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Flexural and fracture behaviour of a cement-based material reinforced with GO nanoplates

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Abstract

In the present research work, the mechanical properties of a cement-based material reinforced with Graphene Oxide (GO) nanoplates are experimentally investigated. In particular, a detail experimental campaign, consisting of three-point bending tests on both unnotched and edge-notched specimens, is performed in order to determine flexural strength and fracture toughness. More precisely, the flexural strength is computed as a function of the experimental values of the peak load according to UNI EN Recommendation, whereas the fracture toughness is analytically determined according to the Modified Two-Parameter Model.

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Keywords: cement composites; flexural strenght; fracture toughness; nanomaterials.

1. Introduction

As is well known, cement-based materials (e.g. mortar and concrete) are the most used construction materials all over the world, and this is primarily due to their low production cost and versatility in response to the design requirements.

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Despite the several merits of such materials, the major disadvantages are attributed to both their low cracking resistance capability (i.e. fracture toughness) and the presence of intrinsic defects (Bazant (2002), Xu and Zhang (2008), Ghaffary and Moustafa (2020)). Therefore, improving the mechanical properties and reducing the size and amount of defects would lead to increase the performance and durability of these materials.

An effective way to enhance the mechanical performance of cementitious materials is obtained by adding nanomaterials (Saloma et al (2015), Zhao et al. (2020)). Among nanomaterials, graphene and its derived materials (such as Graphene Oxide, GO) represent reinforcing 2D-nanofillers (in the form of nanoplates) able to fill the voids in cement paste matrix, leading to lower porosity, higher strength, and better durability. Moreover, according to the technical literature (Qi et al. (2021), GO nanoplates can regulate, during cement hydration reaction, the microstructure of hydration crystals. Consequently, such hydration crystals are characterised by both regular shapes and a uniform distribution in the cement past, leading to an increase of the mechanical strength and fracture toughness of GO-reinforced cementitious materials (Lv et al. (2014)).

In such a context, the goal of the present paper is to investigate the mechanical properties of mortar specimens reinforced with 0.03% in weight of GO nanoplates. In particular, GO is synthesised from natural graphite by using the Brodie method, which involves successive oxidation steps. A detail experimental campaign, consisting of three-point bending tests on both unnotched and edge-notched specimens, is performed in order to determine the flexural strength and the fracture toughness. More precisely, the flexural strength is computed as a function of the experimental values of the peak load according to the UNI EN 196-1 (2016). Moreover, the fracture toughness is analytically determined on the basis of the experimental load against crack mouth opening displacement curves, according to the Modified Two-Parameter Model (MTPM) recently proposed by Vantadori et al. (2018).

Nomenclature

a_0	notch length
B	specimen width
C_i	initial linear elastic compliance
C_u	unloading linear elastic compliance
E	elastic modulus
$K^S_{(I+II)C}$	fracture toughness
L	specimen length
P_f	peak load of flexural tests
$P_{\max}$	peak load of fracture tests
R_f	flexural strength
S	support span
W	specimen depth

2. Experimental campaign

2.1. Raw materials and specimen preparation

The raw materials employ for the preparation of mortar specimens are:
- highly pure graphite powder with an average size of 66 μm;
- limestone Portland cement (42.5R CEM II/A-LL type);
- aggregates consisting of a commercial silica sand with a grain size distribution between 0.08mm and 2mm;
- polycarboxylate superplasticizer (PC) with 40% solid content.

The GO is obtained from the oxidation of graphite carried out by means of the Brodie method. Then, in order to obtain the aqueous solution for the preparation of the mortar specimens, 42% (by weight of cement) of deionized water and 0.3% (by weight of cement) of PC were added to 0.03% (by weight of cement) of GO; finally, a stable GO nanoplate dispersion in aqueous solution is obtained.

The adopted mortar mix design is prepared according to UNI EN 196-1 (2016) and the mixture proportions are: cement:water:sand (by weight) $= 1 : 0.42 : 3$, where the water was replaced by the GO aqueous solution. Moreover, by adopting the above mixture proportions, also plain mortar specimens are prepared as control samples.

