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Effect of GRP By-Product Addition on Plastic and Hardened Properties of Cement Mortars

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ABSTRACT

The possibility of recycle Glass Reinforced Plastic industrial by-product Dust (GRPD) in cementitious materials was considered and the effect of GRPD addition on plastic and hardened properties of cement mortars was investigated. Results revealed that GRPD addition delays the setting time of cement paste, but the delay can be partially recovered by using a previously heated GRPD. Moreover, GRPD is effective in reducing the viscosity and yield stress of cement paste when used as a partial cement replacement. Replacing 5 - 10% of sand volume with GRPD causes an increase in autogenous shrinkage and deformability of mortars as well as a strong reduction in the mechanical performance. However, the risk of cracking induced by restrained drying shrinkage and capillary water absorption is significantly lower in the presence of GRPD. This decrease could involve enhanced durability of GRPD mortars, even if only in a supporting role.

INTRODUCTION

Sustainable building development includes a judicious use of resources, achieved by the use of industrial by-products and post-consumer discarded materials, and a lower environmental impact achieved through reduced natural aggregate mining from quarries [Naik 2007]. Concrete can be a viable solution to environmental problems as it is also possible to re-use solid by-product from other industries in concrete production. This will reduce the need to landfill these materials and the natural aggregate extraction from quarries while still maintaining an acceptable, and sometimes even better concrete quality [Hendriks et al. 2003]. Glass Reinforced Plastic (GRP) is a composite material made of glass fibers dispersed in a resin, usually polyester, widely used in several fields from buildings to furniture to boats. Every year, in Western Europe, GRP processing produces 50000 tons of industrial by-products [Kelderman 2000]. In particular, three types of GRP by-products are produced: GRP bars (1 meter long and 1-2 cm thick, coming from faulty products), small pieces (1-2 cm in size), and Glass Reinforced Polymer Dust, or GRPD (a fine powder about 0.1 mm in size).

At present, GRP 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 of potential recycling options. Concrete made with recycled glass [Shi et al. 2007] or polymeric addition [Carlos et al. 2008; Gorninski et al. 2007] has already been proposed in the literature. Therefore, the feasibility of re-using GRP industrial by-product in manufactured cementitious elements could be considered [Asokana et al. 2009; Tittarelli et al. 2005; Tittarelli et al. 2007].

In previous works [Tittarelli et al. 2005] the GRPD by-product was physically and chemically characterized. In this work, the effect of GRPD addition on the plastic properties of cementitious materials in terms of setting time and rheological properties was evaluated. Moreover, the effect of GRPD addition on the hardened properties of cement mortars, manufactured by partially replacing the aggregate volume with GRPD, was evaluated in terms of mechanical performances, shrinkage behaviors and capillary water absorption.

MATERIALS AND MIXING

Materials

ASTM C150 Type I ordinary portland cement, tap water and dry natural silica sand, having maximum a grain size of 4.5 mm, specific gravity of 2.64 g/cm^3 and water absorption of 2.3% were used.

GRPD coming directly from a shipyard as an industrial by-product was used (Figure 1). Previous works [Tittarelli et al. 2005] showed that GRPD composition was about 20% by volume of glass fibers and 80% by volume of polyester resin. The apparent density was 1.3 g/cm^3. GRPD appeared, by laser diffraction, slightly coarser with respect to a commercial filler or a reference cement ($d_{average}$ = 100 μm). SEM and EDAX analysis showed irregularity in shape and size of GRPD particles formed by polymeric granules surrounding fibres of a low alkali glass. Glass fibers length varied from 0.02 mm to 20 mm. ASTM Designation C289-94 did not point out any potential Alkali-Silica Reactivity of GRPD due to the glassy part.

Fig. 1. GRPD Industrial By-Product

Mixing procedure

Mortar mixtures with cement:sand of 1:3 (by weight) and w/c of 0.50 were manufactured by partially replacing the sand volume with GRPD. The mortar batches were mixed in a laboratory planetary mixer. First, sand was mixed with 30% of the total amount of water for 1 minute. Then, cement was added to the mixture and mixed for 1 minute. The rest of the water, with or without GRPD, was added and mixed for another 5 minutes with a pause for cleaning after 2 minutes. The mortars were placed in the molds, rodded 25 times and vibrated for 1 minute.

TESTING PROCEDURES

Setting time

The time of initial and final set of mortars manufactured by replacing 0-5-10% of aggregate volume with the GRPD was determined using a Vicat apparatus.

