

The effect of wood ash on the properties and durability of lime mortar for repointing damp historic buildings

Lucie Fusade^{a,*}, Heather Viles^a, Chris Wood^b, Colin Burns^b

^a University of Oxford, School of Geography and the Environment, South Parks Road, Oxford OX1 3QY, UK

^b Historic England, Cannon Bridge House, 25 Dowgate Hill, London EC4R 2YA, UK

HIGHLIGHTS

- Comparison of NHL and air lime mortars with different concentrations of wood ash.
- Addition of wood ash leads to higher proportion of pores in the capillary range.
- Wood ash gives a potential positive pozzolanic activity to lime mortar.
- Mortars with wood ash absorb more total water at capillary saturation.
- Optimum amount of wood ash in both NHL and air lime mortars is 20%–40%.

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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. The tight structure of lime and wood ash increases the compressive strength. The fine particles given 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 drying shrinkage.

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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 [1]. The choice of specific and appropriate

materials to make a repair mortar has indeed not only to consider what is available locally [2], but also the current conditions of both the building and the masonry unit as well as the surrounding environment and climate [3]. 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 [4]. Good choice of materials and thorough understanding of their specific

* Corresponding author.

E-mail addresses: lucie.fusade@ouce.ox.ac.uk (L. Fusade), heather.viles@ouce.ox.ac.uk (H. Viles), chris.wood@HistoricEngland.org.uk (C. Wood).

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 [5,6]. 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 [7], 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 [8]. In the 18th and 19th 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* [9], 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 [10]. 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 [11]. 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 19th 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 [12]. 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 [13]. More recent research has suggested wood ash or wood waste ash, as a new pozzolanic material [14] 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 [15–18]. In lime mortar, it is more common nowadays to use fly ash to influence the transport of liquid water and compressive strength [19,20]. In general, the use of

natural pozzolans [21] and organic additives to enhance mechanical properties [22–24] 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.

2. Materials and methods

2.1. Properties of raw materials

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).

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 µm (Fig. 1). As shown in Fig. 1, extremely fine particles (<135 µm) 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 1). From these results, the wood ash does not qualify as a pozzolan, which according to EN 196-5 [25], should contain no less than 25% SiO₂ [21]. The observed physical and chemical characteristics of the wood ash conform to those found in other studies [26,27]. 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 [20,28], although it contains much more K₂O and less SiO₂.

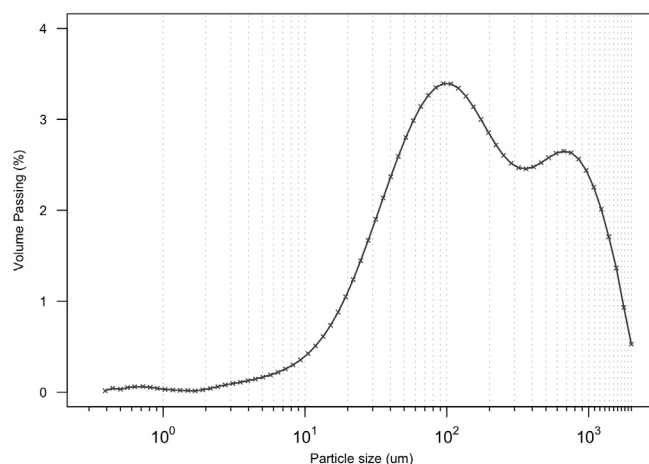


Fig. 1. Particle Size distribution of wood ash from 0.389 to 2000 µm, showing a bimodal distribution with a high proportion of fine particles.

Table 1
Chemical composition of the wood ash used.

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

2.2. Production of mortar samples

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 [13]. 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.

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 (± 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 2). Flow tests were carried out on each mix with a flow table (Matest) following BS EN 1015-3:1999 [29], to ensure a similar consistency was obtained (between 120 and 150 mm) (Table 2). It has to be noted that the more wood ash in the mortar mix, the more difficult it was to obtain a stiff mortar: when mixed with lime and sand wood ash absorbs water added to the mix but when left to stand and remixed again, wood ash releases water giving a soft 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 to use for repointing [30,31]. The initial moisture content of fresh mortar after being mixed was recorded with a Moisture Analyser (A&D MX50) to 0.001 g (Table 3).

Samples were cast in prisms of 40 mm \times 40 mm \times 160 mm in polystyrene moulds for determination of drying shrinkage and compressive strength. Cast cylinders of 50 mm height by 35 mm

Table 2
Water:binder ratio and consistency of the mortar mixes.

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

Table 3
Initial moisture content of each fresh mortar mix, generally increasing as the wood ash content increases.

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

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 samples (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 (± 3 °C), 65% (± 5 %) RH until testing.

2.3. Porosity and pore structure

2.3.1. Open porosity

The open porosity (*op*) was evaluated following the gravimetric method adapted from the standard BS EN 1936:2006 [32]. Cylindrical samples of 50 \times 35 mm were placed in a desiccator under vacuum at low pressure (less than 15 Hg) for one hour 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 three replicates with the formula:

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

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 sample. The total porosity (%) was calculated by the following formula, given in BS EN 1936:2006 [32]:

$$p = \left(1 - \frac{\rho b}{\rho r} \right) \times 100 \quad (2)$$

with ρb , the apparent density and ρr , 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.

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 and 55 psia and high hydraulic pressure range up to 2110 psia. The MIP was performed on one replicate of each mortar mixes than was previously oven dried at 60 °C.

2.3.4. Pore structure

Optical microscopy of thin-sections impregnated in blue resin was performed using a Olympus BX43 microscope at $\times 4$ magnification. One thin section of each mix was made.

2.4. Physical properties of hardened mortars

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 × 40 mm × 160 mm. The change in length was measured with a length comparator (+/- 0.001 mm) (Matest).

