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RILEM TC REPORT

RILEM TC 277-LHS report: How hot are hot-lime-mixed mortars? A review

S. Pavia · R. Veiga · J. Hughes · G. Pesce · J. Valek · J. I. Alvarez · P. Faria · A. Padovnik

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Abstract It is believed that many historic mortars were made using hot-lime mixing techniques. They are back in use today, and their good qualities are often praised, including being more compatible and a better match with historic fabrics. This paper studies the methods of producing hot-lime mortars and putties. It discusses the variables that determine the properties of the resultant mortars such as slaking and calcination, and compares hot-lime mortars with their equivalent putties, and with factory-produced calcium lime and hydraulic lime mortars. The paper concludes that the most important variable that governs the properties of hot-lime mixed mortars is the quantity of water used for slaking, because it determines the temperature reached during slaking which makes the resultant $Ca(OH)_2$ vary from a fairly large size to extremely small, hence producing mortars with different properties. Based on scientific and historic evidence, it is concluded that the best method for hot-lime mixing is dry-slaking (sand-slaking) with long storage, because it combines a high slaking temperature (that reduces particle size and increases the surface area of the hydrate), with gradual slaking (that lowers volume expansion and crack development) and long storage (to ensure complete slaking hence no expansion cracks). Many historic mortars were probably hot-lime mixed. However, it is practically impossible to recreate them today due to the different limestones, kilns, calcination regimes and slaking/storage methods used in the past. Hydraulic and magnesian quicklimes were used historically for hot-mixing. In contrast, most of the factory quicklimes used today are purer limes with higher free lime

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Chair Ioanna Papayianni.

Deputy Chair Jan Valek.

Members Jose I. Alvarez, Beril Bicer-Simsir, Violeta Bokan-Bosiljkov, Claudia Brito De Carvalho Bello, Arnaldo Manoel Carneiro, Paulina Faria, Liberato Ferrara, Caspar J.W.P. Groot, Davide Gulotta, Hande Gunozu Ulusoy, John J. Hughes, Ioannis Ioannou, Heejeong Kim, Loucas Kyriakou, Cristiana Lara Nunes, Pagona Maravelaki, Sagrario Martinez-Ramirez, Vasiliki Pachta, Andreja Padovnik, Chiara Pasian, Giovanni Pesce, Ulrike Peter, Meera Ramesh, Divya Rani, Sara Pavia, Sriram Pradeep Saridhe, Michele Secco, Maria Stefanidou, Cristina Tedeschi, Magdalini Theodoridou, Lucia Toniolo, Rob Van Hees, Rosario Veiga, Anna Arizzi, Kali Kapetanaki, Didem Oktay and Petra Stukovnik.

S. Pavia (✉)
Department of Civil Engineering, Trinity College Dublin,
Dublin, Ireland
e-mail: pavias@tcd.ie

R. Veiga
Buildings Department, National Laboratory for Civil
Engineering–LNEC, Av. do Brasil 101, 1700-066 Lisbon,
Portugal
e-mail: rveiga@lnec.pt

content and a greater reactivity. Therefore, a hot-lime mix made with a factory-produced quicklime may not be more authentic or compatible than a natural hydraulic lime –NHL– mortar designed to suit a specific fabric and application. To ensure quality mortars that can be consistently repeated, a hot-lime mixing specification should contain both the process and the materials including: type of slaking (dry/wet); amount of water used; mixing details and the time at which it takes place; storage time and at what stage does it occur. To control the slaking temperature, the right amount of water should be established (according to free lime content) by trial which will also inform on the amount of yield and hence allow proportioning. With careful site work and specification, high-quality, compatible mortars can be made with both NHLs and hot-lime mixing. However hot-lime mixing requires more time and logistics, closer care and a more complicated specification.

Keywords Hot-lime-mixed mortars · Slaking · Calcination · $Ca(OH)_2$ · Hydraulic lime

1 Introduction

1.1 Context and aim of the work

Within the framework of the activities of the RILEM TC 277-LHS “Specifications for testing and evaluation of lime-based repair materials for historic structures”, one of the requirements is to revise the aspects related to the production of limes and lime-based binders, to review production methods and stardardise them or propose modifications. A group of target binders are hot-mixed lime mortars.

Hot-mixed lime mortars are prepared on site by mixing quicklime with sand and water so that the exothermic reaction of lime slaking takes place during mixing. Some authors state that 90% of the mortars used in the past in exterior applications, up to the 1950s, were probably hot lime mixes, and hence they are a more authentic replication, and probably better compatible with historic fabrics, than the restoration mortars used in the last decades which are mainly made with factory produced NHLs or CLs in the form of dry hydrates or putties (BLFI [1–5]. As a result, there has been a revival of hot lime mixing.

This article reviews, based on scientific literature and the authors’ practical experience, the methods used to obtain hot lime mortars and putties. The factors that influence the performance and characteristics of the resulting mortars, such as slaking and calcination, are particularly discussed. Furthermore, this review report carries out a comparison of hot lime mortars with their equivalent putties and with industrially produced calcium and hydraulic lime mortars.

1.2 Terminology and production methods of hot-lime binders

In hot-lime mixing, there is some confusion on both the production methods and the terminology. The

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J. Hughes
School of Computing, Engineering and Physical Sciences,
University of the West of Scotland, Paisley,
Scotland, UK
e-mail: john.hughes@uws.ac.uk

G. Pesce
Department of Architecture and Built Environment,
Northumbria University, City Campus, Sutherland
Building, Newcastle upon Tyne NE1 8ST, UK
e-mail: GIOVANNI.PESCE@NORTHUMBRIA.AC.UK

J. Valek
Institute of Theoretical and Applied Mechanics, Academy
of Sciences of the Czech Republic, Prosecká 809/76, 190
00 Praha 9, Czech Republic

J. I. Alvarez
Materials and Cultural Heritage, MATCH, Research
Group Department of Chemistry, School of Sciences
University of Navarra C/Irunlarrea, 1, 31008,
Pamplona, Navarra, Spain
e-mail: jalvarez@unav.es

P. Faria
CERIS and Department of Civil Engineering, NOVA
School of Science and Technology Universidade NOVA
de Lisboa, 2829-516 Caparica, Portugal
e-mail: paulina.faria@fct.unl.pt

A. Padovnik
Faculty of Civil and Geodetic Engineering, University of
Ljubljana, Ljubljana, Slovenia
e-mail: andreja.padovnik@fgg.uni-lj.si

terms hydration and slaking are frequently used indiscriminately. Technically, hydration involves mixing lime with water in a ratio that will yield a dry powder, whereas slaking of lime requires the use of water in a ratio of 3:1 or more to produce a wet hydrate. Both slaking and hydration produce an exothermic reaction, but the temperature of the wet hydrate is depressed by the excess of water. In this paper, slaking quicklime with moisture and wet sand, in a ratio that will yield a dry mix is called **dry slaking**, and slaking with water is called **wet or water slaking**. Wet slaking with little water can produce hot-lime mortars but using a water excess turns the quicklime into a putty. In theory, only the quicklime slaked with sand (dry-slaking) should be referred to as hot-lime, because when adding water, the temperature of the quicklime-sand mix drops, and unless the quicklime is very reactive, the mortar may not get hot.