Rheological test

A rheometer with a concentric cylinder fixture was used to investigate the rheological properties of cement pastes with water/binder of 0.4 by replacing the 0-30% of cement volume with GRPD. Class C fly ash was used as reference filler for comparison.

Mechanical tests

To inspect the influence of GRPD addition on compressive and flexural properties of mortars, cylindrical specimens (φ = 50 mm, h = 100 mm) and mortars beams (300×75×37.5 mm) were cast, respectively, at 0-5-10% of sand volume replaced by GRPD. Specimens were left in molds for 2 days and than stripped and cured at 100% RH and room temperature. Compressive and flexural strengths were determined for three specimens of the same type at curing time of 2, 7, and 28 days. In particular, flexural testing was performed according to a RILEM specification [RILEM Committee, 1990] by using notched beam specimens. The notch length was one-third of the beam depth and the specimens were cut immediately before testing. The specimens were loaded using crack mouth opening displacement (CMOD) control. After reaching the peak load, when the load was about 95% of the peak value, the specimens were unloaded and then reloaded.

Shrinkage behavior

The effect of GRPD addition on autogenous, free and restrained shrinkage behavior of mortars with 0-5-10% of sand volume replaced by GRPD was investigated.

The linear autogenous deformation of specimens was measured for 7 days using the corrugated tube protocol [Jensen et al. 1995; Sant et al. 2006]. Two specimens were prepared for each mixture.

Free shrinkage measurements were performed on three prismatic specimens (100×100×300 mm) for each mixture, using a length comparator according to ASTM C 157. Specimens were cured in the molds for 48 hours at 20°C and 100% RH. Then they were demoulded and exposed to drying at T = 23°C, RH = 50% for about 1 month. At the same time, using the same specimens, weight loss measurements were also conducted.

The ring test was performed to evaluate the cracking behavior of mortars in restrained shrinkage conditions. Two specimens were prepared for each mixture. The test was carried out following the suggestions of the standard ASTM C 1581-04. However some geometric modifications were made as already reported elsewhere [Passuello et al. 2009]. Specimens were cured in the molds for 48 hours at T = 23°C and RH = 100%. Then they were demoulded and exposed to drying at T = 23°C, RH = 50% for about 30 days. Steel ring strain measurements were monitored from the demoulding with subsequent readings taken every half-an-hour until the concrete ring cracked. After that, measurements of the cracking widths were taken every day for about 30 days. A microscope with an accuracy of 0.01 mm was used to measure the widths. The results reported in this paper are the average of three measurements taken along the cracking length (top, center and bottom).

Capillary water absorption

Capillary water absorption tests were carried out on mortar specimens with 0-10-20% of sand volume replaced by GRPD according to Italian Standard UNI 10859. Two specimens were tested for each mixture.

RESULTS AND DISCUSSION

All the reported results are the average of the measurements taken from the same specimens of each mixture.

Setting time

The time at which the needle penetrates 25 mm into the mortars at T = 23°C was taken to define the initial setting. As shown in Figure 2, GRPD addition delays the setting time of cement paste by about 2 hours, but the delay is partially recovered by the addition of previously heated GRPD (T = 70°C for 12 or 48 h, respectively). Probably, the adsorption of the un-reacted monomer still present in GRPD on cement surface delays cement hydration [Ramachandran 1984]. Since the polymerization reaction is promoted by temperature, previously heated GRPD contains less monomer than GRPD as it is.

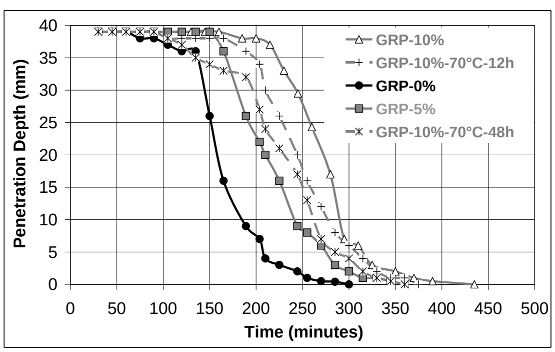

Fig. 2. Setting Time of Different Mortars

Rheological test

Figure 3 shows Shear Stress-Shear Rate curves for the manufactured cement pastes (data were obtained from a "down curve", i.e. decreasing speed). Table 1 reports the relative viscosities and yield stresses. Note that GRPD addition reduces viscosity and yield stress of cement paste more than Fly Ash.

