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An assessment of lime mortars for masonry repair.

S. Pavía, B. Fitzgerald and E. Treacy.

Abstract

Most historic and traditional mortars were made with lime. Due to their nature and function lime mortars weather and need to be replaced. Ordinary portland cement mortars can often be incompatible with historic masonry causing structural and aesthetic damage. Petrographic analysis of original mortars from Clonmacnoise Monastery and Ardamullivan Castle evidenced that they were fabricated with feebly hydraulic and magnesian lime respectively. Within a National Monuments' conservation programme, the original mortars were replicated and tested and the best performers selected to undertake repairs. This paper investigates mortars made with four types of lime binder: fat, feebly-hydraulic, moderately-hydraulic and magnesian lime. The results indicate that lime mortars conduct moisture to a greater extent than OPC mortars. The feebly-hydraulic lime mortar has the lightest microstructure and highest porosity and absorption, being capable of holding the greatest amount of moisture thus being more susceptible to failure by water ingress. The results suggest that both fat and mg-lime binders would perform superiorly in areas subject to moisture ingress. As expected, the hydraulic set provides mortars with an additional strength and therefore both mg and fat limes are weaker in compression than hydraulic limes. However, the strength of the gauged mg-lime mortars is slightly higher than the values typically achieved by pure fat limes suggesting that mg-lime mortar may posses a certain amount of hydraulic set. The lime mortars tested are both physically and chemically compatible with the materials comprising the original masonry at Ardamullivan and Clonmacnoise. The chemical composition of the original mortars is similar to that of the new repair mixes. In addition, all new mixes are physically compatible with the limestones and sandstones comprising the monumental fabrics as they are substantially less dense, more porous and permeable and mechanically weaker than these rocks. Any of the lime mortars tested could therefore be selected to undertake repairs however, the magnesian and fat lime repair mixes are closer in composition to the original mortars and, if a conservative approach is to be taken, these are the best choices to undertake conservation work at the monuments.

Keywords: Aerial lime, bulk and real densities, compressive strength, feebly hydraulic lime, magnesian lime, moderately hydraulic lime, porosity, water absorption.

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INTRODUCTION

Most historic and traditional masonry mortars were made with lime. Currently, lime has become one of the principal materials used in the conservation and restoration of historic buildings. Lime is probably the most versatile structural binder available and can be modified to suit a range of diverse uses and exposures. Quality lime mortars do not contain elements capable of forming harmful salts and are generally more compatible with masonry fabrics than artificial cements.

A national building conservation programme is concerned with the repair of Ardamullivan Castle, Co. Clare, a tower house built with limestone and lime mortar in the 16^{th} century, and Clonmacnoise, Co. Offaly, a medieval monastery designated UNESCO's world heritage site in 2004. The original mortars have weathered by granular disintegration caused by dissolution of their carbonated lime binder [1, 2]. Lime mortars weather when repeatedly subject to the action of moisture and often need to be replaced. In order to conserve the original building, new repair mortars should be quality, durable materials compatible with the existing fabric. The composition and mix proportions of any new repair mortar must take into account the physical properties and composition of the existing masonry and the original mortar to be restored [3]. To ensure quality, the historic mortars at Ardamullivan and Clonmacnoise were studied and, based on the results obtained, new repair mortars were fabricated and tested in the laboratory.

There are two characteristic types of lime: hydraulic and non-hydraulic. They differ in the manner by which they harden and in the properties they display. Hydraulic limes harden to a greater or lesser extent due to a chemical reaction between their active clay particles, lime and water (hydraulic set) whereas non-hydraulic limes harden due to a reaction between CaO in the mix and atmospheric CO_2, a mechanism known as carbonation [4, 5]. Non-hydraulic lime, also known as aerial or fat lime, possesses high permeability, flexibility and plasticity, as well as a tendency to shrink in early stages of hardening, significant solubility in water and low mechanical strength [3, 4, 5]. It is generally advised for use with more ductile, porous and weathered masonry in sheltered areas [3, 6, 7, 8, 9]. Hydraulic limes display an additional mechanical strength due to their hydraulic set. When compared to fat limes, they are assumed to posses lower permeability and flexibility and a better resistance to moisture, frost and salt attack [3, 6, 7, 8, 9]. They are therefore usually advised for use with strong masonry in exposed, damp environments.