There are several methods to produce hot-lime mixed mortars. They feature different slaking and mixing methods and storage. Below, modern production methods are compared with historic narratives. According to modern accounts, two methods are followed today (BLFI [1, 2].

i. *Wet slaking* In this method (also known as hot-lime mixes) the sand and the quicklime are mixed dry and then water is added. Sufficient water is needed because the quicklime rapidly takes water which can cause overheat. However, too much water reduces the heat of reaction, and can lead to the mortar being over-wetted (or drowned). The mortar can be then used while the quicklime has largely slaked but the mortar is still hot, or it can be stored for later use.
ii. Dry slaking (also known as sand-slaking). Quicklime and wet sand are mixed and stored to allow the quicklime to slake by taking moisture from the wet sand and the air. Slaking is slower, and the resultant dry mix can be sieved to remove any lime particles, and then either stored or mixed with water and worked into a mortar. The mortar is normally stored covered with waterproof sheeting and left to mature (for days, weeks or months) after which it is 'knocked up' and used.

Today's methods generally agree with historic methods reported in the literature. Figure 1 illustrates the stages involved in the current method of hot-lime mortar mixing in Slovenia. However, slaking techniques vary in different countries. Historically, dry-slaking was favoured in Spain, Portugal, Italy and China. Quicklime was sprinkled with water several consecutive times, followed by turning and beating. During the process the lime pulverized, and then the lime mounds were covered and left to mature [6, 7]. According to these authors, the mounds were watered on the surface,this makes a crust that protects the material which can be stored for years without losing quality. The mortar was cut from the mound as required by the work. Close to the mound, it was battered well with water until a workable mix was produced. Similarly, in Portugal, the traditional method involved first slaking lime with wet sand for some time, re-wetting the sand until slaking was finished. Then, the minimum water necessary to obtain a workable mortar was added (Veiga pers.com. 2021). According to Margalha et al. [8] the wet lime/sand mix was stored wet for as long as possible. Spanish historic accounts refer to other places in Europe, where lime was slaked with a water excess into a putty and then used for mortar making: ponds were dug on the ground, walled and half-filled with water, and the quicklime was then thrown in (either as lumps or powder) and the resulting mix later sieved. 'However, the lime is of lower quality than ancient Roman materials because of the excessive water with which it is slaked' [6, 7]. The best performance of dry-slaking can be explained with Miller's work [9], who demonstrated that the development of surface area of the $Ca(OH)_2$ is a function of the final slaking temperature: higher ratios of water result in lower final temperatures which produce hydrates with low specific surfaces, and lower water ratios result in higher temperatures and high specific surfaces. The effect of the specific surface area of the $Ca(OH)_2$ crystals (determined by their micrometric or sub-micrometric size) on plasticity and reactivity was also analysed by Rodriguez-Navarro et al. [10] and Cazalla et al. [11].

The superior performance of dry-slaked quicklimes (sand-slaked hot mortars) has been demonstrated in the laboratory. Dai [12] slaked a hydraulic quicklime in three different ways: Wind slaking (or dry-slaking) (quick lime left outdoor in an open shed at 50–95% RH), water slaking (adding excess water and the putty stored for 15 days) and

Fig. 1 Stages involved in the current method of hot-lime mortar mixing in Slovenia

(a) Half of the sand is spread on the ground and covered with crushed quicklime. The volume ratio of quicklime to sand is 1:7-9.

(b) The layer of quicklime is then covered with a second layer of sand.

(c) Water is sprinkled to initiate slaking.

(d) The assemblage slakes for three or four days covered with fabric.

(e) The mortar is prepared with the cooled, slaked lime. When preparing the mortar, the masons shovel across the pile to pick up all the layers.

(f) Finally, standard mixing is carried out in a paddle or drum mixer, and water is added to achieve the desired consistency.

mist spray (1.3 times the theoretically calculated water is sprayed in one day and stored for 15 days). The dry-slaked lime had the highest strength (1.5 MPa at 28 days) and much shorter setting time (3–8 h *vs* 168 h for the water-slaked and 27 h for the mist-slaked). The strength of lime slaked by wind was similar to the NHL2 in EN-459. Pesce et al. [13] slaked pure quicklime with steam at 99 °C compared it to equivalent putties (wet-slaked with water at 20 and 75 °C). The authors found that the dry-slaked lime produced a smaller hydrate and mortars with higher water retention and flowability and slower carbonation than the putties.

In China, the standard historic method was dry-slaking, known as 'wind slaking' [12]. Dai states that at least from the Song Dynasty (from 960 AD) to the end of the Ming Dynasty (seventeenth century), quicklime was predominately dry-slaked with sand,

and only in the case of urgency the lime was wet slaked into a putty. The author includes accounts of ancient dry and wet slaking from the Handbook for Materia Medica written by Su Song c. 1061 AD. Here, the author refers to two kinds of lime: 'lime slaked by wind'(风化) and 'lime slaked by water'(水化): … 'lime slaked by wind means that the quicklime is left under wind and disintegrates automatically. The lime slaked by wind is strong. Lime slaked by water means to pour water onto the quicklime and the quicklime disintegrates by steam. The lime slaked by water is weak'. Dai [12] also includes details of slaking from the book of Heavenly Creations, written by Song Ying-Xing c. 1587. According to the author: For masonry, 'wind slaked lime was firstly sieved, then mixed with water with no additions… The lime produced by this method was very durable and could be used even against seawater erosion'.

Finnish accounts refer to both dry-slaking and putty making as follows: there were several methods of slaking lime. Traditionally, the lime was slaked in pits with abundant water where it was stored from 1 to 10 years. Alternatively, lime could be coated with a thick layer of sand and left over a period of time to naturally slake under the effects of rainfall and atmospheric moisture, or by pouring water over the sand. In some cases, the lime was slaked by air slaking -dry slaked- (or wet slaking) just 2 weeks to 3 months prior to the preparation and use of the mortar [14].

