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Fibre-reinforced lime-based mortars: A possible resource for ancient masonry restoration

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HIGHLIGHTS

- Fibre reinforced hydraulic lime mortars can be used for repairing historic structures.
- Glass and basalt fibres can improve mortar mechanical behaviour in the post-cracking.
- Hydraulic mortars containing 2% of glass fibres have the best mechanical performances.

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ABSTRACT

In order to design binding materials able to historical buildings restoration, physical–mechanical properties and microstructure of fibre-reinforced lime-based hydraulic mortars, have been studied, in comparison with a reference hydraulic lime-based mortar with no addition. Fibre-reinforced mortars, even characterised by larger porosity and lower mechanical strength than the reference, pointed up a clear improvement in the post-cracking behaviour and, regardless of nature and concentration of fibres, turned from brittle materials to ductile materials. It was demonstrated that the addition of as low as 2% of glass fibres leads to a toughening of the mortar and jointly to an improvement of the flexural load.

1. Introduction

The restoration and conservation of buildings and monuments of some hundred years ago making use of Portland cement mortars, a very common practice until recently, is matter of particular concern from either technical or eco-sustainability points of view. Physical–mechanical features of cement mortars are, in fact, too different from those of the original lime-based mortars, in terms, e.g., of brittleness, mechanical strength and thermal expansion coefficient [1], with consequent negative effects on the durability of the masonry works. In addition, from the chemical side, damages may arise as a result of the interaction between cement hydration products and some building stones, as observed, for instance, recently with clay bricks [2]. On the other hand, it is well known that manufacturing and use of increased amounts of Portland cement is a source of environmental alarm, due to exceeding CO_2 production and the connected greenhouse effect.

To overcome the above problems, a re-awaking interest in the use of hydraulic lime for the preparation of repair mortars or plasters has been reported in recent years [3–5]. Hydraulic lime is also attractive for its favourable thermohygrometric features (i.e., transpiration, dehumidifying ability and insulation), which assure appropriate microclimatic conditions.

The major problem in the use of lime-based mortars is, however, connected to their undesirable plastic shrinkage, mainly in dry environments, due to fast water evaporation. This limitation may, however, be overcome by the incorporation of short fibres, able to reduce plastic shrinkage and jointly to improve some properties of the product, such as ductility, flexural strength and durability (in particular freeze–thaw resistance). Fibres, in fact, limiting crack opening and distributing the stress to the nearby matrix, are apparently able to suppress strain localization and to prevent therefore microcracks from developing into macrocracks [6].

Performance depends logically on dimension, nature and surface treatment of fibres. Different types of short fibres have recently been used as reinforcement with the aim to arrest plastic shrinkage and to reduce microcracks [7–10]. Most literature reports are however focused on two fibres: (a) glass fibre [11], commonly used to reinforce cement mortars, concretes, plasters and gypsum and (b) basalt fibre [12], a material originated from volcanic rock, commonly used to reinforce a wide class of composites.

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Table 1
Main technical features of the fibres used.

Fibre	SiO_2/Al_2O_3	Strand	Treat.	Mean length (mm)	Mean diameter (μm)	*E* (GPa)
Glass (G)	6.25	Chopped	Sizing	10	13	75
Basalt (B)	5.2	Chopped	–	4–5	8–10	84

Table 2
Composition of the experimental mortars.

	Lime/sand ratio	Water/solid[a] ratio	Glass fibre (%)	Basalt fibre (%)	Latex (%)
G1	1:3	0.18	1	–	1.5
G2	1:3	0.18	2	–	1.5
B1	1:3	0.18	–	1	1.5
B2	1:3	0.18	–	2	1.5
REF	1:3	0.22	–	–	–

[a] Solid is intended as lime + sand; percentages (w/w) refer to the solid fraction of the mixture.

The latter is a glassy material, too. It is produced by melting of a basalt rock at about 1450 °C, followed by a rapid extrusion. The continuous glass thread is then chopped into fibres of various length. The main features of basalt fibres are: high strength and thermal stability and resistance to high temperature, corrosion, and both acid and basic attack.

This paper aims at evaluating the physical and mechanical effects of the inclusion of the two above fibres in hydraulic lime-based mortars for historical buildings restoration. A preliminary report on this investigation has been presented in an Italian Meeting and published in Italian on a local technical journal [13].

2. Materials and methods

Mortars were prepared using a commercial, natural hydraulic lime, supplied by MGN company (Schio, Vicenza, Italy). Lime origin is unknown but it has likely been obtained by ignition of a local marly limestone. According to the European Standards [14,15], the binder belongs to the class designated as "NHL 3,5" having the following specifications: $SO_3 \leqslant 3\%$ and free $CaO \geqslant 9\%$.

The investigated hydraulic lime, from now onwards designated as NHL, was subjected to preliminary chemical, X-ray and thermal analyses.

Chemical analysis was performed as follows. A weighted sample was first calcined, then subjected to digestion, under microwave-induced heating (Perkin–Elmer Multiwave 3000 oven), in a standard solution prepared by mixing 1 ml of HCl, 1 ml of HNO_3 and 4 ml of HF. After addition of H_3BO_3 (24 ml) to attain fluoride complexation, the solution was analysed by ICP atomic emission spectrophotometry (ICP-OES, Perkin–Elmer Optima 2100 DV).

