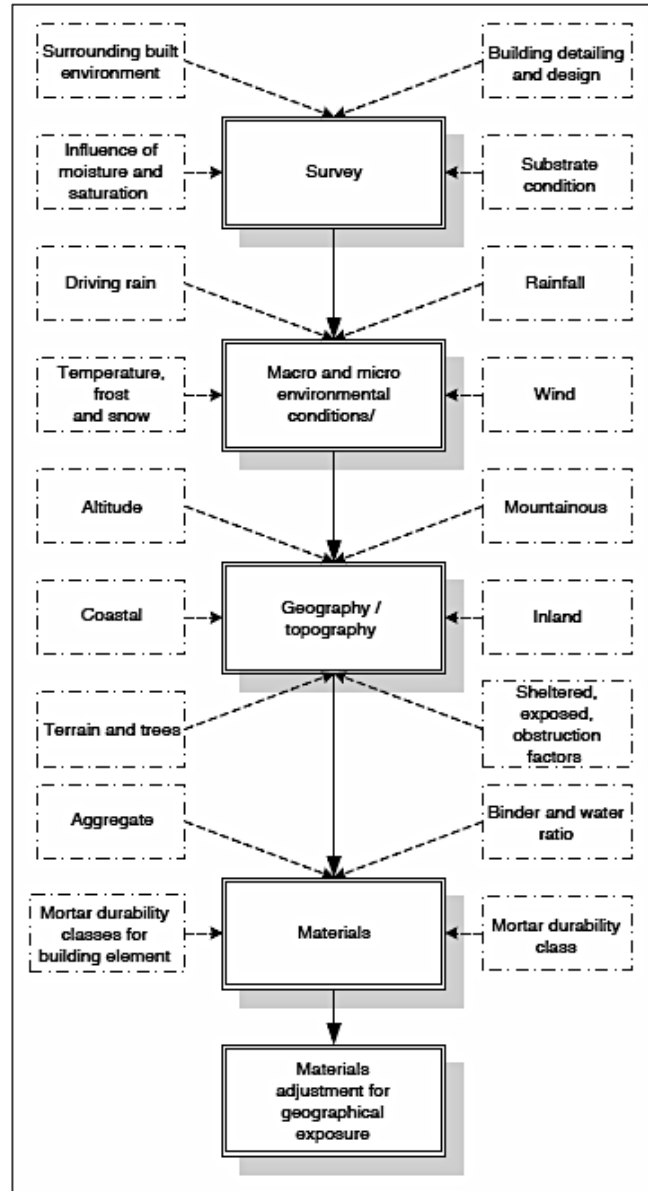


Figure 2.10. Selection process for hydraulic lime mortars after (Forster & Carter, 2011).

Van Hees introduces to this process a broader consideration of factors including conceptual, functional and technical requirements (Figure 2.11). Along those lines, Maurenbrecher (2012) also gives a good overview of various factors to take into consideration, such as the appearance of the mortar. Similarly to Forster & Carter (2011), he suggests that before repointing one should assess the masonry and material deterioration, to evaluate the type of climatic exposure and to use the original mortar “as reference”.

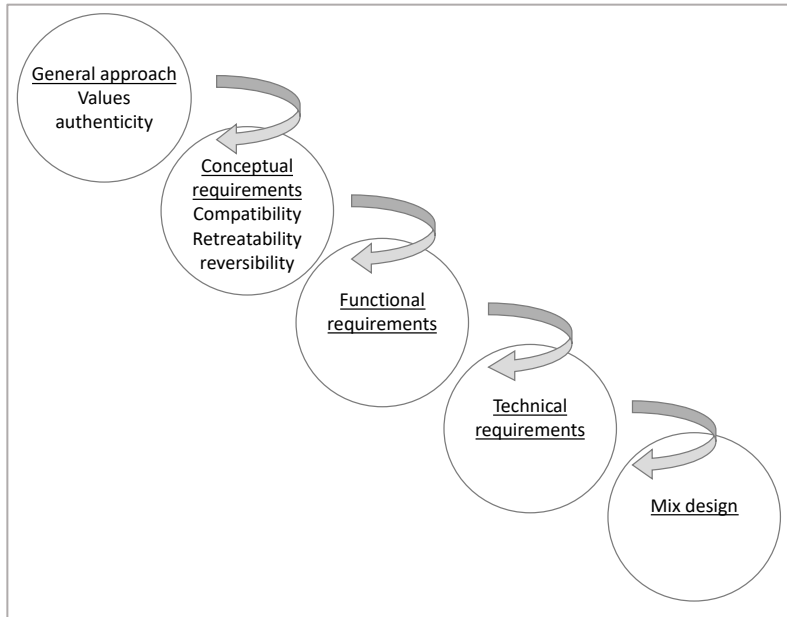


Figure 2.11. Framework for interventions requirements on historic buildings (after (Hees, 2012)).

These various methodologies developed are useful frameworks when considering the design of new repair mortars. However, Veiga (2001) focuses on the replication of the characteristics of the original mortars, where if not available, cannot be taken into account, but interestingly suggests to correct the designed mix if necessary. Forster & Carter (2011) have developed a useful framework to decide on which NHL. If combined with the performance-based approach suggested by Forster (2010), all three factors are considered: the original mortar, the masonry type and the geography. However, the framework developed can be complicated as it requires a survey of the conservation issues of the buildings and a full evaluation of the micro and macro climate and surrounding topography. Van Hees' approaches is simpler, but by being wider it does not detailed what functional, technical and conceptual requirements precisely mean, and consideration of the environmental context to check the effectiveness of the newly designed repair mortar is missing. A simpler but focused approach is perhaps necessary, one that would help carefully design, evaluate new repair mortars to optimise their performance and validate whether they would fit specific environmental and technical (conservation issues

and masonry type) requirements, while considering the conceptual, philosophical and functional requirements of conservation.

### **2.5.2 Overview of repair mortars**

Many studies have been done which have designed a series of repair mortars, characterised them through a series of tests and selected the most suitable one(s). Table 2.8 gives a non-exhaustive overview of repair mortars that have been evaluated as being suitable after such research. The table highlights the range of materials - lime, aggregates and additives -, ratio that can be used to design repair and repointing mortars. However, as Table 2.8 shows, few mortar formulations are specifically designed for repointing, and many are not specific on what the function of the designed mortar will be (Faria *et al.*, 2008). Much research on repair mortar are to be used for stone repair only (and not presented in Table 2.8), using a range of non-hydraulic limes (Myrin & Balksten, 2006; Beck & Al-Mukhtar, 2008) or NHLs (Bianco *et al.*, 2013; Gulotta *et al.*, 2013). In general, ready-mix are shown to be not suitable for conservation (Szemerey-Kiss & Török, 2017). In addition, much research do not specify an environment or a masonry type or give one and not the other, which makes replication of these repair mortars difficult to use for another research. The ratio for repointing is usually 1:3 (Henry & Stewart, 2012), and seems to be generally the one adopted. The table therefore shows the variety of repair and repointing mortars being designed, but also the clear gaps in framing their design.

Little specific research has been done on designing lime mortars for granite or other low-permeability stone masonry. Previous research suggests the use of a range of binders: from cement mortar, to NHL gauged with non-hydraulic quicklime to non-hydraulic quicklime alone (Hughes *et al.*, 2008). Wedd and Westbury recommends the softest and most permeable mortar possible (2002) as most of the movement of moisture occurs through the joints and not the dense masonry.

Table 2.8. Overview of repair mortars that have been found successful and most suitable for conservation and repair on historic masonry, classified by binder type from non-hydraulic to hydraulic.

<b>General repair mortar (mainly mortar joints)</b>					
<i>Binder</i>	<i>Aggregate</i>	<i>Additives</i>	<i>Ratio</i>	<i>Environment / masonry / reasons for being suitable</i>	<i>References</i>
Quicklime lime from lump (Buxton)	flint gravel	brick dust	1:3:0.5 and 1:2:1	weak limestone exposed masonry	(Stewart <i>et al.</i> , 2001)
Quicklime + lime putty	river sand	organic and inorganic origin (not precised)	1:3	good resistance to wetting and drying cycles	(Sumanov <i>et al.</i> , 1995)
Lime putty from quicklime or hydrated lime			1:3 and 1:2.5	not for harsh environment	(Teutonico <i>et al.</i> , 1993)
		brick dust	1: 3:1 or 0.5		
			1:2.5	more durable in exposed environment	(Pavía & Treacy, 2006)
16 months lime putty from quicklime			1:2	good workability and resistance to salts	(Faria <i>et al.</i> , 2008)
Non-hydraulic hydrated lime (lime powder)	siliceous sand and crushed brick		1:1.8		(A Moropoulou, A Bakolas, <i>et al.</i> , 2005)
		ceramic powder	1:2:1		
	river sand		1:3 and 1:2.5	not for harsh environment	(Teutonico <i>et al.</i> , 1993)
		brick dust	1:3 and 1:2.5		
		lignin sulfate	3:9:0.6 or 0.8		(Katsioti <i>et al.</i> , 2009)
		greek natural pozzolans	1:3		(Stefanidou, 2016)
		metakaolin	0.7:3:0.3	Prague	(Valek & Slížková, 2005)
	not specified	jarosite/ alunite precipitate from 0 to 50% lime replacement	not said		(Katsioti <i>et al.</i> , 2009)
Non-hydraulic lime powder CL90 (Calinsa S.A)	pure limestone sand		1:1	high RH	(Lanas <i>et al.</i> , 2005)
	river sand	nopal (cactus)	1:3	Exposed conditions avoid mortar decay under rain	(Ventol <i>et al.</i> , 2011)
		olive oil	1:3	Exposed conditions gives impermeability	

Non-hydraulic lime powder (BASF) + Volcanic pozzolan (S&Bl-silica)	siliceous sand	82% pure calcium stearates 1% of binder and powdered silane 1.5%	1:3	good water-repellent	(Falchi <i>et al.</i> , 2013)
Non-hydraulic lime powder CL90 + Portland cement (CEM II-A/L 32.5)	calcite aggregate (crushed stones)		high cement content	to be more suitable for durability to moisture	(Arandigoyen & Alvarez, 2006)
			lime-rich mortar	higher plastic deformation	
NHL (Unilit Gruppo) + quicklime (Buxton)	flint gravel	pozzolan in lime	1:1:6	robust limestone masonry, Dorset	(Stewart <i>et al.</i> , 2001)
NHL (Unilit Gruppo)	sand		1:5, 1:4, 1:3, 1:2.5		(Teutonico <i>et al.</i> , 1993)
		brick dust	1:5:1, 1:4:1, 1:3:1, 1:2.5:1		
	flint gravel	pozzolan in lime	1:3	robust limestone masonry, Dorset	(Stewart <i>et al.</i> , 2001)
NHL 3.5-Z (Chaux blanche)	medium aggregates	pozzolan in lime	1:2.3		(Kalagri <i>et al.</i> , 2014)
	siliceous sand	crushed brick	6:14	Crete	(Maravelaki-Kalaitzaki <i>et al.</i> , 2005)
NHL 5 (St Astier)	fine river sands (Rhin), coarse river sand (rhin gros)				(Isebaert <i>et al.</i> , 2016),
	Fine, medium and coarse aggregates		1:2.3		(Kalagri <i>et al.</i> , 2014)
	well graded sand (normen sand)				(Isebaert <i>et al.</i> , 2016)
HL2 with additives (Chaux de Paviers)	flint gravel		1:3	robust limestone masonry, Dorset	(Stewart <i>et al.</i> , 2001)
HL5 (Chaux Bruyeres)	pure limestone sand		1:1	high RH	(Lanas <i>et al.</i> , 2005)
<b>Specifically designed for pointing / repointing</b>					
<b><i>Binder</i></b>	<b><i>Aggregate</i></b>	<b><i>Additives</i></b>	<b><i>Ratio</i></b>	<b><i>Environment / masonry - reasons</i></b>	<b><i>References</i></b>
Non hydraulic quicklime (Singleton Birch)	sand		1:4	granite masonry	(Hughes <i>et al.</i> , 2008)
75% Non-hydraulic lime + 25%	limestone aggregate	brick dust (5%)	1:3	limestone masonry (Ireland)	(Pavía, 2005)

magnesium hydroxide					
Non-hydraulic lime		brick dust (1%)	1:3	limestone masonry (Ireland)	
NHL 2 (St Astier)	well graded sand		1:2.25		(Schork <i>et al.</i> , 2013)
NHL 3.5	limestone aggregate	brick dust (1%)	1:2	limestone masonry (Ireland)	(Pavía, 2005)
NHL 3.5 (St Astier)	well graded sand		1:2.25		(Schork <i>et al.</i> , 2013)
NHL 3.5 + lump quicklime (Singleton Birch)			1:4	granite masonry	(Hughes <i>et al.</i> , 2008)
NHL 5 (St Astier)	well graded sand		1:2.25		(Schork <i>et al.</i> , 2013)
NHL 5 + lump quicklime (Singleton Birch)			1:6	granite masonry	(Hughes <i>et al.</i> , 2008)
Portland cement	River sand	plasticizer	1:9		(Duffy <i>et al.</i> , 1993)
		wrda1 27 (Canada)	1:9	good mechanical property and low salt content	(Mosquera <i>et al.</i> , 2002)

### 2.5.3 Technical requirements and criteria for design of new repointing

#### mortars

Researchers, practitioners and scientists agree that the design of a new repair mortar, which introduce materials that differ from the original ones, should follow the fundamental principal of compatibility. Compatibility refers to the appropriateness of fit visually, physically and chemically, both with the existing masonry (Schueremans *et al.*, 2011) and its intended use (Henry & Stewart, 2012). Van Balen *et al.* suggest that compatibility can also be achieved through the sacrificial aspect of repointing mortar, which means that the porosity of the new mortar can be predefined to absorb as much salt as possible so that the mortar will decay rapidly (Van Balen *et al.*, 2005). In this case, the physical and chemical compatibility would not be fully met. Compatibility also refers to respecting the original aesthetic and design of the fabric, its authenticity (ICOMOS, 1994).

Technical criteria have been set to define priorities when selecting repair mortars. For instance Peroni *et al.* (1981) (quoted in (Hughes & Válek, 2003)) give a range of porosity and compressive strength to be achieved but does not give a range for water absorption or water vapour permeability and sets modulus, alkaline element, setting time and flexural strength as also being key criteria. They also do not specify whether different types of repair mortar (for instance repointing) would have different criteria.

Rodrigues and Grossi (2007) have established a “ranking system” based on compatibility indicator of different conservation material. For a repair mortar they suggest to consider the composition (e.g. type of binder, forms of the aggregates), the physical and mechanical parameters (e.g. porosity, capillarity, water vapour permeability, strength), the durability and workability as factors of compatibility. For each properties of the materials they give a low, medium or high risk of incompatibility: for instance, a different binder for the repair mortar represent a high risk of incompatibility. This useful, although complex ranking system, enables to develop repair mortar in complete relation with the original masonry.

Hughes (2012) sets clear requirements to be met to fulfil the desired performance of the mortar, in relation to its function. For pointing mortar, all factors are important - appearance, deformation, adhesion, water penetration resistance, vapour transmission, freeze-thaw resistance, wetting and drying behaviour – while strength and thermal dilatation are the least important parameters (Table 2.9). The rating system developed here is very useful when designing a new repair mortar as it helps to focus on the right and key properties. However, it would have been interesting to have more explanation on how the ranking of the criteria was defined. Compressive strength of NHL is often used to make-decision about which type of NHL to use in relation to a masonry, so that the mortar is softer than the stone masonry (Allen *et*

*al.*, 2003). However as Peroni *et al.*, Rodrigues and Grossi, Hughes and Forster & Carter show, strength should not be the only technical criteria.

Table 2.9 Technical requirements for different classification of repair mortars (after (Hughes, 2012)).

**Table 1** Technical requirements versus classification of mortar

Technical requirement	Mortar type classification						
	Bedding	Pointing	Render	Grout	Plaster	Flooring	Surface repair
Adhesion to substrate (bond)	3 2?	3 2?	3	2	3	2	3
Strength (compressive, flexural, tensile) and hardness	2 <sup>a</sup>	2 <sup>a</sup>	1 <sup>a</sup>	2 <sup>a</sup>	1 <sup>a</sup>	3 <sup>a</sup>	2 <sup>a</sup>
Deformability and elasticity (E modulus)	3	3	2	3	1	2	3
Weather protection							
Water penetration resistance	2	3	3	1	1	2	3
Freeze–thaw resistance	2	3	3	1	0	3	3
Thermal dilatation	1	1	3	1	3	1	3
Vapour transmission	2	3	3	1	3	2	3
Wetting and drying behaviour	2	3	3	1	2	2	3
Aesthetic	1	3	3	0	3	3	3

The rating scheme is 0 = no importance to 3 = very important

<sup>a</sup> In relation to the substrate, the strength and stiffness values for mortar should be less than the masonry units

In buildings which are highly exposed to driving rain, additional technical requirements are necessary for repointing mortar. Mainly, the mortar joints should draw moisture out of the masonry by being more porous than the surrounding stones (Rirsch & Zhang, 2010) so that permeability, water absorption and desorption are key parameters. It has also been seen that mortar for used in very exposed parts of a building should be stronger than those used in more sheltered areas (Wedd & Westbury, 2002).

## 2.6 Summary and implications

This review of the relevant conservation, technical, practical and scientific literature has helped defined why and how repointing could be effective to mitigate water ingress through historic masonry and contribute to a less damp interior. It highlighted the wide range of materials used in the composition of lime mortar and how their individual properties can affect the overall performance of the mortar. It also emphasized the importance of good workmanship in the effectiveness of the

mortar. This review pointed out that the design of new repair mortar should follow a specific methodological approach, taking into account various parameter such as the masonry type and the environment, but that a comprehensive, clear but simple method would be necessary to design, evaluate and validate new repointing mortar for historic building in exposed environments.



## III - RESEARCH FRAMEWORK AND METHODOLOGICAL APPROACH

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The thesis is articulated around three axes which relate to the three objectives: optimisation, evaluation and validation of repointing mortar for dense exposed masonry, which together builds up to answer three research questions: 1. What would be the most effective mortar to repoint hard stone masonry in exposed locations? 2. How do the environmental conditions found on-site affect these mortars? 3. Can these repointing mortars mitigate driving-rain ingress? These axes form the three main objectives on which each study (Chapters IV, V, VI) is based and for which a specific methodology was developed.

### 3.1 Framework

Each objective as defined in Chapter I is the result of identified knowledge gaps within a specific context: highly exposed dense masonry with a need for minimal intervention, in combination with desirable properties of repointing mortars: low absorption, high drying rate and ability to set under damp conditions. The three objectives are characterised by increasing realism. Material optimisation focuses on testing materials under laboratory conditions; evaluation of environmental impact subjects these materials to conditions similar to those found in the field; whilst validation in masonry systems involve materials in test walls subject to realistic environmental conditions. Three studies were developed to help address the three objectives. Each study corresponds to a chapter of the thesis and is a stand-alone manuscript, accepted by or submitted to a peer reviewed journal. The status of the paper is presented at the beginning of the corresponding chapter, along with the names of co-authors who have contributed some elements. The bulk

of the work presented in the three studies has been carried out by the author of this thesis (as explained by the co-author statements in Appendix B).

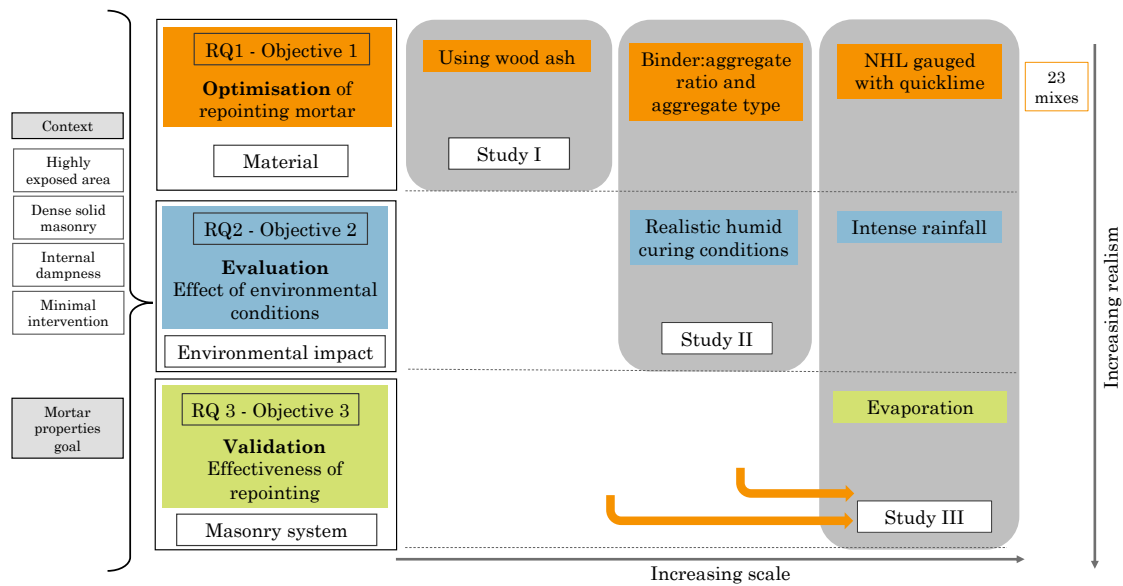


Figure 3.1 Diagram of the structure of the thesis. Arrows show that Study III builds on findings from Study I and II.

Figure 3.1 presents the framework of the thesis and how the three studies address objectives 1 to 3 as well as the key elements that are covered by each study. The development sequence in this thesis builds on each study. The optimisation of repointing mortar is addressed over all three studies, whereas objective 2, on evaluation, is addressed by Study II and III and objective 3, on validation, is mainly addressed by Study III. The mortar mixes chosen for Study III were based on findings from Study I and II. Over the three studies, both the scale and the realism, increase, from mortar samples only, to samples and environmental conditions, to test walls. Together, conclusions and discussion from the three studies and from the thesis help answer the three research questions.

### 3.1.1 Research collaborations

This research builds on the “Damp Towers project”, commissioned by English Heritage and started in 1989 (Wood, 2012; English Heritage, 2013). It looked at four

scales: building investigations and monitoring of churches affected by dampness over 15 years (Wood, 2013); large-scale assessment of the influence of workmanship on purpose-built test walls (Wood, 2010); medium-scale evaluation of different remedial treatments and identification of pathways of moisture ingress using small test walls with a rubble core (Laycock & Wood, 2014); and small-scale testing of mortar cylinders in laboratory, looking at the water movement through these (Wood, 2010). This extended research project concluded that more investigation of the design of repointing mortars for controlling moisture ingress was necessary. These conclusions were used to identify research needs and build the aim of this thesis. The potential for the use of wood ash was also highlighted by the “Damp Towers” project and further investigated by a pilot study (Appendix B). However, the broad scope of the “Damp Towers” research could not be followed-up in this smaller-scale research project and the methodological approach was adapted through the use of smaller mortar samples and single layer test walls, to limit variables, allow repeatability and focus on material understanding.

The thesis research was therefore developed in collaboration with Historic England and the Churches Conservation Trust (CCT); which is the national charity protecting churches at risk, and supported by the Engineering, Physical Science Research Council, Centre for Doctoral Training in SEAHA (Science and Engineering in Arts, Heritage and Archaeology). From this collaboration, an advisory team was created comprising a conservation architect, a conservation officer, a stone mason and a material scientist who advised on materials to test, experiments to set-up and more importantly on practical on-site challenges. Several visits to churches affected by damp issues in Devon, some of them monitored during the “Damp Towers” project, were organised which were essential in gaining understanding of the

conservation issues faced by churches in extremely wet environments and contributed to the choice of a specific case study area.

### ***3.1.2 Case study area***

Through the collaboration with both Historic England and the CCT, and following the “Damp Towers” research, an area of South-West England, specifically North Devon, and a case study building, St Petrock’s Church in Parracombe (51°11'0"N, 3°54'0"W) (Fig. 3.2), were defined. The church was built in the 13<sup>th</sup> Century and is a Grade I listed building consisting of stone rubble with large granite ashlar dressing (Fig. 3.3) and slate roof (Historic England, 1965) and sits on a hill. It is under the care of the CCT since 1971. Interestingly, in 1879, after fears for its stability were expressed, its demolition was proposed. However, John Ruskin led protests and donated £10 to support the preservation of the church and build a new one nearby (The Churches Conservation Trust, 2018).

The church was chosen as a case study for its isolated location and exposure to wind and high rainfall resulting in on-going internal dampness (Fig. 3.3). The closest weather station is Chivenor (51°5'20"N, 4°8'49"W) which gets 1200 to 1500 mm of annual rainfall (Met Office, 2018). In addition, the tower was repointed and grouted in 2006-07 and monitored during the “Damp Towers” project in 2008-09, showing high moisture content throughout the elevation of the tower, especially on the north and west sides. Grouting was identified to have helped the masonry to dry (Wood, 2010), however, internal dampness was still clearly visible ten years later (Fig. 3.3). In this regard it represents many Devon churches. This case study defines the realistic conditions used in Chapter V (Study II) and the types of stones used in Chapter VI (Study III).

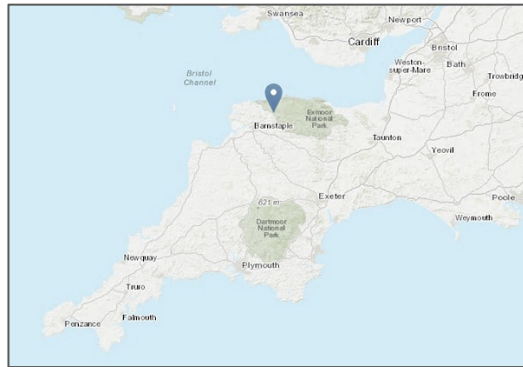


Figure 3.2. Location of Parracombe in North Devon



Figure 3.3. St Petrock's Church, Parracombe. Views of the tower, a buttress and the internal dampness on the West wall.

## 3.2 Methodological approach to mortar optimisation, evaluation and validation

### 3.2.1 A multi-step, multi-method, performance-based approach

In order to optimise, evaluate and validate repointing mortars for exposed masonry this research uses a multi-method, tailored methodology. It combines traditional practice for the preparation of samples, standard material tests methods, some specifically designed laboratory experiments, test wall trials and consideration of historical sources.

Laboratory characterisation (on samples or test walls) enables researchers and practitioners to ensure that selected repair mortars are physically compatible with the masonry unit (Schueremans *et al.*, 2011), and fulfil the technical requirements

of a specific environment (Lindqvist, 2009). It is therefore important that the methodology is designed in relation to a case-study site and a context, and in knowledge of what the ideal performance of the repointing would be (Hees, 2012), for instance in this thesis, capacity to set and dry quickly.

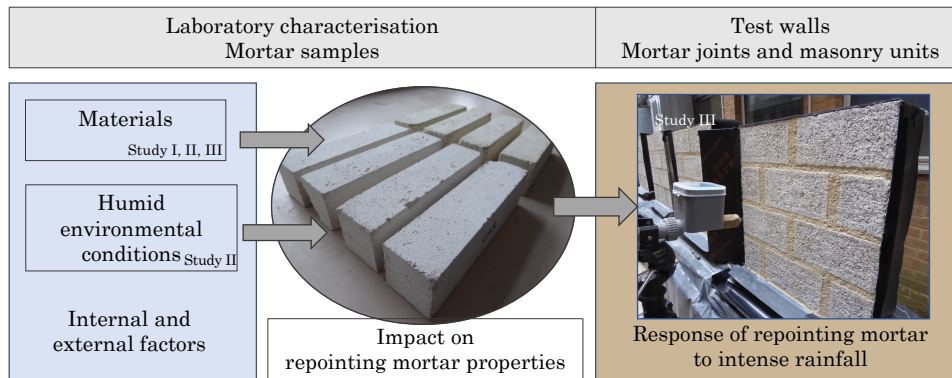


Figure 3.4. Performance based and multi-method approach of the methodology

Figure 3.4 shows how the three studies use different steps of the methodology proposed to characterise and evaluate the mechanical, physical and chemical properties of lime mortars as well as their performance. This methodology takes the “performance-based approach”, suggested by Forster (2010), a bit further. As suggested, it proposes to inform the design of the new mortar based on the characteristics of the existing masonry whilst rather than taking into account the characteristics of the original mortar that has weathered or is not appropriate anymore, considers the environmental conditions in which the mortar will be used. The approach helps find the best and tailored way to assess and specify lime mortars and to draw practical implications and conclusions for a specific building context. By focusing on performance the methodology is designed to target properties in mortar mixes to find which ones would fit the requirements of the ideal repointing mortar for exposed dense masonry (as listed in Chapter I). This methodology enables assessment of the impact of internal and external factors: materials used in the composition of the mortar mixes and the humid environmental conditions, on a

range of properties and to determine how these mortar mixes respond to a specific weather phenomenon: intense rainfall (Fig. 3.4).

### ***3.2.2 Elaboration of mortar mixes: decision-making and workmanship***

Involving an experienced mason in the project (Colin Burns) enabled the setting of criteria about best-practice and workmanship (as listed in section 2.4.3). The design of each studies, and especially decisions on which materials to use was done in discussion with a conservation officer to ensure materials were both available and used in conservation work. For each study, multiple steps were needed from decision-making of the mixes and samples preparation to testing. A summary of the preparatory steps, until the samples were ready for testing, is given below for each study, with Figure 3.5 as illustration of the process to prepare mortar samples.

#### Study I:

- Advice from practitioners about the potential of using wood ash and which one, building from the Damp Towers project.
- Archival research for historic evidence of the use of wood ash in previous mortar compositions.
- Purchase of materials.
- Sample preparation with expert masons (Fig. 3.5 and Table 3.1).
- Laboratory characterisation following standards and other tests (Table 3.2).

#### Study II:

- Advice from practitioners about materials, decision to use NHL 2.
- Visit of CCT churches in Devon (Princetown, Parracombe, Bradstone).
- Collection of environmental data for a case study area (inland Devon).
- Purchase of materials.
- Sample preparation with masons (Fig. 3.5 and Table 3.1).

- Laboratory characterisation at different ages and different conditions following standards and adapted methods.

Study III:

- Advice from practitioners about building test walls without having a large controlled chamber while limiting variabilities during the experimental test and ensuring it was feasible in terms of data collection and accuracy. From their advice, both the designed (as explained in Chapter VI) and the experiment were decided.
- Building of test walls in Cornish granite with masons.
- Choices of mixes building on findings from Study I & II.
- Purchase of materials.
- Sample preparation with masons (Fig. 3.5 and Table 3.1).
- Experimental design to simulate intense rainfall.
- Use of non-destructive technologies to assess moisture temporal level and location within the walls.
- Laboratory characterisation of mortar samples. Further explanation of the experimental design to simulate rainfall is given in chapters IV, V and VI.

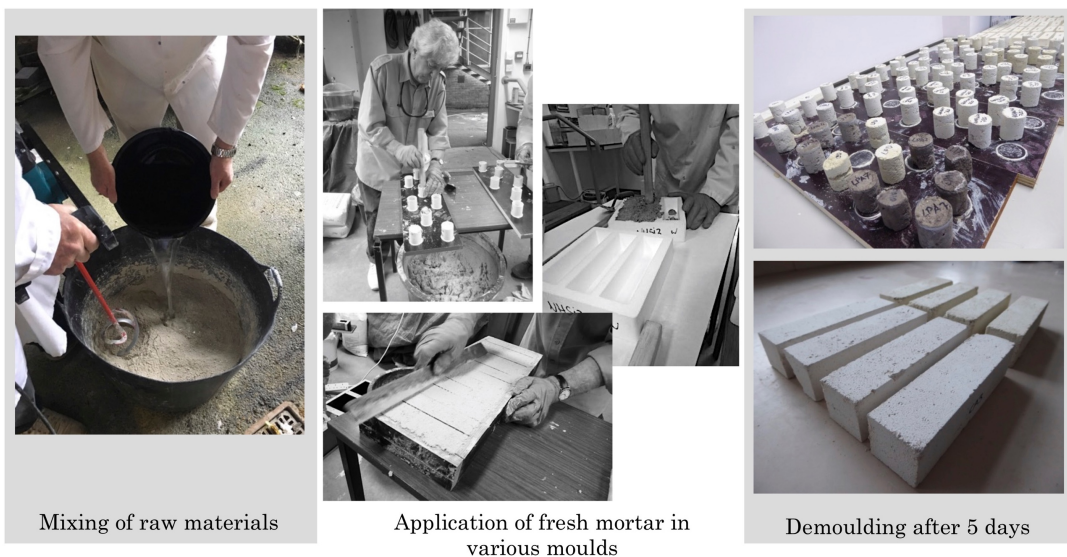


Figure 3.2 Overview of steps for mortar sample preparation followed by curing.

**3.2.3 Mortar compositions**

Table 3.1 summarises the twenty-three repointing mortar mixes used across the thesis. As explained previously (section 3.2.2), advice from practitioners and experts was sought to design each mix. Details of binder:aggregate ratios, material characteristics and fresh mortar properties are given in more detail in each Study (Chapters IV, V, VI).

Table 3.1. Summary of mortar mixes

Mixes	Binder	Aggregates	Additives	Study
AL0	Non-hydraulic lime putty	Quartz sand		Study I
AL1			10% wood ash	
AL2			20% wood ash	
AL3			30% wood ash	
AL4			40% wood ash	
AL7			70% wood ash	
AL10			100% wood ash	
NHL0	NHL3.5			
NHLA1		10% wood ash		
NHLA2		20% wood ash		
NHLA3		30% wood ash		
NHLA4		40% wood ash		
NHLA7		70% wood ash		
NHLA10		100% wood ash		
SSI3	NHL2	Quartz sand		Study II
SSI2				
SCA3		Crushed limestones		
SCA2				
W1	NHL3.5	Quartz sand / Calcitic sand		Study III
W2	Gauged NHL3.5 and quicklime	Quartz sand / Calcitic sand		
W3		Quartz sand	30% wood ash	
W4		Calcitic sand		
W5		Quartz sand / Calcitic sand		

**3.2.4 Summary of analytical methods used**

In all three studies, the same analytical tests were used to characterise mortar samples, on fresh and hardened mortars, following standards, whilst, where necessary, were adapted to fit the requirements of repointing lime mortars. Table 3.2 summarises the tests used and their corresponding standards or methods.

Further details on how each test was performed are given in each study (Chapters IV, V, VI) and are not explained here to avoid repetition. In each study, similar samples size were used when possible (Table 3.3).

Table 3.2. Summary of methods used for laboratory characterisation of repointing mortar. Further details are given in each study.

Type	Tests	Method
<i>Fresh mortar</i>	Consistency	BS EN 1015 5-3:1999
	Initial moisture content	Moisture analyser
<i>Hardened mortar - mechanical properties</i>	Drying shrinkage	Length comparator
	Carbonation depth	Phenolphthalein
	Compressive strength	BS EN 1015-11:1999
<i>Hardened mortar - physical properties</i>	Open porosity	BS EN 1936:2006
	Total porosity	BS EN 1936:2006 - Pycnometer
	Ultrasonic pulse velocity (Study II)	Pundit Lab, Proceq
	Pore structure	Thin sections
	Pore size distribution	Mercury Intrusion Porosimeter
<i>Hardened mortar – response</i>	Capillary absorption	EN 1925: 2000
	Water vapour permeability	EN 1015-19:1999
	Drying rate	EN 16322:2013 (for calculations)
	Moisture level	MOIST350B (2 sensors)
<i>Hardened mortar – durability</i>	Salt weathering (Study II)	(Gulotta <i>et al.</i> , 2015) modified version of RILEM MS-A.2
	Freeze-thaw (Study I)	DD CEB/TS 12390-9:2206

In this research, when possible, simple methods of characterisation and evaluation that could be easily reproducible and at minimum cost were used. Having performed the same set of characterisation methods on all mortar mixes allowed for comparison of the mortars across the three studies. However, not all test results are presented in each study (Chapters IV, V, VI). For instance, drying shrinkage is not presented in Study II and III, carbonation depth is only shown in Study II, compressive strength is not indicated in Study III and Study II does not include water vapour permeability.

Other baseline tests on mortar samples were included in Study I but not analysed further. For example, backscattered images by scanning electronic microscope (SEM) were obtained on small polished and coated samples for all mortar mixes for study I but because the polarised microscopy of thin sections provided satisfactory results, the SEM images are not presented or discussed here. Finally, for the discussion (Chapter VII), it was thought interesting to look at the pore structure of repointing mortar in comparison with the original horizontal and vertical joints so additional thin sections of these were produced, and observations presented. In addition, a cross-analysis of all twenty-three mortars, including a hierarchical cluster analysis and a tailored scoring system has been developed and are being compared in Chapter VII.

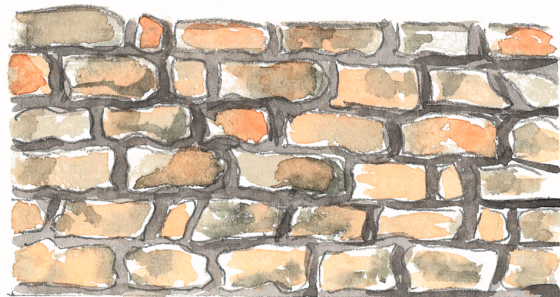
Table 3.3 Summary of mortar samples sizes and replicates

<b>Study</b>	<b>Sample size</b>	<b>Replicates</b>
I	Prisms: 40 mm x 40 mm x 160 mm Cylinders: 50 mm height x 35 mm diameter	3
II	Prisms: 40 mm x 40 mm x 160 mm	3
	Prisms: 40 mm x 40 mm x 80 mm	5 to 6
III	Prisms: 40 mm x 40 mm x 160 mm	5



# PART B

## Studies



*Granite façade in Limousin (Corrèze, France) (by MF)*



## IV- STUDY I - The effect of wood ash on the properties and durability of lime mortar for repointing damp historic buildings

This chapter is based on the published journal paper: Fusade, L. et al. (2019) The effect of wood ash on the properties and durability of lime mortar for repointing damp historic buildings, *Construction and Building Materials*, 212, pp. 500 – 513.  
doi :10.1016/j.conbuildmat.2019.03.326

### Abstract

Historical evidence shows that wood ash has been used in lime mortar to help absorb moisture from masonry walls. In this study, an experimental programme was designed to assess the impact that varying the content of wood ash has on a range of properties of lime mortar and to draw conclusions about the reasons for these impacts. Biomass wood ash was added to mortars made with natural hydraulic lime (NHL) and air lime (AL) as an aggregate replacement at different concentrations: 0% (control mix), 10%, 20%, 30%, 40%, 70% and 100%. Compressive strength, strength activity index, open and total porosity, pore size distribution, water absorption by capillarity, desorption, water vapour permeability, and freeze-thaw durability were assessed after 90 days. The results indicate that fine particles of wood ash induce a higher proportion of pores in the capillary range and a higher open porosity. This tight structure of lime and wood ash increases the compressive strength. The fine particles from the wood ash could also be responsible for the potential pozzolanic activity. Furthermore, by being hygroscopic, wood ash gives lime mortars a capacity to hold more water, resulting in a delayed capillary absorption, while retaining good desorption. The research findings imply that, used at its best potential in medium amounts (20 – 40%), adding wood ash in lime mortar gives a potentially good mortar mix for repointing masonry joints, especially in damp environments. However, in high amounts (70 – 100%) some negative effects are seen, such as high shrinkage.

## 4.1 Introduction

Lime mortar has been used since before Roman times on various constructions and under many different environmental conditions. Rondelet, a leading French architectural theoretician, points out in his *Art de Bâtir* in 1803, that the good performance of Roman mortar results from good workmanship and care as well as the use of appropriate materials (Rondelet, 1803). The choice of specific and appropriate materials to make a repair mortar has indeed not only to consider what is available locally (Forster, 2010), but also the current conditions of both the building and the masonry unit as well as the surrounding environment and climate (Hughes, 2012). The optimum combination of materials (that is, a binder, an aggregate and potentially an additive) comes from understanding the compatibility requirements of the mortar within this structural and environmental context such as for instance, similar or increased permeability, porosity higher than the surrounding stones, ability to set in specific environmental conditions, and relative resistance to frost and salts (Maurenbrecher, 2012). Good choice of materials and thorough understanding of their specific properties is therefore essential to address these conservation issues and requirements.