In France and Britain, it seems that both wet and dry slaking methods were used [6, 7]. Vicat [15] also states, that the quicklime loses properties when slaked with water excess and made into a putty. He refers to three slaking methods: slaking by immersion, dry-slaking ('spontaneous') in the air and ordinary extinction. Ordinary extinction uses a 'proper' quantity of water that is often misjudged and the lime drowned. Vicat says that spontaneous extinction is more suitable for the pure calcium limes than for the hydraulic ones.

Foster [16] refers to historic versions of dry slaking by Rivingtons (1875) as follows: a quantity of the quicklime is measured out, and enough water to slake it is sprinkled over it. The heap of lime is then covered over with the quantity of sand required to make the mortar,this keeps in the heat and moisture, and renders the slaking more rapid and thorough. In a short time, varying according to the nature of the lime, it will be found thoroughly slaked to a dry powder. According to Hughes and Taylor [17], the British Codes of Practice published in 1951 specified a hot mix method that also refers to dry-slaking, and involves pre-hydration of hydraulic limes, mixed with wet sand for > 24 h before mixing.

Dry-slaking is difficult to control and needs more time than wet slaking. Dai [12] showed, using the soundness test, that dry-slaked mixes required from 21 days (open air) to 40 days (indoor) to complete slaking so that the mortar can be safely used without expansion cracks. Time is needed to ensure full slaking and avoid late hydration and consequent cracking. It has been known for thousands of years that long storage improves the quality of the resultant hydrate and the properties of the mortars. A 6-month storage period is often advised by practitioners today. However, the Romans advised up to 3 years [18]. A standard storage time does not exist due to the varying composition of the parent limestone and different calcination conditions, but the common belief is that, in general, the longer, the better, because ageing completes slaking and reduces the size of the hydrate increasing its surface area which can enhance carbonation and strength, and improve viscosity and workability. This has been proven experimentally. Rodriguez-Navarro et al. [10] demonstrated that better workability with longer maturation time is strongly related to the decrease in size and change of morphology of the hydrates. Margalha et al. [8] evidenced that longer slaking improves plasticity, so that the mortar requires less water to achieve a workable consistency. They also found that longer slaking improves strength, and that the maturation time has a very positive influence on flexural and compressive strength, cracking susceptibility and water absorption by capillarity.

2 Characteristics of hot lime mortars reported by former authors and practitioners

Some characteristics are based on site observations, and the fact that the heat released on slaking enhances the lime mortar properties and structure. Hot lime mortars are reported to provide an early stiffening, enhanced bond and workability and improved microstructure and frost resistance (BLFI [1] and

[19], Hunnisett [2–5, 20]. The characteristics of hot-lime mortars stated by these and other authors are summarised below. Hot-mixed lime mortars take up water rapidly as they slake. The heat makes them stiffen faster than bagged NHL mortars or putty mixes [3]. This allows building to faster progress, and the wall can be built higher without mortar squeezing out through overhead weight (BLFI [1]. Masons claim that hot lime mortars produce better quality and cleaner work because the expansion of quicklime on slaking fills joints and reduces the risk of slumping and leaching, and it fills voids improving microstructure and lowering shrinkage so that binder-rich mortars with no retraction can be produced. Practitioners have also reported that they can be used with wet stone and sands in unfavourable weather conditions. It is also argued that the heat generated on slaking causes pore interconnectivity and air entrainment, enhancing microstructure and resistance to frost,that moisture displaced on slaking draws binder to the masonry interface enhancing adherence,that the slaking heat would promote the pozzolanic reaction, should any pozzolans exist, and that the heat (in the alkaline lime medium) can etch the aggregate's surface increasing adhesion (Foster [16, 21]. However, as seen above, the different methods of hot-lime mortar making differ in slaking, mixing and storage methods: hot-lime mortars can be either dry or wet slaked, hence reaching variable slaking temperatures that produce different hydrates, and hence uneven materials. In addition, they can be applied either hot or cold, and can be either stored for some time or not stored at all. These production variables can vary the properties of the resultant mortar.

Finally, it has also been stated that the expansion of lime on slaking can economise raw materials and that quicklime is generally cheaper than NHLs or other proprietary lime products. However, hot lime mixing requires close care and long time periods which are expensive in the twenty-first century. They may also require storage facilities and protection that increase cost. Furthermore, rich-lime mixes require abundant raw materials that can be impractical to transport. However, the environmental impact of hot-lime mixes should be explored, as the lack of industrial hydration/slaking and milling processes that are energy demanding can possibly raise their environmental credentials.

3 Discussion: variables and uncertainties in hot-lime mortar mixing

3.1 Slaking

The quantity of water employed in slaking the lime exerts a powerful influence on the quality of the hydrate [15].

The reaction between CaO and water takes place according to the equation below:

$$\begin{aligned}&\mathrm{CaO} + \mathrm{H_2O} = \mathrm{Ca(OH)_2} + 65.3\,\mathrm{kJ/mol}\\&56\ \mathrm{gmol} + 18\ \mathrm{g/mol} = 74\ \mathrm{g/mol}\\&(\text{atomic weight of Ca} = 40;\ \mathrm{O} = 16;\ \mathrm{H} = 1)\end{aligned}$$

Therefore, slaking liberates 65.3 kJ of heat for each mol of CaO. This heat is sufficient to raise the temperature of 88 kg of water from 21 to 100 °C during slaking of 25.4 kg of CaO [9].

According to the reaction, 1 kg of CaO+0.32 kg water produces 1.32 kg of $\mathrm{Ca(OH)_2}$. This reaction means that, in theory, if the quicklime was pure CaO, the amount of water that must be added to change all the quicklime into a hydrate is 32% of the weight of the quicklime. However, limestones are always impure, and hardly fully and evenly burnt. The amount of impurities reduces the water required for slaking [22]. Therefore, hydraulic and magnesian quicklimes need less water to slake. The impurities also reduce the volume expansion on slaking. Magnesian and hydraulic limes take longer to slake than pure limes, with less heat evolution and less expansion [22]. In addition, if all the water needed for slaking is added at once, expansion is much greater than when added gradually [22]. The heat released on slaking sets the temperature of the slaking process. Miller [9] demonstrated that the temperature reached in the slaking process varies greatly (from 13 to 105 °C) depending on the water/CaO ratios and initial water temperature (Table 1).

The authors also demonstrated that the time for the slaking to be completed greatly varies depending on the solid concentration and the initial water temperature (Table 2). An increase in water ratio at a given temperature increases the slaking time, but an increase in the initial water temperature at a given concentration decreases the slaking time [9].

