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# Analysis of the strain-rate behavior of a basalt fiber reinforced natural hydraulic mortar

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ABSTRACT

Fiber reinforced inorganic materials, such as concrete or mortars are expected to present good mechanical properties under high dynamic loading conditions, such as those induced by earthquakes. Furthermore, basalt fibers, which are being increasingly investigated in structural applications, are also expected to present good performance under high strain-rate conditions.

This paper presents the results of a dynamic characterization of a basalt fiber reinforced natural hydraulic mortar, in order to verify its capability to withstand high dynamic loading conditions. In particular, the reinforced mortar was morphologically characterized by SEM and mercury intrusion porosimetry; then, quasi-static flexural and tensile tests were conducted. Finally, dynamic tensile failure tests were carried out at medium and high strain-rates, using a Hydropneumatic machine and a Modified Hopkinson bar apparatus, respectively. The results were elaborated to derive Dynamic Increase Factors for the tensile strength.

The fiber addition leads to a bridge action effect, and consequently to a more ductile behavior and higher toughness of the fiber reinforced mortar compared to a plain mortar. In addition, the fiber reinforced mortar appears to be highly strain-rate sensitive, as the tensile strength DIF increased up to 5.1, for a high strain-rate of about $10^2\ s^{-1}$.



## 1. Introduction

Dynamic properties of construction materials represent a crucial issue for structural engineering. In fact, the structural design and/or assessment of critical infrastructure or buildings need to take into account particularly severe dynamic scenarios, which could occur on the structures during their lifetime (e.g. severe earthquakes and impact loads). Dynamic mechanical properties of materials can be very different from those exhibited in quasi-static conditions; hence, specific investigations in such dynamic ranges appear necessary, in order to correctly understand the behavior of structures subjected to high dynamic loading conditions.

Currently, research results available in the literature focus mainly on experimental investigation of dynamic mechanical properties of common construction materials, in particular of concrete and mortars [1–7], steel [8–10], and natural stones [11–14].

The dynamic characterization of fiber reinforced concrete or mortars is particularly important. In fact, fiber reinforced mortars or concrete are purposefully designed to compensate the low tensile strength and ductility of plain mortars or concrete, by providing absorbing energy and increasing tensile capacity. Fiber reinforcement can improve fracture toughness, tensile strengths, crack opening control and durability of the reinforced concrete structures [15–17]; furthermore, the significant toughness of fiber reinforced concrete and mortars makes them particularly capable to absorb impulsive actions [15,16]. These materials are often used in structural applications that are potentially prone to high and rapid dynamic actions during their lifetime. For this reason, several experimental activities have been conducted to study the dynamic behavior of fiber reinforced mortars and their strain-rate sensitivity [18–20]. In particular, there is experimental evidence that high strain-rate conditions significantly improve strength and toughness, but only slight improvement is observed in energy absorption and post peak ductility [21,22].

With the same objective, the current paper presents an experimental activity investigating the dynamic tensile behavior of a basalt fiber reinforced natural hydraulic mortar (NHM). Basalt fibers have recently been explored and applied in several structural applications, as a valuable alternative to glass, steel and polymeric fibers, both in fiber reinforced polymers and fiber reinforced

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mortar applications [23–26]. Basalt fibers are characterized by good mechanical properties, including high toughness, low production costs and high durability [27,28]. On the other hand, the interest in NHMs is increasing, because even if they are characterized by lower mechanical properties than cement-based mortars, NHMs have lower production costs and environmental impacts [29,30].

Hence, the objective of the current research is to characterize both the quasi-static and the dynamic mechanical properties of a basalt fiber reinforced NHM, in order to verify whether it could be viable as a material for repairing historic structures in earthquake-prone areas. Specifically, in this study, a detailed quasi-static mechanical characterization of the investigated material is followed by a dynamic tensile test program, at medium and high strain-rates, carried out using a Hydropneumatic machine and a Modified Hopkinson Bar apparatus, respectively. The obtained dynamic tensile properties are elaborated in terms of Dynamic Increase Factor (DIF), quantifying the increase in tensile failure stress at the investigated strain-rate values.

## 2. Materials and methods

### 2.1. Materials

The investigated mortar is composed of a natural hydraulic lime belonging to the 3.5 class, according to EN 459-1 [31]. Table 1 provides both the chemical characterization and the ignition loss (I.L.) of the lime, according to European Standard EN 459-2 [32]. Furthermore, a siliceous fine aggregate was used, almost completely composed of quartz, with traces of calcite and albite (about 4%). Sand grain size was evaluated by mechanical sieving, according to European Standard EN 933-1 [33]. The grain size ranges between 0 and 1 mm, with almost 90% of the weight passing through the mesh of a sieve of 0.5 mm diameter openings.

