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Use of GRP industrial by-products in cement based composites

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The possibility of re-using Glass Reinforced Plastic (GRP) industrial by-product powder in cement based composites was investigated. Firstly, the by-product was physically and chemically characterized. Secondly, mechanical, capillary water absorption and shrinkage measurements were carried out on cement mortars manufactured by replacing the 0%, 10%, 15% and 20% of the aggregate volume with GRP by-product and on self compacting concretes manufactured by replacing the 0%, 25% and 50% of the calcareous filler volume with GRP powder. The obtained results show that GRP industrial by-product powder could be used as a partial aggregate or filler replacement in cement based composites. A decrease in mechanical strength was detected on the cement-based materials manufactured by GRP addition. However, capillary water absorption and drying shrinkage of cement-based materials with GRP addition resulted in significantly lower values than those of the cement-based materials manufactured without GRP addition, involving enhanced durability.

1. Introduction

Sustainable building development includes a judicious use of resources, achieved by the use of industrial by-products and post-consumes discarded materials, and a lower environmental impact achieved through reduced natural aggregate mining from quarries [1,2]. Concrete could be a viable solution to environmental problems since it is also possible to re-use solid by-products from other industries for concrete production. This would reduce the need to landfill these materials and to extract natural aggregate from quarries while still maintaining an acceptable, and sometimes even better, concrete quality [3]. In particular, for self compacting concrete production, a high-volume of very fine material is also necessary in order to make the concrete more fluid and cohesive. Self-compactibility of concrete is generally achieved by adding a certain amount of very fine particles as filler to the mixture.

Glass Reinforced Plastic (GRP) is a composite material made of glass fibres dispersed in a resin, usually polyester, widely used in several fields from building to furniture to boats. Every year, in Western Europe, GRP processing produces 40,000 tons of industrial by-product [4]. In Italy this by-product is land-filled due to: the difficulty of separating the glassy part from the polymeric matrix, its intrinsic thermoset composite nature, the lack of information relating to its characteristics and the insufficient knowledge on potential recycling options. Concrete made with recycled glass [5–10] or polymeric addition [11–20] has already been proposed in the literature. Therefore, the feasibility of re-using GRP industrial by-product in manufactured cementitious elements could be considered [21–23].

In particular, three types of GRP by-products are presently produced:

- *GRP bars*: 1 m long and 1–2 cm thick, coming from faulty products;
- *small pieces*: 1–2 cm in size;
- *a fine powder*: about 0.1 mm in size.

In this work, the finest GRP by-product was physically and chemically characterized in order to outline compatibility issues with cement, if any. Subsequently, cement mortars and self compacting concretes manufactured by partially replacing the aggregate and the calcareous filler volume, respectively, with GRP by-product powder were investigated in terms of mechanical, capillary water absorption and shrinkage measurements.

2. Experimental

2.1. Materials

A GRP powder coming directly from a shipyard as an industrial by-product was used (Fig. 1).

A commercial Portland-limestone blended cement type CEM II/A-L 42.5 R according to the European Standards EN-197/1 was used. The Blaine fineness of cement was 0.415 m^2/g and its specific

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Fig. 1. GRP industrial by-product powder.

Table 1
Chemical analysis of cement.

Oxide	%
SiO_2	29.67
Al_2O_3	3.74
Fe_2O_3	1.80
TiO_2	0.09
CaO	59.25
MgO	1.15
SO_3	3.25
K_2O	0.79
Na_2O	0.26
L.O.I.	11.62

gravity was 3.05. The chemical composition of cement is reported in Table 1. Natural calcareous sand, 5 mm maximum size, volume mass of 2620 kg/m^3 and water absorption of 3.0% was used as aggregate. A 30% aqueous solution of an acrylic-based super plasticizer was added, when required, in order to maintain the same workability level. In the case of SCC, a crushed limestone aggregate (12 mm maximum size), a commercial filler based on limestone powder with specific gravity equal to 2.70 g/cm^3 and a viscosity modifying agent (VMA), based on biopolymers, were also used.

