

Physical properties of magnesian lime mortars

L. Chever · S. Pavía · R. Howard

Received: 16 March 2008 / Accepted: 23 February 2009 / Published online: 7 March 2009
© RILEM 2009

Abstract Magnesian lime is made from dolomitic limestone. The properties of magnesian lime mortars are not yet clearly established: some authors claim that Mg-lime has no hydraulicity and produces poor quality mortars that fracture, while others state that it produces quality hydraulic mortars. Here, Mg-lime was produced by burning magnesium limestone in a traditional limekiln. Mortars were made with increasing proportions of Mg-lime and calcium lime (CL90), and tested according to both European and ASTM Standards, and RILEM recommendations. Shrinkage, compressive and flexural strengths, absorption, capillary suction, density and porosity were evaluated, and the relationships between workability (measured as initial flow), water demand and strength investigated. The process of lime production evidenced that fabrication parameters are instrumental on the quality of Mg-lime and the subsequent mortar's performance. Temperatures over 900°C induced overburning resulting in clinker formation and a lack of reactivity. The choice of kiln fuel and burning arrangement proved essential in order to reach a homogeneous calcination; and sieving of unslaked

and over/underburnt particles as well as trials to determine raw feed proportions, were needed in order to avoid poor quality lime. Testing evidenced that the higher the Mg content, the greatest the mortar's shrinkage. However, shrinkage did not reach unacceptable values and cracking didn't occur. It was also evidenced that the Mg-lime possessed a lower water demand than the CL; and that Mg mortars behave well towards fluids (their capillary suction was lower and their porosity and absorption similar to those of CL90 mortars). The results also suggest that Mg-lime mortars possess compressive and flexural strengths equivalent to those of some feebly-hydraulic lime mortars: Mg-lime strength falls within the EN459-1 strength requirements for natural feebly-hydraulic lime. This research concludes that, providing production is correct, Mg-limes produce reliable masonry mortars which will shrink further but will possess a lower water demand and a slightly higher mechanical strength than CL mortars.

Keywords Magnesian-lime production · Magnesian-lime mortar · Shrinkage · Capillary suction · Water demand · Compressive and flexural strengths

L. Chever · S. Pavía (✉)
Department of Civil, Structural and Environmental
Engineering, Trinity College Dublin, Dublin 2, Ireland
e-mail: pavias@tcd.ie

R. Howard
Office of Public Works, National Monuments Depot,
Athenry, Galway, Ireland

1 Introduction

Dolomite $\text{CaMg}(\text{CO}_3)_2$ is the double compound of magnesium (Mg) and calcium (Ca) carbonates. It is



formed by substitution of Mg atoms into alternate Ca layers of the calcium carbonate (calcite: $\text{Ca}(\text{CO}_3)$) structure, and this is coupled to a change of bond strength and a displacement of atoms. As a result, dolomite is denser and harder than calcite. Ideally, dolomite presents an equal amount of Ca and Mg atoms. However, testing has proved that this is not the case, and dolomite contains an average of 53–58% of Ca per 42–47% of Mg [1–3]. The simple compound Mg carbonate (MgCO_3) also exists, however, a pure deposit of this mineral is rare whereas dolomite is quite common.

Dolomite mainly occurs as a substituting mineral altering the character of a calcareous limestone. This process is often incomplete and, as a result, dolomitic limestones naturally contain varying amounts of dolomite. Limestone can also contain magnesium carbonate (magnesite: MgCO_3) and CaCO_3 separately. The proportion of MgCO_3 can be used to classify the different types of magnesian limestone as presented in Table 1 [4]. The terms “magnesian limestone” and “dolomite” are used for any calcareous rock containing a large proportion of magnesium carbonate either as dolomite or as magnesite.

European Standard EN459-1 [5] defines dolomitic limes as those consisting of calcium oxide and magnesium oxide or calcium hydroxide and magnesium hydroxide without any additions of hydraulic or pozzolanic materials. The standard sets chemical requirements (Table 2) according to the $\text{CaO}+\text{MgO}$ content. In addition, EN 459-1 includes physical requirements for dolomitic limes: requirements for fineness and free water content are the same as for

CLs (the 0.09 mm residue by mass to be $\leq 7\%$ and the 0.2 mm residue $\leq 2\%$; and the free water content 2% or under). Dolomitic limes are also required by EU standards to pass the soundness test; to display a penetration between 10 and 50 mm and an air content value of $\leq 12\%$ for the standard mortar. Currently, the standard does not include requirements for setting times or compressive strength.

The production of magnesian lime slightly differs from that of high-calcium lime. The calcination of dolomitic limestone takes place between 510°C and 750°C , a considerable lower temperature than that needed to decompose calcitic limestone alone: 900°C . Consequently, when the calcite is well burnt, the dolomite tends to be overburnt. The decomposition of dolomite is more complex than that of calcite, and can occur in either one stage (Eq. 1) or two stages (Eqs. 2 and 3) [6].



If calcination follows Eq. 1, the full decomposition of dolomite will take place at 750°C . Whereas decomposition in two stages involves a higher temperature (the reaction in Eq. 2 occurs at approximately 510°C , and this is followed by the reaction in Eq. 3 taking place at 900°C). Each type of limestone has its own optimum burning temperature which needs to be determined through testing, in particular, Mg limestone must be carefully burnt in order to avoid the presence of overburnt particles that may cause problems as explained below.

The slaking of Mg-lime also differs from that of high-calcium lime. Magnesia (MgO) does not readily slake but gradually combines with water at a much slower rate than quicklime (CaO) [6]. Less than 25% of the MgO reacts with water under normal hydration conditions. The presence of impurities and overburnt particles increases the slaking time considerably, therefore it is also important that the lime is correctly burnt and sieved. Unslaked particles can later hydrate leading to mortar fracturing by expansion, thus, it is of great importance that any hydration method is 100% effective. To this aim, industrially, Mg-lime is usually hydrated in an autoclave at pressures of 1.7–7 atm and temperatures of $115\text{--}165^\circ\text{C}$, whereas if the lime is

Table 1 Classification of limestone containing dolomite according to ASTM Standards

Limestone	MgCO_3 content (%)
High calcium limestone	0–5
Magnesium limestone	5–35
Dolomitic limestone	35–46

Table 2 Chemical requirements for dolomitic limes (EN 459-1)

	$\text{CaO}+\text{MgO}$ (%)	MgO (%)	CO_2 (%)	SO_3 (%)
DL 85	≥ 85	≥ 30	≤ 7	≤ 2
DL 80	≥ 80	≥ 5	≤ 7	≤ 2



traditionally slaked, long time periods should be allowed to enable magnesia to fully combine with water subsequently avoiding a delayed hydration.

