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The Effects of Replacing Sand with Glass Fiber-Reinforced Polymer (GFRP) Waste on the Mechanical Properties of Cement Mortars

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Abstract: The aim of this study is to examine the effect of the partial replacement of sand by Glass Fiber-Reinforced Polymer (GFRP) waste on the mechanical properties of cement mortars. Compressive and flexural tests were carried out on mortars containing 0, 3, 5, 10, and 15% (by volume) of GFRP waste. It appears that the incorporation of 3% GFRP waste did not significantly affect the mechanical strength. However, further increasing the GFRP waste content led to a reduction in the mechanical strength. The flexural strength seemed less affected than the compressive strength, since the decrease in flexural strength at a 10% replacement was only 37%, while it was 54% for the compressive strength. However, an improvement in the toughness of the mortar with an increase in the substitution rate was observed. The reference sample displayed a flexural toughness of 0.351 N·m, while the mortar incorporating 15% of GFRP exhibited a flexural toughness of 0.642 N·m. The reuse of GFRP waste in cementitious materials, therefore, constitutes an interesting recycling solution.

Keywords: glass fiber-reinforced polymer; flexural strength; compressive strength; toughness; workability

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1. Introduction

Preserving the environment requires the rational and intelligent use of available resources. In this context, the recycling and reuse of materials becomes essential for reducing pressure on natural resources and carbon emissions [1]. Among the materials that need to be recycled and/or reused are Glass Fiber-Reinforced Polymers (GFRPs). These materials consist of glass fibers dispersed in a resin (e.g., polyester). These materials are widely used in several fields, such as construction, renewable energy (e.g., wind turbine blades), and boats. The recyclability of these materials poses several challenges due to the difficulty of separating the glass fibers from the resin matrix. In addition, due to aging and the different treatments that these materials may have undergone during their lifespan, their properties can vary considerably and can lead to very significant degradation, depending on the medium to which the materials were exposed. This is why these materials are generally landfilled or incinerated [2]. Incineration, which is currently the most used, will no longer be possible in order to protect the environment, particularly to reduce greenhouse gases. In addition, a European directive (1999/31/EC) prohibits the landfilling of large composite parts. So, economically and environmentally viable recycling options are needed.

Currently, there are three main recycling methods, including thermal, chemical, and mechanical recycling [2–5]. There are also some reuse solutions, such as incorporation into thermoplastics, road applications, incineration with energy recovery [6,7], and use as powder or aggregates in cement-based materials [8–11]. Other reuse solutions could be implemented, such as their addition into the paste backfill intended for use in underground salt mines [12]. The reuse of GFRP waste in cementitious materials is considered an economically and environmentally viable solution [2]. GFRP waste is also used in the cement manufacturing process as a raw material and/or energy source. The size of the GFRP waste is first reduced. The mineral part of the GFRP is used to make the clinker, while the organic polymer matrix is converted into energy to heat the rotary kiln [2].

The field of cementitious materials thus represents an interesting recycling option for GFRP waste. This option currently makes it possible both to treat large volumes of this waste and to reduce the extraction of natural aggregates (especially sand). In addition, cementitious materials that incorporate GFRP waste could present very interesting specific properties [9–11,13].

A large number of studies have examined the effects of glass fibers on the behavior of cementitious materials [14–22]. These studies have highlighted the beneficial effects of the incorporation of glass fibers into cementitious materials, such as pozzolanic activity, good fire behavior, and the enhancement of toughness [15–17].

In recent years, several studies have focused on the reuse of GFRP waste in construction materials [8–10,13,21,23,24]. It should be noted that GFRP waste is also incorporated into polymer concrete materials, in which a thermoset polymer entirely replaces the cement paste [11,25,26]. However, this type of "concrete" has a relatively high cost and high sensitivity to creep and shrinkage [11,27,28].

Several studies on the incorporation of GFRP waste into cementitious materials are available [8–10,13,21,23,24]. The data vary depending on the particle size of the waste incorporated (fine or coarse) and the substitution rate [2]. Depending on the grinding process, GFRP waste is incorporated in the form of a powder to replace the cement or fine particles of sand, or in the form of a fiber–resin to partially replace the aggregates. Generally, the incorporation of GFRP waste leads to a loss in the workability of the cementitious material. This is attributed to the flocculation of particles (or fibers), which increases water demand [29,30]. However, the effect on the workability strongly depends on the content, size, and morphological properties of the GFRP waste. The workability is generally reduced with a longer fiber length and higher fiber content. Farinha et al. [31] observed that replacing 20% of fine aggregates by weight with GFRP waste (less than 63 μm) in mortars with the same water content improved workability. In fact, GFRP particles absorb less water than the replaced fine aggregates, thereby reducing water demand. Furthermore, the replacement of coarse aggregates with needle-shaped GFRP waste does not significantly affect the workability. In addition, the water to cement ratio (w/c) gradually increases with the GFRP waste content [32].

The effect of GFRP waste on the mechanical properties should consider the type and size of the substituted waste (fine or coarse aggregate replacement, or supplementary cementitious material). When replacing fine aggregates, some results have shown an increase in the compressive strength, while other studies have reported a decrease in the compressive strength. The reduction in the compressive strength may be due to the lower compressive strength of GFRP particles compared to that of natural aggregates, the weaker bonding of GFRP particles/cement paste, the increase in voids, and the heterogeneous distribution of the waste in the material [8–10,32]. Moreover, an increase in the compressive strength when GFRP waste is used in powder form has also been reported [11,31]. This positive effect can be explained by the reduction in voids and the chemical effects induced by the fine particles of GFRP waste. GFRP waste powder can thereby induce pozzolanic activity and a nucleation effect, leading to the improvement of the mechanical strength [33,34].

