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Influence of natural hydraulic lime content on the properties of aerial lime-based mortars

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HIGHLIGHTS

- Blended lime-hydraulic lime mortars mechanical and physical properties are studied.
- Mechanical strength of blended mortars does not improve with up to 25% hydraulic lime.
- Porosity decreases with increasing hydraulic lime due to a reduction of large pores.
- Blended mortars have a physical behaviour similar to that of the aerial lime mortar.
- Blended mortars are more adequate for restoration than the hydraulic lime mortar.

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ABSTRACT

Blended mortars are commonly used in conservation practices with the purpose of reducing the disadvantages presented by both lime-based and cement-based mortars. However, there is a lack of knowledge concerning the behaviour of such mortars. This paper evaluates the influence of hydraulic lime content on the properties of blended lime-hydraulic lime mortars. For this purpose, mortars composed of aerial lime and different percentages of natural hydraulic lime were tested. Their properties on the fresh state, mechanical strength at early age (28 days) and pore structure, water absorption, drying behaviour and water vapour permeability at long term (3 years) were studied.

Blended mortars with hydraulic lime contents higher than 25% showed higher initial mechanical strength and higher water absorption and desorption rates than the aerial lime mortar, with slight reduction of water vapour permeability. As so, these mortars revealed to be more promising to be used as repair mortars than the hydraulic lime one.

1. Introduction

Render solutions specified today for historic building repair frequently present a reduced compatibility with ancient materials, thus being inappropriate for this specific application [1,2]. To avoid this, mechanical, physical, chemical and aesthetic compatibility with the old masonry must be assured by formulating a repair mortar based on the characteristics of the original mortar, with similar constitution and appearance (when possible) and an adequate performance [2,3].

Recent literature concerning ancient building conservation has gathered some basic performance requirements that restoration mortars should fulfil [4]. In general, a compatible repair mortar should be no stronger than the existing mortar [5,6], considerably weaker than the masonry units and deform significantly before failure [7]. In terms of behaviour in the presence of water, the repair mortar should have similar or greater permeability to water and to water vapour than the existing masonry materials so that the water can evaporate quickly through the mortar pores, which is a key factor in salt induced decay [7]. It also should have good workability and be easy to apply.

Many researchers consider aerial lime as the most suitable material for repair mortars because it was the most common binder in mortar until late in the 19th century and it is chemically compatible with ancient mortars. However, the low strengths, long setting and hardening times, and the loss of traditional know-how in the manufacture and application of lime-based mortars inevitably led to their replacement with cement mortars in conservation practices [8,9]. This substitution has been found to cause serious damage to ancient masonries [10] because cement mortars are too strong and stiff, are less permeable than aerial lime mortars

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[11] and can have a high content of soluble salts that leach out over time, contributing to the decay of the original materials [7,12–14].

Before the industrial production of Portland cement and hydraulic lime, mortars with some hydraulicity were frequently used in an empirical way. This hydraulicity was provided by the addition of pozzolanic materials, whether natural (natural volcanic tuffs) or artificial like (crushed ceramics) to lime [15,16]. It was only in the beginning of the 19th century that Vicat proved that the hydraulicity of a binder is the result of the simultaneous burning of limestone and clay. This finding prompted the industrial production of hydraulic limes and Portland cement.

Hydraulic lime-based mortars are present in ancient structures both as building and restoration materials and in buildings dating from the 19th and the beginning of the 20th centuries [17–20]. Afterwards, cement started to be the dominant binder and the use of hydraulic lime has been scarce.

Even though hydraulic lime and Portland cement are both hydraulic binders, they have different C_3S/C_2S (tricalcium silicate/dicalcium silicate) ratios. Since natural hydraulic lime is produced at lower temperatures (below sintering temperatures), C_2S is the major hydraulic phase. C_3S, C_3A (tricalcium aluminate) and C_4AF (tetracalcium aluminoferrite) can also occur in small amounts, due to a local overheating in the limekiln. Calcium hydroxide or portlandite ($Ca(OH)_2$) is also present in natural hydraulic lime as well as gehlenite (C_2AS). The latter points to burning of the raw material at lower temperatures (<1200 °C) and is representative of natural hydraulic lime and not of cement, which is burnt at higher temperatures. These differences have consequences on the mechanical and physical properties of the mortars made with them.

The addition of hydraulic binders to lime-based mortars is a fairly common practice in conservation works in response to the reported objections to both lime and cement mortars. The use of these blended mortars can be interesting because aerial lime mortars with a certain amount of hydraulic binder added might behave like hydraulic mortars, which are characterised by higher strengths at early ages than aerial lime mortars (but not as high as cement mortars), and a faster setting time, which improves their application, while maintaining the good workability, water retention capacity, ductility and permeability of the aerial lime mortars, ensuring the compatibility with the old materials.

Considering that hydraulic lime mortars have been used since centuries, a lack of systematic studies concerning the behaviour of hydraulic lime and blended lime-hydraulic lime mortars has been reported [20], and might be justified by the fact that, in some countries, the availability of natural commercial hydraulic lime is reduced, so the use of suitable blended lime-cement mortars seems to be easier to prepare and more widely available [21]. As so, recent papers have shown more attention to lime-cement based mortars, focusing on the influence of the B/Ag (binder/aggregate) ratio or cement dosage on the behaviour of these mortars, on their mechanical properties and pore structure [7,21–28].