Finally, Miller [9] measured the surface area (and corresponding particle diameter) of the hydrate

Table 1 Temperatures reached during slaking when using different water/CaO ratios and water at varying initial temperatures [9]

Water/CaO	Initial temperature of slaking water				
	4 °C	10 °C	20 °C	40 °C	60 °C
2.5	105	90	100	100	100
7.5	37	36	43	63	82
10.5	28	29	38	58	77
13.3	22	25	34	54	69
18.0	18	21	30	50	69
25.0	13	19	27	48	65

Table 2 Slaking time (minutes) for quicklime with various amounts of water at various temperatures [9]

Water/CaO	Initial temperature of slaking water					
	4 °C	10 °C	20 °C	40 °C	60 °C	90 °C
2.5	4	3	6	1	2	1
7.5	8	16	7	3	2	1
10.5	18	20	7	4	2	1
13.3	13	23	8	4	2	1
18.0	14	20	7	4	2	1
25.0	18	12	8	4	2	1

produced with varying slaking conditions (Table 3). They demonstrated that low water ratios produce higher reaction temperatures and $Ca(OH)_2$ of high specific surface area. They also evidenced that the surface area of the hydrate widely varies from a low 15,314 cm^2/g to a high 58,300 cm^2/g (Table 3). As it can be seen from Table 3, using water at 10 °C, the SS of the resultant $Ca(OH)_2$ varies greatly with changing water/CaO ratio, from 54,293 to 18,597 cm^2/g. When the initial water temperature increases, the SS variation becomes smaller. However, using slaking water at the ambient temperature of 20 °C, the variation in SS is still very high (52,790 to 29,405 cm^2/g with corresponding particle diameters of 0.50–0.90 microns).

Hassibi [23] states that, theoretically, the closer the slaking temperature is to 99 °C the finer the particle sizes and greater the specific surface of the hydrate, but at these high temperatures, hot spots can develop which will cause hydrates to crystallize and agglomerate forming larger particles with reduced specific surface, hence, in practice, slaking temperatures around 76 °C are better for optimum operation. In an industrial process, the conditions are set to produce a slaking temperature under 100 *°C* that ensures a high specific surface in the resultant $Ca(OH)_2$. However, onsite, this is impossible to control.

The importance of the slaking temperature has been highlighted experimentally. Pesce et al. [13] slaked two limes with water at 20 and 75 °C to produce putties and compared them with a dry-slaked lime, slaked with water vapour at 99 °C. They found that in the steam-slaked the resultant hydrate was smaller than in the putties, and the steam-slaked mortars had higher water retention and flowability and slower carbonation. Malinowski and Hansen [21] sand-slaked (dry) and wet-slaked (to putty) feebly hydraulic quicklime, and compared the resultant mortars. The sand-slaked mortar, after one year of curing in situ, was slightly harder than the putty mortar, despite the slower carbonation. The sand-slaked mortar had higher strength (as measured with the rebound test), slightly higher density, lower total

Table 3 Specific surface (SS) of $Ca(OH)_2$ produced when slaking CaO with various water ratios at different temperatures [9]. Ø= calculated particle diameter (microns)

Water/CaO ↓	Initial temperature of slaking water											
	4 °C		10 °C		20 °C		40 °C		60 °C		90 °C	
	SS (cm^2/g)	Ø (μm)	SS (cm^2/g)	Ø (μm)	SS (cm^2/g)	Ø (μm)	SS (cm^2/g)	Ø (μm)	SS (cm^2/g)	Ø (μm)	SS (cm^2/g)	Ø (μm)
2.5	50,736	0.53	54,293	0.49	52,790	0.50	56,606	0.47	57,355	0.46	58,300	0.46
4.5	–	–	–	–	48,307	0.55	–	–	52,260	0.51	55,255	0.48
7.5	35,246	0.76	34,534	0.77	–	–	47,035	0.57	49,183	0.54	53,070	0.50
10.5	29,133	0.91	29,840	0.89	–	–	45,203	0.59	48,920	0.54	51,126	0.52
13.3	23,166	1.15	24,419	1.09	36,520	0.73	41,080	0.65	45,967	0.58	52,658	0.51
18.0	17,833	1.49	18,968	1.40	31,556	0.84	37,620	0.71	48,307	0.55	53,925	0.49
25.0	15,314	1.74	18,597	1.43	29,405	0.90	40,910	0.65	48,244	0.55	53,295	0.50

porosity, and a higher volume of air voids than the putty mortars.

Furthermore, there are additional factors that affect the specific surface of the calcium hydroxide resulting from slaking, such as the degree of agitation during slaking and the slaking time. Agitation must be provided to prevent local overheating of CaO and to assure that each particle of lime is supplied constantly with water to carry out the entire hydration reaction [9]. To slake a hard-burned lime, the outer layer of the particle must wear off to open the pores for water to penetrate. This is done by vigorous agitation that abrades the outer layer of CaO. This type of lime generally requires more retention time in the slaker [23]. The slaking process is so hard to control, even in industrial environments, that Brooks and Davis [24] envisaged a patent that allowed to ensure the quality of the hydrate by measuring the temperature reached on slaking: ‘It has been found that regardless of the variations in the characteristics of the quicklime, the resulting hydrate is of constant good quality if the lime is slaked in accordance with the temperature’.

Therefore, slaking is an important process in hot-lime mixing that is hard to control on site: the quantity of water controls the slaking temperature which determines the surface area and size of the hydrate, which rules the properties of the resultant limes and mortars. The temperature reached during slaking, the water/CaO ratio and the initial water temperature rule the thermodynamics of the slaking reaction, making the resultant $Ca(OH)_2$ vary from fairly large to extremely small [9]. As aforementioned, this has been known since antiquity, and it is the reason for the storage of limes and for the occasional preference of dry-slaking over water-slaking in historic times.

3.2 The burning of the lime

Even if historic lime mortars were hot-lime mixes, they would be hard to replicate today because quicklimes currently used for hot-mixing are factory-produced, hence burned for a standard time at a temperature usually higher and more consistent than in traditional kilns. Today, many quick limes are burned at around 1000 °C—hard-burnt [25]. Currently, only in Ireland and the UK, there are five commercial quicklimes in pellet, granulated and powdered form, classified as CL90 (EN 459:1), which have been used to produce modern hot-lime mortars (BLFI [1].