Once the fresh slurry is placed in moulds with prismatic shape, it is compacted by means of a flow table; then, the specimens are cured in laboratory for 24 hours under normal climatic conditions and, after demoulding, are submerged in water at room temperature for 28 days.

2.2. Flexural tests

Three-point bending tests on unnotched specimens are performed according to UNI EN 196-1 (2016) in order to determine the flexural strength of both plain mortar (PM) and GO-reinforced mortar (GO) specimens. The tested specimens are characterised by the following geometrical sizes: width (B) × depth (W) × length (L) = 40 mm × 40 mm × 160 mm, and support span (S) = 120 mm.

The tests are performed under load control (with a rate equal to 45 Ns^{-1}) by means of the universal testing machine Instron 8862 (load cell up to 100kN with an accuracy of 0.02%) and each specimen is monotonically loaded up to failure.

By employing the experimental value of the peak load, P_f, the flexural strength, R_f, is computed according to the following equation (UNI EN 196-1 (2016)):

$$R_f = \frac{1.5 \cdot P_f \cdot S}{W^3} \tag{1}$$

2.3. Fracture tests

Three-point bending tests on notched specimens are performed according to the Modified Two-Parameter Model (MTPM) (Vantadori et al. (2018)) in order to determine the fracture toughness of both PM and GO specimens. The tested specimens present a notch in the lower part of the middle cross-section, and are characterised by the following geometrical sizes: width (B) × depth (W) × length (L) = 30 mm × 60 mm × 300 mm, support span (S) = 240 mm and notch length (a_0) = 20 mm.

The tests are performed under Crack Mouth Opening Displacement (CMOD) control, employing a clip gauge (at an average rate equal to 0.15 mmh^{-1}) by means of the universal testing machine Instron 8862 (Fig. 1(a)). In particular, each specimen is monotonically loaded up to the peak load, P_{max}, as reported in Fig. 1(b); then, the post-peak stage follows and, when the load is equal to about 95% of P_{max}, the specimen is fully unloaded. Finally, the specimen is re-loaded up to failure.

By exploiting the experimental measurements in terms of P_{max}, initial, C_i, and unloading, C_u, linear elastic compliances, both the elastic modulus, E, and the fracture toughness, $K^S_{(I+II)C}$, (that is, the mixed mode critical Stress-Intensity Factor) are computed according to the MTPM. Such a model, proposed in the past by Vantadori et al. (2018), allows to take into account the possible crack deflection (i.e. kinked crack), occurring during stable crack propagation, in presence of a Mode I remote loading.

3. Results and discussion

As far as the flexural tests are concerned, the mean value, μ, and the standard deviation, σ, of the peak load, P_f, and the flexural strength, R_f, for both PM and GO specimens are listed in Tab. 1. Only a modest increment (about 4%) of the flexural strength is achieved for GO-reinforced specimens with respect to plain mortar ones. A careful examination of such a result in terms of R_f suggests that the difference between the mean values can be considered as a consequence of aleatory variability and/or measurement errors, that is, the addition of GO seems not to improve the flexural strength of mortar.