In buildings highly exposed to driving-rain, mortar in joints, especially repointing, should help absorb the moisture from the surrounding stones and help the masonry to dry out by evaporation, as well as prevent moisture ingress in the wall (Young, 2007; Laycock & Wood, 2014). One of the materials historically used to help the mortar fulfil this requirement is wood ash. Historic mortars frequently contain traces of ash, often as residues from combustion in the lime kiln (Allen *et al.*, 2003), but the Romans already seemed to have used wood ash in lime mortar mixes as a waterproof component, in buildings found around the Mediterranean in Syria and Jordan (Coutelas, 2009). In the 18<sup>th</sup> and 19<sup>th</sup> centuries in England and France

several experiments were carried out to try and understand and replicate Roman mortars. Practitioners, engineers and theoreticians have developed various manuals and treatises in which we can find details of compositions and recommendations on the use of different aggregates and additives, such as wood ash. In his *Narrative of the Building and a Description of the Construction of the Eddystone Lighthouse with Stone* (Smeaton, 1793), which contains some of the first modern research and experiments on lime-based mortars, John Smeaton reports the suggestion of a composition given to him by Lord Macclesfield in 1757, called the “Ash Mortar”. This is one of the first mentions of adding wood ash in lime mortar in the modern era. This mortar is reported to be much stronger “in places that are sometimes wet, and at others dry” according to Macclesfield’s bricklayers (p. 108). Brian Higgins, in 1780 in his *Experiments and Observations made with the View of Improving the Art of Composing and Applying Calcareous Cements and of Preparing Quicklime* conducted a series of experiments on the effect of wood ashes in mortar (Higgins, 1780). The reasons he gives for the use of “ashes of wood” in lime mortar recalled those of Smeaton’s while adding some further ones: “Some workmen say they are used [...] to save sand; others, that they serve to resist moisture, and those who seem to be best informed affirm, that they hasten the drying and induration” (p. 158). He recommends not to separate the different sort of ashes as it is impractical and would not be done by workmen, but rather to sieve the wood ash only to retain the finer particles. His conclusions were that wood ash in mixes of sand and lime would be able to improve a mortar made with bad lime, and enable it to dry without cracking. He also found that wood ash seems to prevent the mortar from acquiring the same hardness as a mix of lime and sand only, especially when the amount of wood ash is close to equal the amount of lime – the opposite of what this paper has found. In 1836, Valentin Biston, a French engineer, in his *Manuel théorique et pratique du*

*Chauffournier*, refers to Smeaton's recipe in the use of wood ash for buildings successively exposed to humid environments and drying (Biston, 1836). Like Higgins, he explains that ash from all types of wood could be used with the same beneficial effect. These practical manuals and treatises on building construction show that wood ash was already understood by the early 19<sup>th</sup> century as giving the mortar an increased ability to absorb moisture, thus a hygroscopic material, when used as an aggregate in sand replacement. In more recent years, Mendel Goodman, noted that wood ash influences the structural properties of lime plaster, concluding that wood ash as an additive could offer an inexpensive way to improve lime mortars (Mendel Goodman, 1998). According to Henry and Stewart, wood ash, when used as an additive, modifies the properties of non-hydraulic lime mortar by assisting the rate of carbonation and increasing permeability and workability (Henry & Stewart, 2012). More recent research has suggested wood ash or wood waste ash, as a new pozzolanic material (Naik *et al.*, 2001) and recommended its use as partial replacement for cement in concrete as a reuse of organic waste material, showing an increase in strength, durability and water absorption (Udoeyo *et al.*, 2006; Cheah & Ramli, 2012; Siddique, 2012; Ramos *et al.*, 2013). In lime mortar, it is more common nowadays to use fly ash to influence the transport of liquid water and compressive strength (Bras *et al.*, 2010; Wang, 2014). In general, the use of natural pozzolans (Stefanidou, 2016) and organic additives, to enhance mechanical properties (Ventol *et al.*, 2011; Centauro *et al.*, 2017; Thirumalini *et al.*, 2017) has been a growing field of research for repair lime mortar.

While wood ash has historically been used and mentioned several times in building manuals, little scientific research has been conducted on the exact impact it has on the properties of lime mortar. This research aims to determine whether and to what extent varying the amounts of wood ash affects a range of properties

and performances of air and natural-hydraulic limes. The study also addresses the practical implications of using wood ash in lime mortar for repointing buildings exposed to damp conditions.

## **4.2 Materials and Methods**

### ***4.2.1 Properties of Raw Materials***

#### *4.2.1.1 Binder and aggregate*

Two types of lime were used, a one-year-old mature non-hydraulic lime putty (supplied by Cornish Lime) (air lime or AL) and a natural-hydraulic lime (NHL) 3.5 (St-Astier). The aggregate used was a well-graded sharp silica sand with particles from 0.09 to 4 mm (Chardstock).

#### *4.2.1.2 Wood ash*

The wood ash used came from a biomass boiler (West Dean, UK) with high temperature combustion. Prior to use the wood ash was oven dried at 80 °C. To determine the particle size distribution, the wood ash was sieved to remove particles above 2 mm and three samples were selected ensuring even distribution of particles. Samples were each run three times using the liquid dispersion method for laser diffraction particle size measurement (Malvern Laser Particle Sizer Mastersizer 2000). The particles of the wood ash ranged in diameter from 0.39 to 2000 microns (Fig. 4.1). As shown in Figure 4.1, extremely fine particles (< 135 microns) dominate the particle size distribution. The chemical composition of the wood ash was identified with X-Ray Fluorescence (Bruker M4 Tornado), with multi-point measurements on three samples of wood ash, previously oven dried at 80 °C (Table 4.1). From these results, the wood ash does not qualify as a pozzolan, which according to EN 196-5 (British Standards Institution, 2011), should contain no less

than 25% SiO<sub>2</sub> (Stefanidou, 2016). The observed physical and chemical characteristics of the wood ash conform to those found in other studies (Etiégni & Campbell, 1991; Misra & Ragland, 1993). The chemical composition of the wood ash used in this study is very similar to the more commonly used ashes in lime mortar, such as biomass ash and coal fly ash (Pontes *et al.*, 2012; Wang, 2014), although it contains much more K<sub>2</sub>O and less SiO<sub>2</sub>.

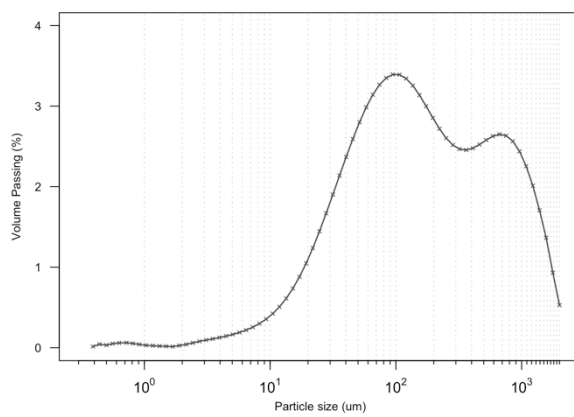


Figure 4.1 Particle size distribution of wood ash, showing a bimodal distribution with a high proportion of fine particles

Table 4.1 XRF data on chemical composition of the wood ash used

Elements	Mass percent
CaO	49.0
K <sub>2</sub> O	25.8
SiO <sub>2</sub>	9.34
MnO	3.43
P <sub>2</sub> O <sub>5</sub>	3.29
MgO	2.66
Fe <sub>2</sub> O <sub>3</sub>	1.98
Al <sub>2</sub> O <sub>3</sub>	1.18
SO <sub>3</sub>	1.02

## 4.2.2 Production of Mortar Samples

### 4.2.2.1 Mortars Compositions and Proportions

Fourteen mortar mixes were prepared, half of them with NHL 3.5, the other half with air lime (AL). The wood ash was added as a replacement for the aggregate at seven different concentrations: 0% (control mix), 10%, 20%, 30%, 40%, 70% and 100%. The binder:aggregate ratio by volume was 1:3, following repointing requirements (Henry & Stewart, 2012). To keep the same 1:3 binder to aggregate ratio by volume, the weight of sand, wood ash and binder was adapted for each mortar mix based on bulk densities.

#### 4.2.2.2 Mixing Procedure and Curing

During mixing, no water:binder ratio was specified but rather water was added as necessary to obtain similar consistency in all mixes ( $\pm 10$  mm by flow), based on the experience of the mason. Very little or no water was added in air lime mortars as the lime putty already brought the necessary water (Table 4.2). Flow tests were carried out on each mix with a flow table (Matest) following BS EN 1015-3:1999 (British Standard Institution, 1999b), to ensure a similar consistency was obtained (between 120 and 150 mm) (Table 4.2). It has to be noted that the more wood ash in the mortar, the more difficult it was to obtain a stiff mortar. To avoid having a fresh mortar mix being too liquid, NHL mortars were left to stand a bit longer than AL mortars before using. A low flow means a stiffer mortar, which is recommended for repointing. The initial moisture content of fresh mortar after being mixed was recorded with a Moisture Analyser (A&D MX50) to 0.001g (Table 4.3).

Table 4.2 Water:binder ratio and consistency of the mortar mixes.

<i>Mortar mixes</i>	<i>Water: binder ratio</i>	<i>Flow (mm)</i>
<i>NHL- 0</i>	2.24	121
<i>10</i>	0.88	116
<i>20</i>	1.11	129
<i>30</i>	1.02	126.5
<i>40</i>	1.20	121
<i>70</i>	1.35	131
<i>100</i>	1.84	127
<i>Air lime</i>		
<i>0</i>	0.10	123
<i>10</i>	0.00	134
<i>20</i>	0.04	136
<i>30</i>	0.05	135
<i>40</i>	0.03	147
<i>70</i>	0.25	145
<i>100</i>	0.33	149

Specimens were cast in prisms of 40 mm x 40 mm x 160 mm in polystyrene moulds for determination of drying shrinkage and compressive strength. Cast cylinders of 50 mm height by 35 mm diameter were prepared for determination of

water absorption, drying, and porosity, and disks of 12 cm diameter and 10 mm thickness used to measure vapour permeability. All specimens (three replicates of each mortar) were demoulded after 5 days and kept for 90 days in a ventilated environmental chamber (Sanyo-FE 300H/MP/R20) at 20 °C ( $\pm 3$  °C), 65 % ( $\pm 5$ %) RH until testing.

### 4.2.3 Porosity and Pore Structure

#### 4.2.3.1 Open Porosity

The open porosity ( $op$ ) was evaluated following the gravimetric method adapted from the standard BS EN 1936:2006 (British Standard Institution, 2006). Cylindrical samples of 50 x 35 mm were placed in a desiccator under vacuum at low pressure (less than 15 mm Hg) for one hour and then allowed to soak in distilled water for 24 hrs at ambient temperature, enabling determination of the saturated mass ( $ms$  in g) and immersed mass ( $mh$  in g). The open porosity (%) was calculated as the mean of three replicates with the formula:

$$op = \frac{ms - md}{ms - mh} \times 100 \quad (1)$$

#### 4.2.3.2 Total Porosity

The total porosity ( $p$ ) is the ratio between the volume of open and closed pores and the apparent volume of the specimen. The total porosity (%) was calculated by the following formula, given in BS EN 1936:2006 (British Standard Institution, 2006):

$$p = \left(1 - \frac{\rho_b}{\rho_r}\right) \times 100 \quad (2)$$

with  $\rho_b$ , the apparent density and  $\rho_r$ , the real density, determined with a Pentapyc 5200e Gas Pycnometer (Quantachrome) with 19 psi and pressure time of one minute. One sample of each mortar mix, previously oven dried at 60°C, was analysed.

#### *4.2.3.3 Mercury Intrusion Porosimetry (MIP)*

The pore size distribution was measured using mercury intrusion porosimetry analysis with a Porosimeter (Quantachrome PoreMaster 33 Hg), with low gas pressure range between 0.2-55 psia and high hydraulic pressure range up to 2110 psia. The MIP was performed on one replicate of each mortar mix, previously oven dried at 60°C.

#### *4.2.3.4 Pore Structure*

Optical microscopy of thin-sections impregnated in blue resin was performed using a Olympus BX43 microscope at x4 magnification. One thin section of each mix was made.

### ***4.2.4 Physical and Mechanical Properties of Hardened Mortars***

#### *4.2.4.1 Drying shrinkage*

Drying shrinkage was assessed on three replicates of each mortar mix once demoulded, at 7 and 28 days using prisms of 40 mm x 40 mm x 160 mm. The change in length was measured with a length comparator ( $\pm 0.001$  mm) (Matest).

#### *4.2.4.2 Strength Activity*

The procedure to measure compressive strength followed BS EN 1015-11:1999 (British Standard Institution, 1999a) on six half prisms (cut from prisms of 40 x 40 x 160 mm). The testing machine (Matest Unitronic Load Frame Tester) was used with a 10 kN load cell and a loading rate of 50 N/s. Results are reported as the mean of all six replicates in N/mm<sup>2</sup>.

The pozzolanic reactivity was assessed by the strength activity index (SAI) method, according to ASTM C618 (ASTM International, 2010) and BS 3892 (British Standards Institution, 1992), and calculated from the mean compressive strength

(N/mm<sup>2</sup>) of six replicates as a ratio to the compressive strength of control mortar with the following formula to the nearest 0,01:

$$SAI = A/B \quad (3)$$

where A is the compressive strength of the different wood ash mortars (N/mm<sup>2</sup>) and B, the compressive strength of the control mortar (N/mm<sup>2</sup>).

#### **4.2.5 Water Absorption and Evaporation Behaviour**

##### *4.2.5.1 Capillary Absorption*

The determination of water absorption coefficient due to capillarity of hardened mortar followed the standard test EN 1925: 2000 (British Standard Institution, 1999c) for highly absorbent stone. Samples (50 x 35 mm cylinders) were oven dried for 24 h at 70 °C (±2 °C) to constant mass ( $m_d$  in g) and placed in 3 mm of distilled water. The mass of each replicate at defined times was determined using a balance (Sartorius) at 0.01g precision until full saturation of the samples. The increase in mass ( $m_1$  in g) by the surface immersed (A) (g/cm<sup>2</sup>) of each replicate was expressed as a function of the square root of time ( $\sqrt{t_1}$ ) in minutes ( $mn^{1/2}$ ). The water absorption coefficient by capillarity (WACC) (g/cm<sup>2</sup>mn<sup>1/2</sup>) was determined by the formula given by the standard as a mean of the three replicates:

$$WACC = \frac{m_1 - m_d}{A \cdot \sqrt{t_1}} \quad (4)$$

##### *4.2.5.2 Drying*

The drying rate was monitored over 100 hours in steady laboratory conditions (23°C ±1 °C 53% RH ±6%) on samples (50 x 35 mm cylinders) having previously been fully saturated under vacuum for 24 hrs. The change of mass ( $m_1$  in g) was recorded at regular time intervals until constant mass was reached. The drying rates for the first drying phase (D1) (g/m<sup>2</sup>h) and the second drying phase (D2) (g/m<sup>2</sup>h<sup>0.5</sup>) were

calculated according to EN 16322:2013 (British Standards Institution, 2013) as a mean of three replicates with the following formulae:

$$D1 = \frac{m1-mf}{A.t1} \quad (5)$$

$$D2 = \frac{m1-mf}{A.\sqrt{t1}} \quad (6)$$

With  $mf$ (g), the final mass recorded,  $A$  the surface of evaporation ( $\text{g}/\text{cm}^2$ ) and  $t1$  (hrs) the time elapsed from the beginning of the test and  $\sqrt{t1}$  the square root of this time ( $\text{hrs}^{0.5}$ ).

#### 4.2.5.3 Water Vapour Permeability

The water vapour permeability (Wvp) was determined following EN 1015-19:1999 (British Standards Institution., 1999) using the wet cup method. Disks of 12 cm diameter were sealed on top of a cup containing a saturated solution of potassium nitrate ( $\text{KNO}_3$ ) to provide a RH of 93.2%, and kept in an environmental chamber (Sanyo-MLR-351) at 20 °C, 50 % RH. The mass was recorded at intervals of 24 hrs for 7 days. The water vapour permeability was calculated based on the mean of three replicates at each time interval using the formula given by the standard:

$$W_{vp} = \frac{1}{A\Delta p / (\Delta G / \Delta t) - RA} \cdot t \quad (7)$$

in  $\text{kg}/\text{m.s.Pa}$  (then adapted to  $\text{g}/\text{m.day.KPa}$ ), with  $A$  the area of the open mouth of the test cup ( $\text{m}^2$ ),  $\Delta p$  the difference in water vapour pressure (1010.244 Pa),  $\Delta G / \Delta t$  the water vapour flux ( $\text{kg}/\text{s}$ ),  $RA$  the water vapour resistance of the air gap between the specimen and the salt solution ( $4.80\text{E}+10 \text{ m}^2\text{s}/\text{g}$ ) and  $t$  the thickness of the specimen.

#### **4.2.6 Durability**

Durability was assessed using a modified freeze-thaw test adapted from DD CEB/TS 12390-9:2206 (British Standards Institution, 2009). Prisms of 50 x 50 x 150 mm were sealed on five sides with a rubber sheet and placed in polystyrene to provide thermal insulation. After being fully saturated in distilled water, a small layer of water was left on top of the specimen. One replicate of each mortar mix was exposed to 32 thermal cycles from 20°C to -10°C in 16 hours, and back to 20°C in 6 hours followed by a steady state for 2 hours in an environmental chamber (Sanyo-FE 300H/MP/R20). Visual assessment was done at regular intervals.

### **4.3 Results**

#### **4.3.1 Porosity and Pore Structure**

##### *4.3.1.1 Open and Total Porosity*

The open porosity, calculated by gravimetric measurements, is the part of the total porosity connected to the surfaces of the samples, and so influences water transport properties (Hall & Hoff, 2009). Figures 4.2a and b show a significant increase of open porosity after 40% of wood ash for both NHL and AL mortars. Not much change is seen between 10% and 20% of wood ash, after which the open porosity starts increasing at or above 30%.

The total porosity was calculated from the apparent and real densities of each sample. The total porosity in NHL and AL mortars with low to medium wood ash contents (10% - 40%) is fairly similar, between 32% and 38% (Fig. 4.2). After 40% of wood ash content in both mortar types, results obtained show a significant decrease in total porosity, likely related to misreading and therefore are not presented here. In comparison to the control mortar, the total porosity of NHL mortars is lower while

the open porosity is higher, whereas in AL mortars total porosity slightly increases while the open porosity also increases in comparison to the control mortars. Overall, up to 40% of wood ash there is little difference between the open and total porosity in NHL in comparison with greater difference in AL mortars, showing that most of the porosity in NHL mortars is open, essential for water transport. In both mortar types (NHL and AL) at 40% of wood ash content most of the porosity is dominated by open porosity (Figure 4.2).

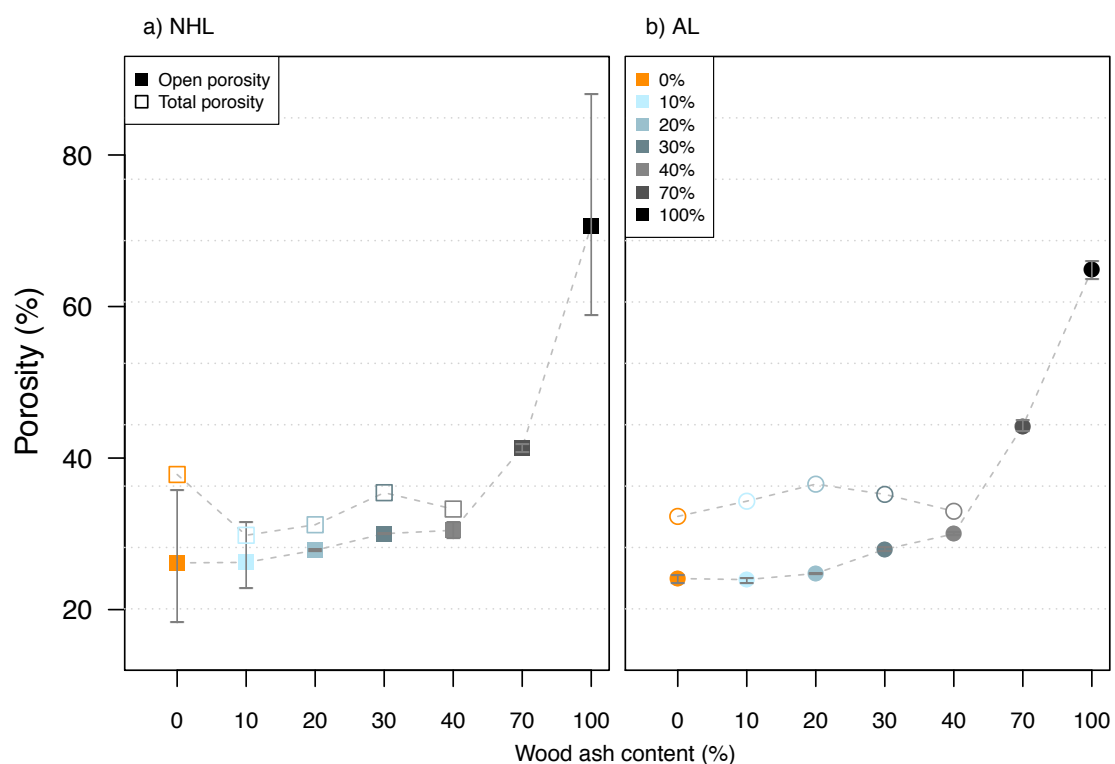


Figure 4.2. Open and total porosity in relation to wood ash content of a) NHL mortars and b) AL mortars. Error bars indicate the minimum and the maximum values recorded. Dashed lines help see the trends.

#### 4.3.1.2 Pore Size Distribution

In both NHL and AL mortars, the general increase of porosity due to the addition of wood ash (Fig. 4.2) is visible also in the higher volume of pores being intruded by mercury (Figure 4.3). It also shows that no macropores ( $> 1$  mm) are present in the mortars. It is to be noted that there is no common agreement on the boundaries of capillary pores: they are sometimes considered in the micropore range (0.1 to 1,000

capillary pores: they are sometimes considered in the micropore range (0.1 to 1,000 microns) (Wendler & Charola, 2008; Charola & Wendler, 2015), or larger than micropores from 0.1 to 10 microns (Gong *et al.*, 2014) or from 1 to 1,000 microns (Siegesmund & Dürrast, 2014) with micropores considered to be below 0.1 microns (Wendler & Charola, 2008; Siegesmund & Dürrast, 2014; Charola & Wendler, 2015). In this study we consider pores between 1 to 1000 microns (1 mm) to be mainly relevant to capillary absorption by capillarity and called “capillary pores”, with pores from 0.1 to 1 micron to be smaller capillary pores. Therefore, in both mortar types with wood ash (NHL and AL) most of the proportion of pores is in the form of capillary pores and “smaller capillary pores”. Mortars with wood ash show a higher volume of capillary pores, with a shift from few larger capillary pores to more smaller ones. AL mortars have a broader pore size distribution from 0.01 up to 100 microns than NHL mortars, comprising both larger and finer capillary pores. NHL mortars have a pore size distribution from 0.01 up to 4 microns.

In NHL mortars, adding wood ash up to 30% (Fig. 4.3a) increases the volume of pores in the range of 0.4 to 10.5 microns, while the finer capillary pores (between 0.01 to 0.4 microns) are kept constant. From 40% of wood ash the pore size distribution clearly increases between 0.01 and 11 microns, therefore increasing the volume of pores responsible for capillary absorption. AL mortars (Fig. 4.3b) with up to 30% wood ash show a clear increase in the smaller capillary pores partly responsible for vapour diffusion, with pore size distribution between 0.03 to 0.4 microns, while keeping constant the volume of pores between 0.4 and 100 microns diameter. At 40% wood ash, a similar pore size distribution is observed but with an increase of pore volume between 2 and 11 microns diameter and a clear decrease from 11 to 100 microns. From 70% wood ash NHL mortars show a shift with a clear peak of capillary pores from 3 to 11 microns.

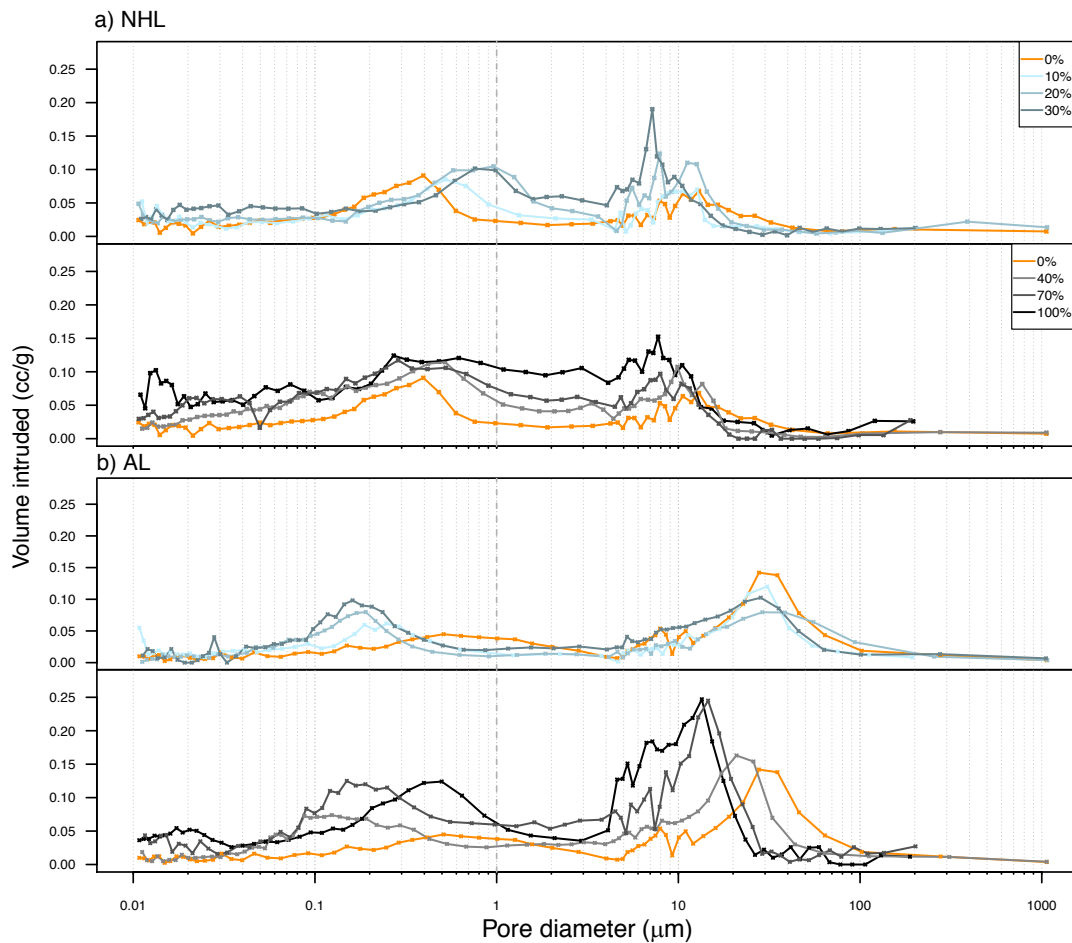


Figure 4.3. Pore size distribution done with MIP of a) NHL mortars and, b) AL mortars. The dashed line represents the threshold between capillary pores (1 to 1000  $\mu\text{m}$ ) and smaller capillary pores (0.1 to 1  $\mu\text{m}$ ).

#### 4.3.1.3 Pore Structure

The thin sections of selected mortars (Fig. 4.4) show that the more wood ash in the mix, the denser the pore structure. The pore structure is developed mainly by the evaporation of water through the curing and hardening process, leaving a complex system of interconnected pores (Banfill & Forster, 1999; Hall & Hoff, 2009). In correlation with the pore size distribution (Fig. 4.3), visible pores seem to be smaller than 500 microns, with no coarser pores visible in the mix. Wood ash seems to be fully blended into the lime, forming a dense structure.

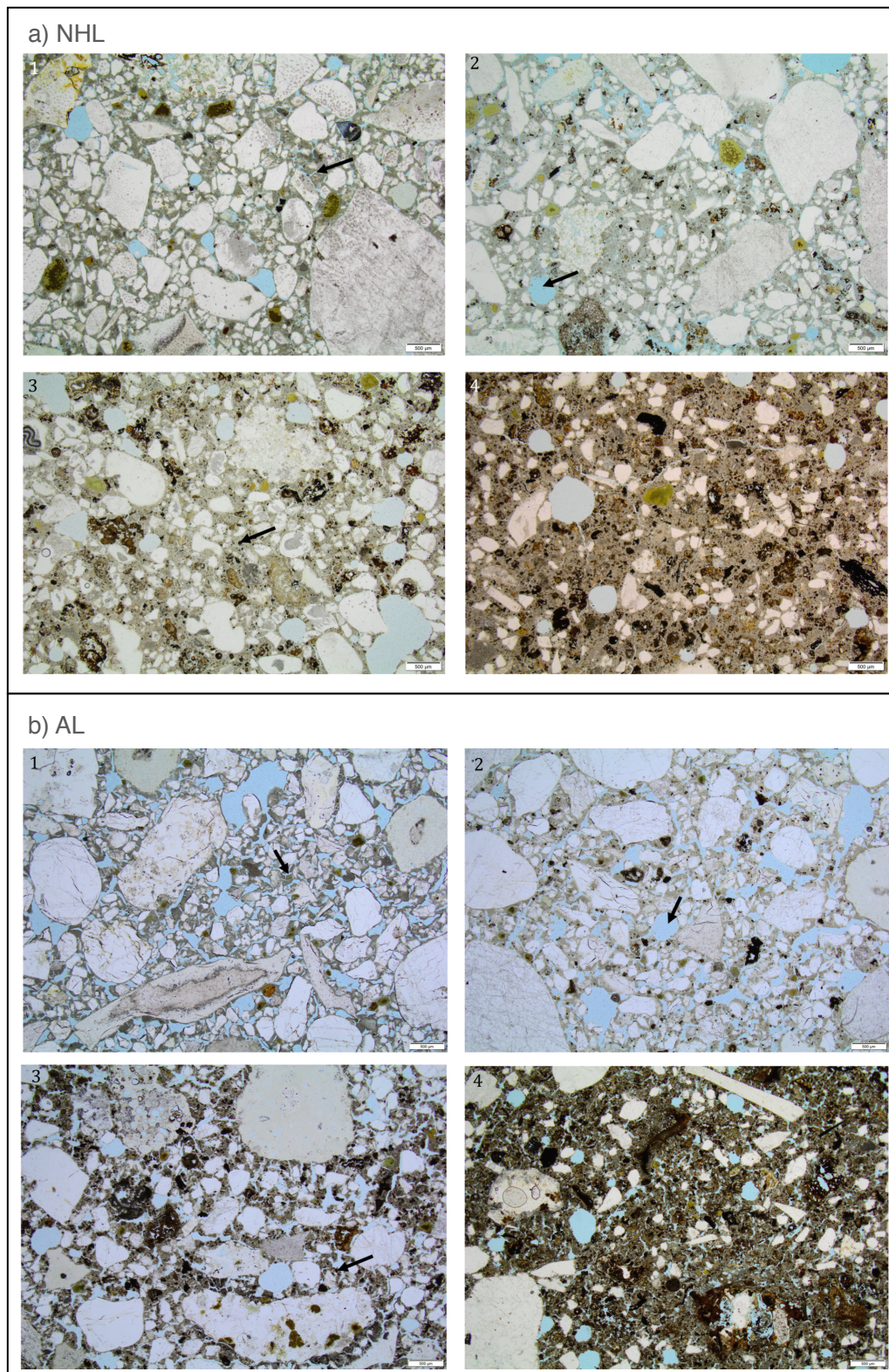


Figure 4.4. Thin sections impregnated with blue resin showing the pore structure of mortars under petrographic microscope at x4 magnification. The scale bar is 500  $\mu\text{m}$ . Mortars with a) NHL and b) AL mortars: 1- 0% wood ash, 2- 20%, 3- 40% and 4- 70% showing a denser structure and a higher porosity as the wood ash content increases. Arrows point to shrinkage cracks (1), pores (2), and particles of wood ash (3).

The AL mortars (Fig. 4.4b) show many micro cracks in the control mortar and in the wood ash mortars, correlating with drying shrinkage observations (Fig. 4.5). Therefore, pores in AL mortars are more interconnected than in NHL mortars, mainly because of the presence of micro-cracks. The NHL mortars (Fig. 4.4a) are recognisable by the round pores created and by the complex structure resulting from the setting through carbonation and hydraulic set.

### ***4.3.2 Physical and Mechanical Properties of Hardened Mortars***

#### *4.3.2.1 Drying Shrinkage*

There was no significant difference in shrinkage measured at 7 and 28 days, therefore only the 28-day data are presented. For both mortar types (NHL and AL) the influence of wood ash content on the water/binder ratio and the drying shrinkage is visible and the same pattern is observed: as the wood ash content increases both increase. As seen in Table 4.2, wood ash seems to be more demanding of water to obtain a similar consistency, so that the more wood ash added in a mix results in an increase of water/binder ratio. Wood ash, as a hygroscopic material, would absorb water as it is added. This could explain the difference in water/binder ratio between the NHL control mortar and the wood ash ones. This is also visible in the initial moisture contents in Table 4.3. The very low water/binder ratio of AL mortars is a result of using lime in the form of putty, therefore providing water by itself.

Figure 4.5 illustrates that the AL mortars generally show higher shrinkage at 28 days than the NHL ones. Although NHL mortars have a higher water/binder ratio, shrinkage is minimised, mainly staying under 1%. This is likely to be linked directly to the hydraulic set of the NHL mortars, that uses water and moisture from the air to harden (Allen *et al.*, 2003), therefore minimising the shrinkage in comparison to AL mortars. Shrinkage is usually influenced by the amount of water

added in a mix and by the size of the aggregates. Coarse aggregates also contribute to the volume stability of lime mortar samples, reducing shrinkage, whereas the use of fine aggregates comes with a risk of higher shrinkage (Stefanidou & Papayianni, 2005). Therefore, higher wood ash content introduces a higher proportion of fine particles, resulting in a higher drying shrinkage. Drying shrinkage of the pointing mortar or cracks in the masonry allow ingress of moisture and causes dampness through a wall (Young, 2007; Laycock & Wood, 2014). For repointing mortar, it is therefore essential that shrinkage remains at a minimum, in order to ensure a good bond at the interface between the stones or bricks and the mortar joints.

Table 4.3. Initial moisture content of each fresh mortar mix, generally increasing as the wood ash content increases.

Mortar mixes	Initial Moisture Content (%)
<i>AL</i>	
0	20.4
10	23.7
20	21.9
30	24.3
40	33.6
70	36.9
100	53
<i>NHL</i>	
0	16.7
10	26.3
20	21.3
30	22.5
40	24.9
70	33.6
100	50.8

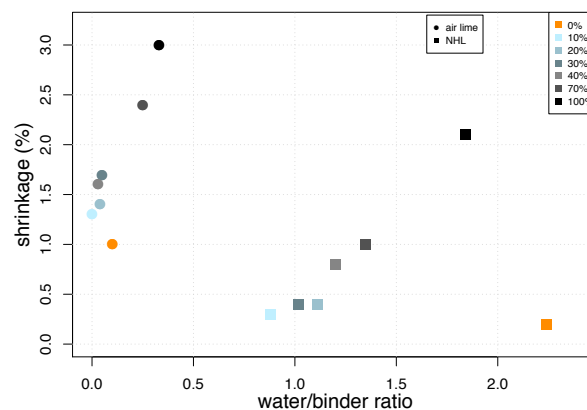


Figure 4.5. Relationship between drying shrinkage and water/binder ratio of each mortar at 28 days, showing a clear link between the increase of wood ash and the water demands of the fresh mortar, correlated with higher shrinkage.

#### 4.3.2.2 Strength Characteristics

Compressive strength is usually dependent on the hardening rate of lime mortar and the development of a pore structure. Here samples were tested at 90 days. Results are presented in Figure 4.6 and demonstrate an overall increase of compressive strength with increased wood ash contents in both NHL and AL mortars compared to the control mortars. For AL mortars with 100% wood ash, the

machine failed to read data for all replicates and machine failure meant that only one replicate of AL 30% could be read.

Usually, NHL mortars have higher compressive strengths than those made with air lime (Allen *et al.*, 2003), here with wood ash, both mortar types gain similar compressive strength. For the NHL mortars, a clear increase in compressive strength occurs from more than 30% wood ash content ( $> 2 \text{ N/mm}^2$ ) (Fig. 4.6a). AL mortars show a significant increase in compressive strength from about 20% wood ash content ( $> 2 \text{ N/mm}^2$ ) (Fig. 4.6b). It seems that 20% of wood ash is a threshold in both NHL and AL mortars: in NHL it is the lowest compressive strength value, which may be because there is not enough wood ash to give full strength benefits yet (cf NHL 30% which has clear higher compressive strength) whereas in AL mortars it gives the highest compressive strength value. This may be due to wood ash impacting the strength of AL mortars at lower concentrations than in NHL mortars. However, no correlation with open porosity can be found. It seems indeed, that after 40% wood ash for NHL and 30% for AL, the lack of sand makes the compressive strength decrease (while still being higher than the control mortars).

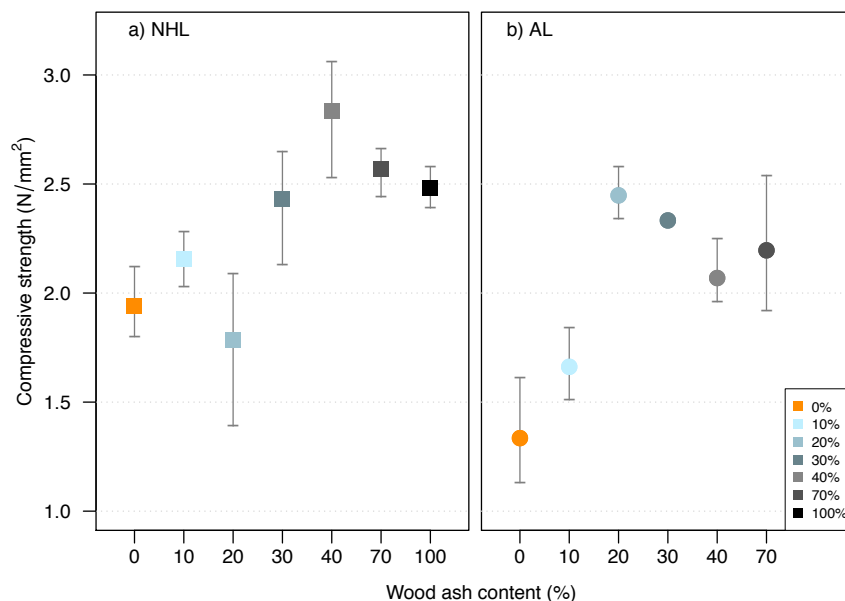


Figure 4.6. Compressive strength ( $\text{N/mm}^2$ ) of a) NHL and wood ash mortars, and b) AL and wood ash mortars. The error bars show the maximum and minimum value.

Overall the compressive strengths observed here are always lower than those of common historical building materials, such as a porous sandstone (between 25 and 60 N/mm<sup>2</sup>), oolitic limestones (between 20 and 80 N/mm<sup>2</sup>) or traditional bricks (Siegesmund & Dürrast, 2014). It is important that the mortar strength is much lower than the surrounding masonry unit to ensure that permeability remains, so that drying out and crystallisation of salt through evaporation occurs in the mortar, which even if it deteriorates can be repaired more easily (Oliver, 1997). Here it is interesting to notice that the increase in strength does not mean less porosity, showing that these ash mortars can be durable but permeable.