On the contrary, in the past, lime calcination varied depending on the local limestone and the available fuel, and calcination temperatures were generally lower than today, and uneven in the different kiln areas [26]. The authors provide an account of historic lime burning in Ireland: ‘lime was burned all over the country, in kilns of different size, with burning conditions varying depending on the limestone and fuel locally available’. The authors cite different fuels that would have rendered different temperatures and dwelling times over the burning process: ‘In Dublin, coal was used to burn the local Calp limestone. Coal was also used in Boyle, Co. Roscommon and in County Leitrim. In County Galway, different fuels were used, for example, in Ballinasloe and Clifden, mainly turf was used whereas in the city of Galway, English and Scotch coal were imported for lime burning'.

It has been proven experimentally that the quality of the lime produced in traditional kilns is subject to variability which depends on the type of fuel, the size of rock fragments used as kiln feed, the ratio of stone to fuel and the arrangement of the burning layers [27]. The authors carried out calcination experiments in a traditional, vertical-shaft kiln, using timber, turf and coal, and noted that when using timber and turf, the kiln temperature was difficult to control, reaching high peaks to later suddenly drop, whereas when using coal, the temperature was easier to maintain over the burning operation. For the magnesian lime tested, the authors selected coal as fuel, and an arrangement consisting of two alternate layers of stone sandwiched between three layers of fuel (for rock fragments of maximum 5 cm length).

Ontiveros-Ortega et al. [28] demonstrated empirically that limestone calcination (and the optimum calcination temperature) depends on the porosity and crystalline structure of the limestones. The authors also highlight the importance of visual indicators which allow to control the process such as the smoke (volume and colour) and the appearance of the calcined stone. The burning process was traditionally judged visually: burning at excessive temperatures causes sintering and a less reactive lime that usually appears darker [26]. When overly burned, the limestone is heavy, compact and dark, covered with a kind of enamel [15]. According to Finnish accounts, burning times varied from 30 to 60 h [14]. Vicat [15] states that the capacity and the form of a furnace contribute to an equable and proper calcination. He refers to the burning of the lime as follows: 'practice can alone indicate the proper time for calcination. It varies with a multitude of circumstances, such as the quality of the wood (dry, green),the direction of the wind, if it favours the draft or otherwise…'. Dai [12] includes details of calcination from the book of Heavenly Creations, written by Song Ying-Xing c. 1587. According to the author: (1) The quality of limestone for lime production was assessed mainly according to colour, (2) 90% of the kiln fuel was coal and the rest firewood or charcoal, (3) The quicklime was divided into two categories, 'block quick lime' was of good quality, the 'kiln ash or ash dregs' was of bad quality.

The degree of burning the limestone to produce quicklime influences to a great extent the type of $Ca(OH)_2$ that will be later produced by slaking: a soft-burned quicklime will react quickly, raising the temperature fast, but an overburnt lime reacts slowly to give a low temperature rise [9]. Therefore, historic hot-lime mixed mortars can probably display variable properties based on the burning of the lime alone.

3.3 Evidence of hot-lime mixing in old mortars

The presence of particles of un-slaked and over/under-burnt lime and the remains of kiln fuel, often found in historic lime mortars, are considered evidence of hot- lime mortar mixing (BLFI [1, 2, 29]. However, as discussed below, this is unlikely. Even the contrary can be argued as evidence of hot-lime mixing, because, in some hot-mixing methods, sieving is carried out to remove the lime particles before mortar mixing and placement.

The presence of kiln fuel and particles of un-slaked and over/under-burnt lime do not necessarily result from hot-lime mixing, but they can generate from any processes lacking control over burning and slaking operations. Contamination with kiln fuel takes place when collecting the lime from the kiln with traditional methods, hence kiln fuel can be present in a mortar regardless of the subsequent mixing method. Furthermore, rather than hot-lime

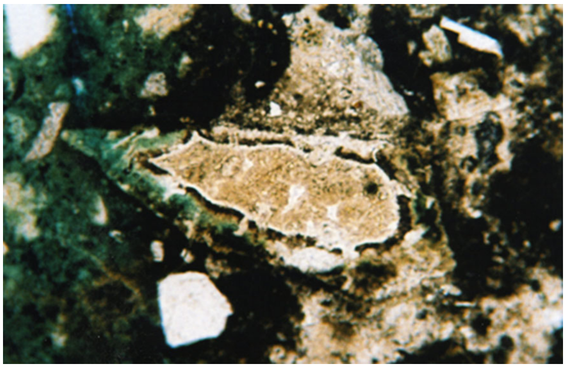

Fig. 2 Alkali silica reaction in chert aggregate. The wide reaction rim indicates strong reactivity that could have been enhanced by heat. Jiggistown House. Natural light 10X

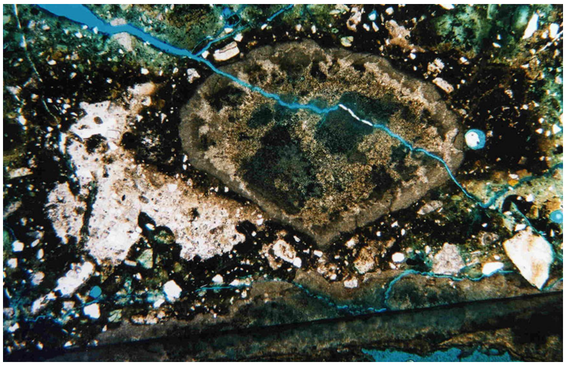

Fig. 3 Siliceous limestone aggregate, partially fired and displaying a strong reaction with the binder, surrounded by hydraulic cement. Jiggistown House. Natural light 2X

mixing, the presence of over/under-burnt lime particles indicates uneven kiln temperatures during firing. Chever et al. [27] measured kiln temperatures in a traditional, vertical-shaft kiln. They found temperatures ranging from 700 to 800 °C, occasionally reaching over 900 °C. The authors noted that when the temperature reached over 900 °C the resultant (magnesian) lime was over-burnt and hence did not slake, and it had to be stored for a year to produce a useful hydrate. The authors discarded hot-lime mixing based on the low reactivity of the magnesian quick lime produced. Therefore, over/underburnt lime particles can be due to variable limestone composition: dolomite –$CaMg(CO_3)_2$– decomposes at lower temperature (510–750 °C) than calcite-$CaCO_3$ (~900 °C), consequently, when calcite is well burnt, dolomite is over-burnt [27]. Unslaked particles can appear either due to variable limestone composition, lack of water or poor mixing. Magnesia (MgO) does not readily slake but gradually combines with water at a much slower rate than quicklime (CaO) [27]. Lime particles can be due to poorly mixed hydrated powder or lime putty, or even to the reprecipitation of calcium carbonate [30].