2.4.2. Strength activity

The procedure to measure compressive strength followed BS EN 1015-11:1999 [33] on six half prisms (cut from prisms of 40 × 40 × 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/mm².

The pozzolanic reactivity was assessed by the strength activity index (SAI) method, according to ASTM C618 [34] and BS 3892 [35], and calculated from the mean compressive strength (N/mm²) 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/mm²) and B is the compressive strength of the control mortar (N/mm²).

2.5. Water absorption and evaporation behaviour

2.5.1. Capillary absorption

The determination of water absorption coefficient due to capillarity of hardened mortar followed the standard test EN 1925:2000 [36] for highly absorbent stone. Samples (50 × 35 mm cylinders) were oven dried for 24 h at 70 °C (±2 °C) to constant mass (*md* 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 0.01 g precision until full saturation of the samples. The increase in mass (*m_i* in g) by the surface immersed (*A*) (g/cm²) 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/cm²mn^{0.5}) was determined by the formula given by the standard as a mean of the three replicates:

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

2.5.2. Drying

The drying rate was monitored over 100 h in steady laboratory conditions (23 °C ± 1 °C 53% RH ± 6%) on samples (50 × 35 mm cylinders) having previously been fully saturated under vacuum for 24 h. The change of mass (*m₁* in g) was recorded at regular time intervals until constant mass was reached. The drying rates for the first drying phase (D1) (g/m²h) and the second drying phase (D2) (g/m²h^{0.5}) were calculated according to EN 16322:2013 [37] as a mean of three replicates with the following formulae:

$$D1 = \frac{m_1 - mf}{A \cdot t_1} \quad (5)$$

$$D2 = \frac{m_1 - mf}{A \cdot \sqrt{t_1}} \quad (6)$$

With *mf*(g), the final mass recorded, *A* the surface of evaporation (g/cm²) and *t₁* (hrs) the time elapsed from the beginning of the test and $\sqrt{t_1}$ the square root of this time (hrs^{0.5}).

2.5.3. Vapour permeability

The water vapour permeability (Wvp) was determined following EN 1015-19:1999 [38] using the wet cup method. Disks of 12 cm diameter were sealed on top of a cup containing a saturated solution of potassium nitrate (KNO₃) 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 was calculated based on the mean of three replicates at each time interval using the formula given by the standard:

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

in kg/m.s.Pa (then adapted to g/m.day.KPa), with *A* the area of the open mouth of the test cup (m²), Δp 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 sample and the salt solution (4.80E + 10 m²s/g) and *t* the thickness of the sample.

2.6. Durability

Durability was assessed using a modified freeze-thaw test adapted from DD CEB/TS 12390-9:2206 [39]. Prisms of 50 × 50 × 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 sample. One replicate of each mortar mix was exposed to 32 thermal cycles from 20 °C to −10 °C in 16 h, and back to 20 °C in 6 h followed by a steady state for 2 h in an environmental chamber (Sanyo-FE 300H/MP/R20). Visual assessment was done at regular intervals.

3. Results

3.1. Porosity and pore structure

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 [40]. Fig. 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. 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 (Fig. 2).

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. 2) is visible also in the higher volume of pores being intruded by mercury (Fig. 3). It also shows

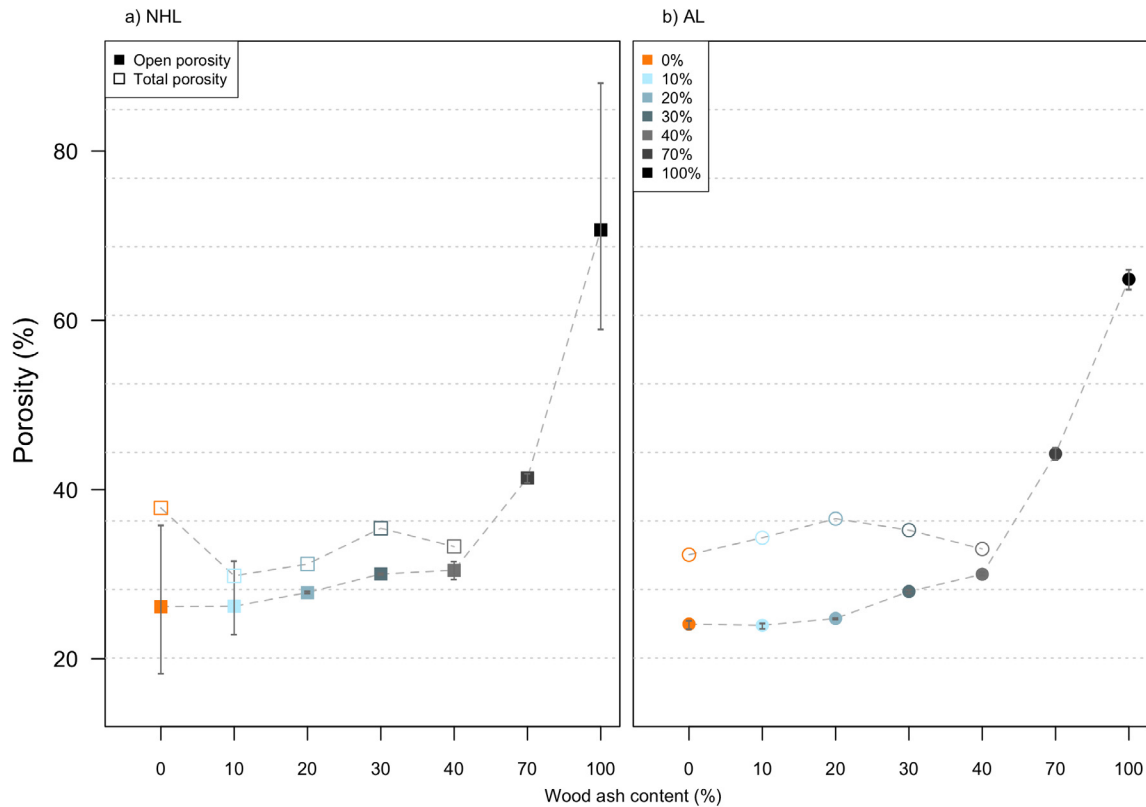


Fig. 2. Open and total porosity in relation to wood ash content of a) NHL mortars and b) AL mortars. Error bars indicate the minimum and the maximum values recorded. Dashed lines help see the trends.

