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Evaluation of properties of magnesian lime mortar.

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Abstract

Due to their nature and function, historic lime mortars weather and often need to be replaced. Petrographic analysis of original mortars from Ardamullivan Castle evidenced that they were fabricated with a dolomitic limestone. Within, Ardamullivan Castle's conservation programme it was considered to replicate the original mortars to undertake conservation works to the Castle. However, documentary research revealed that there is a lack of agreement on the properties of magnesian lime as well as a lack of experimental work in the subject. Therefore, it was deemed necessary to evaluate the properties of magnesian lime prior to its use. To this aim, dolomite was calcinated in a limekiln and the lime obtained slaked for a year. Magnesian lime mortars were then fabricated and tested in the laboratory. Porosity, densities, compressive strength, capillary suction and absorption were evaluated. The lower values of capillary raise, porosity and absorption obtained for the magnesian lime mortars when compared to those of feebly hydraulic limes suggest that magnesian lime binders would perform superiorly in areas subject to the presence of moisture. In compression, the feebly-hydraulic mix is four times stronger than the mg-lime mortar. The mg-lime mortar outperforms the feebly-hydraulic lime mix in all tests except for compressive strength. However, the compressive strength of the mg-lime mix is enough to withstand the stresses and strains typically induced when confined within conventional masonry. The results of this investigation suggest that, provided the lime has been adequately calcinated and slaked, mg-lime mortar can perform well as a building material.

Keywords: Magnesian lime, lime mortar, hydraulicity, NHL2, capillary suction, water absorption, porosity, densities, permeability, compresive strength.

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1 Introduction

A national building conservation programme is concerned with the repair of Ardamullivan Castle, Co. Clare, Ireland, a tower house built with limestone and lime mortar in the 16th century. The original mortars weathered by granular disintegration caused by dissolution of their carbonated lime binder Pavía [1]. Mortars are an essential part of a built structure. However, due to their nature and function, they are sacrificial materials with a life-span much shorter than the fabrics with which they are mixed. They weather when repeatedly subject to the action of moisture and often need to be replaced. In order to conserve the original building fabric, new repair mortars should be quality, durable materials compatible with existing stone or brick. The composition and mix proportions of any new mortar must take into account the physical properties and composition of the masonry to be re-pointed, as well as the composition and condition of the original mortar to be restored Pavía et al. [2]. To ensure quality, both the historic mortar and the stone masonry of Ardamullivan Castle were studied, and new repair mortars designed based on the results obtained.

It is a common practice in Ireland to design repair mortars based on information evidenced from the petrographic analysis of original mortars. Petrographic analysis evidenced that the mortars were fabricated with a dolomitic limestone. Within the Castle's conservation programme, it was considered to approximately replicate the original magnesian-lime mortars to undertake repairs. However, 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 [3], 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 calcinating 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 Seely [5]. In order to assess the quality of magnesian limes, it was deemed necessary to evaluate the properties of magnesian lime through the experimental and analytical study in this paper.

2 Materials and methods

2.1 Petrographic analysis

Petrographic microscopy is an established technique for mortar analysis Charola et al. [6]. 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 Pavía et al. [7]. Twenty samples of original mortars were gathered from the site. The type, composition and proportions of aggregate, binders and additions were recorded in order to design matching replicas. 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. They 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, and 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. Relative proportions of aggregate and binder were calculated with graphics of visual estimation of percentaje by volume Tucker [8].

2.2 Magnesian lime technology: Calcinating, slaking and mixing.

A dolomite consisting of 70-90% Ca Mg $(CO_3)_2$ was sourced from Kilkenny quarries, calcinated in a lime kiln and slaked for a year. The lime obtained was off-white to grey colour. The technology of magnesian lime differs from that of fat or purer calcitic limes. On one hand, magnesian carbonate (dolomite: Ca Mg $(CO_3)_2$) has a lower calcination temperature than calcium carbonate (calcite: Ca CO3). Calcite decomposes at 900°C while the conversion of Mg (CO_3) to magnesia (MgO) begins at 725 °C therefore, the kiln temperature needs to be lower than when calcinating purer limestones Holmes at al. [9]. Furthermore, magnesian limes slake at a slower speed than purer fat limes therefore they need to slake for longer periods. Their slaking reaction is exothermic however not as energetic as when slaking fat limes. Finally, magnesian limes expand very little as a result of slaking (the higher the magnesium content the lower the expansion) whereas fat limes approximately double their volume in the process.

Table 1: Binder and proportions of repair mortars and control mix.

