Construction and Building Materials 153 (2017) 569–577

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Advanced mechanical characterization of NHL mortars and cohesive simulation of their failure behavior

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HIGHLIGHTS

- Full mechanical characterization of NHL mortars including the fracture energy.
- Great influence of water/lime ratios on the mechanical properties.
- Different results of compressive strength in prisms and cylinders.
- Numerical simulation of the cohesive behavior of NHL mortars.
- Numerical demonstration of shape and size effects in the compressive tests.

ARTICLE INFO

Article history:
Received 11 November 2016
Received in revised form 19 May 2017
Accepted 13 July 2017

Keywords:
Natural hydraulic lime (NHL) mortar
Water/lime ratio
Mechanical characterization
Fracture energy (G_F)
Size effect
Cohesive simulation

ABSTRACT

An advanced mechanical characterization of two natural hydraulic lime (NHL) mortars, with water/lime ratios of 0.8 and 1.1, is reported, including direct measurement of the compressive strength on two types of specimens, prisms and cylinders, the flexural strength, the tensile strength, the Young's modulus and the fracture energy. The results are significantly lower for the higher water/lime ratio. Besides, the compressive strength depends very much on the type of specimen used. A cohesive simulation is performed to prove that such variations in the compressive strength are due to the effect of the shape and size of the specimen.

1. Introduction

Lime-based mortars are widely used for restoration of historic buildings and structures and, for this reason, the research on these materials is abundant [1]. The most important characteristic of lime-based mortars is their compatibility with the substrate material in terms of chemical, physical and structural behavior. This is crucial to avoid further degradation due to the differential behavior between the original and the repair materials. In this sense, natural hydraulic lime (NHL) mortars can be used instead of air-hardening or lime-pozzolan mortars when early strength gain is essential. NHL mortars offer a promising solution due to their similarity with the in situ materials and their mechanical efficiency for the structural restoration of masonry [2]. Besides restoration, NHL presents further benefits: it is an eco-efficient material, it consumes low amount of energy during their production process, it generates reduced carbon dioxide emissions and it consumes carbon dioxide during the process of carbonation [3].

Knowledge about the mechanical properties of mortar is key to ensure a good performance of masonry walls [4]. In general, NHL mortars are well studied in terms of compressive and flexural strengths. For instance, Lanas et al. [2] have studied these properties according to curing time and binder/aggregate ratios. They concluded that angle-shaped aggregates, like limestone, contribute to strength increment while rounded-shaped aggregate causes strength reduction due to the increase of large pores. Kalagri et al. [3] have investigated the influence of aggregate size and type of binder on the flexural and compressive strength of NHL mortars. They showed that for the same type of binder, the use of coarse aggregates improves the mechanical properties. Marastoni et al. [5] proposed a method to estimate the material's strength envelope by representing the mortar's state of failure on the Mohr's plane. Experimental data were obtained from Brazilian tests on core drilled masonry samples with one diametral mortar joint and from double punch tests on extracted mortar joints. They

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http://dx.doi.org/10.1016/j.conbuildmat.2017.07.127
0950-0618/

pointed out that the compressive strength from the latter type of tests was 10% higher than that obtained from standard tests on prisms, mainly due to the different boundary conditions of the two types of tests.

The direct measurement of quasi-static elastic modulus of NHL mortars is not so well documented. Maravelaki-Kalaitzaki et al. [6] studied the modulus of elasticity in NHL mortars with pozzolanic additions and Drougkas et al. [7] obtained indirectly the elastic modulus of lime based mortars from the masonry and brick characteristics. They also derived relations between the compressive strength and the elastic modulus and compared their results with those in the standards. They observed discrepancies among the results obtained from various types of specimens and recommend using cylinders to measure mechanical properties, provided proper curing throughout the specimen is achieved. Others, like Rosell and Cantalapiedra [8] measured the dynamic Young's modulus by using ultrasonic impulse velocity and the static Young's modulus by performing conventional bending tests in lime and cement mortars. Nežerka et al. [9] studied the dynamic Young's modulus of lime based pastes using the resonance method and Pozo-Antonio [10] measured the dynamic Young's modulus in lime based and lime-cement based mortars with pure limestone aggregate.

Regarding the study of the fracture energy of lime based mortars, there is hardly any research so far, despite of the fact that it is an important parameter to characterize the ductility and fracture behavior of the material. Pereira et al. [11] studied the fracture energy of lime-cement mortars produced with different binders and sands. They concluded that the fracture energy was higher for artificial sand mortars for all classes and all types of binders. We did not find any previous work reporting fracture energies of pure NHL mortars.