X-ray diffraction (XRD) patterns for phase identification were obtained using a Philips PW 1730 diffractometer (rad. Cu Kα1).

Simultaneous thermogravimetric (TG) and differential thermal analyses (DTA) were carried out in the temperature range 25–1000 °C, using a Netzsch STA409 PCLuxx apparatus (alumina crucibles; N_2 gas flow; heating rate: 10 °C/min).

A siliceous fine aggregate (sand), supplied by Gras Calce company (Trezzo sull'Adda, Milan, Italy) was used, too. Such material was subjected to XRD and grain size analyses. Particle size distribution was obtained by mechanical sieving, according to European Standards [16].

Two different types of fibres were added to the mortars: (a) a glass fibre, type E, earth-alkaline network modifier, supplied by Mapei, Milan, Italy, pre-treated with an acrylic sizing (referred to as G throughout the text) and (b) a basalt fibre, supplied by Basaltex, Wevelgem, Belgium (referred to as B). The main technical features of both fibres, made available by the suppliers, are reported in Table 1. Fine powders, obtained by grinding both fibres, were analysed by XRD. Fibres were employed as chopped strands. Mortar mixtures, whose composition is shown in Table 2, were prepared adding to the solids suitable amounts of water to obtain a normal consistency and a good workability. Binder to aggregate ratio (w/w) was fixed at 1:3. G or B fibres were added at two different rates (1% or 2%). In order to improve workability and placement of the mortars after fibres addition, 1.5% (w/w) of a polymeric latex (Mapei) was added to each mixture. A reference mortar (REF in Table 2), containing no fibres and no latex was also prepared and tested.

According to standard procedures, all the mortars were cured for 28 days in a climatic chamber (MSL, mod. Humichamber EC 125) in the following conditions: temperature, 20 °C; relative humidity, 95% during the first 7 days and 65% during the residual 21 days [17].

Table 3
Chemical analysis (weight%) of lime used in this study.

SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O	SO_3	I.L.
9.75	1.98	0.16	65.11	2.29	0.79	0.24	0.30	19.32

Apparent and real density, open porosity and pore size distribution were evaluated by mercury intrusion porosimetry using a Micromeritics (Autopore III) porosimeter.

Mechanical characterization of the mortars was carried out according to European Standards [17]. Three-point flexural tests were performed using an Instron 5566 compression machine, with a 5 kN load cell. Processing flexural test curves allowed Young module and flexural toughness to be calculated. Compression strength tests were carried out on the two fragments of each compact, resulting from the above flexural test, using an Instron 8501 machine, equipped with a 50 kN load cell. The loading rate was 0.6 mm/min in each test. All the measurements were performed in triplicate.

Microstructure of the fracture surfaces of the hardened compacts was investigated by scanning electron microscopy (SEM, Cambridge S440).

3. Results and discussion

Table 3 reports the chemical analysis of lime, whereas Fig. 1a shows the X-ray diffraction pattern of the same material. The bumps appearing in the diffraction pattern of Fig. 1a are likely related to the possible presence of amorphous phases, considering that the material is of natural origin. DTA and TG profiles, not reported here for the sake of brevity, show, as expected, two endothermic effects at about 441 °C and 756 °C, connected to $Ca(OH)_2$ dehydration and $CaCO_3$ decarbonation. Combining all the above experimental data, points out that the investigated NHL is constituted essentially by $Ca(OH)_2$, $CaCO_3$ and calcium silicates (CH, C and CS, respectively in Fig. 1a). The high CaO content of NHL (Table 3) demonstrates the prevalence of high-basicity CS, which suggests either the raw material (marly limestone) to have been treated at high temperature or the final product to have been enriched in CS by adding some Portland clinker.

Fig. 1b reports the X-ray diffraction pattern of the siliceous aggregate. It is mostly a quartz sand, with minor amounts (some units percent in total) of a feldspar (possibly albite, A in the figure) and calcite, detected by TG and DTA, whose traces are not reported here. The grain size, measured by sieving, was found to be <1 mm, with almost 90% passing through a 0.5 mm sieve.

The X-ray diffractograms in Fig. 1c and d refer to fibres G and B, respectively (Table 1). Both materials proved to be completely amorphous. The large shoulder between 20° and 35°2Θ in Fig. 1c is normally interpreted in terms of a random network.

Table 4 summarizes the physical parameters measured for all the manufactured mortars. The values of real density of the four fibre-reinforced mortars, averaging 2.63 g/cm^3, are not significantly different. This amount is higher than the corresponding value for the REF mortar (2.47 g/cm^3), likely due to the higher water/solid ratio chosen for the preparation of the latter (Table 2). The apparent density and logically the open porosity show, on the contrary, substantial differences. As expected, mortars with included fibres are remarkably more porous than the REF mortar (porosity: 45–52% vs. 36%; apparent density: 1.22–1.45 g/cm^3 vs. 1.59 g/cm^3). This is due, in general, to the interruption of the continuity of material microstructure, as a result of the inclusion of heterogeneities in a