The carbonation process for Mg-lime may also differ from that of high-CL. Lanas et al. [7] state that the strength development of Mg-lime mortars is probably mainly due to the carbonation of portlandite. They refer to former authors that found no evidence of $\text{Mg}(\text{OH})_2$ carbonating to MgCO_3 and evidenced the complexity of the Mg^{2+} , HCO_3^- , CO_3^{2-} , H_2O system, strongly influenced by external conditions such as temperature, pH, P_{CO_2} and flow. These authors propose to attribute the higher strength of Mg-lime mortars when compared to that of CL mortars to other mechanisms such as calcite formation through dedolomitization.

Due to their different composition, production parameters (calcination and slaking) and hardening mechanism, the physical properties of Mg-lime mortars differ from those of CL mortars, however, these differences are not yet clearly established. Furthermore, there is a lack of agreement on the properties of Mg-lime mortars. Cowper [8] does not attribute any hydraulic properties to Mg-lime. According to this author, lime putty (non hydraulic) is obtained from highly-Mg limestone. On the contrary, Mg-limes have been reported to possess a certain amount of hydraulic set and develop a good ultimate strength. Smith, completing Vicat's work [3], indicated that Mg-lime "acquires a firm consistency and even as a common stucco has been described as of extreme hardness". Former authors stated that Mg-lime can harden underwater like hydraulic lime. Burn [9] reported researches conducted by Deville on specimens of magnesia stating that dolomite "after being calcined at a heat below dull redness, [...] forms underwater a stone of extraordinary hardness". Hydraulicity is confirmed by Vicat [3] who indicated that magnesia alone, when in sufficient quantity, will render pure lime hydraulic. Contemporary authors have also stated that Mg-lime can set underwater, however it is best if the paste is allowed to dry before immersion [10]. Nonetheless, the Mg-lime in this report did not set underwater, a certain amount of initial set may have taken place during immersion, however, this was not measured. Mg-lime has been reported as a good material provided it has been burnt carefully and given time to fully hydrate [11–13]. However,

contemporary authors have stressed problems caused fracturing when exposed outdoor. Seeley [11] claims that Mg-lime must not be overburnt; that a dry-slaking process must be employed followed by wet slaking for an extended time period; and that the lime must not contain coarse particles as it leads to popping and pitting. Mg-lime mortars can fail when exposed to pollution due to their magnesium compounds transforming into magnesium sulphates. These disruptive salts, soluble in water, can lead to weathering of the mortar and possibly affect adjacent structural materials.

This study follows on from previous work by Fitzgerald [12] and Pavía et al. [13]. The authors discussed the hydraulicity of Mg-lime by comparing the physical properties of Mg-lime mortars with those of natural, feebly-hydraulic lime and CL mortars. The strength of the Mg-lime mortars tested was higher than that typically reached by CL mortars. Based on this and the petrographic analysis of the binder, the authors suggest that Mg-lime mortar possesses a certain amount of hydraulic set. They also evidenced that, although the capillary suction of the Mg-lime mortars was initially higher, the overall suction was significantly lower than that of the hydraulic mortars tested. The authors state that Mg-lime mortars would perform well in moisture areas, and would withstand the strains typically induced when confined within conventional masonry. The authors finally suggest that, provided the lime has been adequately burned and slaked, Mg-lime mortar can perform well as a building material.

The objective of this research is to assess some of the most relevant physical properties of Mg-lime mortars. Work explores mechanical behavior through testing of both flexural and compressive strengths. Permeability was investigated by measuring capillary suction, water absorption and porosity. In addition, density was evaluated, and the relationship between workability (measured as the initial mortar flow) and the mortar's water demand evaluated. This research provides data on the physical properties of Mg-lime mortars by establishing and correlating values for the above properties and monitoring their variation. These properties not only relate to mortar quality and application but also to durability and structural performance. They govern both the behavior of mortars within built fabrics and their interaction with the masonry units.

2 Materials and methods

2.1 Lime production

The lime was produced by burning a dolomitic limestone quarried in Kilkenny and supplied by Roadstone Provinces Ltd. The magnesium content in this rock ranges between 10% and 20% and the amount of silica is low (1–2%). This implies a Ca Mg(CO₃)₂ content over 33%, the remaining being CaCO₃ except for 1–2% silica. The chemical composition of a representative sample of the current production, analysed with X-Ray Fluorescence (XRF), Atomic Absorption (AA), Inductively Coupled Plasma (ICP) and gravimetry by BHP, Limerick, is included in Table 3.

The stone was burned in a mixed-feed kiln lined with refractory brick, with a height of approximately 3.50 m and a total capacity of 4.1 m³. However, the kiln was charged to its small load volume capacity (0.63 m³) because this made it easier to control the burning process. The raw feed was charged through the top of the kiln shaft.

The lime production was undertaken at the Office of Public Works' Depot in Athenry, Co. Galway. The kiln operation was intermittent. Calcination experiments were carried out with different types of fuel including timber, turf and coal. Turf, also known as peat, is a decaying vegetable matter often found in

Table 3 Chemical composition of a representative magnesium limestone sample of the current production

	%	Method of analysis
Calcium	44.10	XRF
Magnesium	10.50	XRF
Silica (SiO ₂)	1.14	XRF
Iron	0.33	AA
Aluminium	0.01	AA
Zinc	<0.01	AA
Sulphur	0.05	XRF
Cadmium	<0.01	AA
Chromium	<0.01	AA
Cobalt	<0.01	AA
Manganese	0.04	AA
Nickel	<0.01	AA
Lead	<0.01	AA
Boron	<0.01	ICP
Organic matter	<0.10	Gravimetry

uplands and bogs in Ireland which can be used as a fuel when dried. During the experiments, it was noted that, when using timber and turf, the kiln temperature was difficult to control, reaching high peaks to later suddenly drop. As a result, coal (a Polish anthracite) was selected, because the temperature was easier to maintain and control over the burning operation. Alternate layers of stone and coal were charged through the top of the vertical stack. The fuel was initially ignited with wood, and the draught maintained by periodically letting air into the kiln.