Table 4.4. Strength Activity Index (SAI) of mortar with wood ash.

% wood ash	SAI NHL	SAI AL
10	1.11	1.25
20	0.92	1.83
30	1.25	1.75
40	1.46	1.55
70	1.32	1.65
100	1.28	/

As previously stated, wood ash does not appear to qualify chemically as a pozzolanic material (Table 4.1). However, the observed increase in strength could suggest pozzolanic activity. Research has shown that to assess the pozzolanic activity of a material the SAI can be correlated with the Frattini test (Donatello *et al.*, 2010) or Chapelle test (Pontes *et al.*, 2012). According to ASTM C618 (ASTM International, 2010) and BS 3892 (British Standards Institution, 1992), SAI over 0.8 indicates positive pozzolanic activity. Table 4.4 therefore shows that all mortar mixes with wood ash have a SAI higher than 0.8, indicating potentially positive pozzolanic activity. SAI of 100% AL mortar could not be calculated as no value of compressive strength was recorded due to failure of the machine. The highest positive pozzolanic signs are shown by AL mortars between 20% and 70% of wood

ash content (Table 4.4). Pozzolanic materials have the ability to change the properties of a lime mortar, such as decreasing the setting time, and increasing the strength and durability (Stefanidou, 2016). Such properties could be beneficial for the long-term durability and in particular the ability of repointing mortar to set under damp conditions.

### **4.3.3 Water Related Properties**

#### *4.3.3.1 Water Absorption and Evaporation*

The orange line in Figure 4.7 represents the control mix, containing 0% of wood ash. In both mortar types (NHL and AL), when saturation by capillary absorption is reached, samples with wood ash absorb similar or more total water than the control mortars. This again shows the hygroscopic capacity of wood ash. It can also be seen that samples with wood ash, except AL 10%, have a capillary saturation point delay by 15 minutes (Fig. 4.7a and 4.7c), as a longer time is needed for the sample to reach full capillary saturation. Absorbing more water in more time is a positive effect, as it would enable the mortar to better absorb moisture from the surrounding masonry unit and help it dry out.

Looking at the rate of absorption (Table 4.5), in NHL and AL mortars with up to 40% wood ash, the rate is either similar (because of a high SD) to the control mortars or significantly decreased. This is because for the same volume over the same time these mortar mixes have a higher total water content at saturation, therefore absorption takes longer. However, when this phenomenon is too extreme, as in mortars with high amounts of wood ash (70-100%), for both NHL and AL mortars, the amount of water absorbed to reach saturation is so much higher, that the rate of capillary absorption is significantly increased (Fig. 4.7). This pattern relates to the clear increase in both the open porosity values (Fig. 4.2) and the higher

proportion of capillary pores (Fig. 4.3) for both NHL and AL mortars from 70% wood ash.

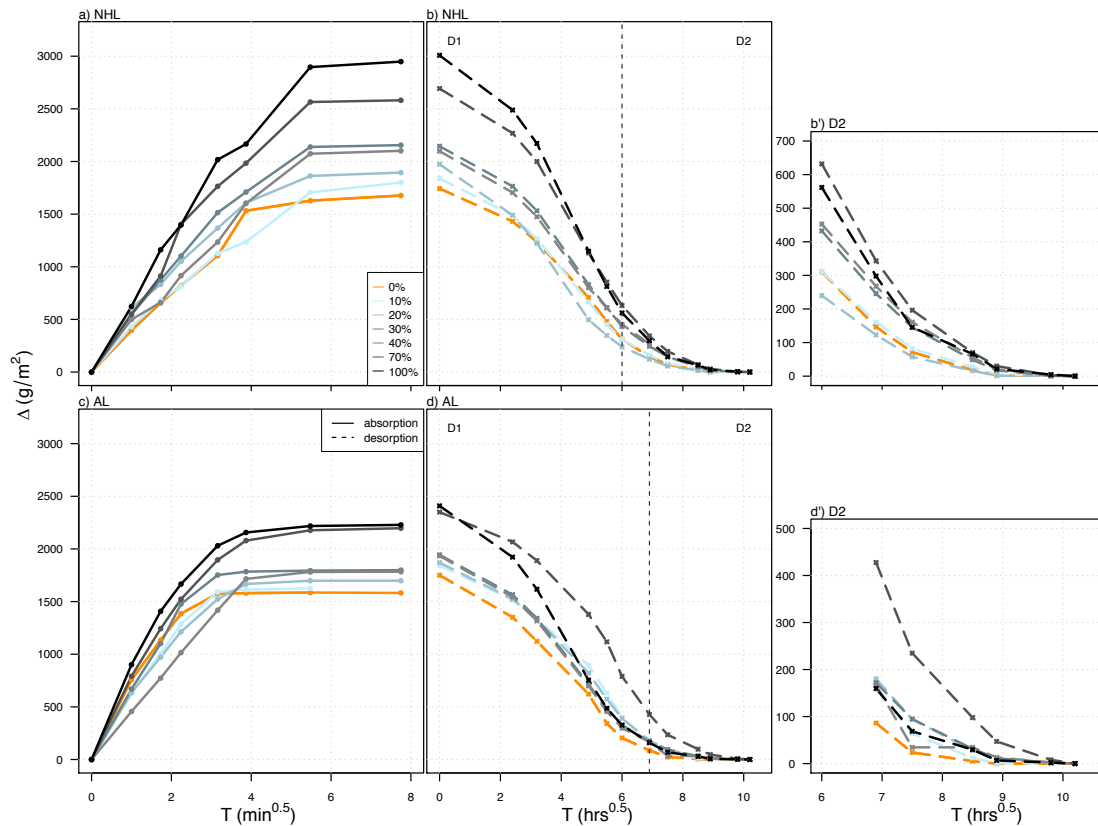


Figure 4.7. Capillary absorption a) c) and desorption b) d) curves of NHL mortars a) b) and AL mortars c) d) showing a higher rate as the wood ash content increase. The dashed line signals the end of the first phase drying (D1) until 30 and 36 hours. b) and d) are zoomed in graphs of the relevant section (D2) from b) and d).

AL mortars have much higher pore volumes in the larger capillary range (Fig. 4.3b), explaining the faster capillary water absorption than NHL mortars (Wendler & Charola, 2008; Siegesmund & Dürrast, 2014) (Table 4.5). For AL with 30% wood ash, the straight line of absorption reveals a very quick rate – this may be due to cracks in the mortar mixes. It seems overall that for mortars with low to medium wood ash content (10 – 40% - apart for NHL 20%), when the compressive strength increases, the WACC decreases, as expected. However, in high ash content mortars, when the compressive strength increases the WACC also increases, likely related to the denser structure and hygroscopic properties of wood ash.

Table 4.5. WACC, drying rates (D1 and D2) and water vapour permeability of each mortar mixes showing an increase of drying rate, sorptivity and permeability performances as the wood ash content increases.

Mortar mixes	WACC (g/m <sup>2</sup> .mn <sup>1/2</sup> )		First drying rate D1 (g/m <sup>2</sup> .h)		Second drying rate D2 (g/m <sup>2</sup> .h <sup>1/2</sup> )		Water vapour permeability (W <sub>vp</sub> ) (g/m.day.kPa)	
	mean	SD	mean	SD	mean	SD	mean	SD
<i>NHL</i>								
<i>0</i>	377.83	±29.60	39.47	±3.80	66.85	±13.99	3.35	±0.45
<i>10</i>	302.51	±3.01	42.58	±2.26	68.70	±7.14	3.27	±0.09
<i>20</i>	336.46	±13.16	48.10	±1.40	52.78	±5.98	3.61	±0.12
<i>30</i>	390.93	±6.64	47.80	±2.45	98.70	±11.46	3.84	±0.43
<i>40</i>	379.05	±3.88	45.77	±3.48	104.80	±15.06	3.70	±0.43
<i>70</i>	474.71	±7.93	58.04	±5.91	141.63	±43.52	4.51	±0.88
<i>100</i>	529.14	±7.64	68.75	±2.87	123.55	±18.88	5.59	±0.82
<i>AL</i>								
<i>0</i>	503.97	±23.62	41.91	±1.76	21.55	±5.74	2.79	±0.56
<i>10</i>	508.86	±15.13	38.39	±1.98	42.36	±4.21	2.26	±0.51
<i>20</i>	428.66	±12.15	40.16	±2.91	51.07	±11.43	2.97	±0.28
<i>30</i>	477.56	±8.78	44.96	±2.05	49.40	±8.25	3.11	±0.30
<i>40</i>	444.18	±3.12	45.16	±1.82	39.76	±7.73	2.54	±0.28
<i>70</i>	533.51	±43.32	41.65	±4.92	121.99	±23.66	3.17	±0.14
<i>100</i>	551.69	±38.82	58.54	±1.81	43.28	±2.37	4.34	±0.47

Figure 4.7b and 4.7d shows the evaporation curves of samples previously saturated under vacuum, hence why they start with a higher water content than where the WACC experiment stopped in Figure 4.7a and 4.7c. The two-phase drying was identified according to BS EN 16322:2013 (British Standards Institution., 2013). The first phase drying (D1) for NHL mortars is shorter (30 hours) than AL mortars (36 hours). The absorption and desorption curves are indeed different for both mortar types (NHL and AL). Despite their initial higher water content, mortars with wood ash (except AL 70%) reach a relatively similar water content to the control mortars at the end of the first phase of drying, therefore showing a similar or higher D1 rate than the control mortars (Table 4.5). A long first phase drying shows a high liquid conductivity (British Standards Institution., 2013) and is here also linked to the higher open porosity of wood ash mortars (Fig. 4.2).

D2 was calculated with square root of time as presented in Figure 4.7b' and 4.7d'. Except for NHL 20%, D2 increases as the wood ash content increases, with

70% wood ash giving the highest values in both NHL and AL mortars. This shows that mortars with wood ash have a good capacity for drying, making them suitable for stone or brick masonry in humid environments, as both liquid and vapour water will be able to move out of the material (Siegesmund & Dürrast, 2014). When constant mass is reached (at 9 hrs<sup>2</sup>, Fig. 4.7b' and d'), mortars with wood ash seem to retain slightly more water than the control mortars, showing again the hygroscopic property of these ash mortars. Overall, in comparing NHL and AL mortars, NHL mortars absorb water slower and have quicker evaporation whereas AL mortars absorb water quicker and have slower evaporation.

#### *4.3.3.2 Water Vapour Permeability*

Water vapour permeability (Wvp) governs the movement of water vapour in porous materials (Hall & Tse, 1986; Snow & Torney, 2014) and, in this sense, allows the material to breathe (Banfill & Forster, 1999). It is an essential requirement for mortar in joints to help dry out the surrounding masonry units, where the liquid water has evaporated. Table 4.5 shows an increase of Wvp in both NHL and AL mortars as wood ash content increases, following similar trends to the drying rates and open porosity (Fig. 4.7 and 4.2). NHL mortars show a higher Wvp as they have higher volumes of small capillary pores (0.01 to 1 microns) whereas AL mortars have finer capillary pores but at lower volumes (Figure 4.5). Figure 4.8 indicates that water vapour permeability is closely linked to other absorption and pore structure related properties. In NHL mortars, as vapour permeability increased, WACC also increased, whereas less clear correlation is found in AL mortars (Fig. 4.8a). Similarly, good correlation is shown between vapour permeability and open porosity (Fig. 4.8b). In addition, it seems that from 20% of wood ash, while compressive strength increases, water vapour permeability also increases (except for AL 40%),

which would enable such repointing mortar to be durable while also being permeable.

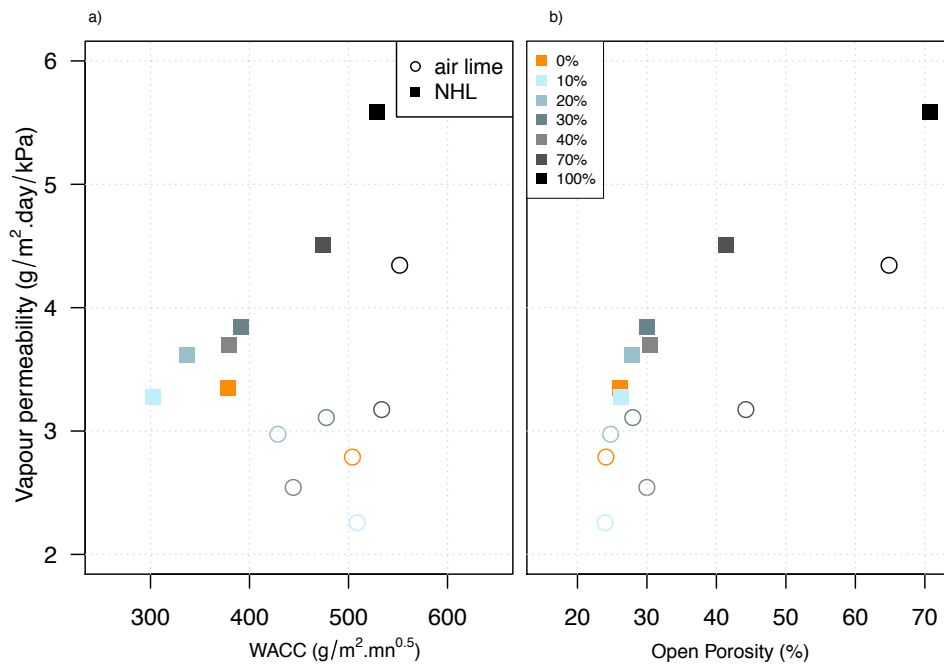


Figure 4.8. Relationship between the water vapour permeability and a) the capillary absorption, and b) the open porosity

#### 4.3.4 Durability to Freeze-Thaw Cycles

Figure 4.9 shows the surface degradation and cracks formed in selected samples during the durability test. It is clear that the NHL mortars have resisted such harsh cycles, whereas the AL mortars show signs of decay from 7 cycles and laminations and cracks from 14 cycles, and more intensively at 32 cycles. In AL mortars, the more wood ash in the mix, the more degradation is observed on the surface. NHL mortars have demonstrated a capacity to absorb water more slowly and release it more quickly than AL mortars, especially at D2 (Table 4.5), and have overall higher water vapour permeabilities (Fig. 4.8). This could explain why these AL mortars, when exposed to extreme cycles, absorb water too quickly and do not release it quickly enough so that when freezing occurs more water is still held in the samples, causing damage. Colour change can also be noted on AL mortars from 40% and high

causing damage. Colour change can also be noted on AL mortars from 40% and high damage of the surface from 70% wood ash. Both effects are negative if the mortar is to be used in repointing.

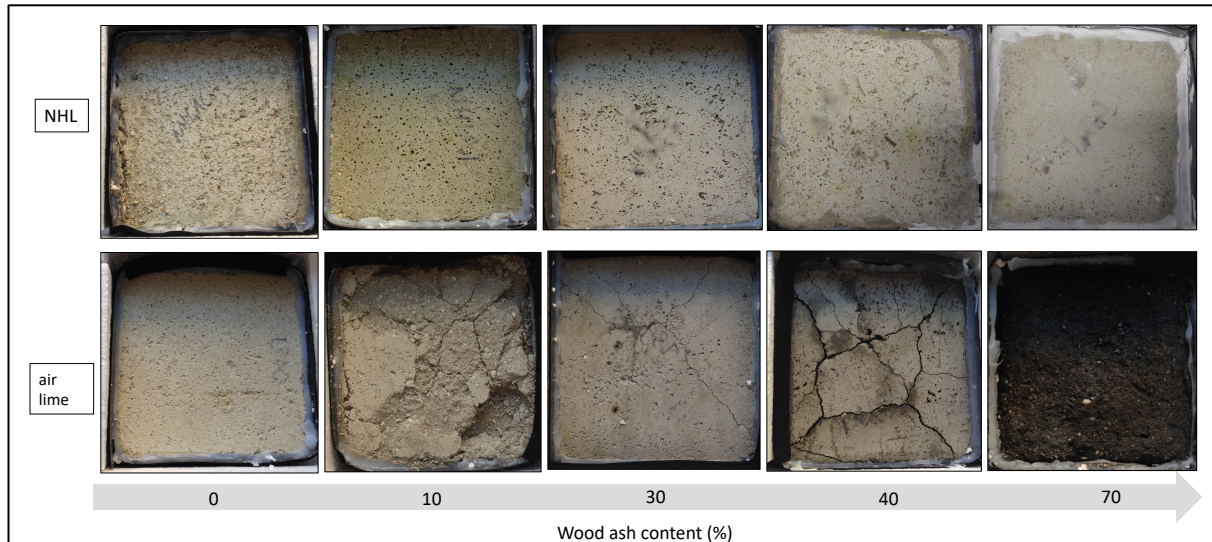


Figure 4.9. Surface weathering after 32 freeze-thaw cycles. The test was also performed on 20% wood ash and 100% with similar results to 10% and 70%.

## 4.4 Discussion

### 4.4.1 Effect of Varying the Amount of Wood Ash in Different Limes

Adding wood ash in a mix has clear effects on many properties of NHL and AL mortars and changes how the mortars perform both positively and negatively. Similarities and differences can be seen between lime mortars with low to medium wood ash contents (10% to 40%) and high ash contents (70% to 100%). As soon as wood ash is added, both mortar types (NHL and AL) present higher pore volumes in the capillary range (1 micron to 1 mm), in comparison to the control mortar, with fewer larger capillary pores and more smaller ones, a capacity to absorb and hold more water, leading to delayed capillary saturation, higher open porosity and vapour permeability and increased compressive strength. Low to medium amounts of wood ash (10% to 40%) in both NHL and AL mortars seem to lead to positive impacts for

use as a repointing mortar, such as lower or unchanged capillary absorption rate, while showing rapid water release, leading to an unchanged or increased drying rate. In high ash content mortars (70% to 100%), properties are more significantly changed, with much higher open porosity, compressive strength and increased WACC, sometimes accompanied by negative effects on the mortars– i.e. high shrinkage, low durability.

Some differences can be noted between AL and NHL mortars. NHL mortars absorb water by capillarity slower and have a quicker evaporation rate than AL mortars which absorb water quicker but have slower evaporation, explained by the AL mortars having higher pore volumes in the larger capillary range (Fig. 4.3b) (Wendler & Charola, 2008). However, NHL mortars have higher water vapour permeability, likely explained by the higher volume of smaller capillary pores (Fig. 4.3a). Overall, NHL mortars with wood ash seem more durable (less shrinkage and better ability to resist freeze-thaw) while having good permeability.

#### ***4.4.2 Reasons for the Effect of Wood Ash on Lime Mortars***

The change of properties in lime mortars offered by wood ash is due to the specific characteristics of wood ash: its fine particles, hygroscopic properties and chemical composition. Based on the experimental programme in this study, Figure 4.10 shows the link between the characteristics of wood ash and the properties and performance changes observed in these lime mortars.

First, the fine particles that comprise the wood ash (Fig. 4.1) have a clear effect on drying shrinkage, on durability and on pore structure. However, as seen for AL mortar, too many fine particles increase the drying shrinkage negatively because the aggregates are not coarse enough to provide stability of the mortar (Fig. 4.5). In addition, finer particles increase the surface area in the aggregate, here the wood ash, in contact with lime (Coutelas, 2009). This could lead to higher setting time, but

here it seems to be the reason for the positive pozzolanic activity. As more lime particles are in contact with wood ash, the silicate oxide ( $\text{SiO}_2$ ), potassium oxide ( $\text{K}_2\text{O}$ ), and aluminium oxide ( $\text{Al}_2\text{O}_3$ ), even in small quantities, would react with the calcium hydroxide ( $\text{Ca(OH)}_2$ ) of the lime. Lime mortars also show a general increase in compressive strength where the sand has been replaced by ceramic waste or other ash wastes (Faria Rodrigues, 2005; Matias *et al.*, 2014). In general, natural organic additives have been found to form an increased bond between the additives and the lime (Ventol *et al.*, 2011; Thirumalini *et al.*, 2017). In this research, the strength activity index, based on increase of compressive strength, has shown a potential positive pozzolanic activity (Table 4.4). Other research has found that ash materials (biomass fly ash and fly ash) in mortars were also reactive (Pontes *et al.*, 2012). However, while tested at 28 days, they were less reactive, with SAI around 0.6 and 0.8, which could be explained by the low reactivity of the materials at early age (Pontes *et al.*, 2012).

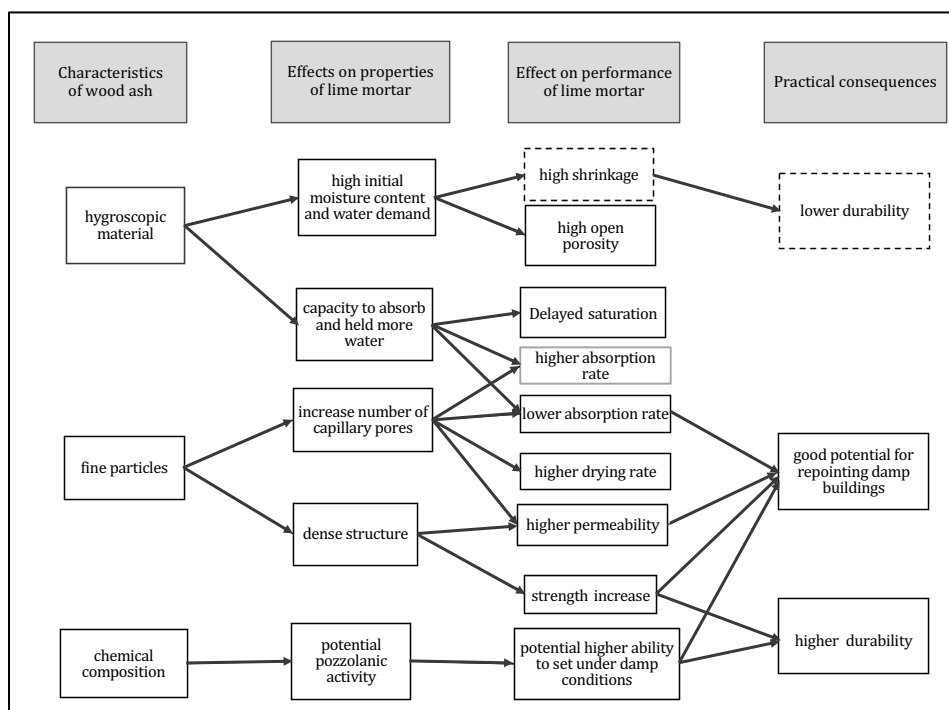


Figure 4.10. Flow chart of the relationship between the characteristics of wood ash and the property and performance change observed in lime mortars and the practical consequences for the use of these mortar mixes. The dashed box relates to AL mortars and the light grey box to high ash content mortar (70 to 100% ash).

Furthermore, these fine particles contribute to the formation of a dense pore structure as the content of wood ash increases (Fig. 4.4), that means that the binder and the wood ash are well blended in a tight structure. This tight structure could explain the higher compressive strength observed. This structure also leads to a higher proportion of capillary pores (1 micron to 1 mm) (Fig. 4.3). The higher volume of capillary pores are responsible for the higher vapour permeability, open porosity and highest total water absorbed by capillarity.

Finally, results have shown that mortars with wood ash have a higher water absorption capacity for a similar volume than the control mix and seem to trap water (Fig. 4.7). This is due to the hygroscopic properties of wood ash as a material that tends to hold on to water and later release it quickly. Furthermore, results demonstrate that wood ash, by being hygroscopic, and therefore demanding of more water, gives mortars a high water/binder ratio and a high initial moisture content (Fig. 4.5) which has a direct impact on the open porosity and drying shrinkage.

#### ***4.4.3 Practical Implications***

This research has shown how adding wood ash impacts on the performance of both NHL and AL mortars. It is essential to understand how these results could affect conservation practice and to draw recommendations from these findings to use wood ash best. Fresh mortar with wood ash tends to become stiff quickly, but if mixing is done again, the wood ash releases some of the trapped water. This is a good property for repointing mortars as it enables a sticky mix to be applied in the wall.

In general, the mortar joints should be more permeable than the masonry to promote drying, and help soluble salts migrate out through the mortar (Maurenbrecher, 2004). The mortar should therefore have a high evaporation rate,

good permeability, and minimum shrinkage and cracks. Therefore, control of moisture ingress and movement in a historic masonry wall is linked to the durability of the entire masonry (Groot & Gunneweg, 2010). Wood ash mortars have been shown to increase both the water vapour permeability and drying and evaporation ability of both mortar types. The fact that wood ash attracts water could help stone and brick masonry dry out.

However, it is important to acknowledge the potential negative mechanical effects wood ash can have. It is essential that minimum drying shrinkage is ensured for repointing mortars, to avoid cracks at the interface with stone and the joints. Dampness through a wall is most commonly caused by shrinkage of the pointing mortar or cracks in the masonry (stones or bricks), which allows ingress of moisture (Young, 2007; Laycock & Wood, 2014). In addition, a dense structure that traps moisture can lead to low durability when exposed to repeated freeze-thaw cycles. Whilst repointing should help attract moisture and be less durable than the surrounding masonry units, it still needs to perform well for a reasonable amount of time.

Many studies have concluded that to reduce water penetration the performance of the pointing mortar is critically important (Forster, 2010; Hughes, 2012). It is therefore necessary to develop a mortar that will fit the structural and environmental requirements of a specific historic building: such as, for instance, being soft, porous, highly permeable, quick to dry, and able to set in specifically damp conditions. This is why using a well-designed composition that compensates for negative effects is essential. NHL, in this respect, would use the extra water for hardening through the hydraulic set, ensuring lower shrinkage and has shown a higher capacity to absorb water slowly and release it quickly (Fig. 4.7, Table 4.5) as well as a good durability to frost. Figure 4.10 shows the link between the necessary

criteria for a good repointing mix and adding wood ash in lime mortar mixes. The practical recommendation drawn from this research for a repointing mix would be to use wood ash between 20% and 40% as an additive or aggregate replacement with NHL 3.5 or 2.

Finally, in a growing context of “green specification” and reuse of material (Forster *et al.*, 2011), developing a material with up to 40% of aggregate replacement with a waste product such as biomass wood ash could be sustainably highly beneficial.

#### **4.5 Conclusions**

An experimental programme was designed to assess to what extent varying the content of wood ash had an impact on a range of properties of lime mortar and to draw conclusions about the reasons for these changes.

Four main findings are due to the fine particles and the hygroscopic properties of wood ash:

- Wood ash, because it is hygroscopic, gives mortars the ability to absorb more total water at capillary saturation, therefore delaying their saturation in time and generally slowing down the capillary absorption (up to 40%) (except for NHL3.5) or increasing it (70 % – 100%).
- Wood ash mortars, although absorbing more water, have an increased ability to dry out, showing an increase in drying rate.
- Fine particles create a denser structure leading to a higher proportion of pores in the capillary range. Wood ash mortars have a higher open porosity and vapour permeability, correlated with the amount of wood ash in the mortar mix.

- The denser structure also increases the compressive strength which can be responsible for the potential pozzolanic activity.

The research findings imply that, used at its best potential in medium amounts (20 – 40%), wood ash added to lime mortar gives a potentially good mortar mix for repointing masonry joints, especially in humid environments. It would have the ability to set under damp conditions, gain strength, possess good permeability and drying capacity, while showing low shrinkage and cracks. However, in high amounts (70% – 100%) some negative effects are seen, such as high drying shrinkage.

Further research with an unchanged amount of coarse aggregate to reduce shrinkage and an investigation of the effect of wood ash on different ages of mortars would give more insight on the full potential of this material.

## V. Study II - A comparison of standard and realistic curing conditions of natural hydraulic lime repointing mortar for damp masonry: impact on laboratory evaluation

This chapter is based on the published journal paper: Fusade, L., Viles, H. (2018), A comparison of standard and realistic curing conditions of natural hydraulic lime repointing mortar for damp masonry: impact on laboratory evaluation. *Journal of Cultural Heritage*. doi:10.1016/j.culher.2018.11.011  
Modifications compared with the published version are that the supplementary information has been included here in the main body of text.

### Abstract

Environmental conditions can affect the curing and performance of natural hydraulic lime (NHL) mortars. This study considers a specific historic environment: traditional masonry exposed to high humidity and rainfall, with a particular focus on Devon. Repointing mortar are especially exposed. The research assess what, if any, differences these environmental conditions would make to mortar properties through laboratory evaluations before repointing work begins. Realistic curing conditions (as likely found on site) of 15°C, 85 % RH, representing an average of summer climate in Devon were compared with standard recommended laboratory conditions of 20°C, 65 % RH. A range of mixes, representing some conservation pointing mortars, was prepared using NHL2 (St Astier), quartz sand, and crushed Portland limestone in 1:3 and 1:2 binder to aggregate ratios by volume. The influence of curing conditions on carbonation depth, strength development, internal textural structure, pore structure and water uptake at 28 and 90 days is discussed (called here early and medium ages) and the response of NHL mortars to both this humid environment during evaporation and salt crystallisation have been assessed. Results show that significant differences are found in laboratory evaluations of mechanical properties of the same NHL mortar exposed to different curing conditions especially at an early age and for mortar made with quartz sand. Laboratory evaluation should be made on samples cured under realistic conditions if information on the early to medium-term (up to 90 days) characteristics of NHL mortar is required. Overall, realistic humid curing conditions help NHL mortars gain good internal structure more quickly, minimising the risk of early failure of pointing mortar exposed in a harsh humid environment.

## 5.1 Introduction

### 5.1.1 *Why repoint damp historic buildings?*

Throughout the centuries, lime mortars have been used under a very wide range of environmental conditions. In England, where the climate is often wet, lime mortar is found in many types of historic masonry built before the 1850s. Orientation and topography are key in assessing the impact of wind-driven rain on historic masonry walls (British Standards Institution, 2008). When dealing with historic buildings highly exposed to rainfall and with interior dampness problems, conservation officers first recommend maintenance of the building features, such as the drainage system, conditions of the roof elements, etc (Oliver, 1997; Forster & Carter, 2011). When this has been ensured but interior dampness is still present, conservation work on the masonry is considered, such as rendering, grouting or repointing (Henry & Stewart, 2012). Previous research has shown that a render, flat work or harling, often helps to hold most of the water until the rain stops when evaporation will allow the masonry to dry out (Wood, 2012). However, render can be aesthetically disruptive and therefore repointing has two clear advantages: firstly, it is far less disruptive since it ensures a minimal intervention to the historic masonry (Forster, 2010); secondly, it is less costly (Wood, 2012).

In a masonry unit, one of the main roles of pointing mortar in a joint is to draw moisture out of the wall to help it dry out (Rirsch & Zhang, 2010; Maurenbrecher, 2012). Observations from practitioners (such as conservation officers and craftsmen) and scientific research have both identified that failure of weathered original pointing mortar or previous inappropriate interventions lead to rainwater and moisture ingress through the joints (Rirsch & Zhang, 2010). In these cases, mortar needs to be replaced by repointing. The performance of the pointing mortar is

therefore critically important to reduce water penetration in the masonry (Forster, 2010; Hees, 2012; Hughes, 2012).

In addition to being an efficient solution in dealing with water ingress, it is also important to consider that repointing meets some main conservation principles. Indeed, it is recommended that conservation interventions for repair retain the heritage values of a site by respecting the appearance and ensuring minimal intervention on the original fabric, as well as long-term stability and sustainability (ICOMOS, 1964; Drury & McPherson, 2008; Forster, 2010). Research has highlighted that material changes, through weathering or decay, or through intervention replacing the original materials, can be associated with a change of values of the building (Taylor & Cassar, 2008; Douglas-Jones *et al.*, 2016). This is where repointing should be carefully thought through, from philosophical to practical considerations and functional requirements (Hees, 2012). If new materials are introduced - being different to the originals - this should be for preserving the building as a whole and meeting its current needs and conserving its values. The performance of repointing mortar should therefore be carefully assessed by characterising the mechanical and physical properties of mortars and how they develop and respond to a specific environment, prior to application. With this in mind, and to avoid drawing too general conclusions from one scientific study, we focus here on a specific historic environment: traditional masonry, as for instance found in church towers, exposed to high humidity and rainfall in places such as Devon, in the south west of England.

### ***5.1.2 The environment (temperature, relative humidity and rainfall) affects hardening of lime mortar***

There are several examples of pointing mortar which have resisted humid environments (Borges *et al.*, 2014). All repair interventions on a historic building,

such as repointing, have to consider the climatic environment (Forster & Carter, 2011; Hughes, 2012). This is especially important in the context of climate change: research has shown that due to predicted increase of rainfall and wind-driven rain in some locations, more water will impact masonry, remaining wetter longer (Banfill *et al.*, 2016) and increasing the wetting and drying cycling (Orr *et al.*, 2018); which would impact the overall performance of lime mortar.

Environmental conditions have an impact on the early days of lime mortar, during the setting and hardening process of the fresh mortar. Research has shown that this hardening process, also called carbonation, is governed by the temperature and relative humidity (RH) of the environment (Livesey, 2012). This combination of temperature and relative humidity in the environment in which lime mortar will harden is called the curing condition. As the diffusion of CO<sub>2</sub> in the pores depends on the water content, climate can directly influence the rate of carbonation (Van Balen & Van Gemert, 1994). In addition, variations in temperature and relative humidity produce different reactions with lime, such as mineral transformation of portlandite (Ca(OH)<sub>2</sub>) into calcite (CaCO<sub>3</sub>) that will have an important effects on the internal development and structure of lime mortar (Lanas & Alvarez, 2003; Grilo *et al.*, 2014).

However, when testing mortar, recommended laboratory curing conditions of 65% RH, 20°C (British Standards Institution, 2006) are used which are often quite different from the on-site environmental conditions. There is no consensus on the optimum temperature for carbonation, sometimes suggested at 15 °C (Livesey, 2012), or 20 °C (Van Balen & Van Gemert, 1994) and researchers suggest that the most favourable RH for carbonation to occur is between 55% and 75%, while carbonation would reduce between 55% to 45% and 75% to 85% (Revie, 2018). Indeed, diffusion of CO<sub>2</sub> is slower in water than in air, as water blocks the porous

system (Van Balen & Van Gemert, 1994; Houst *et al.*, 2002; Cultrone *et al.*, 2005), so research has shown that for carbonation to occur well, masonry exposed to rain should be sheltered. Carbonation is also not the only property that should be considered. Some studies have compared the maritime or outside environmental conditions with standardised curing conditions, and identified that higher RH allows a higher rate of carbonation and hydration process (Lanas *et al.*, 2005) and contributes to reducing pore size (Grilo *et al.*, 2014). However, these environmental conditions were very site specific and no implications for laboratory evaluation was drawn.

Although curing conditions have to be considered on a case by case basis, no research has yet clearly stated whether curing conditions make a significant difference both to the early development of the internal structure and performance of lime mortar, and whether it is important to cure samples under realistic conditions for laboratory characterisation. In general, for humid temperate environments, such as in Devon, the combined effect of low temperature and high humidity can lead over time to the saturation of the mortar, which then presents the risk of failure (Livesey, 2012). This is why prior scientific evaluation and characterisation of how the mortar would develop and perform in such environments is necessary to ensure that the repair mortar will be compatible with the masonry unit (Schueremans *et al.*, 2011) and fulfil the technical requirements of a specific environment (Lindqvist, 2009).

## **5.2. Research aims**

This study compares curing under realistic environmental conditions, such as those found in Devon, with curing under standard laboratory conditions to understand better what, if any, differences these environmental conditions would

make to the natural hydraulic lime mortar structure and durability. It focuses on evaluating the development of the internal structure of mortar samples after curing for 28 and 90 days, producing early and medium-aged mortars respectively. Finally, using easily available and commonly used analytical methods it evaluates whether it is of significant importance to use realistic curing conditions for laboratory characterisation, if the mortar is to be applied on a specific site or building.

### **5.3. Materials & Methods**

#### ***5.3.1 Mortar preparation and curing***

##### *5.3.1.1 Compositions of the mortar mixes and properties of the fresh mortars*

A range of mixes, representing some conservation pointing mortars, was prepared by a professional mason. Mortars were made using a natural-hydraulic lime (NHL) 2 (St Astier). When using lime under humid built environmental conditions, NHLs are often favoured as they allow for a hydraulic set while being feebly hydraulic and without gaining too much strength (Allen *et al.*, 2003). They harden through a two-phase process: initially a 'hydraulic set', resulting mainly from the formation of calcium silicate hydrates (C–S–H) and calcium aluminate hydrates (C–A–H), followed by carbonation (Forster, 2004). Formations of these hydrates gives NHLs their hydraulicity, which means that they need moisture in the air to set and therefore have the capacity to cure under humid environmental conditions (Allen *et al.*, 2003). This initial setting also gives them an early strength gain, essential for resisting extreme environmental conditions (Kalagri *et al.*, 2014).

Two types of aggregates were used, a well-graded sharp quartz sand (Chardstock) and porous, sand-sized crushed limestone (Portland). The grain size distribution of each aggregate was measured by sieving and showed a similar well-graded distribution (0.76 to 4 mm), with the crushed limestone having more smaller

grains (between 0.15 and 0.60 mm) than the quartz sand (Figure 5.1). Two binder to aggregate ratios by volume were used, a binder-rich one (1:2) and a standard repointing one (1:3). To follow the 1:2 and 1:3 binder to aggregate ratio by volume, the weight needed for each aggregate and binder was adapted for each mortar mix based on bulk densities.

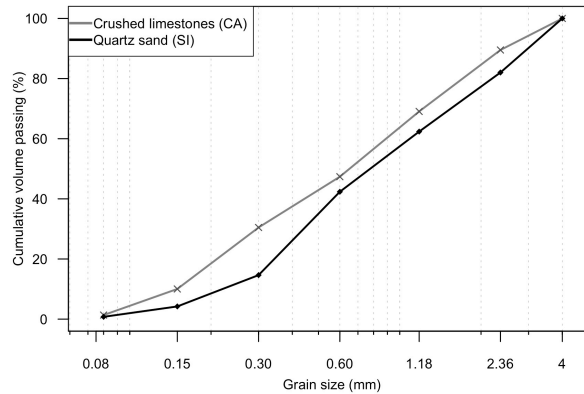


Figure 5.1 Grain size distribution of Chardstock quartz sand and crushed Portland limestone, showing a similar well-graded distribution, with the crushed limestone having more smaller grains than the quartz sand.

During mixing, water was added based on the experience of the mason to obtain similar consistency (135 mm ( $\pm 10$ ) being the targeted flow for repointing mortar consistency). Flow tests were carried out on each mix with a flow table (Matest) following BS EN 1015 5-3:1999 (British Standard Institution, 1999b). The initial moisture of each aggregate was 10.43% for the quartz sand and 1.38% for the crushed limestone, explaining the need for less water for the CA mixes, which therefore have the lowest water:binder ratio (Table 5.1). The Initial Moisture Content (IMC) was recorded with a Moisture Analyser (A&D MX50) in %.

Table 5.1 Summary of mortars prepared and properties of fresh mortars

Mortars	Aggregate	Binder:aggregate ratio (by volume)	Water:binder ratio	Flow (mm)	Initial Moisture Content (%)
<b>SI3</b>	Quartz sand	1:3	0.79	131	14.74
<b>SI2</b>	Quartz sand	1:2	0.45	132	14.52
<b>CA3</b>	Crushed limestone	1:3	0.11	145	14.58
<b>CA2</b>	Crushed limestone	1:2	0.19	138	16.02

### 5.3.1.2 Curing conditions and sample sizes

Specimens were divided into two groups and placed in different curing conditions in two environmental chambers (Sanyo-FE 300H/MP/R20 and Sanyo-MLR-351). The two curing conditions were chosen as follows - one recommended by standards (SC) at 20 °C ( $\pm 1$  °C), 65% ( $\pm 8\%$ ) RH until testing (British Standard Institution, 2010), and the other chosen to represent realistic conditions (RC) of an average of summer climate in Devon 15 °C, 85% (these values fluctuate between day and night). Data was taken from the weather station at Chivenor. Calculation shows that these two curing conditions have similar absolute humidities (0.011kg/m<sup>3</sup>). Therefore, any differences of properties between mortars cured under these different conditions is due to the lower temperature or higher RH.

