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The effects of dosage and production process on the mechanical and physical properties of natural hydraulic lime mortars

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HIGHLIGHTS

- Advanced mechanical characterization of seven types of NHL mortars.
- Influence of five factors on the mechanical properties of NHL mortars.
- Relationship between mechanical and physical properties of NHL mortars.
- Empirical equations among mechanical properties of NHL mortars.

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ABSTRACT

Natural Hydraulic Lime (NHL) mortars are well-extended in restoration works presently. However, there is still a lack of standardization on their dosage methodology. Thus, seven types of mortar were fabricated and five factors which have an influence on their properties have been studied, in particular the water-binder ratio, the mold material, the aggregate size and type and the different curing conditions. Furthermore, an advanced mechanical characterization has been performed on these mortars, including the measurement of the fracture energy. Finally, some empirical equations for determining the relationships between these mechanical properties were proposed, which could be helpful when simulating the numerical models of historical constructions.

1. Introduction

Due to their good compatibility with the original material of ancient constructions and to their durability, lime-based mortars are used extensively in restoration works [1–4]. Despite their long track record, there is still a lack of standardization insofar as their dosage methodology and production process. Traditionally, the expression "1:3" has been used to define the dosage of a lime mortar. This expression is related with the binder-aggregate ratio by apparent volume and is also mentioned in the old treatises of Vitruvio, Alberti, Paladio and Benito Bails [5,6]. This dosage method is the one traditionally used in construction due to its facility for measuring in blocks, buckets, or any other measuring instruments. It was not until the 19th century, that industrialization made the relationship between volume and weight proportions possible [6].

However, the matter of dosage has not been well-defined. For example, the amount of water was never indicated, despite its strong influence on mechanical properties. The physical properties, especially the density, of the materials in use (binder and aggregate) were not explained either. This fact absolutely complicates the matter of the dosage of lime mortars. The expression "1:3" can refer to slaked lime (aerial or hydraulic), lime putty, with river or crushed aggregate, and result in different weights [6].

Regarding the dosage or the factors affecting the fabrication process of lime mortars, Moropoulu et al. [7] recommended that the appropriate binder-aggregate ratio for restoration synthesis could be 1:3 by volume. Lanas and Alvarez [1] prepared aerial lime mortars with different binder-aggregate ratios, ranging from 1:1 to 1:5 by volume and studied their influence on the mechanical properties. In order to obtain normal consistency and good workability, the corresponding water-binder ratios were ranged from 0.5 to 1.2. They observed a correlation between binder amount and mortar strength. However, in the case of high binder contents, the increase in voids led to strength reduction. They also concluded that angular

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limestone improved the strength of the mortar. Gameiro et al. [8] studied the influence of binder-aggregate ratio on the physical and chemical properties of air lime-metakaolin mortars. The water-binder ratios were also varied to get adequate workability (consistency range: 129 mm–144 mm, from dry to plastic lime mortars). They found that mortars with low binder-aggregate ratio (1:3 by volume) seemed to develop carbonation sooner and therefore reach their highest strength relatively early while mortars with higher binder-aggregate ratio (1:1) presented lower carbonation rates. The latter is not appropriate for use in conservation works due to its high shrinkage and strong mechanical properties, which is incompatible with substrate material.

Referring to NHL mortars, Kalagri et al. [9] investigated the effect of aggregate size and the binder type on microstructure and mechanical properties, the water-binder ratio by weight was between 0.49 and 0.61, the consistency was 160 mm for all the mixes. The experimental results showed that coarse aggregates enhanced the compressive and flexural strengths, increased the packing density, decreased the water demand and consequently, reduced the open porosity. They also proposed an equation in regard to the compressive strength and the median pore radius. Moreover, Lanas et al. [10] studied the influence of binder-aggregate ratios and aggregate attributes on the mechanical properties of NHL mortars. They prepared five different binder-aggregate ratios from 1:1 to 1:5 in terms of volume and four different types of aggregates. The consistencies were from 128 mm to 159 mm by varying the water-binder ratio. They observed that specimens with more binder content had higher compressive and flexural strengths and, additionally, the highest strengths were reached with limestone aggregates.

As for the influence of water content, a general tendency was observed by Papayianni and Stefanidou [11], Xu et al. [12]. As the water-binder ratio increases, the porosity increases and as a consequence, the mechanical properties decrease, that is to say, the mortar becomes weaker.