Concerning the flexural strength, according to Ribeiro et al. [11], a partial replacement rate of sand aggregates with GFRP waste, not exceeding 8% by weight, has a positive effect. Farinha et al. [31] reported an increase in the flexural strength of 155% at 365 days; the reference mortar had a flexural strength of 1.94 MPa and the mortar with 50% (by volume) GFRP waste had 4.95 MPa.

Asokan et al. [24] investigated the effect of the replacement of fine aggregates by GFRP waste powder and fiber in concrete and cement composites. The substitution rates ranged from 5 to 50 wt%. The results showed that the compressive strength decreased with the GFRP substitution rate, while the bending strength with 5% of GFRP waste was enhanced compared to that of the reference sample. Moreover, the density of concrete with 50% GFRP waste was reduced by about 12% [24].

Correia et al. [8] examined the substitution of sand by fine GFRP waste (about 96% of the particles measure less than 63 μm) with volume replacement rates ranging from 5 to 20%. For the 5% substitution, the tensile splitting strength and the modulus of elasticity of the concretes were slightly reduced by 2.7% and 3.0%, respectively. The compressive strength decreased by about 19.4%. At higher substitution rates (>5%), the mechanical properties were significantly decreased. It has to be kept in mind that the incorporation of GFRP waste can lead to a workability (or slump) loss that can be overcome with the addition of a superplasticizer or an increase in the water content (water to cement ratio). The increase in substitution rates significantly increases the amount of water needed to maintain the workability [8,24]. This is why concretes containing GFRP waste are often fabricated with an equivalent water to cement ratio.

Tittarelli and Moriconi [10] investigated the possibility of reusing GFRP waste coming directly from a shipyard as a partial aggregate or filler replacement in cement-based composites. The authors specify that a high GFRP replacement rate (15% and 20%) significantly decreases the mortar workability, and a superplasticizer was added (0.25% and 1 wt% of cement) in order to maintain the workability. Tests were performed on cement mortars manufactured by replacing 0%, 10%, 15%, and 20% of the aggregate volume with a GFRP byproduct and on self-compacting concretes (SCC) manufactured through replacing 0%, 25%, and 50% of the calcareous filler volume with GFRP powder. GFRP powder is composed of 20% (v%) glass fibers and 80% (v%) polyester resin. A strong reduction in compressive strength (up to about 25%) was observed both in mortars and self-compacting concretes. The capillary water absorption and drying shrinkage of the GFRP cementitious composites are decreased by about 70% and 50%, respectively, compared to the reference samples without GFRP waste.

Furthermore, it is interesting to note that some studies have reported an improvement in the toughness of cementitious materials incorporating GFRP waste. Overall, the use of recycled GFRP waste in concrete/mortar has contributed to the reduction in crack propagation [29,35–37]. This improvement in toughness is very interesting because it can limit the effects of restrained shrinkage. In addition, it is possible to further improve the toughness of the cementitious material and its mechanical properties by improving the dispersion and orientation of the recycled GFRP fibers [37].

All these studies show that the reuse of GFRP waste in cement-based materials can be interesting. Generally, the partial substitution of sand by GFRP waste results in a reduction in the compressive strength, which can be explained in part by the increase in water demand to maintain satisfactory workability. Additionally, it appears that the incorporation of GFRP waste slightly affects the flexural strength [24]. It is even thought that incorporation of GFRP waste could reduce the brittleness of the cementitious material.

The aim of this study is to examine the effect of the partial substitution of sand with GFRP waste from a shipyard on the compressive and flexural strength of cement mortars. Particular focus will be placed on improving the toughness of the mortar with the incorporation of GFRP waste. In addition, the reduction in mechanical strength (notably, the compressive strength) is partly due to the increase in water demand. This work also aims to examine the contribution of an addition of superplasticizer, instead of an increase in the w/c ratio, on the loss of compressive strength.

2. Materials and Methods

Materials

Glass fiber-reinforced polymers coming directly from the deconstruction of out-of-use pleasure boats were used. These composites are mainly composed of glass fibers and polyester resin (Figure 1). Large composite parts were first shredded in an Alpine® grinder (Hosokawa Alpine, Augsburg, Germany) and then ground with a Retsch® SM300 grinder (Haan, Germany) at 1500 rpm, using a 4 mm grid.

(**a**) (**b**)

Figure 1. (**a**) Large parts of composites before grinding; (**b**) GFRP-based composites after grinding.

An ordinary Portland cement CEM I 52.5R provided by Lafarge Holcim (Teil, France) was used. Its particle size distribution was determined using a laser granulometer (LS 13320 Beckman Coulter, Villepinte, France) (Figure 2). The Blaine fineness of this cement is 0.44 m^2/g.

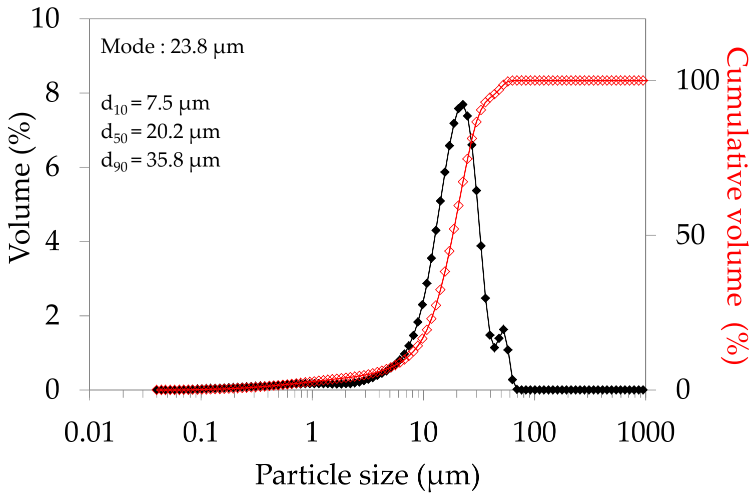


Figure 2. Particle size distribution of the cement.

