# Sustainable waste recycling solution for the glass fibre reinforced polymer composite materials industry

A.C. Meira Castro, M.C.S. Ribeiro, J. Santos, J.P. Meixedo, F.J.G. Silva, A. Fiúza, M.L. Dinis, M.R. Alvim

## ABSTRACT

In this paper the adequacy and the benefit of incorporating glass fibre reinforced polymer (GFRP) waste materials into polyester based mortars, as sand aggregates and filler replacements, are assessed. Different weight contents of mechanically recycled GFRP wastes with two particle size grades are included in the formulation of new materials. In all formulations, a polyester resin matrix was modified with a silane coupling agent in order to improve binder-aggregates interfaces. The added value of the recycling solu- tion was assessed by means of both flexural and compressive strengths of GFRP admixed mortars with regard to those of the unmodified polymer mortars. Planning of experiments and data treatment were performed by means of full factorial design and through appropriate statistical tools based on analyses of variance (ANOVA).

Results show that the partial replacement of sand aggregates by either type of GFRP recyclates improves the mechanical performance of resultant polymer mortars. In the case of trial formulations modified with the coarser waste mix, the best results are achieved with 8% waste weight content, while for fine waste based polymer mortars, 4% in weight of waste content leads to the higher increases on mechanical strengths.

This study clearly identifies a promising waste management solution for GFRP waste materials by developing a cost-effective end-use application for the recyclates, thus contributing to a more sustainable fibre-reinforced polymer composites industry.

## Keywords

Mechanical recycling process, Thermoset composite wastes, Polymer mortars, Mechanical behavior, Nonparametric statistical analysis, Waste management

## 1. Introduction

Glass fibre reinforced polymer (GFRP) composite materials are widely used in the construction, automobile and aeronautic industries, mostly due to their excellent strength to weight ratio, corrosion resistance and the possibility of being tailored or designed according to specific end-use applications [1–4]. The pultrusion process is one of the oldest and most well-known continuous process for manufacturing GFRP structural profiles [5]. Pultruded GFRP profiles are commonly used in infrastructures for wastewater facilities, reinforcement of concrete structures, and more recently, in composite construction systems alongside moulded gratings and sandwich panels [5,6]. In Europe, the waste materials generated by the GFRP pultrusion industry are usually sent to landfills, due to the difficulty recycling them. This non-sustainable practice is mainly due to both the different nature of the constituent materials (e.g., glass fibres, organic matrix and different types of inorganic fillers) and the cross-linked nature of thermoset resins that prevents a remoulding process as a viable option [7,8].

Until now, the amounts of GFRP wastes generated by manufacturing processes and at building sites have correlated to the overall production and consumption of GFRP based products. However, it is foreseen that with the contribution of construction and demolition debris from GFRP based products approaching the end of their useful life, the waste-to-production ratio will increase. In view of the present and antecipated Waste Management legislations (e.g., EU 1999/31/EC; EU 2000/53/EC; EU 2000/76/EC; EU 2006/12/EC), with increasingly limitative policies on landfill and incineration, the GFRP industry, manufacturers and suppliers, must tackle the situation by identifying possible recycling solutions in order to maintain the sustainability of their products for the construction sector [9–11].

However, two different but interdependent issues must be solved prior to embracing the recycling approach. The first issue relies on the recycling process itself (-*What is the best recycling process for these materials?*-), and the second one concerns the end-use applications for the recyclates (-*In which products might the recyclates be incorporated in order to give an added value and constitute a cost-effective end-use application?*-).

With regard to the first issue, a complete review of current recycling technologies for thermoset FRP composites can be found in Pickering [7]. According to published scientific literature, there are three main recycling processes that can be used to get some value from FRP thermostable materials: (a) incineration, with partial energy recovery from heat generated during combustion of the organic part; (b) thermal and/or chemical recycling, such as solvolysis, pyrolysis and similar thermal decomposition processes, with partial recover of reinforcing fibres; and (c) mechanical recycling, involving the composite break-down by shredding, milling, comminution or other similar mechanical processes, resulting in size reduction to fibrous and/or powdered products that can be reincorporated either as reinforcement or filler into new composite materials.