Mortar	(aggregate: binder) % by volume	Binder
Mix 1	3:1	Kilkenny dolomite lime
Mix 2	3:1	Kilkenny dolomite lime
NHL 2	3:1	Natural, feebly-hydraulic lime

Following slaking, the lime was mixed with a calcareous aggregate in the proportions 3:1 to produce repair mortars. An excess of water was used in mix 1. A feebly-hydraulic lime mortar was tested simultaneously as a control mix (see table 1). The mortars were moulded and remained in laboratory conditions (20°C/50-60% humidity) for approximately 30 days. Tests were then conducted on 6 mortar cubes of each mix according to the relevant standards.

2.3 Permeability

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The movement of fluids through mortar has an impact on its durability. Lime mortars allow movement of fluids to a greater extent than Portland cement mortars and concrete, 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. Permeability is the overall movement of fluids throughout a material. Two tests were conducted to determine permeability: the capillarity test was conducted to determine the rate of penetrability due to capillary suction and the absorption test was carried out in order to quantify the volume of pore space effective in transporting fluids and the total amount of water the mortar is capable of holding.

2.3.1 Capillarity test

Determination of water absorption coefficient by capillarity was carried out according to BSEN [10]. The dry mass, m_d, as well as the area, A, of the face were measured. The samples were weighed (m_i) at specific pre-set time intervals, up to 60 minutes. Testing recommendations were altered in order to adapt the standard to lime mortars samples. E.g as mortar is generally more porous than stone and will therefore intake more water at a quicker pace the test was extended up to a time of 60 instead of 1440 minutes. The water absorption coefficient (by capillary suction) is expressed in eqn (1):

$$C_1 = \frac{m_i - m_d}{A\sqrt{t_i}} \quad (\mathrm{g/m^2.s^{0.5}}) \qquad (1)$$

2.3.2 Absorption test

The mortars were submerged in water at atmospheric pressure until a constant weight was achieved (W_a) UNE [11]. Absorption is expressed in eqn (2) as the percentage of water absorbed in relation to the dry mass (W_d) of the specimen.

$$WA = \frac{W_a - W_d}{W_a} \mathrm{x} 100 \quad (\%) \qquad (2)$$

2.4 Densities and porosity

These properties were tested in accordance with RILEM [12]. Density is a measure of the degree of consolidation of a solid. It informs of grain packing and mechanical resistance. 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. Bulk and real densities are important in assessing the extent of some forms of decay in the mortar and in determining the extent to which the pore space can be filled by an impregnation treatment RILEM [12]. 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 eqns (3) and (4) below:

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

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. Porosity of mortars is of great importance as it has a significant effect in the performance of the materials in relation to water, frost, salt weathering and chemical weathering, and therefore partially determines mortar durability.

$$P = \frac{m_s - m_d}{m_s - m_h} x100 \qquad (4)$$

2.5 Compressive strength

This is the load per unit area under which the new repair mortars fail. In lime mortars, the compressive strength is related to the amount of hydraulic set which in turn relates to the mortar durability. The compression test was conducted with the water saturated mortars. A uniaxial, unconfined, uniformly-distributed load was manually applied at a slow pace and continuously increased until failure occurred. The strength was calculated with eqn (5) below, where A is the cross sectional area and F the failure stress.

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

3 Results and discussion

3.1 Properties and composition of the building stone

The building stone was subject to a previous study Pavía [13]. According to this study, this is a Carbonifeous limestone of local origin consisting mainly of calcite (95%) and quartz (5%). The density values are high and the porosity extremely low (0.27-1.09 %). The capillary suction is also low (water raised to 5-6 mm after a 24 hours period, remaining stable after a 48 hours period). The compressive strength of the limestone is high, similar to that of the Leinster Granite (102.0 -159.5 N/mm^2).

3.2 Petrographic analysis of the original mortar

Mortar analysis revealed that dolomite is present both as aggregate and in the lime binder. Fragments of partially calcinated dolomite were recorded in the mortar, indicating that magnesian limestone was calcinated to obtain the lime (see figure 1). Newformed minerals evidenced within the binder suggest that the lime possesses some hydraulicity. Most aggregate is calcareous in composition. However, a fine, sharp dolomite aggregate as well as siliceous aggregate are present in lower proportions. The mortar porosity is high including pores and occasional fractures. Microscopic examination suggests that the porosity is partially secondary, having been enhanced through weathering.

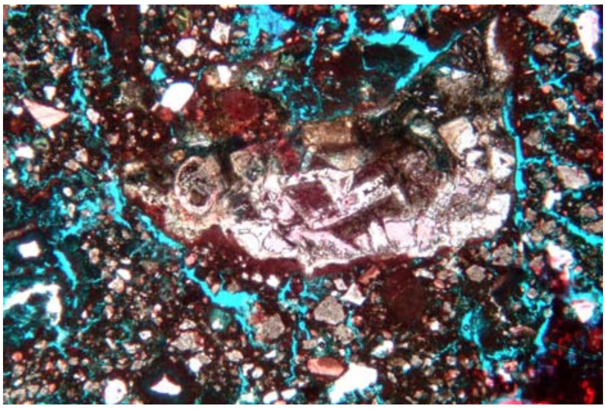

Figure 1. Microphotograph of partially calcinated dolomite (centre). 2X. Parallel polars.

