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The role of aggregate characteristics on the performance optimization of high hydraulicity restoration mortars

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HIGHLIGHTS

- Enhanced packing density resulted in water/binder ratio reduction up to 26%.
- Optimized packing density allows reduced binder content for the same strength level.
- Tailored properties of restoration mixtures enhance performance and compatibility.

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ABSTRACT

Performance characteristics of mortars are governed by the type of binder, type and grain size distribution of aggregates and their mix proportions. Aiming at parametric optimization of NHL restoration mortars, this study discusses the effect of physical and geometrical properties of aggregates on fresh and hardened mortars, tested after 28 days of curing. Four different sands 0/2 mm were studied and ten mixtures were prepared with natural hydraulic lime (NHL5). The effect of gradation, packing density and shape of aggregates was studied, versus the mechanical properties and porosity. The results highlight the crucial role of the morphological parameters of aggregates, especially of packing density, on the development of microstructure and the mechanical performance of mortars. The contribution of aggregates to tailoring and controlling the mechanical and microstructural properties of repair mortars is also demonstrated in this work. To this end, it was proved that the mechanical performance of mortars is controlled by the combination of both binder amount and packing density of the aggregates.

1. Introduction

The effect of physicochemical and geometrical characteristics of aggregates on the performance of cement based mortars and concretes – although thoroughly studied and described in several papers, directives and standards [1,2] – is always an issue for the construction sector, since it affects the performance of the entire building structure.

In the case of restoration mortars, which are usually case-specific designed according to performance and compatibility requirements, the characteristics of raw materials is one the most influential parameters for the modification and optimization of their performance.

Each of their components (binder, aggregates, water), as well as their relative proportions in the mixture affects the rheological properties of fresh mixtures [3,4] as well as the microstructure and mechanical properties of the hardened mortars [5]. During mixing, workability of the mixture is controlled by the interaction between aggregate particles and the binder and is closely related to the amount of binder (b/a ratio) and the water requirement (w/b ratio) of the initial mixture. The way in which those ratios affect workability are well known and studied in great extent [6–8]. Moreover, an important factor affecting the microstructure and mechanical properties of mortars is the type and the hydraulicity index of the binder [9,10].

The fact that mortars' performance can be modified by altering the properties of raw materials, led historically to their use in diverse building applications. Modification of the above parameters allows the parametric design of modern mortars, especially in the field of conservation of built heritage, where each monu-

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ment poses a different set of microstructure, performance and durability requirements [11,12]. The interrelated properties of raw materials and final mixtures are of particular interest for the design of restoration mortars, where the choice of raw materials is often guided by compatibility requirements [13], while their properties and characteristics contribute in meeting the expected performance requirements [14,15]. Aiming to contribute towards a successful design of modern restoration mortars, the effect of physical and geometrical characteristics of aggregates on the properties of fresh and hardened NHL mixtures is studied in this paper. Thus, the results obtained could lead to the enhanced performance and reduced cost of interventions in both restoration works and modern construction projects. The results provided could be also of interest for industrial production of pre-mixed mortars and contribute to the successful implementation of aggregates.

The selection of NHL binder was based on the fact that hydraulic lime mortars offer a promising solution for conservation interventions, due to their compatibility with original building materials and their mechanical efficiency for structural restoration of stone masonry [8]. Besides restoration, further benefits promote NHLs as an eco-efficient material including low energy consumption during production process, reduced carbon dioxide emissions, as well as carbon dioxide consumption during carbonation. More specifically, by replacing Portland cement with NHL results in reduction of total CO_2 emissions between 75 and 81% [16,17]. Finally, the free-lime ($Ca(OH)_2$) present in the initial material provides a great potential for the initiation of an autogenous, self-healing mechanism, when needed [18,19].

Qualitative requirements of aggregates are described in several standards [20–23], aiming to provide generic specifications for building and construction applications. However, what they do not offer is the correlation between the properties of aggregates and their impact on mortar properties (fresh and hardened). Among other parameters, the physical and geometrical characteristics of the aggregates form the link between the intent of the initial mix design (quality of raw materials) and the performance of the resulted, hardened mortar.

Aiming to highlight the parameters that control the optimum binder quantity needed for achieving desired performance characteristics of fresh mixtures, this approach considers fresh mortars as a composite system where voids between aggregate particles are filled with different amounts of paste. In this context, the mixtures studied consider three different binder proportions, respective to the volume of voids measured among aggregate particles.

Depending on w/b and b/a ratios, the developed microstructure and the consequent open porosity are modified, affecting the mechanical performance of hardened mixtures.

Furthering the effect of previously published results [10], this work aims to emphasize on the particular properties and morphological characteristics of aggregates in the sand fraction (0/2mm) that can be successfully elaborated in practice and used as a tool, during the design of "tailor-made" mixtures.