The kiln temperature was measured using a thermocouple (Type K), suitable for temperatures up to 1100°C. The data were recorded with a Gemini Tinytag Data Loggers, Model TGI-3250, Range-10, connected to the software program PN SWCD-0009. The thermocouple resided horizontally, in a conduit 1.5 m above the frustrum's floor. According to the measurements recorded, the temperature varied between 700°C and 850°C, however, it occasionally reached over 900°C. When the temperature reached over 900°C, it was evidenced that the resultant lime did not slake and had to be discarded. This was probably the result of over-burning resulting in clinker formation.

The raw kiln feed consisted of rock fragments of similar size, from approximately 5 cm (maximum length) down (Fig. 1). Initially, the ratio of stone to fuel was approximately 1:1, however, following initial trials; the amount of fuel was slightly increased in order to achieve a more even calcination. As aforementioned, the burning was intermittent, performed as a single-batch operation. Calcination trials were undertaken with different amounts of burning layers. Based on these trials, a particular layer arrangement, consisting of two alternate layers of stone sandwiched between three layers of fuel, was finally selected. Trials were performed with additional layers (three alternate layers of stone sandwiched between four layers of fuel), however, it was evidenced that a smaller burning was more controllable and resulted in a more homogeneous calcination. The layered arrangement burned for 24 h subsequently collapsing, to be then drawn from the bottom of the kiln with a traditional, long-handle shovel. Following unloading, additional stone and fuel were loaded and the burning operation repeated. It was evidenced during burning that, following calcination, approximately 20% of the rock was





Fig. 1 A view of the kiln used to produce the lime

underburnt, while the same percentage was overburnt and the balance was the quick lime produced. Both the under and overburnt rock particles were removed by sieving. In addition, it was also noticed that a small amount of fuel remained unburnt. Since the stone and the fuel were amalgamated in the kiln and discharged together, the lime was contaminated with fuel. These were separated, prior to slaking, by sieving through a mesh.

The reactivity of the quick lime produced was low, hydrating at a slow pace: it took between 2 h and 3 h for the quick lime to slake through, evolving little heat during the process. Most of the quick lime batches left approximately 5% residue after slaking. This was mostly overburnt dolomite suggesting that, even though the kiln temperature remained between 700°C and 850°C in most batches, it locally reached over 900°C.

It was decided for the lime to remain stored immersed for a year, in order to allow a throughout hydration and avoid fracturing by expansion of unslaked particles. Hot-lime working was discarded based on both, the low reactivity of the quick lime produced, and advice by former authors on wet slaking Mg-lime for extended time periods [11].

This lime is not commercially available, and was only burnt at a small scale for two purposes: first in order to complete the research on which this paper is based, and, second, to undertake repairs to Ardamullivan Castle, a National Monument originally rendered with Mg-lime mortars. The resultant lime was of a grey to ivory colour. It was used to produce a plastering mortar for the external masonry walls of Ardamullivan Castle. Works were carried out in 2002, and the mason observed that the mortar possessed a good workability and showed good adhesion.

2.2 The aggregate

A siliceous French sand was used in all mixes. Its particle size distribution was established according to EN812-103.1 [14] and compared with the standard CEN reference sand in EN196-1 [15]. The results appear in Fig. 2. As it can be seen from these results, the sand has a good grading and is very similar to the CEN sand, with less fine particles (under 300 μm) and more particles greater than 2360 μm . The sand consists of angular grains of medium sphericity of mainly quartz with lower amounts of feldspar and occasional amorphous silica [16].

2.3 Mortar mixing and curing

The lime was tested following a year of immersed storage. All mortars tested are 1:3 mixes (binder:sand

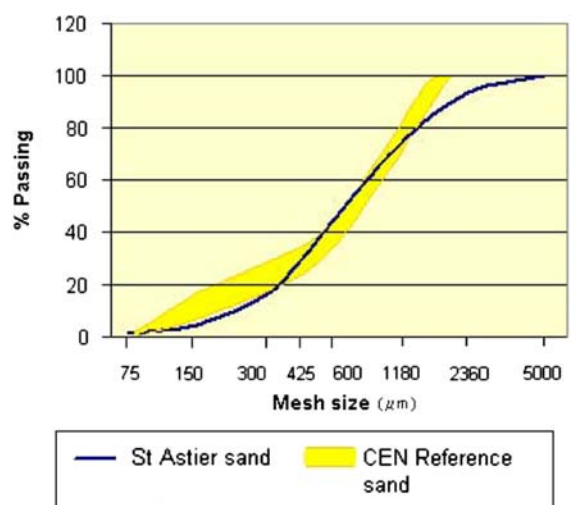


Fig. 2 Particle size distribution of the aggregate compared with the standard CEN sand

by weight). Initially, five mortar mixes were made. Four included Mg-lime contents of 100, 50, 25 and 10% respectively (the remaining binder being CL90) while a pure CL90 mortar was produced to serve as reference. These mortars were mixed by hand, adding sand to the putties until they reached a satisfactory consistency and tested for shrinkage, densities, porosities, water absorption, capillary suction, compressive and flexural strength. In these mixes, the water contained within the putties proved sufficient to achieve a good workability and no mixing water was added. In addition, three different mixes of each of the five mortar types above were made, each including the exact amount of water required in order to attain a specific flow (165, 175 and 185 mm respectively). The water content of these mixes, expressed as a percentage of the mortar's mass, is included in the results (Fig. 9). All the mortars were kept in their moulds for a week and later placed in a curing chamber for 49 days at 20°C temperature and 60–70% humidity. All tests were carried out using 160 × 40 × 40 mm prisms except for densities and water absorption, undertaken using 55 mm –edge cubes.