CEN standard sand [38] was chosen. The particle size distributions of the sand and composites were determined according to the NF EN 933-1 standard [39] through vibratory sieving using sieves of 2 mm, 1.6 mm, 1 mm, 0.5 mm, 0.16 mm, and 0.08 mm. Composites particles larger than 2 mm were removed. The particle size distributions are shown in Figure 3. It can be noted that the composites contain more fines particles than standard sand.

The absolute density of the raw materials was measured with a pycnometer (Micromeritics AccuPyc 1330, Micromeritics Instrument Corporation, Norcross, GA, USA). These measurements were performed in triplicate (Table 1).

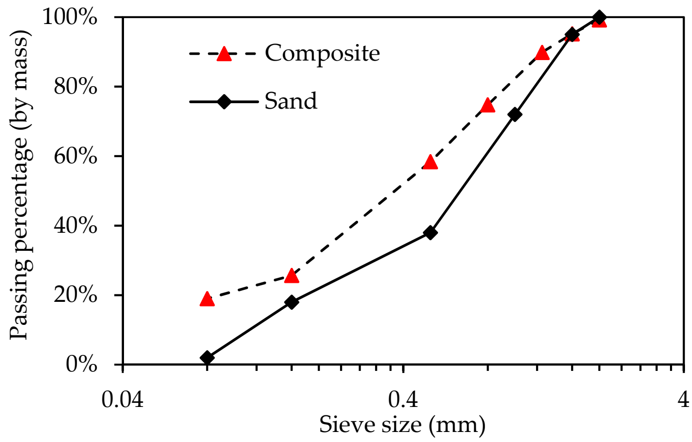


Figure 3. Particle size distribution of the standard sand and composite (GFRP).

Table 1. Absolute density of the raw materials.

Materials	Cement	Sand	Glass Fibers	Resin Polyester	Composites
Measured density (g/cm^3)	3.2	2.7	2.6	1.2	1.6

It is often reported in the literature that the incorporation of composites leads to a significant loss of workability, which can be avoided either by increasing the water content (water to cement ratio) or by incorporating a superplasticizer. In fact, due to flocculation, composites (especially fine fraction <80 µm) can "absorb" or trap part of the mixing water leading to workability loss. In order to assess the workability loss due to the incorporation of composites, yield stress measurements were performed on cement pastes using a rotational rheometer AR 2000EX (TA Instruments, New Castle, DE, USA) equipped with four-blade vane geometry. The yield stresses were measured with the stress growth procedure [40–42] in triplicate. The effect of the superplasticizer and water to cement ratio was examined in cement paste with the 15% replacement of cement with the fine fraction of composite (Table 2). Cement pastes were mixed with deionized water at ambient temperature (20 $\pm$ 2 °C) in a planetary agitator according to the following sequence: 5 min mixing at 500 rpm, scraping the mixer walls to homogenize the mix (30 s), and 2 min mixing at 1000 rpm. A polycarboxylate-based superplasticizer with a dry extract of 20% was added after 5 min of mixing (delayed addition).

Table 2. Composition of the cement pastes.

Samples	Cement (g)	Water (g)	Composite (g)	SP (%m of Powder *)
Reference	100	50	0	0
CP-15	92.5	50	7.5	0
CP-15-SP	92.5	50	7.5	0.5
CP-15-WC	92.5	60	7.5	0

* Powder: cement and composite, dry extract dosage.

Absorption tests were also carried out on the composites according to the EN 1170-6 standard [43]. So, for mortar composition, an equivalent water to cement (w/c) ratio considering the "absorbed" water is used (Table 3) to achieve the same workability.

The mortars were prepared according to the European standard [38]. The composition of the different mortars is shown in Table 3. Due to the difference in density (Table 1), a part of the volume of sand was replaced by composites. Four replacement rates were used: 3, 5, 10, and 15 vol%.

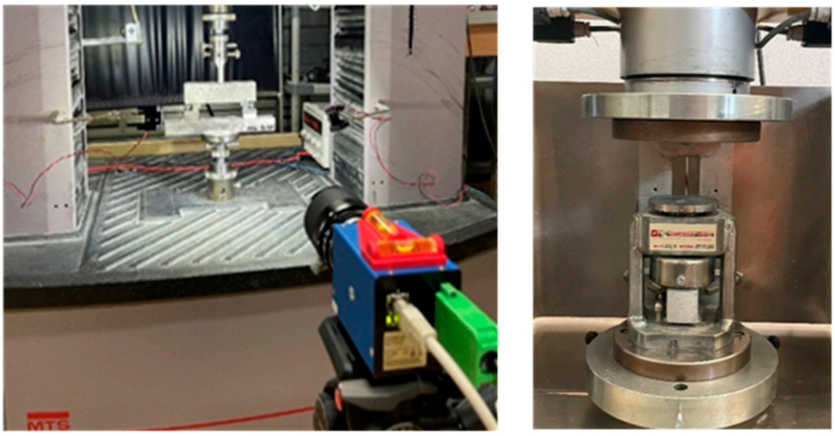
Table 3. Composition of the studied cement mortars.