Documentary research revealed that there is a lack of agreement on the properties and quality of magnesian limes as well as a lack of experimental work in the subject. According to Cowper [5], non-hydraulic lime is obtained from highly magnesian limestone. However Vicat [4] states that magnesia alone, when in sufficient quantity, will render pure lime hydraulic. Vicat also claims that lime obtained from slaking and calcining magnesian limestone is capable of hardening underwater and, in time, *" it acquires a firm consistency, and even as a stucco it has been described as of extreme hardness".* Contemporary authors stress problems caused by the tendency of magnesian lime to fracture when exposed outdoor [10].

In order to assess the quality of magnesian limes, it was deemed necessary to evaluate the properties of magnesian lime through the experimental work.

The aim of this paper is to assess the quality of four common forms of lime binder including fat, feebly-hydraulic, moderately-hydraulic and magnesian lime by evaluating some of their main properties as building materials. To this aim, lime mortars were produced in the laboratory and tested for the properties governing moisture movement including water absorption, densities and porosity as well as for mechanical strength, and the values obtained compared to those of reference OPC mortars.

METHODOLOGY

The following analytical techniques and laboratory tests were used:

Petrographic Analysis

Petrographic microscopy is an established technique for mortar analysis Charola et al. [11]. A petrographic study of a mortar informs on the type, origin and proportions of the raw materials used for its fabrication. It enables to assess current condition, decay processes and reasons for failure, thus providing base data needed in order to design improved mixes or mortar replicas for conservation works [3, 12]. Twenty samples of original mortars were gathered from the sites. Mortar samples were pre consolidated by impregnation with resin under vacuum. Thin sections were cut with oils to avoid damaging water-soluble minerals in the mortars. The thin sections were polished to the thickness of approximately 20 microns, covered with a glass slip and examined with a petrographic microscope holding eye pieces of 2, 10. 20 and 40 magnifications, using transmitted both natural and polarised light. In order to distinguish the different carbonate minerals, the samples were dyed with a chemical solution containing alizarin and potassium ferro cyanide. The type, composition and proportions of aggregate, binders and additions were recorded in order to design matching replicas.

Mixing and Curing

The same aggregate and similar binder to aggregate ratio were used in all samples. In any batch, three sets consisting of 6 x 50mm cubes were made, each set using a binder of either OPC, fat, magnesian or hydraulic lime. The OPC mix was tested as a reference mortar. The binder to aggregate ratios are included in table 1 below. The aggregate used was a sub-angular, washed sand of glacial origin containing a high proportion of quartz.

The fat lime was slaked and provided as a putty. The lime was firstly broken down in the mixing apparatus for approximately 2 minutes and the aggregate added and mixed for a further 15 minutes. The feebly and moderately hydraulic limes were provided as a dry powder including an estequiometric amount of water. The lime and aggregate were placed in the mixer and small quantities of water were added until the mix was seen to take on an appropriate consistency and workability. The mix proportions were to give a water/binder ratio 0.8 for feebly-hydraulic and slightly higher for fat lime.

The moulds containing mortar were placed in a humid curing chamber. The atmospheric conditions in the chamber were monitored daily. The resultant average humidity of the curing chamber was approximately 60%, and the temperature varied between 16.9 and 19.7°C. A damp cloth was placed over the cubes after an initial curing period of 8 hours to restrict moisture loss in order to prevent fracturing by shrinkage. A total of approximately 45 days were allowed for the mortars to develop strength by carbonationand/or hydraulic set.