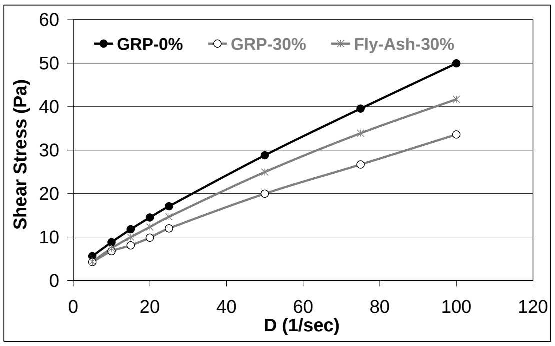

Fig. 3. Shear Stress vs Shear Strain of Different Cement Pastes

Table 1. Viscosity and Yield Stress of Different Cement Pastes

Mixture	Viscosity (Pa×s×10^3)	Yield Stress (Pa)
GRP-0%	408.9	6.5
GRP-30%	298.9	4.2
Fly Ash-30%	375.4	5.1

Mechanical tests

The mechanical characterization showed that GRPD addition caused a strong reduction in compressive strength (about 50%) (Figure 4) and modulus of rupture MOR (about 20%) (Figure 5) when wet curing conditions are adopted. The much lower strength of plastic particles with respect to silica sand [Siddiquea et al. 2008; Batayneh M. et al. 2007] certainly contributes to the decrease in mechanical performance of GRPD mortars.

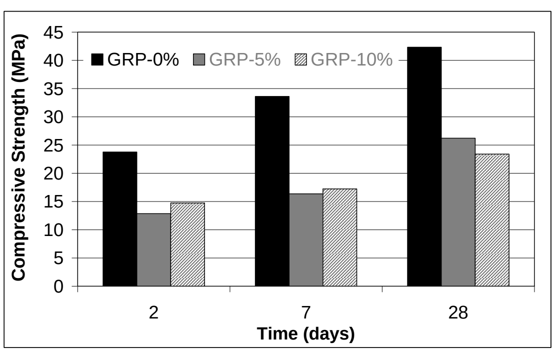

Fig. 4. Compressive Strength vs Time of Different Cement Mortars

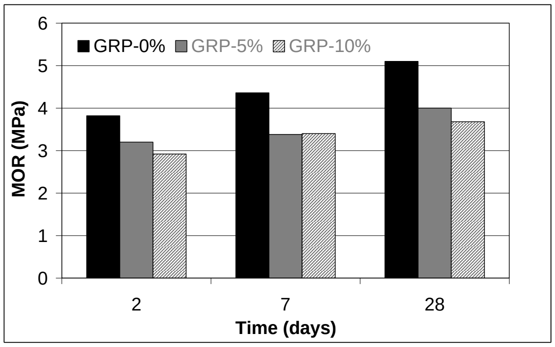

Fig. 5. MOR vs Time of Different Mortars

However, flexural tests (Figure 6) showed an increase in ductility of mortars with GRPD addition in terms of lower elastic modulus (Figure 7) and higher ultimate CMOD (Figure 8).