2.4 Outdoor exposure

As aforementioned, the Mg-lime fabricated was used to produce external plasters for the masonry walls of Ardammullivan Castle. Works were completed in the summer of 2002, therefore, the mortars have been exposed outdoor for 6 years. So far, neither fracturing (induced by expansion due to a delayed hydration) nor detachments have been observed in the mortars at the Castle.

2.5 Water demand and initial flow

A mortar's water content determines its initial flow, and this in turn characterizes workability, a property often defined by the mason by qualitatively describing the mortar's consistency. As aforementioned, three additional mixes of each of the five initial mortar types above (100% Mg lime, 50% Mg lime, 25% Mg lime, 10% Mg lime and 100% CL90) were made; each including the exact amount of water required in order to attain specific flows of 165, 175 and 185 mm respectively. The initial flow was measured, according to EN459-2 [16], for two purposes: to assess the

mortar's water demand and to investigate the relationship between water content and strength.

2.6 Shrinkage

Testing was based on American cement standards [17]. The drying shrinkage is defined as the decrease in length of the specimen, measured along the longitudinal axis, when the decrease is caused by any factor other than applied forces. During the curing period, shrinkage was measured with gauges accurate to 0.002 mm, on a daily basis for the first two weeks and then regularly for a month.

2.7 Permeability

Testing for permeability enables to understand the presence and movement of fluids. The ingress of carbon dioxide and water is particularly meaningful as it affects carbonation. Two tests were conducted to determine permeability: the capillarity test (to assess the amount of water ingress by capillary rise) and the absorption test (to quantify the volume of voids accessible to fluids).

2.8 Water absorption coefficient by capillary rise

C ($\text{kg m}^{-2} \text{s}^{-0.5}$) was expressed according to the equation below [18], where m_d is the dry mass; A the area of the specimen and m_i the mass at time intervals.

$$C = \frac{m_i - m_d}{A\sqrt{t_i}}$$

2.9 Water absorption

This was calculated as the percentage of water absorbed in relation to the dry mass (m_d) [19] (m_a -saturated mass).

$$\text{WA}(\%) = (m_a - m_d/m_d)100$$

2.10 Densities and porosity

The bulk (δ) and real (δ_r) densities were determined with the equations below [20], where m_d is the dry mass; m_h the hydrostatic mass and m_s the mass at atmospheric pressure.



$$\delta = \frac{m_d}{m_s - m_h} \quad \delta_r = \frac{m_d}{m_d - m_h} \quad (\text{g/cm}^3)$$

The open porosity was calculated according to the following equation [20].

$$P = \frac{m_s - m_d}{m_s - m_h} \times 100$$

2.11 Compressive strength

The compressive strength R_c (MPa) was measured using the equation below [16]; where A (mm^2) is the sectional area and (F) the load at which failure occurred.

$$R_c = \frac{F}{A}$$

2.12 Flexural strength

It was calculated using the equation below [15], where F_f is the peak load (N); b the side of the prism (mm) and l the distance between supports (mm).

$$R_{ff} = \frac{1.5 \times F_f \times l}{b^3} \text{ (MPa)}$$

3 Results

3.1 Shrinkage

The decrease in length of the samples appears in Fig. 3 for the first week and in Fig. 4 for the entire month. Table 4 indicates the total amount of shrinkage and the corresponding decrease in length. The results evidenced that the decrease in length is significant as, depending on the composition of the mix, the samples shrink between 1.71% and 3.20% of their original length which corresponds to a reduction in length ranging from 2.74 to 5.12 mm in a 16 cm sample. However, shrinkage was uniform and no significant cracks appeared in any of the samples. The samples containing more Mg-lime seem to shrink further, however, the results do not show a clear relationship between the proportion of Mg-lime in the mix and the drying shrinkage, as the 50% Mg-lime mix shrinks nearly twice as much than the 100% Mg-lime mix. The results also evidenced that the shrinkage of the CL90

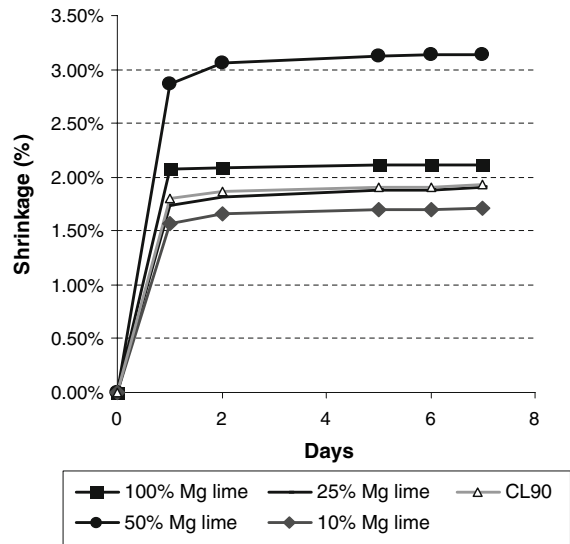


Fig. 3 Shrinkage during the first week of curing

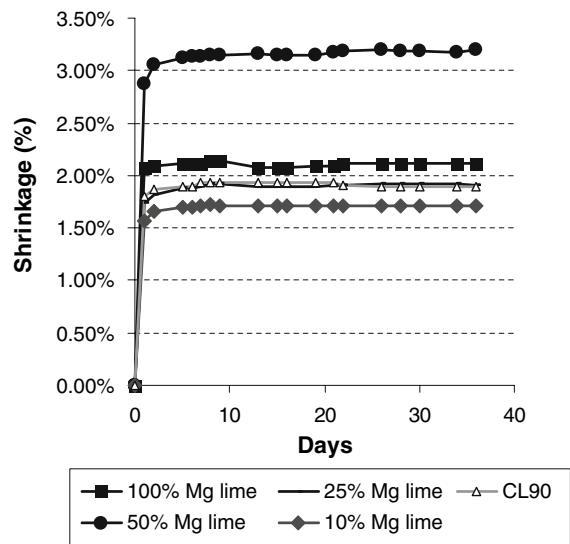


Fig. 4 Shrinkage during the first month of curing

Table 4 Total shrinkage and corresponding decrease in length in relation to the Mg-lime content of the mortar

	100% Mg-lime	50% Mg-lime	25% Mg-lime	10% Mg-lime	CL90
Decrease in length (mm)	3.38	5.12	3.06	2.74	3.04
Shrinkage (%)	2.11	3.20	1.91	1.71	1.90

reference mix was not significantly different from that of the mixes with a low Mg content. It was further noticed, that the decrease in length mainly occurred during the first two days when the mortar initially stiffens by evaporation.

