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Geopolymer matrix for fibre reinforced composites aimed at strengthening masonry structures

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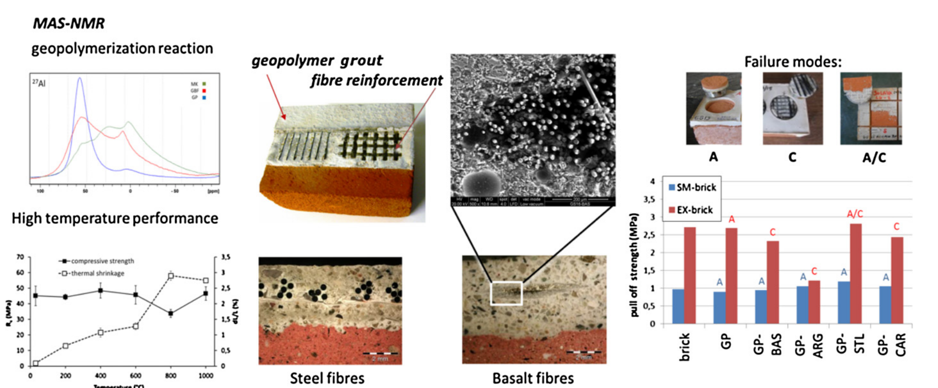
HIGHLIGHTS

- A stable, highly adhesive metakaolin/slag geopolymer grout was developed and extensively characterized.
- A geopolymer grout was used to bond reinforcing fibre nets and fabrics to clay bricks giving excellent adhesion.
- Four type of fibres commonly used in FRP and FRCM were bonded to clay bricks and tested by pull-off.

GRAPHICAL ABSTRACT



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ABSTRACT

The paper presents the assessment of a metakaolin-slag-sodium-silicate GeoPolymer (GP) grout as a matrix for bonding four bidirectional meshes made of basalt, glass, carbon fibres and two unidirectional ultra-high tensile strength steel fabrics to soft mud and strong extruded clay bricks for strengthening purposes. A detailed chemical/physical characterization of the geopolymer is given, evidencing the completion of the geopolymerization reaction and the good stability of the geopolymer to leaching, freeze-thaw cycles and high temperature treatments as well as its adequate mechanical properties. Pull-off tests proved the excellent adhesion strength of the geopolymer grout, also embedding meshes and fabric, to both types of clay bricks.

1. Introduction

Continuous maintenance processes are required to endure the effects of hazardous natural events on existing masonry structures and Architectural Heritage (AH), and to mitigate their effects by

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promoting activities of structural repair and restoration. The application of Externally Bonded Fibre Reinforced Polymers (EB-FRP) has in the last decades become a common solution especially for strengthening existing concrete structures, which need to comply with the most recent building codes, and also of existing brick masonry structures, especially those belonging to the AH where interventions need to meet dedicated restoration requirements [1,2]. Nonetheless, EB-FRPs present some shortcomings, like a lack of vapour permeability and fire resistance, which are better solved with the use of inorganic matrices based on cement or lime mortars [3]. Therefore, Fibre Reinforced Cementitious Matrix (FRCM) composites and Steel Reinforced Grouts (SRG) using inorganic matrices as binders have been proposed in the last decade as an alternative to FRPs. Advantages of FRCM and SRG over FRPs include: better compatibility with masonry substrates and traditional craftsmanship, reversibility, better behaviour under high temperatures, resistance to Ultra-Violet (UV) radiation, vapour permeability, greater deformability and lower cost [3]. Nevertheless, traditional inorganic mortars, especially lime based ones, often present low adhesion to the parent substrate and between the composite layers [4,5]. Geopolymers are relatively new inorganic binder materials that appear promising in solving these limitations while maintaining the positive aspects of FRCMs [6,7]. Geopolymers are inorganic materials produced from aluminosilicates typically activated with alkali hydroxide and/or alkali silicate solutions. Different aluminosilicate or calcium-aluminosilicate source materials can be used, for example dehydroxylated aluminosilicate clay mineral (e.g. metakaolin) and industrial wastes resulting from high temperature processes such as fly ash or ground blast furnace slag, among others. Geopolymers are also non-inflammable and have good resistance towards acids [8–10]. They are also green materials for a greener economy, since they can be derived from by-products or the recycling of industrial waste materials and can be obtained with 10 times lower CO_2 emission than Portland cement [11]. Geopolymer grouts and mortars can be obtained by charging the geopolymer binder with economical river sand. Geopolymer mortars have been investigated by several authors based on the use of different reagents: fly-ash [12], metakaolin [13–16], tungsten mine waste [17], ground granulated blast furnace slag [18, 19], metakaolin-slag [20], hybrid metakaolin-epoxy [21], rice husk ash and palm oil fuel ash [22, 23]. Fibre Reinforced GeoPolymer (FRGP) is the combination of a geopolymer grout with fibre meshes or fabrics, similarly to Steel Reinforced Grouts (SRG) or Fibre Reinforced Cement Mortars (FRCM). Although a lot of work has been done on geopolymer fibre composites, using both short fibres and multiple laminated layers of fabrics [24–27], few reports exist on FRGPs for strengthening of structural elements, and most investigations focus on strengthening Reinforced Concrete (RC) beams [11,14,28–32]. Ferone et al. [14] investigated the applicability of ultra-high strength steel fabric bonded with a geopolymer matrix as a reinforcement for RC beams. The preliminary results of the bending tests indicated an excellent behaviour of the tested geopolymer matrix. The failure load of the reinforced beams was approximately twice that of the control beam. Similar results were obtained by Menna et al. [31] for ultra-high strength steel fibre fabric bonded to RC beams using a metakaolin based geopolymer matrix combined with silica filler. Katakalos et al. [32] investigated the performance of RC beams strengthened using steel fibre sheets bonded with a geopolymer matrix. The ultimate load capacity of the strengthened beams was about 45% larger than the control beam. From these results it appears that geopolymer binders/mortars combined with steel fibre sheets/fabrics are well suited for RC beam strengthening. A less straightforward scenario is available in literature for carbon fibre reinforcements. Toutanji et al. [28] compared two strengthening solutions for R.C. beams made by bonding carbon fibre sheets by an epoxy and a geopolymeric binder. The results showed that the latter inorganic matrix was as effective as the epoxy one in increasing the strength and the stiffness of the RC beams. Nonetheless, the inorganic strengthening solution showed a more brittle failure mechanism. Menna et al. [31] observed poor adhesion of the geopolymer carbon fabric composites so that a negligible strengthening of the reference R.C. beams was obtained. Lastly, Vasconcelos et al. [30] applied reinforcing carbon fibre sheets on concrete prisms by using a metakaolin based geopolymeric grout. The carbon fibre sheets were pre-impregnated with an epoxy resin and placed within the geopolymer grout before the setting of the resin. The geopolymer was aimed at bonding the Carbon Fibre Reinforced Polymer (CFRP) to the concrete substrate. The authors observed that the adhesion, via pull-off tests, of geopolymer grouts was in between 0.10 and 1.25 MPa depending on the activator concentration and on the amount of sand. Whereas, the pull-off strength was always lower than 0.20 MPa when the pre-impregnated CFRP was inserted within the geopolymeric grout. This low adhesion strength was attributed to either a negative shrinkage of the geopolymers or to the unfortunate combination of pre-impregnated CFRP and geopolymers.

