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Energy absorption at high strain rate of glass fiber reinforced mortars

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Abstract. In this paper, the dynamic behaviour of cement mortars reinforced with glass fibers was studied. The influence of the addition of glass fibers on energy absorption and tensile strength at high strain-rate was investigated. Static tests in compression, in tension and in bending were first performed. Dynamic tests by means of a Modified Hopkinson Bar were then carried out in order to investigate how glass fibers affected energy absorption and tensile strength at high strain-rate of the fiber reinforced mortar. The Dynamic Increase Factor (DIF) was finally evaluated.

1. Introduction

Even if the use of glass fibers to reinforce concrete was first proposed in Russia before the 2-nd World War, the industrial use of Glass Fiber Reinforced Concrete (GRFC) dates back to the 1970's, after the development by Pilkington Corporation in 1967 of a suitable glass formulation to produce Alkali-Resistant glass fibers containing zirconia [1].

Nowadays glass fibers with improved alkali resistance allow a structural use of GFRC [1–3], otherwise limited by the embrittlement of glass fibers caused by the alkaline environment of the Portland cement paste.

Therefore, GFRC was extensively used in the industrial production of prefabricated elements, especially precast façade panels. Nowadays, an alternative solution to GFRC is basalt fiber reinforced concrete, that can similarly limit cracking and absorb impact energy [4].

While many articles describe the static behaviour of GFRC, its dynamic behaviour has been much less studied. A reference study on toughness and impact tests on GFRC panels was carried out by Mobasher and Shah [5].

Glinicki et al. [6] studied impact on GFRC plate specimens through drop weight instrumented test device that allowed to detect the maximum impact load, the energy absorbed up to the maximum load and the energy absorbed up to total failure, thus obtaining an impact-to-static energy absorption of 1.7–1.8 for the GFRC plate elements considered.

The impact behaviour of facade panels made of GFRC was investigated by Enfedaque et al. [7] by shooting steel spheres with high velocity on square samples of different GFRC panels, and by then calculating energy absorption as the kinetic energy difference of the projectile before and after impact.

Yldirim et al. [8] studied the impact behavior of different Fiber Reinforced Concretes (FRC) including GFRC. By using practically the same drop-weight method of ACI 544 2R-89 [9], impact test was performed time after time on cubical FRC samples with side 100 mm until failure occurred. Glass fibers were shown to be as effective as steel fibers and more effective than polypropylene fibers to prevent first cracking. While samples reinforced with steel fibers needed a much higher number of impact tests until failure occurred with respect to samples reinforced with both glass and polypropylene fibers, the latter ones needing almost the same number of impacts to failure. Adding glass fibers to steel fibers was very effective to delay failure, better than adding polypropylene fibers.

Sangeetha [10] studied the favourable effect of additives such as superplasticizer, air retaining agent and retarder on impact strength of GFRC plates.

In this paper the effect of adding glass fibers on the dynamic behaviour of cementitious mortars was investigated. Dynamic tensile tests at high strain rate were performed by means of a Modified Tensile Hopkinson Bar device. Also, reference static tests to evaluate flexural, tensile, and compression strength of the mortars were carried out.

2. Experimental procedure

Standard Portland cement (CEM I, 52.5 R in accordance with EN 197-1 [11]) and standard sand, as prescribed by the EN 196-1:2005, were used [12]. A reference cement mortar (water/cement ratio: 0.5) was prepared.

Fiber reinforced specimens were prepared through adding glass fibers to the cementitious mixture. Fiber content was 3 and 5%. Fibers with length 12 mm and diameter 14 μm were used. Immediately after mixing, the mixtures were introduced into the steel mould to manufacture the specimens, whose surface-were smoothed and covered by means of a polyethylene film. Water evaporation during the first hours was thus avoided, and the specimens were then cured at 20 °C and 95% R.H.