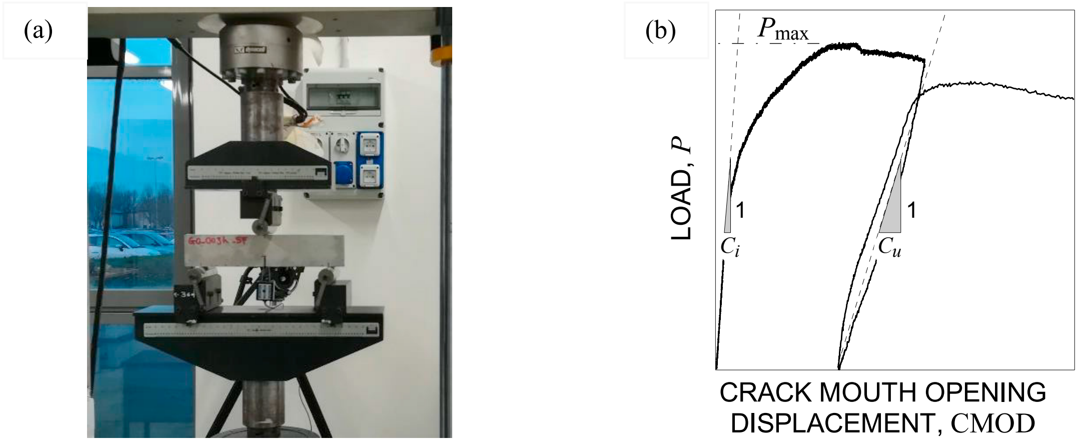

Fig. 1. Fracture tests: (a) experimental set-up; (b) load – CMOD plot.

Table 1. Flexural test results: peak load and flexural strength of PM and GO specimens.

SPECIMEN TYPE	P_f [kN]		R_f [MPa]	
	μ	σ	μ	σ
PM	1.994	0.103	5.285	0.297
GO	1.993	0.108	5.516	0.213

Regarding the fracture tests, Fig. 2 shows the experimental load-CMOD curves for only one specimen of each examined type, being the curves very similar to each other. A significant increase of the peak load, P_{max}, can be noticed for GO-reinforced specimens in comparison to PM ones.

The mean value μ, and the standard deviation, σ, of peak load, P_{max}, elastic modulus, E, and fracture toughness, $K^S_{(I+II)C}$, for each specimen type (that is, PM and GO specimens) are listed in Tab. 2.

It can be observed an increase of 23% of the peak load for GO-reinforced specimens with respect to plain mortar ones, whereas the elastic modulus is almost constant.

Moreover, the best performance in terms of fracture toughness is observed when GO nanoplates are used as reinforcement materials, with an increase of fracture toughness mean value of about 14% with respect to PM specimens.

4. Conclusions

In the present research work, the flexural strength and fracture toughness of a cement-based material reinforced with GO nanoplates have been experimentally investigated.

In particular, three-point bending tests, on both unnocthed and notched prismatic specimens, have been carried out in order to determine the flexural strength and the fracture toughness of plain mortar and GO-reinforced mortar.

On the basis of the experimental results, it can be concluded that the addition of GO nanoplates is able to improve the mechanical properties of the present cement-based material and, in particular, to increase the mortar resistance to fracture (with a $K^S_{(I+II)C}$ mean value equal to 0.950 MPa·m$^{0.5}$), in agreement with the results reported in the recent technical literature.

A detail chemical and structural characterisation of GO-reinforced mortar through SEM images and EDS patterns is in progress in order to investigate the role of the GO nanoplates in regulating the microstructure of hydration crystals.

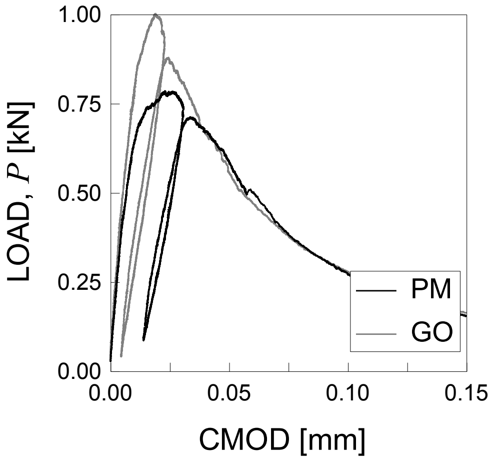

Fig. 2. Experimental load – CMOD curves of PM and GO specimens.

Table 2. Fracture test results: peak load, elastic modulus and fracture toughness of PM and GO specimens.

SPECIMEN TYPE	P_{max} [kN]		E [GPa]		$K^S_{(I+II)C}$ [MPa·m$^{0.5}$]	
	μ	σ	μ	σ	μ	σ
PM	0.741	0.043	32.984	0.649	0.835	0.044
GO	0.916	0.086	33.752	0.418	0.950	0.049

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