During the first week, when most of the shrinkage occurred, the conditions were adequate with a 20°C temperature and 60% relative humidity. However, on day 10, an incident occurred leading to a 31°C temperature and 100% humidity remaining for 2 days. This did not harm the mortars, nevertheless, the mortars showed a slight increase in length which disappeared during the following 2 days.

3.2 Densities and porosity

These properties reached similar values in all the mortars investigated (Table 5). As it can be seen from the values and their standard deviation, the results are consistent. In general, the differences between the Mg mixes and the CL mortars are not significant and may be related to compaction. However, for the highest Mg contents (100% and 50%), there is a slight tendency for the porosity, as well as for the difference between real and bulk densities, to increase with the proportion of Mg: the 100% Mg mortar shows the greatest difference between bulk and real densities suggesting that this material holds the greatest

amount of pores; and this agrees with the porosity results evidencing that, the higher the amount of Mg-lime, the greater the mortar porosity. This tendency did not persist in the mortars with lower amounts of Mg-lime, as the porosity of the 10% mix is slightly higher than that of the 25% mix.

3.3 Water absorption

As it can be seen from the results of this test and their standard deviation (Table 6 and Fig. 5), the results are consistent. The water absorption values are very similar, probably too close to suggest any significant pattern. However, there is a slight tendency for the water absorption to increase with the proportion of Mg-lime in the binder, a tendency which is consistent with that of the open porosity and density results above.

3.4 Capillary suction

The results of the capillary suction test are included in Fig. 6 and Table 7. It can be seen from the Table, that some of the results are not as consistent as those from previous tests (the standard deviation is larger). These inconsistencies can be ascribed to differences in compaction, as this affects pore connections and therefore capillary suction. The results show

Table 5 Densities and porosity of Mg-lime and CL mortars

Mortar type	Bulk density			Real density			Porosity %		
	Value	Average	σ	Value	Average	σ	Value	Average	σ
100% Mg-lime	1.88	1.88	0.016	2.60	2.60	0.002	27.6	27.4	0.006
	1.90			2.60			26.7		
	1.87			2.60			27.9		
50% Mg-lime	1.89	1.90	0.015	2.61	2.62	0.010	27.6	27.2	0.003
	1.91			2.62			27.0		
	1.91			2.62			27.1		
25% Mg-lime	1.89	1.91	0.019	2.61	2.61	0.006	27.5	27.0	0.006
	1.91			2.62			27.1		
	1.93			2.62			26.4		
10% Mg-lime	1.92	1.91	0.012	2.61	2.61	0.010	26.7	26.9	0.002
	1.89			2.60			27.1		
	1.91			2.61			26.9		
CL90	1.92	1.90	0.016	2.61	2.61	0.008	26.6	26.9	0.004
	1.89			2.60			27.2		

σ —Standard deviation



Table 6 Water absorption of magnesium and CL mortars

Mortar type	Sample notation	WA %	Average	σ
100% Mg-lime	A4	12.73	12.61	0.003
	A5	12.25		
	A6	12.86		
50% Mg-lime	B4	12.70	12.43	0.002
	B5	12.25		
	B6	12.33		
25% Mg-lime	C4	12.57	12.33	0.002
	C5	12.36		
	C6	12.07		
10% Mg-lime	D4	12.09	12.29	0.002
	D5	12.50		
	D6	12.27		
CL 90	E4	12.17	12.34	0.003
	E5	12.52		

σ —Standard deviation

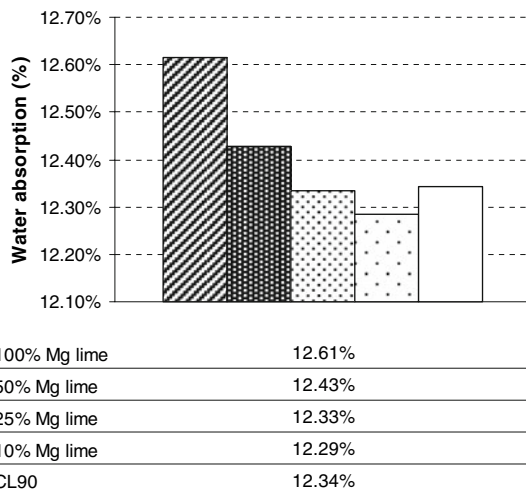


Fig. 5 Water absorption of Mg-lime and CL mortars

significant differences: the 100% Mg-mix possesses a suction coefficient 2.76 times lower than that of the CL90 mortar. The results also indicate that, roughly, the greater the Mg-lime content, the lower the capillary rise, and that increasing Mg-lime content considerably lowers suction by capillarity. In addition, as the absorption coefficient is related to the fineness of the pore structure, the results suggest that the pore system of the CL mortars is finer than that of the Mg-lime mortars.

