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Natural hydraulic lime versus cement for blended lime mortars for restoration works

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HIGHLIGHTS

- Comparative study of blended lime-cement and blended lime-hydraulic lime mortars.
- Pore structure of mortars has implications on water transport and mechanical properties and overall compatibility.
- Properties of blended lime mortars were more affected by cement than by natural hydraulic lime.
- Strength did not improve when natural hydraulic lime or cement contents up to 25% were added.
- The blended lime mortar with 50% natural hydraulic lime was the most promising mix to be used as repair mortar.

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ABSTRACT

The paper analyses the potential of blended lime-cement mortars to substitute blended lime-natural hydraulic lime mortars as repair mortars in restoration works, since the availability of natural hydraulic lime is reduced in many countries, unlike cement. The study focuses on the pore structure of both types of blended mortars and its implications on their water transport properties, initial mechanical strength and overall incompatibility risk. The influence of binder type and composition and of binder/aggregate ratio on pore structure was discussed. Cement altered more markedly the mechanical and water transport properties of blended mortars than hydraulic lime, with consequences on compatibility. Considering the properties evaluated, blended lime-cement mortars can be used but cement content should be higher than 25% (of total binder mass), so that there is a strength increase at early age, and lower than 50%, in order to not significantly affect compatibility. Nevertheless, the blended lime mortar with 50% natural hydraulic lime presented the highest potential for restoration.

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1. Introduction

An adequate choice of repair mortars is critical for the success of a restoration intervention. The mortar solution to be applied should be compatible with the ancient materials and durable. Lime-based mortars have been increasingly used for this purpose in order to achieve the required compatibility with the old materials. For this reason, several articles have been published on the virtues of using lime-based mortars for restoration [1–3]. Nevertheless, the loss of traditional know-how in the manufacture and application of these mortars and the existence of disadvantages regarding their use, such as low strength at early ages and slow setting and hardening times, is also recognised.

On the other hand, the use of hydraulic binders in repair mortars, especially cement, has been associated with compatibility problems due to their excessive strength and stiffness, low permeability and release of soluble salts [1,3–10].

In this context, blended mortars can be an interesting alternative if they are able to combine the advantages of both aerial lime and hydraulic binders: aerial lime can contribute to mortars workability, water retention, ductility and permeability, potentially ensuring the compatibility with the old materials, while hydraulic lime or cement can contribute to higher strengths at early ages and a faster setting time, improving their application.

The most studied blended mortars have been lime-cement ones, with the majority of the studies focusing on the influence of cement content or B/Ag (binder/aggregate) ratio on their mechanical behaviour and pore structure and its influence on the capillary absorption and moisture transport, phenomena related to the

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durability, degradation and service life of building materials [8,11–17].

Recent studies carried out in the field of repair mortars have encouraged the use of mortars based on natural hydraulic lime for restoration purposes, since they allow reducing the risk of incompatibility with the old materials [9,10,18]. In particular, a previous study carried out by our research group [19] allowed concluding that adding natural hydraulic lime contents greater than 25% by mass of the total binder to aerial lime mortars moderately increases strength at early age (28 days) while causing no significant changes in the physical properties in the long term (3 years). These results allowed concluding that blended lime-natural hydraulic lime mortars present potential to be used as repair mortars in restoration works.

However, natural hydraulic lime has a reduced availability when compared with Portland cement in many countries [11]. As so, it may be useful to know whether blended lime-cement mortars have a similar behaviour to blended lime-natural hydraulic lime mortars, since lime-cement mixtures are more widely available. In fact, from the review of the literature carried out, it is noticeable the absence of studies regarding a systematic comparison of the behaviour of blended lime mortars made with cement and hydraulic lime.

The performance and durability of a repair mortar and its compatibility with the old materials is strongly influenced by its pore structure.

In aerial lime mortars, porosity occupies an important volume and is found in two main forms: spherical and elongated, highly convoluted, pores [12,20]. The spherical pores are air voids, usually in the order of above 100 μm to few mm, formed due to the entrapped air during mixing and insufficient compaction [20]. These pores can be found in contact with aggregates or in the paste. The elongated pores are cracks caused by shrinkage during drying and most of them are interconnected with the spherical ones [12]. Capillary pores, in the range of 0.1–100 μm in size, represent the greatest part of the lime mortars porosity and are formed in the paste and in the interface between the paste and the aggregate (Interfacial Transition Zone – ITZ) during the hardening process from residual spaces occupied by kneading water. These pores are highly interconnected and play an important role in water transport by capillarity. W/B (water/binder) ratio and B/Ag ratio influence capillary porosity [21,22].

