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Lightweight natural lime composites for rehabilitation of Historical Heritage

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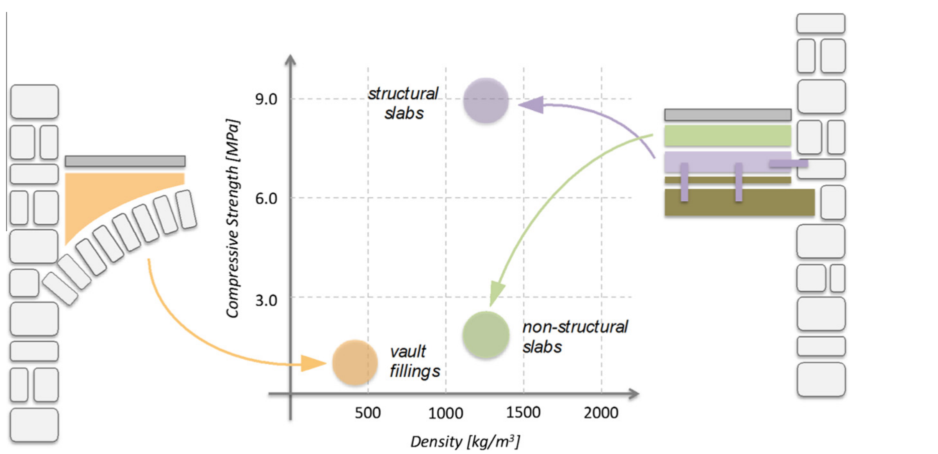
HIGHLIGHTS

- Lightweight natural lime mortar is developed for Historical Heritage rehabilitation.
- Vault filling & floor overlay, usually made with Portland Cement (PC), are targeted.
- The mortars proposed are chemically/physically/mechanically more compatible than PC.
- Mortar strength, density, stiffness, cost, and carbon footprint are compared.
- Several factors are varied and optimum mortars are selected for each application.

GRAPHICAL ABSTRACT



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ABSTRACT

Failure and deterioration of structural interventions on masonry buildings demonstrated the need for compatible repairs. Mechanical, chemical, transport properties and density of Portland Cement concrete are poorly compatible with lime mortar masonry structures.

Several natural lime composites are developed in this study for compatible Historical Heritage rehabilitation. Two relevant interventions with different strength/density requirements are considered: masonry vault filling and wooden floor non-structural overlay. Density minimization is attained with various lightweight aggregate (LWA) types/contents; different LWAs in one same mortar are also employed. Composites' density, strength, stiffness, cost, and carbon footprint are compared; the influence of different factors is discussed.

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1. Introduction

Selection of proper materials and technologies for structural repair of historical heritage is a delicate process, where mechanical, physical, chemical, cultural, and aesthetical requirements are often conflicting. Each of the most common construction materials (i.e., timber, steel, and concrete) has its own advantages and shortcomings. Concrete represents the most practical solution for complex shapes and irregular surfaces – such as masonry vaults and old wooden floors – due to its flowability. Nevertheless, the cement based materials commonly applied for these applications are poorly compatible from a mechanical, physical, and chemical point of view. The detrimental effect of poor mechanical compatibility has been observed in vaults retrofitted by adding cement based materials as extrados reinforcement or by applying lightweight reinforced concrete as new filling material in substitution to the existing uncoherent one. In these massive interventions, the new heavy and stiff cementitious composite added to the vault may be detrimental to the structural behavior and lead to the early collapse during strong earthquakes. For this reason, retrofit of such historic horizontal partition elements should set lightness and moderate resistance and stiffness as main requirements for the new repair materials. Physical and chemical compatibility is particularly important in masonry walls, where an inappropriate intervention will generate a disruption of the operational mechanisms regulating moist retention and movement. For instance, the application of brittle, cementitious mortars to stonework has several negative effects, including: (i) hindering moisture release, (ii) separating from the substrate through autogenous shrinkage, (iii) mechanical incompatibility generating differential response to mechanical actions and thus damage and further debonding, and (iv) detrimental chemical reactions caused by the chemical composition of Ordinary Portland Cement (OPC) concrete [1]. OPC concrete has a different chemistry and microstructure than the one of ancient lime concretes due to modern cement manufacturing techniques (OPC is calcined at very high temperature and interground with gypsum) and to the employment of specialized additives to modify workability and final properties. Natural hydraulic lime mortars similar to the ones employed in past ages represent a far better alternative in these applications.