In accordance with EN 196-1:2005 [12], the flexural strength of prismatic specimens ($40 \times 40 \times 160\,mm^3$) was

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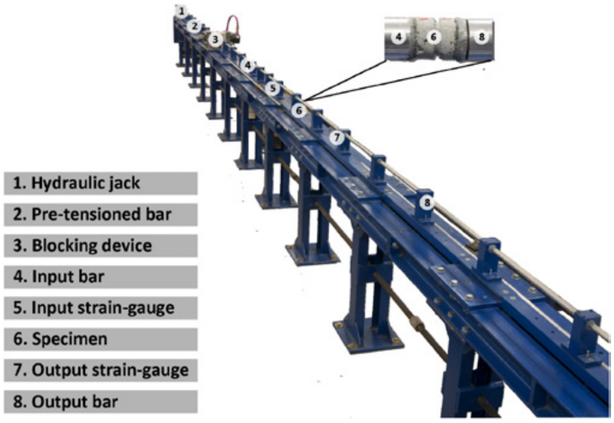

Figure 1. The Modified Hopkinson Tensile Bar used in this experimental research.

evaluated by means of the three-point bending test. Then, compressive strength tests were carried out on the two prism halves obtained from the bending test.

After the same curing period, prismatic specimens were cored to obtain cylindrical specimens (h = d = 20 mm, h/d = 1) in order to perform dynamic test by means of a Modified Hopkinson Bar device of the DynaMat Laboratory (SUPSI) in Lugano.

The MHB device consisted of two circular aluminium bars, called input and output bars, both 20 mm in diameter but with different lengths of 3 m and 6 m, respectively. The sample was glued between these bars using a bi-component epoxy resin. The input bar was connected to a high strength steel pretension bar (6 m in length and 12 mm in diameter), that was used as pulse generator. The way of performing the test and a deep description of the MHB device used in this research is widely reported in [13]. The Hopkinson bar device is considered as a profitable technique in order to characterize materials behaviour at high strain rate, as proofed by a large amount of papers published in this field [14–16].

Thereafter, the stress, the strain and the strain-rate in the sample can be derived from Eqs. (1), (2) and (3):

$$\sigma_E(t) = E_0 \frac{A_0}{A} \varepsilon_T(t) \quad (1)$$

$$\varepsilon_E(t) = -\frac{2C_0}{L} \int_0^t \varepsilon_R(t) dt \quad (2)$$

$$\dot{\varepsilon}(t) = -\frac{2C_0}{L} \varepsilon_R(t) \quad (3)$$

where, L is the specimen length, A_0 is the cross-sectional area of output and input bars, A is the initial cross-sectional area of the specimen gauge length portion, E_0 is the elastic modulus of the bars, $C_0 = (E_0/\rho)^{1/2}$ is the bar elastic wave speed, ρ is the bar density and t is time.

In order to obtain reliable data for the evaluation of the energy absorption at high strain-rate, at least three tests for each material were performed.

Table 1. Flexural tensile and compressive strength of reference and fiber reinforced mortars from static tests.

	Flexural tensile strength	Compressive strength
	MPa	MPa
Reference mortar	6,57 ± 0,13	70,20 ± 1,65
Glass fiber 3%	7,78 ± 0,31	57,58 ± 2,44
Glass fiber 5%	8,37 ± 0,69	50,46 ± 2,13

3. Results and discussion

The values of static flexural and compressive strength are summarized in Table 1, that shows that tensile strength was significantly increased by glass fibers, thus meaning that an effective bond between fibers and mortar was developed. Compressive strength of the reference mortar was instead significantly higher than that of the GFRC samples, meaning that the fiber reinforced samples behave as if fibers were inclusions scattered throughout the mortar.

Dynamic tests at high strain-rate were performed using the MHB device ranged between 500 and 600 GPa/s.

The study was conducted with the aim of investigating the capability of glass fibers of dissipating energy in the reinforced concrete of structures subjected to exceptional actions like blasts and collisions, where impact loading occurs at high strain-rate.

Through carrying out tensile tests at high strain-rate on both mortars reinforced with glass fibers and on the reference mortar, the influence of the addition of fibers on energy absorption and tensile strength of samples subjected to high impact loading was studied.

In order to achieve accurate stress-strain diagrams at high strain-rate, stresses and displacements were detected at high frequency (1 Msample/s), thus allowing to calculate energy absorption and get the maximum stress with good precision.

Tables 2–4 report the experimental results for each test carried out on samples made of glass fiber reinforced mortars and of the reference one. In particular, the Stress-Rate is the slope of the stress flow evaluated in function of time in the elastic regime, Max Tensile Stress is the highest value obtained for each test while Fracture strain, Fracture time and Displacement at fracture are the corresponding strain, time and displacement values respectively. Failure time is the time where the stress goes to zero. Eventually, Total energy is the energy represented by the area under the stress-crack opening displacement curve.