Permeability

Permeability is the overall movement of fluids throughout a material. The movement of fluids through mortar has an impact on its durability. Two tests were conducted to determine permeability: the porosity and the absorption tests. These enabled to quantify the volume of pore space effective in transporting fluids and the total amount of water the mortar is capable of holding.

Absorption Test

The mortars were submerged in water at atmospheric pressure until a constant weight was achieved (W_a). Absorption is expressed in Eq. (1) as the percentage of water absorbed in relation to the dry mass (W_d) of the specimen.

$$WA = \frac{W_a - W_d}{W_a} \text{x} 100 \quad (\%) \qquad (1)$$

Densities and Porosity

These properties were tested in accordance with RILEM [13]. Real density is the volume mass of the impermeable material and it is measured as the ratio of the mass of the dry sample to the impermeable volume of the sample. Bulk or apparent density is the ratio of the mass of the dry sample to the bulk volume of the sample. The samples were dried to a constant mass m_d and submerged in an evacuation vessel. The hydrostatic weight m_h and the weight at atmospheric pressure m_s were measured. The bulk (δ) and real (δ_r) densities where calculated according to the Eqs. (2) and (3) below:

$$\delta = M_d / M_s\text{-}M_h \qquad \delta_r = \frac{m_d}{m_d - m_h} \quad (\text{g/cm}^3) \qquad (2, 3)$$

Porosity is the ratio of the volume of the pores accessible to water to the bulk volume of the sample and it is usually expressed as a percent according to Eq. (4).

$$P = \frac{m_s - m_d}{m_s - m_h} \text{x} 100 \qquad (4)$$

Compressive Strength (unconfined)

This is the load per unit area under which the new repair mortars fail. A uniaxial, unconfined, uniformly-distributed load was manually applied at a slow pace and continuously increased until failure occurred. The strength was calculated with Eq. (5) below, where A is the cross sectional area and F the failure stress.

$$R = \frac{F}{A} \quad (\text{Mpa}) \qquad (5)$$

RESULTS

The microphotographs below summarise the microstructure and composition of the original pointing mortars at Clonmacnoise and Ardamullivan while table 1 below contains a summary of the results obtained from laboratory testing.

Petrographic Microscopy

According to the petrographic analysis, the pointing mortar at Ardamullivan Castle was fabricated with a sharp, limestone aggregate including a significant siliceous fraction mixed with lime in approximate proportions 2-3:1 (aggregate:binder in % by volume). Fragments of under-burned dolomitic limestone were occassionaly recorded in the mortars suggesting that a magnesian limestone was calcined in order to obtain the lime. Microscopic examination evidenced the presence of retraction fractures and dissolution of carbonated lime binder.

At Clonmacnoise, all mortars analysed are slightly hydraulic and binder rich (2-3:1 by volume). Some hydraulicity is arising from the presence of reactive aggregate of microcrystalline silica. In addition, two out of the thirteen mortars studied, are hydraulic due to the presence of pozzolanic additions: brick dust. It is not certain whether the lime itself possessed some hydraulicity. The mortars were fabricated with limestone aggregate. The limestone sand varies from angular to sub-rounded and naturally includes a significant siliceous fraction composed of quartz and reactive chert. In all samples analysed the lime binder is weathered, fractures have been enhanced through dissolution causing loss of adhesion between aggregate and binder.

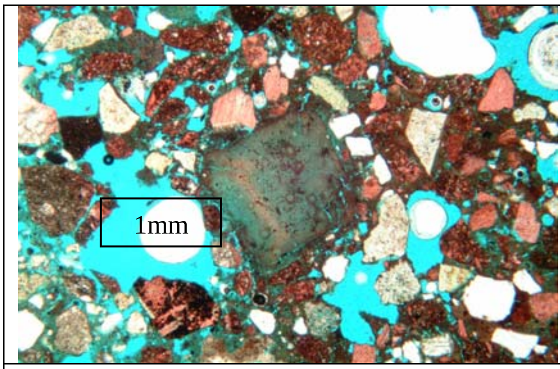

Fig. 1 Petrographic microscope photograph of an original pointing mortar from Clonmacnoise including limestone, quartz and chert aggregate in a high-porosity lime binder. X2. Natural light.