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 – 1000 μm) [41,42]; or larger than micropores: from 0.1 to 10 μm [43] or from 1 to 1000 μm [44] where micropores are then considered to be below 0.1 μm [41,42,44]. In this study we consider pores between 1 and 1000 μm (1 mm) to be mainly relevant to capillary absorption by capillarity and called “capillary pores”, with pores from 0.1 to 1 μm 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 μm , than NHL mortars, comprising both larger and finer capillary pores, as noticed in previous studies comparing AL and NHL binders [22]. NHL mortars have a pore size distribution from 0.01 up to 4 μm .

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

3.1.3. Pore structure

The thin sections of selected mortars (Fig. 4) show that the more wood ash in the mix, the denser the pore structure seems to be, in the sense that with the lack of sand and with the wood ash fully blended into the lime, the matrix is tighter. The pore structure is developed mainly by the evaporation of water through the curing and hardening process, leaving a complex system of interconnected pores [40,45]. In correlation with the pore size distribution (Fig. 3), visible pores seem to be smaller than 500 μm , with no coarser pores visible in the mix. The general increase of porosity as the wood ash content increases (Fig. 2) is not clearly visible here and so seems to be linked to smaller capillary pores not fully visible at this magnification. The NHL mortars (Fig. 4a) are recognizable by the round pores created and by the complex structure resulting from the setting through carbonation and hydraulic set. The AL mortars (Fig. 4b) show many micro cracks in both the control mortar and in the wood ash mortars, correlating with drying shrinkage observations (Fig. 5). Therefore, pores in AL mortars are more interconnected than in NHL mortars, mainly because of the presence of micro-cracks.

3.2. Physical and mechanical properties of hardened mortars

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 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.

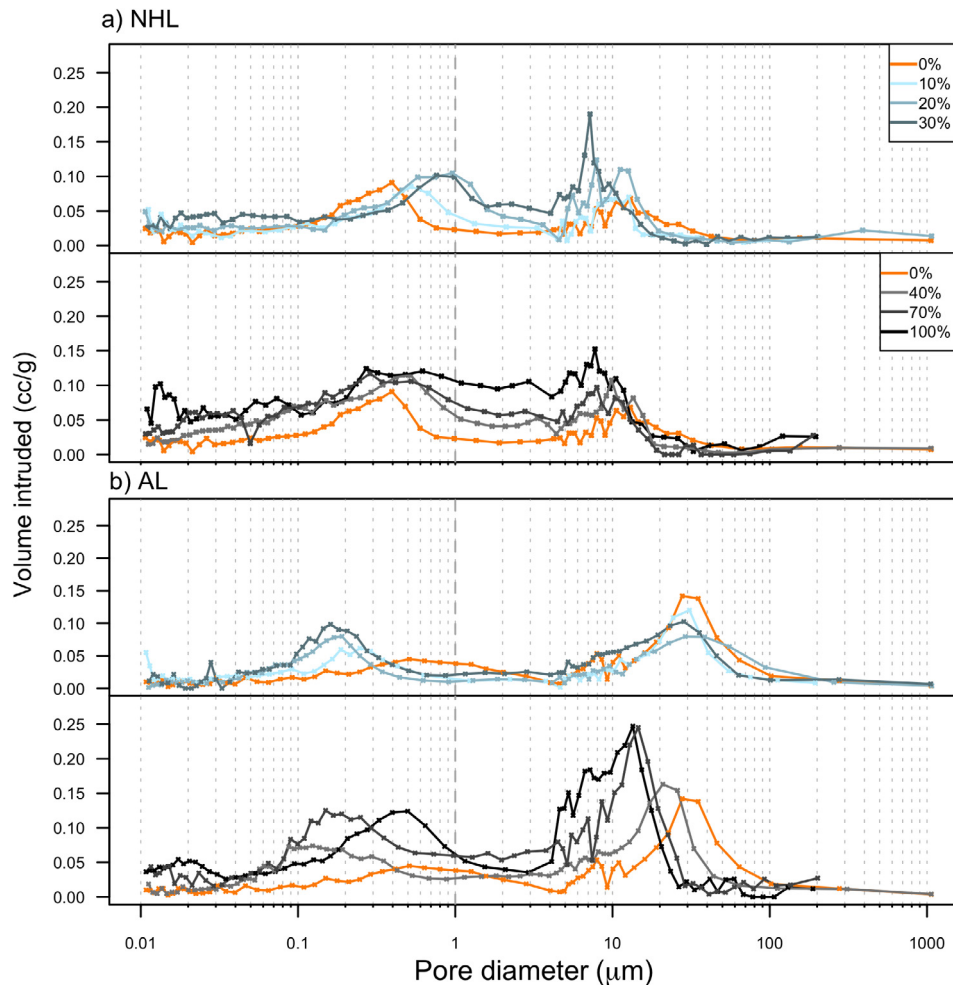


Fig. 3. Pore size distribution done with MIP of a) NHL mortars and, b) AL mortars. The dashed line represents the threshold between capillary pores (1–1000 μm) and smaller capillary pores (0.1–1 μm).