Surprisingly, and to the best knowledge of the authors, little or no literature exist on the use of FRGPs as strengthening materials for brick masonry structures. Indeed, geopolymer grouts appear well suited to match the best performances of inorganic matrices for masonry substrates. They can also meet the dedicated restoration requirements of the AH, thanks to their typical chemical composition and porosity which is similar to that of clay bricks.

The objective of the present work is an assessment of the applicability of a geopolymer grout as a matrix of FRGPs for strengthening brick masonry structures. The geopolymer grout was prepared by mixing metakaolin, slag, Na-silicate, fine granulated sand and wollastonite powder.

The geopolymer grout was used to impregnate and bond four bidirectional meshes made of basalt, alkali resistant glass, carbon fibres and two unidirectional Ultra High Tensile Strength Steel (UHTSS) fabrics to soft mud and strong extruded clay bricks. The geopolymerization reaction was checked through comparative X-ray diffraction (XRD) and magic angle-spinning nuclear magnetic resonance (MAS-NMR) analyses of raw materials and of the resulting geopolymer. The mechanical characteristics of the geopolymeric grout were assessed through compression, flexural, splitting and elastic modulus tests. Drying shrinkage, leaching, freeze-thaw behaviour, density, porosity and water absorption were determined. High temperature mechanical stability and thermal shrinkage of the grout was measured up to 1000 °C. The adhesion strength of the geopolymer grout and related FRGPs to the two types of bricks was investigated by pull-off tests. Lastly, the fibre bundle impregnation was observed by scanning electron microscopy.

2. Materials and methods

2.1. Geopolymer grout

The metakaolin (MK) (medium particle size 1.2 μm BET 6.031 m^2/g) used for the geopolymer binder was produced in-house by calcining in an oven for 5 h commercial kaolinite powder (MiMac Srl CE Italy) at 750 °C. The granulated blast furnace slag (GBFS) used was from ILVA Metallurgical Plant (Taranto, Italy) and was reduced to a grain size of (60–400 μm, D50 = 200) prior to use. A sodium-silicate activator with modulus $SiO_2/Na_2O = 1.5$ was prepared by mixing LUDOX® TM-50 colloidal silica and NaOH pellets (Sigma-Aldrich analytical grade) with distilled water at least 24 h prior to use. The quantity of water in the alkali activator was adjusted to achieve a H_2O/Na_2O ratio of 12. The quantitative chemical analysis by EDS of the reagents are shown in Table 1.

Based on the chemical composition of the reagents, the binder generic SiO_2/Al_2O_3 molar ratios (activator + solid precursors) can be evaluated as 4.5 while $Na_2O/SiO_2 = 0.4$ and $Na_2O/Al_2O_3 = 1$.