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Evolution of mechanical properties and drying shrinkage in lime-based and lime cement-based mortars with pure limestone aggregate

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HIGHLIGHTS

- NHL5 (1:1.75) achieved higher values of strength among NHL mortars.
- Pure lime mortars have higher drying shrinkage.
- NHL5 (1:1.75) is recommended as repair mortar in Cultural Heritage.

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ABSTRACT

In order to understand the behavior of the natural hydraulic lime, pure lime and lime cement-based mortars as a repair mortar it is necessary to investigate their mechanical-properties.

In this paper, the specimens were made with limestone aggregate as the restorers prepared the restoration works. The mechanical-strength as well as the evolution of Young's modulus and the drying shrinkage were monitored. The study was performed under curing conditions which lead to the development of a suitable mortar strength within the first 28 days without having to wait for longer curing periods.

The study revealed that NHL5 (1:1.75) mortar exhibits, for 28 days in a 70 ± 5% RH chamber, better results from the point of view of strength and shrinkage. A NHL5 (1:1.75) mortar could be a good candidate to be used like a repair mortar due to its good response to the movements of the stones in the buildings and its higher strengths. However the shrinkage in a lime cement-based mortar as well as a pure lime-based mortar is high enough as to cause a decrease in their strength. This information is very useful for the design of repair mortars.

1. Introduction

Before the beginning of 20th century the most widely used binder in the construction activity were lime based mortars, i.e. calcium lime, lime with pozzolan and hydraulic lime. After those years, the lack of stronger mortars with quicker hardening properties induced the development of the Portland cement. The replacement of the lime based binder was imminent. Years later, several authors indicated that the use of concrete mortars in our Cultural Heritage showed several disadvantages, such as crystallization processes of the salts present in the cement-based mortars that can damage the stone and the low flexibility of the cement-based mortars, which may cause structural problems when the building is subject to movements [1–3].

Hydraulic lime sets by hydration and non-hydraulic lime by carbonation with exposure to CO_2, without being able to set under water. For Natural Hydraulic Lime (NHL) mortars, the lime is obtained from limestone with silica and/or alumina. The presence of these impurities in historical lime based-mortars was not harmful and the content of silica (SiO_2) and alumina (Al_2O_3) was responsible for the hydraulic character [4,5]. Therefore, NHL mortars gain strength by the hydration of hydraulic components and the carbonation of the lime. Hydraulic reactions require a humidity of 80% or more because under this condition, the mortar surface cannot absorb CO_2 and carbonation is almost inexistent. Carbonation is achieved if the evaporation of the free water is produced due to a reduction of the relative humidity to 70% but with a consequently higher drying shrinkage causing some microcraking around aggregates [6]. The presence of cracks causes a reduction in strength and stiffness [4]. Nevertheless, no-hydraulic lime is produced from a high purity source of calcium carbonate such as

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Table 1
Chemical analysis of the main components of the NHL2, NHL5, the Portland cement CEM V, lime putty and the limestone aggregate. Bulk density (ρ) is also provided.

Sample	LOI (%)	SiO_2 (%)	CaO (%)	MgO (%)	X_2O_3 (%)	SO_3 (%)	Na_2O (%)	K_2O (%)	ρ (kg/dm^3)
NHL2	25.25	10.03	68.53	3.29	0.89	1.37	0.09	0.05	0.66
NHL5	18.6	22.45	43.13	2.15	10.00	1.30	0.59	1.67	0.65
CEM V	6.94	16.23	58.28	4.65	9.99	2.35	0.38	0.35	1.15
Lime putty	–	0.65	97.8	1.15	0.09	0.10	0.00	0.12	1.35
Limestone aggregate	44.67	0.53	50.40	2.74	1.09	0.47	0.06	0.04	2.60

LOI: loss of ignition indicates the weight loss due to calcinations at 975–1000 °C.
X_2O_3: percentage of Fe and Al oxides together.

Table 2
Results of XRD in the aggregate: +++: 60–90%; +: 3–10%.