Therefore, particles of un-slaked and over/under-burnt or unslaked lime can appear in hot-lime mixed mortars as well as in any other traditional mortars. Consequently, they can hardly represent evidence of hot- lime mixing alone. However, there are microscopic features such as the widespread presence of strong, alkali-silica reaction (Fig. 2) that indicate high reactivity, and hence can indicate hot-lime mixing. Pavia [31] states that the presence of widespread reaction rims in sand grains due to alkali-silica reaction (ASR) or alkali-aggregate reaction (AAR) can indicate high reactivity, unusually high for the typical alkaline conditions afforded by lime binders, suggesting that heat enhanced the reaction which can be considered evidence of hot-mixing. Instances of these have been found in historic mortars such as Jiggistown House, Naas, Ireland. Here, unusually high reactivity inferred from alkali-silica reaction (Fig. 2), and widespread cements of hydraulic nature (Figs. 2 and 3) can be considered evidence of hot-lime mixing.

3.4 The nature of the burned limestone

The quicklimes used for hot mixing today are produced with more or less pure limestones of high free-lime content. In contrast, the composition and reactivity of historic quicklimes was subjected to significant variation. Historic mortars were typically made with local materials. Hot-lime mixing just requires sufficient free lime to produce heat on slaking, hence historically, dolomitic or hydraulic limestones as well as purer limestones could have been used for hot-lime mixing, depending on the nature of the limestone available. A local pure limestone (e.g.~90%$CaCO_3$) would have produced highly-exothermic quicklimes with abundant free lime, whereas local dolomitic limestones could have produced hardly reactive quicklimes. Furthermore, hydraulic quicklimes have been used for hot-mixing both in the past and today. The remains of partially-burned, siliceous limestones in historic mortars, showing extensive aggregate reaction and silica cements (Fig. 2), suggests that limes with hydraulic properties were used for hot-lime mixing. Dai [12] slaked hydraulic quicklime in three different ways, to reproduce historic mixes, and compared the resultant mortars, and Malinowsky and Hansen [21] made hot-lime mixed mortars with a local hydraulic lime, to match the original mortars to restore Läckö Castle. Today, it is difficult to replicate historic hot-lime mixed mortar made with hydraulic lime, because it is not easy to obtain hydraulic quicklimes from producers. This would need intervention at the right stage of the production process, as carried out for a small project in Scotland in 2008, with a contractor who had access to the materials (J Hughes pers.com. 2021). If some hot-lime mortars were made with hydraulic limes in the past, it can be argued that they are more compatible with modern NHL mixes than with a modern, hot-lime mortar made with pure, factory-produced quicklime.

3.5 How to standardise hot-lime mixes for consistent quality and performance.

3.5.1 Slaking

The amount of water used, the moisture in the sand, how the mortar is mixed and battered during and after slaking, and the storage time need to be specified for quality control and repeatability. In the different methods of hot-lime mixing, slaking can take place either with limited water or none at all, and the resultant mix can be either stored for days, weeks or years or not stored and applied hot. These varying conditions would produce hydrates of unpredictable surface areas and hence different carbonation and hardening rates, and varying rheology and strength. Furthermore, the mixes can be more or less stirred, and consequently hot spots can be either dissipated or created depending on the amount of beating which will further affect the slaking temperature and the properties of the resultant hydrate. With so many variables, it is impossible to determine the characteristics of the resulting $Ca(OH)_2$ and hence the properties of the final mortars. Mixing hot-lime mortars is hard to standardise. The mixing of high volumes of material on site can be unmanageable and the resulting mix inconsistent [3]. As indicated by Hughes and Taylor [17], improved preparation methods are needed in hot lime mortar technology, requiring longer slaking, quicklime crushing and screening guidelines. According to Hunnisett Snow [2], sufficient water needs to be used, as the quicklime rapidly takes up the water and the mix can overheat. Conversely, too much water reduces the heat of the reaction and can lead to the mortar being over-wetted, or ‘drowned’.

The method of preparation needs to be investigated for each particular quicklime. The right amount of water needs to be established considering the reactivity of the lime (free lime content) which will determine the heat produced, the temperature and duration of the slaking process and the amount of expansion. Hot-lime mixing requires storage to ensure that slaking is complete. Hughes and Taylor [17] produced hot lime mixes with Lias lime (moderately hydraulic) from Somerset and Fife lime (dolomitic-hydraulic) from Scotland. Despite calculating the amount of water to produce a hydrate, they found that delayed slaking was a problem, causing the mortar breakdown and the collapse of some masonry wallettes.

3.5.2 Proportioning

Achieving accurate proportioning in hot lime mixes is difficult for various reasons. On site, mortars are proportioned by volume. How does this translate into the equivalent mass, if the bulk density of the different limes varies, and so does the expansion caused on slaking? Due to the differing bulk densities of limes, the same proportioning in different sites, will result in unlike mortars. Furthermore, quicklimes slake differently, and the expansion and heat released vary according to their free lime content. As proposed by former authors, proportioning can be established by trail by determining reactivity and yield. Based on these two parameters, you can predict the mixing process and the proportions [17]. Besides, hot lime mortars are typically formulated as binder-rich mixes, therefore the density and expansion of the quicklime has a strong impact. High shrinkage and cracking are often found in laboratory produced hot mixes [8, 17]. Proportioning by trial slaking followed by a suitable storage can avoid this wastage. Function and application need to be considered as a certain amount of shrinkage can be acceptable for certain applications such as bedding, but not for others such as rendering. In Portugal, it is believed that hot-lime mixing was mainly for used bedding masonry, so that shrinkage cracks could close with the wall load pressure (R. Veiga pers. com. 2021). It should be relatively easy to establish the specific surface area of the particles and the composition (in particular the free lime). If the surface area is unknown, at least the grading should be specified. The type of sand is another variable that can affect the properties of the end mortar as well as the nature of the substrate (mainly the initial rate of absorption of the masonry unit). Therefore, they should be included in the specification.