3.3 Capillary suction of repair mortars

The results of capillary suction are included in the graphs below, representing the mass of water absorbed divided by the area of the immersed base of the cube as a function of the square root of time. A linear function was used to approximate the data points on the graph. The values of the correlation coefficient, R^2, between the measured data points and the regression line were used to validate the calculations. As can be seen from the graphs, the amount of water absorbed through capillarity action by NHL 2 was greater than that absorbed by the magnesian limes. The magnesian lime absorbed a greater amount initially but then slowed down unlike the NHL 2, which was slow at the beginning absorbing a greater amount of water as time increased. The absorption coefficients calculated are included in table 2. From these coefficients it is also clear that the NHL absorbs more water than the magnesian lime mortar. These suggest that magnesian lime would perform superiorly in areas subject to capillary raise.

Table 2. W*ater absorption coefficient by capillary rise.*

Mortar	**C_1 (Kg/m^2.s$^{0.5}$)**
NHL 2	21.62
Magnesian Lime Mix 1	18.76
Magnesian Lime Mix 2	13.80

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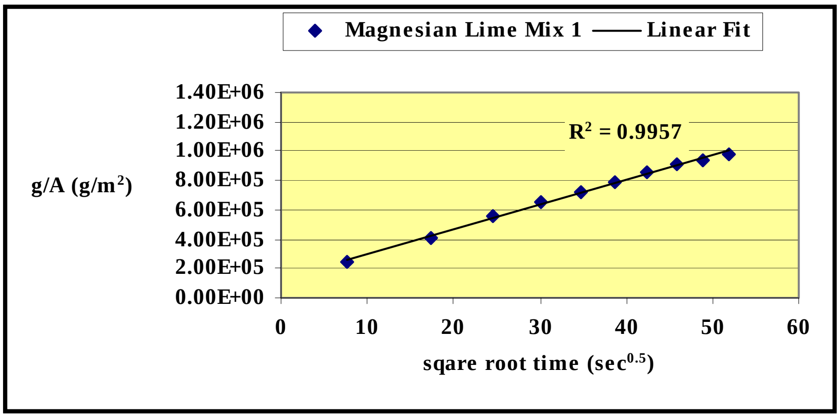

Figure 2. *Capillary suction for magnesian lime mix 1*

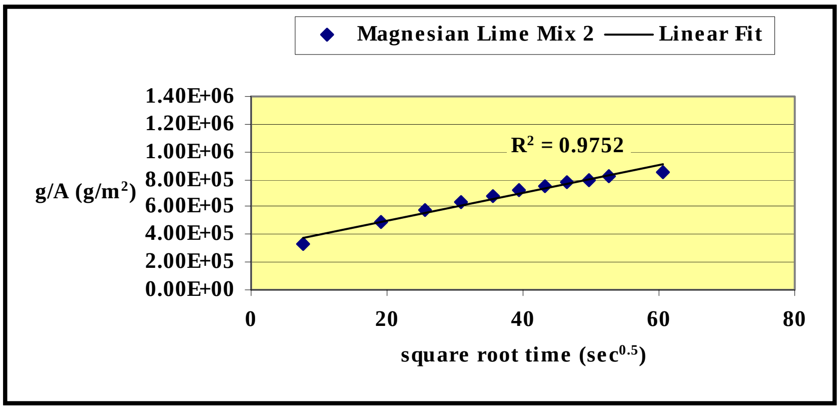

Figure 3. *Capillary suction for magnesian lime mix 2.*

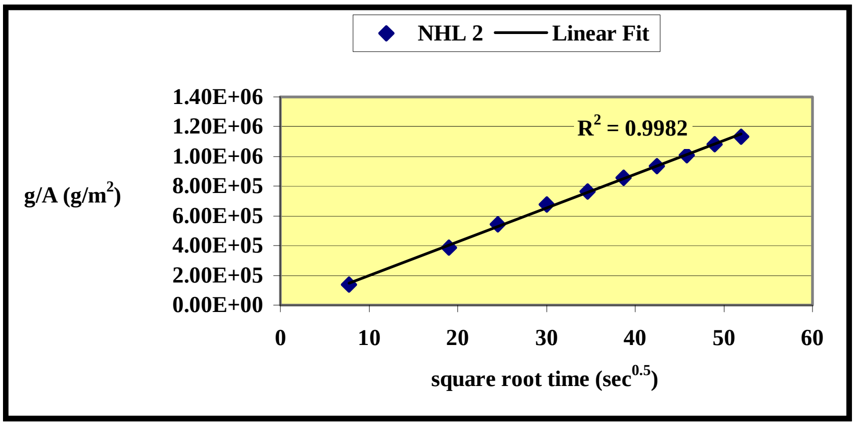

Figure 4. *Capillary suction for NHL2.*

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3.4 Water absorption of repair mortars

The values of water absorption by immersion are summarised in figure 5 below.