2. Experimental

2.1. Properties of raw materials/ sands

Aiming to study the effect of aggregates on the qualitative characteristics of fresh mixtures and hardened mortars, a set of mixtures was prepared using a natural hydraulic lime of high hydraulicity (St Astier NHL5) and four different types of aggregates, in the same sand fraction (0/2 mm). The selection of NHL5 was based on the requirement for enhanced strength properties at early stage, in an attempt to study the effect of aggregate properties on the performance of hardened mixtures at such an early curing period.

The selected sands include the natural standard sand [24] (S1), two types of river sands (S2 and S3) and a quarry sand (crushed limestone) with angular particles (S4).

More specifically, the natural aggregates used are differentiated on the basis of their gradation [25], as shown in Fig. 1. Gradation curve of the standard sand (S1) exhibits two inflection points which correspond to grain-sizes of 0.25 and 0.5 mm. Sand S3 is richer in the coarser fractions (i.e. larger than 0.5 mm), in contrast to S2 sand that excels in the finer fractions, (i.e. smaller than 0.25 mm). Therefore, S2 sand simulates the grain size of the standard sand S1 in finer fractions whereas sand S3 in the coarser. Finally, in order to eliminate the factor of gradation characteristics (i.e. Cu, Modal diameter, fines%) and examine the effect of the grains' shape (angularity), the gradation of the crushed sand (S4) was modified to fit that of standard sand (S1).

Based on the grading curves of natural aggregates (Fig. 1), uniformity coefficient (Cu) and percentage of fines (% fines) were calculated [26].

Uniformity coefficient (Cu) expresses the grading homogeneity of the sand and is calculated by the following equation:

$$C_u = \frac{D_{60}}{D_{10}}$$

D_{10} and D_{60} refer to the maximum sieve opening through which passes 10 and 60% of the grains respectively.

Modal diameter of aggregate particles was calculated in order to highlight differences among the particle distributions. Modal diameter or Mode represents the most frequent value, which reflects the value of the aggregate class with the higher frequency. Modal diameter identifies with m_i (sieve opening) that for which the highest frequency (% retained weight, f_i) appears [27].[1]

Moreover, fines (% of the material that passes through 63 μm sieve), physical properties of sands such as bulk density (p_b), particle density (p_{tr}) and packing density (p_p) were determined according to the standard procedure described in EN 1097-3:1998 [28].

Representative samples from each sand were measured water-saturated (m_2), surface-dry (m_1) and after complete drying (m_4) in a container of known volume (m_3).

Particle density was calculated by the following equation:

$$p_{tr} = \frac{m_4}{m_1 - (m_2 - m_3)}$$

To determine the apparent density under compaction, the weight of each sample was measured in a known volume container (after compaction). Apparent density (bulk density) was calculated by the following equation:

$$p_b == \frac{m}{V_{bulk}}$$

where m: weight of each sample, V_{bulk}: container volume, Voids% is calculated by:

$$Voids\% = 100 * \frac{p_{tr} - p_b}{p_{tr}}$$

Packing density was calculated according to the equation:

$$pp = 1 - Voids\%$$

The values obtained are presented in Table 1.

Additionally, chemical and mineralogical analyses were carried out by energy dispersive X-ray spectroscopy (FEI Quanta Inspect SEM/EDX) and X-ray diffraction (Siemens D500) respectively, using a 0.03°/5 s step and Cu Ka radiation.

Standard sand (S1) exclusively consisted of quartz, sands S2 and S3 consisted mainly of quartz and some minor feldspar phases, while S4 was characterized as calcitic, containing less than 2% of alumino-silicate impurities.

Aiming to define the geometrical characteristics of aggregates and highlight the differences between natural and crushed aggregates, polished sections of different fractions for both sands were examined in a FEI Quanta-Inspect scanning electron microscope (SEM), in backscattered mode [29]. The differences between the two sands were more obvious in the 1/2 mm fraction, at a field of view (ROI) double the maximum grain size, as seen in Fig. 2.

2.2. Mix proportions

All mixtures were prepared using NHL5 and the selected aggregates. Since packing density is calculated and referred to volume [28], for all sands, the optimum binder to aggregate ratio (b/a) was calculated by volume, according to each of the aggregates' packing density. The volume proportions (*v/v*) of the raw materials were then converted to weight proportions *(w/w)*, in order to ensure accuracy and precision during the mixing process. For this conversion, real density values of all components were determined.

Considering that the density of the cementing paste depends on the amount of water used, its density was corresponded to a water/ binder ratio of 0.5 and it was calculated at 1700 kg/m^3. This ratio was derived through a series of tests, aiming at producing a homogeneous paste with optimum packing of the NHL particles [30]. In

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