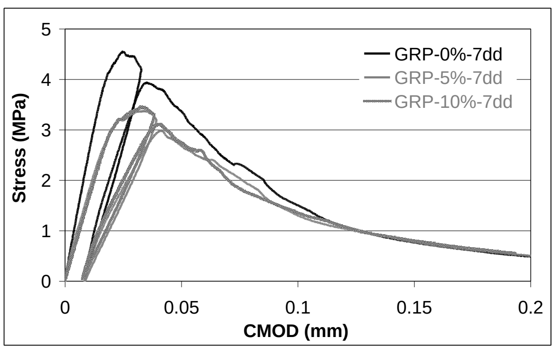

Fig. 6. Stress vs CMOD Curves of Different Mortars after 7 Days of Wet Curing

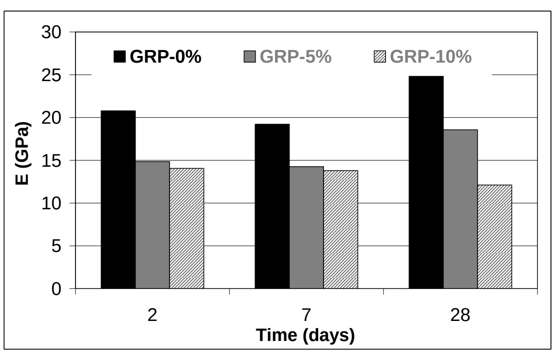

Fig. 7. Elastic Modulus of Different Mortars

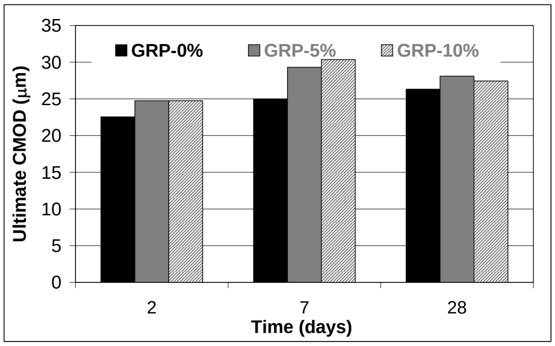

Fig. 8. Ultimate CMOD of Different Mortars

Shrinkage behavior

In the sealed system, the GRPD addition increases autogenous shrinkage of cement mortars (Figure 9). This may be due to the lower elastic modulus of GRPD mortars or/and because GRPD may be adsorbing/absorbing water. As a matter of fact, this increase is partially recovered by adding in the mixture the water adsorbed/absorbed by GRPD (GRPD-10%+water in Figure 9). From the slump test, this water was evaluated at approximately 40% by GRPD weight.

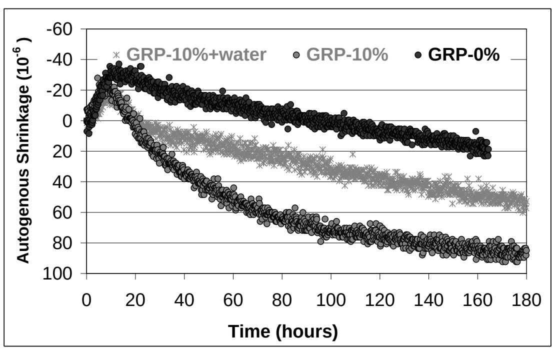

Fig. 9. Autogenous Shrinkage of Different Mortars

For the unsealed case, more water is lost from the GRPD system than from the plain system at the same environmental conditions (Figure 10) although a slightly less shrinkage is observed in GRPD systems (Figure 11).

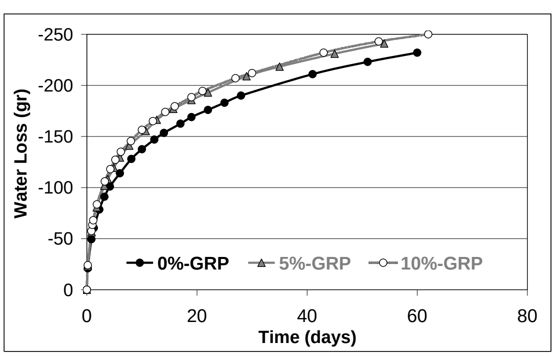

Fig. 10. Water Loss from Different Mortars at T = 23°C and RH = 50%

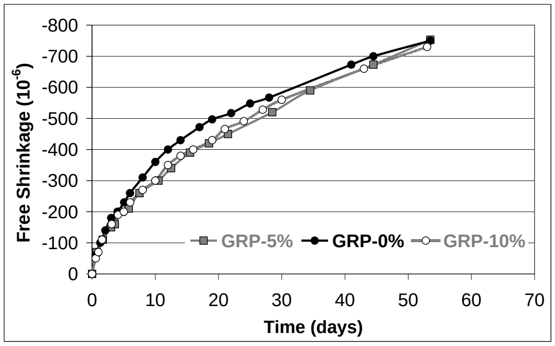

Fig 11. Free Shrinkage of Different Mortars at T = 23°C and RH = 50%

Finally, the GRPD system shows reduction in cracking potential due to restrained shrinkage. In particular, GRPD addition decreases restrained shrinkage strain and its development rate, which lead to a delay of the age of initial cracking by about 1 day at 10% of sand volume replacement and up to 3 days at 5% of sand volume replacement (Figure 12). Moreover, an initial slight reduction in the crack width was recorded in GRPD mortars but followed by an increase in the rate of width growth (Figure 13). This indicates an absence of any reinforcing effect by the GRPD addition.