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 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.

Fig. 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 [7], 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 [46]. 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 cause dampness through a wall [5,6]. 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.

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 Fig. 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 [7], 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. 6a). AL mortars show a significant increase in compressive strength from about 20% wood ash content ($>2 \text{ N/mm}^2$) (Fig. 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

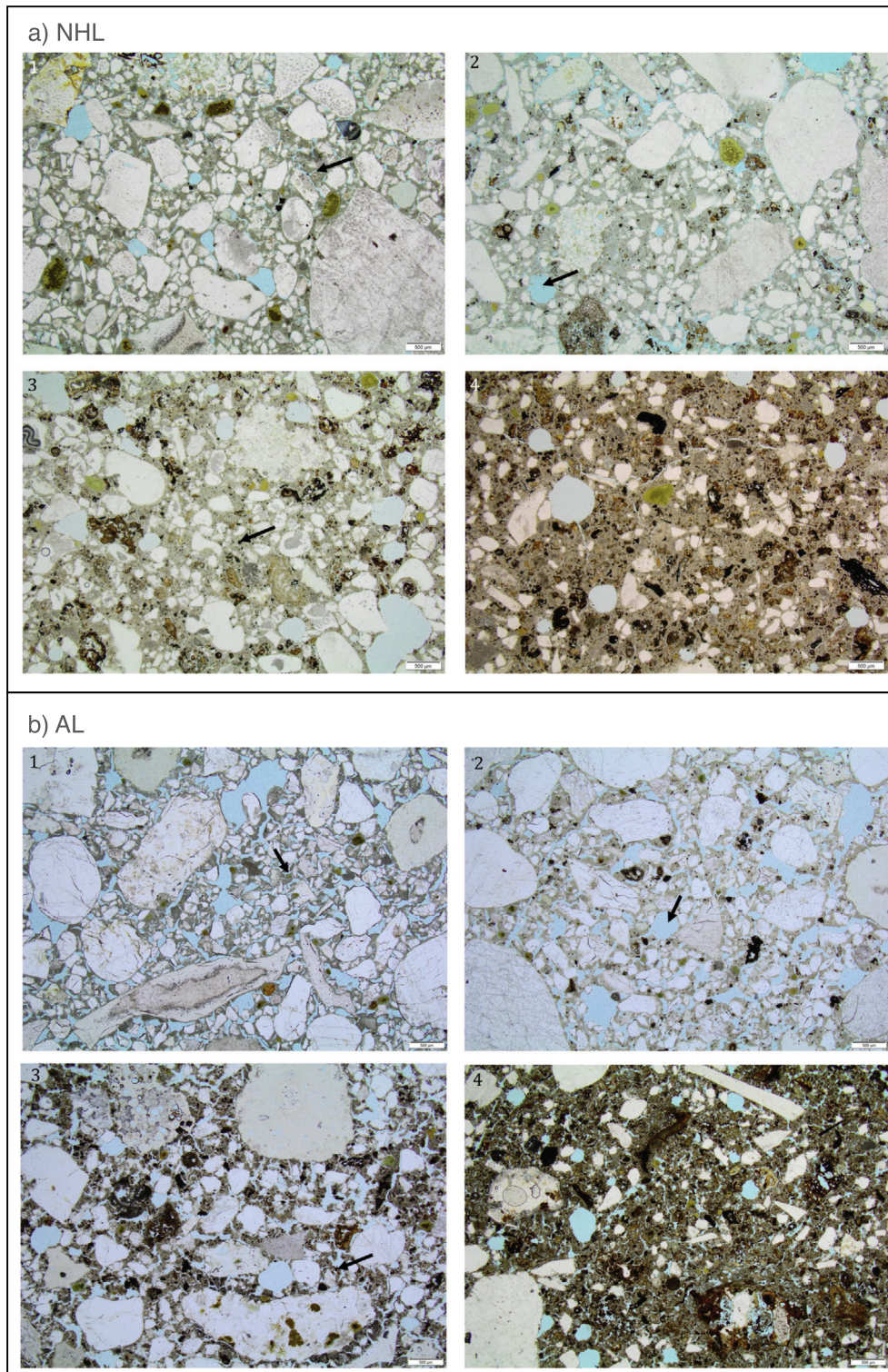


Fig. 4. Thin sections impregnated with blue resin showing the pore structure of mortars under petrographic microscope at $\times 4$ magnification. The scale bar is 500 μm . Mortars with a) NHL and b) AL mortars 1: 0% wood ash, 2: 20%, 3: 40% and 4: 70% showing a higher porosity as the wood ash content increases. Arrows point to shrinkage cracks (1), pores (2), and particles of wood ash (3). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

and 30% for AL, the lack of sand makes the compressive strength decrease (while still being higher than the control mortars).

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^2), oolitic limestones (between 20 and 80 N/mm^2) or traditional bricks [44]. 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 [47]. 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.

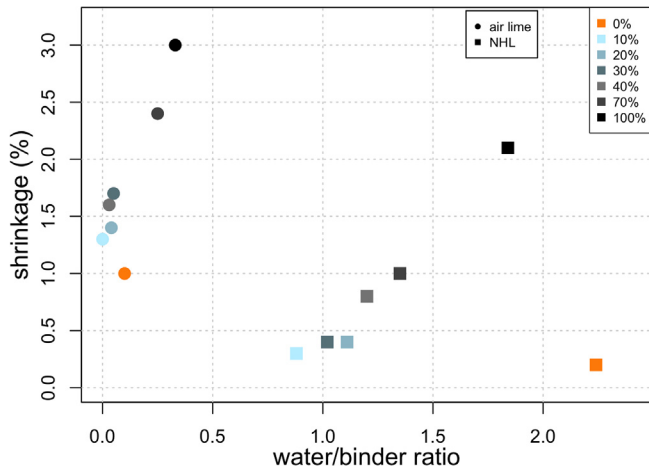


Fig. 5. Relationship between drying shrinkage and water/binder ratio of each mortar at 28 days, showing a clear link between the increase of wood ash and the water demands of the fresh mortar, correlated with higher shrinkage.