Specimens were made in the laboratory in prisms of 40 mm x 40 mm x 160 mm using polystyrene moulds (Table 5.2). All specimens were demoulded after 5 days and tested at 28 and 90 days (chosen to represent ‘early age’ and ‘medium age’ mortars respectively).

Table 5.2. Summary of samples sizes and number of replicates for each mortar mix used in each test.

<i>Test</i>	<i>Sample size</i>	<i>n#</i>
<i>UPV</i>	Prisms	3
<i>Carbonation depth</i>	Half prisms	5
<i>Compressive strength</i>	Half prisms	5 - 6
<i>WACC</i>	Half prisms	6
<i>Drying</i>	Half prisms	3 per conditions
<i>Open Porosity</i>	Half prisms	5
<i>Salt uptake</i>	Cubes (40 mm x 40 mm x 40 mm)	4

### ***5.3.2 Mechanical properties of hardened mortars***

#### *5.3.2.1 Carbonation depth*

The mean carbonation depth was measured by spraying phenolphthalein on freshly broken specimens. Phenolphthalein is a pH indicator commonly used for determination of carbonation depth, that turns pink above a pH of about 9.3 (Lawrence, 2006). When applied on the surface of a freshly broken mortar, the uncarbonated area, composed of calcium hydroxide ( $\text{Ca(OH)}_2$ ), is stained pink, whereas the carbonated area, composed of calcium carbonate ( $\text{CaCO}_3$ ), remains unstained. The depth of the unstained area was then measured from the four faces with a calliper (0.01 mm), giving a mean value for each of the three replicates.

#### *5.3.2.2 Compressive strength*

The compressive strength was measured according to BS EN 1015-11:1999 (British Standard Institution, 1999a) on five half prisms (cut from prisms of 40 x 40 x 160 mm) at 28 days and six at 90 days. The testing machine (Matest Unitronic Load Frame Tester) was used with a 10 kN load cell and a loading rate of 50 N/s. Results are reported as the mean of all replicates in  $\text{N/mm}^2$ .

#### *5.3.2.3 Ultrasonic pulse velocity*

Ultrasonic measurements were carried out on three prisms (40 x 40 x 160 mm) of each mix, with a Portable Ultrasonic Non-destructive Digital Indicating Tester (Pundit Lab, Proceq, UK) with 54 Hz frequency transducers. Direct transmission was used with transducers placed at each end of the specimen on the long axis of the prisms. The propagation velocity ( $v_p$ ) (km/s) was measured and results reported as the mean of three measurements on each three replicates of each mix.

### 5.3.3 Pore structure

#### 5.3.3.1 Mercury Intrusion Porosimetry (MIP)

The pore size distribution was measured using mercury intrusion porosimetry with a Porosimeter (Quantachrome PoreMaster 33 Hg), with low gas pressure range between 0.2-55 psi and high hydraulic pressure range up to 2110 psi. MIP was performed on one replicate of each mortar mix, previously oven dried at 60 °C.

#### 5.3.3.2 Pore structure

Optical microscopy of thin-sections impregnated in blue resin was performed using a Olympus BX43 microscope at x10 magnification with transmitted light. One thin section of each mix was made and observed.

#### 5.3.3.3 Open porosity

The open porosity (*op*) was evaluated following the gravimetric method adapted from the standard BS EN 1936:2006 (British Standard Institution, 2006). Five half prisms were oven dried for 24 hrs at 70 °C ( $\pm 2$  °C) to constant mass (*md* in g). Samples were then placed in a desiccator under vacuum at low pressure (less than 15 mm Hg) for one hour and allowed to soak in distilled water for 24 hrs at ambient temperature, enabling determination of the saturated mass (*ms* in g) and immersed mass (*mh* in g). The open porosity (%) was calculated as the mean of five replicates with the formula (1):

$$op = \frac{ms-md}{ms-mh} \times 100 \quad (1)$$

#### 5.3.3.4 Capillary absorption

The determination of water absorption coefficient due to capillarity of hardened mortar followed the standard tests BS EN 1015-18:2002 for the design and size of samples (British Standards Institution, 2006) and EN 1925: 2000 for the interval of measurements for highly absorbent stone (British Standard Institution, 1999c).

Samples were oven dried for 24 h at 70 °C ( $\pm 2$  °C) to constant mass ( $md$  in g), cut in half, sealed using a moisture and vapour-proof sealant (Parafilm M), and placed in 3 mm of distilled water. The mass of each of the six replicates at defined time was determined using a balance (Sartorius) at 0.01 g precision. The increase in mass ( $m_1$  in g) by the surface immersed ( $A$ ) ( $m^2$ ) of each replicate was expressed as a function of the square root of time ( $\sqrt{t_1}$ ) in minutes ( $mn^{0.5}$ ). The water absorption coefficient by capillarity (WACC) ( $g/m^2mn^{0.5}$ ) was determined by formula (2) given by the standard as a mean of the six replicates:

$$WACC = \frac{m_1 - md}{A \cdot \sqrt{t_1}} \quad (2)$$

### 5.3.4 Performance in humid environment

#### 5.3.4.1 Drying behaviour

The drying rate was monitored for 120 hours under two environmental conditions: laboratory at 23 °C ( $\pm 2$  °C), 55% RH ( $\pm 5\%$ ), and realistic (Devon) at 15 °C, 85% RH ( $\pm 5\%$ ). Three replicates of each mix in half prisms, having previously been fully saturated under vacuum, were used. The change of mass ( $m_1$  in g) was recorded every 2 to 3 hours for the first 12 hours then every 15 hours ( $\pm 3$  hrs) using a balance (Sartorius) at 0.01 g precision. For the 28 days test, two drying sets were done, one until 52 hours, the other one from 50 hours until the end. The water content ( $Wc$ ) ( $g/cm^2$ ) was calculated as a mean of the three replicates using formula (3):

$$Wc = \frac{(m_1 - md)\rho_w}{V} \quad (3)$$

Where  $md$  (g) is the oven dry mass of the replicates,  $\rho_w$  ( $g/cm^3$ ) the density of water at 20 °C and 15 °C degrees, and  $V$  ( $cm^2$ ) the volume of the sample (Hall & Hoff, 2009).

#### 5.3.4.2 Salt uptake

The salt uptake and crystallisation test was performed according to Gulotta et al. (Gulotta *et al.*, 2015) who followed a version of RILEM MS-A.2 procedure. Specimens (half prisms) were tested at 360 days. Eight replicates of each mortars were used and divided in two groups: four having been cured under standard conditions for 360 days, and four cured under realistic conditions for 90 days and then stored under standard conditions. Specimens were oven dried at 60 °C for 24 hours and sealed on the long faces with a vapour-proof sealant (Parafilm M). Immersion for 2 hours in a 10% sodium sulphate solution, followed by a drying period of 22 hours at 20 °C, 80% RH, constituted a daily cycle. Four daily cycles formed a weekly cycle, after which the weight of each specimen was recorded. Three weekly cycles were performed.

### 5.4. Results

In order to determine whether the same mortar mix exposed to different curing conditions would develop different properties, it is important to statistically compare these results. Because all comparisons are paired (comparing one mix, under two curing conditions, for each age and type of testing) paired t-tests were used (Table 5.3). Realistic curing conditions make a significant difference to the test results for most of the mortars after 28 days of curing. Less significant differences are shown after 90 days of curing. The types of differences and the reasons for them are further explained for each test below.

Table 5.3 Summary of the t-test results of property development under standard conditions (SC) and realistic conditions (RC): p-values under 0.05 indicate that the means are significantly different, shown by boxes in grey. N indicates the number of measurements taken. Boxes in lighter grey indicate that one replicate was considered to have failed and not included in the calculation. Statistically significant differences occur mostly after 28 days and for both ages in SI mortars.

Conditions	Mortars	Carbonation (n=12)		Compressive strength (n=5 to 6)		Pulse velocity (n=9)		Open Porosity (n=5)	
		28 d	90 d	28 d	90 d	28 d	90 d	28 d	90 d
SC	SI3	7.2E-09	9.9E-05	2.6E-03	1.1E-01	1.0E-05	9.0E-03	3.5E-02	6.2E-01
RC		1.6E-08	5.6E-01	1.7E-03	1.5E-01	4.6E-08	6.1E-04	5.0E-02	2.3E-04
SC	SI2	7.5E-06	5.5E-02	1.5E-01	2.8E-01	7.2E-06	9.8E-01	2.9E-01	9.0E-03
RC		8.7E-04	8.0E-01	5.6E-02	8.3E-01	2.5E-05	9.5E-01	1.8E-03	1.8E-03
SC	CA3								
RC									
SC	CA2								
RC									

#### 5.4.1 Mechanical properties

##### 5.4.1.1 Carbonation depth

As seen previously, the hardening and setting process, involving a hydraulic set followed by carbonation, is highly influenced by the curing conditions (temperature, RH) of the mortar (Van Balen & Van Gemert, 1994; Livesey, 2012), but also by the water:binder ratio (Houst *et al.*, 2002). The phenolphthalein test gives an indication of the carbonation depth, highly influenced by porosity, but cannot be directly correlated to the carbonation profile and hydration (Houst *et al.*, 2002).

Figure 5.2 shows that mortars cured under realistic conditions have a significantly higher carbonation depth at 28 days, between 1.10 and 2.70 mm deeper than mortars cured under standard conditions. Although we could argue that higher RH would favour the hydration of the anhydrous calcium silicates and aluminates (Revie, 2018) this may be offset by the reduction in temperature. However, at 28 days, the values are too low and the mortars too young to draw clear conclusion. Indeed, the belite responsible for the hydraulicity only starts appearing after 28 days

(Forster, 2004). At 90 days, the carbonation depth is similar or slightly higher under standard conditions. However, as Table 5.3 shows, these differences are not statistically significant. In addition, binder-rich mortars (SI2 and CA2) experience a lower carbonation depth because in these mixes more binder has to set and carbonate.

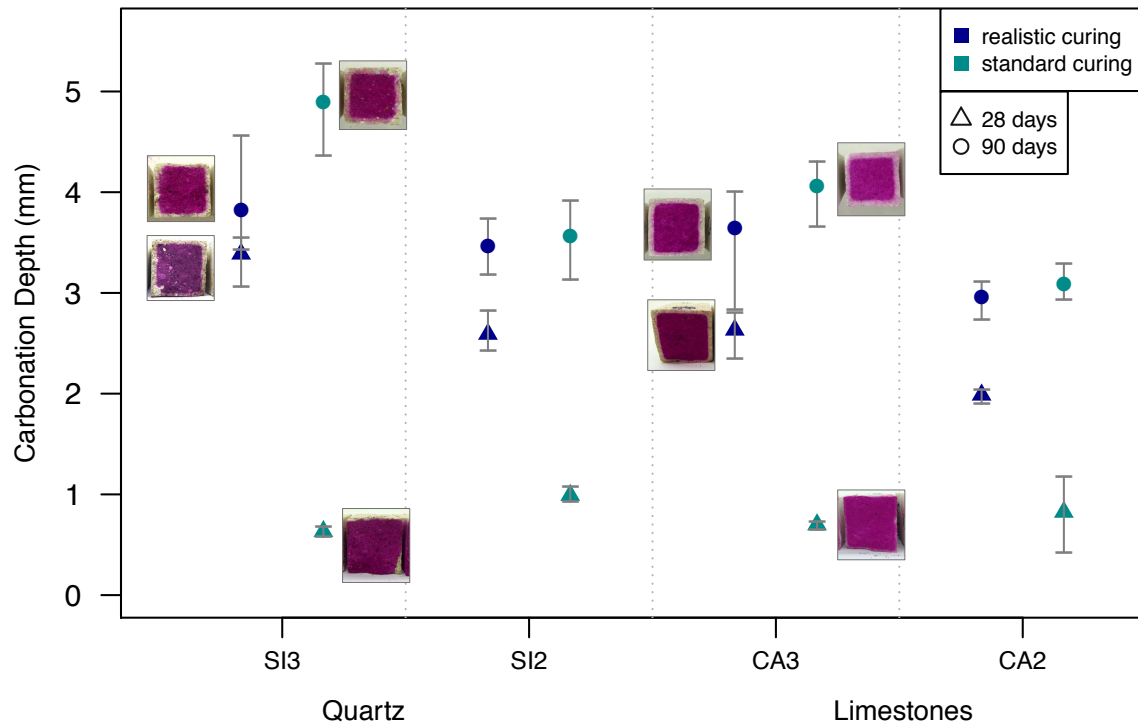


Figure 5.2. Comparison of the carbonation depth (mm) of samples cured under SC and RC at 28 and 90 days ( $n=3$ ). Error bars indicate the minimum and maximum values. The pictures show the uncarbonated area (stained) and the carbonated area (unstained) after phenolphthalein spraying. The same patterns were seen on the SI2 and CA2 samples so are not presented here.

#### 5.4.1.2 Compressive strength

When water evaporates from the fresh mortar, pores are created giving access to  $\text{CO}_2$  which contributes to the mineral transformation of portlandite ( $\text{Ca}(\text{OH})_2$ ) into calcite ( $\text{CaCO}_3$ ) (Hall & Hoff, 2009; Arizzi *et al.*, 2013). This process is directly impacted by the environment and especially by the amount of moisture of the air, as water slows down the transport of  $\text{CO}_2$ . Higher porosity and higher calcite contents often equal higher compressive strength (Lanas & Alvarez, 2003).

For quartz sand rich mortars, those exposed to realistic conditions show significantly higher compressive strength at 28 days than those cured under standard conditions (Fig. 5.3). This is likely due to higher hydration as lower temperature could increase the mineral reaction responsible for strength gain (Livesey, 2012). However, at 90 days, the variation within samples is too high so that no significant difference can be determined (Table 5.3). The binder-rich mix (SI2) shows higher compressive strength, as noted in previous research (Lanas & Alvarez, 2003): as lime is a porous material, more CO<sub>2</sub> can access lime and carbonate, gaining strength. In mortars made with crushed limestone no significant differences are seen between the two curing conditions and between the two binder:aggregate ratios (Fig. 5.3, Table 5.3).

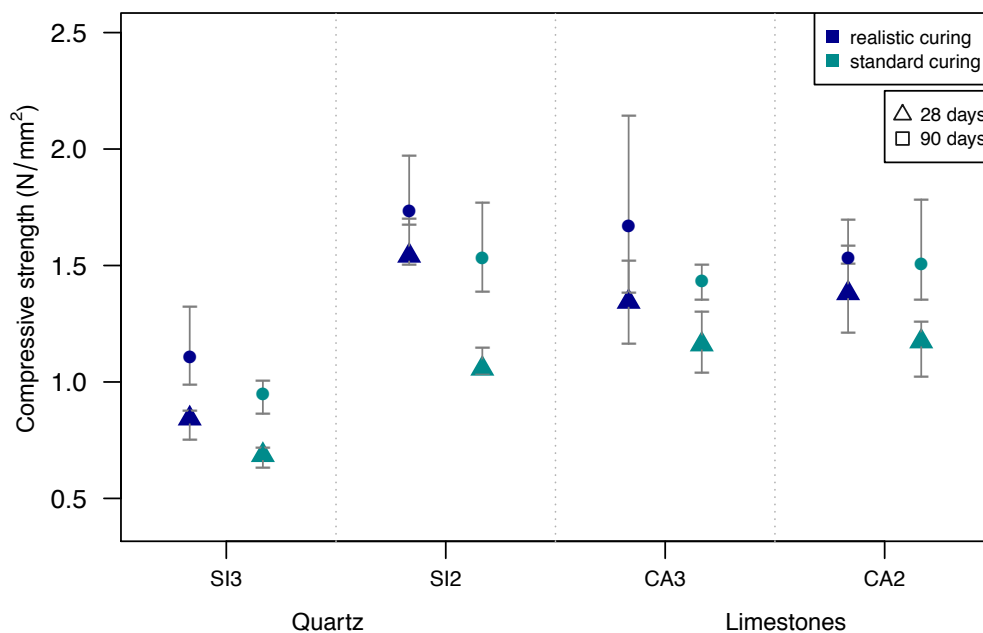


Figure 5.3. Development of compressive strength (N/mm<sup>2</sup>) under standard and realistic curing conditions (n=5 or 6) showing higher early strength gain under RC. Error bars indicate minimum and maximum values.

#### 5.4.1.3. Internal structure – pulse velocity

Research has shown that ultrasonic pulse velocity (UPV) can be used as a non-destructive technique to assess internal material changes or decay in porous building materials used in cultural heritage, such as lime mortars (Cazalla *et al.*,

1999; Arizzi *et al.*, 2013; Vasanelli *et al.*, 2015). UPV gives an indication of the presence of cracks and overall of the internal quality of the material. Previous research has shown the correlation of compressive strength with UPV and that carbonation degree and porosity affect UPV the most (Arizzi *et al.*, 2013). In this study, we use UPV as a proxy to assess what the compressive strength and carbonation depth could suggest: a denser internal structure is formed more quickly in the mortar when exposed to realistic humid environmental conditions.

The general trend shows indeed that mortars cured under realistic conditions (RC) have a higher velocity propagation (vp) after both 28 and 90 days of curing (Table 5.4). A higher propagation velocity represents a denser internal structure, as pores and cracks would slow down the vp. This higher vp for RC mortars, could suggest that their internal structure is denser, more compact, or that their degree of carbonation is higher (Cazalla *et al.*, 1999). This difference is particularly significant at 28 days for all mortars and at both ages for SI mortars (Table 5.4). In all mortars, the decrease of vp from 28 to 90 days may be a sign of more cracks or more pores.

Table 5.4. Summary of the ultrasonic pulse propagation velocity results (km/s) (n=9). A higher vp represents a denser and more intact internal structure. SC: Standard conditions, RC: Realistic conditions.

Conditions	Mortars	28 days		90 days	
		mean (km/s)	SD	mean (km/s)	SD
SC	SI3	0.843	±0.027	0.498	±0.160
RC		1.020	±0.063	0.687	±0.091
SC	SI2	1.100	±0.032	0.945	±0.128
RC		1.471	±0.076	1.399	±0.204
SC	CA3	1.272	±0.045	1.405	±0.080
RC		1.471	±0.072	1.407	±0.270
SC	CA2	1.181	±0.053	1.404	±0.063
RC		1.410	±0.093	1.384	±0.132

Overall, CA mortars show a higher vp than SI mortars, explained by their denser structure and fewer shrinkage cracks. The vp of CA samples under RC does

not change from 28 to 90 days, which could imply that their internal structure is mainly formed during the first 28 days of curing. The differences between mortar mixes with different aggregates may be explained by the denser structure of CA mortars which have pore volumes concentrated in the same range.

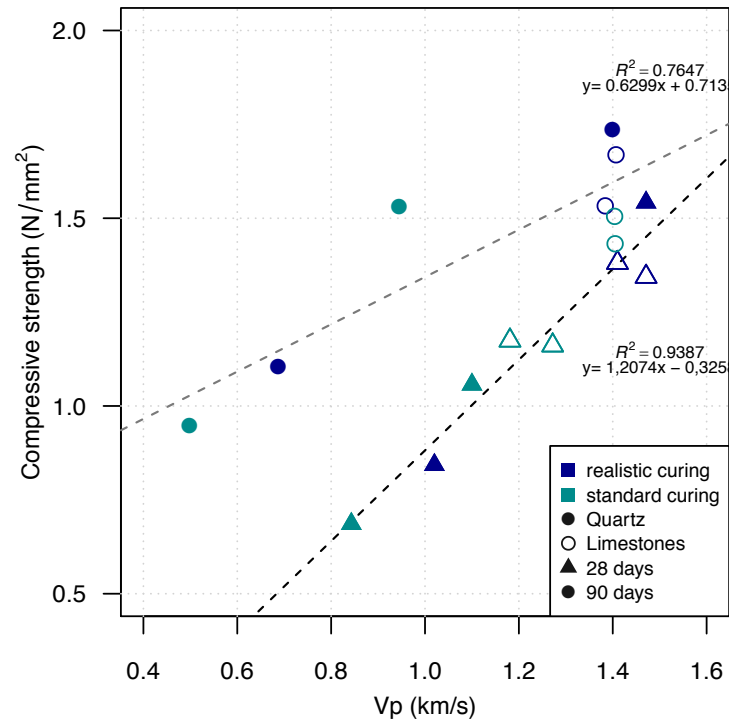


Figure 5.4. Relationship between  $v_p$ , age of testing, and compressive strength. Regression lines show a higher correlation between compressive strength and  $v_p$  at 28 days (black dashed line) than at 90 days (grey dashed line).

Figure 5.4 highlights that when the compressive strength of samples increases over time it impacts the internal structure of the mortar resulting in a higher propagation velocity (around 1.4 Km/s), except for SI3, for which  $v_p$  decreases. Propagation velocity therefore confirms the hypothesis that mechanical properties develop quicker in mortars exposed to realistic curing conditions. It is interesting to see whether the impact of curing conditions can also be seen in the pore structure, as research has shown a relationship between mechanical properties and pore structure (Lanas *et al.*, 2004).

### 5.4.2 Pore structure

#### 5.4.2.1 Pore size distribution and Pore structure

In this study we consider pores between 1 to 1,000 microns (0.001 to 1 mm), in the range of micropores to be mainly relevant to absorption by capillarity (Siegesmund & Dürrast, 2014) and called “capillary pores”, and pores from 0.1 to 1 microns to be “smaller capillary pores”. Mortars made with quartz sand (Fig. 5.5a) show a lower overall porosity than the ones made with crushed limestone (Fig. 5.5b), but with a higher proportion of larger capillary pores (between 8 and 40 microns). Most of the pores in the mortars made with crushed limestone are in the fine capillary pores range. This likely explained their dense structure. Mortars of 1:3 ratio have more of a bimodal pore size distribution, whereas the binder-rich mortars (1:2 ratio) show a unimodal distribution, with few larger pores.

The different curing conditions do not translate into important differences in the same mortar mix, as the pore size distribution remains similar. Cured under realistic conditions, SI3 mortars show a decrease in the volume of smaller capillary pores, between 0.03 to 0.5  $\mu\text{m}$ , and SI2 mortars show a decrease of capillary pores, between 0.08 and 5  $\mu\text{m}$  (Fig. 5.5a). In mortars made with crushed limestone cured under realistic conditions the proportion of pores between 0.02 to 2 and 5  $\mu\text{m}$  slightly increases, which could show an even denser structure (Fig. 5.5b).

Figure 5.5a' and b' illustrate that mortars made with crushed limestone have a denser matrix, fewer drying shrinkage cracks and no coarser pores than those found in the mortars made with quartz sand. The blue colour of the matrix in Figure 5.5b' shows that the mortar is more porous. In SI samples (Fig. 5.5b') more shrinkage cracks are visible on samples cured under standard conditions, but in general, the curing conditions have no clear influence on the interconnectedness of the pores.

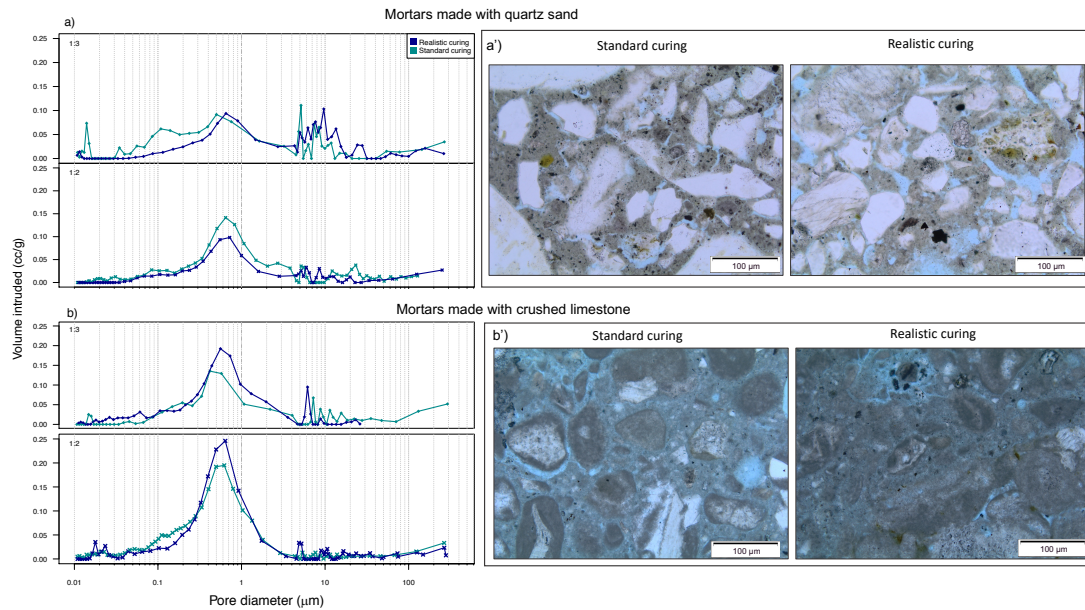


Figure 5.5 Pore size distribution with MIP of a) Mortars made with quartz sand b) Mortars made with crushed limestone, the dashed line shows the limit of capillary pores from 1  $\mu\text{m}$  to 1 mm.

Thin sections impregnated with blue resin showing the pore structure of a') Mortars made with quartz sand and b') Mortars made with crushed limestone, under petrographic microscope with transmitted light at x10 magnification. The scale bar shows 100 microns.

#### 5.4.2.2 Open porosity

The open porosity is the part of the total porosity connected to the surface of the samples, and so influences water transport properties (Hall & Hoff, 2009) and gives an indication of the near surface (rather than internal) changes. When mortar carbonates and as minerals transform over times, the porosity decreases over time. During the curing and hardening process, evaporation of water leaves pore spaces, and the development of a complex pore structure (Hall & Hoff, 2009; Arizzi *et al.*, 2013).

The expected decreased or unchanged porosity from 28 to 90 days is slightly visible under realistic conditions (Fig. 5.6). However, under standard conditions the average open porosity seems to be unchanged or increased over time. Significant differences are observed in open porosity between mortars cured under standard and realistic conditions after both 28 and 90 days of curing in most cases, although only

at 28 days for SI3, and only at 90 days for CA3 (Table 5.3). Overall, RC mortars at 28 days have a higher open porosity than SC ones, except SI3, and at 90 days, a significantly lower open porosity (Table 5.3 and Fig. 5.6).

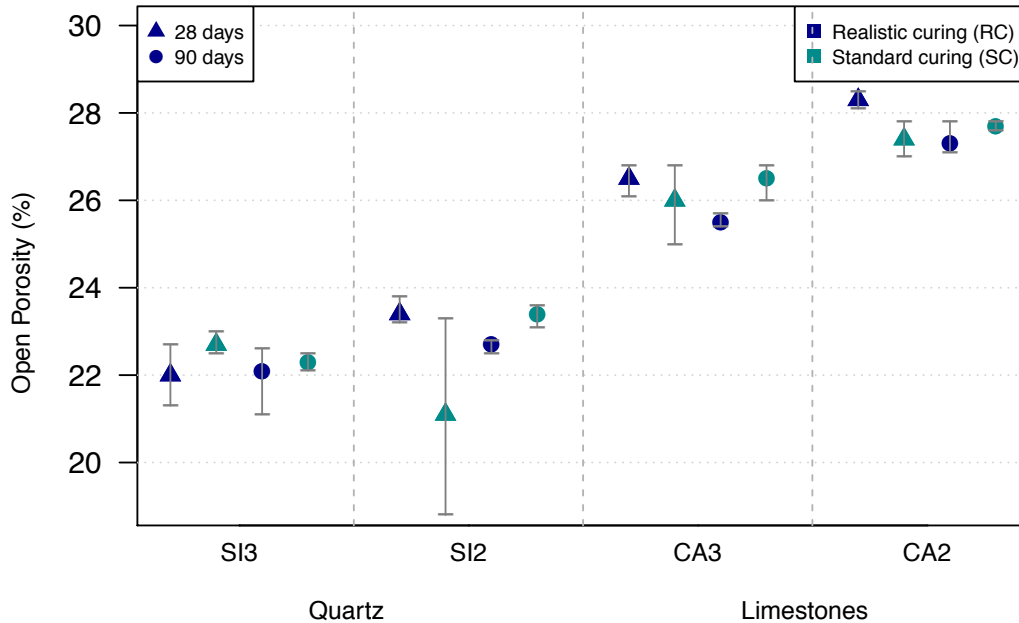


Figure 5.6. Comparison of the development of the open porosity under RC and SC at 28 and 90 days. Error bars indicate minimum and maximum values.

Figure 5.6 also highlights that mortars made with crushed limestone have a much higher open porosity than those made with quartz sand. Because they required less water to obtain similar consistency (Table 5.1), the higher porosity cannot be explained by a higher amount of water in the mix, but seems to be brought by the porous calcitic aggregates themselves. This can also be seen in Figure 5.5b' where no clear pores are found, but where an overall porous matrix is evident.

No clear correlation can be established between the carbonation depth and the open porosity. However, at 28 days, except for SI3, higher carbonation depths are linked to lower open porosity (Fig. 5.7). This could correlate with the fact that RC mortars seem to initially develop more quickly and then slow down after 28 days. It seems however, as expected, that when the open porosity is low, the compressive strength is higher.

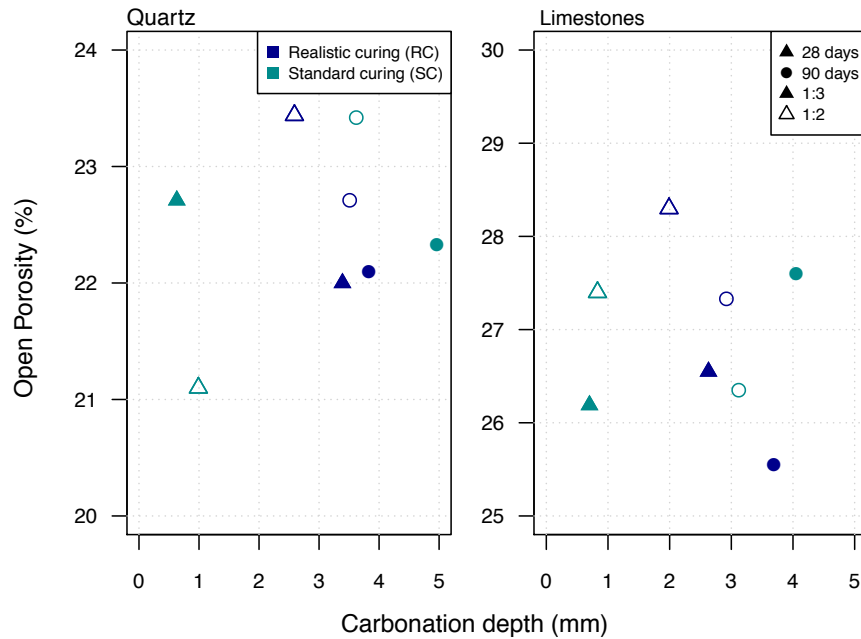


Figure 5.7. Relationship between open porosity and the carbonation depth of mortars made with quartz sand and mortars made with crushed limestone.

#### 5.4.2.3 Capillary absorption

Figure 5.8 indicates that mortars cured under standard vs realistic conditions behave similarly in terms of capillary absorption. However, the calculation of the coefficient of capillary absorption (Table 5.5) shows that in general RC mortars absorb water more slowly, except CA2 at 90 days. This is particularly true for SI3 mortars and CA2 mortars at 28 days. This very slight difference between mortars cured under different conditions suggests that the capillary structure is not as affected by the curing conditions as the mechanical properties are.

In SI mortars, Figure 5.8 shows a slight delay in saturation for binder-rich samples (dashed line) at both 28 and 90 days, and higher absorption coefficient for 1:3 ratio mixes (Table 5.5). In CA mortars, the opposite is seen, the binder-rich mix (CA2) has a higher capillary absorption rate. In general, despite being more porous, mortars made with crushed limestone have a slower capillary absorption. Figure 4a-b show indeed that the pores of CA mortars are in the smaller capillary pores range, explaining their slower capillary uptake (Wendler & Charola, 2008; Siegesmund &

Dürrast, 2014). No difference of behaviour is seen between 28 and 90 days, which would suggest that most of the capillary structure is formed at the early days of the mortar curing process.

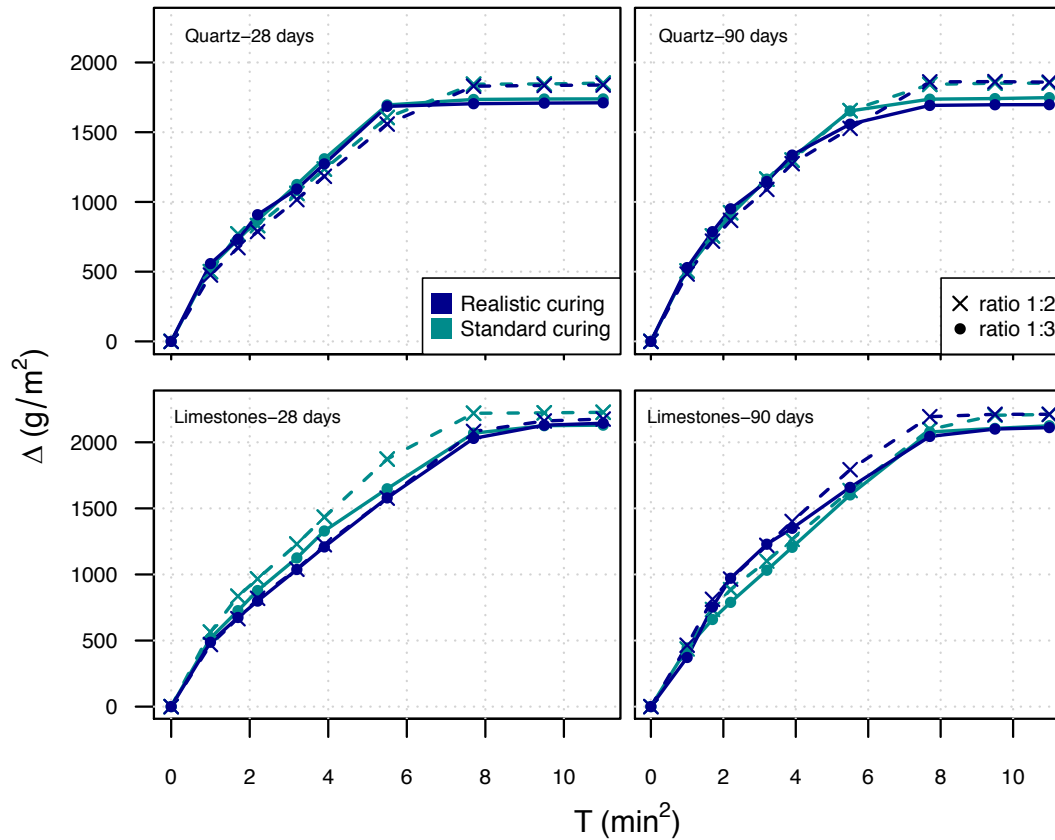


Figure 5.8. Capillary absorption of samples under realistic and standard conditions over time. The dashed lines represent the binder-rich mortars (SI2 and CA2).

Table 5.5. Water absorption by capillarity coefficient (WACC,  $\text{g/m}^2.\text{mn}^{0.5}$ ,  $n=6$ )

Conditions	Mortars	28 days ( $\text{g/m}^2.\text{mn}^{0.5}$ )	90 days ( $\text{g/m}^2.\text{mn}^{0.5}$ )
SC	SI3	295.45	291.27
RC		288.30	275.19
SC	SI2	228.67	230.48
RC		229.08	228.67
SC	CA3	255.26	259.29
RC		250.39	257.86
SC	CA2	276.74	259.98
RC		256.68	274.92

### ***5.4.3 Performance in humid environments***

In humid environmental conditions it is essential to assess how the mortar will behave under wetting and drying cycles – rain and evaporation. As seen previously, with rainfall predicted to increase with shorter cycles in many places (Orr *et al.*, 2018), the behaviour of mortar during evaporation is critical to the overall preservation of the building.

#### *5.4.3.1 Drying behaviour under different environments*

The ability of mortar to absorb moisture and then to dry out is essential to ensure that moisture will be drawn out of the masonry unit, therefore reducing the threat of ingress of water through the wall to the inside of the building.

Figure 5.9 shows no clear differences between drying curves and rates of mortars cured under realistic and standard conditions. The fact that hardly any difference is seen in the drying curves of samples cured under standard or more realistic conditions, suggests that the pore structure responsible for the absorption and desorption of moisture in both liquid and vapour state forms in a similar way when lime mortar is cured under different conditions.

When exposed to realistic humid environment of drying (15 °C, 85% RH ( $\pm 5\%$ ), as opposed to drier laboratory conditions, the evaporation rate of all the tested mortars is much slower (Figure 5.9). Under laboratory conditions of drying (plain line in Fig. 5.9), the two stages of drying are visible. For samples analysed after 28 days of curing, the second stage drying starts after approximately 70 hours (Fig. 5.9 28 days), and is being delayed to after 80 hours for samples cured for 90 days (Fig. 5.9 90 days). Under the two drying conditions, realistic humid environment and drier laboratory conditions, mortars cured for 90 days show a similar drying pattern, especially for CA samples (Fig. 5.9b). The longer first-stage drying observed in both drying conditions in RC and SC samples at 90 days shows that, in general, longer

curing leads to faster drying times. Indeed, during the first stage, water travels as a liquid to the surface, and so longer first-stage drying should be beneficial for the whole masonry as the liquid water in the bulk of the wall will have time to travel to the surface and dry out (Pender *et al.*, 2014). Finally, CA mortars have a higher water content than SI mortar, and binder-rich mixes as well, which can be related to their general previously observed higher open porosity (Fig. 5.6).

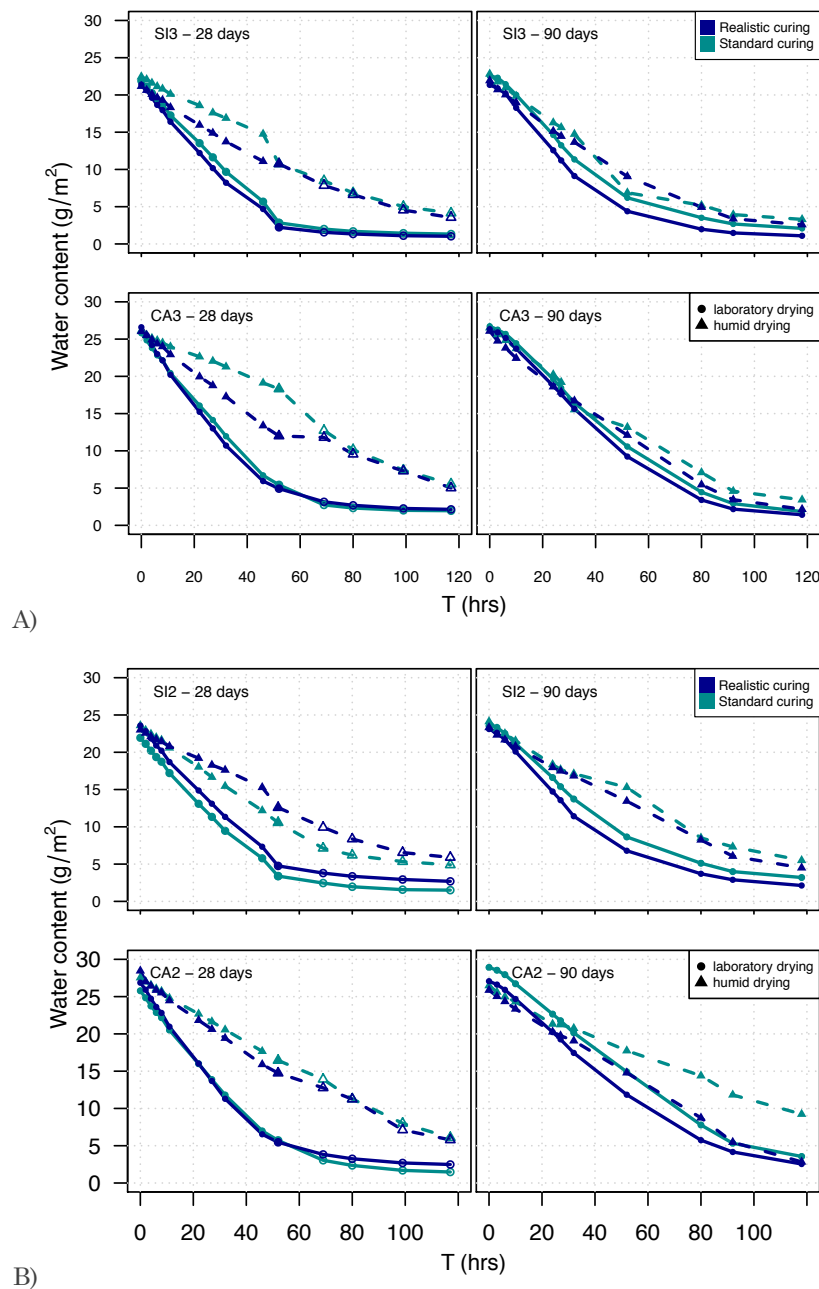


Figure 5.9. A) Drying curves of SI3 and CA3 mortars cured under SC and RC and dry under laboratory (plain line) and humid environment (dashed line). Empty marks at 28 days show the second drying test added to the first one . B) Data for SI2 and CA2 mortars.

