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Resonant acoustic evaluation of mechanical properties of masonry mortars

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HIGHLIGHTS

- Acoustic tests showed lower dispersion and higher elastic moduli than static tests.
- $E_{Dynamic}$ showed a mutual correlation with f_c and E_{Static}.
- Mixes with greater amount of lime had lower strength and much higher deformability.
- Lime had a strong influence in the variation of mechanical properties with age.
- Mortar with lime showed a behavior over time influenced by hydration and carbonation.

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ABSTRACT

This study aims to establish relationships between dynamic and static mechanical properties for masonry mortars containing lime. An experimental research was conducted with four mortar mixes of different compositions. Acoustic and compression tests were performed at different ages. Acoustic tests showed lower dispersion and higher elastic moduli than static tests. A good relationship between them was found assuming a power law (R^2 = 0.966). Dynamic elastic modulus showed a mutual correlation with compressive strength and static elastic modulus (R^2 = 0.982). A new equation was proposed to represent mechanical properties *vs.* age considering the coupling between the hydration and carbonation hardening mechanisms.

1. Introduction

Dynamic behavior of masonry structures has been on focus of recent research, involving NDT evaluations using sonic [1] and ultrasonic [2] testing, and especially structural assessment based on ambient vibrations [3–6]. A common strategy in this type of assessment is updating a Finite Element Method (FEM) model until the analytical and experimental responses match. This FEM model must represent precisely the geometry, stiffness, mass and boundary conditions that are found in the real structure, otherwise damage identification is an impossible task. After FEM model calibration, which can be performed manually by an experienced engineer or through an optimization procedure, damaged areas are identified according to the reduction of stiffness.

Different approaches can be employed to simulate masonry panels with FEM models. Rekik and Lebon [7] assume that a masonry structure can be modeled by a homogenous material considering the contribution of the block, mortar and block/mortar interface. Wei and Hao [8] consider the homogenization of masonry based on constitutive relations of brick and mortar materials. According to Baraldi et al. [9,10], for numerical simulation of historical masonry composed of stone blocks and mortar, the first can be treated as rigid blocks while the second as interfaces. Independent of the approach assumed for simulation, mortar properties have a great influence on the stiffness of masonry panels. In accordance to this, Baraldi et al. [10] noticed in modal analyses that, for a given geometry and boundary conditions, natural frequencies depend linearly on the square root of elastic modulus of mortar and on the inverse of the square root of block density.

Although the importance of the dynamic properties of masonry mortars, very limited research is found in the literature on this topic. Swamy and Rigby [11] performed resonant frequency tests of prisms made with cement pastes, mortars and concrete. They

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studied the relation between static (E_{static}) and dynamic elastic modulus (E_d), as well as correlations for E_d and dynamic shear modulus (G_d) to the cube compressive strength. Boumiz et al. [12] studied the mechanical properties of cement pastes and mortars at early ages. They performed ultrasonic tests to evaluate the dynamic elastic modulus and Poisson's ratio. A power law was obtained to relate the compressive strength and dynamic elastic modulus. Eiras et al. [13] studied the behavior of Portland cement mortars subjected to oven drying. They could evaluate how the moisture decrease, micro structural modification and shrinkage affect the dynamic properties obtained in vibration nondestructive tests.

However, their results cannot be direct applied to masonry mortars because of the composition of the mortars tested that has not included lime. It is well known that lime is frequently added in a great amount to masonry mortar mixes because of the significant increase in workability. When lime is included, several properties of mortars change as a consequence of the different hardening mechanisms in comparison to Portland cement. The hydrated lime hardens due to carbonation (Paiva et al. [14]), as shown by Eq. (1), while Portland cement hardens mainly due to hydration of calcium silicates (Mehta and Monteiro [15]), according to Eqs. (2) and (3). In masonry mortars both mechanisms are frequently present.

$$Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O \quad (1)$$

$$2(CaO)_2 \cdot SiO_2 + 4H_2O \rightarrow (CaO)_3(SiO_2)_2(H_2O)_3 + Ca(OH)_2 \quad (2)$$

$$2(CaO)_3 \cdot SiO_2 + 6H_2O \rightarrow (CaO)_3(SiO_2)_2(H_2O)_3 + 3Ca(OH)_2 \quad (3)$$

In a previous study of the authors (Haach et al. [16]), 36 cylindrical specimens (50 mm × 100 mm) of masonry mortars were tested by acoustic method and then subjected to axial compression at 90 days of age. Four mortar mixes were produced, with a fixed binder/aggregate ratio. The parameter varied was the amount of lime included in the composition. The acoustic tests obtained results with lower dispersion than the static tests. Besides this, a strong correlation was obtained between dynamic elastic modulus and compressive strength as well as between dynamic and static elastic modulus. The acoustic tests were considered an interesting nondestructive alternative to determination of elastic modulus of masonry mortars.