The basalt fibers used in this investigation were obtained by fusion of volcanic rocks with basaltic composition ($SiO_2/Al_2O_3 \approx 5.2$) at about 1450 °C, followed by a rapid extrusion. The continuous glass thread was then chopped into fibers of various lengths. In particular, chopped strand fibers with a mean length of 4–5 mm and a mean diameter of 8–10 μm were used. Fiber density was equal to 2.75 g/cm$^3$, whereas Young's modulus was equal to 84 GPa. Furthermore, the fibers were characterized by a tensile strength and a failure elongation of 4.84 GPa and 3.15%, respectively. The main features of these fibers are: high strength and thermal stability and resistance to high temperature, corrosion, and both acid and basic attack.

Finally, in order to improve the workability and the placement of the mortars after fiber addition, 1.5% (w/w) of a polymeric latex (Mapei) was added to each mixture.

Mortars were manufactured using a binder to aggregate ratio equal to 1:3 (w/w); two weight percentages of basalt fibers were used as reinforcement, 1% and 2%, hereafter referred to as B1 and B2, respectively. A reference plain mortar, hereafter referred to as REF, was also manufactured. The compositions of all the tested mortars are summarized in Table 2.

The water content of each mortar was set to achieve the same consistence (140 ± 10 mm) evaluated through the flow table method, according to European Standard EN 1015-3 [34].

**Table 1**
Chemical analysis (weight%) of the hydraulic lime.

| $SiO_2$ | $Al_2O_3$ | $Fe_2O_3$ | 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 |

**Table 2**
Composition of the experimental mortars (w/w).

| | Lime/sand | Water/solid[a] | Basalt fiber (%)[a] | Latex (%)[a] |
|---|---|---|---|---|
| REF | 1:3 | 0.22 | – | – |
| B1 | 1:3 | 0.18 | 1 | 1.5 |
| B2 | 1:3 | 0.18 | 2 | 1.5 |

[a] Calculated with respect to the solid fraction of the mixture (lime + sand).

Then, mortar mixing was performed: the binder, the sand and the fibers were dry mixed and well homogenized. An appropriate amount of water was added and a planetary mixer (mod. Hobart) was used, mixing at low speed over a period of 15 s. Then, the mortar was mixed for a further period of 75 s at low speed. The mortars were then molded in prismatic steel casts (40 × 40 × 160 mm) and demolded 48 h later. Curing was carried out for 28 days in a climatic chamber at a constant temperature of 20 °C and at a relative humidity of 95% during the first 7 days, and of about 65% during the remaining 21 days.

### 2.2. Quasi-static characterization

A quasi-static mechanical characterization of the mortars was carried out following the European Standard EN1015-11 [35], by means of three-point flexural tests, conducted on specimens 40 × 40 × 160 mm of dimensions, using an Instron 5566 machine, with a 5 kN load cell. Fig. 1 depicts a specimen during the test. Compression tests were also conducted on the two fragments of each specimen failed after the flexural tests, using an Instron 8501, equipped with a 50 kN load cell. The loading rate in both flexural and compression tests was 0.6 mm/min. The tests were conducted after 7 and 28 days of curing (see Section 2.1) and all the measurements were performed in triplicate. On the failed specimens, the fracture surfaces were also morphologically characterized by means of scanning electron microscopy observations (SEM, Cambridge S440). Furthermore, for all the specimens, the total porosity and the pore size distribution were evaluated by means of mercury intrusion porosimetry (Micromeritics WIN9400 Series).

### 2.3. Dynamic characterization

A dynamic direct tensile characterization was conducted on cylindrical specimens with both diameter and height of 20 mm (height/diameter = 1), drilled out from prisms 40 × 40 × 160 mm of dimensions. Quasi-static direct tensile tests were also carried out, in order to have reference results for the dynamic behavior.

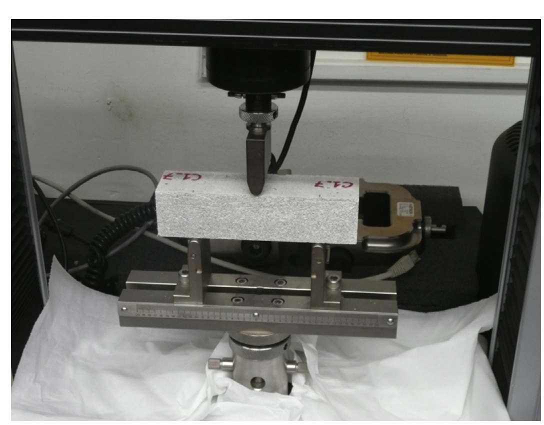

**Fig. 1.** A specimen during the three point flexural test.