### 5.4.3.2 Salt Uptake

In a masonry unit, in order to preserve the historic stones, it is important that the mortar is able to uptake more salt than the surrounding masonry. It is interesting to evaluate whether the different curing conditions of the mortar will make a significant difference to durability when it is exposed to salt crystallization during evaporation. Figure 5.10 shows that an increase in mass due to the uptake of both water and salt can be seen over the three weekly cycles for all mortars. The general patterns for all mortars seem to be that for those cured under standard conditions, experience a slowing of water and salt uptake at the third weekly cycle, whereas those cured under realistic conditions remain higher, except for SI3 mix (i.e. they take up more water and salt over time). In SI3 samples, the same pattern is seen for SC and RC samples, although RC samples have a higher mass difference.

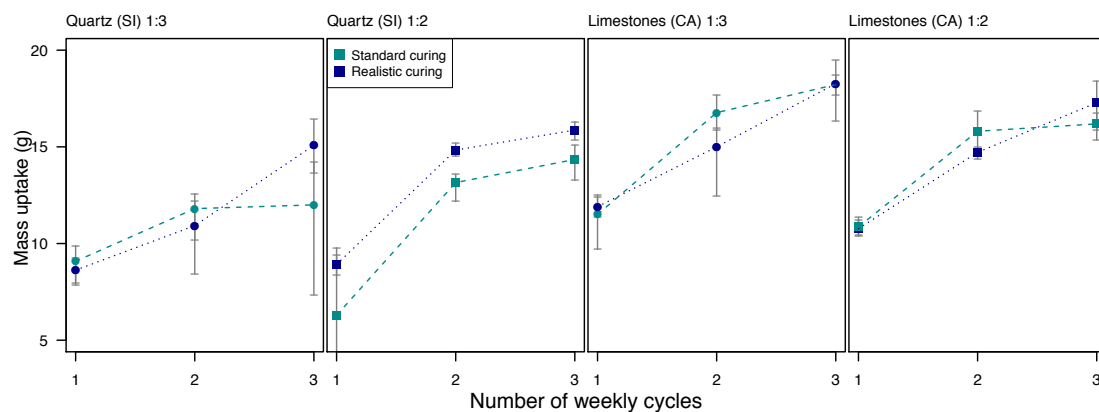


Figure 5.10. Mass uptake (in g, calculated as the mean of 4 samples) due to water and salt at each weekly cycle (4 daily cycles) for mortars initially cured under different conditions. Samples cured under RC show a more consistent mass uptake.

The increased uptake of salt at the surface of the mortar samples after each weekly cycle is visible in Figure 5.11. This is due to the accumulation of salt inside the sample that travels to the surface over time. However, no clear difference is visible between mortar samples which have been subject to standard and realistic curing. However, differences can be seen in the accumulation patterns of mortars

made with quartz sand vs those made with crushed limestone, with salt on SI mortars being more granulated around sand grains. For CA mortars, it seems that the salt uptake occurs mainly on carbonated areas: the centres of the samples (uncarbonated area) have indeed less salt visible on the surface. The surface of SI mortars was more affected by weathering due to salt and loss of material.

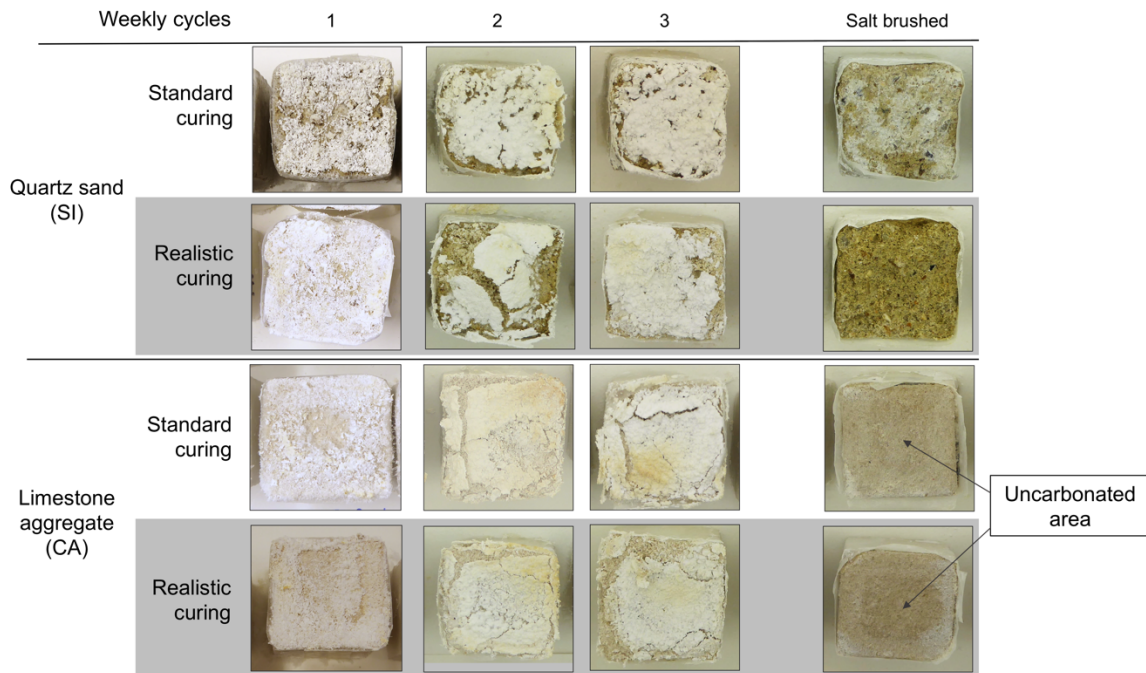


Figure 5.11. Patterns of salt uptake over three weekly cycles of mortars (SI3 and CA3) cured under different conditions. Patterns are similar for SI2 and CA2 mortars and are therefore not presented here. Salt was removed after each weekly cycle. The last column shows the effect of salt weathering on the surface of mortars after three weekly cycles, once the salt had been brushed off.

In general, the salt remained in pores after the test, which decreased the open porosity of samples (Table 5.6). The decrease in open porosity is more pronounced for mortars cured under standard conditions, except for SI3. This suggests that perhaps for mortars cured under realistic conditions, most of the salt taken up had migrated to the surface, whereas it would have stayed and blocked some pores in the SC mortars.

Table 5.6 Decrease in open porosity after salt uptake and crystallisation (n=4).  
 SC: Standard conditions, RC: Realistic conditions.

Conditions	Mortars	% decrease	
		mean	SD
SC		-10.08%	±0.02
RC	SI2	-7.44%	±0.02
SC		-8.01%	±0.02
RC	SI3	-10.77%	±0.02
SC		-14.05%	±0.19
RC	CA2	-9.67%	±0.03
SC		-31.03%	±0.09
RC	CA3	-4.96%	±0.04

## 5.5. Discussion

### *5.5.1 The different curing conditions make a significant difference in some properties*

Curing the same natural-hydraulic lime mortars under two different conditions makes some difference to many properties, especially mechanical and physical properties, at both 28 and 90 days. As Table 5.7 shows, at 28 days, mortars cured under realistic conditions show higher mechanical properties, a mix of higher and lower porosity and lower or unchanged sorptivity. Indeed, when mortars are cured under realistic humid conditions the carbonation depth at an early age is between 1.10 and 2.70 mm deeper than samples cured under standard conditions (Fig. 5.1), the compressive strength between 14% and 31% higher at 28 days and 2% to 14% at 90 days (Fig. 5.3), the propagation velocity between 14% and 25% higher at 28 days and 28% to 36% higher at 90 days for SI samples (Table 5.3), and the capillary absorption decreases up to 8%. The main differences are seen at 28 days and for mortars made with quartz sand. At 90 days, fewer differences are seen.

These results indicate that the mechanical properties and internal structure of NHL mortars cured under realistic humid conditions form quicker - i.e. the values

obtained at an early age (28 days) are similar to those of medium age (90 days). This could be explained by the more humid conditions affecting the overall structural development of NHL, perhaps preventing the formation of too many shrinkage cracks. It could also suggest that, at an early age, natural-hydraulic lime mortars are more impacted by and receptive to their environment.

The capillary absorption coefficient slows down slightly when mortars are cured under realistic conditions. However, as the capillary absorption and the evaporation curves show, the ability of mortar to uptake and release water does not seem to differ between specimens exposed to standard and realistic curing conditions. This may suggest that the formation of the pore structure is not greatly affected by the outside environment, backed up by the MIP data in Figure 5.4. In particular, CA mortars have a denser structure (Fig. 5.4b'), which could explain why they are less affected by the environmental conditions. Mortars made with quartz sand show the greatest differences in characteristics between those cured under realistic and standard conditions for 28 and 90 days.

Table 5.7 Summary of the effect of realistic conditions (RC) as opposed to standard ones (SC) on properties evaluated. ↗ means that samples under RC obtain higher data than SC samples, ↘ lower data and ↔ shows unchanged data. Arrows in blue show significant differences in all binder:aggregate ratios (see Table 5.1).

Property	Quartz (SI)		Crushed limestone (CA)	
	28 days	90 days	28 days	90 days
<i>Carbonation depth</i>	↗	↘	↗	↘
<i>Compressive strength</i>	↗	↗	↗	↗
<i>Propagation velocity</i>	↗	↗ and ↔	↗	↔
<i>Open porosity</i>	↗ and ↘	↘	↗	↗ and ↘
<i>Capillary absorption</i>	↗ and ↔	↘	↘	↘
<i>Evaporation</i>	↔	↔	↔	↔
<i>Salt uptake</i>	↗		↗	

### ***5.5.2 Overall response of mortars in humid environment***

Comparing the development at early to medium ages of different natural hydraulic mortars under realistic humid conditions and their response to evaporation and salt uptake helps understand how these mortars would perform in humid environments once applied as repointing mortar.

Realistic curing conditions, such as those found in Devon, could be beneficial, as the performance in uptake and release of water is only slightly affected, while their strength develops more quickly than those cured under standard conditions. This quicker internal development could benefit the performance of mortar exposed to rainfall. Indeed, a mortar reaching its hardened state quicker (Fig. 5.3) while having a greater ability to take up salt (Fig. 5.8) could perform well, and with less danger of failure, under a harsh environment experiencing series of intense rainfall events and ongoing masonry dampness. In addition, a lower capillary absorption would slow down the ingress of moisture. This would be greatly beneficial for the preservation of the overall masonry unit exposed to wind-driven rain and dampness.

### ***5.5.3 Implication for laboratory evaluation of lime mortar***

Characterisation of mortar mixes in the laboratory prior to on-site application is necessary to ensure mortars fit-for-purpose are chosen to be used. This study has shown that if the development of the mortar over different ages is to be assessed, in particular early to medium term, using realistic curing conditions similar to the ones in which the mortar is going to be applied is important. Indeed, in the early curing period (up to 28 days), the mechanical properties of the mortar have been shown to develop at a different rate. Curing under realistic conditions (close to the ones on-site) gives a better insight of how natural hydraulic lime mortars would develop during the early stages and enables the practitioners to understand how mortars

would respond to this specific environment. However, if the overall performance of the mortar, beyond medium-term curing (i.e. more than 90 days), is being assessed, standard curing conditions should be adequate.

## 5.6. Conclusions

In this study, realistic curing conditions, based on an average of summer climate in Devon, were used to understand the effect of this humid environment on the development at early and medium-term curing ages of selected natural-hydraulic lime mortars. This study has shown that although using realistic curing conditions can have an impact on some mechanical properties, the differences become less pronounced over time. Three main findings are:

- For the same natural hydraulic lime mortar exposed to different curing conditions significant differences are found, in particular on the mechanical properties and internal structure formation. Over the early to medium-term (up to 90 days curing time) natural hydraulic lime mortars are affected by the surrounding humid environment (RH and temperature). The main difference is seen in mortars made with quartz sand, for which realistic conditions have a more significant impact than those made with crushed limestone.
- The above results imply that the design of appropriate laboratory conditions (close to realistic ones) to characterise natural hydraulic lime mortar before repointing is particularly important for an assessment of the early to medium-term behaviour of the mortar. Over longer time scales, and an evaluation of the overall performance after 90 days, standard conditions are likely to be adequate.

- Finally, humid curing conditions seem to be beneficial for minimising the early risk of failure of the repointing mortar and to preserve the overall masonry unit exposed to cycles of wetting and drying. Indeed, the study has shown that during curing under humid conditions natural hydraulic lime mortars can gain a quicker good internal structure more quickly, while retaining the ability to take up salt and water. These characteristics should help preserve the masonry units from deterioration.

Further testing on mortars made with other materials, under different conditions, and at earlier and later ages would also be interesting and provide a fuller assessment of the significance of curing conditions to repointing mortar performance.



## VI- STUDY III - Drying out traditional masonry - Response of lime-mortar joints in granite test walls after intense rainfall, before and after repointing

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This chapter is based on the published paper:

Fusade, L., Orr, S.A., Wood, C., O'Dowd, M., Viles, H., (2019), Drying response of lime-mortar joints in granite test walls after an intense rainfall and after repointing. *Heritage Science*, 7(38). doi: 10.1186/s40494-019-0277-7

### Abstract

When rain impacts a building façade, it is essential that once it has entered, it leaves by evaporation to help the building dry out. Accumulation of moisture can lead to internal dampness, moulds and decay of valuable masonry by salt weathering. In a solid masonry wall where the stone is of low permeability, such as granite, which is found in many historic buildings, rain water mainly enters and leaves through mortar joints. If a granite stone masonry needs repointing, the repair mortar must allow the overall masonry dry out. This study evaluates the drying response of various lime-based repointing mortars mixes in small granite stone masonry (test walls) artificially submitted to an intense short rain event that are left to dry. It determines the influence of materials, joint types, workmanship and whether repointing could mitigate moisture ingress and help masonry dry out. Five test walls were built of Cornish granite with five different lime mortar mixes combining NHL 3.5 (St Astier) gauged with non-hydraulic quicklime (Shap), quartz and calcitic sand and biomass wood ash as additives. Simulated intense rain was sprayed on each wall over a 3.25 hour spell. Drying was monitored over a week with a microwave moisture device (MOIST350B). Measurements were done at surface and depth on both mortar joints and granite units. Each wall was then repointed with the same mortar mix initially used when built and the same rain simulation was performed to evaluate differences repointing could make to the moisture level. This study developed a novel experimental setting which allowed comparison of the drying response of different mortar types in a low-porosity stone masonry system and the effect of repointing. The action of mortar in dealing with most moisture movements in the test wall and absorbing moisture from the stones was demonstrated. Gauged binder and wood ash additives decreased the capillary absorption capacity of mortars; while retaining a good drying rate. This study has also shown that after repointing the depth of the mortar joints had a lower moisture level than before. Therefore repointing reduces the threat of water ingress and shows that it could be a suitable conservation intervention to mitigate water ingress and accelerate drying.

## 6.1 Introduction

Many historic and traditional solid masonry walls in England and other temperate maritime environments are exposed to high amounts of rainfall and wind driven rain (Gething, 2010). When driving rain hits a building façade, even when a masonry wall is of considerable thickness (as found in historic church towers for instance) (English Heritage, 2013), it will enter the wall face through mortar joints, cracks and at the interface between stone and mortar as demonstrated by Wood and Laycock in their test walls' experiment (Laycock & Wood, 2014). Driving rain can lead to moisture ingress through the masonry wall resulting in liquid water ingress and/or internal dampness (Oliver, 1997). In addition, a lot of water can enter a wall from defects on the roofs and parapets. Water is one of the main agents of building materials deterioration leading to chemical and physical weathering and surface erosion on brick, mortar and stone (Erkal *et al.*, 2012), biological growth (Pender *et al.*, 2014), frost damage and salt efflorescence (Oliver, 1997; Siegesmund & Dürrast, 2014) and damp internal conditions (Oliver, 1997; Abuku *et al.*, 2009). An increasing frequency of rainfall has therefore been identified as one of the main threats of climate change to historic buildings (Brimblecombe & Grossi, 2007).

It is therefore essential that once it has entered, moisture leaves masonry by evaporation to help it dry, even partially (Hall *et al.*, 1984; Hughes, 1987). In a solid ashlar masonry wall, most of the moisture movement occurs through mortar joints. This is especially true for stone units of low permeability and low-porosity, such as granite, where rain water mainly enters and leaves through mortar joints (Kenneth, 1995; Young, 2007; Hughes *et al.*, 2008). During drying and evaporation, liquid water travels to the surface of building materials bringing any soluble salts that are present (Laurie & Milne, 1927; Hughes, 1987). Mortar in joints should absorb moisture from the surrounding masonry units, by having a stronger capillary force than the stones with coarser pores (Wiggins,

2015). If most of the evaporation occurs at the surface of the joints, then so will any salt crystallisation and efflorescence. This will minimise damage to the individual stones, such as disintegration. Climate change is expected to cause more driving rain and therefore which will increase the threats to masonry structure, mainly due to salt crystallisation (Hall *et al.*, 2011; Orr *et al.*, 2018), so the role and performance of mortar is becoming even more important.

A significant number of historic buildings, especially churches, in southwest England are built with hard low permeable stones, such as granite (Child, 2007). Buildings of low porosity stones often suffer from water ingress and high interior dampness if the mortar is also a dense and low-permeable material that does not encourage evaporation through the outside walls (Oliver, 1997; Young, 2007; English Heritage, 2013). Weathered old pointing mortar or previous interventions that suffer from the use of inappropriate materials or bad workmanship during repair can also prevent moisture from leaving the building (Kenneth, 1995). The performance of the pointing mortar, and especially of repointing in the case of repair, is therefore critically important in reducing water penetration through the masonry and also to help it dry out (Hees, 2012; Hughes, 2012). Careful repointing is thus one of the remedies against the ingress of water and internal dampness (Oliver, 1997; Young, 2007). It has also been shown that workmanship, which includes the comprehensive clearing of loose debris, careful compaction and filling (Pickles *et al.*, 2017), types of finishing (Kenneth, 1995) and protection of the new mortar, can significantly influence the water resistance of joints (Newman, 1989; Ashurst & Dimes, 1998; Groot & Gunneweg, 2010). Rendering and grouting can be very effective at preventing moisture ingress and assisting drying, as the render would hold water before it enters into the masonry (Wood, 2012). However, in many cases for listed buildings repointing is often the only possibility because it is less visually intrusive, a minimal intervention and less costly. When deciding on a repair mortar for historic masonry it is

essential to consider the material properties, the workmanship and the masonry type, in relation to the building's exposure and environmental conditions if it is to be effective (Kenneth, 1995; Forster & Carter, 2011).

Research has been published on developing suitable mortars to use with granite. Mosquera et al. and O'Brien et al. argue that because the calcium in lime-based mortar reacts with sulphates from the environment and form salts that damage granite, cement with a high sand content should be used (O'Brien *et al.*, 1995; Mosquera *et al.*, 2002). However, as Hughes pointed out, the use of cement for historic buildings is usually inappropriate and not recommended and therefore appropriate lime mortars need to be developed (Hughes *et al.*, 2008). In addition the amount of sulphate in the atmosphere has nowadays drastically reduced. Hughes et al, have tested several compositions of mortar for repointing granite, which included using quicklime (Hughes *et al.*, 2008). Moreover, understanding the response of a masonry system to driving rain, comprising masonry units, mortar joints, but also a core filled with loose stones, rubble and mortar, is complex (Sass & Viles, 2010; Orr & Viles, 2018). Therefore some studies have used test walls to understand the effect of water ingress and compare conservation treatments (Laycock & Wood, 2014) and to evaluate the response of a specific material to driving rain, mainly focusing on brick walls (Groot & Gunneweg, 2010; Rirsch & Zhang, 2010), or on stone (Válek *et al.*, 2010). The bond of a range of pointing mortars with sandstone has also been evaluated with small masonry wall (Maurenbrecher *et al.*, 2000). However, little investigation has been done which compares different mortars designed specifically for dense exposed masonry and their drying performance in test walls.

Therefore, suitable lime mortars for pointing and repointing low porosity stone masonry walls needs to be designed and tested to establish how effective they are at helping the drying process. Testing needs to develop a tailored and comprehensive way of assessing and validating these mortars. This study specifically looks at how various lime-

based repointing mortar mixes in a small and dense stone masonry system (granite test walls) respond to drying and evaporation after an intense short rain event. It aims to determine whether moisture movement happens through mortar joints, the influence of materials, joint types and workmanship, and whether repointing could mitigate moisture ingress and help masonry dry out.

## 6.2 Materials and Methods

### 6.2.1. *Granite*

In southwest England, Devon especially, a significant number of the historic buildings and churches with their tall towers are made of a grey granite, such as Dartmoor granite (Child, 2007). For this study, a light grey Cornish granite (Pipper & Sons) with an open porosity of 0.87% ( $\pm 0.05\%$ ) and a density of 2.89 g/cm<sup>3</sup> ( $\pm 0.05$ ) was selected.

### 6.2.2 *Lime mortar mixes and preparation*

The composition of the lime mortar mixes was decided based on results from previous research looking at mortar for highly exposed areas (Chapter IV, V) and impermeable dense stone (Hughes *et al.*, 2008). Natural hydraulic lime 3.5 (NHL) has been demonstrated to be suitable for conservation purposes (Lanas *et al.*, 2004; Maravelaki-Kalaitzaki *et al.*, 2005; Henry & Stewart, 2012), especially for exposed masonry because it has the ability to set in humid environmental conditions through hydration processes (Banfill & Forster, 1999; Allen *et al.*, 2003).

The binder:aggregate ratio by volume was 1:3, following repointing requirements (ASTM, 2012; Henry & Stewart, 2012). To keep the same ratio by volume, the weight of the binder, sand and wood ash was adapted for each mortar mixes based on bulk densities. Table 6.1 summarises the composition of the mortars used in each wall. NHL (St Astier) gauged with non-hydraulic quicklime (Shap Lime 5 mm to dust) at 0.25 part of the binder ratio was used with quartz (Chardstock sand) and / or calcitic aggregates (Moreton

Cullimore sand). Both sands showed a similar particle size distribution (from 0.76 to 4 mm). Additives of biomass wood ash at 30% of the aggregates volume was also added in some mixes (Table 6.1). Wood ash was previously oven dried at 80 °C for 24 hrs and sieved to retain particles below 2 mm (ranging from 0.4  $\mu$ m to 2 mm). Quicklime was added granulated to the already dried mixed NHL and aggregate, generating low heat in contact with moisture of the sand. Water was then added as necessary and quicklime was fully slaked when the mortar was used; avoiding visible lime inclusions at the surface of the joints.

Table 6.1. Compositions of the mortar mixes in each wall and proportions of materials. The grey box indicates that the material is present in the mix.

#	Binder (volume 1)		Aggregates (volume 3)			Paired walls for comparison	
	NHL 3.5	Gauged with quicklime	Quartz sand	Calcitic sand	Wood ash additives (30% of the aggregates)		
Wall 1 (control) W1	100%		50%	50%		Pair A	
Wall 2 W2	75%	25%	50%	50%			Pair B
Wall 5 W5	75%	25%	35%	35%	30%		
Wall 3 W3	75%	25%	70%		30%	Pair C	
Wall 4 W4	75%	25%		70%	30%	Pair C	

As Table 6.1 shows, the composition of the mortar in each wall varies by one variable so that pairs of walls can be compared to each other to assess the effect of one specific material. W1 and W2 are paired to compare the effect of using a binder gauged with quicklime (pair A), W2 and W5 are paired to identify the effect of wood ash (pair B) and W3 and W4 to compare the use of different aggregates (pair C).

During mixing, no specific water:binder ratio was specified but rather water was added as necessary to obtain similar consistency in all mixes ( $\pm 10$  mm by flow), based on the experience of the mason. Flow tests were carried out on each mix with a flow table (Matest) following BS EN 1015 5-3:1999 (British Standard Institution, 1999a), to ensure a similar consistency was obtained (110-125 mm for building the walls and 107-119 mm for repointing).

### 6.2.3 Laboratory characterisation of mortar and granite samples

Five specimens of each mortar mix were made in the laboratory in prisms of 40 mm x 40 mm x 160 mm using polystyrene moulds. All specimens were demoulded after 5 days and kept for 90 days until testing in a ventilated environmental chamber (Sanyo-FE 300H/MP/R20) at 20 °C ( $\pm 3$  °C) and 65% ( $\pm 5$ %) RH. The polystyrene moulds did not contribute to the dewatering of the mortar samples, so that the mortar cured in a mould should have had a similar early development than the mortars cured between granite.

#### 6.2.3.1 Open Porosity

The open porosity ( $op$ ) was evaluated following the gravimetric method adapted from the standard BS EN 1936:2006 (British Standard Institution, 2006). Five half prisms of each mortar mix and three samples of granite of 50 mm x 50 mm were placed in a desiccator under vacuum at low pressure (less than 15 mm Hg) for 1 h and then allowed to soak in distilled water for 24 h at ambient temperature, enabling determination of the saturated mass ( $ms$  in g) and immersed mass ( $mh$  in g). The open porosity (%) was calculated as the mean of the five replicates with formula (1):

$$op = \frac{ms - md}{ms - mh} \times 100 \quad (1)$$

#### 6.2.3.2 Drying behaviour

The drying rate was monitored for 100 h on laboratory samples left in the same sheltered area as the walls (16.7 °C ( $\pm 1.5$  °C), 80.4% ( $\pm 10$ %) . Three replicates of each mortar mix in half prisms, having previously been fully saturated under vacuum, were used at 90 days. The change of mass ( $m_1$  in g) was recorded every 8 to 12 h using a balance at 0.01g precision (Sartorius). The water content ( $Wc$ ) (g/cm<sup>3</sup>) was calculated as a mean of the three replicates with the following formula (2):

$$Wc = \frac{(m_1 - md)\rho_w}{v} \quad (2)$$

Where  $md$  (g) is the oven dry mass of the replicates,  $\rho_w$  (g/cm<sup>3</sup>) the density of water at 20°C degrees, and  $V$  (cm<sup>3</sup>) the volume of the sample (Hall & Hoff, 2009).

### 6.2.3.3 Capillary Absorption

The determination of the water absorption coefficient due to capillarity of hardened mortar followed both BS EN 1015-18:2002 (British Standards Institution, 2006) and EN 12525: 2000 (British Standard Institution, 1999b) for highly absorbent stone. Samples were oven dried for 24 h at 70 °C ( $\pm 2$  °C) to constant mass ( $md$  in g), cut in half, sealed using a moisture and vapour-proof sealant (Parafilm M), and placed in 3 mm of distilled water. The mass of each of the six replicates at defined time was determined using a balance (Sartorius) at 0.01g precision until full saturation of the samples. The increase in mass ( $m_1$  in g) by the surface immersed ( $A$ ) (g/cm<sup>2</sup>) of each replicate was expressed as a function of the square root of time ( $\sqrt{t_1}$ ) in minutes (mn<sup>0.5</sup>). The water absorption coefficient by capillarity (WACC) (g/cm<sup>2</sup>mn<sup>0.5</sup>) was determined by formula (3) given by the standard as a mean of the six replicates:

$$WACC = \frac{m_1 - md}{A \cdot \sqrt{t_1}} \quad (3)$$

### 6.2.3.4 Water vapour Permeability

The water vapour permeability (Wvp) was determined following EN 1015-19:1999 (British Standards Institution., 1999) using the wet cup method. Disks of 12 cm diameter and 10 cm thickness were sealed on top of a cup containing a saturated solution of potassium nitrate (KNO<sub>3</sub>) to provide a RH of 93.2%, and kept in an environmental chamber (Sanyo-MLR-351) at 20 °C, 50 % RH. The mass was recorded at intervals of 24 h for 7 days. The water vapour permeability (kg/m.s.Pa (then adapted to g/m.day.KPa)) was calculated based on the mean of four replicates at each time interval using formula (4) given by the standard:

$$Wvp = \frac{1}{A \Delta p / (\Delta G / \Delta t) - RA} \cdot t \quad (4)$$

where  $A$  the area of the open mouth of the test cup ( $\text{m}^2$ ),  $\Delta p$  the difference in water vapour pressure (1010.244 Pa),  $\Delta G/\Delta t$  the water vapour flux (kg/s),  $RA$  the water vapour resistance of the air gap between the specimen and the salt solution ( $4.80\text{E}+10 \text{ m}^2\text{s/g}$ ) and  $t$  the thickness of the specimen.

#### 6.2.4 Experimental set-up of the test walls and repointing

The experiment was designed to represent a low porosity masonry unit of dressed stones, as often found in southwest England, exposed to high intensity driving rainfall. For the purpose of enabling comparison between test walls and mortar joints the variables were minimised by not having a rubble core and by larger joints than usually found in ashlar dressing.

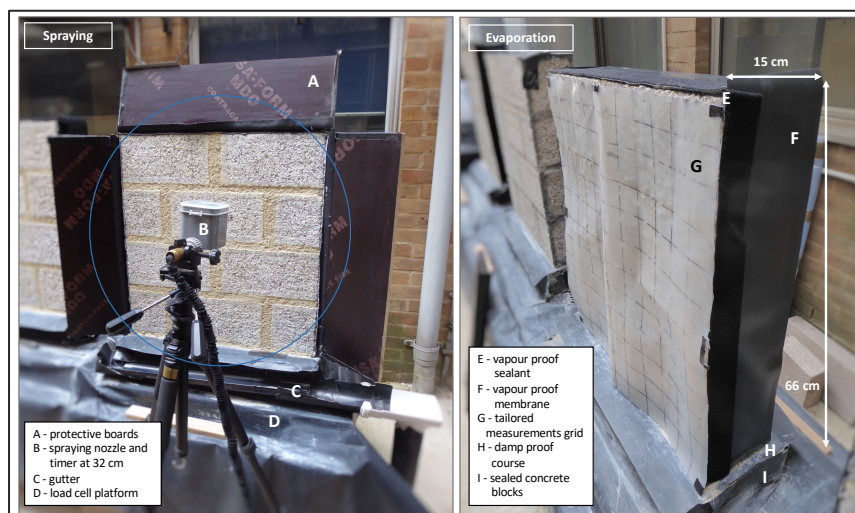


Figure 6.1. Experimental set up for spraying and monitoring drying. The protective board in plywood were preventing water from touching the other face of the wall and gutters were collecting the run-off water. The blue circle represents the area sprayed.

Five purpose-built test walls of 66 cm high, 62 cm large and 15 cm deep were constructed (Fig. 6.1). The granite had a rough finish, also called a pick face (Purchase, 2015), as found in traditional and vernacular constructions, which also improves grip and adhesion of the mortar. The horizontal joints are continuous and all joints are between 1.5 and 2 cm thick to enable measurements. Each test wall was built with a different lime mortar (Table 6.1) to enable comparison of their response to driving-rain. The walls were

cured for a 100 days in a sheltered laboratory area, protected from natural rain, wind and direct solar radiation.

After seven months each test wall was repointed. The same mortar as previously used (Table 6.1) was used again in order to only assess the effect of repointing, inducing a greater compaction at the surface of the joints, and not of different materials. Mortar in joints was removed to 1.5 cm deep using a reciprocating machine with a diamond or tungsten cutting edge or hand tools if necessary (Fig. 6.2). Best practice was followed in mixing and applying the repointing mortar (Maurenbrecher, 2012; Pickles *et al.*, 2017) (Fig. 6.2). The exact same rain simulation, as explained in section 2.2, followed by drying and evaporation monitoring, was repeated on each repointed wall.



Figure 6.2. Removal of the former mortar joints and repointing.

### **6.2.5 Rain simulation and evaporation monitoring**

Prior to spraying, the sides of the walls were sealed with vapour proof membrane (DPC, Visqueen) and vapour proof double sided mastic sealing tape (Pavatape 12, NBT) to force evaporation through the main faces (Fig. 6.1). The walls were built on load cell platforms in order to control the amount of water they received was similar (data not shown here).

Each wall was sprayed simulating a short intense and extreme rain spell in Devon. An intense spell of 5 hours or less in duration, likely to occur once every 5 years for a wall orientated southwest was chosen from the weather data from Chivenor (51°5'20"N,

4°8'49"W) (Pérez-Bella *et al.*, 2012; Orr & Viles, 2018). Rainfall was simulated using tap water from a cone low-flow nozzle with a uniform spray distribution. A stop-valve timer at a distance of 32 cm from the wall released 15 seconds of water every three minutes resulting in  $10.32 \text{ L m}^{-2}$  of simulated rain sprayed on the wall over a 3 hours and 15 minutes spell. The timer was mounted on a tripod, so the height could be adjusted to be at the centre of the wall enabling an even distribution. In Figure 6.1 the blue circle shows where the rain arrive on the face of the wall. The protective board in plywood were preventing water from touching the other face of the wall and a gutter was collecting the run-off water.

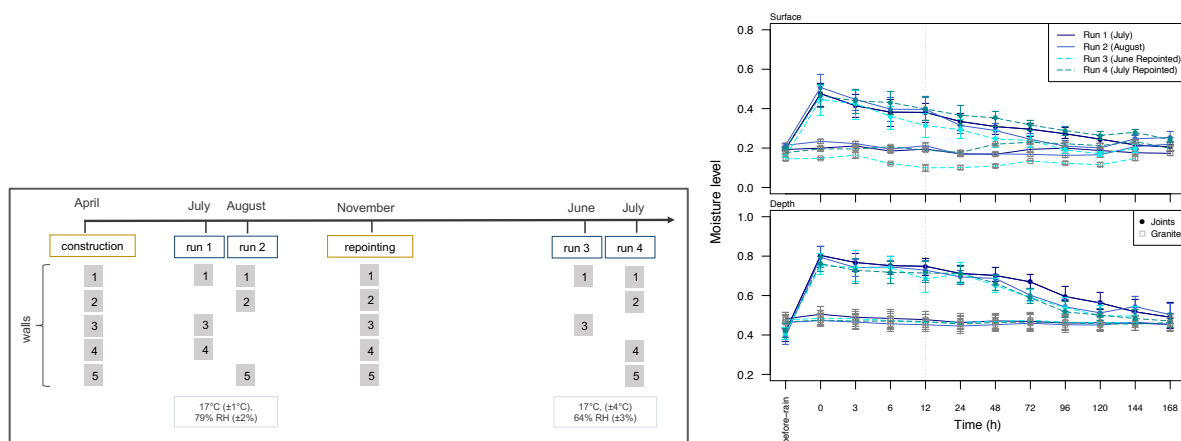


Figure 6.3. A) Timeline of the construction, repointing and of each experimental run showing the test walls tested at each run. B) Comparison of the control wall for each run of spraying and evaporation. The dashed line show the transition between time intervals: from every 3 and 6 h to every 12 h.

After the simulated rainfall, evaporation of each wall was monitored for one week (168 h) using a microwave moisture device (MOIST350B, hf sensor, Leipzig, DE). A tailored grid was designed for each wall ensuring that both mortar joints and granite were measured in a consistent pattern. The measuring points where the sensors were placed were approximately every 5 cm as shown on Figure 6.1. Figure 6.3a summarises the several runs of spraying and evaporation monitoring for each wall, on the initial ones and once repointed. Overall the constant environmental conditions in the sheltered area were a steady moderately cold but humid climate: 17 °C ( $\pm 1$  °C) and 79% RH ( $\pm 2\%$ ) for the

initial test wall and mortar joints; and 17 °C, ( $\pm 4$  °C) and 64% RH ( $\pm 3\%$ ) for drying monitoring after repointing; with negligible wind, no direct solar radiation.

Figure 6.3b shows the behaviour of the control wall (wall 1) after rain is simulated and during evaporation for every run. Wall 1 shows similar moisture level values and evaporation behaviour for each run, showing minimal variation between each run and little influenced of the slightly different environmental conditions. This enables good comparison of the other walls with the control wall at each run (Fig. 6.3a).

The microwave moisture device is a non-destructive and non-invasive technique, therefore suitable to use on historic buildings (Válek *et al.*, 2010) and unaffected by the salt content of the building materials (Lataste & Göller, 2018). MOIST350B works by producing electromagnetic waves reflected by the material surface (Göller, 2006). The ratio of reflected and transmitted waves is called the reflection coefficient and is measured by the different reflection sensors of the device (Göller, 2006). By multiplying the reflection coefficient with a fixed known factor the moisture meter gives a direct reading in a unitless “Moisture Index” (MI), which is an arbitrary unit (Orr, *et al.*). The MI is useful to assess relative change in moisture content over time but has not been calibrated against exact moisture content, therefore throughout the study it remains an arbitrary number. In this study, two reflection sensors-heads were used to monitor the evaporation rate at near surface and depth: the R1M sensor, measuring up to 2-3 cm, in the 900-1400 MI range (referred here as “Surface”), and the PM sensor, measuring up to 20 to 30 cm in the range of 1300-2400 MI (referred here as “Depth”) (Lataste & Göller, 2018). In dense stone like granite because the microwave loses energy faster as it travels, it is considered that the reading from the PM sensor is at 15 cm (British Standard Institution, 2017). Because they are in different ranges, the data from surface and depth are not directly comparable.

Measurements on all the mortar joints and granite units of one wall were then averaged over time and for both surface and depth to enable comparison between walls. In this study, the MI values have been normalised from 0 to 1, as a ‘relative’ indicator, where higher data implies higher moisture levels. The difference of moisture level over time ( $\Delta M$ ) was calculated with the normalised data with the formula (5):

$$\Delta M = M_i - M_t \quad (5)$$

Where  $M_i$  the mean value of joints or granite at a specific time over 168 h and  $M_t$ , the mean value of joints or granite recorded “before-rain”.

The % change of moisture level between the data measured on the original test walls and after they were repointed was calculated with formula (6):

$$\% \text{changeMI} = \frac{\Delta MR - \Delta M}{\Delta MR} \times 100 \quad (6)$$

Where  $\Delta MR$ , data from the repointed wall and  $\Delta M$  data from the same wall (1), before repointing.

Few studies have used the microwave moisture meter on both mortar joints and masonry units and especially not for comparison of different mortar properties. The microwave moisture meter was chosen for this study for its ease of use and data handling. It has also been proven to give accurate results when calibrated against gravimetric measurements of different building stones for a range of water contents (Orr *et al.*). In addition, the device enables easy measurement within the thick masonry walls of historic buildings because it measures at different depths and access is only needed to one side of the wall.

## 6.3 Results

### 6.3.1 Moisture movement through mortar joints

Figure 6.4a and c shows data of moisture level (normalised) over time at near surface and at depth for all the joints in all five walls. Granite is not present in Fig. 6.4a and c as

very little differences seen. Fig. 6.4b, b' & d, d' show the differences of moisture level from the measurement taken before rain (formula 5), which could be considered as a relatively dry state ( $T=0$ ) (). Figure 6.5 presents the results of laboratory drying of mortar samples in the same sheltered area. Figure 6.6 shows the visual appearance of the back of the wall after spraying and 3.25 h of drying.