The consistent results obtained in this previous research stimulated the authors to expand the analysis in this paper. A greater number of cylindrical samples (240) were now produced allowing determination of dynamic and static properties at 7, 14, 28, 60, 90 and 120 days. The evolution of mechanical properties over time could be evaluated. Besides this, taking into account the different mixes and ages of testing considered in the present work, a very wide range of static and dynamic properties was generated, allowing more robust regression analysis in comparison to the previous paper from the authors. Prismatic specimens (50 mm × 50 mm × 340 mm) were also produced, making possible the determination of the dynamic transverse modulus (G_d) and Poisson's ratio (ν_d), consequently allowing a more complete determination of dynamic properties of masonry mortars.

Thus, the objective of this study is to characterize the dynamic elastic properties of masonry mortars (E_d, G_d and ν_d), their evolution with time and establish a robust correlation with mechanical properties obtained from static tests (f_m and E_{static}).

2. Methodology

The mortar compositions evaluated in this study were specified by BS 5628-1 [17]. Static and acoustic experimental tests were conducted to measure static and dynamic mechanical properties and analyze possible correlations.

2.1. Material properties

The mixes of mortars were prepared using Portland cement, lime and sand. Four mixes of mortar were prepared keeping the same binder/aggregate proportion: 1:3 (Portland cement:sand), 1:0.5:4.5 (Portland cement:lime:sand), 1:1:6 (Portland cement:lime:sand) and 1:2:9 (Portland cement:lime:sand). The water/binder ratios for the each mix of mortar were 1.00, 1.31, 1.90 and 2.00, respectively.

Portland cement type II specified according to the classification of ASTM C150 [18] was used in the mixes. The hydrated lime used is a commercial lime of type N for masonry purposes, according to ASTM C207-06 [19]. The sand used in this study is graded as zone 1 with a maximum diameter of 0.60 mm and a fineness modulus of 1.74 according to ABNT NBR 7211:2009 [20], which specifies sand properties for load-bearing masonry (Fig. 1). Some physical properties of materials are indicated in Table 1.

2.2. Test specimens

Mixing of mortars was performed in accordance with the recommendations given in ABNT NBR 13276:2002 [21]. The cement, lime and fine aggregate were mixed without addition of water until they were thoroughly blended in a mixer of vertical axis. The water was added and the mortar was mixed until it became homogeneous in appearance and had the desired consistency. Flow table test was performed according to ASTM C1437 [22] and the flow value obtained to produce a satisfactory workability was equal to 250 mm.

Sixty cylindrical specimens with 50 mm of diameter and 100 mm of height (height-diameter ratio of 2:1) were cast according to ABNT NBR 13279:1995 [23] for each mix totalizing 240 specimens. In addition, at least two prismatic specimens with 50 mm × 50 mm × 340 mm (length × height × width) were also cast from each mortar mix. Cylindrical and prismatic specimens were made in 4 layers of approximately equal volume and consolidated through rodding. Thirty strokes were used to compact each layer. Specimens were maintained in the laboratory environment for one day. After that, the molds were removed and the specimens were immediately stored in the moist chamber for curing until the age of testing. Static and acoustic tests were conducted in six different ages: 7, 14, 28, 60, 90 and 120 days. Prismatic specimens

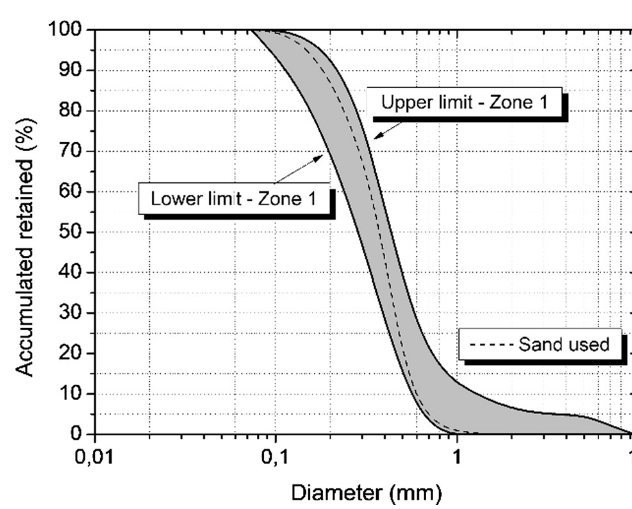

Fig. 1. Grading curve of sand.