Table 4 Properties of the hot-lime mixed mortar produced as illustrated in Fig. 1

Fresh properties	
Wet Density (EN 1015–6)	2015 kg/m^3
Consistency by Flow Table (EN 1015-3)	126 mm
Water Retention Capacity (EN 1015–8)	91%
Air content (EN 12,350-7)	3.7%
Hardened properties	
Dry density (EN 1015-10)	1894 kg/m^3
Total porosity (SIA 262/1)	32%
Capillary porosity (SIA 262/ 1)	26%
Content of air pores (SIA 262/ 1)	6%
Coefficient of absorption after 24 h (EN 1015–18)	0.31 kg/(m^2 min^{0,5})
Compressive strength (EN 1015–11)	1.8 MPa
Flexural strength (EN 1015–11)	0.5 MPa

Composition quicklime: sand=1:9 (volume ratio). Measured at 90 days with 40 × 40 × 160 mm specimens. Dolomite sand graded up to 4 mm

3.5.3 *Case studies*

It seems that currently, hot-lime mixed mortars are blended with NHLs. In Scotland, Frew [32] illustrates 24 case studies where NHL-blended hot-lime mortars have been used as external renders for repair. In Ireland, blended mixes are also used. According to BLFI [1] NHL-gauged, hot-lime mixes often contain equal proportions of quicklime and NHL. A mix comprising 1:1:6 (quicklime: NHL3.5: sand by volume) will give a final mix of 1:2 (lime: sand) after slaking (on the basis that the quicklime doubles in volume when slaked) which the authors classify as a very feebly hydraulic lime. The authors also state that blending NHL5 with quicklime in equal proportions will still give an overall free lime content greater than any current NHL2 in the market.

The following hot-lime mixes have been trialled and tested BLFI [1]:

Mix No. 1—Quicklime/sand at 1:4 by volume. C S =0.3- 0.6 MPa (35 d–180 d).
Mix No. 2—Quicklime/sand at 1:4 + 10% Oyster shell by volume of lime. CS=0.3–0.6 MPa (35d–180d).
Mix No. 3—Quicklime/ NHL3.5 (France)/sand at 1:1:6 by volume CS=0.5–1.7 MPa (35d–180d).
Mix No. 4—Quicklime/ NHL3.5 (Ireland)/sand at 1:1:6 by volume CS=1.1–2.5 MPa (35d–180d).

The properties of the hot-lime mixed mortar produced as illustrated in Fig. 1 are included in Table 4. Surprisingly, the strength of this hot-lime mixed mortar (which was made with quicklime alone) is superior to some of the NHL blended mortars above.

4 Comparison of hot-lime mortars with their equivalent putties, and with CL and NHL mixes

The properties of mortars made using different hot-lime mixes (Table 5) and putties are compared with calcium lime and magnesian lime mortars made with factory-made, dry hydrates (Table 6). The results in Table 5 evidence the improvement of mortar properties with storage in both dry-slaking and putty making. However, the differences in the properties between the putty and hot-mixed mortar are not significant, and they compare well with factory hydrates. The results in Table 5 agree with Pesce et al. [13]. In general, a consistent improvement with the use of hot lime mix process is not evidenced.

The hot-lime mortar results in the literature are as variable as the methods and materials used in hot mixing. Malinowsky and Hansen [21] used a slightly hydraulic lime to produce hot-lime mixed renders (dry-slaked) and compared them with renders made with the same quicklime but slaked as putty. They state that the hot-lime plasters had higher compressive strength (estimated with rebound hardness), slightly higher density, lower water absorption and slower carbonation than their putty equivalents. They also had, on average, lower total porosity but their volume of air voids was higher. Dai [12] used a hydraulic quicklime (hydraulic index CI=0.21 -0.54 based on chemical analysis) to prepare dry-slaked,

Table 5 Mechanical and physical characteristics of calcium lime mortars made using different slaking methods in Veiga [30]

Lime type/storage	Lime: sand (vol)	Flexural strength (MPa) 90 d	Compressive strength (MPa) 90 d	Modulus of elasticity 90 d (MPa)	Coefficient of capillarity 90 d (kg/m^2.min1/2)	Open porosity 90 d (%)
Margalha [33]						
Lime powder	1:3	0.52	1.33	–	0.8	–
Dry slaking (sand slaked) for 1 day	1:3	0.47	0.96	3816	1.6	–
Dry slaking (sand slaked) for 7 days	1:3	0.50	1.08	3658	1.5	–
Lime putty (1 month maturation)	1:3	0.37	1.06	4091	1.5	–
Lime putty (5 years maturation)	1:3	0.63	1.42	4748	1.3	
Valek et al. [34]						
Lime powder CL90	1:3	0.07	1.40	–	0.9	29
Quicklime,hot method, 2 calcination T	1:3	0.05	1.60		2.8	33
	1:3	0.10	1.60		2.5	32
Lime putty (2 years maturation)	1:3	0.11	0.90	–	2.8	33
Lime powder CL90	1:0.9	0.07	1.60	–	3.0	34
Quicklime,hot method, 2 calcination T	1:0.9	0.05	0.60	–	-	38
		0.12	0.80	–	4.0	36
Lime putty (2 years maturation)	1:0.9	0.12	0.80	–	3.5	32
Faria-Rodrigues et al. [35]						
Lime powder	1:2	0.32	0.75	2100	0.4	35
Micronized quick lime extinguished in putty	1:2	0.63	1.09	3100	0.3	37
Lime putty (16 months maturation)	1:2	0.23	0.35	1600	1.2	40

hot-lime mortars, and compared them with water slaked mortars made with the same quicklime. The dry-slaked lime had the highest strength (1.5 MPa at 28 days) and much shorter setting time (3–8 h vs 27–168 h for the water-slaked). Their performance is similar to the NHL2 in EN-459.

The calcium lime mortars made using different slaking methods in Table 4 compare well with mortars made with factory produced hydrates (Table 6). However, the upper limit values of the factory-produced hydrates are usually higher. The values also compare well with NHL 3.5 mortars of designations iv, v and vi (Table 7).

As stated by [39], natural hydraulic limes provide a group of binders able to offer the flexibility and permeability necessary to match the characteristics of a wide range of masonry units and methods of construction. NHLs are well known, even graded based on strength (Table 7). Livesey [39] established relationships between lime content, water content and strength development overtime of NHL mortars, that can be used to predict the effect of design proportions to make adjustments, if needed, to achieve a specific designation grade and predicting strength at different ages. Some authors claim that the properties and microstructure of NHL mortars are very different from hot-lime mixes mainly due to their lower free lime content, and hence they are not compatible with substrates and are not true replicas [3, 20]. However, as demonstrated above, some hot-lime mixed mortars are/were made with hydraulic quicklimes, hence their structure can be closer to a NHL than a pure CL, quicklime mix.