As previously stated, wood ash does not appear to qualify chemically as a pozzolanic material (Table 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 [48] or Chapelle test [28]. According to ASTM C618 [34] and BS 3892 [35], SAI over 0.8 indicates positive pozzolanic activity. Table 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). Pozzolanic materials have the ability to change the properties of a lime mor-

Table 4

Strength Activity Index (SAI) of mortars 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	/

tar, such as decreasing the setting time, and increasing the strength and durability [21]. Such properties could be beneficial for the long-term durability and in particular the ability of repointing mortar to set under damp conditions.

3.3. Water related properties

3.3.1. Water absorption and evaporation

The orange line in Fig. 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 (i.e. the material has the capacity to hold on to water). It can also be seen that samples with wood ash, except AL 10%, have a capillary saturation point delay by 15 min (Fig. 7a and c), 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 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

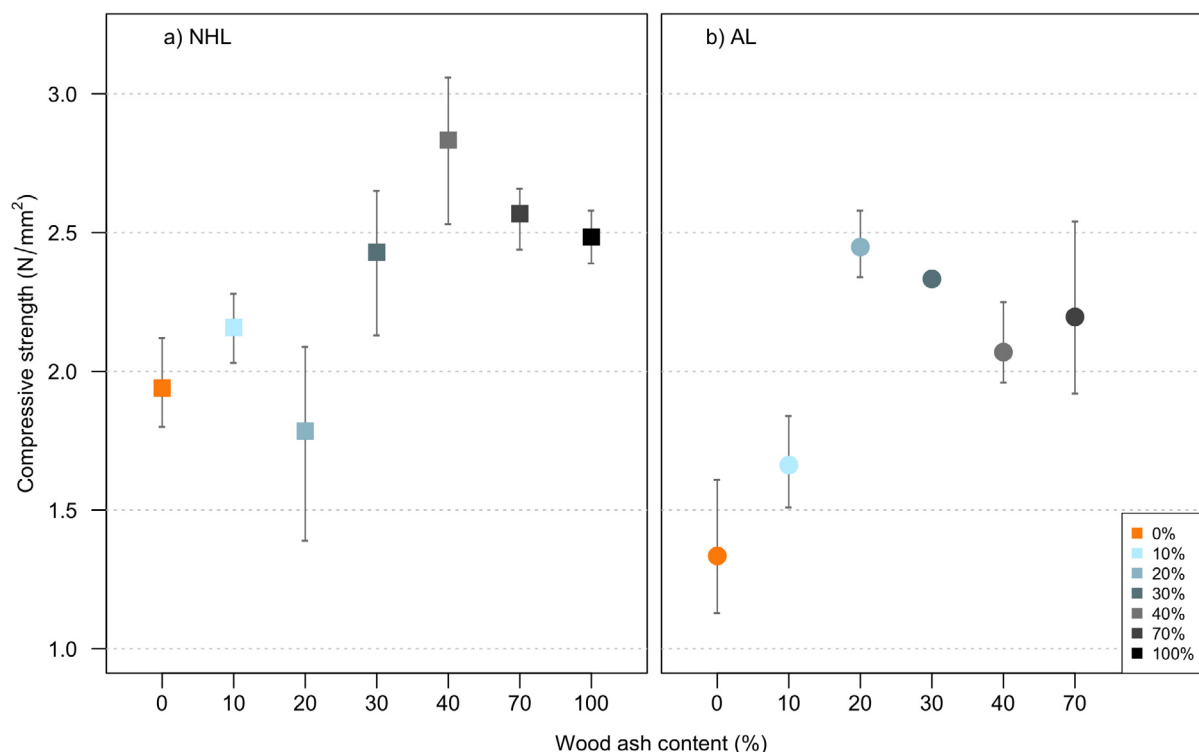


Fig. 6. Compressive strength (N/mm²) of a) NHL and wood ash mortars, and b) AL and wood ash mortars. The error bars show the maximum and minimum values.