2.2. Specimens

Mortar mixtures with cement to sand ratio 1:3 (by weight) and w/c of 0.50 were manufactured by replacing the 0%, 10%, 15% and 20% of aggregate volume with the GRP industrial by-product powder. The use of GRP by-product powder as partial aggregate replacement did not show any segregation problem and the resultant mixtures show similar characteristics to traditional ones. At 15% and 20% replacement rate, GRP appreciably decreases mortar workability and, at these rates, a super plasticizer was added at a dosage of 0.25% and 1% by weight of cement, respectively, in order to achieve comparable workability.

Self-compacting mixtures with w/c of 0.60 were manufactured, by replacing 0%, 25%, and 50% of calcareous filler volume with the GRP powder. The relative mixture proportions are reported in Table 2. The average diameter (Φ_{fin}) of the slumped concrete, the time elapsed to achieve a mean diameter of 500 mm (t_{500}) and the time to reach the final configuration (t_{fin}) were both detected, according to Italian Standard UNI 11041:2003 [24]. As shown in Table 2, all concretes had a sufficient deformability under their own weight strictly related to the (Φ_{fin}) value; moreover the t_{fin} values, which are related to viscosities, fall in the acceptable range, $\leqslant$12 s. An acrylic based superplasticizer was used in every case but at different dosages in order to guarantee a slump flow of at least 600 mm (Table 2). It was dosed at 1% by weight of cement in the case of calcareous filler and at 1.3% and 1.8% in the case of 25% and 50% of calcareous filler volume partially replaced by GRP.

Table 2
Self compacting concrete mixture proportions (kg/m^3) and results of slump-flow test.

Mixture	SCC-0%	SCC-25%	SCC-50%
Water	188	188	188
Cement	305	305	305
Natural sand	660	660	660
Crushed aggregate	900	900	900
Calcareous filler	236	177	118
GRP powder	–	28	56
Superplasticizer	3	4	5.5
VMA	0.3	0.3	0.3
ϕ_{fin} (mm)	670	630	630
t_{500} (s)	1	2	2
t_{fin} (s)	7	9	10

2.3. Tests

2.3.1. Tests on the GRP powder

FT-IR spectroscopy, thermo gravimetric analysis and X-ray diffraction analysis were carried out to characterize the GRP powder. Scanning electronic microscopy was also used to observe the powder grains morphology. Apparent density and water absorption were determined according to Italian standard UNI EN 1097-6:2002 [25]. The particle size distribution was evaluated by laser diffraction. Finally, the alkali–silica reactivity, as a consequence of the presence of glass, was tested following the ASTM Designation C 289-94 [26].

2.3.2. Tests on cement-based materials

2.3.2.1. Mechanical characterization. For each mixture, prismatic specimens (40 × 40 × 160 mm) were manufactured and wet-cured for 28 days at room temperature. Compressive and flexural strengths were determined on specimens at curing times of 2, 7, and 28 days by observing strength loss for an increasing dosage of the GRP powder at different curing times.

2.3.2.2. Capillary water absorption tests. Capillary water absorption tests were carried out on the manufactured cement-based materials according to the procedure reported in the Italian Standard UNI 10859 [27], respectively.

2.3.2.3. Drying shrinkage test. For each mixture, prismatic specimens (100 × 100 × 500 mm) were prepared according to Italian Standard UNI 6555:1973 [28]. After 1 day of wet curing, the specimens were stored at constant temperature (20 ± 2 °C) and constant relative humidity (50 ± 2%).

