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Basalt fiber reinforced natural hydraulic lime mortars: A potential bio-based material for restoration

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ABSTRACT

Physico-mechanical properties and the microstructure of basalt fiber reinforced hydraulic lime-based mortars were investigated. Three different mortars were characterized, one based on natural hydraulic lime and a siliceous aggregate and two dry premix of natural hydraulic lime, selected inert aggregates and selected crushed bricks and tiles. The effect of three different types of basalt fibers at two contents on mechanical and water absorption through capillarity was investigated. Fiber reinforced mortars showed a marked improve in post-cracking behavior and compressive strength which was found to depend strongly on the type of matrix and basalt fiber. Reinforced mortars exhibited a lower capillary water absorption coefficient than the reference mortars regardless of type of matrix and basalt fiber. Despite the promising results, the study highlighted the need to optimize both the surface treatment of basalt fibers and their content in the mortars with a view to defining a suitable material for masonry restoration.

1. Introduction

Hydraulic lime mortars are a traditional building material that has been used for thousands of years with the Romans that first achieved a great knowledge about the preparation and applications of these hydraulic mortars, which proved to be durable [1,2]. As clearly stated by Sabbioni et al. [3], hydraulic lime represents the connecting link with Portland cement, the modern hydraulic binder developed in the mid nineteenth century. In this regard, ordinary Portland cement and related products have rapidly become the material of choice in building and restoration fields [4,5]. Nonetheless, hydraulic lime-based mortars are present in many historical structures and buildings which have significant cultural interest, especially when they are in need of restoration. In most cases restoration interventions have employed cement-based mortars that, despite their widespread use, have shown several incompatibilities causing extensive damage to the ancient masonry [6–8]. These incompatibilities can be summarized as follows: high mechanical strength, efflorescence phenomena owing to formation of large amounts of soluble salts by migration of alkaline ions, low water permeability with excessive water retention [4,9]. Owing to these problems, the last years have been marked by an increasing interest in using lime-based mortars in restoration activities, as compatibility between the new repair mortar and original components has been considered as a central issue, this compatibility being both physical, chemical and mechanical in nature [4,10]. This attention has triggered detailed investigations of characteristics and properties of both aerial and hydraulic lime-based mortars [4,5,9–16], the lack of which contributed to their replacement by cement-based mortars. One of the major concern envisaged for the full exploitation of lime-based mortars is represented by their undesirable plastic shrinkage connected with shrinkage cracking, in addition to relatively low mechanical properties and brittle nature. Such limitations can be effectively tackled with the use of fiber reinforcement, which is a common practice in cement-based materials [17–25]. Nevertheless, there are few available papers in the literature dealing with the addition of fibers in lime-based mortars [26–28]. Chan and Bindiganavile [26] added polypropylene fibers up to 0.5% by volume in a natural hydraulic lime mortar (NHL 2) and reported that fiber reinforcement was effective in improving post-peak stress carrying capacity in compression, flexure and shear. They also found that at a given water content, there is an optimum content of fibers beyond which the fiber efficiency does not increase any more. The same authors in [27] investigated also the dynamic response of such lime-based composites and highlighted that polymeric fibers are able to impart post-peak energy dissipation to hydraulic lime mortar but reported a post-peak flexural toughness decrease with an increase in the rate of loading. Polypropylene fibers were

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found to be a suitable reinforcement also for aerial lime-based mortars [28], where at low content (0.06 wt%) an improvement of mechanical strength and durability in freezing–thawing cycles and reduction in shrinkage cracking were observed. At 0.5 wt%, the presence of fibers turned out to be detrimental to both mechanical strength and water vapor permeability. Recently, Iucolano et al. [29] investigated the effect of both basalt and glass fibers on physical and mechanical properties of natural hydraulic lime mortar (NHL 3.5) at two different weight percentages, namely 1 and 2 wt%. Both fibers were found to modify the toughness and flexural behavior of reinforced mortars, even though a decrease in compressive strength occurred. This can be considered as one of the first attempt at using basalt fibers as reinforcement in lime-based mortars for restoration purposes. In this framework, the present study aims at deepening the understanding of the effect of basalt fibers on mechanical and physical properties of hydraulic lime-based mortars. In this regard, three different types of basalt fibers (two types of milled fibers and one type of chopped fibers) were added at two different weight contents to three different hydraulic lime-based mortars: one based on a natural hydraulic lime (NHL 3.5) and siliceous feldspathic aggregate, one based on dry premix of NHL 3.5 and selected inert aggregates (MC) and one based on dry premix of NHL 3.5, selected inert aggregates and crushed bricks and tiles (*cocciopesto*) (MCC). The use of different types of fibers characterized by dissimilar aspect ratios and shape was dictated by the fact that closely related to the fiber composite mechanics is the efficiency of the fibers and the interfacial bond strength between the fiber and matrix. The length and diameter of the fiber influence its bond strength with the matrix and the properties of the composite depend strongly on the fiber orientation and content. The rationale behind the choice of basalt fibers lies in the current need for sustainable and energy efficient construction materials that has steered extensive research on alternative materials able to reduce the cost and environmental impact of construction process [30–35]. Unlike synthetic fibers, natural fibers of mineral origin (such as basalt fibers that are continuously extruded from high temperature melt of selected basalt stones, which are volcanic, over-ground, effusive rocks saturated with 45–52% SiO_2) can provide a cheap and sustainable approach without suffering from the inherent limitations of plant-based fibers that are mainly due to undesired interfacial reactions resulting in reduction in strength and toughness as a result of weakening of the fibers [34].