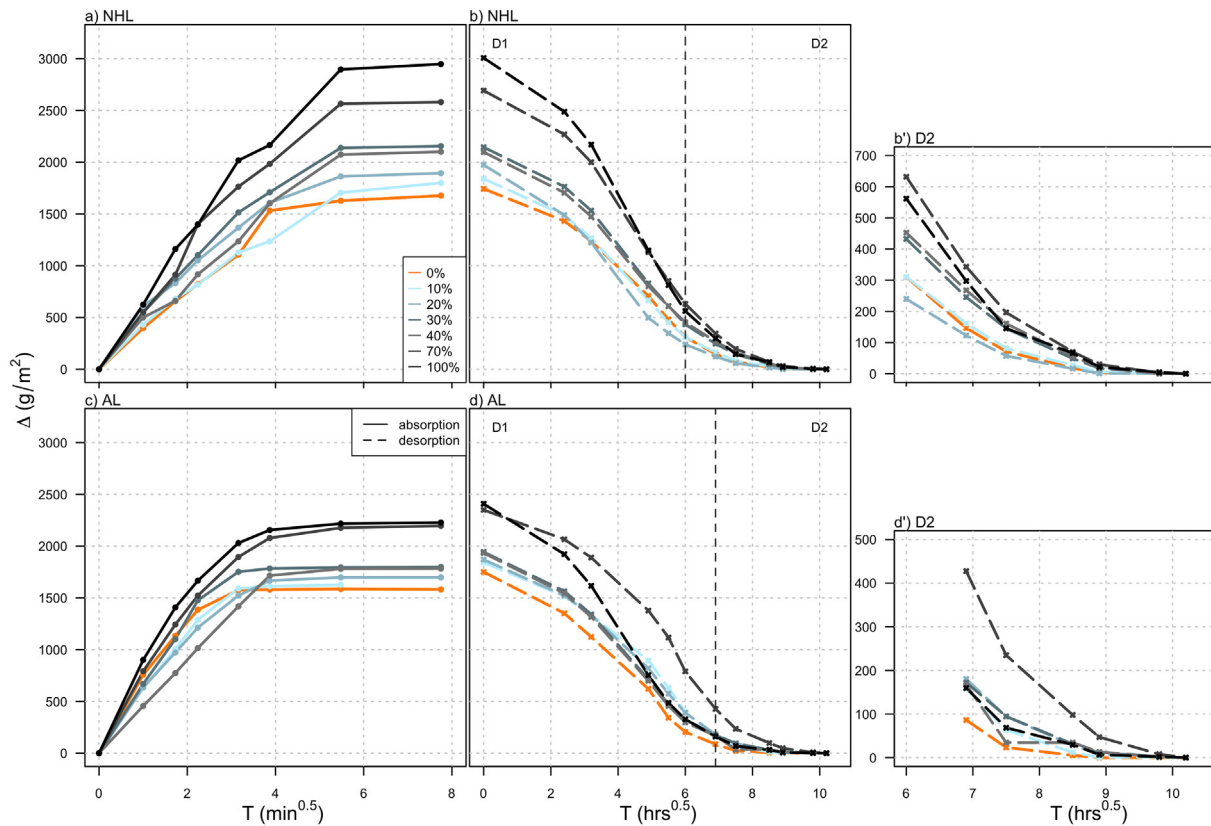


Fig. 7. Capillary absorption a) c) and desorption b) d) curves of NHL mortars a) b) and AL mortars c) d). The dashed line signals the end of the first phase drying (D1) until 6 and 6.5 h^{0.5} (30 and 36 h). b') and d') are zoomed in graphs of the relevant section (D2) from b) and d).

Table 5

WACC, drying rates (D1 and D2) and water vapour permeability of each mortar mix.

Mortar mixes		WACC (g/m ² .mn ^{0.5})		First drying rate D1 (g/m ² .h)		Second drying rate D2 (g/m ² .h ^{0.5})		Water vapour permeability (W _{vp}) (g/m.day.kPa)	
		mean	SD	mean	SD	mean	SD	mean	SD
NHL	0	377.83	±29.60	39.47	±3.80	66.85	±13.99	3.35	±0.45
	10	302.51	±3.01	42.58	±2.26	68.70	±7.14	3.27	±0.09
	20	336.46	±13.16	48.10	±1.40	52.78	±5.98	3.61	±0.12
	30	390.93	±6.64	47.80	±2.45	98.70	±11.46	3.84	±0.43
	40	379.05	±3.88	45.77	±3.48	104.80	±15.06	3.70	±0.43
	70	474.71	±7.93	58.04	±5.91	141.63	±43.52	4.51	±0.88
	100	529.14	±7.64	68.75	±2.87	123.55	±18.88	5.59	±0.82
AL	0	503.97	±23.62	41.91	±1.76	21.55	±5.74	2.79	±0.56
	10	508.86	±15.13	38.39	±1.98	42.36	±4.21	2.26	±0.51
	20	428.66	±12.15	40.16	±2.91	51.07	±11.43	2.97	±0.28
	30	477.56	±8.78	44.96	±2.05	49.40	±8.25	3.11	±0.30
	40	444.18	±3.12	45.16	±1.82	39.76	±7.73	2.54	±0.28
	70	533.51	±43.32	41.65	±4.92	121.99	±23.66	3.17	±0.14
	100	551.69	±38.82	58.54	±1.81	43.28	±2.37	4.34	±0.47

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. 7). This pattern relates to the clear increase in both the open porosity values (Fig. 2) and the higher proportion of capillary pores (Fig. 3) for both NHL and AL mortars from 70% wood ash.

AL mortars have much higher pore volumes in the larger capillary range (Fig. 3b), explaining the faster capillary water absorption than NHL mortars [41,44] (Table 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 tighter structure, higher proportion of capillary pores and hygroscopic properties of wood ash.

Fig. 7b and d show 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 Fig. 7a

and c. The two-phase drying was identified according to BS EN 16322:2013 [37]. The first phase drying (D1) for NHL mortars is shorter (30 h) than AL mortars (36 h). 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 5). A long first phase drying shows a high liquid conductivity [37] and is here also linked to the higher open porosity of wood ash mortars (Fig. 2).

D2 was calculated with square root of time as presented in Fig. 7b' and d'. 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 [44]. When constant mass is reached (at $9\text{ h}^{0.5}$, Fig. 7b' and d'), mortars with wood ash seem to retain slightly more water than the control mortars (they do not dry out as much as the control mortar), showing again the hygroscopic property of these ash mortars in the sense that wood ash holds on to water. 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.

3.3.2. Water vapour permeability

Water vapour permeability (Wvp) governs the movement of water vapour in porous materials [49,50] and, in this sense, allows the material to breathe [45]. It is an essential requirement for mortar in joints to help dry out the surrounding masonry units, where the liquid water has evaporated. Table 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 (Figs. 4 and 2). NHL mortars show a higher Wvp as they have higher volumes of small capillary pores (0.01 to $1\text{ }\mu\text{m}$) whereas AL mortars have finer capillary pores but at lower volumes (Fig. 5). Fig. 8 indicates that water vapour permeability is closely linked to other absorption and pore structure related properties. In NHL mortars, as Wvp

increased, WACC also increased, whereas less clear correlation is found in AL mortars (Fig. 8a). Similarly, good correlation is shown between Wvp and open porosity (Fig. 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.