3. Results and discussion

3.1. Tests on the GRP powder

Thermo gravimetric analysis (Fig. 2) showed that GRP powder composition was about 20% by volume of glass fibres and 80% by volume of organic material identified by FT-IR spectroscopy as polyester resin. The water absorption and apparent density were 20% and 1.3 g/cm^3, respectively. Since apparent density of natural sand or calcareous filler is 2.6 g/cm^3, partial replacement of natural sand or calcareous filler with GRP powder decreases the density of cement-based materials. GRP powder appeared, by laser diffraction, slightly coarser with respect to a commercial filler or a reference cement (Fig. 3). SEM and EDAX analysis (Fig. 4) showed GRP particles irregular in shape and size formed by polymeric granules

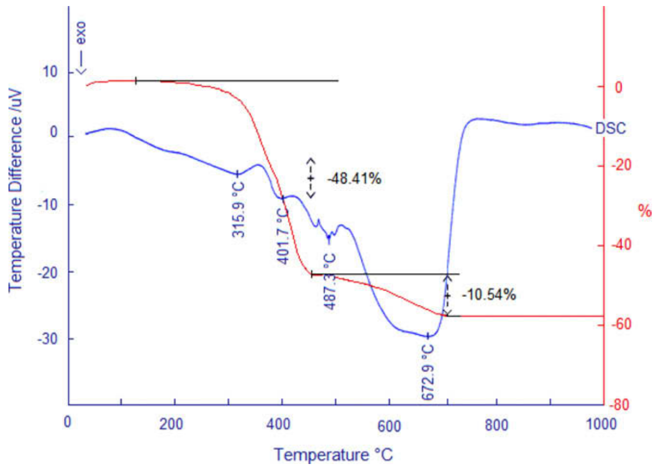

Fig. 2. Thermo-gravimetric analysis of GRP industrial by-product powder.

surrounding fibres of a low alkali glass. Glass fibres length varied from 0.02 mm to 20 mm. X-ray analysis did not reveal any crystalline phase and for this reason it is not reported here.

ASTM Designation C289-94 did not show any potential Alkali–Silica Reactivity of GRP by-product due to the glassy part since points R_c and S_c in Fig. 5, lie on the innocuous side of the curve. Moreover, good durability of polyester resin against alkali attack is generally reported in the literature [12]. Therefore, GRP addition would seem chemically compatible with cement and its use as partial aggregate or filler replacement to produce new cement based composites could be considered.

3.2. Tests on the cement based composites

3.2.1. Mechanical characterization

The development with time of flexural and compressive strength of mortars and self compacting concrete manufactured with increasing GRP by-product addition as a partial aggregate or

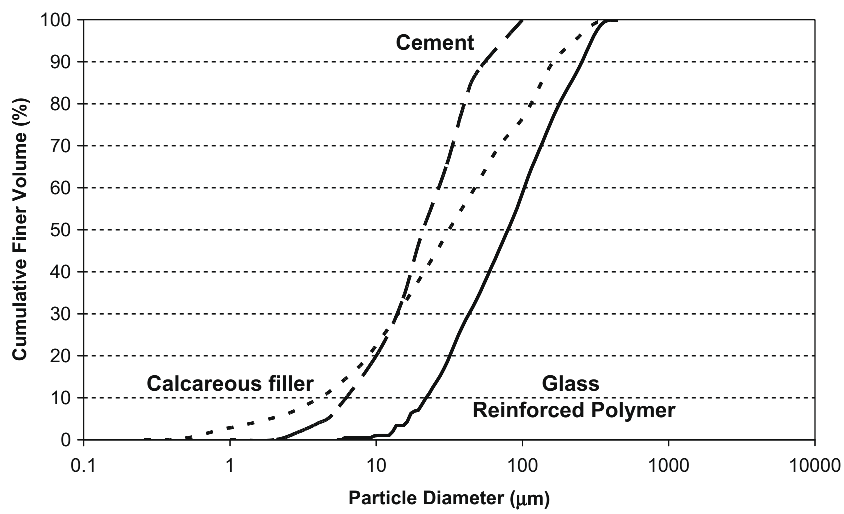

Fig. 3. Laser diffraction measurements of GRP powder, commercial filler and reference cement.