Mechanical recycling presents significant environmental and economic advantages over the other proposed recycling processes. In fact, mechanical size reduction does not produce atmospheric pollution by gas emissions or water pollution from chemical solvent effluents, nor does it demand the use of sophisticated and undoubtedly expensive equipment such the ones required by the other processes. As far as drawbacks are concerned, two issues may be raised: safety hazards (risk of ignition during the gridding process due to the presence of initiator plus promoter that are not consumed during polymerisation reaction), and the lower value of final product (a mix of powdered and fibrous material, which must compete with virgin reinforcing fibres and filler materials) [12]. However, since GFRP products obtained by pultrusion do not contain promoter, as the polymerisation reaction is activated by thermal dissociation of the initiator, the risk of fire ignition during the grinding process is avoided.

On the other hand, assuming that feasible market outlets exist for the recyclates, mechanical recycling can be considered as the most cost-effective recycling technique, as far as clean GFRP waste materials proceeding from promoter-free manufacturing processes are concerned, for which the reinforcing fibres have relatively low economic value [7,12,13].

Regarding the second issue, the end-use applications for the recyclates, several promising applications for ground FRP wastes have been investigated over the last years. Filler or reinforcement material for artificial wood [14], high density polyethylene (HDPE) plastic lumber [15], rubber pavement blocks [16], dense bitumen macadam [17], bulk (BMC) and sheet (SMC) moulding compounds [18], wood particleboard [9] and core material for textile sandwich structures [19], were some of the foreseen potential recycling applications. The most extensive research work has been carried out on Portland cement concrete, in which grinded GFRP and CFRP wastes have been incorporated either as reinforcement, aggregate or filler replacement [20–26]. Potential applications of concrete materials modified with GFRP waste include pre-cast paving slabs, roof tiles, wall panels, paving blocks and architectural cladding materials. Still, most of the above envisaged end-use applications have not yet met commercial success for one or more of the following reasons: (a) tendency of recyclate addition to negatively affect the mechanical properties of final composite; (b) negative cost balance in which recycling costs outweighed the market value of virgin product; and (c) incompatibility problems arising from alkalis-silica reaction (in the case of cementicious matrix binder and depending of the glass fibre nature).

With the above in mind, this study aimed at developing a new waste management solution for mechanically recycled GFRP wastes in order to meet main criteria for cost-effectiveness.

Previous studies carried out by the present research group [27], highlighted the potential of using recycled GFRP wastes from the GFRP pultrusion industry as reinforcement and partial substitute of fine aggregate in polymer concrete (PC) materials. These high-performance concrete materials are cementless concretes in which an organic thermoset polymer, usually an acrylic, epoxy or unsaturated polyester resin, is applied as a binder matrix for the aggregates [28]. High specific strength, fast curing time, very low permeability, and high resistance to chemicals, weathering and frost attack are some of the enhanced properties of these materials compared to conventional concretes [29–32]. It is also recognised that the great ability of PC materials for incorporating recycled waste products is one of their main assets. This is mainly due to the hermetic nature and superior binding capacity of resin matrices. Industrial wastes and by-products, such as fly ash, slag, wood shavings, contaminated foundry sand, marble wastes, cork powder and granules, tire rubber crumbs, textile wastes, plastic chips proceeding from milled waste electrical cables, grinded PET and PVC wastes, have been successfully used for partial replacement of filler and mineral aggregates components in PC materials e.g., [33–38]. However, little research so far addressed the (re)use of mechanically recycled GFRP wastes in concrete–polymer composites.

Compared to related end-use applications of ground GFRP wastes in cementicious based concrete materials, the proposed solution overcomes some of the problems that have been found, namely: (a) incompatibilities arisen from alkalis-silica reaction [39]; (b) decrease in the mechanical properties due to higher water–cement ratio required to achieve the desirable workability [22,23,25]; and (c) weak adhesion at recyclates–binder interfaces.