Drying is the transfer of liquid water of the porous building materials to the surrounding environment (Hall *et al.*, 1984). Drying therefore is expected to depend on both the external conditions and on the materials properties (Wiggins, 2015). It is well established that drying occurs in two stages (Hall & Hoff, 2009). First phase drying is defined by the transport of liquid water to the surface of the materials followed by evaporation (British Standards Institution, 2013). Until all liquid water has travelled to the surface, evaporation at the surface occurs at a constant rate under constant conditions. Stage I drying is therefore highly influenced by the boundary external conditions (temperature, RH and air flow) (British Standards Institution, 2013). The second stage of drying starts when transport of liquid water to the surface is no longer possible so that the rate of evaporation slows down (British Standards Institution, 2013). Stage II drying is characterised by water vapour diffusion mechanisms and therefore influenced by the microstructure of the materials (Hall *et al.*, 1984; Pender *et al.*, 2014).

At absorption and during the first 24 h of evaporation, at surface (Fig. 6.4a) and depth (Fig. 6.4c), all mortar joints show a similar order of moisture level (wall 2 having the lowest and wall 4 the highest), and start drying at the same time. After 24 hours, at depth, some test walls (specifically walls 3, 4, 5) experience a more abrupt drying (lower moisture level) than the other walls.

The first 24 h of drying seems to correspond to stage I drying. Due to the constant external conditions (17 °C, ( $\pm 1$  °C) and 79% RH ( $\pm 2\%$ )), mortar joints throughout the wall behave similarly up to 24 hours of drying at surface (Fig. 6.4a) and depth (Fig. 6.4c). Stage I

drying is mainly determined by the environmental boundary conditions and it has been demonstrated that as the RH increases, the rate of drying decreases (Hall *et al.*, 1984). Previous drying tests have shown that mortars dried under such high humidity (15 °C, 85% RH) show a longer stage I drying (Chapter V). This long stage I can also be seen in Figure 6.5, where it last up until 73 hours for laboratory samples in the same sheltered area. A long stage I drying could be beneficial to allow the bulk of the masonry to fully dry out (Pender *et al.*, 2014), which is here shown as the depth dries out as much as the surface (Fig. 6.4c).

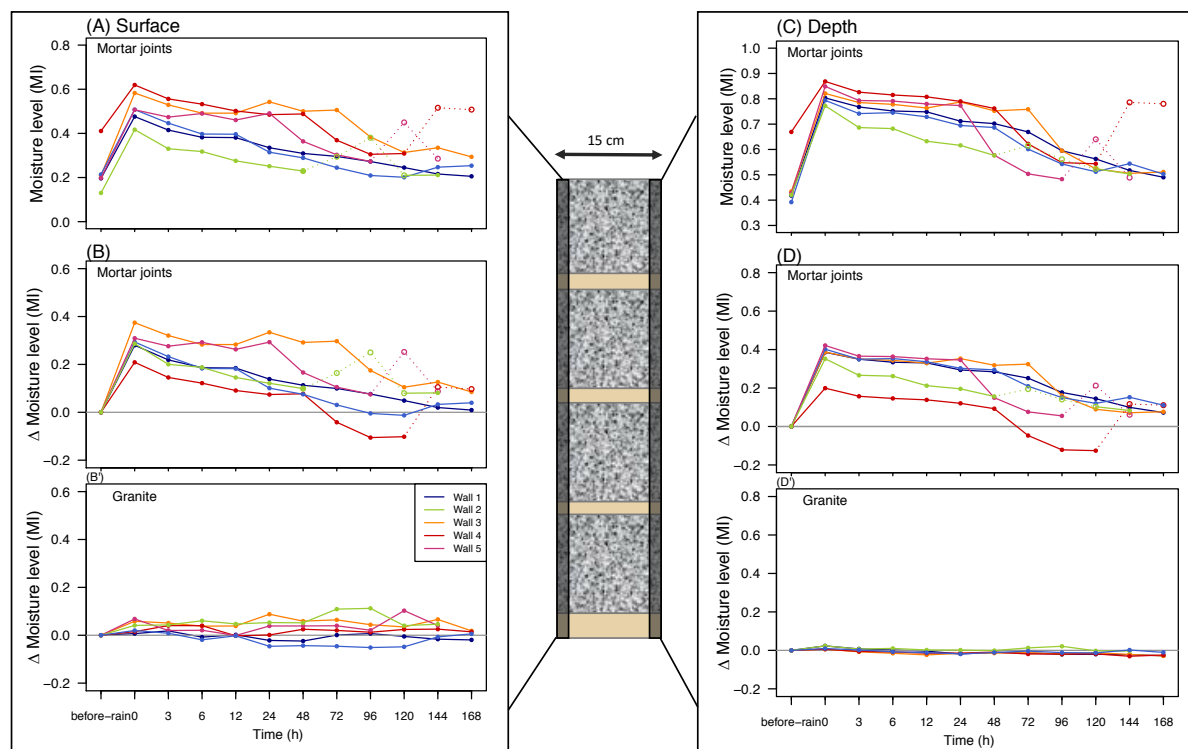


Figure 6.4. Comparison of all mortar joints and granite units over time, based on their moisture level value at surface (A) and depth (C) and on the differences of moisture level from the “before-rain” measurement point at surface (B) and depth of the wall (D). Dashed lines and blank points represent the effect of high RH due to a rain event outside the sheltered area. The two blue lines for wall 1 represent the two runs of testing.

$t_0$  hrs = rain simulation and MI 0 (B and D) = value at start of the experiment. Data from surface and depth cannot be directly compared.

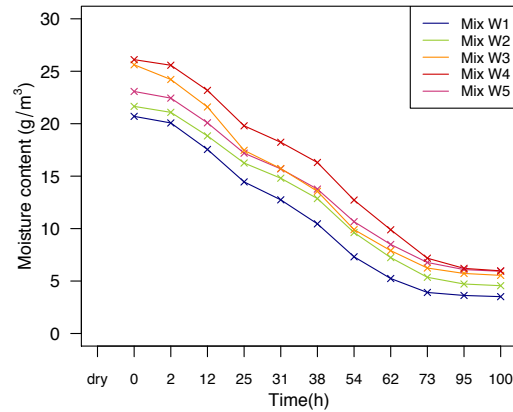


Figure 6.5 Drying curves of laboratory mortar samples left to dry in the same sheltered area (n=3)



Figure 6.6. Visual assessment of the back of the test walls after 3 h of spraying and 6 h of evaporation (T=6 h). Water ingress visible through the bottom joint in all wall was not measured.

Figures 6.4b & d enable to see the capacity of absorption of the test walls from a “dry” state (“before-rain”) and the capacity of drying (as the curve goes back to a value close to the 0 line). As expected, mortar joints show higher absorption capacity (Fig. 6.4b and d) than the granite units (Fig. 6.4b’ & d’), showing that with the low-permeable granite, the joints are dealing with most of the moisture movement, especially at depth. As Figure 6.6 illustrates, as expected, most of the water travels through the mortar joints, although the edges of the granite show signs of having absorbed little water.

Figure 6.4b’ shows that the granite at surface is slightly affected by the natural rain events outside the sheltered area resulting in a more humid environment. It also illustrates that for some walls (walls 2, 3, 5) the moisture level of the granite remains higher than at the start (“before-rain”) throughout evaporation, whereas for walls 1 and 4 (red and blue lines), the moisture level of the granite quickly goes back to its initial value (represented

by the 0 line) or even below. Although difficult to clearly identify this could give an indication of the action of mortar joints in absorbing moisture from the granite.

The walls in which mortar joints reach their 0 state or below show that the granite units also reach their initial value (Fig. 6.4b., walls 1 and 4), whereas walls in which mortar joints do not dry out as much (Fig. 6.4b., walls 2, 3 and 5), experience a granite unit that remains wetter (Fig. 6.4b'). However, it could be argued that the effect of the increase of RH due to external conditions on walls 2 and 3 prevents the mortar joints from drying out fully. Comparing Figure 6.4a and 6.4b shows that mortar joints in wall 4 have likely absorbed moisture from the air before testing, therefore resulting in high moisture level (Fig. 6.4a) and capacity to dry below its starting point (0) (Fig. 6.4b). When stage II drying starts (after 24 hours or later for some walls), the differences seen between each test wall may be explained in more details by material characteristics.

### ***6.3.2 Material comparison***

In Figure 6.4a and c, higher value means higher moisture level. It is clear that mortar joints from the different walls show different moisture level both after rain at absorption ( $t=0$  hrs) and during drying ( $t= 3$  h to 144 h). As seen in Figure 6.4a, mortar joints in wall 1 and especially wall 2 (which is made with mortar containing quicklime), show the lowest moisture level, whereas walls which have joints composed of mortars with wood ash (walls 3, 4, 5) show a higher moisture level. The same pattern is also seen in the drying curves of laboratory mortar samples (Fig. 6.5). This shows that differences in the behaviour of mortar joints of each wall can be attributed to the different mortar compositions and not to environmental factors. Differences in absorption and drying of each wall can also be seen in Figure 6.6 which shows the water egress through the back of the wall after spraying and six hours of drying. Figure 6.7 compares the behaviours of pairs of individual walls (as explained in Table 6.1), using the same data set than in Figure 6.4a & c.

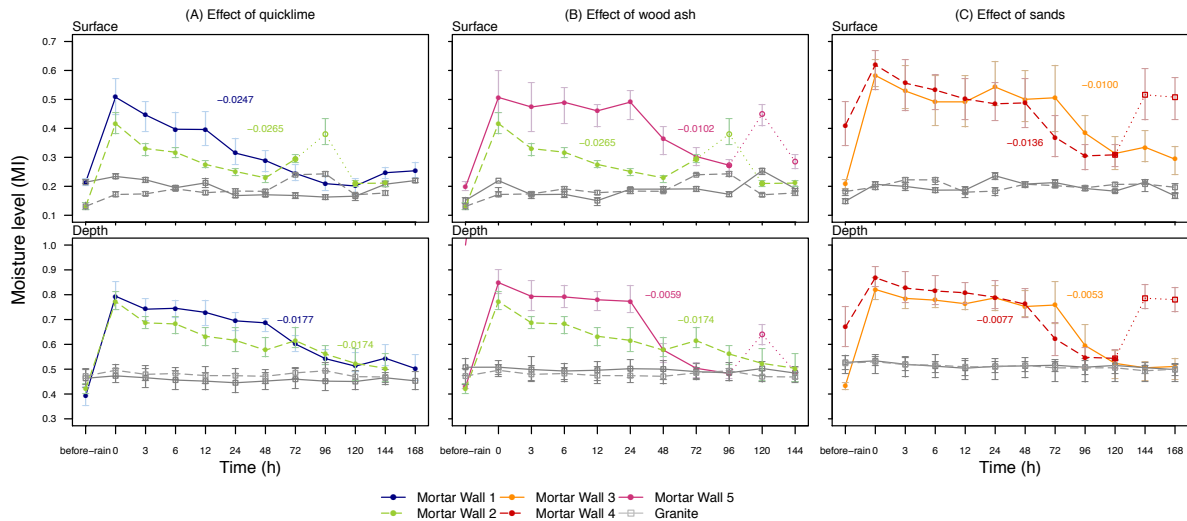


Figure 6.7. Comparison of detailed material differences. (A) Wall 1 (control) with wall 2 show the effect of using quicklime, (B) wall 2 and 5 illustrate the difference when wood ash is used (wall 5 being the same mix as wall 2 but containing wood ash), and (C) wall 3 and wall 4 show the differences between quartz (wall 3) and calcitic aggregates (wall 4). Error bars indicate the first and last quartile and dashed lines show the effect of high RH due to natural rain. Linear regression was calculated on the straight drying slope, corresponding to stage II drying. The x-axis represents different time intervals.

Figure 6.7a compares mortar joints made with NHL 3.5 (wall 1) and with gauged binder: NHL 3.5 and non-hydraulic quicklime (wall 2). At surface, mortars in wall 1 and 2 show similar drying patterns and little differences between their moisture level, considering that wall 1 mortar has a higher MI level at T<sub>0</sub>. However, Figure 6.4b has also shown that joints in wall 2 never reached their 0 state (“before rain”) and wall 2 mortar show the slowest WACC and lowest water vapour permeability (Table 6.2) and. It means that in wall 2 capillary saturation is reached slower than for mortar in wall 1 and that vapour permeability travels slower through mortar joints. The mortar would be less capillary active to absorb moisture from the surrounding masonry units. Because less water is absorbed by the material, the drying slope is quicker than mortar joints in wall 1 that has absorbed more moisture. At depth, mortar joints in wall 1 have a slower drying rate than wall 2 joints (Fig. 6.4d and 6.7a). This can also be noticed in Figure 6.6 (wall 1), where the joints visually show higher moisture level than the ones in wall 2. Mortar in wall 1 has indeed the higher capillary absorption rate (Table 6.2).

Gauging binder with quicklime seems to affect the pore structure of the mortar by reducing its capillarity ability and permeability as shown by Figure 6.8, where capillary pores are in lower proportion in wall 2. Only pores from 1 mm to 1  $\mu\text{m}$  are practically relevant for capillary transport (Siegesmund & Dürrast, 2014), which could explain the lower capillary coefficient (WACC) of wall 2 (Table 6.2). This could show that adding quicklime in mortar could help minimise water absorption and ingress through a masonry system. The bimodal distribution of pores of wall 1 mortar could be explained by the higher water demand of the fresh NHL mix, which would create larger pores (Banfill & Forster, 1999). The control in Figure 6.8 represent a NHL 3.5 with only quartz sand.

Table 6.2. WACC, open porosity and vapour permeability values of the mortar mixes applied in each wall, based on laboratory samples. “Q” refers to *Quicklime* and “WA” to wood ash as compositions.

		WACC ( $\text{g}/\text{m}^2\text{mm}^{0.5}$ ) (n=6)		Open porosity (%) (n=5)		Water vapour permeability ( $\text{g}/\text{m}\cdot\text{day}\cdot\text{kPa}$ ) (n=4)	
		mean	SD	mean	SD	mean	SD
<b>W1</b>		282.22	10.94	20.33	0.21	2.328	0.248
<b>W2</b>	Q	192.37	3.87	23.32	0.25	1.876	0.062
<b>W3</b>	Q WA	253.74	5.95	26.06	0.29	2.402	0.168
<b>W4</b>	Q WA	275.57	23.85	25.65	0.19	1.938	0.102
<b>W5</b>	Q WA	197.86	6.96	21.74	0.63	2.111	0.137

Figure 6.8. Pore size distribution by MIP of mortar mixes found in wall 1 and 2. Dashed line represent the limit of indication of the capillary pores (1 to 1000  $\mu\text{m}$ ).

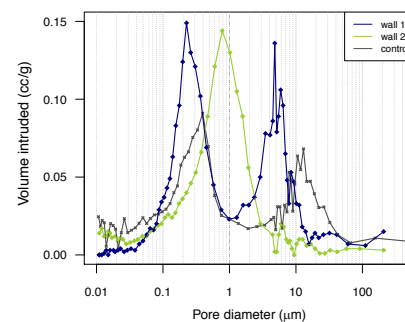


Figure 6.7b allows comparison between mortar mixes made with and without wood ash (e.g. wall 5 vs wall 2). The mortar containing wood ash keeps a high moisture level longer after rain has been sprayed (between 24 and 72 hours after the rain event), while demonstrating a relatively sudden drying response: over three days the moisture level value is back where it was “before-rain”. This results in two clear phases of drying. At depth (Fig. 6.4d and 6.7b), joints in wall 5 also remain wetter longer than those in wall 2, but reach a lower moisture level after drying for 7 days. Previous research has shown the capacity of lime mortars made with wood ash to absorb high water content and to have an increased ability to dry out (Chapter IV).

The increase in the proportion of pores in the capillary range of these mortars (1  $\mu\text{m}$  to 1 mm) has also been demonstrated, explaining the higher WACC. Material with a high proportion of capillary pores will dry more efficiently under the same conditions and will also show high evaporation because the capillary drying regime is helping to dry out the masonry (Wiggins, 2017). The fact that joints remain wetter longer at surface and depth could prevent the accumulation of water which can lead to more water ingress. When joints have reached saturation and cannot absorb more water, if another rain event occurs before they have started to dry out the water would likely run-off the façade. When mortar joints remain wetter longer at the surface, it could also show the movement of moisture within the joint: the liquid water moves through the wall until it reaches the surface and can evaporate. Despite having a high absorption at depth, no ingress of moisture from the back of the wall could be seen for wall 5 (Fig. 6.6).

Little difference of moisture level throughout drying and evaporation is seen between the use of different aggregates comparing wall 3 and 4 (Fig. 6.7c). However, joints in wall 3, made with quartz sand, remain wetter longer as perhaps more moisture was absorbed, in relation to being the more porous and permeable of mortar mixes tested in laboratory (Table 6.2).

Comparing wall 3 and 4 with wall 5, which contains mixed aggregate, mortars made with one aggregate and with additives of wood ash, hold water longer (Fig. 6.7b & c). Calcitic aggregates have been shown to increase to proportion of pores below 1  $\mu\text{m}$  and give higher porosity (Lanas & Alvarez, 2003), as shown by Figure 6.8 for wall 2. It is clearly illustrated in Figure 6.8, where the porosity of wall 1, made with both quartz and calcitic sand, is much higher than of a control mortar mix made of NHL 3.5 and quartz sand only.

### 6.3.3 Comparisons between joints

Figure 6.6 already illustrated that for each test wall, the egress of moisture at the back of the wall was visually different depending on the joints and area of the wall. Figure 6.9 uses the same data set than Figures 6.4a & c and 6.7 in order to compare over time horizontal (beds) and vertical (perpend) joints, and all joints separately of walls 1 and 3.

Vertical and horizontal mortar joints in wall 1 show differences in absorption ( $T=0$  hrs) and drying (from  $t=3$  hrs), especially at depth (Fig. 6.9a). Vertical joints show higher moisture level, which is probably linked to workmanship and the difference in the pressure applied during building the test walls (Laycock & Wood, 2014). Indeed, for this wall 1, water egress at the back of the wall was especially visible at weak points at the angle between perpend and bed joints.

However, in all other test walls no significant differences are seen between perpend and beds, as joints in wall 3 illustrates (Fig. 6.9c). If there is little difference, as in walls 4 and 5, vertical joints show a higher moisture level, and horizontal joints dry quicker. Vereecken has shown that bed joints are a preferred pathway for moisture (Vereecken & Roels, 2013), which here is only visible for the drying.

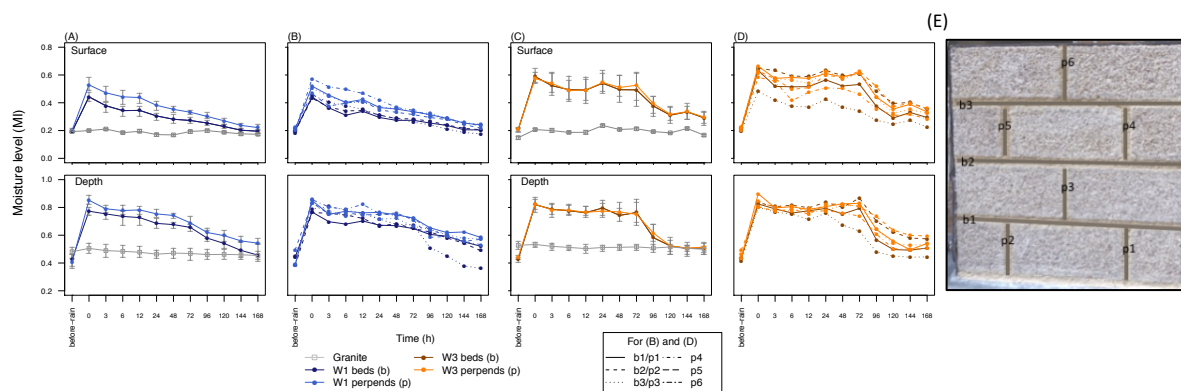


Figure 6.9. Differences of drying curve between perpend joints (p) and bedding joints (b) in wall 1 (A) and wall 3 (C) and between each joint of wall 1 (B) and wall 3 (D). E) indicates the location of each joint. Error bars indicate the first and last quartile. The x-axis represent different time intervals.

Figure 6.9b & d show that differences within a same wall between perpend and beds can be noted. For walls 1 and 3, b3 joint (Fig. 6.9e) is drier at both surface and depth (Fig.

6.9b & d). It is expected as it is the highest one, less affected by run-off and more exposed to the air. Whereas in wall 4, b1 is the driest, as Figure 6.6 (wall 4) shows it as well. In walls 3 and 2, p6 is the driest joint, again probably because it is the less exposed to run off, and it is higher in the test wall (Fig. 6.9e). The other perpend shows equal moisture level in all other walls, apart in wall 5 where p1 is much wetter, as Figure 6.6 (wall 5, bottom right joint) shows, which is also likely due to workmanship or simply to more water.

### 6.3.4 After repointing each test wall

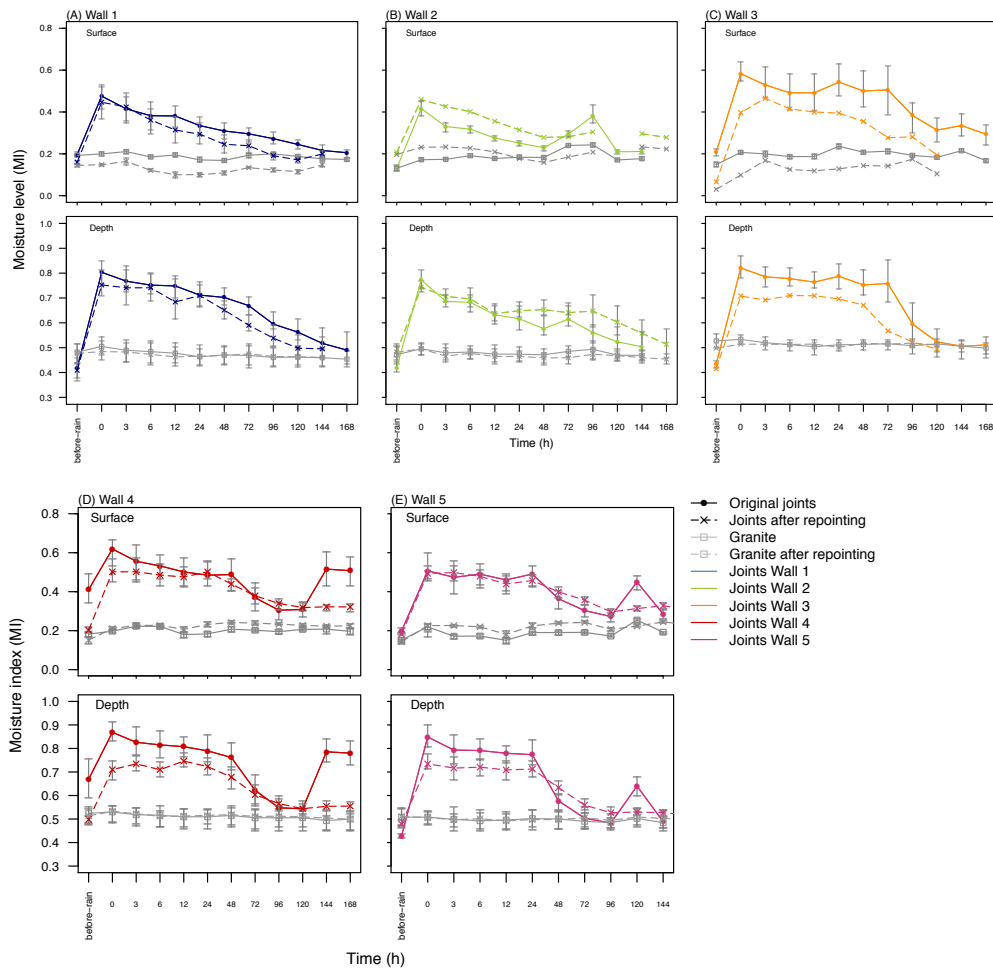


Figure 6.10. Differences of moisture level of the mortar joints over time before and after being repointing. Error bars indicate the first and last quartile. The x-axis represent different time intervals.

Figure 6.10 shows moisture level data for the absorption and desorption curves of each of the original test walls, using both the same data set than Figure 6.4a & c and data for

the same walls repointed. Surface therefore corresponds to the repointed part of the wall. Figure 6.11 represents the percentage changes of moisture level at absorption during the simulated rain and over evaporation and drying, between the original wall and the repointed wall, calculated with formula (2). For the same rainfall simulation followed by drying, differences in the amount of moisture level at absorption and during drying can be seen in mortar joints of all the test walls after repointing.

Figure 6.10 shows that at both surface and depth, in each wall, the mortar joints follow a similar drying curve before and after repointing suggesting that the composition of the mortar is a major factor affecting the response of the joints. Similar patterns as Figure 6.7 are therefore seen based on the composition of the mortar joints and materials specificity: the key variable is wood ash, the type of sand does not have a significant influence.

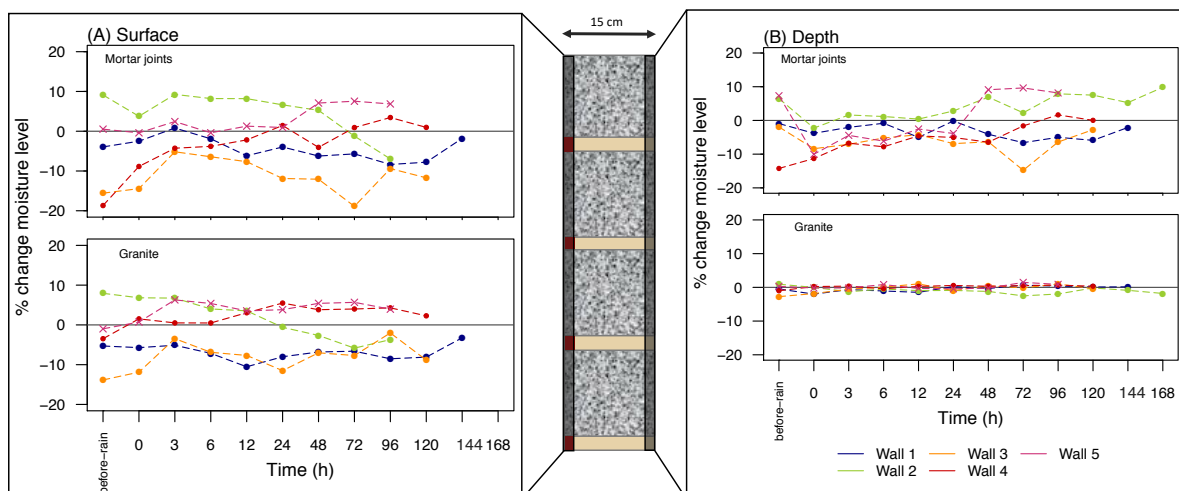


Figure 6.11. % change of moisture index value measured over time on joints and granite between the original walls (represented by the 0 value) and the repointed walls at surface (A) and depth (B). Negative changes show that the data measured on the repointed wall are lower than the original wall. x axis represents different time intervals.

Figure 6.11 clearly shows the differences between the original wall and the wall after it has been repointed. The moisture level right after the rain event ( $t=0$  h) is similar or lower for all mortar joints at surface and depth. This could show that repointing minimised the amount of moisture absorbed throughout the wall, and especially at depth.

More specifically, after drying for 24 h, at the surface of mortar joints (i.e. the repointed parts), all but wall 2 and wall 5 (green and pink curves) show a lower moisture level after repointing (Fig. 6.11a). In walls 4 and 5, the granite at surface, remains with a higher moisture level throughout the test, whereas joints at depth have a lower moisture level after repointing. This could show that for these walls, the moisture stayed mainly at the surface of the test walls. Walls 1 and 3 (blue and orange lines) have overall a lower moisture level after repointing, due perhaps to more run off and so less water entering the joints.

At depth, again apart from wall 2 and 5, mortar joints also show a lower moisture level after repointing (Fig. 6.11b). The lower moisture level after repointing at depth could be explained both by the effect of repointing and by the mortar in the joints being older (broadly 18 months since construction), where the porosity and capillary capacity could have decreased. It could also show that repointing helps the wall dry quicker. The lower moisture level measured on most mortar joints (Fig. 6.11b) is also visible on Figure 6.12 by visual assessment, where minimal moisture egress can be seen on each wall compared to Figure 6.6.



Figure 6.12. Visual comparison of the back of the test walls after spraying and after 6 hours of evaporation ( $t=6$  h). The blue boundaries highlight the egress of moisture. Missing parts of the walls are due to the location of the camera, but most of the moisture pattern are shown here.

However, as shown by Figure 6.11, mortar joints in wall 2 show the highest moisture absorption at the back of the wall. After repointing, mortar joints in each wall seems to behave slightly differently as to where the moisture moves and how the test wall dries out. Wall 2 has higher moisture level at surface until 48 hours, and higher at depth

after 48 hours which perhaps shows that the evaporation occurred mainly through the back of the walls.

#### **6.4. Discussion**

This study found that moisture movement in and out of the dense low-porous masonry test walls clearly occurred through the mortar joints (Fig. 6.4). This was achieved by combining simulation of an intense rainfall and monitoring of the drying response of different mortars near the surface and at depth and monitoring their behaviour once repointed over 7 days, under constant environmental conditions. It showed that when mortar joints do not dry enough to reach their initial state (“before-rain”), the granite units remain slightly wetter at surface (Fig. 6.4b and d, walls 2, 3, 5), illustrating the action of mortar in absorbing moisture from the masonry. The study found no clear differences between beds and perpend joints. Differences noticed in joints within each test wall were mainly attributed to their location in the test walls - bottom of the wall being wetter and top of the wall having better evaporation - and to workmanship - weaker points at the angle between beds and perpend joints showed quicker moisture ingress (Fig. 6.6 & 6.9).

In comparing the different test wall types in combination with laboratory mortar samples, the study also showed that all materials that were added affected the absorption and drying performance of the mortars (Fig. 6.7). Both quicklime and wood ash delayed the capillary absorption of mortar (Table 6.2). Gauged NHL with quicklime (mainly seen in wall 2) showed a lower moisture level overall, which could minimise water ingress, while having a quick drying rate. NHL mortar (wall 1) had a quick absorption and a lower evaporation, which made this mortar less suitable to help a masonry dry out (Fig. 6.7a). Mixed aggregates mortars (wall 2 and 5 mainly), perhaps by their bimodal pore size

distribution (wall 2, Fig. 6.8), seems to be good at mitigating water ingress while showing a good capacity to dry out (Fig. 6.4).

Finally, comparison of each test wall between its two states: original and repointed, showed that all repointing mortar types could help minimise the moisture level at absorption both throughout the wall and while the wall dries out at depth and increase the drying rate (Fig. 6.11).

#### ***6.4.1 From samples to test walls to real masonry***

The methodology and experimental design developed in this study enabled a confident comparison of the mortar joints in the five test walls during absorption and over drying. By combining best-practice workmanship, specific mortar design and rain simulation this research found a novel way to test the suitability of mortar for granite masonry and repointing mortar. Each wall was built identically, by the same mason, received the same amount of simulated rain and was tested under constant environmental conditions. This gave confidence levels when comparing the different wall types. Although differences in moisture level of different joints within one wall could be attributed to workmanship, those differences were minimal and did not alter the overall comparison between each mortar joints and test walls. The environmental conditions during drying monitoring of the repointed test walls had lower RH (by 15%) which could partly explain the higher drying rate of the repointed walls. However, because the temperature was identical and the differences in RH low, the difference found after repointing can still be taken into account.

The single-layer test walls were a clear and easy way to look at the response of a masonry system to driving rain, on the façade, at near-surface, and at the depth. However, it is important to remember that a large masonry often consists of two single stone layers (often ashlar dressed) and a core made of rubble stone, mortar and both through stone and voids that are an easy conduct of liquid water through the depth of the wall toward

the inside of the building. The benefit of looking at two depths suggests the data could be used for real traditional masonry wall with a rubble core. The depth would then correspond to the core of the wall.

The microwave meter allowed straightforward monitoring of the drying and evaporation of the different materials in the test walls: mortar and granite at surface and depth over time. The MI calculated from microwave moisture data allows comparison between granite and mortar. Other electromagnetic devices (such as ground penetrating radar) were used in this study to measure the moisture level of the different building materials (not presented here) and found similar results in the comparative behaviour of mortar joints and granite units. In addition, the drying curves found in laboratory experiments (Fig. 6.5) showed similar ranking of moisture level – wall 5 with the highest moisture content and walls 1 and 2 with the lowest. However, the drying in water content in  $\text{g/cm}^2$  recorded in the laboratory cannot be directly compared to the MI values without calibration and the drying curves of the mortar samples are different to the curves recorded with MI values. In addition, MI values from the R1M (surface) and the PM (depth) sensors cannot be directly compared, which could lead to some confusion when analysing the data.

#### ***6.4.2 Repointing and the suitability of the tested mortars for a dense masonry wall***

To reduce deterioration and internal dampness, ingress of moisture through the wall should be limited so that moisture stays at the outer surface of the wall. This study has shown that when the test walls were repointed, the depth of the wall absorbed less water than before repointing, therefore reducing the threat of water ingress and showing that repointing could mitigate water ingress and induce a quicker drying. As Figure 6.13 shows, this may be due to two proposed scenarios. In scenario 1, the repointing mortar absorbs slowly and holds on to water when saturation is reached, so that, although the

evaporation is slower, no more liquid water can be absorbed into the mortar and vapour evaporation can take place. Scenario 1 type of repointing would work under continuously wet environmental conditions that would prevent the mortar from drying out correctly. The repointing mortar would then hold on to water, preventing water accumulation and ingress, and encouraging run-off. In scenario 2, the repointing mortar is highly permeable with a quick absorption capacity and a high evaporation rate, facilitating its drying. Scenario 2 type of repointing would work well under many wetting and drying cycles due to rain events, as a mortar that dries quickly and absorb quickly would be able to perform well, mitigating moisture ingress through the wall.

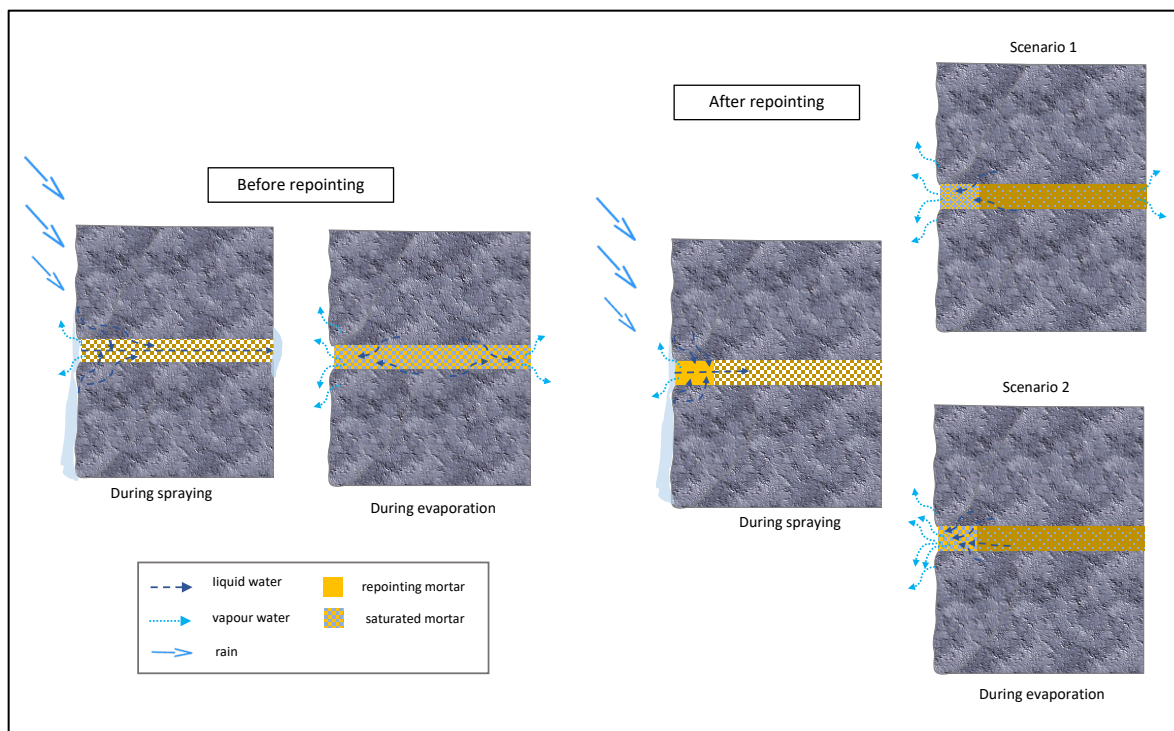


Figure 6.13. Proposed schematic and simplified explanation of the movement of moisture between dense masonry units and lime mortar joints, during spraying and evaporation, and before and after repointing showing how and why repointing would help mitigate moisture ingress through wall.

Based on different specific environmental conditions some tested mortar may be more suitable than others. Based on Figures 6.11 and 6.12, and on material characteristics, once repointed, walls 1, 2 and 3 could correspond to scenarios 1 and walls 4 and 5 to scenarios 2. This effect of the repointing may be due to the interface between the new and

old mortar in joint, acting like a resistance, or to the denser pore structure of repointing mortar than of the bedding one due the pressure applied on the repointing mortar while applying it. This has important implications for consideration of repointing under specific environments or on different wall exposition, and for the role of workmanship in contributing to the functional role of repointing.

## 6.5. Conclusions

A comprehensive experiment was designed to assess the response to an intense rainfall event of different building materials within a specific masonry system – lime mortar and granite, at two levels – surface and depth, and two timeframes – at absorption and over a week of drying and evaporation. This study proved that the experiment was suitable to enable comparison of different mortar joints types and of the test walls before and after repointing. Five main findings were made:

- The action of mortar in controlling moisture movement in the wall and absorbing moisture from the masonry was demonstrated.
- Differences of evaporation between horizontal and vertical joints in the same test wall were mainly attributed to their location in the test walls and workmanship.
- The selected composition of lime mortars, gauged with quicklime and wood ash additives gave mortar a decreased capillary absorption capacity and a good drying rate, making them suitable for use under very wet environmental conditions (i.e. mortars in wall 2 and 4), while mixed aggregate increased the capillary absorption.
- This study has shown that when test walls were repointed, the depth of the wall absorbed less water than before repointing, therefore reducing the threat of water ingress and increasing the drying capacity.
- At the surface, repointed wall behaved differently, and two scenarios were identified, each suitable for slightly different environmental conditions:

Scenario 1, repointing mortar holds on to water when saturation is reached, so that no more liquid water can be absorbed into the mortar and vapour evaporation is favoured – suitable for under continuously wet environmental conditions, preventing water accumulation and ingress. Scenario 2, the repointing mortar has a high evaporation rate, facilitating its drying, so moisture stays mainly at the surface – suitable for mortar under many wetting and drying cycles as mortar that dries quickly and absorb slowly.

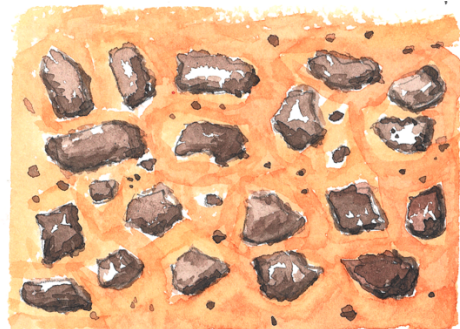
These findings have important practical implications when considering both the design of mortar for dense and low-porous masonry and of repointing, and when evaluating the performance and role of repointing mortar.