However, and while aerial lime mortars have a limited amount of pores lower than 0.1 μm in diameter [21], called sorption pores, cement mortars have a considerable amount of pores below that size. In fact, cement mortars have a totally different pore structure from aerial lime mortars and, therefore, from ancient mortars. That is the origin of most compatibility problems between cement mortars and ancient masonries.

The pore structure of cement based materials is composed of air voids, capillary pores, hollow shell pores and gel pores. Air voids are large, nearly spherical, isolated pores located in the cement paste, from entrapped air during mixing. Since these pores are not interconnected, they do not interfere in permeability [23,24]. Capillary pores, similar to the ones found in lime mortars, are the pores that dominate transport processes and in cement mortars have pore sizes around 0.1–10 μm [23–26]. These pores have to be continuous and not contain adsorbed water or a narrow entrance, even if the pores themselves are large [23], in order to allow the movement of fluids. Hollow shell pores are voids enclosed by a dense layer of hydration products and are located in the bulk paste, ranging in size usually from 1 to 15 μm [24,27] and their contribution to permeability is not well established [28]. Gel pores are pores that are associated with the formation of hydration products (localised between calcium-silicate-hydrate sheets) and have a size below 0.01 μm. Gel pores do not contribute much to the permeability of the cement paste, due to their small size, affecting essentially the hydration rate [23,24].

The pore structure of hydraulic lime mortars is close to that of cement mortars with unimodal pore size distributions, while aerial lime mortars present bimodal distributions. It is frequent the presence of spherical, mostly isolated, pores typical of cement-based materials. The existence of elongated pores (cracks) is less common than in aerial lime mortars, since in hydraulic lime and cement mortars the matrix is strong enough to resist to shrinkage stresses [12].

Blended lime mortars have an intermediate pore structure between that of a lime mortar and that of a hydraulic mortar, according to the relative amount of each type of binder, which becomes more complex with hydraulic binder increase [15].

The main purpose of this paper is to perform a comparative analysis of blended lime-natural hydraulic lime mortars and blended lime-cement mortars in order to assess their suitability to be applied as repair mortars in restoration works. The comparative analysis to be carried out will focus on the factors affecting the pore structure of both types of blended mortars (binder type and composition and binder/aggregate ratio) and its implications on water transport properties and on mechanical strength. Based on these characteristics, the overall incompatibility risk of the tested mortars will be evaluated in order to identify the blended mortar formulations with lower incompatibility risk and, thus, potentially more suitable for restoration purposes.

2. Experimental work

2.1. Mortars preparation

Mortars were made with hydrated lime powder (CL 90 according to EN 459-1:2002 [29]) from Calcidrata, natural hydraulic lime (NHL 5 according to EN 459-1:2002 [29]) from Secil Martingança and Portland cement (CEM II B/L 32.5 according to EN 197-1:2000 [30]) from Secil, all 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 CuKα (30 kV/15 mA) radiation and a speed of 2°/min, from 2° to 80° 2θ. The results were compared with the International Centre for Diffraction Data (ICDD) database.

The diffraction patterns obtained for the binders used are illustrated in Fig. 1. XRD results for the aerial lime showed two mineralogical phases: portlandite ($Ca(OH)_2$), as the main phase, and calcite ($CaCO_3$). The natural hydraulic lime used was composed of portlandite ($Ca(OH)_2$), calcite ($CaCO_3$) and, in minor quantities, some calcium silicates. The diffractogram of cement revealed the presence of bicalcium and tricalcium silicates, with some tetracalcium aluminoferrite, tricalcium aluminate/gehlenite and portlandite, and vestiges of gypsum.

Two fine aggregates from different sources, commonly used in Portugal in the formulation of mortars, were employed. Both aggregates are siliceous as evidenced by the XRD pattern obtained (Fig. 2) and have a similar particle size, ranging mainly between 0.3 and 2 mm (Fig. 3). These were dried at 100 ± 5 °C for 48 h before the preparation of the mortars.

An aerial lime mortar (A), a natural hydraulic lime mortar (H) and a cement mortar (C) with B/Ag ratios of 1:3 by volume were taken as reference. The two fine 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 of 1:3 by volume was converted to weight, resulting in a ratio of 1:8 for mortar A, 1:4.5 for mortar H and 1:4.1 for mortar C. Based on the reference aerial lime mortar (A), with a 1:8 B/Ag

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