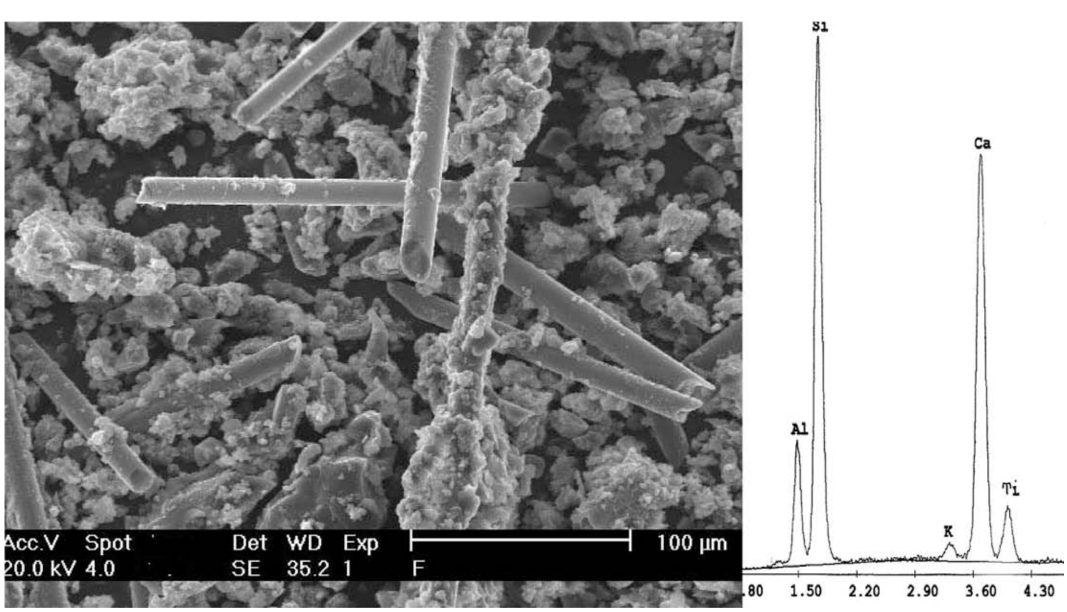

Fig. 4. SEM and EDAX analysis of GRP powder.

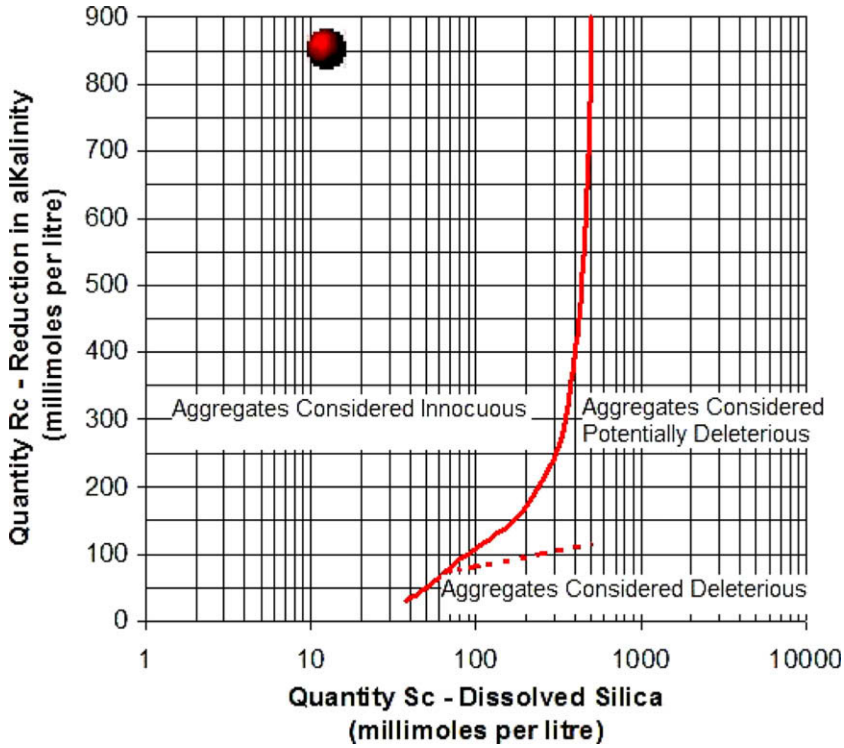

Fig. 5. The innocuous character of GRP powder according to ASTM Designation C289-94.