3.4. Durability to Freeze-Thaw cycles

Fig. 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 5), and have overall higher water vapour permeabilities (Fig. 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 damage of the surface from 70% wood ash. Both effects are negative if the mortar is to be used in repointing.

4. Discussion

4.1. Effect of varying the amount of wood ash in different limes

Adding wood ash in a mortar 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%–40%) and high ash contents (70%–100%). As soon as wood ash is added, in comparison to control mortar, both mortar types (NHL and AL) present higher pore volumes in the capillary range ($1\text{ }\mu\text{m}$ – 1 mm) with fewer larger capillary pores and more

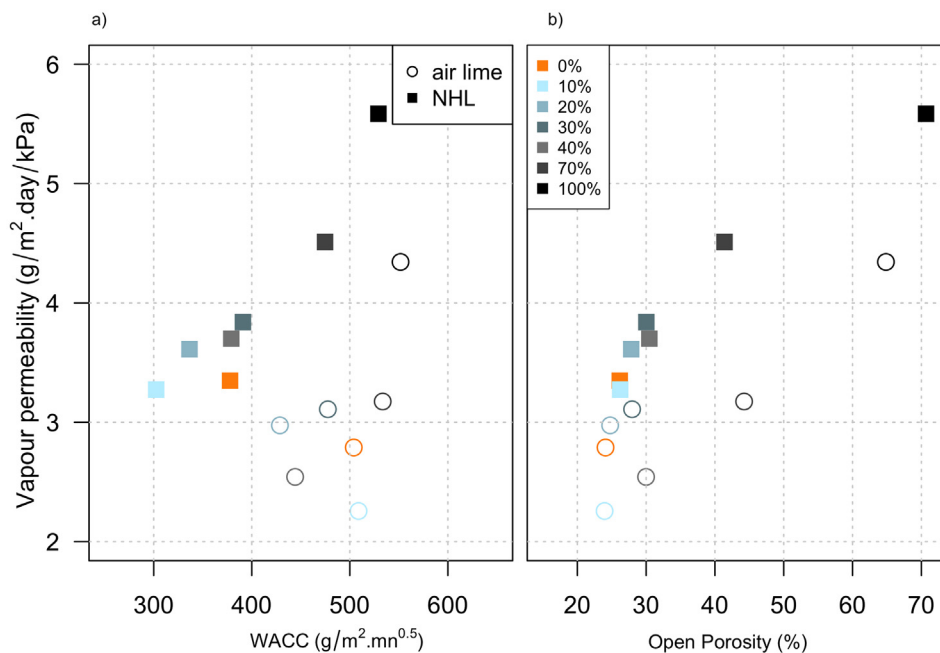


Fig. 8. Relationship between the water vapour permeability and a) the capillary absorption, and b) the open porosity.

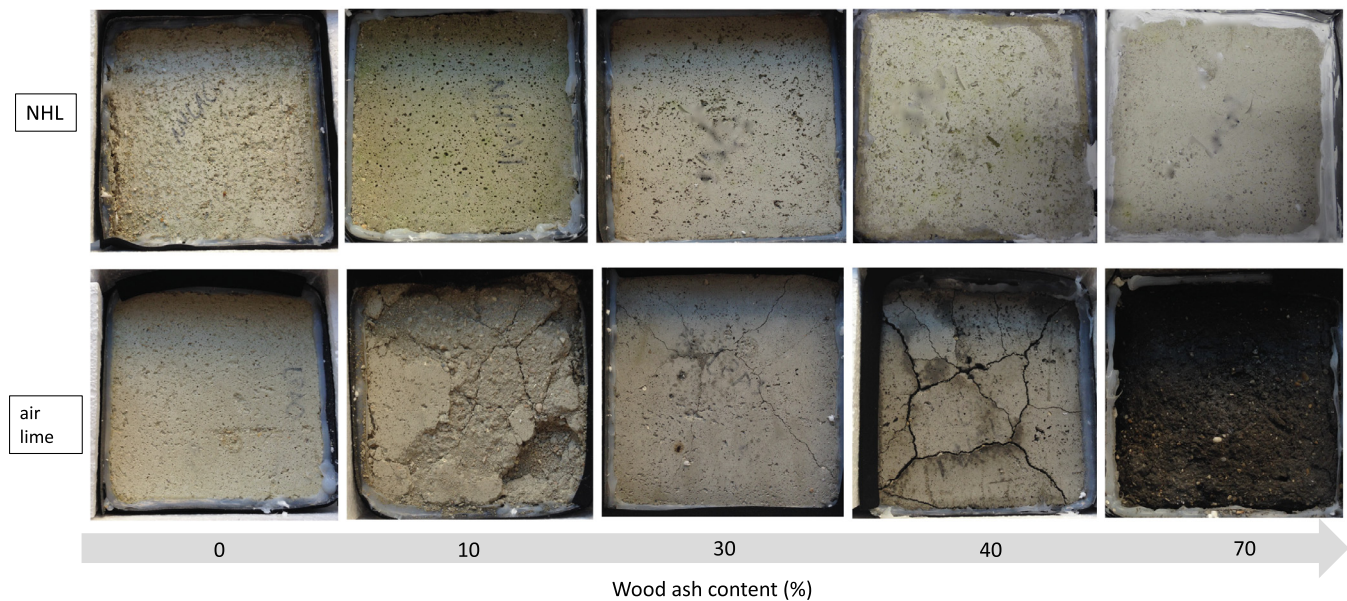


Fig. 9. Surface weathering after 32 freeze-thaw cycles. The test was also performed on 20% wood ash and 100% with similar results to 10% and 70%.

smaller ones, as well as a capacity to absorb and hold more water leading to delayed capillary saturation, in addition to higher open porosity and water vapour permeability and increased compressive strength. Low to medium amounts of wood ash (10–40%) 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 (70–100%), 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. 3b) [41]. However, NHL mortars have higher water vapour permeability, likely explained by the higher volume of smaller capillary pores (Fig. 3a). Overall, NHL mortars with wood ash seem more durable (less shrinkage and better ability to resist freeze-thaw) while having good permeability.