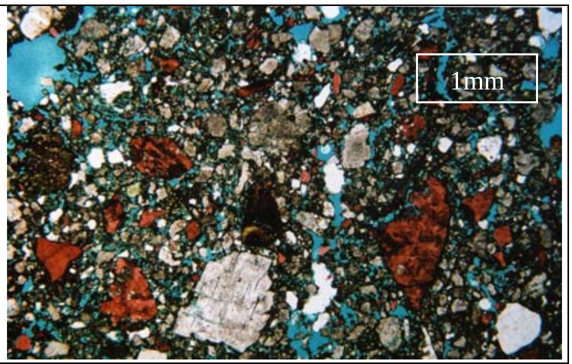

Fig. 2 Petrographic microscope photograph of an original pointing mortar from Ardamullivan including dolomite, limestone, quartz and chert aggregate in a carbonated lime binder. X2. Natural light.

As aforementioned, the results obtained from laboratory testing including water absorption, real and bulk densities, porosity and compressive strength are summarised in table 1 below.

Water Absorption

This property relates to both the porosity and permeability of the mortar. The results of the water absorption tests indicate that feebly-hydraulic lime possesses the highest water absorption with a value of 17.11%. Fat lime reaches an average value of 13.5% and, as expected, the binders with highest hydraulicity (NHL3.5 and OPC) display some of the lowest values (10-12%). However, the OPC mortars absorb more water than NHL3.5, magnesian lime and some of the fat lime mixes. This unexpected result can be due to a late hydration of the cement paste. The mg-lime mortars show lower water absorption values, comparable to those of hydraulic binders (10.39-11.55%). It is generally accepted that non-hydraulic lime binders absorb more water than hydraulic limes and the higher the hydraulicity the lower the ability in transporting fluids. This tendency however is not evident from the results obtained. On the contrary, according to these results, the NHL 2 mortar possesses a greater absorption than the magnesian mixes, suggesting that these have a smaller volume of pore space effective in transporting fluids.

Table 1. Summary of results from laboratory testing including densities, porosity, water absorption and compressive strength of OPC, fat, feebly hydraulic (NHL2), moderately hydraulic (NHL 3.5) and magnesian lime mortars. NHL –natural hydraulic lime.

Mortar proportions and binder type	Real density (g/cm^3)	Bulk density (g/cm^3)	Total porosity (%)	Water absorption (%)	Compressive strength (N/mm^2)
Fat lime mortars					
2.5:1 Fat Galway lime	2.43	1.94	20.38	9.46	0.58
3:1 Fat Clonmacnoise lime	2.36	1.76	25.8	14.08	1.32
Magnesian lime mortars					
3:1 75% Fat Galway lime 25% $Mg(OH)_2$	2.31	1.77	23.19	11.55	1.86
3:1 75% Fat Galway lime 25% Kilkenny dolomite lime	2.34	1.84	21.44	10.95	1.57
3:1 Kilkenny dolomite lime	2.35	1.75	22.7	10.39	0.59
Natural feebly hydraulic lime mortars					
2.5:1, NHL 2	2.49	1.73	30.1	17.11	-
3:1, NHL 2	2.50	1.83	27.03	12.97	2.18
Natural moderately hydraulic lime mortars					
2:1, NHL 3.5	2.50	1.94	22.34	10.23	2.37
Ordinary Portland Cement Mortars					
2.5-3:1, OPC	2.39	1.84	23.1	12.28	18.94

Densities and Porosity

Density is a measure of the degree of consolidation of a solid, informing on grain packing and mechanical resistance. It can be seen from table 1 that the feebly-hydraulic mortar shows the greatest difference between bulk and real densities suggesting that this material holds the greatest amount of pores while the magnesian and fat lime mortars showed similar values comparable to those of NHL3.5 and OPC mortars. The average bulk density for the magnesian and feebly hydraulic mixes is lower than those of the more hydraulic mortars. The values of bulk density indicate that the OPC and NHL3.5 mortars are the materials with the densest microstructure followed by the fat lime mortar.