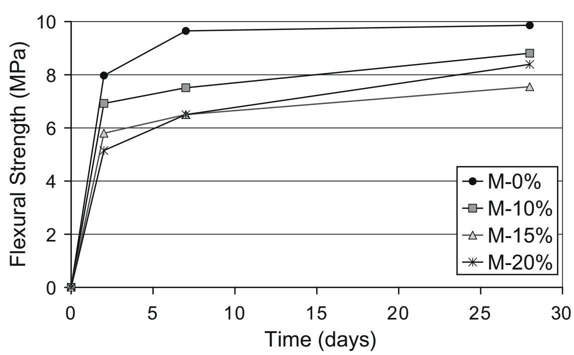

Fig. 6a. Development with time of flexural strength of mortars manufactured with sand partially replaced by GRP at dosages of 0%, 10%, 15% and 20% by volume, respectively.

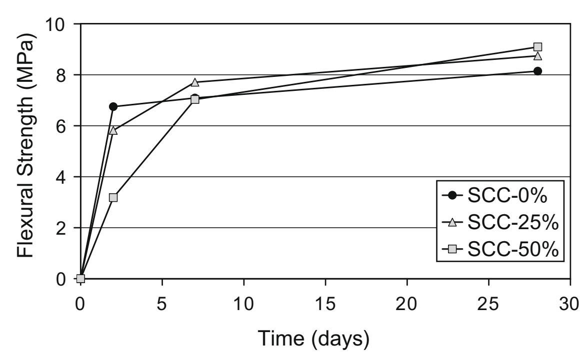

Fig. 6b. Development with time of flexural strength of SCC manufactured with a calcareous filler, partially replaced by GRP at dosages of 0%, 25%, and 50% by volume, respectively.

calcareous filler volume replacement, respectively, is given in Figs. 6a, 6b, 7a and Fig. 7b. The results show that GRP addition caused a strong reduction in compressive strength (up to about 25% depending on the addition rate) (Figs. 7a and 7b). A similar behaviour, but with a lower effect due to the presence of glass fibres, was observed in the flexural strengths (Figs. 6a and 6b) of the tested samples. The reduction in mechanical performance was due to the fact that the strength of the plastic particles and of the interface between plastic particle and cement paste is lower than those of the natural sand or calcareous filler [16,17,20]. Therefore, both the use of cement based composites with GRP particles and the percentage of replacement should be controlled, according to the allowable strength of the structural element to be constructed.

3.2.2. Water absorption

Figs. 8a, 8b shows the results of capillary water absorption tests obtained on mortars and self compacting concretes with increasing GRP addition. It is evident that the GRP addition was able to decrease the capillary water absorption, despite the lower compressive performance of cement-based materials with GRP addition.

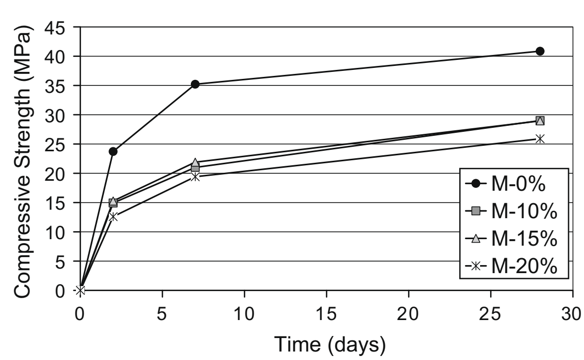

Fig. 7a. Development with time of compressive strength of mortars manufactured with sand partially replaced by GRP at dosages of 0%, 10%, 15% and 20% by volume, respectively.