The main purpose of this study consists in incorporating different contents of mechanically recycled GFRP waste (powdered and fibrous mixtures) into polyester polymer mortars (PM) as partial replacement for sand aggregates and filler. In order to improve the adhesion between organic and inorganic constituents, a silane coupling agent was used in all formulations as an additive introduced in the polymer resin matrix. The added value of recycling solution was assessed by means of both flexural and compressive loading capacities of GFRP admixed mortars with regard to unmodified PMs. Planning of experiments and data treatment were performed by means of full factorial design and through appropriate statistical tools based on analyses of variance (ANOVA). These methodologies have shown to be powerful tools in the optimisation processes of mixtures, mix designs and processing parameters e.g., [40–42].

## 2. Materials and methods

PM specimens were prepared by mixing an unsaturated polyester resin (20% w/w) with different sand aggregates/GFRP waste ratios. Processed GFRP waste, with two different size grades, was used as partial substitute for sand aggregates in the proportion of 4%, 8% and 12% of total mass weight. Plain polymer mortar specimens were also casted and tested in order to compare mechanical and functional properties with those of GFRP waste admixed mortars. The composition of plain formulation was developed in previous studies on statistical significance of synergetic effects between material components [42,43].

### 2.1. Raw materials

The GFRP waste material used in this investigation was supplied by a local pultrusion manufacturing company. It was the result of shredding leftovers from the cutting and assembly processes of pultrusion profiles at building sites. Once shredded, the GFRP waste was further processed by milling on a heavy-duty Cutting Mill laboratory unit (Retsch, model SM2000). Two different size grades of milled GFRP waste were obtained using bottom sieves inside the grinding chamber with differently-sized meshes. The obtained recycled products, shown in Fig. 1, consist of a mix of powdered and fibrous material with different quantities of varying length glass fibres, hereinafter designated by coarse (CW) and fine (FW) pultrusion waste.

The GFRP recyclates were characterised with respect to organic and inorganic fraction contents and particle size distribution. The results of burning tests carried out on five random samples showed a composition with an average inorganic material content of 71% (w/w) corresponding to glass (55% w/w) and calcium carbonate (16% w/w), and an average resin content of 29% (w/w). The particle size distributions of both types of recycled wastes, obtained by sieving and laser diffraction techniques, showed a range of particle sizes ranging from 1.5 μm up to 1800 μm or 2500 μm, with an average particle (or fibre) diameter of 390 μm or 950 μm, and a fineness modulus of 1.64 or 2.69, for FW or CW admixtures, respectively. Both grades of recyclates have the same proportion of glass fibre, calcium carbonate and organic resin and only differ with regard to particle size distribution. Siliceous foundry sand (SP55, Sibelco Lda), with a rather uniform particle size between 50 μm and 850 μm, and an average diameter of 245 μm, was used as sand aggregate. Additional information concerning the particle size distributions of GFRP waste recyclates and sand aggregates can be found in Ribeiro et al. [27].

An unsaturated polyester resin (AROPOL FS3992, Ashland®) with a styrene content of 42% (w/w), was used as polymer binder. The polymerisation process of the resin system was activated by cobalt octoate (0.5 phr), as promoter, and 50% methyl ethyl ketone peroxide solution (2 phr), as initiator. Physical and mechanical properties of cured resin are shown in Table 1.

An organofunctional silane chemical solution (Dow Corning® Z-6032), with 40% (w/w) of active silane in methanol, was used as an adhesion promoter of resin binder to both inorganic aggregates and GFRP recyclates. The Z-6032 silane contains a vinylbenzyl and amine organic groups and a trimethoxysilyl inorganic group. It can be used as a coupling agent either as a polymer additive or as surface pre-treatment of inorganic materials. In this study, the Z-6032 silane solution was applied as an additive to the polyester resin binder in the proportion of 1% of active silane by weight of resin.