The paper focuses on the assessment of the influence of natural hydraulic lime content on the properties of blended aerial lime-hydraulic lime mortars. For this purpose, mortar mixtures were produced by substituting lime with natural hydraulic lime in various percentages. The influence of hydraulic lime content on the mechanical properties of the blended mortars is discussed at a curing age of 28 days, with the objective of assessing the potential of the tested mortars to overcome some of the frequently referred disadvantages of aerial lime mortars, namely their low strengths, long setting and hardening times, without losing the advantages of using aerial lime as binder. The paper also addresses the effect of hydraulic lime content on the pore structure and moisture transfer of blended mortars at a curing age of 3 years. The results provide fundamental insight into the properties of blended mortars, contributing to the body of knowledge needed to the proper selection of suitable mortar mixtures for conservation practices.

2. Experimental work

2.1. Mortars preparation

Mortars were prepared with hydrated lime powder (CL 90 according to EN 459-1:2002 [29]) from Calcidrata and a natural hydraulic lime (NHL 5 according to EN 459-1:2002 [29]) from Secil Martingança, both available as commercial products. The mineralogical phases of these binders were determined by X-ray Diffraction (XRD), according to the diffraction powder method, using a Rigaku Miniflex II diffractometer with Cu Kα (30 kV/15 mA) radiation and a speed of 2°/min, from 2° to 80° 2θ. The results were compared with the ICDD database. XRD results for the aerial lime (Fig. 1) show two mineralogical phases: portlandite ($Ca(OH)_2$), as the main phase, and calcite ($CaCO_3$). XRD analysis of the natural hydraulic lime showed the presence of portlandite ($Ca(OH)_2$), calcite ($CaCO_3$) and, in minor quantities, some calcium silicates.

Two fine aggregates from different sources but with similar grain size distributions were used (Fig. 2). Both aggregates were mainly composed of quartz, as evidenced by the XRD pattern obtained (Fig. 1), and their particle size ranged mainly between 0.3 and 2 mm (Fig. 2). The aggregates were previously dried at 100 ± 5 °C for 48 h before the preparation of the mortars.

An aerial lime mortar (A) and a hydraulic lime mortar (H) with B/Ag (binder/aggregate) ratios of 1:3 by volume were taken as reference mortars. This B/Ag ratio was selected because it is a common ratio adopted in research studies in the aim of lime based mortars [10,30,31]. The two aggregates were used in equal volumetric proportions (1:1.5:1.5 – binder:fine aggregate 1:fine aggregate 2). To avoid imprecision in the mixing process the B/Ag ratio 1:3 by volume was converted to weight, resulting in a ratio of 1:8 for mortar A and 1:4.5 for mortar H. Based on the reference aerial lime mortar (A), with a 1:8 B/Ag ratio by mass, four lime-hydraulic lime ratios were defined by partially replacing aerial lime with hydraulic lime in 10%, 25%, 50%, 75% by mass of the total binder, corresponding respectively to mortars AH10, AH25, AH50 and AH75. Table 1 presents the B/Ag ratios of the tested mortars.

All mortar mixtures were prepared using the necessary water amount (water/binder ratio) to obtain a consistency of 165 ± 5 mm measured by the flow table test [32], which gave good workability.

The mortars were produced based on the procedures established in EN 196-1:1996 [33]. For the preparation of the mortars, and before the addition of the aggregate, lime and natural hydraulic lime were intimately mixed.

After production it was determined the consistency of the fresh mortar, which was measured by the flow table test (EN 1015-3:1999 [32]), as well as its water retention capacity (EN 1015-8:1999 [34]).

Mortars were moulded in prismatic 40 × 40 × 160 (mm) casts and de-moulded 7 days later. Dry curing was used for lime and lime-hydraulic lime mortars (20 ± 5 °C and 60 ± 10% *RH*) and wet curing for the hydraulic lime mortar (20 ± 5 °C and 95 ± 5% *RH*). Mortar specimens remained in their respective curing conditions until testing.

At least 6 specimens of each mortar were prepared.

2.2. Analytical methodology

2.2.1. Mechanical properties

The mechanical properties of the tested mortars were evaluated directly through flexural and compressive strength tests based on EN 1015-11:1999 [35], after a curing time of 28 days. The three-point flexural strength test was performed on five specimens of each mortar mix, on a Seidner Form + Test SBP 100 testing machine, using a loading rate of 50 ± 10 N/s. The compressive strength test was performed on six of the resulting halves, for each mortar mix, on a Toni Pact 3000 testing machine and using a loading rate of 2400 ± 200 N/s. The reported results are the average value of the identical specimens.

2.2.2. Pore structure

The pore structure was evaluated in prismatic mortar specimens with 3 years of curing time in two ways: porosity and pore size distribution.

Open porosity was determined by the water saturation test with a hydrostatic scale according to RILEM guidelines [36] and was performed on at least two of the resulting halves of the flexural test, for each mortar mix. The specimens were previously dried under 60 °C inside an oven until constant mass was obtained. The reported results are the average value of the similar specimens.

The porosity and the pore size distribution of the mortars were determined by Mercury Intrusion Porosimetry (MIP). This test was performed using a Micromeritics AutoPore IV 9500 mercury porosimeter with a range of pressure between 0.345 and 229 MPa.

2.2.3. Water absorption by capillarity and saturation coefficient

The water absorption by capillarity and the saturation coefficient were determined on prismatic mortar specimens after a curing time of 3 years.