Samples	Cement (g)	Water (g)	Sand (g)	Composites (g)	Equivalent w/c
Reference	450	225	1350	0	0.50
GFRP3	450	225	1309.5	24.5	0.50
GFRP5	450	262	1282.5	40.8	0.58
GFRP10	450	298	1215	81.5	0.66
GFRP15	450	335	1147.5	122.3	0.74

The mixing procedure was carried out according to EN 196-1 standard [38]. First, water and cement were placed into the bowl and mixed at low speed for 30 s. Then, sand was added continuously during the next 30 s, and the mixing was performed at high speed for an additional 30 s. The mixer was then stopped for 90 s. During the first 30 s, the mixer walls were scraped to homogenize the mortar, and the mixing then continued for 60 s at high speed.

For each mortar composition, three specimens were prepared and placed in prismatic molds 40 × 40 × 160 mm^3. After 24 h, all the samples were demolded and immersed in water at 20 °C for 28 days.

The mechanical tests were carried out in accordance with the NF EN 196-1 standard at 28 days [38]. For each mortar composition, a three-point bending test was performed on three specimens (40 × 40 × 160 mm^3) using an MTS machine-100kN (MTS Systems, Créteil, France) equipped with a camera for image acquisition under a displacement rate of 0.5 mm/min (Figure 4a). Fifteen samples were tested using the 3-point bending test.



(**a**) (**b**)

Figure 4. Three-point bending test (**a**) and compression test (**b**).

The compressive strength was measured on two halves of the prism broken on the bending test using a loading machine 3R RP400E-425kN (Montauban, France) with a loading speed of 2.4 kN/s (Figure 4b). Six specimens were used to determine the compressive strength of each mortar composition.

The flexural toughness can be described by the energy under the load-deflection curve up to the final deflection. It is worth pointing out that the final (or design) deflection should be unchangeable for mortar mix once it is specified, while the first crack peak can vary from sample to sample [44]. In this study, the flexural toughness was assessed by calculating the total energy (precrack and postcrack energies) under the load-deflection curve (Figure 5).

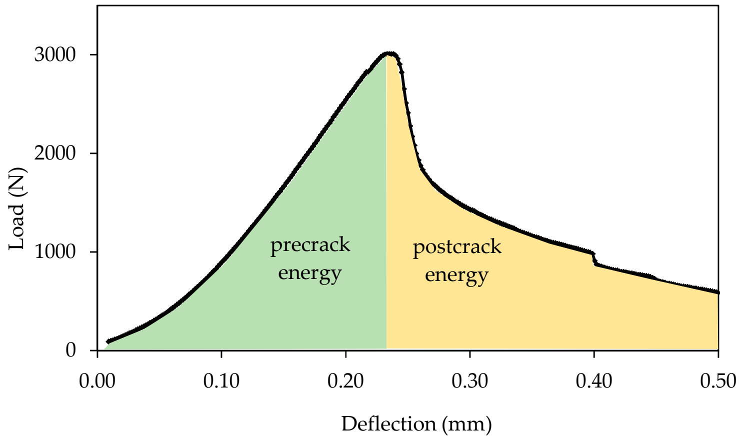


Figure 5. Determination of the flexural toughness.

3. Results and Discussion

3.1. Effect of the Fine Fraction of the Composite on the Workability

Yield stress measurements were performed to examine the effect of the fine fraction of GFRP (less than 80 µm) on the workability of the cement paste. It can be noted that the yield stress is a strong indicator of the workability of cement-based materials and can be directly correlated to the slump [45]. It corresponds to the minimum shear stress required to induce a flow. Figure A1 presents an example of the shear stress–shear strain curves obtained with the stress growth procedure. The yield stress corresponds to the maximum shear strain (peak or plateau).

Figure 6 presents the effect of the incorporation of a fine fraction of GFRP on the yield stress of the cement paste. The yield stress of the neat cement paste (reference) was 35 Pa. The substitution of 15% cement with a fine fraction of GFRP led to a significant increase in the yield stress (240 Pa), indicating a loss of workability. In fact, this workability loss is due to the flocculation of the glass fiber/resin particles. So, part of the mixing water is trapped in the composite. Others studies have highlighted this flocculation effect of glass fibers, which increases the water demand [29,30]. The dispersive action of the superplasticizer (CP-15-SP) allowed the yield stress to be decreased (80 Pa). The workability was thus improved by releasing the water trapped in the flocculated particles.

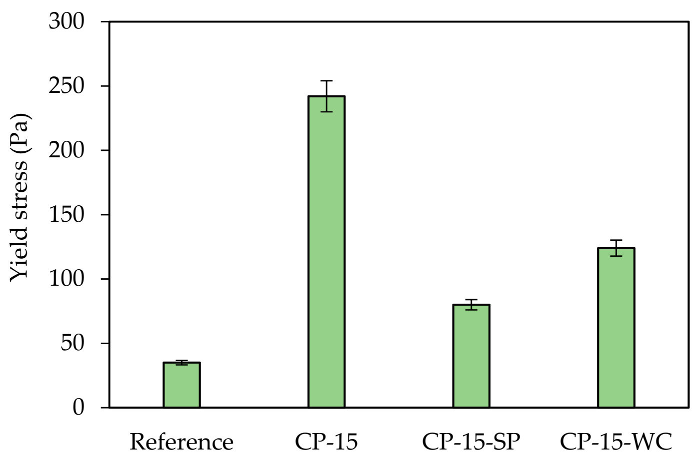


Figure 6. Yield stress of the studied cement pastes.