The goal of the study presented in this manuscript is to develop cement-free highly compatible materials for structural and non-structural repair of historical heritage. Each repair application has its own main target, that is, low deformability, strength, or low weight increase. Therefore, depending on the application, the repair material has to meet various mechanical and weight requirements. A range of repair materials is developed in this study, while the following major parameters are monitored and compared: compressive strength (f_m), Elastic Modulus (E), and density (ρ).

Lime can be divided in two main categories depending on its reactivity to water: air lime and lime with hydraulic properties (i.e. Natural Hydraulic Lime). Compared to air lime, Natural Hydraulic Lime (NHL) is able to complete carbonation also in wet environment and underwater; in addition, NHL exhibits better mechanical performance and faster hardening [2–4]. NHL, defined as a "lime with hydraulic properties produced by burning of more or less argillaceous or siliceous limestone with reduction to powder by slaking with or without grinding" [5], is employed as binder in this study. To be classified as "natural", this lime needs not to contain any other admixture, neither those can be eventually added during the mixing process.

Weight reduction is attained by adding various types and amounts of lightweight aggregate (LWA). LWA represents the weakest component of the obtained lightweight natural lime composite (LWNLC) and the resulting strength and stiffness decrease needs to be assessed. In order to formulate appropriate mixture compositions, preliminary absorption tests on different LWAs are performed, as absorption of mixing water can significantly affect workability, final weight and hardened properties. Finally, cost and carbon footprints of the materials developed are assessed and compared.

1.1. Why natural hydraulic lime?

Natural lime represents an optimum solution in terms of compatibility, low carbon footprint, and practicality for several applications, including bedding, plastering, injection or filling, masonry reconstruction, and structural overlays. Some of the main advantages of natural lime are briefly summarized hereafter.

In terms of compatibility, lime mortar is well accepted as repair material by experts in restoration because most of the historical heritage – especially in Europe – was built with the use of lime. The first known applications of limes with hydraulic properties deliberately used as building materials are attributed to John Smeaton in mid-18th century; the same binder had been applied since then for two centuries, without systematic studies nor scientific surveys. Thorough information is now available on this topic [4–7].

From a mechanical and physical point of view, lower stiffness of lime mortar, compared to the ones of OPC mortar, can represent a relevant advantage in the field of repair or partial reconstruction of masonry portions, where lack of mechanical compatibility between old and new materials often lead to early damage and failure [8]. Furthermore, the overall crack behavior of lime is more favourable than the one of Portland cement, as lime mortars tend to develop multiple thinner micro-cracks. In comparison with Portland cement, lime has a lower hardening rate, which, in combination with the effect of carbonation, allows for a significantly lower shrinkage cracking if the fresh mortar layer is pressed/tight after the major drying shrinkage had occurred [2].

In addition, lime is far more chemically compatible with masonry than Portland cement is. The crystalline phases resulting from the high temperature of calcination of OPC, that is, tri-calcium aluminate (C_3A), and tetra-calcium alumina ferrite (C_4AF), and the gypsum added during the manufacturing process can have harmful effects on masonry by taking part into aggressive chemical reactions. In particular, C_3A reacts with sulphates and water generating sulphate attack, which causes deterioration of mortar joints, bricks, and stones, while the reaction of C_4AF with gypsum induces damaging expansion. At the same time, the moist released by masonry into concrete can accelerate the harmful effects of those same compounds on the durability of concrete itself. All in all, the different chemistry of natural lime mortar makes it not only more compatible to masonry but also more durable than OPC concrete overall [2,9–12].

The low porosity of OPC concrete does not allow the masonry to dry and thus the moist remains entrapped in the masonry, compromising structural health and ambient comfort [13]. Moisture may also accumulate underneath the cement based plaster, thus causing cement based plaster to detach or delaminate from the masonry support.

Finally, lime has insignificant levels of toxicity because basically made of Calcium Hydroxide and, in some cases, Magnesium Hydroxide. Lime manufacturing is much more environmentally sustainable than OPC manufacturing. As a matter of fact, the CO_2 produced during calcination is lower due to the lower temperature of calcination. In addition, air lime during calcinations frees CO2 and during carbonation captures it [14,15].

1.2. Applications and targets

On the basis of the previous observations, cement based composites should be avoided in the retrofit of existing masonry buildings. In the last years, with increasing attention paid to eco-compatibility