Figure 2 allows to compare the behaviour of the mortar reinforced with 3% and 5% glass fiber with that of the reference mortar.

It can be observed that the addition of 3% and even more of 5% of glass fibers (samples G3% and G5%) led to a better post- peak behaviour, with energy absorption much higher than in the reference mortar (Fig. 2a). The improved post-peak behaviour is also highlighted by the much higher failure time of both G3 and G5 mortars (Tables 3 and 4) with respect to that of the reference mortar. It can be also noted that tensile strength at high strain-rate resulted increased by the addition of 5% glass fibers, while was shown to be almost the same of that of the reference mortar

Table 2. Results for the reference mortar.

Sample	Stress Rate	Max Tensile Stress	Fract. strain	Fract. time	Failure time	Displ. at fract.	Failure displ.	Total energy
	GPa/s	MPa	‰	μs	μs	μm	μm	J/m^2
RM_01	556	12,2	0,30	32	44	6	25	177
RM_02	639	12,7	0,33	32	41	7	20	151
RM_03	476	12,4	0,32	35	46	6	25	177
RM_04	550	9,8	0,26	33	62	1	79	249
Average	555	11,8	0,30	33	48	5	37	188
STD	66	1,4	0,03	1	9	3	28	42

Table 3. Results for the mortar reinforced with glass fibers (3%).

Sample	Stress Rate	Max Tensile Stress	Fract. strain	Fract. time	Failure time	Displ. at fract.	Failure displ.	Total energy
	GPa/s	MPa	‰	μs	μs	μm	μm	J/m^2
G3%_01	873	15,7	0,18	30	58	4	48	195
G3%_03	496	14,1	0,33	36	272	6	867	1260
G3%_04	412	10,8	0,35	34	218	7	681	815
G3%_04	553	10,5	0,52	35	167	10	518	947
Average	584	12,8	0,34	33	179	7	528	804
STD	201	2,5	0,14	3	91	3	351	447

Table 4. Results for the mortar reinforced with glass fibers (5%).

Sample	Stress Rate	Max Tensile Stress	Fract. strain	Fract. time	Failure time	Displ. at fract.	Failure displ.	Total energy
	GPa/s	MPa	‰	μs	μs	μm	μm	J/m^2
G5%_01	470	14,2	0,58	35	222	12	686	1536
G5%_02	480	12,9	0,41	28	237	8	778	1214
G5%_03	566	11,6	0,34	32	241	7	760	909
Average	505	12,9	0,44	32	233	9	741	1220
STD	52	1,3	0,12	4	10	3	49	314

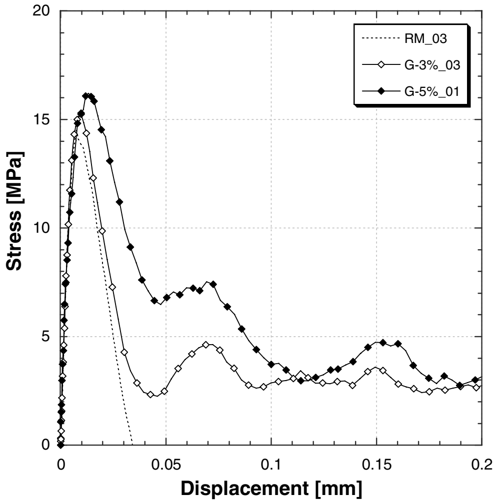

Figure 2. Stress as a function of displacement for reference and glass reinforced mortars.

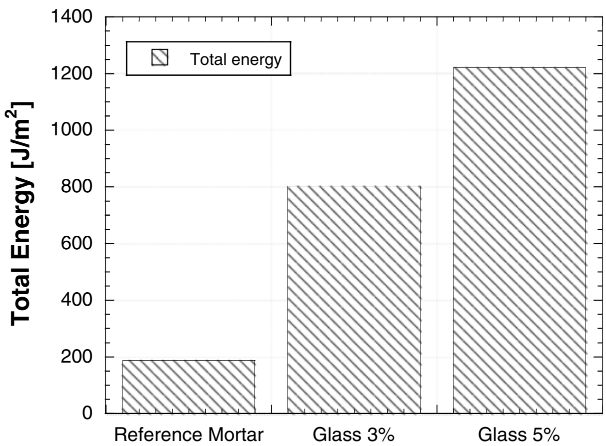

Figure 3. Comparison of total energy for different fiber content in glass.