Table 6 Mechanical and physical characteristics of calcium lime (CL) and magnesian lime mortars made with factory-made, dry hydrates.+Lanas et al. 36,++ [37],+++ [38]

Lime type	Lime:sand (vol)	Flexural strength (MPa)90 d	Compressive strength (MPa) 90 d	Open porosity (%) 90 d
Lime powder (CL90), type 1+	1:1	0.42–0.80*	1.43–2.00*	26.13**
Lime powder (CL90), type 1+	1:2	0.38–0.75*	1.39–1.60*	22.98**
Lime powder (CL90), type 1+	1:3	0.35–0.62*	1.00–1.40*	20.69**
Lime powder (CL90), type 1+	1:4	0.30–0.59*	0.97–1.35*	19.34**
Lime powder (CL90), type 1+	1:5	0.27–0.50*	0.83–1.22*	18.58**
Lime powder (CL90), type 2+	1:1	0.35–0.8*7	1.02–2.00*	29.80**
Lime powder (CL90), type 2+	1:2	0.25–0.85*	0.86–2.23*	25.33**
Lime powder (CL90), type 2+	1:3	0.22–0.63*	0.58–1.93*	23.65**
Lime powder (CL90), type 2+	1:4	0.20–0.70*	0.60–1.92*	20.68**
Lime powder (CL90), type 2+	1:5	0.18–0.75*	0.48–2.00*	20.75**
DL 85 powder++	1:1	0.60–1.48*	1.20–2.80*	22.34**
DL 85 powder++	1:2	0.50–1.70*	1.00–3.56*	19.70**
DL 85 powder++	1:3	0.50–1.25*	1.10–4.00*	17.65**
DL 85 powder++	1:4	0.61–0.92*	1.12–3.18*	16.86**
DL 85 powder++	1:5	0.48–1.00*	1.10–2.73*	16.64**
CL 90-S powder+++	1:1	1.20	2.41	33.08

*Upper and lower values of 4 tests as a function of different aggregates; **average value of 4 tests as a function of different aggregates. DL- dolomitic lime

Furthermore, compatibility between masonry substrates and lime mortars is often determined based on moisture transfer and water vapour permeability, and the differences between the different types hot-lime mixes and NHL mortars have not yet been established.

5 Conclusion

The key question is: how hot does a hot-lime mortar become? Or, in other words, what temperature is reached during slaking? Slaking is the most important process in hot-lime mixing: the quantity of water used for slaking controls the slaking temperature which determines the surface area and particle size of the end hydrate, that rules the properties of the resultant limes and mortars. The water/CaO ratio and the initial water temperature rule the thermodynamics of the slaking reaction, because they determine the temperature reached during slaking which makes the resultant $Ca(OH)_2$ particles vary from fairly large to extremely small.

Based on scientific and historic records, it is concluded that the best method for hot-lime mortar mixing is likely dry-slaking (sand-slaking) with extended storage. The high slaking temperature produced in dry slaking would reduce the particle size and increase the surface area of the resultant hydrate. Furthermore, gradual slaking with moisture reduces volume expansion minimising the risk of cracking. In addition, extended storage would ensure that the quicklime is fully slaked but not drowned, hence providing strong mortars. Dry-slaking is difficult to control and needs more time than wet slaking to complete the process (e.g. 21–40 days for a hydraulic quicklime) so that the mortar can be safely used without expansion cracks. Dry-slaked mortars carbonate slower than putties due to their lower water content and lower porosity, however they are stronger and are reported to have higher water retention and flowability, lower total porosity and a higher volume of air voids than their putty equivalents.

It is possible that many historic mortars were made by dry-slaking the lime with sand, hence using hot-lime mixing technology. Unusually high reactivity, inferred from extensive aggregate-binder reactions and widespread cements of hydraulic nature, can be

Table 7 Mortar designations for NHL3.5 mortars based on strength [39]

Mortar designation	NHL 3.5: sand (vol)	91d compressive strength (MPa)
i	*	6.5
ii	1:1$^{1/2}$	3.5
iii	1:2	2.5
iv	1:3	1.0
v	1:4	0.5
vi	1:5	0.3

* Designation i can be achieved with a 1:1 NHL5 or adding a pozzolan to a 1:1 NHL3.5 mortar

considered evidence of hot-lime mixing. In the past, firing and slaking conditions were arranged to suit the local limestones and fuels, and there were regional patterns in the slaking and mixing techniques. Therefore, even if historic lime mortars were hot-lime mixes, it would be practically impossible to recreate them today due to the different limestones, kilns, calcination regimes and slaking/storage methods used in the past.

The quicklime used for hot-lime mixing today is different from historic quicklimes. Furthermore, it seems that current practitioners are blending quicklime with NHLs (factory produced dry hydrates) to produce hot-lime mixed mortars which defeats the initial purpose of using hot-lime mixes as historic replicas and introduces more variables in the product. Therefore, a hot-lime mix made today with factory-produced quicklime may not be more authentic or compatible than a NHL mortar, made with factory-produced dry hydrate, designed to suit a specific fabric and application.

It is likely that the heat released on slaking improves some mortar properties. However, the different slaking and mixing methods of hot-lime mixing would release varying amounts of heat, producing different materials. Therefore, the improvement of structure and properties due to hot-lime mixing need to be studied on an individual basis.

To ensure quality mortars that can be consistently repeated, a hot-lime mixing specification, needs to include both the process and the materials used. Slaking is the most important process, hence it should be closely specified including: the type of slaking (dry or wet); the amount of water used; how much and when the mortar is mixed and battered during and after slaking; the moisture in the sand; the storage time; and at what production stage does storage take place. The right amount of water should be established for a given quicklime, considering the reactivity of the lime i.e. the amount of free lime which determines the heat produced on slaking, and the temperature and duration of the slaking process. The proportioning can also be established by determining the reactivity and yield of the quicklime. The properties of the quicklime are also important, especially the surface area (or grading if the surface area is not known) and the composition (amount of free lime), because they determine the heat produced, and hence the slaking temperature which rules the properties and quality of the hydrate and the mortars. The bulk density of the quicklime and the 28 / 90-day compressive strength of a standard (EN 459) mix would also be useful in a specification. Finally, the type of sand and the nature of the substrate (mainly the initial rate of absorption of the masonry unit) can also be included.

Dry-slaking has more complicated logistics of production than putty making. Hot-lime mixing requires abundant time and close care. Any mistakes made during preparation are likely to have a strong impact on the final product. NHLs and CLs produced as dry hydrates are easier to work with and require less time, care and preparation. Many comply with building standards and therefore are well characterised in composition and requirements, hence producing more or less consistent mortars that can be specified much easier than hot-lime mixes. With careful site work and specification, high-quality, compatible mortars can be made with a wide range of binders, including natural hydraulic limes and the limes produced from hot-lime mixing.

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