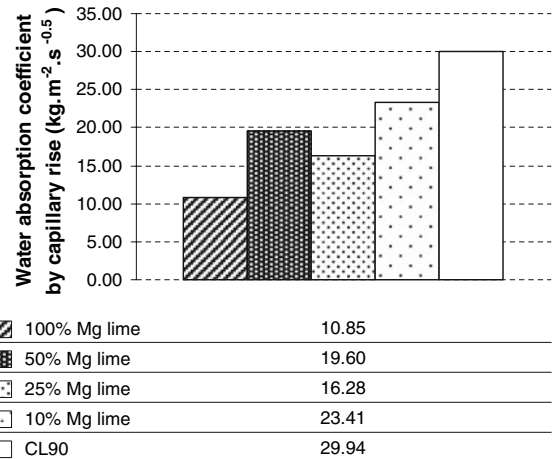


Fig. 6 Capillary suction of Mg-lime and CL mortars

Table 7 Capillary suction of Mg-lime and CL mortars

Mortar type	Sample notation	Capillary suction	Average	σ
100% Mg-lime	A4	10.04	10.85	0.721
	A5	11.10		
	A6	11.41		
50% Mg-lime	B4	13.14	19.60	5.659
	B5	23.71		
	B6	21.94		
25% Mg-lime	C4	15.61	16.28	0.603
	C5	16.78		
	C6	16.45		
10% Mg-lime	D4	28.28	23.41	6.991
	D5	15.39		
	D6	26.53		
CL 90	E4	29.14	29.94	1.120
	E5	30.73		

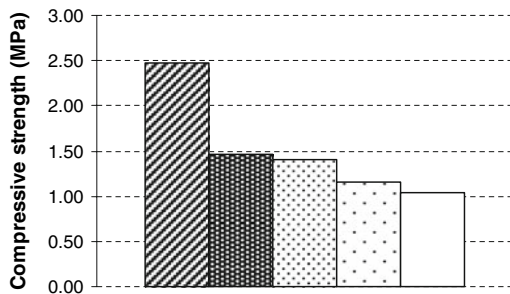
σ —Standard deviation

3.5 Compressive strength

The compressive strength results (at day 56th) can be found in Fig. 7 and Table 8. Their low standard deviation indicates that these are consistent.

According to these results, the 100% Mg-lime mortar, reaching a compressive strength of 2.48 MPa, is approximately 2.4 times stronger than the CL mortar, and the greater the amount of Mg-lime in the mix, the greater the compressive strength. The 50%





100% Mg lime	2.48
50% Mg lime	1.46
25% Mg lime	1.41
10% Mg lime	1.16
CL90	1.05

Fig. 7 Compressive strength of Mg-lime and CL mortars

Table 8 Compressive strength of Mg-lime and CL mortars

Mortar type	Sample notation	Rc (MPa)	Rc average	σ
100% Mg-lime	A1	3.14	2.48	0.574
	A2	2.18		
	A3	2.10		
50% Mg-lime	B1	1.81	1.46	0.305
	B2	1.30		
	B3	1.26		
25% Mg-lime	C1	1.46	1.41	0.048
	C2	1.38		
	C3	1.38		
10% Mg-lime	D1	1.32	1.16	0.161
	D2	1.13		
	D3	1.00		
CL 90	E1	1.14	1.05	0.167
	E2	0.85		
	E3	1.14		

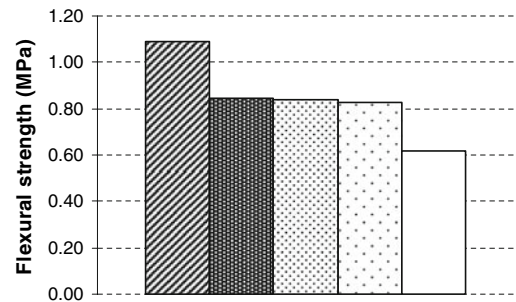
σ —Standard deviation

Mg-lime displays a strength 41% higher than that of the CL mix while the 10% Mg-lime is over 10% stronger than the CL mix. The compressive strengths recorded are comparable to those reported by previous authors [7, 12, 21]. In addition, the values obtained compare well to those of equivalent 1:3, NHL2 mortars previously studied [22, 23]. This suggests that Mg-lime develops strength similarly to feebly-hydraulic lime, reaching comparable ultimate values

as regards resistance to compression. In addition, the strength of some Mg-lime mortars may fall within the EN459-1 strength requirements for natural feebly-hydraulic lime (≥ 2 to ≤ 7 at 28 days) [5].

3.6 Flexural strength

The flexural strength results can be found in Fig. 8 and Table 9. The values are consistent, ranging from



100% Mg lime	1.09
50% Mg lime	0.84
25% Mg lime	0.84
10% Mg lime	0.83
CL90	0.62

Fig. 8 Flexural strength of the Mg-lime and CL mortars

Table 9 Flexural strength of Mg-lime and CL mortars

Mortar type	Sample notation	Rf (MPa)	Rf average	σ
100% Mg-lime	A4	0.90	1.09	0.174
	A5	1.23		
	A6	1.15		
50% Mg-lime	B4	0.57	0.84	0.235
	B5	0.99		
	B6	0.97		
25% Mg-lime	C4	0.68	0.84	0.167
	C5	1.01		
	C6	0.83		
10% Mg-lime	D4	0.90	0.83	0.060
	D5	0.79		
	D6	0.79		
CL 90	E4	0.64	0.62	0.029
	E5	0.59		

σ —Standard deviation



the 0.62 MPa of the CL to the 1.09 MPa of the 100% Mg mix. The 10%, 25% and 50% Mg-lime mixes showed a similar resistance to flexion, reaching an average 0.84 MPa. These values are comparable to those of NHL2 mortars (flexural strengths ranging between 0.7 MPa and 1.7 MPa on the 28th day [22, 23]), however, the strength development may be slightly slower than that of NHL2. According to the results obtained, the 100% Mg-lime mortar is 1.75 times stronger in flexion than the CL mortar, and, roughly, the greater the amount of Mg-lime in the mix, the greater the flexural strength.