(or even slightly lower) when the percentage of fibers was 3%.

Figure 3 allows to easier compare one another the values (reported in Tables 2–6) of total energy of the reinforced mortar and the reference one.

Figure 4 shows the images (obtained from the optical microscope) of the plan view and the lateral view of the failure surface of samples G3%_03. It can be noted that glass fibers of sample G3%_03 were cut and debonded by tension failure occurred under dynamic conditions.

Figure 4. Images (obtained from the optical microscope) of lateral view of the failure surface of sample G3%_03.

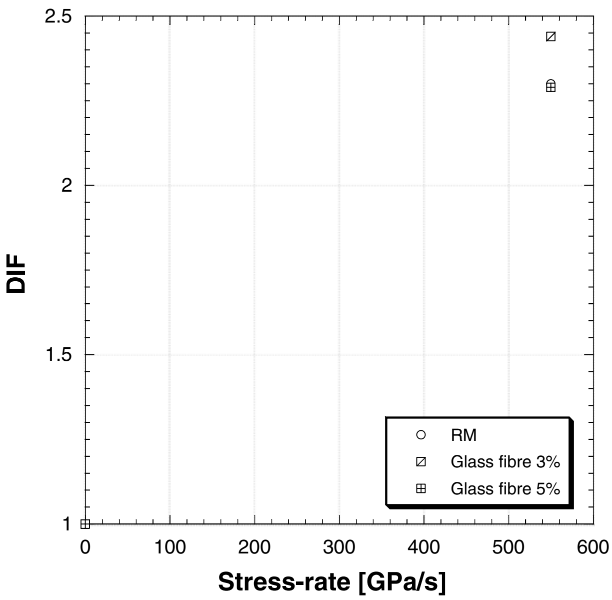

Figure 5. Dynamic Increase Factor vs. Stress-rate.

Finally, also the Dynamic Increase Factor (DIF) was evaluated (Fig. 5) as the ratio between the dynamic strength and the static strength of the material. For this aim, by using the same specimens geometry used for high strain-rate tensile tests, also direct static tensile tests (0.5 MPa/s) were performed.

Testing three specimens for each mortar RM, G3%, G5%, their tensile strength resulted 5.11 ± 0.0 MPa, 5.23 ± 0.5 MPa, 5.24 ± 1.2 MPa, respectively.

The DIF 2.30 for the reference mortar is a typical expected value for this material [17–19]. The lowest fiber addition (3%) led to a DIF slight increase for mortar G3% (2.44), while fiber addition until 5% brought on DIF values of 2.29 for mortars G5%, thus practically the same of the reference mortar. Therefore, DIF was shown to be little affected by fiber addition, and to vary little with fiber content.

It can be also noted a low DIF decrease with the fiber content increase from 3% to 5% of glass fibers. This means that, under dynamic conditions, the increase of fiber content was ineffective to improve micro-crack bridging [20,21].

Nevertheless, as seen before, comparison with plain mortars shows that the addition of glass fibers, while improving energy absorption under dynamic loading, only slightly increases tensile strength with respect to the reference mortar.

4. Conclusions

The dynamic behaviour in tension of mortars reinforced with glass fibers has been investigated. The experimental study has allowed to study the effect of the addition of glass fibers to a cementitious mortar on its dynamic behaviour.

From the dynamic tensile tests at high strain-rate carried out by means of a Modified Hopkinson Bar device, the following conclusions have been gathered:

– static flexural strength of the mortar was highly increased by the addition of glass fibers.
– dynamic tensile strength was significantly increased by the addition of 5% glass fibers, while was only slightly increased by the percentage of 3%.
– the addition of glass fibers to the cementitious mortar improved its post-peak behaviour under dynamic tension loading.
– fracture energy resulted highly increased by the addition of 5% glass fibers (7.2 times the fracture energy of the reference mortar), but was significantly increased also by a fiber content of 3% (4.6 times that of the reference mortar).
– DIF of mortars reinforced with glass fibers was practically the same as that of the reference mortar.

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