2. Materials and methods

2.1. Mortars

Three different types of mortars were used with three different types of basalt fibers. One type of mortar was prepared using a commercial natural hydraulic lime (NHL) supplied by St. Astier which is produced from burning and slaking of a pure chalky limestone with siliceous content. In particular, the present NHL strictly conforms to the class designated as NHL 3.5 (henceforth labeled as "NHL") in accordance with the European standard EN 459 [36]. A siliceous feldspathic aggregate (sand) was also used. The second type of matrix was based on a dry premix of NHL 3.5 and selected inert aggregates (henceforth labeled as "MC") while the third one was similar to MC but with the further addition of selected crushed bricks and tiles (*cocciopesto*) (henceforth labeled as "MCC"). Both MC and MCC were supplied by Calci Idrate Marcellina S.p.A.

Three different types of basalt fibers, all supplied by Basaltex NV, were added to the mortars: (a) BSC D-L-WET (henceforth labeled as "CH"), basalt continuous filament roving chopped to a length of 6.35 mm, filament diameter in the range 10–19 μm and with a silane sizing; (b) MF01 (henceforth labeled as "MF1") milled basalt fibers obtained by milling basalt continuous filament fibers of the 10–17 μm filament diameter range with a silane sizing; (c) MF02 (henceforth labeled as "MF2") milled basalt fibers with a silane sizing. Fig. 1 shows the photographs and scanning electron micrographs of the different basalt fibers used in the present investigation. Mortar mixtures, whose compositions are summarized in Table 1, were prepared adding to the solids proper amounts of water to get a good workability and consistency. Binder to aggregate ratio for NHL specimens was fixed at 1:1 (by weight). Basalt fibers were added at two different weight contents (3% and 10%). A reference mortar (henceforth labeled as "REF") without basalt fibers was prepared for each type of hydraulic lime-based mortar. All mortars were cured in water for 28 days according to UNI EN 196-1 [37].

2.2. Analysis of raw materials

The mineralogical phases were determined by means of X-ray diffraction using a Philips X'Pert diffractometer according to the diffraction powder method, with a CuKα1 radiation, step size of 0.020°, time per step of 2 s from 5° to 80°.

The siliceous feldspathic aggregate was subjected to grain size analysis by mechanical sieving.

Thermogravimetric analysis (TGA) was carried out using a SDT Q600 (TA Instruments) using platinum crucibles at 10°/min heating rate in air flow (50 ml/min) from 30 °C to 1000 °C.

2.3. Mechanical evaluation

Mechanical characterization of the mortars was carried out in accordance with European standard EN 1015-11 [38] on a Zwick/Roell Z010 universal testing machine equipped with a 10 kN load cell. Three-point flexural tests were performed on five specimens for each configuration with a support span of 80 mm, a cross-head speed of 2 mm/min and a pre-load of 5 N. A displacement transducer was placed at the span center to measure the beam center deflection in order to evaluate the Young's modulus of the mortars. Compression strength test was carried out on the two fragments of each specimen resulting from the previous flexural test.

2.4. Water absorption measurement

Water absorption measurements were carried out on three cubic samples of dimensions (5 cm × 5 cm × 5 cm) for each type of mortar. The test was performed in accordance with the methodology described in the standard EN 15801 [39]. The capillary water absorption coefficient of the material was determined as the slope of the initial stage of the capillary absorption curve.

2.5. Microstructural characterization

Microstructural and morphological characterization of the fracture surfaces of the hardened specimens was performed by scanning electron microscopy (SEM) (SEM Philips XL40, FESEM Zeiss, Auriga). All specimens were sputter coated with gold prior to examination.

3. Results and discussion

Raw materials, namely NHL, MC, MCC and siliceous aggregate, were characterized by XRD and TGA analysis. Weight loss curves (TG) and derivative curves (DTG) for the three different hydraulic limes show two endothermic effects in the following temperature ranges, namely 390–411 °C and 713–755 °C (Fig. 2), which can be