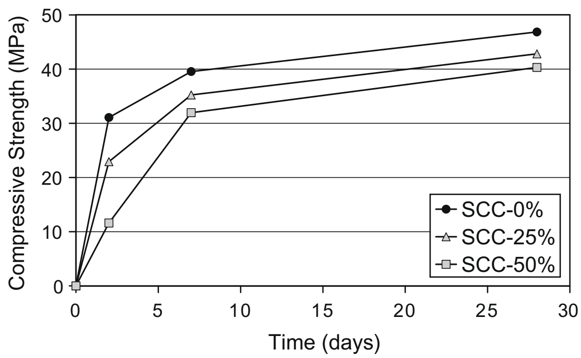

Fig. 7b. Development with time of compressive strength of SCC manufactured with a calcareous filler, partially replaced by GRP at dosages of 0%, 25%, and 50% by volume, respectively.

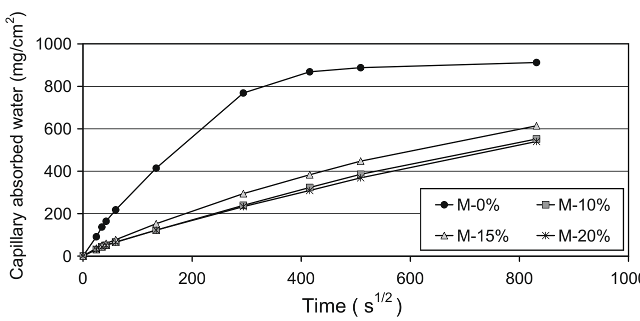

Fig. 8a. Capillary water amount absorbed as a function of time per square unit by mortars manufactured with sand partially replaced by GRP at dosages of 0%, 10%, 15% and 20% by volume, respectively.

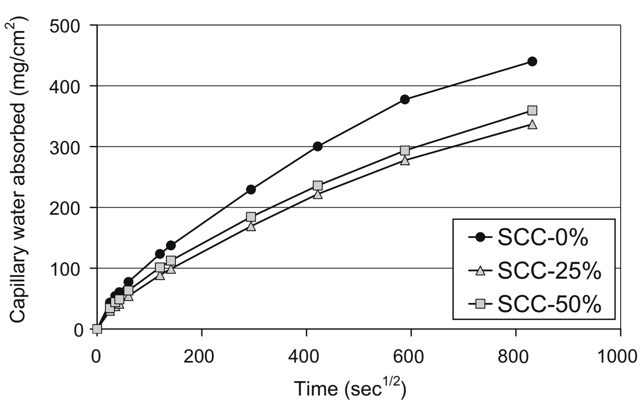

Fig. 8b. Capillary water amount absorbed as a function of time per square unit by SCC manufactured with calcareous filler partially replaced by GRP at dosages of 0%, 25%, and 50% by volume, respectively.

In particular, the relative capillary absorption coefficient (CA_{rel}), defined as the ratio between the capillary absorption coefficient (CA) of the GRP cement based material to that of the same material without GRP addition (Tables 3a and 3b), showed that GRP was able to decrease the capillary water absorption by about 70% in mortars and up to about 30% in self compacting concretes. The capillary absorption coefficient (CA) represents the slope of the initial (up to $t = 30$ min) linear part of the water absorption curve reported in Figs. 8a and 8b. Therefore, water absorption is initially more effectively counteracted by the presence of GRP.

The relative capillary absorption index (IC_{rel}) is defined as the ratio of the area subtended by the water absorption curve of the

Table 3a
Capillary absorption coefficients (CA), relative capillary absorption coefficients (CA_{rel}) and relative absorption capillary index (IC_{rel}) for mortars manufactured with sand partially replaced by GRP at dosages of 0%, 10%, 15% and 20% by volume, respectively.