Table 1
Physical and mechanical properties of cured resin (Aropol FS3992).

| Resin properties | Method | Value |
|---|---|---|
| Heat deflection temperature (°C) | ASTM D-648 | 95 |
| Barkoll hardness | ASTM D-638 | 45 |
| Tensile strength (MPa) | ASTM D-790 | 60 |
| Flexural strength (MPa) | ASTM D-2583 | 110 |
| Elongation at break (%) | ASTM D-638 | 3.2 |

### 2.2. Trial program and testing procedures

Six different GFRP waste admixed mortar formulations were manufactured by varying the type (CW or FW) and content (4%, 8% or 12%) of GFRP waste and subsequently characterised. The following notation was adopted: CW or FW accounts for the type of GFRP waste and the subsequent number for the content of waste admixture. Waste-free polyester PMs (W0), were also investigated for comparative analysis purposes. The manufacturing process of PM formulations followed RILEM recommendation CPT PC-2:1995 [44]. For each formulation, four standard prismatic specimens ($40 \times 40 \times 160$ mm$^3$) were casted. All test specimens were allowed to cure (8 h/30 °C plus 3 h/80 °C) before being tested in bending and compression with equal ageing time after conditioning for 24 h at 23 °C/50% RH.

Prismatic PM specimens were tested in three-point bending up to failure as specified by RILEM CPT PCM-8 test method [45]. One of the two leftover parts of each broken specimen in bending was tested afterwards in compression following the procedure described in UNE 83821:1992 test standard [46]. The flexural and compression test methods conditions were similar to those specified in EN 196-1:2005 [47], which is the test standard commonly used for the determination of strength of cement mortars.

### 2.3. Statistical analysis

Results were statistically analysed using the Matlab 7.6.0 (R2008a) software. Analyses of variance were performed according to a two-factor full factorial design of experiments. 'GFRP waste type' and 'GFRP waste content' were considered as factors, with two (CW and FW) and four (0%, 4%, 8% and 12%) variation levels, respectively. A $2^1 4^1$ full factorial design leads to eight different formulations, however, both formulations CW0 and FW0 were in fact the same composition: 20% of resin, 80% of foundry sand and 0% of CW (or FW) admixture. Hence, for data treatment purposes, these mix design formulations, with equal composition, share the same replicates.

Initially, parametric analyses of variance (ANOVA) were considered. However, the analyses of residues previously performed according to Shapiro–Wilk's and Levene's tests showed that ANOVA's assumptions related to the normality and homoscedasticity were not met (Table 2) [48–50]. – Therefore, the nonparametric

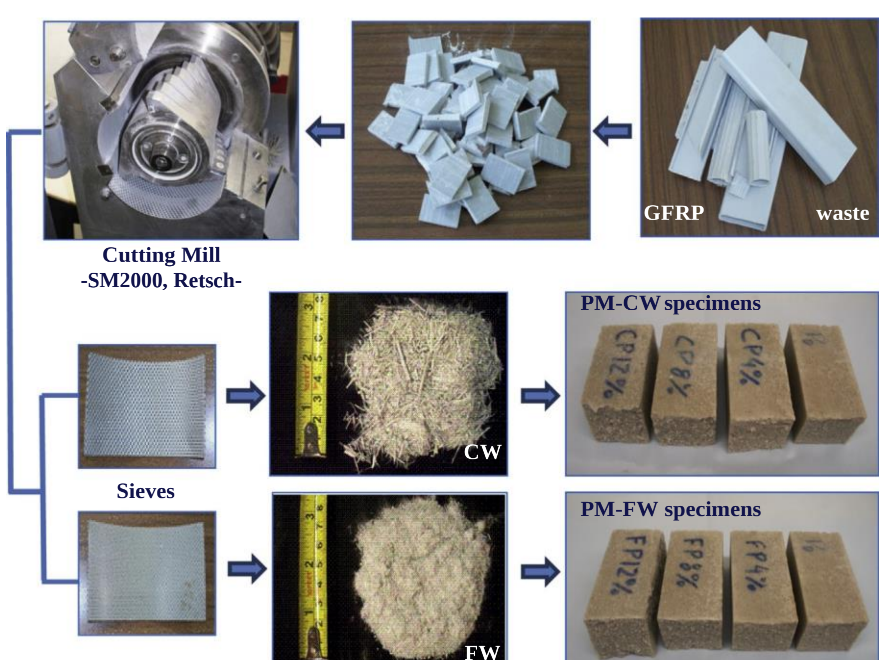


Fig. 1. GFRP scrap material, resultant recyclates after mechanical recycling, and test specimens (one of each trial formulation) after being tested in flexural.