Furthermore, the workability can also be improved by increasing the water to cement ratio (CP-15-WC). This increase makes it possible to reduce the yield stress (124 Pa) without necessarily deflocculating the particles. The supplement of water just compensates for the water trapped between the particles. However, this increase in the water content is expected to decrease the mechanical strength.

3.2. Effect of the GFRP Waste on the Mechanical Strength

Flexural and compressive tests were performed after 28 days. The results are summarized in Tables A1 and A2 (Appendix A).

Figure 7 presents the effect of the partial replacement of sand with the composite on the compressive strength. For the control sample without GFRP, the compressive strength was 57 MPa. The substitution of 3% of sand with GFRP slightly affected the compressive strength. Beyond this rate, a significant drop in the compressive strength was observed. It is worth noting that the loss of the compressive strength cannot be only due to the sand replacement but also to the increase in the water content (equivalent w/c).

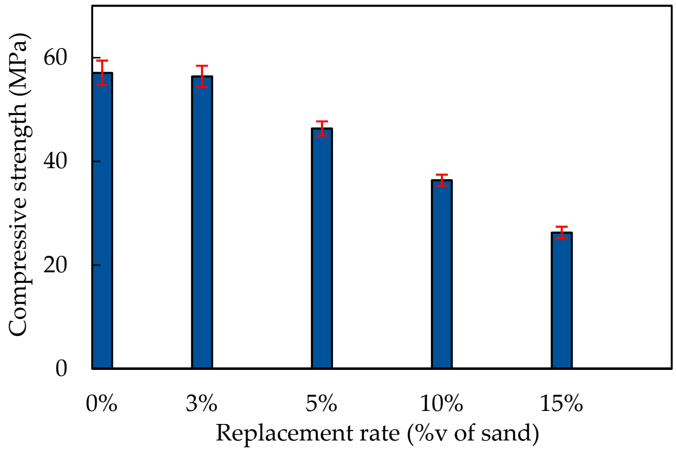


Figure 7. Effect of the GFRP on the compressive strength of the cement mortars.

As shown in Figure 8, adding a superplasticizer without changing the water/cement ratio made it possible to limit the loss of the compressive strength. The cement mortar with 15% GFRP and the same w/c ratio as the reference sample (w/c of 0.5), but with 0.5%SP, had a compressive strength of 41.1 MPa, while the cement mortar with the same replacement rate, but with an equivalent w/c of 0.7, displayed a compressive strength of 26.3 MPa. The addition of water, which compensates for the water absorbed to maintain workability, therefore caused a significant loss of compressive strength probably due to an increase in the porosity. The superplasticizer dosage required to maintain the workability with w/c of 0.5 was 0.5% (dry extract). This dosage was too high, and its contribution to reducing the loss of compressive strength was not significant. In addition, the flexural strength did not seem to improve with the addition of the superplasticizer. This is why adjusting w/c ratio appears more suitable than adding a superplasticizer, when a high compressive strength is not required.

Furthermore, the flexural strength as a function of the replacement rate is shown in Figure 9. It can be noted that the partial substitution of sand with GFRP was accompanied by a reduction in the flexural strength. The reference sample displayed a flexural strength of about 8 MPa, while the cement mortar with 15% composite exhibited a flexural strength of 5.8 MPa.

The reduction in the strengths, in particular the compressive strength, can be explained by a poor bonding of the GFRP particles/cement paste, an increase in voids, and a heterogeneous distribution of waste in the mortar [8–10,32]. The microstructure of the fractured surface of the cement mortars after the bending test was observed by scanning electron microscopy (SEM Quanta 200 FEG-FEI Company, Hillsboro, OR, USA) (Figure 10). The SEM images highlighted a heterogeneous distribution of fibers, which tended to agglomerate. These agglomerated fibers can trap part of the mixing water, leading to workability loss. In addition, the adhesion of the cement paste to the fibers seems poor, probably due to resin residue.

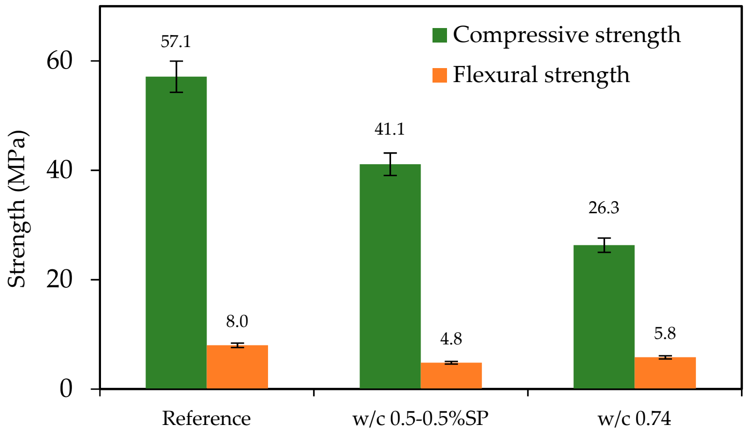


Figure 8. Compressive strength of the cement mortar with 15% GFRP.

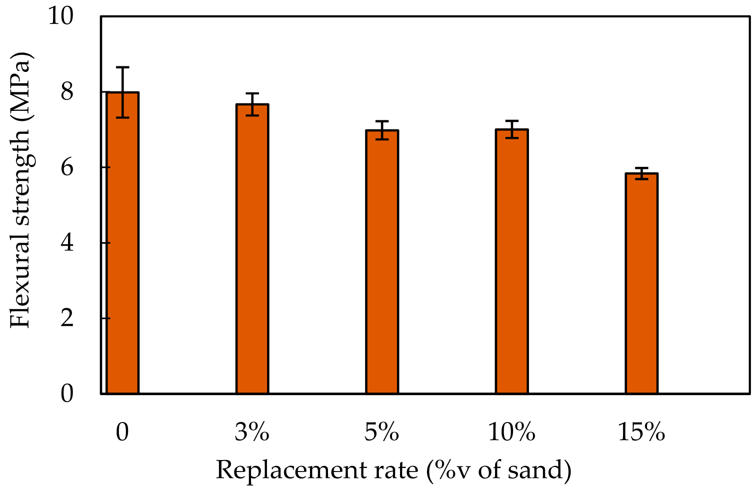


Figure 9. Effect of the GFRP on the flexural strength of cement mortars.