Mixtures	CA ($mg/cm^2\ s^{-1/2}$)	CA_{rel}	IC_{rel}
M-0%	3.87	–	–
M-10%	1.20	0.31	0.43
M-15%	1.41	0.36	0.50
M-20%	1.20	0.31	0.42

Table 3b
Capillary absorption coefficients (CA), relative capillary absorption coefficients (CA_{rel}), and relative absorption capillary index (IC_{rel}) for SCC manufactured with calcareous filler partially replaced by GRP at dosages of 0%, 25%, and 50% by volume, respectively.

Mixture	CA ($mg/cm^2\ s^{-1/2}$)	CA_{rel}	IC_{rel}
SCC-0%	1.43	–	–
SCC-25%	0.94	0.66	0.74
SCC-50%	0.81	0.81	0.80

GRP cement based material to the area of the absorption curve of the reference one (Figs. 8a and 8b) and it is related to the corresponding amount of water absorbed during the full contact time. As shown in Tables 3a and 3b, when more prolonged contact between water and the cement matrix occurs, the value of IC_{rel} is lower than 0.5 and 0.8 for the manufactured mortars and self compacting concretes, respectively. This implies that aggregate partial replacement by GRP addition in mortars is able to reduce the water absorption by at least 50% while the filler partial replacement by GRP addition is able to reduce water absorption by at least 20% in self compacting concretes. This fact is explained by the non-sorptive property of GRP inclusions that contribute to slowing down the propagation of the imbibition front by forcing the hydrous flow to bypass them, i.e. by increasing tortuosity [18].

3.2.3. Drying shrinkage test

Figs. 9a, 9b shows the results obtained up to 1 month of storage at room temperature and constant relative humidity (50 ± 2%). It is evident how the drying shrinkage of the mortars with GRP by-product turned out to be up to 50% of the drying shrinkage of reference mortar without GRP, while the drying shrinkage of SCC with GRP addition turned out to be almost 33% lower than the drying shrinkage of SCC without GRP. This behaviour confirms some results already reported in the literature concerning concretes manufactured with another type of recycled plastic waste [20]. Moreover, if shrinkage is restrained and no creep effects are

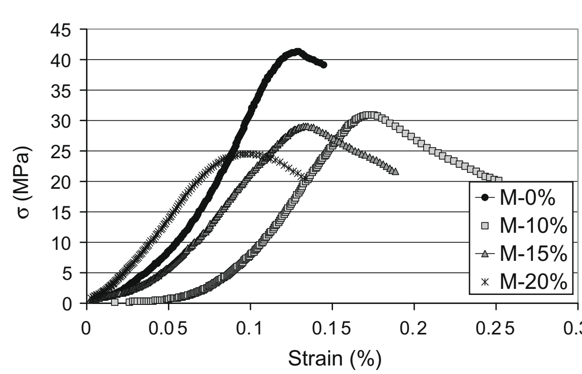

Fig. 9a. Compressive stress–strain curves of mortars manufactured with sand partially replaced by GRP at dosages of 0%, 10%, 15% and 20% by volume, respectively, after 28 days of wet curing.

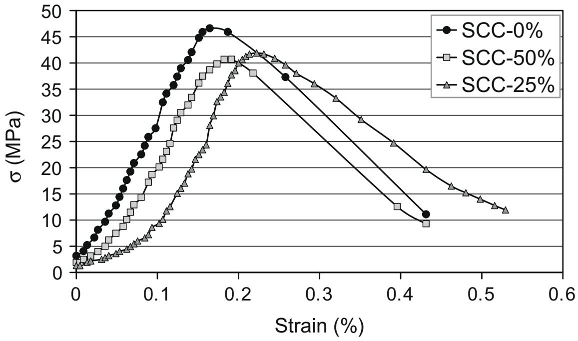

Fig. 9b. Compressive stress–strain curves of SCC manufactured with calcareous filler partially replaced by GRP at dosages of 0%, 25%, and 50% by volume, respectively, after 28 days of wet-curing.