Table 2
Residuals analysis for two-way ANOVA test results for compressive and flexural strength responses.

| Test | Statistic | df1 | df2 | $p$-value |
|---|---|---|---|---|
| *Compression response* | | | | |
| Shapiro–Wilk's test | 0.8893 | – | – | 0.0048 |
| Levene's test | 2.7857 | 7 | 24 | 0.0286 |
| *Flexural response* | | | | |
| Shapiro–Wilk's test | 0.8654 | – | – | 0.0016 |
| Levene's test | 2.6512 | 7 | 24 | 0.0351 |

Kruskal–Wallis two-way ANOVAs were used to test the null hypothesis (i.e., to verify if each factor independently considered has significant influence on flexural and compressive strength responses, to determine the main contributions of each factor to global variance, and to identify any eventual interaction effect across them). A data rank transformation was made considering the entire set of observations from smallest to largest, and the usual parametric procedure was then applied to the ranks of the data instead of to the data themselves [51,52].

In all performed analyses, factors effects with a significance level of 5% or lower ($p$-value 6 0.05) were considered statistically significant. In addition, to complete the analyses of variance, for the 4-level factor and in cases where the null hypothesis was rejected, the multiple comparisons among factors were performed using the Tukey-HSD's post hoc test [51,53,54].

## 3. Results and discussion

### 3.1. Compressive test results and statistical analysis

Table 3 summarises compressive test results obtained for all trial formulations.

The obtained results show that the average compressive strengths achieved in all but one of the modified formulations with GFRP waste admixtures improved when compared to those obtained for the reference formulation (FW0/CW0). The exception was found for FW12 trial formulation in which a decrease on compressive loading capacity was observed with regard to waste-free formulation. The results also show that CW based formulations present, in general, an improved compressive behaviour than compared to homologous formulations modified with FW recyclates.

Basic descriptors are supported by the results of nonparametric Kruskal–Wallis two-way analysis of variance (ANOVA) by ranks presented in Table 4. The ANOVA results are presented using the $p$-value approach to hypothesis testing (i.e., $p$-value 6 significance level). Tukey's post hoc test results, identifying the significant pairwise differences, are graphically presented in Fig. 2.

From the two-way nonparametric ANOVA results, it is clear that both factors, 'GFRP Waste Content' ($p$-value 6 0.00005) and 'GFRP Waste Type' ($p$-value = 0.0004), have significant influence on compressive strength response at a 5% significance level. However, there is no interaction effect between the two factors ($p$-value = 0.0697). According to Tukey's test results for the 4-level factor (Fig. 2), the null hypothesis is rejected due to statistical differences between marginal median values of the control and 4–8% GFRP waste containing formulations; there is however no evidence of differences between these two mix compositions (i.e., W0 = W12 – W4 = W8).

Two-way ANOVA results also lead to the identification of the most influential factor on compressive strength response as being the 'GFRP Waste Content', followed to by the´ GFRP Waste Type' with minor relevance. The respective percent contributions to global variation (P), computed as the ratio of the pure sum of squares of the factor to the total sum of squares, as expressed by Eq. (1), are respectively, 61% and 12%.

$$P_X(\%) = [(SS_X - MS_E \cdot df_X)/SS_T] \times 100 \quad (1)$$

where $P_X$ is the percentage of contribution or relative influence of the factor (or interaction) on the global variance observed; $SS_X$ and $df_X$ are the sum of squares and degrees of freedom of the factor (or interaction), respectively; $MS_E$ is the mean sum of squares associated to the error; and $SS_T$ is the total sum of squares.

### 3.2. Flexural tests results and statistical analysis

Table 5 summarises flexural test results obtained for all trial formulations.

As was the case for compressive strength response, the partial replacement of sand aggregates by GFRP waste admixtures has a strong influence on flexural strength response of modified formulations However, different trends were observed for the effect of GFRP waste admixtures: whereas increases on bending strength were observed for all CW admixed mortar formulations; in the FW test series, only the trial formulation with 4% in weight of FW admixture showed improved flexural behaviour over the control formulation.