Mortar porosity is of great importance as it has a significant effect in the performance of the materials in relation to water, frost, salt and chemical weathering and therefore partially determines mortar durability. The results from the porosity tests showed that the porosities of the lime mortars tested fell whithin the typical range of historic lime mortars [12, 14, 15]. The porosity of NHL2 is the highest at 27-30% while those of the most hydraulic binders (OPC and NHL 3.5) are the lowest at 22-23%, comparable however to the values obtained for both magnesian and fat limes.

Compressive Strength

In mortars, the compressive strength is related to the amount of hydraulic set of the mortar binder which in turn relates to mortar durability. Both of the natural hydraulic limes tested as well as the OPC possess a hydraulic set which provides mortars with an early strength. Therefore, as expected, the mechanical strength increases proportionally with the hydraulicity of the binder. Therefore both fat and magnesian lime mixes are weaker in compression than those mortars incorporating a hydraulic binder.

The feebly hydraulic lime is approximately 4 times stronger than the pure magnesian lime (table 1). However, when gauged with fat lime, the magnesian lime mortars display strength values slightly higher than those typically achieved by purer calcitic (fat) limes.

CONCLUSIONS

The test results on the properties governing moisture movement agree with the values of capillary suction and durability previously calculated by the authors [16, 17] producing good indications of the degree to which lime mortars permit flow through their fabrics. The results indicate that lime mortars conduct moisture to a greater extent than OPC mortars, which is one of their advantages as they made structures breathable. The movement of fluids is also applicable to gases such as carbon dioxide, the absorption of which is highly advantageous as it aids carbonation (mechanism of lime mortar hardening) and consequently strengthens the mortar.

The lime mortars tested display high porosities. However, the feebly-hydraulic lime mortar possesses the highest porosity and water absorption being capable of holding the greatest amount of moisture, thus being more susceptible to failure by water ingress in damp or exposed conditions. These results agree with those from the density test indicating that feebly-hydraulic lime mortar is the material with the lightest microstructure. The lowest values of porosity and absorption shown by the fat and mg-lime mortars when compared to those of the feebly-hydraulic mortars suggest that both fat and mg-lime binders would perform superiorly in areas subject to presence of moisture. As expected, the hydraulic set of the natural hydraulic limes (NHL2 and NHL3.5) provides the mortar with an additional initial strength, and therefore both mg and fat limes are weaker in compression than hydraulic limes. However, the strength of the gauged mg-lime mortars is slightly higher than the values typically achieved by pure fat limes suggesting that mg-lime mortar may posses a certain amount of hydraulic set.

The lime mortars tested are both physically and chemically compatible with the materials comprising the original masonry at Ardamullivan and Clonmacnoise. The chemical composition of the original mortars is similar to that of the new repair mixes consisting of mainly carbonated lime, limestone sand and siliceous aggregate [1, 2, 12]. All new repair mortars are also physically compatible with the limestones and sandstones comprising the monumental fabrics at Ardamullivan and Clonmacnoise, as they are substantially less dense, more porous and permeable and mechanically weaker than the aforementioned rocks [1, 2, 12]. Furthermore, the physical properties of the new repair mortars match those of the original pointing as the porosity of the original pointing mortars ranges between 17.17 and 25.65 % and the water absorption varies between 7.92 and 12.77 % [1, 2, 12]. According to this, any of the lime mortars tested could be selected to undertake repairs however, the magnesian and fat lime repair mixes are closer in composition to the original mortars at Ardamullivan and Clonmacnoise respectively, therefore, if a conservative approach is to be taken, these are the best choices to undertake conservation work at the monuments.

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