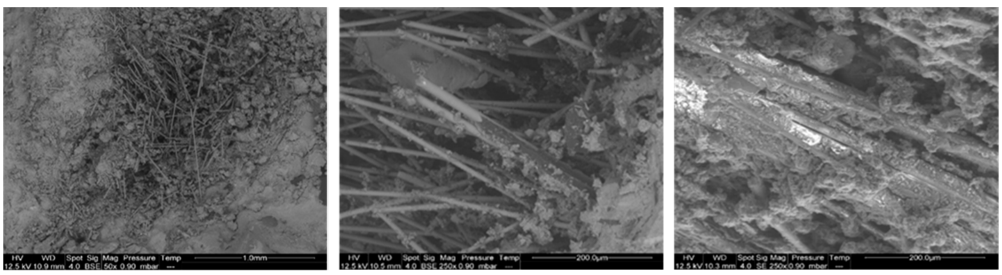


Figure 10. SEM observations of the fractured surface of the cement mortar containing 10% GFRP (BSE).

As shown in Figure 11, the compressive strength was more affected by the sand replacement than the flexural strength was. The decrease in the compressive strength in mortar containing 15% GFRP was approximately 54%, while the flexural strength decreased by 37%. Additionally, the decrease in the flexural strength of 10% GFRP mortar was only 14%, while the compressive strength decreased by 37%.

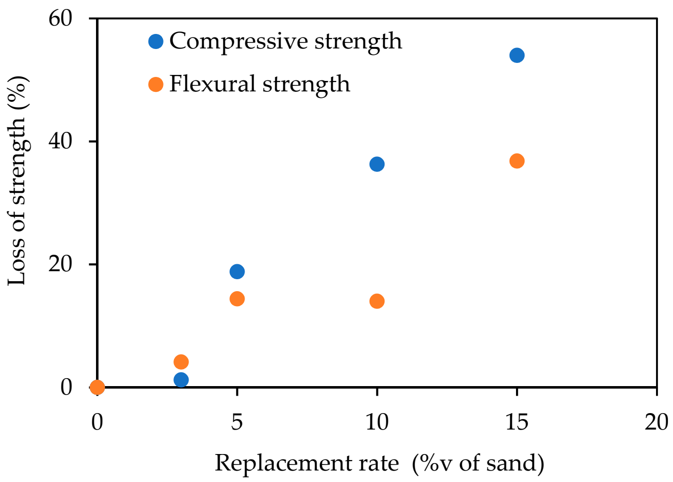


Figure 11. Loss of the compressive and flexural strength as a function of the replacement rate.

The 3-point bending test allowed the observation of a less sudden and less fragile failure with the incorporation of GFRP. The brittleness of the cement mortar seems to be attenuated with the replacement of sand with GFRP. In fact, at the rupture, the reference mortars split into two halves, while the samples containing the GFRP waste showed crack propagation but did not split into two halves, suggesting that brittleness has improved.

As shown in Figure 12, the incorporation of GFRP affects the shape of the post-peak force–deflection curves. These curves, obtained from three-point bending tests, reveal that the reference mortar displayed a rapid decrease in the load with a rapid propagation of cracks after initiation. This type of curve is characteristic of brittle rupture. For the cement mortars containing GFRP, the load gradually decreased after the peak suggesting an attenuation of brittleness. It is worth noting that some studies have reported an improvement in the toughness of cementitious materials incorporating GFRP waste, which contributes to the reduction in crack propagation, especially due to restrained shrinkage [29,35–37].

In order to evaluate the attenuation in the brittleness of mortars containing GFRP, a flexural toughness corresponding to the total energy under the loading curve was determined [44]. Figure 13 presents the variation in the flexural toughness as a function of the replacement rate, and Table A3 summarizes the obtained results.

It can be noted that the mortars incorporating GFRP display a higher toughness than the reference mortar. In fact, the rupture of the reference mortar without GFRP is very brittle as soon as the first crack appears. This reference mortar displays a flexural toughness of 0.351 N.m, while the mortar incorporating 15% GFRP has a relatively higher toughness (0.642 N·m), despite the reduction in the flexural strength, indicating a reduction in the brittleness after the initiation of the first crack. Therefore, it seems that the fibers contained in the GFRP help slow down the propagation of cracking. However, it has to be kept in mind that the improvement in the brittleness depends on the degradation of the fibers in the strongly alkaline environment of the cement paste (alkaline hydrolysis) [46,47]. The microstructure of the fractured surface of the cement mortars after the bending test showed the presence of glass fibers in the cement matrix after 28 days (Figure 10). However, it will be necessary to verify the non-degradation of these fibers over longer periods of time.

This improvement in the flexural toughness would make it possible to limit the effects of restrained shrinkage. However, in order to limit the reduction in strengths, an improvement in the dispersion and orientation of the GFRP waste must be carried out. The results obtained in this work are encouraging and clearly show that this waste can be incorporated in cementitious materials.