Once again, the nonparametric Kruskal–Wallis analysis of variance by ranks was applied and the obtained results are presented in Table 6. Tukey's post hoc test results, identifying the significant pairwise differences, are graphically presented in Fig. 3.

According to the two-way nonparametric ANOVA test results presented in Table 6 it is also clear that both factors, 'GFRP Waste Content' and 'GFRP Waste Type', have a significant effect on flexural response of modified mortars (obtained $p$-values were, respectively, <0.00005 and 0.0002). Tukey's test results (Fig. 3) for the 4-level factor showed that the null hypothesis is rejected due to statistical differences between marginal median values of W0/W12 and W4/W8 trial formulations (i.e., W0 = W12 – W4 = W8). The interaction between the two factors was also found to have an effective influence on flexural strength ($p$-value = 0.0019). The interaction effect is considered significant due to statistical differences of flexural behaviours of CW4, CW8 and FW4 trial formulations with regard to the other formulations (Tukey's test results not presented in this paper).

The percent contributions to global variation (P) of 'GFRP Waste Content' and 'GFRP Waste Type' factors and correspondent interaction are 38%, 17% and 16%, respectively.

### 3.3. Discussion

In order to get a better understanding of the influence of the incorporation of GFRP waste on mechanical behaviour of modified PMs, the main effects of each factor and the interaction effect across them are plotted and highlighted in response graphics in Figs. 4 and 5, respectively for compressive and flexural strength responses.

Table 3
Measures of central tendency and dispersion for compressive strength of trial formulations.

| Comp. Str. (MPa) | CW trial formulations | | | | FW trial formulations | | | |
|---|---|---|---|---|---|---|---|---|
| | 0% | 4% | 8% | 12% | 0% | 4% | 8% | 12% |
| Mean | 81.29 | 97.52 | 104.69 | 82.41 | 81.29 | 84.80 | 84.51 | 77.20 |
| Max. | 82.07 | 98.91 | 105.32 | 84.54 | 82.07 | 86.18 | 86.62 | 83.38 |
| Min. | 80.45 | 96.54 | 103.88 | 78.94 | 80.45 | 83.28 | 81.89 | 74.12 |
| St. Dev. | 0.74 | 1.00 | 0.66 | 2.42 | 0.74 | 1.27 | 2.10 | 4.31 |

Table 4
Two-way Kruskal–Wallis ANOVA test results for compressive strength.

| Kruskal–Wallis source | Sum Sq. | df | Mean Sq. | Chi-sq | $p$-value |
|---|---|---|---|---|---|
| GFRP waste content | 1852.6 | 3 | 617.5 | 28.10 | 0.0000 |
| GFRP waste type | 378.1 | 1 | 378.1 | 17.20 | 0.0004 |
| Interaction | 176.6 | 3 | 58.9 | 2.68 | 0.0697 |
| Error | 527.5 | 24 | 22.0 | | |
| Interval | 2934.9 | 31 | | | |

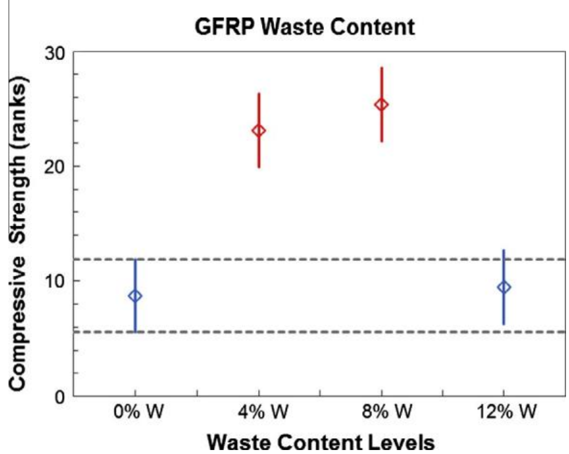


Fig. 2. Tukey's post hoc test results for compressive strength response concerning the 4-level factor ('GFRP waste content').