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, Fig. 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. 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. 5). In addition, finer particles increase the surface area in the aggregate, here the wood ash, in contact with lime [8]. 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 (SiO_2),

potassium oxide (K_2O), and aluminium oxide (Al_2O_3), even in small quantities, would react with the calcium hydroxide ($\text{Ca}(\text{OH})_2$) 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 [51,52]. In general, natural organic additives have been found to form an increased bond between the additives and the lime [23,24]. Previous studies have also demonstrated that organic additives are distributed differently in AL and NHL binders [22] but this was not noticed here. In this research, the strength activity index, based on increase of compressive strength, has shown a potential positive pozzolanic activity (Table 4). Other research has found that ash materials (biomass fly ash and fly ash) in mortars were also reactive [28]. 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 [28].

Furthermore, these fine particles contribute to the formation of a dense pore structure as the content of wood ash increases (Fig. 4), this means that the lime 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 ($1\text{ }\mu\text{m}$ – 1 mm) (Fig. 3). The higher volume of capillary pores are responsible for the higher water 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. 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. 5) which has a direct impact on the open porosity and drying shrinkage.

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.

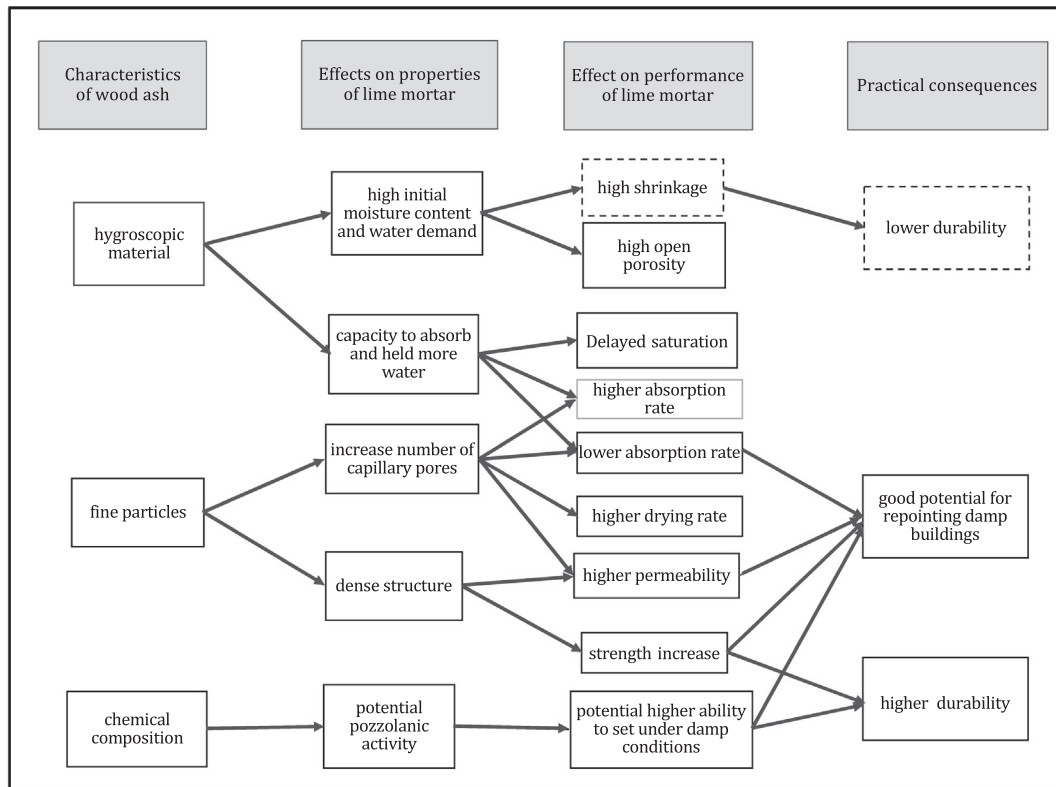


Fig. 10. Flow chart of the relationship between the characteristics of wood ash and the property and performance change observed in lime mortars with wood ash, leading to practical consequences. The dashed box relates to AL mortars and the light grey box to high ash content mortar (70–100% wood ash).

In general, the mortar joints should be more permeable than the masonry to promote drying, and help soluble salts migrate out through the mortar [53]. 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 [54]. Wood ash mortars have been shown to increase both the water vapour permeability and drying and evaporation ability of both mortar types. In addition, 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. Indeed, 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 [5,6]. Therefore, high concentration of wood ash as additives should be avoided for both AL and NHL binders. 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 [2,3]. 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 those 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. Fig. 10 shows the link between the necessary criteria for a good repointing mix and adding wood ash in lime mortar mixes. In practice, fresh mortar made 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. 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 sustainable construction and reuse of waste material, a mortar with up to 40% of aggregate replacement with a waste product such as biomass wood ash would be sustainably highly beneficial.

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 NHL 30%) 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 water vapour permeability, correlated with the amount of wood ash in the mortar mix.

- The tighter structure of lime and wood ash increases the compressive strength. The fine particles given by the wood ash could also 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.

Conflicts of interest

None.

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