3.7 Water demand and initial flow

The initial flows of the mortars in relation to their water content are presented in Fig. 9. The water content is expressed as a percentage of the mortar's mass. It can be evidenced from the results, that the CL mortars require more water than the Mg-mixes in order to achieve a specific flow. For example, the 100% Mg-lime mix requires 4.18% less water than the CL mortar to reach the 185 mm flow diameter; and 3.09% and 1.48% less water to reach the 175 mm and 165 mm diameters respectively. This suggests that CL possesses higher water demand than Mg-lime. This can be due to a greater fineness of the CL. It can also be

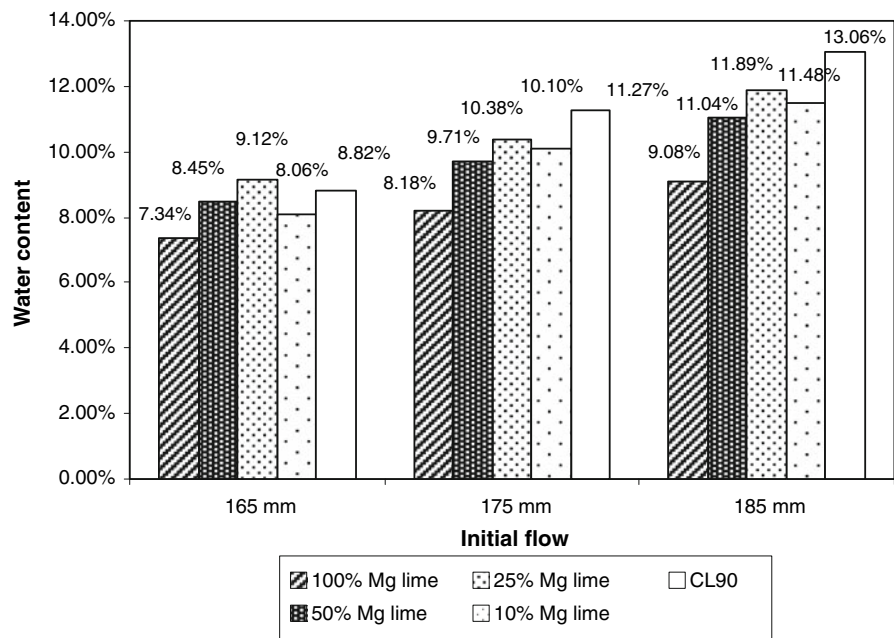
evidenced from the results that, in general, the higher the amount of Mg-lime in the binder the lower the amount of water required in order to reach a specific flow, thus the lower the water demand.

3.8 Correlation between water content and compressive strength

The compressive strength of the mortars mixed to flow is included in Table 10 and Fig. 10. As it can be seen from the standard deviation values, the results are consistent.

According to these results, all the mortars mixed to flow reached lower compressive strength values than those initially tested for compressive strength (Fig. 7). This was expected, as water was added to the mortars in order to attain specific flows, and this undermined their strength. With the exception of the 100%Mg-mix, the mortars mixed to 165 mm flow reached the greatest strength (this was also expected as the 165 mm flow samples contain the lowest amount of water). The only instance where a higher flow (175 mm) reached a higher strength was the 100% Mg mortar. This may be related to the presence of a certain amount of hydraulic set as, in order to optimize strength, mortars of higher hydraulicity require higher flow values than lower

Fig. 9 Initial flow of the mortars in relation to their water content



hydraulicity mixes [22, 24]. However, long term hydration during immersed storage may have removed any significant hydraulic properties of the Mg lime tested.

Table 10 Compressive strength of mortars mixed to flow as per table

Mortar type	Sample notation	Flow diameter (mm)	Average Rc (MPa)	σ
100% Mg-lime	100M1	165	0.79	0.06
	100M2	175	0.82	0.13
	100M3	185	0.67	0.13
50% Mg-lime	50M1	165	1.08*	0.05
	50M2	175	1.01*	0.05
	50M3	185	0.82*	0.11
25% Mg-lime	25M1	165	0.58	0.00
	25M2	175	0.53	0.06
	25M3	185	0.48	0.05
10% Mg-lime	10M1	165	0.52	0.05
	10M2	175	0.35	0.03
	10M3	185	0.23	0.05
CL 90	CL1	165	0.67*	0.02
	CL2	175	0.50*	0.05
	CL3	185	0.43*	0.02

All the values are the average of three samples except for * (average of 6). σ —Standard deviation

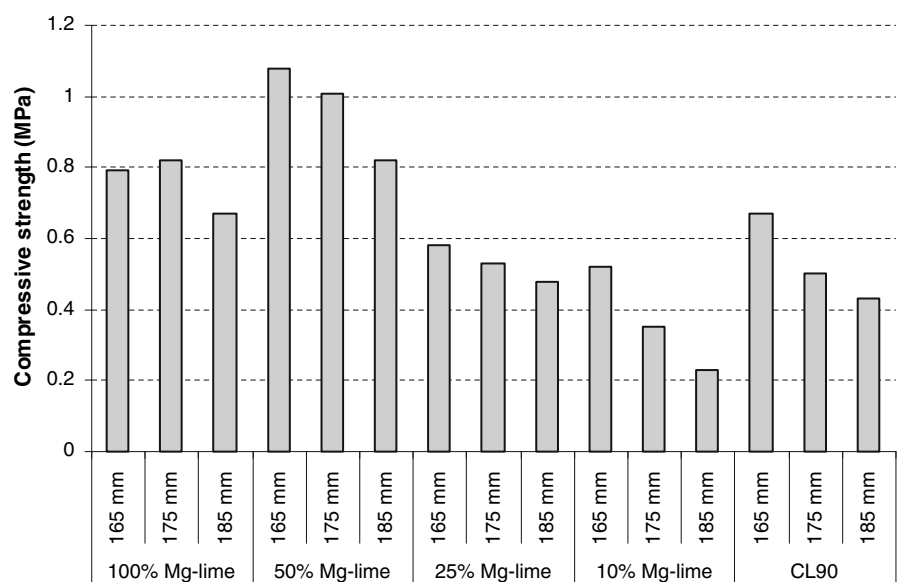
4 Conclusion

The traditional lime production process undertaken evidenced that fabrication parameters are instrumental on the quality of Mg-lime and the subsequent mortar's performance. Temperatures over 900°C induced over-burning, resulting in clinker formation and a lack of reactivity of the resultant lime; and the choice of fuel and burning arrangement proved essential in order to reach a homogeneous calcination. In addition, it was evidenced that sieving of unslaked and over/underburnt particles, and trials to determine burning temperature and raw feed proportions and arrangement, were essential in order to avoid a poor quality lime.