Furthermore, there are other aspects, such as the material of the molds used and the different curing conditions, which also affect the fabrication process of NHL mortars. No research has been performed on the former. However, for the latter, Lanas et al. [13] fabricated the aerial and hydraulic lime-based mortars and subjected them to different environments. They concluded that, in general, higher relative humidity (RH) increased the mechanical properties of NHL mortars. Grilo et al. [14] studied the mechanical and mineralogical properties of natural hydraulic-metakaolin mortars under different curing conditions. They observed that lower humid conditions favored a carbonation reaction (which governed aerial lime mortars), while high humid curing aided a hydration reaction (which partially governed NHL mortars). Thus, they concluded that humid conditions (95 ± 5%) favored compound hydration and pozzolanic reactions, which were relevant for the development of mechanical properties of NHL mortars. Grilo et al. [15] also agreed that higher RH curing regimes benefited these processes and also contributed to void infilling.

However, the study of the influence of all these factors on the fracture properties of NHL mortars, like fracture energy and characteristic length, is not so well-documented. In our previous work [16], the effect of two water-binder ratios (0.8 and 1.1) on mechanical properties of NHL mortars were studied alongside with the influence of shape and size. The results show that there was an apparent size effect on the compressive strength, that is, the value measured from prism was much larger than that from cylinder, the ratio could reach 1.6. In addition, there are no empirical equations for the mechanical properties of these mortars as the ones proposed by the FIB Model Code [17] and ACI Building Code [18] for concrete. Thus, the aim of the paper is to determine the influence of different factors (water-binder ratio, type and size of aggregate, curing condition and material of mold) affecting the dosage and fabrication process of NHL mortars on the mechanical properties, including the compressive strength of prisms and cylinders, the flexural strength, the splitting tensile strength, the elastic modulus and the fracture energy. Furthermore, some empirical formulas determining a relationship between these properties and the compressive strength are proposed for the first time.

The rest of the paper is organized as follows. The next section describes the experimental procedure. In Section 3 a thorough analysis of the results and discussion are provided in addition to formulas which establish relationships between the mechanical properties of NHL mortars. Finally, our conclusions are presented in Section 4.

2. Experimental procedure

2.1. Raw materials

The binder used for all seven types of NHL mortar was a commercial lime of class NHL 3.5, in accordance with EN 459-1 [19] and was supplied by "Socli, Italcementi Group" (France). It had a density of 2580 kg/m^3 and an apparent density of 850 kg/m^3. Different aggregates were used as well. The common one was a commercial crushed limestone with a maximum grain size of 4 mm. In addition, crushed limestone with a maximum grain size of 2 mm and river sand with a maximum grain size of 4 mm were also used in the fabrication of various mortars. The particle-size distribution curve of aggregates, determined according to EN 1015-1 [20], is presented in Fig. 1.

The apparent particle density and the apparent density of each type of aggregate are listed in Table 1, in accordance with the standards EN 1097-6 [21] and EN 1097-3 [22], respectively.

2.2. NHL mortar preparation

In total, seven types of NHL mortar were prepared and tested (see Table 2). First, as a reference material, a NHL mortar with a binder-aggregate ratio of 1:3 by volume was fabricated according to the traditional treatises and the recommendations of the references mentioned in Section 1 [5,7,11,14]. A water-binder ratio of

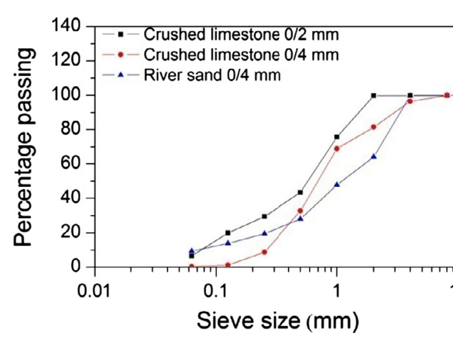

Fig. 1. Aggregates grading curves.

Table 1
Apparent particle density and apparent density of each type of aggregate.

	Apparent particle density (kg/m^3)	Apparent density (kg/m^3)
Standards	EN 1097-6 [21]	EN 1097-3 [22]
Crushed limestone 0/4 mm	2680	1820
Crushed limestone 0/2 mm	2740	1810
River sand 0/4 mm	2590	1460