Aggregate	Calcite ($CaCO_3$)	Quartz (%)
Limestone aggregate	+++	+

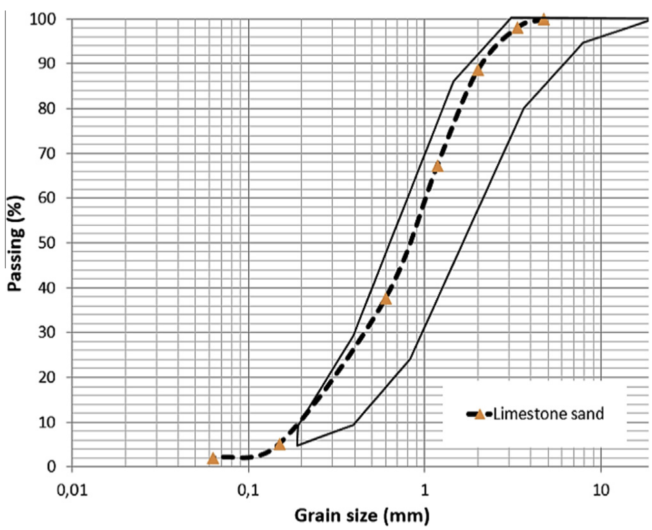

Fig. 1. Grain size distributions of the limestone aggregate used in the experience.

limestone (generally higher than 95%). Natural Hydraulic Limes (NHL) come from argillaceous limestone after its slaking and as a hydraulic lime, they present the ability to gain strength through hydration under water.

British Standard classified NHL into NHL2, NHL3.5 and NHL5 according to their compressive strength (MPa) after 28 days. These limes were used with sand at a ratio 1:3 and their compressive strength was 2, 3.5 and 5 MPa respectively [7]. In the case of non-hydraulic lime, quicklime is produced after a heating of pure calcium carbonate up to between 950 and 1070 °C. Then, this is slaked-hydrated by mixing it with water in order to form lime putty.

During the cement production, the limestone reaches temperatures over 1200 °C and during this process, called sintering, calcium silicates (C_3S, but not C_2S) and calcium aluminates (C_3A) are formed. In NHL, which are formed below 1200 °C, C_2S is the major hydraulic phase, but C_3S could be found in small amounts due to a local overheating in the kiln. Calcium hydroxide appears in NHL but it is not present in cement [8,9].

Several problems occurred during these last 50 years mainly with restored buildings [1], encouraging different authors to study the reason of these conservation problems related to physical and mechanical properties [10]. Van Balen et al. found that lime mortars, with their low compressive strength, can develop a better durability of the masonry over time than cement based mortars [11]. Researchers have developed their studies in the influence of the cement addition on the strength development, aiming to find the right proportion between cement and lime in order to promote the hardening reaction by the cement hydration. In this sense, they have tried to ensure that a higher strength of mortar is achieved in a minimum range of time. Cizer et al. indicated that the cement hydration contributes to the early stage strength development while carbonation is mainly promoted after 3 days and increases gradually in the following 180 days [12]. They concluded that mortars showing an increased lime content also presented more pronounced carbonation processes. The mechanical strength of lime mortars increased when the cement was added (0–40%), but it decreased in cement based mortars when a small amount of lime is added (the addition of 25% of lime gave a decreasing of 50% of its strength) [13]. Cizer et al. revealed that cement-lime mortars have a lower compressive and flexural strength than cement-based mortars [12]. They demonstrated that the compressive strength development was obtained after 180 day but the flexural strength was established beyond 28 days [12].

Other differences between the mortars which were made with different aggregates are determined by other authors as well. Aggregates have been used to improve the resistance to the moisture and the response to freeze–thaw cycles and to increase the mechanical properties of the mortar [14]. Manita and Triantafillou concluded that in repair mortars [15], sand in comparison to brick fragments as an aggregate causes a greater degree of strength development within the first 28 days. In both cases, after these 28 days, strength values did not increase. Lanas et al. concluded that NHL mortars with limestone aggregates exhibited higher strength than those with siliceous aggregates [9].

Besides strength, the ability of the mortar to accommodate to movements is very important, something connected to its

Table 3
Summary of prepared mixes.

Sample	Binder/Ag by volume	Cement/lime by weight (%)	Aggregate (g)	NHL (g)	Cement (g)	Lime putty (g)	Water/binder by weight	Added water (g)
NHL5 (1:1.75)	1:1.75	–	1500	431	–	–	0.70	302
NHL5 (1:2)	1:2	–	1500	358	–	–	1.00	358
NHL2 (1:3)	1:3	–	1500	196	–	–	1.00	196
0.75L:0.25CV:2	–	73	1500	–	144	492	–	86
1L:2.5	1:2.5	–	1500	–	–	525	–	–
0.75L:3	0.75:3	–	1500	–	–	437	–	–