With regard to durability and performance, the good condition of the mortars following 6 years of exposure suggests that, long-term immersion (the lime was stored immersed for 12 months), allowed a throughout hydration subsequently avoiding fracturing by expansion of unslaked particles. Therefore, in production systems lacking from industrial hydrators, immersion over long periods may be advisable in order to avoid delayed hydration causing fracturing by expansion.

This research concludes that there is a direct relationship between the Mg content of a lime binder and a mortar's shrinkage, and that the higher the Mg content the greatest the shrinkage. However, when the Mg-lime is correctly produced, shrinkage of Mg-lime mortars is slow and uniform, not reaching

Fig. 10 Effect of water content on compressive strength



unacceptable values and not leading to cracking. In addition, this study concludes that the Mg-lime tested has a lower water demand than CL. Therefore, in order to produce a mortar with a specific workability, the Mg-lime will require less water than the CL, and this may be related to a greater fineness of the CL.

The results evidenced that the capillary suction of the Mg-lime mortars is lower, while their pore volume (evaluated through the measurement of porosity and absorption) is similar to that of CL mortars. This suggests that the pore system of the Mg mortars is coarser than that of the CL mortars, which agrees with the coarser grain of the Mg-lime deduced from its lower water demand. This also indicates that Mg-lime mortars possess a good behavior towards fluids, which can enhance carbonation and thus hardening, while enabling good performance in moisture areas.

Finally, this paper concludes that a Mg-lime binder provides a mortar with compressive and flexural strengths equivalent to those typically reached by some natural, feebly-hydraulic lime mortars, and that the strength of some Mg-limes fall within the EN459-1 requirements for natural feebly-hydraulic lime.

Based on the above, this research concludes that, providing production is correct, Mg-limes produce reliable masonry mortars which will shrink further but will possess a lower water demand and a slightly higher mechanical strength than CL mortars.

Acknowledgements In particular, the authors thank Paul McMahon, Senior Architect, OPW, for supporting and guiding this project. The authors thank National Monuments, OPW, Ireland, and The École Nationale des Travaux Publics de l'Etat (ENTPE), Vaulx en Velin, France, for funding this research. We are very grateful to Patrick Veale, Environmental Laboratory, Department of Civil Engineering, for helping us with the chemistry. The authors thank Larry Byrne of Clogrennanne Lime; Edward Byrne of The Traditional Lime Co. and Laurent Tedeschi and Pierre Bergoin of St Astier/CESA for donating materials for testing. We also thank Frank Fitzgerald of Roadstone Provinces Ltd., for providing the chemical composition of the stone. The testing was carried out in the Department of Civil Engineering, Trinity College Dublin. We are grateful to Eoin Dunne and Martin Carney for their assistance in the Materials and the Soils Laboratory; and Dave McAuley for his help with the equipment.

References

- Howe JA (2001) The geology of building stones. Donhead, Shaftesbury (1st edn 1910)
- Tucker ME, Wright VP (1992) Carbonate sedimentology. Blackwell, Oxford
- Vicat LJ (1837) Mortars and cements. Donhead, Shaftesbury (2003)
- ASTM C51-71 (1976) Classification of limestone containing dolomite. American Society for Testing and Materials
- EN 459-1 (2001) Building limes – part 1: definitions, specifications and conformity criteria. European Committee for Standardisation, CEN
- Oates JAH (1998) Lime and limestone: chemistry and technology, production and uses. Wiley-VCH, Germany
- Lanas J, Perez Bernal JL, Bello MA, Alvarez JI (2006) Mechanical properties of naturally hydraulic lime based mortars. *Cement Concr Res* (36):951–960. doi:10.1016/j.cemconres.2005.10.004
- Cowper AD (1927) Lime and lime mortars. Special report no. 9. Department of Scientific and Industrial Research. Donhead, Shaftesbury (1998)
- Burn RS (1871) Masonry, bricklaying and plastering. Donhead, Shaftesbury (2001)
- Holmes S, Wingate M (1997) Building with lime: a practical introduction. ITDG, London
- Seeley NJ (2003) Magnesian and dolomitic lime mortars in building conservation. *J Build Limes Forum* 10:38–45
- Fitzgerald B (2004) An assessment of some fundamental engineering properties of magnesian lime mortar. Dissertation, University of Dublin, Trinity College
- Pavía S, Fitzgerald B, Howard R (2005) Evaluation of properties of magnesian lime mortar. In: Brebbia CA, Torpiano A (eds) Structural studies, repair and maintenance of heritage architecture IX, Malta, June 2005. Vol 83 WIT Transactions on the built environment. WIT Press, Southampton, pp 375–384
- EN 812-103.1 (1985) Method for determination of particle size distribution. European Committee for Standardisation, CEN
- EN 196-1 (2005) Methods of testing cement – determination of strength. European Committee for Standardisation, CEN
- EN 459-2 (2001) Building lime – test methods. European Committee for Standardisation, CEN
- ASTM C 596-96 (1996) Standard test method for drying shrinkage of mortar containing hydraulic cement. American Society for Testing and Materials
- EN 1925 (1999) Natural stone test methods. Determination of water absorption coefficient by capillarity. European Committee for Standardisation, CEN
- UNE 67-027-84 (1984) Determinación de la absorción de agua de ladrillos de arcilla. Instituto Español de Normalización, AENOR
- RILEM (1980) Essais recommandés pour mesurer l'altération des pierres et évaluer l'efficacité des méthodes de traitement. *Materiaux et Constructions*. Bull Rilem 13(75): 216–220
- Pavía S (2005) Design of quality, durable mortar for the conservation of historic masonry fabrics. In: Dhir R, Jones M, Zheng L (eds) Proceedings of the 6th international congress: repair and renovation of concrete structures. Dundee. Thomas Telford, London, pp 469–476
- Hanley R, Pavía S (2008) A study of the workability of natural hydraulic lime mortars and its influence on strength. *Mater Struct* 41(2):373–381. doi:10.1617/s11527-007-9250-0

-
23. Pavía S, Toomey B (2007) Influence of the aggregate quality on the physical properties of natural feebly-hydraulic lime mortars. *Mater Struct* 41(3):443–620
24. Hanley R (2006) The relationship between workability and strength of lime mortars. MSc dissertation. Trinity College, University of Dublin