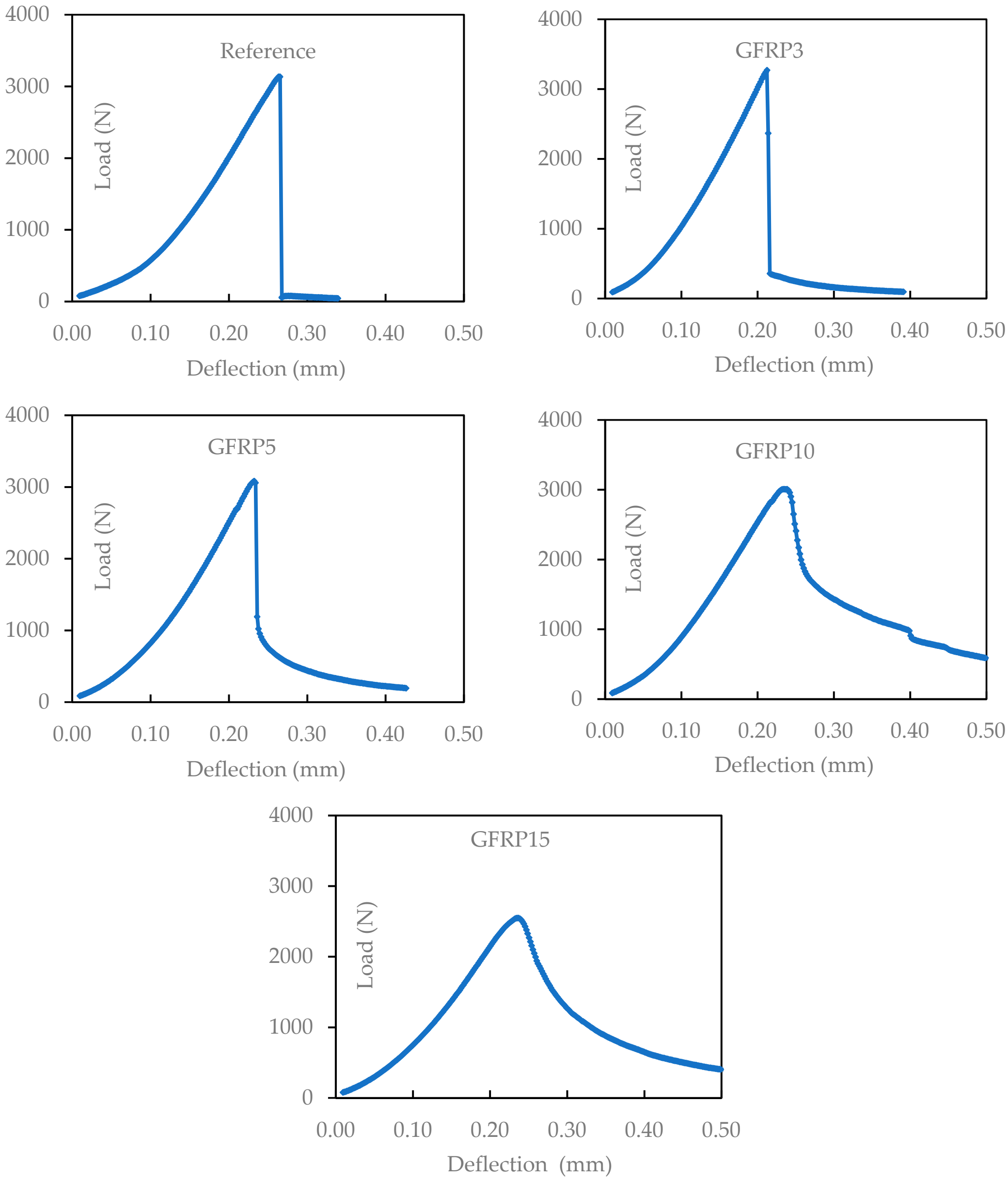


Figure 12. Load–deflection curve obtained with a 3-point bending test for different proportions of GFRP within mortars.

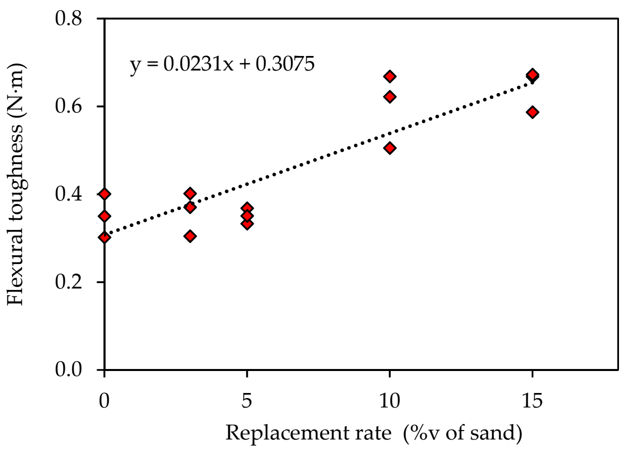


Figure 13. Flexural toughness as a function of the replacement rate with GFRP waste.

4. Conclusions

This study aimed to investigate the effect of the incorporation of glass fiber-reinforced polymer waste (GFRP), coming from a shipyard, on the mechanical strength and workability of cement mortars.

The substitution of 3% of sand volume with GFRP waste does not affect the workability and mechanical strengths. However, increasing the GRFP content results in workability loss due to the flocculation of the GFRP particles, which increases the water demand. This workability loss requires an adjustment of the water to cement ratio, but the mechanical strengths are reduced. Adding superplasticizer can improve the workability without increasing the water to cement ratio, but the required dosage is relatively high. Moreover, the addition of the superplasticizer does not significantly limit the loss of strength. The compressive strength appears to be more affected by the incorporation of GFRP waste than the flexural strength. The decrease in the flexural strength of 15% GFRP mortar is only 37%, while the compressive strength decreases by 54%. The decrease in the mechanical strengths can be explained by a poor bonding of the GFRP particles/cement paste, an increase in voids, and a heterogeneous partitioning of waste in the mortar.