Table 6
Two-way Kruskal–Wallis ANOVA test results for flexural strength.

| Kruskal–Wallis source | Sum Sq. | df | Mean Sq. | Chi-sq | $p$-value |
|---|---|---|---|---|---|
| GFRP waste content | 1115 | 3 | 371.7 | 14.71 | 0.0000 |
| GFRP waste type | 496.125 | 1 | 496.1 | 19.63 | 0.0002 |
| Interaction | 508.375 | 3 | 169.5 | 6.71 | 0.0019 |
| Error | 606.5 | 24 | 25.3 | | |
| Interval | 2726 | 31 | | | |

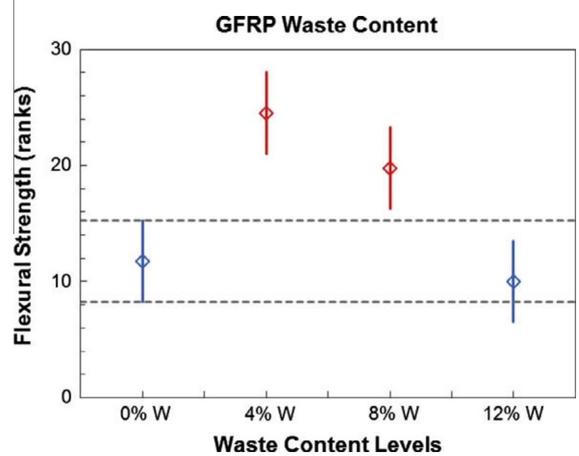


Fig. 3. Tukey's post hoc test results for flexural strength response concerning the 4-level factor ('GFRP waste content').

### 3.3.1. *Effect of GFRP waste content*

'GFRP Waste Content' is the most influential factor on compressive and flexural strength responses of modified mortars, contributing with 61% and 38%, respectively, to global variation. As stressed by response graphs of the main effect of 'Waste content' plotted in Figs. 4 and 5, the partial replacement of sand aggregates by GFRP recyclates, has a significant incremental effect on mechanical strengths of modified PMs for the lower replacement contents (4% and 8%), regardless GFRP waste type. However, distinct trends were observed for the effect of waste admixture on mechanical performance depending on both the amount of waste addition and the mechanical response itself (compression or bending).

Up to 8% waste content, compressive loading capacities of PMs increase with increasing addition of GFRP recyclates. Average compressive strength increases of 12.1% and 16.4% corresponding to the addition of 4% and 8% in weight of GFRP waste, respectively, were observed with regard to unmodified PMs. The increase in compressive strength with GFRP waste content may be attributed to a more continuous particle size distribution of the sand/waste particles mix. Relevant to this feature is the input of the powder fraction of GFRP waste to the sand aggregate filler, which contributes to a dry-packed overall aggregate with lower void volume. Generally, aggregate mixtures with higher bulk densities lead to higher compressive strengths, due to improved aggregate compaction.

Regarding the flexural strength response, the trend of increasing load capacity with increasing addition of GFRP waste up to 8% content is not verified. Average increases on bending capacity of 12.2% and 7.3% were found for 4% and 8% in weight of GFRP waste additions, respectively. It was expected that fibrous fraction of GFRP recyclates would have a significant reinforcing effect and lead to a higher improvement on flexural behaviour. Flexural strength did actually improve for the CW test series up to 8% waste content, where progressive increases of 12.1% and 15.8% were observed for CW4 and CW8 trial formulations, respectively. However a strong decrease on flexural strength was observed for FW homologous test series when FW waste content was increased from 4% to 8%. This decreasing tendency became even more marked with further addition of fine waste (FW12). A possible explanation for observed behaviour is suggested: CW admixture presents larger contents of fibrous material with higher lengths, providing a superior bending reinforcing effect than FW admixture. This subject should be clarified in a future study that will focus on the microstructure analysis of mortar specimens.