# PART C

## Discussion and Conclusions



*Details of a sandstone façade of a house in Maine  
(Sarthe, France) (by MF)*



## VII. DISCUSSION

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The overall aims and objectives of this research were to design and optimise various repointing mortars for highly exposed historic buildings, define a suitable method to evaluate them and assess whether repointing can work to mitigate damp problems in these exposed conditions. Three research questions were posed in Chapter I: What would be the most effective mortar to repoint hard stone masonry in exposed locations? How do the environmental conditions found on-site affect these mortars? Can these repointing mortars mitigate driving-rain ingress? This thesis has shown that when using a range of materials in carefully designed repointing mortars, properties can be optimised to cope with specific environmental conditions and masonry types. The experimental design has demonstrated that realistic curing conditions impact the early term development of mortar samples so that laboratory evaluation can be conducted under standard curing conditions of mortar samples if the medium to long term properties are of interest. It was also shown that single layer test walls are a suitable way to evaluate the response of mortar joints to absorption and drying after an intense rain spell.

The following discussion brings together and builds upon the discussions and conclusions presented in each study (Chapters IV, V, VI). The objectives introduced in Chapter I to address the research questions are presented and discussed in each section below, with the findings related to each research questions. Section 7.1 discusses how the composition of lime repointing mortar could be optimised to fit specific criteria when used in exposed historic buildings (objective 1), focusing on the various materials used in this thesis. Section 7.2 examines the multi-method methodological approach and how to find a clear way to evaluate repointing mortar

for exposed buildings (objective 2 and 3). Section 7.3 explores whether repointing could work to mitigate rain ingress and help a building dry out and why it could not, proposing different scenarios (objective 3). Section 7.4 proposes a comparison of grouping and scoring system of the mortar mixes analysed. Finally, section 7.5 discusses the wider issue of extrapolations from laboratory samples to test walls to real buildings, and how to be sure that these mortars would help sustainably preserve masonry. Recommendations for future research are also presented.

### **7.1 Optimising the design of repointing mortar composition for exposed and dense masonry**

*“[Les] eaux [...] font le troisième élément de la composition du mortier (car il y feu à la chaux, terre au sable, eau pour leur agglutination, et la fumée forme d’air nubileux, qui respondent aux quatre éléments du monde).”*

*« Waters [...] make the third element of the composition of mortar (as there is fire to lime, earth to sand, water for their binding, and smoke a type of nebulous air, that respond to the four elements of the world).”*

*Philibert Delhorme, livre I chap. XVI, p.28, 1626 (translation by the author)*

This research has identified a range of specific materials (wood ash additives, porous aggregates, feebly hydraulic binder gauged with quicklime) in various combinations and used them to design repointing mortars for highly exposed dense masonry. In the introduction (Chapter I) some criteria were set, based on literature, for the ideal repointing mortar to be applied on historic, dense masonry in highly exposed and wet environmental conditions. Based on technical, mechanical and functional requirements of repointing mortar in exposed masonry walls, the criteria were defined as follow:

- The repointing mortar should be able to set and perform under humid environmental conditions, while experiencing minimal shrinkage.
- It should be able to absorb moisture from the surrounding masonry units (here mainly dense and hard stones) while minimising the absorption of water from rain.
- Therefore, the repointing mortar should mitigate moisture ingress from rain.
- Finally, the repointing mortar should have the ability to dry out quicker than the surrounding masonry, minimising the risks of salt efflorescence and frost damage to the historic stones.

It is clear that some of those criteria are incompatible. However, the experimental research developed throughout this thesis has designed repointing mortars whose properties and performances are close to these ideal ones. In total, twenty-three different mortar compositions were formulated, based on practitioners' recommendations and previous scientific research (Table 3.1). Four types of lime were used, non-hydraulic lime putty, NHL 2, NHL 3.5 and NHL 3.5 gauged with non-hydraulic quicklime, three aggregates: quartz sand, calcitic sand and crushed limestone and one additive, biomass wood ash, at various concentrations. The combinations used in the mortar mixes in each study are shown in Figure 7.1. The use of each material is summarised and contrasted below.

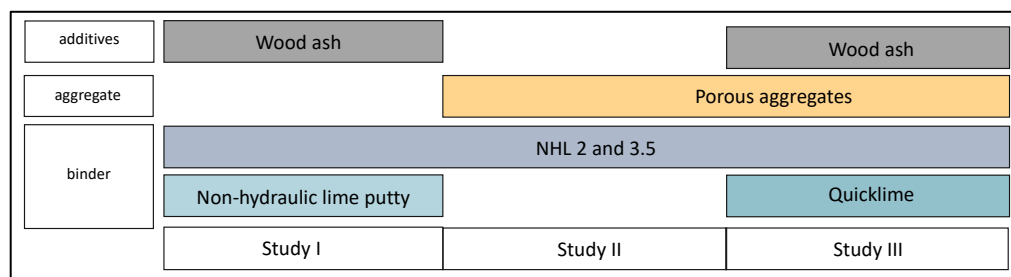


Figure 7.1 Summary of materials used in the composition of lime mortars across the thesis and discussed below

### ***7.1.1 On the use of wood ash in lime mortars (Study I and study III)***

Study I (Chapter IV) assessed the effect of wood ash on a range of properties of mortars made with air lime (non-hydraulic lime putty) and natural hydraulic lime (NHL 3.5) and to what extent varying the ash concentration would change these properties. The goal was to understand on one hand what wood ash does to a range of properties and on the other hand whether these changes of properties could be beneficial for repointing mortars to be used on exposed historic buildings. The study showed that wood ash, being hygroscopic and bringing fine particles, gives mortar a denser structure leading to high proportion of pores in the capillary range (Fig. 4.3). Positive effects of wood ash in lime mortars for use in exposed buildings found in this study included: higher open porosity – an advantage for highly porous masonry stones, delayed capillarity saturation – enabling more water to be absorbed, good ability to dry out (Fig. 4.7), and a potential pozzolanic activity – beneficial for mortar to set under damp conditions (Table 4.4). The high absorption of water may also lead to a poulticing effect of wood ash. Negative impacts included high drying shrinkage, especially for non-hydraulic lime mortars and at high amounts of wood ash (Fig. 4.5).

Based on these findings, some of the mortars used in Study III (Chapter VI) were designed with an optimum amount of wood ash (30% of the aggregate part). The results found in Study III were in alignment with findings of Study I, in the sense that joints with mortars made with wood ash (wall 3, 4 and 5) had a better ability to absorb water and keep it longer (Fig. 4.4). Wood ash seems therefore to be a useful and positive material to add to lime mortar exposed to high rainfall. If the recommended optimal amount (between 20 and 40% of the aggregate) is followed it seems to help absorb moisture from the surrounding masonry units and from rainfall. The research in Study III recommended its use with NHL 3.5 as the

durability test done in Study I showed that non-hydraulic lime would not resist harsh environment enough.

Using biomass wood ash is sustainable as it makes use of a waste material. Building materials for construction are currently finding more sustainable direction (Forster *et al.*, 2004). In addition to using lime, which uses less energy to produce than cement, which makes lime an energy efficient material (Sickels-Taves & Allsopp, 2005), the use of biomass wood ash in lime mortar could be a way for heritage conservation to make use of waste materials as well. Replacing aggregate, that is becoming a rare resource, is also highly beneficial.

However, in this thesis, only one type of wood ash was assessed, and the exact details of which type of wood burnt was unknown. It is likely that different types of wood ash would have different properties. In addition, the grey colour given by wood ash to lime mortar can on one hand suit the aesthetic of some building façades and their original mortar, but on the other hand, if undesirable aesthetically, can be overcome by adding a light pigmented layer on top of the repointing mortar.

### ***7.1.2 On the use of porous aggregate in lime mortars (Study II and III)***

In this thesis porous aggregates were used in order to bring more porosity to the mortars, especially when a hydraulic binder was used. Study II (Chapter V) clearly showed that crushed limestone gave lime mortar a higher porosity than siliceous quartz sand (Fig. 5.6), a dense pore structure and were less affected by the change in curing conditions. These mortars appear to be a good option for repointing exposed buildings. Previous studies (Lanas & Alvarez, 2003; Scannell *et al.*, 2014; Szemerey-Kiss & Török, 2017) have shown that the use of calcareous aggregate improves the strength of the mortar and change the porosity, the later was verified in Study II. In developing a specific repointing mortar, limestone aggregates are often used with limestone masonry (Pavía, 2005) so that compatibly between

materials is ensured. Based on these findings, the mortars developed for the test walls experiment (Study III, Chapter VI) were designed with calcareous sand, a more available material. However, in Study III, no clear differences in water absorption and drying were reported for mortar joints made with calcareous vs quartz sand.

This thesis, in line with the literature reviewed in Chapter II, has demonstrated that calcareous aggregates can improve the porosity of NHL mortar for repointing dense masonry. However, when tested in realistic conditions (test walls) the different binders and additives had more significant impact on the performance of the mortar than the aggregate type.

### ***7.1.3 On the use of natural-hydraulic lime (Study I, II, III)***

All three studies use NHL as one of the main binders (Fig. 7.1). Study I (Chapter IV) has shown that when used with wood ash, NHL 3.5 was preferred to air lime to reduce the amount of drying shrinkage due to the addition of fine particles (Fig. 4.5). Study II (Chapter V) has demonstrated that NHL 2 under humid conditions gained a good internal structure quickly (Fig. 5.4), beneficial for a durable and suitable repointing. NHL 2 was used in Study II in order to have a feebly hydraulic mortar that could be used in wet environment and with a range of dense stones. When the use of granite was decided for Study III, NHL 3.5 was suitable and more appropriate for high exposure. In Study III (Chapter VI) each test wall, made with NHL 3.5 gauged with quicklime, exhibited a good ability to dry, all reaching a fairly dry state after a week of evaporation.

As repointing is fully exposed to the external environment, durability issues are important and so NHL binders (2, 3.5 and 5) have been used for the design of repointing mortar in previous studies (Pavía, 2005; Schork *et al.*, 2013), sometimes gauged with quicklime (Hughes *et al.*, 2008). NHL binders are also often

recommended for severe exposure as shown in Chapter I (Hughes, 1987; Mack & Speweik, 1999). The use of natural-hydraulic lime is nowadays often under debate amongst practitioners, mainly because it has been shown that NHLs from different manufacturers have different characteristics of strength over time (Gulotta *et al.*, 2013; Figueiredo *et al.*, 2016) so that concerns are that it could become stronger than expected over time. However, for historic buildings with hard stone masonry situated in highly exposed areas the use of NHL seems to be key in terms of giving an early setting and strength gain. Indeed, NHL mortars can easily cure under humid environmental conditions (Allen *et al.*, 2003; Kalagri *et al.*, 2014) and can deal with intense wetting and drying cycles, while still having a good capillary permeability to enable the masonry to dry out. Studies have also shown that non-hydraulic lime, in the form of lime putty, is not resistant enough in facing absorption and desorption of water (Teutonico *et al.*, 1993).

The challenge of this thesis was to design a hydraulic binder fit for purpose for low porosity masonry, therefore able to deal with important moisture transport. Therefore, the combination of porous aggregate with NHL seemed to be an ideal composition (Fig. 5.8, 5.9, 6.4). Besides, Study III (Chapter VI) also identified that gauged quicklime helps improve the properties of NHL mortars minimises and delays the capillary absorption (Fig. Table 6.2, Fig.6.7a) .

#### ***7.1.4 On the use of quicklime (Study III)***

Gauged NHL with quicklime is often used to give an easier to use mix and as Study III shows, it helps minimise capillary absorption because of the bond it creates between the sand and the binder with chemical reactions absorbing moisture during slaking. In Study III, quicklime was used in small lumps (2 mm to dust) in order to avoid uncarbonated lime lumps and failure of the pointing and repointing mortar. Mixing quicklime with air lime was also recommended by many architectural and

building construction treatises in the 17<sup>th</sup> and 18<sup>th</sup> centuries in order to obtain a better mix of lime and sand (Blondel, 1777; Rondelet, 1803). Currently in built heritage conservation interest is increasing in the use of non-hydraulic quicklimes only, called hot lime mixes, due to their many benefits as well as their compatibility and authenticity (Henry, 2018). However, it has been made clear that under wet and exposed conditions, hot lime mixes could fail and that NHL gauged with quicklime should be more durable (Artis, 2018). The research in this thesis also shows that NHL gauged with quicklime gives the positive effects of both quicklime and NHL, workability, minimal capillary absorption and durability to wet environment for highly exposed repointing (Fig. 7.10, 7.11). Gauged quicklime with NHL would also minimise the hydraulicity of NHL. The use of hydraulic quicklime could also be considered.

#### ***7.1.5 Summary on materials***

The materials used in this study are therefore both traditional and in current use in conservation. The designed mixes have proved to be able to be optimised to enhance the performance of repointing mortar under wet and exposed conditions, by increasing or decreasing some key properties. Details of the reasons why and for which environmental conditions is discussed later in Section 7.3. Further evaluation of NHLs from other manufacturers and of non-hydraulic lime with known pozzolan could also be investigated for such repointing mortars.

## **7.2 Developing a suitable scientific evaluation of repointing mortar**

### ***7.2.1 Multi-method evaluation and validation, combining scientific research and practical requirements***

The methodological approach developed in the three studies in this thesis combined multi-method analysis at different spatial scales - laboratory samples at micro (mm), macro scale (cm) and test walls (m) - over different timeframe – fresh mortars, hardened mortar at early (28 days) to medium (90 days) term for samples and at slightly longer term for repointed test walls (100 to 545 days). The performance-based approach taken with the end goal of developing a repointing mortar with low capillary absorption and high drying rate, allows the evaluation and the validation to be done based on key criteria (as set in the introduction). The methodology therefore proved able to successfully evaluate repointing mortars by determining whether and how different materials impact upon key properties and how mortars respond to external environments (during curing conditions – Study II, and after intense rain events – Study III). In all three studies (Chapter IV, V, VI), the mortars were characterised with the same or similar tests (Table 3.2) which enables comparison of the twenty-three mortars across the three studies with a high confidence level. Variables were limited as much as possible and the mortars designed in each study informed the design of the next study, allowing overall comparisons.

The methodology enabled a concise but comprehensive characterisation of the mortar mixes adapted to fit the functional and technical requirements of repointing lime mortars to be applied under wet conditions (Table 3.2). For this reason, capillary absorption tests in Study II and III were done on sealed samples to simulate mortar in a masonry joint and drying tests were done under two environmental conditions to better reflect realistic ones. Mortar samples were not

sealed for the drying test to fully understand how the material dries-out, but one could argue that by being sealed in four faces the test would have better replicate the situation of repointing mortar in a joint. Considering the climatic conditions found in Devon, where frost is less likely to damage masonry than salt, it was decided that a salt uptake test would be more appropriate than the freeze-thaw test used in Study I. However, although repointing should absorb salt, it is more important to assess its ability to absorb moisture by capillarity first, as with water will come soluble salts.

A mix of methods, comprising destructive and non-destructive techniques, laboratory and in-situ was selected (Table 3.2). Most of the characterisation methods used were easily available and easy-to-use with the intention that practitioners on-site could replicate these methods. As discussed in Study III, the use of a microwave moisture meter has been shown to successfully characterise the moisture dynamics of the granite units and the mortar joints over several days, allowing comparison of mortars between walls, with the added benefit of near-surface and depth readings. The moisture microwave meter could however not be used on small laboratory mortar samples as the probe is too large and the electromagnetic wave needs further length to travel.

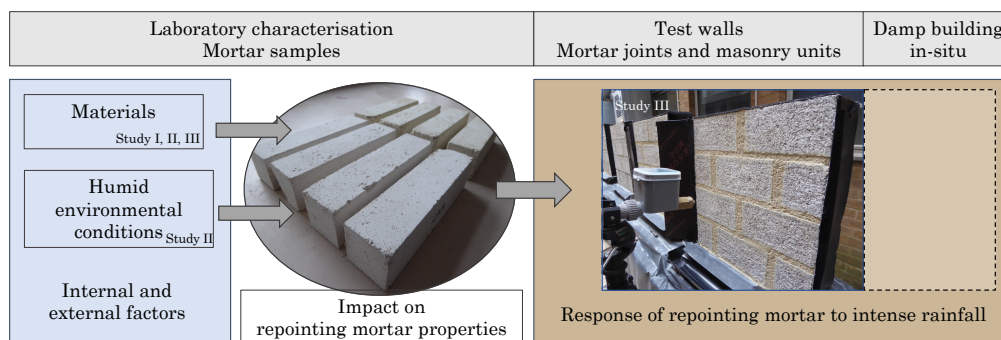


Figure 7.2. Methodological approach throughout the thesis, as seen in Chapter III (Fig. 3.4) , comprising here further validation on real damp historic buildings.

In general, mortar samples were tested at 90 days in the laboratory following standard requirements. This was shown to be sufficient to obtain a suitable evaluation of the mix designed to check whether they would fit the functional and technical requirements of pointing mortar for damp buildings. However, full validation of the mortars required a longer-term approach. This was given by the test walls, that were tested firstly at 100 days, than at 18 months (545 days) after being built, once repointed. Longer term experiment on the test walls would also be useful to validate the repointing mortars. Further large scale and long-term validation with application in situ and monitoring over several years would really extend the methodology developed (Fig. 7.2). Whilst this was beyond the scope of this thesis, it should be followed-up in future, using the designed repointing mortars from Study III.

### ***7.2.2 Proposed framework for assessing repointing mortar for highly exposed buildings and simplified evaluation***

In making the link between laboratory scientific evaluation of the materials chosen, practitioners requirements and in situ conditions, this research has developed a suitable way to optimise, i.e. design, a suitable mortar composition, and evaluate and validate its use (Fig. 7.3). Based on the criteria set in the introduction and specified in literature (Hughes, 2012) as well as on what this research has shown in terms of evaluation, an extended framework for specifying and evaluating repointing mortar for damp buildings can be defined. This extended framework is presented in Figure 7.3, building from Van Hees' (Fig. 2.11).

This thesis indeed emphasizes that a spiral methodology is necessary (Fig. 7.3), which leads to the re-design of repointing mortars, following satisfactory evaluation and validation. The process evaluates whether the mortars designed would fit the set requirements. If it does not, the mixes can be re-designed. Finally, conformity to

the environmental and conceptual requirements of the designed mixes is necessary for the final validation of the effectiveness of the mortar. If still changes need to be done, this validation process helps to redefine the compositions, making a spiral methodology. Figure 7.3 also shows how each study fit into the spiral methodology:

1. A first set of mortars was designed for Study I, then evaluated.
2. A second set of mortar was designed for Study II and also evaluated. Finally
3. Mortar mixes were redesigned, evaluated again, and finally validated in Study III.

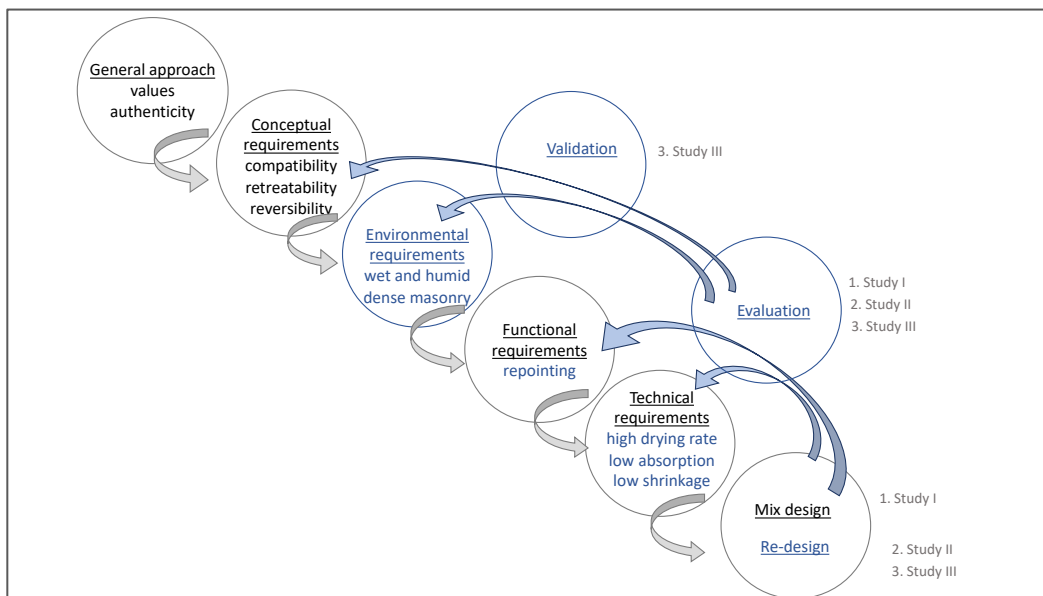


Figure 7.3. Framework for repointing interventions: each requirement leads to the design of the mix which then needs to be evaluated and validated. In blue, elements that have been added from the original framework from Hees, 2012 (Fig. 2.11). 1, 2, 3 illustrate how each study fits in this spiral methodology.

This research has determined a concise and clear way to evaluate and validate repointing mortar for dense masonry in humid conditions. Some technical parameters have been identified:

- As the masonry is dense the compressive strength of the repointing mortar is of little importance.

- Realistic humid curing conditions from medium to long term (curing from 28 to 90 days) give similar results to laboratory conditions, therefore samples can be tested on site prior to application with expected similar results (Study II).
- Porosity is a good property for comparison but does not give enough insight into how the mortar would respond to mortar ingress. For instance, in Study III, the open porosity measured in the laboratory could not predict the rate of absorption and drying and behaviour of the mortar joints during drying and evaporation. However pore size distribution gives more details on the proportion of capillary pores.
- Pore size distribution is therefore a good proxy to explain water absorption and drying behaviour, as all three studies have shown.
- Water absorption, vapour permeability and drying rate are essential properties to measure to evaluate the performance of mortar under wet conditions.
- Vapour permeability is an important test but it is tedious to execute
- High drying shrinkage and lack of durability to freeze thaw cycles were useful ways of disqualifying some mortars (see Study I).

Hughes (2012) had determined technical factors important for repointing mortar: the appearance, deformation, adhesion, water penetration resistance, vapour transmission, freeze-thaw resistance, wetting and drying behaviour. In this thesis, as one aim was to find a simplified methodology for a specific masonry and environment not all of these criteria were considered important to be evaluated.

Therefore, with the idea of having a simplified validation system based on the above identified technical parameters as well as basic and easy to operate tests, the degree of complexity vs usefulness of each tests to evaluate repointing mortar can be determined (Fig. 7.4).

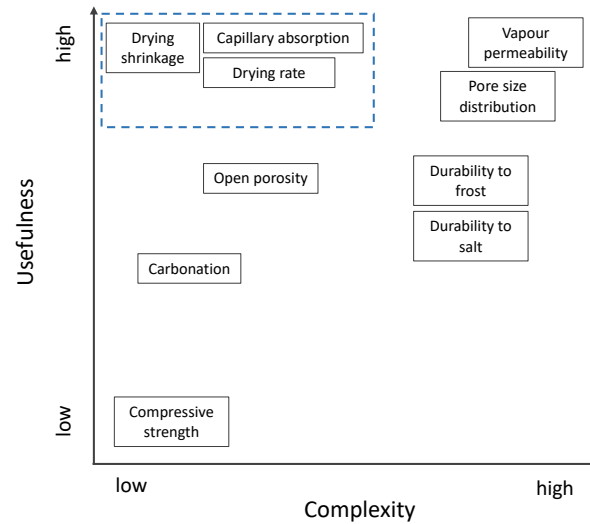


Figure 7.4. Complexity vs usefulness of tests on hardened lime mortar to assess their effectiveness as repointing mortar for severely exposed dense masonry. The blue box shows the tests that could be selected for a simplified evaluation.

Figure 7.4 identifies drying shrinkage measurement, water absorption by capillarity and drying rate tests, as being the most useful and the least complex to operate and can be done as proxies and representative measures to evaluate repointing mortars for dense masonry. Based on these three identified essential parameters, a detailed scoring system (discussed in Section 7.4.) has been developed in order to choose the mix design based on conceptual, environmental, functional and technical requirements (Fig. 7.3), as a result of the three studies.

### 7.3 Could repointing work to mitigate moisture ingress in solid dense masonry?

In light of the three studies (Chapters IV, V, VI) and review of relevant literature in Chapter I, this section discusses whether repointing could work to mitigate moisture ingress in dense masonry walls and help masonry dry out.

### ***7.3.1 Yes – conceptual explanation and proposed theory***

Study III (Chapter VI) proposed different scenarios to try and explain how repointing seemed to work in the test walls (Figure 6.13). In scenario 1, the repointing mortar absorbs slowly and holds on to water when saturation is reached, so that, although the evaporation is slower, no more liquid water can be absorbed into the mortar and vapour evaporation is privileged. This would work under continuously wet environmental conditions that would prevent the mortar from drying out correctly. In scenario 2, the repointing mortar has a high absorption high evaporation rate, facilitating its drying, which would work well under many wetting and drying cycles due to rain events, as a mortar that dries quickly would be able to perform well, mitigating moisture ingress through the wall. These two proposed scenarios where repointing mortar helps the masonry to dry out are mainly due to the mix design. In this sense, addition of wood ash from 20% to 40% of the aggregate volume, use of crushed limestones and calcitic sand, and gauged NHL with quicklime offer suitable repointing mortar mixes, better than the control ones.

One other explanation of why repointing could work to both mitigate moisture ingress and help the surrounding masonry to dry out, seems to be based on the compaction that is required when applying the repointing mortar on the original bedding mortar. Previous research showed that mortars with intense compaction presented higher strength (5-9% higher), lower open porosity (1-2% lower), and reduction of the proportion of large pores (100-10 $\mu$ m) and micro pores (diameter <0.01 $\mu$ m) (Stefanidou, 2005). Such mortars are dominated by mesopores (10-0.01 $\mu$ m), situated mainly in the capillary range, therefore responsible for most of the movement of water. This would explain why repointing mortar would do well in managing movement of water, absorption and desorption. Looking at the pore structure, a denser matrix with fewer pores is visible on the repointing mortar in

two walls (Fig. 7.5ab) in comparison to the original mortar in beds and perpend joints of wall 1 where more shrinkage cracks and larger pores are visible (Fig. 7.5cd).

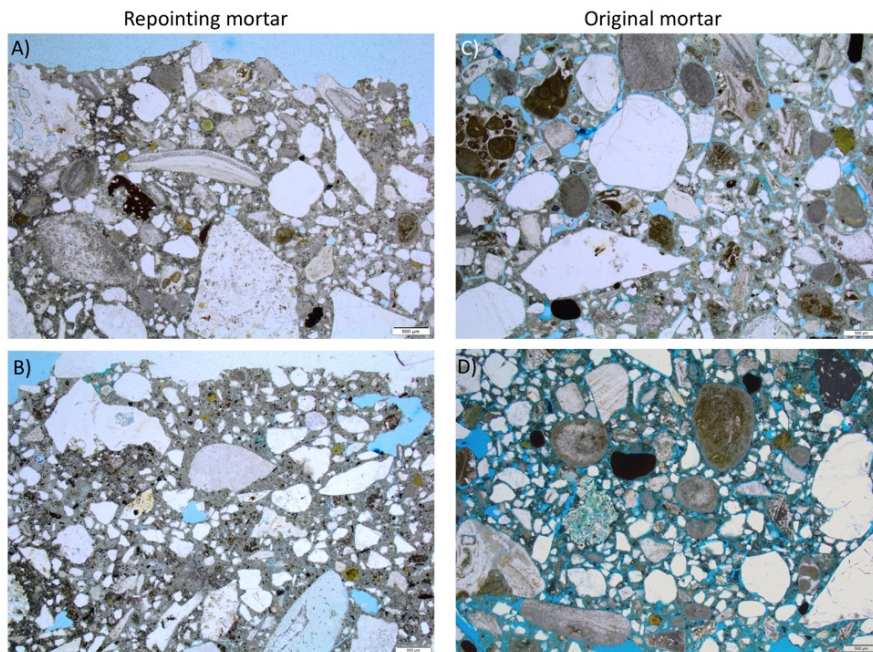


Figure 7.5. Thin section impregnated in blue resin seen under polarizing microscope showing the repointing mortar with the external surface of wall 1 A) and wall 3 B) and the original mortar in the horizontal joint C) and vertical joint D). 500 $\mu$ m scale bars.

### 7.3.2 No – reasons for failing

It is also possible to argue that the effectiveness of the optimised mortar would perhaps be different once applied on a real masonry. Indeed it was shown that sometimes repointing to high standard fails, as the empty joints are filled and water finds its way inside more than before (Wood, 2012). However, this thesis did not look at this effect and better in situ tests would be required. Besides, the mortar designed here are to be used with dense granite and if used with softer stones there is a possibility that they would not work. Finally, as it was raised by the English Heritage Damp Towers project, “re-pointing alone is not sufficient to stop water entering from driving rain” (Wood, 2013, p. 21), and should be paired with other interventions such as internal heating and clear maintenance of the gutters and roof elements, even if a rather effective mortar is found.

### ***7.3.3 The most suitable solution in some contexts***

This thesis has demonstrated that for repointing to work in highly exposed dense masonry, carefully thought compositions and workmanship have to be taken into consideration. While the repointing mortar should be able to set and gain strength, a good capillarity capacity, especially to allow effective evaporation, is needed so that most of the moisture transport can happen in the joints and moisture would not find its way inside the building. In this sense, a repointing mortar for dense masonry may not be suitable for more porous and permeable stones or bricks as it could be too or not enough permeable. Suitable mortars for dense severely exposed masonry could comprise NHL 3.5 gauged with quicklime, to give hydraulicity, good workability and comply with current conservation recommendations, with quartz sand or crushed Portland limestones which showed to give a good porosity (Section 7.1.2) and with additives of wood ash between 20% to 40%, to improve both the absorption capacity of the mortar from the surrounding stone and the evaporation rate.

Only in some cases, repointing is the only masonry intervention possible in order to respect the conservation principle of minimal intervention, as stated in English Heritage Conservation Principles, Policies and Guidance (Drury & McPherson, 2008) and the Venice Charter (ICOMOS, 1964).

## **7.4 Making decisions on suitable repointing mortar mixes**

Assigning one mortar to be the ideal mortar for repointing would be impossible as many of the mortars designed in this thesis appeared to show similar properties. Besides, in balancing a range of properties several mortars could prove to be good candidates at effectively mitigating water ingress. Based on literature

and discussion with masons and other practitioners, Figure 7.6 represents an ideal, generally accepted, view of which mortar types to use under which environmental conditions and with which masonry type.

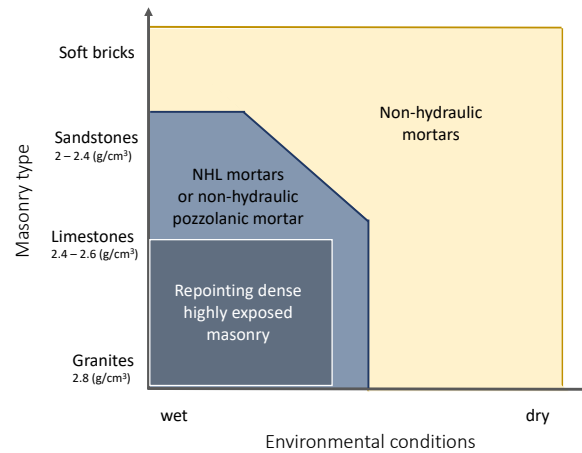


Figure 7.6 Schematic representation of which repointing mortar to use when taking into account both the masonry type and the environmental conditions with a focus on dense and highly exposed masonry. The stone types are ordered by bulk density from Siegesmund & Dürrast (2014).

However, no clear framework, combining scientific research and practitioners' views, exists to simply but efficiently evaluate whether a designed repointing mortar would work for a specific type of masonry and climatic conditions. The following discussion therefore proposes to determine groups from the twenty-three mortars studied to see which ones could fit within the box of "Repointing dense and highly exposed masonry". The discussion also helps define whether some of the mortar mixes designed would not work under some environmental conditions and masonry types.

Following the proposed simplified evaluation of repointing mortar (section 7.2.2) while taking into account both the masonry and the environment, this section discusses the possibility of grouping mortars according to two techniques. On one hand, a hierarchical cluster analysis that considers a wide range of properties to try and statistically define groups of mortars, on the other hand a scoring system

developed using three key parameters (Fig. 7.4) which enables the grouping of some mortar mixes and allocating them to environmental conditions under which they would be the most effective. These two ways of determining groups are compared to define a pilot method to efficiently and simply evaluate repointing mortar for exposed masonry.

#### ***7.4.1 Statistical groups of mortar mixes***

Hierarchical cluster analysis was chosen and performed in order to combine the twenty-three mortars into various groups based on the following eight properties or variables:

- Open porosity (%)
- WACC ( $\text{g/m}^2 \cdot \text{mn}^{0.5}$ )
- Vapour permeability ( $\text{g/m} \cdot \text{day} \cdot \text{KPa}$ )
- Drying rate ( $\text{g/m}^2 \cdot \text{h}$ )
- Compressive strength ( $\text{N/mm}^2$ )
- Carbonation depth (mm)
- Drying shrinkage (mm)
- Fraction of capillary pores (above  $0.1 \mu\text{m}$ )

This type of cluster enables the analysis to arbitrary decide on a number of groups as the opposite of k-means clusters and builds a hierarchy from bottom-up. The complete linkage method was used. The raw data used, before being normalised, are presented in Table 7.1.

The explanation of each mix is given in Table 3.2, although AL mortars are here referred as LPA. Because no value could be recorded for the compressive strength of LPA10 (Fig. 4.6), this mix was not taken into account as it introduces missing value and creates its own group.

Table 7.1. Raw data of the eight variables for the twenty-three mortar mixes used in the cluster analysis.

Mix	Open Porosity (%)	WACC (g/m <sup>2</sup> ·mn <sup>0.5</sup> )	Vapour permeability (g/m.day.KPa)	Drying rate (g/m <sup>2</sup> .h)	Compressive strength (N/mm <sup>2</sup> )	Carbonation depth (mm)	Drying shrinkage (mm)	% pores above 0.1µm
LPA0	24.10	503.974	2.789	14.704	1.335	6.2	1.649	67.19
LPA1	23.96	508.855	2.257	16.975	1.662	7.1	2.072	64.41
LPA2	24.77	428.663	3.109	16.806	2.448	13.3	2.193	63.77
LPA3	27.96	476.563	2.974	16.845	2.333	7.7	2.678	64.00
LPA4	29.99	444.175	2.543	16.638	2.069	7.2	2.485	69.33
LPA7	44.24	533.514	3.174	23.146	2.196	6.5	3.907	69.44
LPA10	64.85	551.694	4.344	20.372	NA	14.5	4.861	63.64
NHL0	26.17	377.829	3.349	15.520	1.940	10.0	0.367	66.15
NHLA1	26.23	302.509	3.274	15.974	2.158	9.4	0.423	66.10
NHLA2	27.83	336.458	3.613	15.903	1.785	8.6	0.655	68.66
NHLA3	30.02	390.932	3.840	19.007	2.429	8.8	0.683	69.70
NHLA4	30.47	379.049	3.701	18.494	2.833	7.9	1.339	64.47
NHLA7	41.39	474.713	4.511	24.508	2.568	6.6	1.614	68.49
NHLA10	70.68	529.138	5.585	26.690	2.484	4.8	3.297	67.19
SSI3	22.33	291.270	2.850	15.423	0.947	5.0	0.790	65.67
SSI2	23.42	230.480	2.928	15.346	1.531	3.6	1.194	62.96
SCA3	27.60	259.290	3.095	18.962	1.432	4.1	1.600	70.15
SCA2	26.35	259.980	3.279	18.987	1.505	3.1	1.414	63.64
Wall 1	20.33	282.220	2.328	14.003	1.152	8.0	0.440	66.67
Wall 2	23.32	192.370	1.876	15.925	1.068	5.3	1.706	63.49
Wall 3	26.06	253.740	2.402	16.625	1.767	7.1	1.478	50.87
Wall 4	25.65	275.570	1.938	18.487	1.348	7.3	1.189	50.30
Wall 5	21.74	197.860	2.111	15.476	2.054	5.9	1.413	49.83

Results of the analysis shown in Figure 7.7 gave several clear groups with four highlighted. If two groups are considered (blue boxes), the high level concentration of wood ash (NHL 10 and LPA7) puts these two mortars apart from the rest. When four groups are formed (yellow boxes) the non-hydraulic lime mortars (LP) are distinctive of the other mortars and mortars with a medium to high content ash (NHL3, NHL4, NHL7) formed another group. Groups 1, 3 and 4 can be explained by their different properties mainly based on the binder and additives types. Group 1 and 4 gather mortar mixes that are also not included in the scoring system in section 7.4.2 because of their high drying shrinkage. The rest of the mortar mixes,

in group 2, although from different studies and made of different materials do not seem to be differentiated.

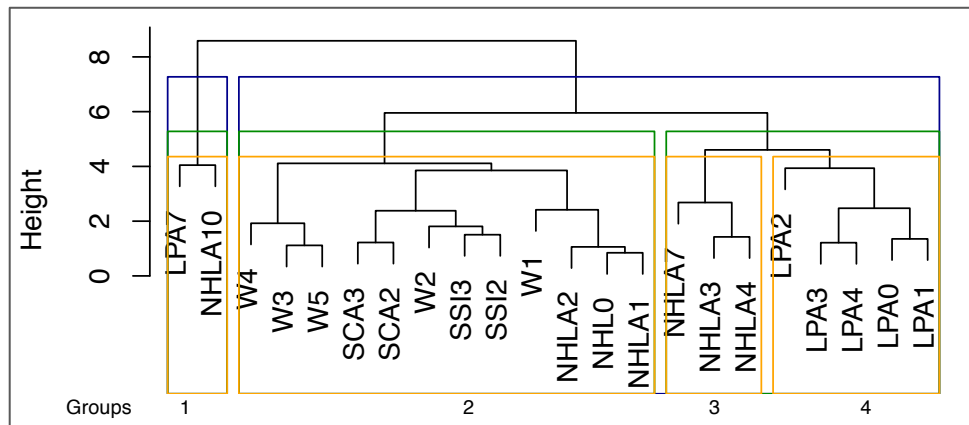


Figure 7.7 Hierarchical cluster analysis of groups of mortar with all mortars except LPA10.

#### 7.4.2 Developing a qualitative scoring system

Another way to group the twenty-three repointing mortars and validate whether they could be efficient in a highly exposed dense masonry involves a tailored scoring system, along the lines of the one developed by Hughes (2012) and explored in Chapter I (Table 2.9). To develop a scoring system, following the proposed simplified evaluation of repointing mortar (section 7.2.2), three key properties were used to classify and make decisions: drying shrinkage (mm), water absorption by capillarity (WACC) ( $\text{g}/\text{m}^2 \cdot \text{mn}^{0.5}$ ) and drying rate (DR) ( $\text{g}/\text{m}^2 \cdot \text{h}$ ) (Fig. 7.4). Instead of assigning a number, each property is defined as “low”, “medium” or “high” based on the requirements needed of the repointing mortar in a dense masonry under a specific environmental condition (Table 7.2).

Two environmental conditions are chosen here, which can also correspond to different expositions of parts of a building (for instance, north-west chimney to a south wall). The broader category of highly exposed environment is divided as follows (based on the scenario developed in Study III ,Chapter VI, although slightly

different as defined from environmental condition and not the behaviour of repointing mortar):

- Condition 1: high level of continuous rain and humid conditions, the masonry has little chance to dry out and so the repointing should have low water absorption to mitigate water ingress, holding on to moisture, combined with a high drying rate;
- Condition 2: short and intense rain spells, giving chances for wetting and drying cycles to happen so the mortar could have a higher water absorption ability, with still a high drying rate.

Table 7. 2. Summary of what « low », « medium » and high » means.