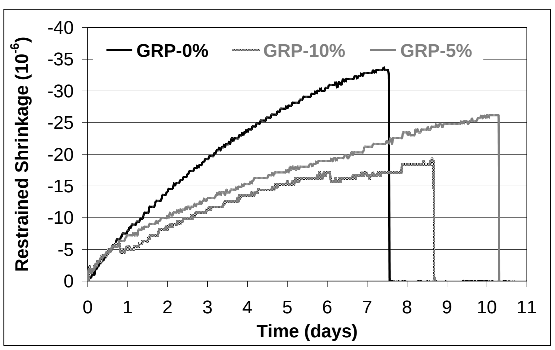

Fig. 12. Restrained Shrinkage of Different Mortars at T = 23°C and RH = 50%

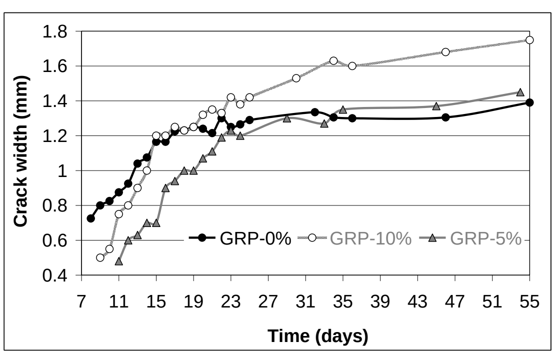

Fig. 13. Crack Width Induced by Restrained Shrinkage of Different Mortars at T= 23°C and RH = 50%

Capillary water absorption

In Figure 14 it is evident that the GRPD addition decreases the capillary water absorption of mortars. In particular, the relative capillary absorption coefficient (CA_{rel}) shown in Table 2, defined as the ratio between the capillary absorption coefficient (CA) of the GRPD cement based material to that of the same material without GRPD addition, showed that GRPD was able to decrease the capillary water absorption of about 70% in mortars. The capillary absorption coefficient (CA) represents the slope of the initial (up to t = 30 minutes) linear part of the water absorption curve. Therefore, water absorption is initially more effectively counteracted by the presence of GRPD. The relative capillary absorption index (IC_{rel}) shown in Table 2 is defined as the ratio of the area subtended by the water absorption curve of the GRPD cement based material to the area of the absorption curve of the reference one (Figure 14) and it is related to the corresponding amount of water absorbed during the full contact time. As shown in Table 2, when more prolonged contact between water and the cement matrix occurs, the value of IC_{rel} is about 0.4 for the manufactured mortars. This implies that aggregate partial replacement by GRPD addition in mortars is able to reduce the water absorption by 60%.

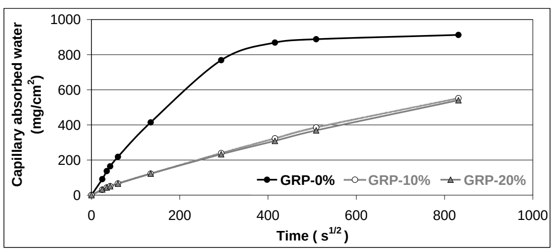

Fig. 14. Capillary Absorbed Water vs Time by Different Mortars

Table 2. Relative Capillary Absorption Coefficients (CA_{rel}) and Relative Absorption Capillary Index (IC_{rel}) for Mortars Manufactured with Sand Partially Replaced by GRPD at Dosages of 10-20 % by Volume, respectively.

Mixture	CA_{rel}	IC_{rel}
GRP-10%	0.31	0.43
GRP-20%	0.31	0.42

CONCLUSION

Experiments were performed to determine how GRPD industrial by-product alters the fresh and hardened properties of cementitious materials. It has been noted that the GRPD addition delays the setting time of cement paste but the delay could be partially recovered by using a previously heated (T = 70°C) GRPD. Moreover, when used as a partial cement replacement, GRPD resulted in more effectively reducing the viscosity and yield stress of cement paste than fly ash. Higher autogenous shrinkage and ductility, as well as a strong reduction on the mechanical performance, were detected on mortars manufactured by partially replacing the sand volume with GRPD addition when wet curing conditions are adopted. However, capillary water absorption and the risk of cracking induced by restrained drying shrinkage are significantly lower in mortars manufactured with GRPD. Further investigations have to be carried out in order to explain these behaviours.

The results demonstrated the potential of incorporating GRPD to manufacture durable cement-based elements. This may lead to a viable technological option to help with GRP by-product management, leading to cross-sector waste recycling applications within the construction industry. Potential applications of cementitious materials with GRP by-product might include repair mortars or pre-cast elements, such as paving slabs and blocks, roof tiles and architectural cladding panels where high structural performance is not required but rather good durability in terms of low risk of cracking and low capillary water absorption.

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