Thus, the aim of the present study is to provide a full mechanical characterization of NHL mortars with water lime ratios of 0.8 and 1.1, particularly including the measurement of the fracture energy. Relating to fresh state, the consistence is the most important characteristic in order to allow a good application [11] and therefore it was also measured. Concerning hardened mortars, compressive strength on prisms and cylinders, flexural and indirect tensile strengths, Young's modulus, fracture energy and characteristic length were evaluated. These material parameters are useful for the design of repair masonry mortars. They were also used to model the mortar's failure behavior using cohesive models. In particular, we numerically reproduced the load vs crack mouth-opening curves of the fracture tests, simulated the compressive tests on prisms and performed a size-effect study. It shows that the differences in the values of the compressive strength from the two types of test stem from the effects of the size and shape of the specimen. The numerical model is also used to obtain a reference value for the compressive strength that can be considered a true material property. It roughly coincides with the value obtained from cylinders.

The rest of the paper is organized as follows. Next section describes the experimental procedure. Experimental results are presented and analyzed in Section 3. In Section 4 a thorough numerical analysis and discussion are provided. Finally, some conclusions are extracted in Section 5.

2. Experimental procedure

2.1. Raw materials

The natural hydraulic lime used was a commercial lime of class NHL 3.5, according to EN459-1 [12] and it was supplied by "Socli, Italcementi Group" (France). It has a density of 2.58 g/cm^3 and an apparent density of 0.85 g/cm^3.

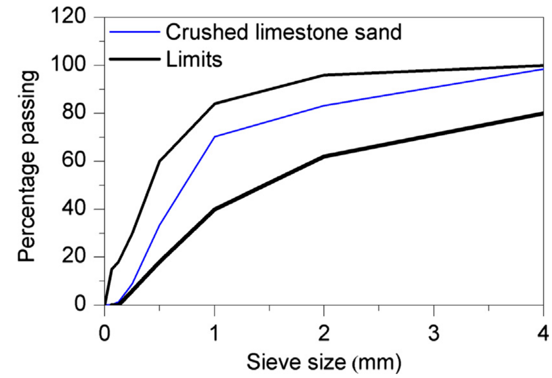

Fig. 1. Crushed limestone sand grading curve.

The sand used was a commercial crushed limestone common sand. The particle size distribution curve, determined according to EN1015-1 [13] is presented in Fig. 1. The sand has an apparent particle density of 2.68 g/cm^3 according to EN1097-6 [14] and an apparent density of 1.82 g/cm^3 according to EN1097-3 [15].

2.2. Mortar composition and preparation

Two mortar compositions were studied by using two water/lime ratios: 0.8 and 1.1 by volume. The lime/aggregate ratio used for both of them was the traditional one, 1:3 by volume. Volume proportions of compounds were converted in weight to avoid measurement imprecision on mixing process (see Table 1). The mortars were made with consistence of the flow table test of 130 mm and 240 mm, dried and fluid, respectively, according to standard EN1015-3 [16].

The mixture was performed according to standard EN1015-2 [17]. We made $40 \times 40 \times 160$ mm^3 prisms and 75 mm in diameter and 150 mm in height cylinders using steel molds, which were lubricated with mineral oil to prevent adhesion of the mortar to the mold walls. The mortar was poured in two layers when using the prismatic moulds and in three layers when using the cylindrical ones, each compacted with 25 strokes of the tamper. In total, 18 prismatic and 6 cylindrical samples were prepared for each type of mortar. They were demolded two days later according to standard EN1015-1 [13]. Curing was executed in the humidity chamber until the day of testing (RH 95% ± 5% and 20 °C ± 2 °C).

2.3. Test procedures

The characteristics of the mortars were evaluated by laboratory tests. For fresh state the consistence was measured. For hardened state the flexural, compressive and indirect tensile strengths, Young's modulus, fracture energy and characteristic length were evaluated at 56 days as well as the open porosity. The flexural and compressive strengths were determined according to EN1015-11 [18]. The flexural strength was measured by three point bending on three $40 \times 40 \times 160$ mm^3 specimens using an Instron 1011 testing machine at a low rate of loading (10 N/s). The compressive tests were conducted on the remaining six half-prisms from the bending tests. The compression was centered in the middle of the longest face on a surface of 40×40 mm^2. The tests were performed in load control at a rate of 50 N/s. We used an Instron 1011 testing machine for the NHL 1.1 and an Instron 8805 testing machine for the NHL 0.8, as it required higher capacity. The reported results are the mean and the coefficient of variation of the three and six specimens respectively.

Splitting tensile strength (f_{ct}) was measured through quasi-static splitting tests (Brazilian tests) on four $40 \times 40 \times 80$ mm^3