Furthermore, it seems that the incorporation of GFRP waste can enhance the flexural toughness, which increases from 0.351 N.m for the reference sample to 0.642 N·m for the sample with 15% GFRP. This improvement in the toughness can be very interesting from a practical point of view, particularly to limit the effect of the restrained shrinkage. The optimization of the dispersion and distribution of GFRP waste should be performed in order to improve the mechanical behavior.

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Appendix A

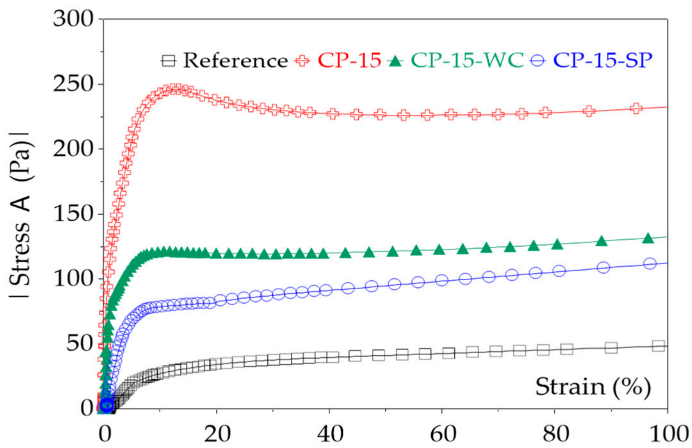

Figure A1. Shear stress–shear strain curves of studied cement pastes.

Table A1. Results of the 3-point bending tests at 28 days.

Samples	Stress (MPa)	Strain (%)	Average Stress (MPa)	Average Strain (%)	Standard Deviation
Ref-1	7.35	0.64	7.98	0.63	0.67
Ref-2	7.92	0.66			
Ref-3	8.68	0.6			
GRFP3-1	7.55	0.64	7.67	0.59	0.29
GRFP3-2	7.45	0.5			
GRFP3-3	8	0.64			
GRFP5-1	7.23	0.56	6.98	0.53	0.24
GRFP5-2	6.96	0.54			
GRFP5-3	6.75	0.5			
GRFP10-1	7.04	0.56	7.00	0.56	0.23
GRFP10-2	7.21	0.58			
GRFP10-3	6.76	0.54			
GRFP15-1	5.95	0.56	5.84	0.62	0.15
GRFP15-2	5.67	0.52			
GRFP15-3	5.89	0.78			

Table A2. Results of the compressive tests at 28 days.

Mortars	Stress (MPa)	Average Stress (MPa)	Standard Deviation	Incorporation Rate
Ref1-1	58.22	57.07	2.37	0%
Ref1-2	59.99			
Ref 2-1	x			
Ref 2-2	54.02			
Ref 3-1	57.73			
Ref 3-2	55.38			
GRFP3-1-1	54.12	56.38	2.06	3%
GRFP3-1-2	55			
GRFP3-2-1	54.5			
GRFP3-2-2	58.32			
GRFP3-3-1	58.69			
GRFP3-3-2	57.65			
GRFP5-1-1	47.84	46.34	1.37	5%
GRFP5-1-2	47.12			
GRFP5-2-1	45.33			
GRFP5-2-2	47.75			
GRFP5-3-1	45.13			
GRFP5-3-2	44.89			

Table A2. *Cont.*

Mortars	Stress (MPa)	Average Stress (MPa)	Standard Deviation	Incorporation Rate
GRFP10-1-1	35.1	36.37	1.07	10%
GRFP10-1-2	35.98			
GRFP10-2-1	36.51			
GRFP10-2-2	38.33			
GRFP10-3-1	36.29			
GRFP10-3-2	36			
GRFP15-1-1	27.10	26.27	1.14	15%
GRFP15-1-2	27.57			
GRFP15-2-1	25.87			
GRFP15-2-2	24.35			
GRFP15-3-1	26.72			
GRFP15-3-2	26.03			

Table A3. Flexural toughness of the cement mortars.

Sample	Load at the First Crack (N)	First Crack Deflection (mm)	Load at the Final Deflection (N)	Final Deflection (mm)	Total Energy * (N·m)	Flexural Toughness (N·m)
Ref-1	3040	0.26	44	0.34	0.302	
Ref-2	3380	0.27	43	0.42	0.350	0.351
Ref-3	3838	0.26	92	0.34	0.400	
GRFP3-1	3237	0.27	100	0.44	0.370	
GRFP3-2	3273	0.21	97	0.39	0.304	0.359
GRFP3-3	3497	0.26	153	0.39	0.401	
GRFP5-1	3083	0.23	194	0.43	0.368	
GRFP5-2	2882	0.23	363	0.31	0.333	0.351
GRFP5-3	2880	0.21	298	0.34	0.351	
GRFP10-1	3008	0.24	436	0.59	0.668	
GRFP10-2	3077	0.24	420	0.46	0.505	0.598
GRFP10-3	2917	0.22	178	0.74	0.622	
GRFP15-1	2548	0.24	188	0.74	0.587	
GRFP15-2	2421	0.22	266	0.79	0.668	0.642
GRFP15-3	2529	0.32	346	0.73	0.672	

* Total energy under the load–deflection curve.

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