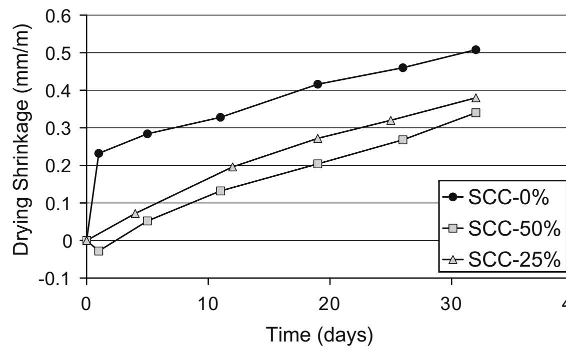

Fig. 10b. Drying shrinkage measurements up to 1 month carried out on SCC manufactured with calcareous filler partially replaced by GRP at dosages of 0%, 25%, and 50% by volume, respectively.

Table 4a
Comparison between flexural strength after 28 days of drying and tensile stress induced by drying shrinkage at the same age for mortars manufactured with natural sand partially replaced by GRP at dosages of 0%, 10%, 15% and 20% by volume, respectively.

Mixture	Flexural strength (MPa)	Tensile stress induced by shrinkage (MPa)
M-0%	9.86	15.3
M-10%	8.81	6.0
M-15%	7.55	11.8
M-20%	8.39	15.7

Table 4b
Comparison between flexural strength after 28 days of drying and tensile stress induced by drying shrinkage at the same age for SSC manufactured with natural sand partially replaced by GRP at dosages of 0%, 10%, 15% and 20% by volume, respectively.

Mixture	Flexural strength (MPa)	Tensile stress induced by shrinkage (MPa)
SCC-0%	8.14	14.91
SCC-25%	8.74	11.10
SCC-50%	9.09	8.63

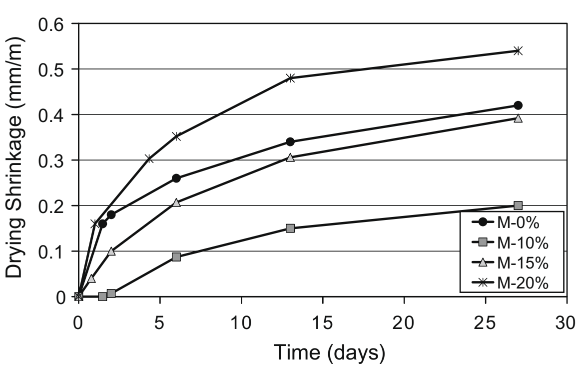

Fig. 10a. Drying shrinkage measurements up to 1 month carried out on mortars manufactured with sand partially replaced by GRP at dosages of 0%, 10%, 15% and 20% by volume, respectively.

considered, the lower the modulus of elasticity such as that of GRP cement based composites, the lower will be the induced elastic tensile stress for a given shrinkage strain. The results (Tables 4a and 4b) obtained by multiplying the shrinkage strain after 28 days of drying with the secant elastic modulus [29] at the same age calculated from the relative stress–strain curves (Figs. 10a, 10b), underline that the risk of cracking induced by drying shrinkage is in general lower in cement based composites manufactured with GRP addition.

4. Conclusions

The salient conclusions from this study on the feasibility of reusing GRP industrial waste powder, otherwise landfilled, in cementitious elements are:

- GRP powder, composed of 20% and 80% in volume of glass fibres and polyester resin respectively, is compatible with cement.
- A strong reduction in compressive strength (up to about 25%) was detected in mortars and self compacting concretes where GRP powder was used as partial replacement of either fine aggregate in mortars or filler material in self compacting concrete, when wet curing conditions are adopted.
- Capillary water absorption and drying shrinkage of GRP cementitious composites resulted significantly lower (up to about 70% and 50%, respectively) than those of the reference ones made without any GRP addition. This decrease could involve enhanced durability even if only as a supporting role.

The results demonstrate the potential of incorporating GRP powder to manufacture durable cement-based elements. This may lead to a viable technological option from the point of view of GRP by-product management, leading to cross-sector waste recycling applications within the construction industry.

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