<b>Properties</b>	<b><i>Low</i></b>	<b><i>Medium</i></b>	<b><i>High</i></b>
<b>Drying Shrinkage</b>	< 1.6 mm	> 1.6 mm	
<b>WACC</b>	< 300 g/m <sup>2</sup> .mn <sup>0.5</sup>	> 250 g/m <sup>2</sup> .mn <sup>0.5</sup>	> 300 g/m <sup>2</sup> .mn <sup>0.5</sup>
<b>Drying rate</b>	< 16 g/m <sup>2</sup> .h	low WACC/DR ratio	> 16 g/m <sup>2</sup> .h

Table 7.2 summarises what “low”, “medium” and “high” means for each properties, which was decided based on the data from Chapter IV, V and V and on own assessment. For both environmental conditions, it is an absolute requirement that the drying shrinkage is low. Therefore mixes with high drying shrinkage (> 1.6 mm) were not considered suitable. Mixes with low drying rate (< 16 g/m<sup>2</sup>.h) would not be selected unless they have a low water absorption-drying rate ratio. A low ratio, calculated by WACC/DR, means that even though the drying rate is lower than the other mortar mixes, the capillary absorption is fairly low too so that it counterbalance the lower DR. However, it could also mean that these mortars are not very permeable and therefore not able to absorb moisture from the surrounding

masonry. For the WACC, a low value was determined as being below  $300 \text{ g/m}^2 \cdot \text{mn}^{0.5}$ , while a high value is above  $300 \text{ g/m}^2 \cdot \text{mn}^{0.5}$ . Based on these values some repointing mortars were selected to fit the two defined humid environmental conditions. Table 7.3 shows the steps to assign each environmental conditions based on the thresholds explained above.

The scoring qualitative system works on a basis of colour coding for green: required, orange: preferred and red: non-suitable, which help define which mortar would fit different environmental conditions (Fig. 7.8).

Table 7.3. Steps to follow to determine whether a mortar mix fit into one of the selected environmental conditions. In dark blue, high WACC ( $> 300 \text{ g/m}^2 \cdot \text{mn}^{0.5}$ ); in light blue, low WACC ( $< 300 \text{ g/m}^2 \cdot \text{mn}^{0.5}$ ); in green, high DR ( $> 16 \text{ g/m}^2 \cdot \text{h}$ ) or low ratio WACC/DR ratio if DR is low.

Mortar mixes	Step 1 : select a low drying shrinkage (mm)	Step 2 : define the WACC ( $\text{g/m}^2 \cdot \text{mn}^{0.5}$ ) threshold needed	Step 3 : select a high DR ( $\text{g/m}^2 \cdot \text{h}$ )	Step 4 (if needed): Find a low absorption / drying ratio	Suitable environmental conditions	
NHL0	0.367	377.829	15.520	high		
NHLA1	0.423	302.509	15.974	medium		
NHLA2	0.655	336.458	15.903	medium		
NHLA3	0.683	390.932	19.007	medium		2
NHLA4	1.339	379.049	18.494	medium		2
SSI3	0.790	291.270	15.423	low	1	
SSI2	1.194	230.480	15.346	low	1	
SCA2	1.414	259.980	18.987	low	1	
SCA3	1.600	259.290	18.962	low	1	
W1	0.440	282.220	14.003	medium		
W3	1.478	253.740	16.625	low	1	
W4	1.189	275.570	18.487	low	1	
W5	1.413	197.860	15.476	low	1	

Conditions 1					Suitable mortars, fitting the green boxes: SSI3, SSI2, SCA2, SCA3, W3, W4, W5
Properties	low	medium	high		
WACC	< 300				
DR			> 16		
Shrinkage	< 1.6				

Conditions 2					Suitable mortars, fitting the green boxes: NHLA3, NHLA4 And orange boxes: SSI3, SCA2, SCA3, W4.
Properties	low	medium	high		
WACC			> 300		
DR			> 16		
Shrinkage	< 1.6				

Figure 7.8. Scoring colour coding system in order to assess the suitability of repointing mortar for specific environment.

### 7.4.3 Comparison of the two systems - discussion

From both approaches, groups have been defined. Similar groups could be found: groups 1 and 4 from the cluster analysis grouped mortars with high drying shrinkage that were not included into the scoring system and groups 2 and 3 were similar to mortars found suitable for Conditions 1 and 2 (Fig. 7.8).

Table 7.4. Pros and cons of the use of each grouping approach

	<i>Pros</i>	<i>Cons</i>
<b>Cluster analysis</b>	Rich data set, enabling quick comparison of many mortar mixes and variables.	Arbitrary number of groups and no consideration of the environmental and masonry requirements
<b>Scoring system</b>	Considers the environmental requirements. Decisions based on knowledge of the mixes. Only three properties are required	Subjective set of threshold, can vary.

Cluster analysis takes into account more variables so that a larger data set can be incorporated into the analysis. Once the data have been acquired it can be performed by a range of people whilst obtaining the same results. However, it is clear that a statistical approach does not take into account the context in which the

mortar would be applied and it requires many variables to be performed, which would not be feasible in many cases in conservation.

The scoring system approach, despite choosing thresholds in a subjective manner, could be further discussed with practitioners. Therefore, it is possible that some mortars selected for Condition 1 could be suitable in Condition 2 as well, as shown by the mixes fitting into the orange box (Fig. 7.8, condition 2). Because it only requires three properties easy to obtain (Fig. 7.4), this system could be implemented on-site by practitioners.

Overall, the pilot scoring system is the most appropriate tool to ensure the most efficient lime mortars are used – that is, lime mortar that can help mitigate water ingress, and mainly help moisture to evaporate from the wall, and to validate these mortars in knowledge of a masonry type (conceptual and technical requirements), environmental conditions (environmental and functional requirements). Further trials to test the system would be interesting. These two approaches have helped define a number of mortar mixes that would fit into the box of ‘Repointing dense and highly exposed masonry’ in Figure 7.6.

## 7.5 Further discussions, limitations and recommendations

*“For, indeed, the greatest glory of a building is not in its stones, or in its gold. Its glory is in its Age, and in that deep sense of voicefulness, of stern watching, of mysterious sympathy, nay, even of approval or condemnation, which we feel in walls that have long been washed by the passing waves of humanity.”*

John Ruskin, *The Lamp of Memory*, X, p.99 (Ruskin 1849)

This final section explores and discusses three main aspects of masonry conservation and mortar design: the limitations of the work, raising the issue of drawing conclusions on the suitability of repointing mortars for in-situ interventions

from laboratory and test wall work; the questions of finding the balance in conservation interventions, sustainable preservation of a building or simply managing and following change and the reason for mitigating decay; finally recommendations for future research are listed.

***7.5.1 How to extrapolate from lab to test walls to real buildings? and does it all rest on workmanship?***

As discussed in Section 7.2 the methodology explored in this thesis relied on laboratory samples and test walls. However, on real historic buildings, mortar mixes that behave perfectly in the laboratory could perform very differently while used in-situ, mainly because the application of mortar plays a large role in its effectiveness. Laboratory work can also appear removed from reality so that full-scale in-situ testing is necessary for a real evaluation (Stewart *et al.*, 2001). Nevertheless, laboratory characterisation (on samples or test walls) enables the researcher to precisely and scientifically ensure that the repair mortar will be physically compatible with the masonry unit (Schueremans *et al.*, 2011) and fulfil the technical requirements of a specific environment (Lindqvist, 2009) while limiting variables. Understanding materials and the behaviour of mortar mixes prior to their application on site is therefore essential to avoid using the wrong material that would cause more damage to the masonry and in order to make informed decisions. In this line, some tests could have been even more adapted to repointing mortar, such as sealing all faces but one of the mortar samples during drying tests to simulate repointing mortar in a joint.

In addition, voids that are often found in thick church masonry and conduct liquid water more easily are difficult to reproduce without increasing the number of variables. This thesis chose to limit the variables and to have single layer test walls in order to gain a clear understanding of the reasons for the performance of different

repointing mortars. Having replicable experiments with the minimum of variables was a necessary components to enable comparison between materials. The RH and temperature during the evaporation monitoring on the test walls could not be exactly controlled and so variations were observed which could have affected slightly the rate and behaviour of evaporation. However no direct sun-light and no wind could affect the evaporation limiting the external factors. These minimally controlled environmental conditions allow for better comparison of the test walls but are not fully representative of in-situ ones.

Moreover, one could argue that an ideal and suitable mortar would not work if it is not mixed and applied according to best-practice, and at the other extreme, that a bad mortar applied well could function well. Any conservation intervention on a historic buildings requires careful workmanship to be effective and durable (Snethlage *et al.*, 1989). In addition, many conservation interventions on historic buildings are done by general building companies (English Heritage & Creative & Cultural skills, 2013). The issue of workmanship emphasizes the importance to do scientific research in collaboration with masons and conservation officers. This thesis addresses workmanship by working in collaboration with masons and conservation officers (Chapter III) and by following best-practice steps (Table 2.7). In this way, scientifically researched mortars are used to the best-practice and vice versa: best-practice is followed while making mortar samples for scientific research. Seemingly the issue of workmanship raises the point that more knowledge exchange and collaborations need to happen. One challenge is to ensure that conservation interventions using lime mortars are done by conservation trained masons.

### ***7.5.2 Mitigating the rate of decay or managing change?***

Buildings evolve, are affected by weathering and erosion, or more drastic intervention at times; are used and inevitably decay, especially in a context of

climate change. DeSilvey argues that processes of decay can be “additive as well as destructive” (DeSilvey 2017, p.20) in the line of Ruskin for whom restoration was “the most total destruction which a building can suffer” (Ruskin 1849, p. 103).

As argued in Section 7.3, repointing can mitigate moisture ingress and help dry out masonry when the materials are carefully chosen, evaluated and validated, but often needs applying in conjunction with other internal and external interventions on the building (heating, maintenance, etc.). Repointing could be a way to find the balance between the inevitable interventions to preserve damp masonry in historic buildings, while simply managing and adapting to change. Perhaps the key to understanding and choosing to repoint is that as a minimal intervention, designing and evaluating repointing mortar may be a way to accompany the building in a slow sustainable decay, without too much intervention. Repointing, by combining past materials and practice and current context, can help the building move to a new form (DeSilvey, 2017). It provides specific and tailored care to a building (Ruskin, 2011), while being efficient and minimally destructive. In this sense, repointing, when carefully thought through, beyond the materiality involved, ensures a slow preservation of historic buildings for generations to come.

### ***7.5.3 Future research and recommendations***

The previous sections have briefly touched on recommendations for future research. On materials, design of more mixes involving gauged quicklime at different concentrations and non-hydraulic lime mortar with known pozzolan (for instance brick dust) would be interesting as it would expand the type of masonry the researched repointing mortars could be applied on. Building on this, further validation of repointing mortars under various environmental conditions, such as colder or warmer, but still humid, would give wider practical recommendations. Especially in a context of climate change, evaluating the response of pointing mortar

under known predicted changes of increase and more intense rainfall would be particularly beneficial. Finally, following from section 7.3, further evaluation of the impact of compaction when placing repointing mortar, as one reason why it would be able to prevent moisture ingress through dense masonry wall and help it dry out, would be necessary. Further long-term testing on test walls and real historic buildings would contribute to validate the mortars optimised in this thesis, determining whether they would help buildings be less damp.



## VIII – CONCLUSIONS

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The aim of this thesis was to investigate the role of repointing mortars in the conservation of historic buildings in exposed environments. The thesis addressed this aim within a framework which considered the material properties of repointing mortars (lime, aggregate, and sometimes additives), workmanship and the broader masonry context (masonry type, environmental setting). Three research questions were posed: What would be the most effective mortar to repoint hard stone masonry in exposed locations? How do the environmental conditions found on-site affect these mortars? Can these repointing mortars mitigate driving-rain ingress?

The thesis has shown that the design of repointing mortars can be optimised for a specific environmental context using carefully chosen materials. Key scientific findings have been made on the effect of using specific materials in lime mortars, such as wood ash, porous aggregates and quicklime, contributing to increasing the understanding of traditional and historical materials. In addition, the thesis has brought further understanding of the impact of wet environmental conditions (such as curing conditions and intense rainfall) on the properties of lime mortars. Finally, this research has contributed to determining how repointing can help mitigate moisture ingress in historic masonry. These findings have significant implications for decision-making on repair interventions for the conservation of historic buildings, especially in a context of climate change. The novel pilot scoring system developed could have considerable implications for more effective and durable repointing interventions. Moreover, in combining a scientific approach with consideration of traditional workmanship, the thesis has made a novel contribution to the field of heritage science.

This chapter summarises the main findings and answers the research questions in section 8.1 and further explains the scientific and practical implications and contributions of this thesis in section 8.2.

## 8.1 Summary of findings

### *Optimise* (objective 1)

The research has successfully demonstrated that the composition of repointing mortars can be optimised by using traditional and historical materials. Several research findings regarding the use of materials have been highlighted:

- The dense structure given by wood ash increases the compressive strength and gives a potential pozzolanic activity, beneficial for lime mortars to set quickly under wet environmental conditions.
- The addition of wood ash as additives gives lime mortars the ability to absorb more total water at capillary saturation, increasing the capillary absorption.
- gauged NHL with quicklime slows down the capillary absorption
- Mortars with gauged quicklime and wood ash as additives, when used as repointing mortar, are good at mitigating water ingress while showing a good capacity to dry out

The thesis has also shown that only some specific compositions are suitable and effective as repointing mortars for low-porous and highly exposed masonry. For instance non-hydraulic lime putty mortars were not durable enough and especially affected by drying shrinkage.

### *Evaluate* (objective 2)

The thesis evaluated the effect of humid environmental conditions on the development and performance of lime mortars. Four key findings are:

- Significant differences are found in laboratory evaluations of mechanical properties of the same NHL mortar exposed to different curing conditions especially at an early age and for mortar made with quartz sand. Over the early to medium-term (up to 90 days curing time) natural hydraulic lime mortars are affected by the surrounding humid environment (RH and temperature).
- Laboratory evaluation should be made on samples cured under realistic conditions if information on the early to medium-term (up to 90 days) characteristics of NHL mortar is required. Over longer time scales, and for an evaluation of the overall performance after 90 days, standard conditions are likely to be adequate.
- Realistic humid curing conditions help NHL mortars gain good internal structure more quickly, minimising the risk of early failure of pointing mortar exposed in a harsh humid environment.
- The novel experiment using test walls was a clear and easy way, limiting variables, to evaluate the response of mortar joints to an intense rainfall and monitor their evaporation over time and at surface and depth.

Overall the thesis successfully developed an evaluation method to determine whether and how different materials impact upon key properties and how mortars respond to external environments. The combined multi-methods enabled analysis at different spatial scales - laboratory samples at micro (mm) and macro scale (cm) and test walls (m) - and over different timeframes – fresh mortars, hardened mortar at early (28 days) to medium (90 days) for samples and at slightly longer term for repointed walls (100 to 545 days). The above findings permit the definition of three key properties as proxies to evaluate repointing mortars for dense masonry, being the most useful and the least complex, so that they could easily be used on-site for

instance: drying shrinkage measurement, water absorption by capillarity and drying rate test.

*Validate* (objective 3)

The thesis also aimed at determining whether different lime-based repointing mortars mixes effectively respond when exposed to driving-rain, in other words, assessing their performance to validate them or not. The main finding is that when test walls were repointed, the depth of the wall absorbed less water than before repointing, therefore reducing the threat of water ingress. Reasons for this performance were drawn: the compaction at application reduced the amount of coarse pores, encouraging the creation of smaller pores responsible for capillary movement of water. The use of test walls was a suitable way to validate these mortars but further long-term experiment, especially on real buildings, would be necessary to ensure final validation.

The research conducted emphasised a circular novel methodology: designing mortar based on several criteria and environmental contexts, evaluating whether the mortar designed would fit the requirements, if it doesn't, redesign other mixes, and finally validating the more effective mixes for their conformity to the environmental and conceptual requirements. The thesis therefore addresses objective 3, but also goes beyond by developing a scoring system which could be used to help choose repointing mortars to validate them in-situ.

Overall, the thesis has successfully answered the three research questions, by researching specific materials to optimise the composition of lime mortars, giving them a high capacity to dry out, a good porosity or ability to absorb moisture and being durable enough; by developing a simplified and straightforward spiral methodology to evaluate repointing mortar for exposed masonry; and by suggesting

a scoring system approach to validate their effectiveness in a specific environmental conditions. The thesis has shown that humid external environmental conditions, as found on-site, affect the early development of mortar mixes but not in the long term. In addition, by assessing the performance, mainly evaporation, of repointing mortar in test walls, the thesis has shown that repointing mortar, in combination with the compaction needed when it is applied, can contribute to mitigate water ingress for exposed historic buildings.

## **8.2 Implications and contributions of the research**

### Scientific contributions

The findings listed above highlight the scientific contribution of the thesis in giving a further understanding on both the behaviour of some materials to use in lime mortars, and on the comprehension of the effects of external factors – here humid curing conditions and intense rainfall – on the properties and performance of lime mortars. In addition, by combining a scientific approach with strong involvement of traditional workmanship and consultation of historical resources the thesis made a novel contribution to the approach of heritage science and enhanced knowledge sharing.

### Practical implications for heritage conservation intervention and repair

The scientific findings have a broad practical implication in built heritage conservation as they impact the decision-making on the composition of lime mortars. For instance, the research findings implied that wood ash should be added to 20 to 40% as additives of the aggregate to be used at its best potential and give a good mortar mix for repointing masonry joints, especially in humid environments. In addition, the use of crushed limestone as aggregate made a significant difference in porosity and durability. Moreover, the circular methodology developed of optimising,

evaluating, validating and re-designing in consideration of the environmental context, masonry type, technical requirements and conservation issues will help carefully defined repointing mortars. These findings would have a broader application internationally, to tropical climate for instance. The pilot scoring system developed could have considerable implications for more effective and durable repointing interventions. Indeed, by making scientific evaluation more available and more straightforward, it would contribute to conservation intervention being done more effectively.

### Wider contributions

Having an efficient tool for decision-making, such as the scoring system, and a better understanding of materials and their development and response to a specific environment is essential to efficiently address the challenges of climate change and building resilience. Along those lines, replacing sand contributes to greener conservation intervention and use of waste material, reducing energy consumption. Finding efficient conservation solutions, such as good optimisation of repointing mortar and understanding of the impact of these conditions on the mortar, will help preserve and use more historic buildings situated in highly exposed environments. For instance St. Petrock's church could become less damp. Moreover, better use of materials will give more sustainable conservation interventions, lasting longer therefore allowing to spent less over time on repair so that more architectural heritage could be preserved.

## IX- REFERENCES

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# APPENDICES



*Details of composite façade in Languedoc  
(Haute-Garonne, France) (by MF)*



## A. PILOT STUDY

### Wood ash as an additive: a study of its influence on the physical properties of lime mortars

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This appendix presents a pilot study of the use of wood ash in lime mortars and was published in *Proceedings of the 4<sup>th</sup> Historic Mortars Conference HMC2016*, Santorini, Greece, 10-12 October, 2016, p.367-374.

#### Abstract

Developing a suitable mortar for repointing intervention that is able to mitigate rain penetration is necessary to prevent dampness in historic buildings. This research examined the effect of wood ash on the physical properties of lime mortars. Wood ash was used in three concentrations (0%, 50% and 100%). The permeability of each mix was assessed by determination of the water absorption by capillarity coefficient (EN 1925 :2000) and by drying rate tests. The open porosity was evaluated by means of the liquid absorption method (BS EN 1936:2006). Optical microscopy on thin-sections was also performed, and standard methods used to assess the degree of carbonation. Wood ash added in a mix was found to significantly increase the degree of carbonation and to influence the porosity of lime mortars by increasing the number of very small pores. Of greatest relevance to preventing dampness in buildings, wood ash was also found to increase the drying rate of lime mortars.

## A.1. Introduction

Moisture is the most common agent of degradation in historic buildings, leading mainly to structural disruption, biological growth and dampness. Moisture mainly enters through joints by capillary absorption (Rirsch & Zhang, 2010). One of the primary functions of mortar is to mitigate penetration and accumulation of rainwater in the joints (Allen *et al.*, 2003). In addition, the joints between the masonry units should act as conduits to draw moisture out of a wall, taking harmful soluble salts away from the historic stones (Holmes & Wingate, no date). For this reason, repair mortar should be more porous and more permeable than the historic masonry (Hughes, 2012). In the past, repointing interventions have often used impermeable mortar, such as cement-based mixtures. Because of their high salt content, excessive strength and low porosity these mortars trap moisture inside the wall (Hansen *et al.*, 2008). It is therefore necessary to develop a mortar that will fit the requirements of a repair mortar: being soft, porous, highly permeable, quick at drying, and able to set in specifically damp conditions.

Very little research has been done on the specific design requirements needed for repointing lime mortar facing situations with frequent driving rain. Recent research has investigated the impact of pozzolanic additives on the performance of lime mortars (Veiga *et al.*, 2009). According to Henry and Stewart (Henry & Stewart, 2012), wood ash, used as an additive, modifies the properties of non-hydraulic lime mortar by assisting the rate of carbonation and increasing permeability and workability. Therefore, wood ash could induce pozzolanic properties to a mix, giving non-hydraulic lime mortar the ability to set under damp conditions. Historic mortars frequently contain traces of ash (Allen *et al.*, 2003): there is evidence that Roman-era mortars used wood ash–lime mixes as a waterproof component. More recently research has been done on the use of wood ash as a partial replacement for cement,

enhancing durability and thus contributing to sustainable construction (Ramos *et al.*, 2013)(Fava *et al.*, 2011). Mendel Goodman has shown the influence of wood ash on the structural properties of lime mortar used as plaster, concluding that wood ash, as an additive, could offer an inexpensive way to improve lime mortars (Mendel Goodman, 1998). The current research builds on these findings and examines the effect of wood ash on the properties and performances of natural-hydraulic and non-hydraulic (air lime) mortars and discusses the reason for the influence.

## A.2 Materials & Methods

### A.2.1 Materials

#### A.2.1.1 Composition of the mixes

Five different mixes of mortars with 3 replicates of each were prepared using a binder-to-aggregate ratio of 1:2.5. Two binders were used, lime putty (one year old) and NHL 3.5 (St. Astier). The basic aggregate used was a well-graded and sharp Chardstock sand.

Table A.1. Composition of the 5 mixes used, in bold the ones made with wood ash, represented by an “A” in the mix name.

Mix Names	Composition	Ratio by Volume	% of wood ash of the aggregates
LPS	non-hydraulic lime putty : sand	1:2.5	0
<b>LPSA</b>	<b>non-hydraulic lime putty : (sand: wood ash)</b>	<b>1:2.5</b>	<b>50</b>
NHLS	NHL 3.5 : sand	1:2	0
<b>NHLA</b>	<b>NHL 3.5 : wood ash</b>	<b>1:2.5</b>	<b>100</b>
<b>NHLSA</b>	<b>NHL 3.5 : (sand: wood ash)</b>	<b>1:2.5</b>	<b>50</b>

Wood ash (WA) was used in three concentrations (0%, 50% and 100%) with the last of these only trialled in the NHL 3.5 mortar (Table A.1). The mixes with 0% WA were control mixes (LPS and NHLS) representing those commonly used by

practitioners that are well characterised. Samples were cured for 90 days in a sheltered outside area, away from risk of frost. They were then transported to a laboratory for testing where the conditions were 22 °C ( $\pm 3$  °C) and 45% RH ( $\pm 10\%$ ).

#### *A.2.1.2 Characteristics of wood ash*

Wood ash of biomass boiler at high temperature was used as an additive. The type of wood burnt was unknown. The particle size distribution of WA was measured using a Mastersizer 2000 (Malvern, UK). The particles ranged in diameter from 0.39 microns to 2 mm. This range of particles, dominated by extremely fine particles (< 135 microns), should have an impact on the porosity of the mortar (Gibbons, 2010). Ion chromatography LC20 analysis of the soluble chemical compounds of the wood ash was performed using a Thermo Scientific Dionex. Results have shown the presence of Sulfate ( $\text{SO}_4^{2-}$ ) and Potassium (K) in the highest concentrations.

### **A.2.2 Methods**

#### *A.2.2.1 Carbonation Depth*

The carbonation depths were assessed by applying phenolphthalein on the freshly broken surfaces of each mix. Following the method employed by Chang and Chen (Chang & Chen, 2006), 8 measurements (in mm) were taken and the average calculate on each mixes in order to assess the percentage of surface that has carbonated.

#### *A.2.2.2 Surface Hardness*

The surface hardness was determined using the Equotip impact device 3 (Proceq, UK) with the standard type D probe. Surface hardness can be correlated to the strength of the material (Binda & Modena, 1997). Five measurements were taken on each replicate of each mix.

### A.2.2.3 Water absorption by Capillarity

The determination of water absorption coefficient due to capillarity of hardened mortar followed the standard test EN 1925: 2000 (British Standard Institution, 1999) for highly absorbent stone. The samples were oven dried for 48 h at 70 °C ( $\pm 2$  °C) to calculate the oven dry mass ( $m_d$ ). The mass of each sample at defined times was determined using a scale at 0.01 g precision. The increase in mass ( $m_1$ ) by the surface immersed ( $A$ ) ( $\text{g}/\text{cm}^2$ ) of each replicate was expressed as a function of the square root of time ( $\sqrt{t_1}$ ) in seconds ( $s_{0.5}$ ). The water absorption coefficient by capillarity ( $WACC$ ) was determined by the formula given by the standard (British Standard Institution, 1999):

$$WACC = \frac{m_1 - m_d}{A \cdot \sqrt{t_1}} \quad (1)$$

This coefficient of capillary rise shows the rate of capillary absorption of each mix and gives an indication of the permeability of each mix (Allen *et al.*, 2003).

### A.2.2.4 Drying Capacity

All samples were immersed in distilled water for 48 h and were then left to dry in a LEEC drying cabinet at 25 °C ( $\pm 3$  °C) and 60% ( $\pm 15$ ) RH. The loss of mass of the saturated mortars was monitored every 2 h over 10 hours and then every 24 h over 6 days (120 h) until the oven-dry mass ( $m_d$ ) was reached again. The decrease of water content was calculated by  $(m_i - m_d)/m_d$  and expressed as a function of time (in min). The drying rate was calculated in  $\text{g}/\text{m}^2$  per  $s_{0.5}$  in order to enable comparison with the  $WACC$ .

### A.2.2.5 Pore System

The open porosity ( $P_o$ ) was evaluated by means of the liquid absorption method, following the gravimetric method adapted from the standard BS EN 1936:2006 (British Standard Institution, 2006). After being oven dried for 48 h at 70 °C ( $\pm 2$  °C)

until constant mass was reached, all samples were allowed to soak in distilled water for 48 h at ambient temperature. The oven dry mass ( $m_d$ ) and saturated mass ( $m_s$ ) were determined using a scale at 0.01 g precision.  $P_o$  was calculated with the following formula (Hall & Hoff, 2009):

$$P_o = \frac{m_s - m_d}{V_{\rho_w}} \times 100 \quad (2)$$

Optical microscopy of thin-sections impregnated in blue resin was performed using a Leica MZ10 F stereomicroscope at magnification up to 80x.

### A.3 Results

#### A.3.1 Carbonation Depth

For all binders the addition of WA clearly increases the carbonation depth. This is particularly true for NHL mixes where the surface carbonated increases from 15.2% to 36.3% to 52.1% of the surface of the sample (0%, 50% and 100% of WA). The carbonated surface of lime putty mixes increases from 20.9% to 22.8% (0% to 50% WA). The acceleration of the carbonation process could be explained as wood ash mortars have an increased permeability to carbon dioxide (CO<sub>2</sub>) (Mendel Goodman, 1998).

#### A.3.2 Surface Hardness

Fig. A.1 presents data on surface hardness, and demonstrates lower hardness for NHL mixes with (as compared to without) wood ash. As NHL-based mortars gain compressive strength as they cure (Allen *et al.*, 2003), having a lower hardness is a positive impact for repair mortar. For the lime putty, the values of hardness with and without wood ash are not noticeably different.

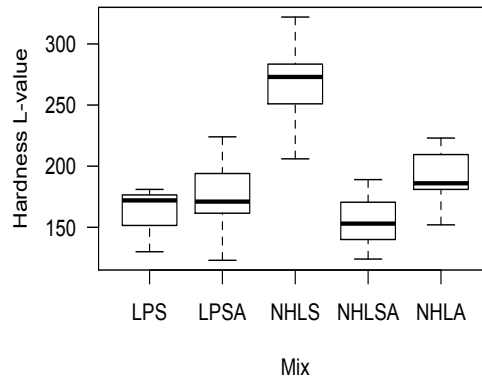


Figure A.1. Hardness value of the lime putty mixes (LPS and LPSA) and NHL mixes (NHLS, NHLSA and NHLA). NHL mixes with wood ash have a lower hardness.

### A.3.3 Pore structure

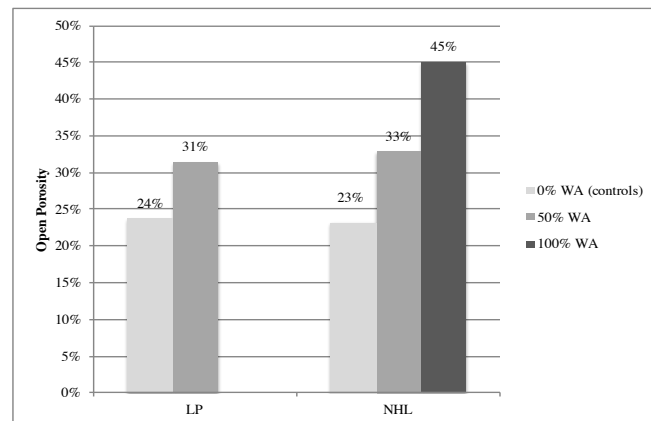


Figure A.2. Open porosity, showing a higher open porosity for mixes with wood ash.

All mixes have overall a relatively high open porosity, illustrated in Fig. A.2. When wood ash is added there is a clear increase of the open porosity. It gives an indication of a likely high permeability and that wood ash seems to induce creation of pores.

Thin sections of LPS (Fig. A.3a) show a highly interconnected pore structure in blue. Most of the pores are small and of irregular, angular shape. Larger pores are interconnected with smaller pores. In the LPSA mix (Fig. A.3b) the particles of wood ash is clearly merged within the binder and seems to have a tendency to

surround pores. The NHL mixes (Fig. A.3c) reveal round pores with almost no interconnectivity, which should result in lower open porosity. The aggregates are well bounded and well dispersed in the binder resulting in a dense structure. As Figure A.3d illustrates, the wood ash is again well merged with the binder.

In both types of binder the number of pores visible does not seem to increase drastically when wood ash is added. However, because the open porosity is much higher in WA modified mortars, it seems that wood ash enhances a micro porosity and likely have an impact on the water absorption.

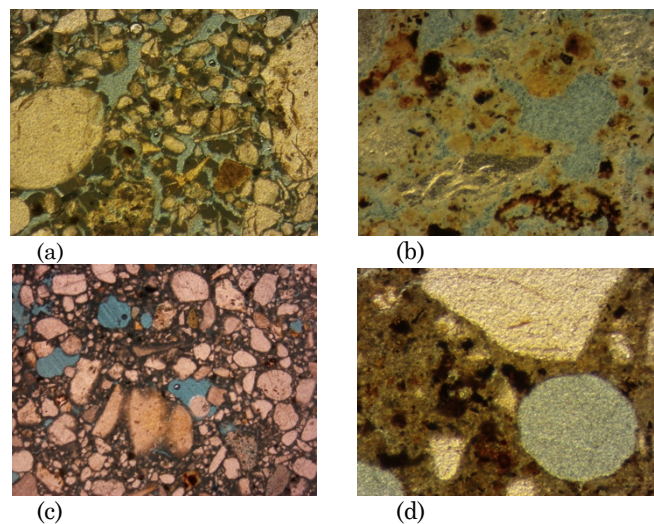


Figure A.3. Thin section microscopy under stereomicroscope. The pores are impregnated in blue resin. Magnification: LPS (a) x3.2, LPSA (b), x80, NHL (c) x3.2, NHLA (d) x80.

### A.3.4 Permeability

Wood ash generally increases the WACC. Capillaries are the very fine micro-pores found in porous materials. Figure A.5a shows that WA slightly increased the water absorption in LP mixes. However, WA greatly increases the water absorption by capillarity of NHL mixes: Fig.A.4b shows steeper curves of absorption for NHLA and NHL. The more ash in the mix, the more water is absorbed. This could be likely due to the water retention capacity of wood ash. The increase in rate of capillary absorption indicates a high number of fine interconnected pores or a high

capacity of the material to absorb water. This high water absorption capacity correlates the open porosity data.

As the curves in Fig.A.4c-d illustrate, although the WA modified mixes have a higher water absorption capacity and water content, they reach their oven dry mass of 0% water content at the same time as the control mixes. This shows a higher drying capacity. The especially higher drying rate of NHLA shows the clear impact of wood ash compared to the control mix. Wood ash seems to have less effect on the LP mix, which is perhaps explained by the capacity of lime putty to retain water (Holmes & Wingate, no date). Drying capacity is an important property as it contributes to prevent dampness inside a building (Henry & Stewart, 2012). In addition one of the desirable characteristics of pointing mortar is to not resist drying (Maurenbrecher, 2012). Therefore, the fact that wood ash increases the drying capacity of lime mortar is a positive impact.

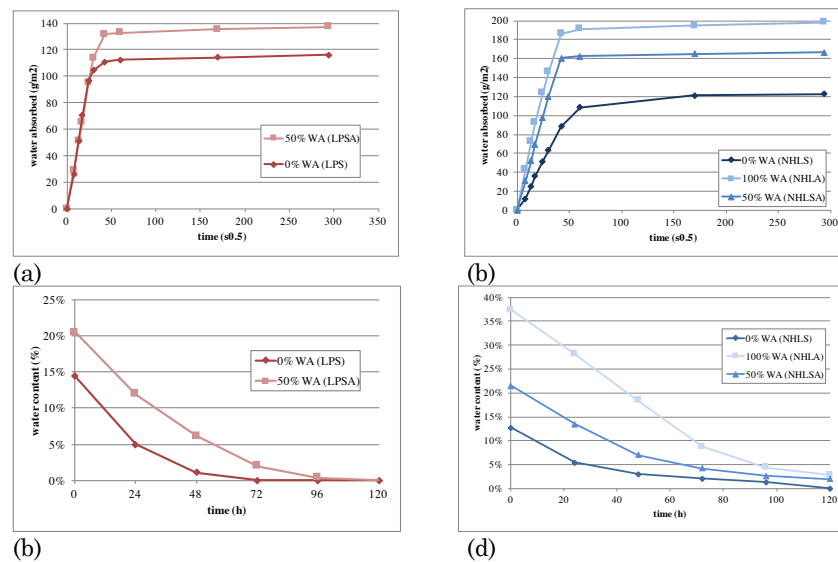


Figure A.4. WACC curves of LP (a) and NHL mixes (b). WA increases the WACC in both limes: LPS WACC=280 g/m<sup>2</sup>.s0.5, LPSA WACC=325 g/m<sup>2</sup>.s0.5; NHLS: WACC= 191 g/m<sup>2</sup>.s0.5 NHLSA: WACC= 383 g/m<sup>2</sup>.s0.5 NHLA: WACC= 440 g/m<sup>2</sup>.s0.5.

Drying curves of LP (c) and NHL (d) : WA increases the drying rate (D) : LPS : 21 g/m<sup>2</sup>.s0.5, LPSA : 25 g/m<sup>2</sup>.s0.5, NHLS : 20 g/m<sup>2</sup>.s0.5, NHLSA : 27 g/m<sup>2</sup>.s0.5, NHLA : 37 g/m<sup>2</sup>.s0.5.

#### A.4 Discussion and Conclusions

The research has demonstrated that the addition of wood ash to lime mortar has a demonstrable impact on material performance. In future, further microscopic analysis and chemical composition will reinforce conclusions and curing conditions of the samples will be more adapted to standard. Based on the results obtained the following general conclusion can be reached: wood ash has a positive effect on lime mortars in increasing the degree of carbonation, the permeability and the porosity. Of greatest potential for preventing dampness in buildings, this study showed that wood ash increased the drying rate capacity of lime mortars. The positive impact of wood ash on the permeability of lime mortar seems to be due to both the capacity of WA to absorb and retain water and the high number of fine particles it contains, enhancing the micro-porosity. The addition of wood ash helps to meet the requirements for pointing mortar application in damp conditions. The ability of NHL to set under damp conditions, combined with the impact of wood ash on increasing drying rate and giving a lower hardness value, results in a highly suitable mix for pointing intervention on buildings exposed to driving rain.

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## **B. CO-AUTHORS STATEMENTS**

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This Appendix regroups the statements of the co-authors of each publications (submitted or published) that the bulk of the work presented in the three studies (Chapter IV, V, VI) has been carried out by the author of this thesis.

As a co-author of the following publication I confirm that the first author Lucie Fusade has made a substantive contribution to the paper, which includes the conceptualisation of the research project, data collection, data analysis, writing and revising the manuscript.

**Fusade, L.,** Viles, H., Wood, C., Colin, B. 'The effect of wood ash on the properties and durability of lime mortar for repointing damp historic buildings', *Construction and Building Materials*, in review

(name and position)

Colin Burns

Consultant Mastermason

(signature and date)

A handwritten signature in black ink, appearing to read 'Colin Burns', written in a cursive style.

14<sup>th</sup> December 2018.

As a co-author of the following publication I confirm that the first author Lucie Fusade has made a substantive contribution to the paper, which includes the conceptualisation of the research project, data collection, data analysis, writing and revising the manuscript.

**Fusade, L.,** Orr, S.A., Wood, C., O'Dowd, M., Viles, H. 'Drying out traditional masonry - Response of lime-mortar joints in granite test walls after an intense rainfall, before and after repointing', *Heritage Science*, in review.

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Meriel O'Dowd 11<sup>th</sup> Dec. 2018  
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As a co-author of the following publication I confirm that the first author Lucie Fusade has made a substantive contribution to the paper, which includes the conceptualisation of the research project, data collection, data analysis, writing and revising the manuscript.

**Fusade, L.,** Orr, S.A., Wood, C., O'Downd, M., Viles, H. 'Drying out traditional masonry - Response of lime-mortar joints in granite test walls after an intense rainfall, before and after repointing', *Heritage Science*, in review.

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Researcher, School of Geography and the Environment  
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5 December 2018

As a co-author of the following publications (published and/or submitted) I confirm that the first author Lucie Fusade has made a substantive contribution to each of the publications, which includes conceptualisation of the research project, data collection, data analysis, writing and revising the manuscript.

**Fusade, L.,** Viles, H., Wood, C., Colin, B. 'The effect of wood ash on the properties and durability of lime mortar for repointing damp historic buildings', *Construction and Building Materials*, in review

**Fusade, L.,** Viles, H., (2018) 'A comparison of standard and realistic curing conditions of natural hydraulic lime repointing mortar for damp masonry: impact on laboratory evaluation', *Journal of Cultural Heritage*, doi:10.1016/j.culher.2018.11.011

**Fusade, L.,** Orr, S.A., Wood, C., O'Downd, M., Viles, H. 'Drying out traditional masonry - Response of lime-mortar joints in granite test walls after an intense rainfall, before and after repointing', *Heritage Science*, in review

Heather Viles, Professor and Head of the School of Geography and the Environment  
(name and position)

A handwritten signature in black ink, appearing to read 'Heather Viles', with a long horizontal line extending to the right.

13<sup>th</sup> December 2018  
(signature and date)

As a co-author of the following publications I confirm that the first author Lucie Fusade has made a substantive contribution to each of the papers, which includes conceptualisation of the research project, data collection, data analysis, writing and revising the manuscript.


**Fusade, L.,** Viles, H., Wood, C., Colin, B. 'The effect of wood ash on the properties and durability of lime mortar for repointing damp historic buildings', *Construction and Building Materials*, in review

**Fusade, L.,** Orr, S.A., Wood, C., O'Downd, M., Viles, H. 'Drying out traditional masonry - Response of lime-mortar joints in granite test walls after an intense rainfall, before and after repointing', *Heritage Science*, in review

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26<sup>th</sup> Jan. '19