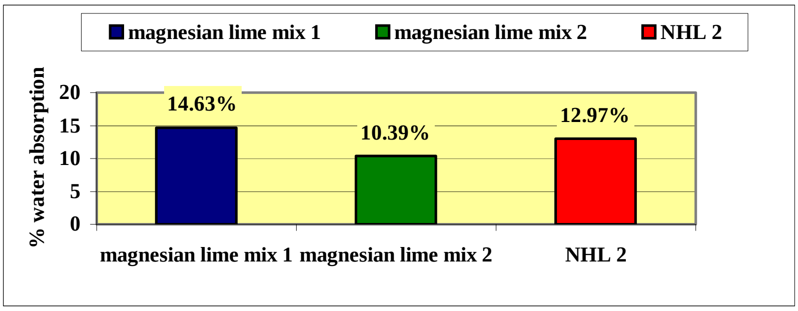

Figure 5. *Water absorption by immersion at atmospheric pressure.*

Magnesian lime mix 1 displays a higher water absorption than mix 2. This is probably due to the excess water used in the making of mix 1. 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 is not evident from figure 5, on the contrary, according to the results obtained, the NHL 2 mortar possesses a greater absorption than magnesian mix 2, suggesting that the magnesian mix has a smaller volume of pore space effective in transporting fluids.

3.5 Densities and porosity of repair mortars

The magnesian mortar has a slightly higher bulk density while the NHL2 mortar has a higher real density.The average bulk density for the magnesian mixes ranges from1606 to 1855 while the NHL mortar reaches 1831 as an average. The average real density ranges from 2209 to 2509 for the magnesian mortar and reaches an average of 2509 for NHL. Mg-lime mix 1 has the highest porosity of all mixes (27.31%). This is probably due to the excess water in the mix. Mg-lime mix 2 contains the lowest amount of pores (22.7%). The porosity of NHL2 is close to that of mg-lime mix 1 (27.03%).

3.6 Compressive strength of repair mortars

The feebly hydraulic lime is approximately 4 times stronger than the mg-lime (figure 7). This was expected as feebly hydraulic limes possess a hydralic set which provides mortars with an early strength. The strength of the magnesian lime mix fabricated with an excess of water is the lowest. This was also expected, as an excess of water greatly undermines mortar strength. The stregth values of the mg-lime mortar mixed correctly are comparable to the highest strength values shown by non-hydraulic limes (0.3-0.5 MPa, Holmes et al [9]).

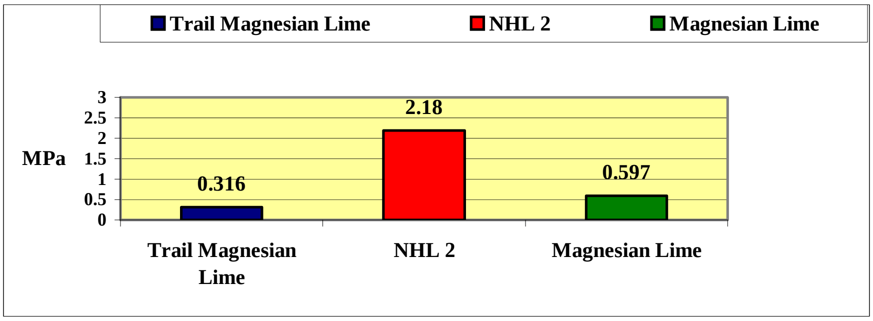

Figure 7. Compressive strength for all mixes

4 Conclusions

The mg-mix fabricated with an excess of water proved to be defective underperforming in all tests. The conclusions below are drawn from the performance of mg-mortar correctly mixed (mix 2). The lowest values of capillary, porosity and absorption shown by the mg-lime mortars when compared to those of the feebly hydraulic mortars suggest that mg-lime binders would perform superiorly in areas subject to presence of moisture. As expected, the hydraulic set of NHL 2 provides the mortar with an additional initial strength, and therefore mg-limes are weaker in compression than feebly hydraulic limes. However, the strength of the mg-lime mortar is slightly higher than the top values typically achieved by purer calcitic limes. These, together with the binder's hydraulic nature evidenced with petrographic analysis, suggest the possibility of mg-lime possessing hydraulic set. The mg-mortar outperforms the hydraulic mix in all tests except for compressive strength. However, the mg-lime mix would withstand the stresses and strains typically induced when confined within conventional masonry. The results suggest that, provided the lime has been adequately calcinated and slaked, mg-lime mortar can perform well as a building material.

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