Above 8% content in waste addition, decreases on both flexural and compressive strength responses occur with regard to PM formulations with lower contents of GFRP waste (for 12% content in waste addition, average decreases of 1.8% and 4.3% were observed on compressive and flexural strengths, respectively, of GFRP waste modified PMs over unmodified PMs). As larger amounts of sand are

Table 5
Measures of central tendency and dispersion for flexural strength of trial formulations.

| Flexural. Str. (MPa) | CW trial formulations | | | | FW trial formulations | | | |
|---|---|---|---|---|---|---|---|---|
| | 0% | 4% | 8% | 12% | 0% | 4% | 8% | 12% |
| Average | 36.00 | 40.35 | 41.70 | 37.35 | 36.00 | 40.40 | 35.53 | 31.52 |
| Max. | 36.79 | 41.33 | 43.10 | 41.29 | 36.79 | 41.63 | 37.40 | 32.93 |
| Min. | 35.60 | 39.28 | 39.05 | 31.27 | 35.60 | 38.89 | 33.23 | 29.59 |
| St. Dev. | 0.53 | 0.93 | 1.81 | 4.30 | 0.53 | 1.18 | 1.84 | 1.48 |

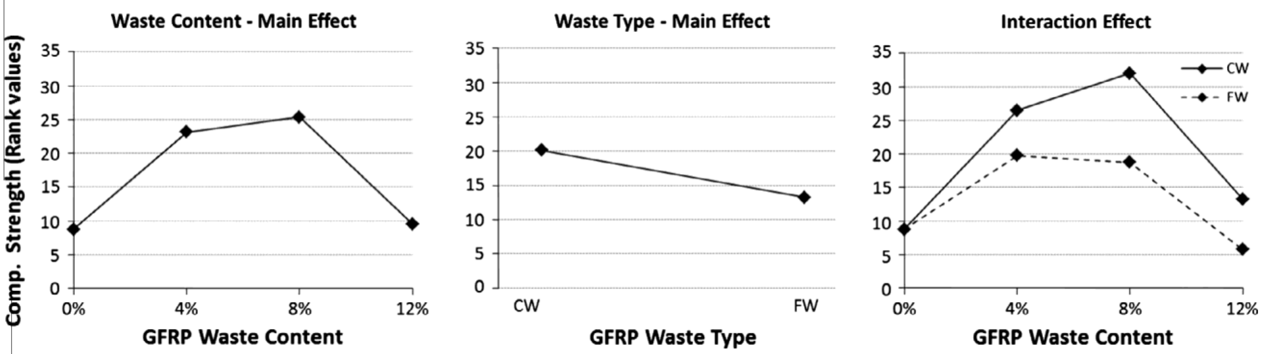


Fig. 4. Compressive strength response: main effects and interaction effect plots (marginal means ordered by ranks).

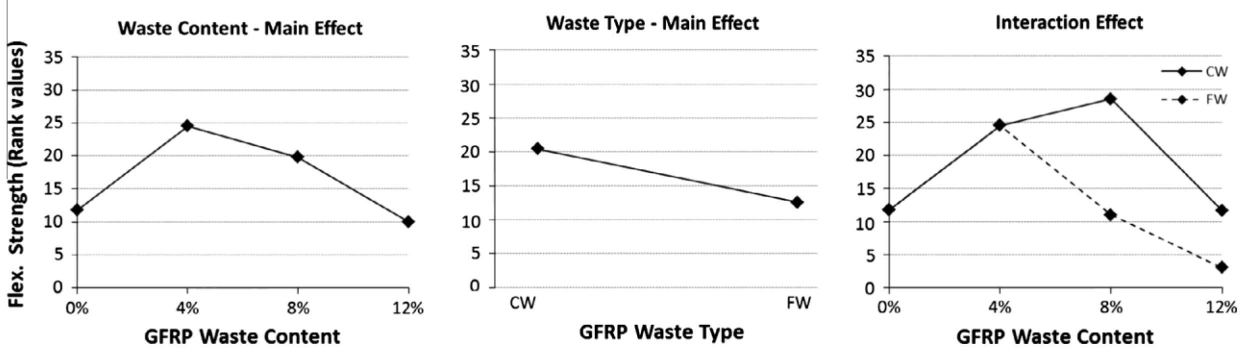


Fig. 5. Flexural strength response: main effects and interaction effect plots (marginal means ordered by ranks).

replaced by GFRP waste throughout both CW and FW test series (from 0% to 12%), the overall specific surface area of aggregates increases, while resin content is kept constant at 20% in weight in all formulations. The higher specific surface area of GFRP waste particles compared to sand particles, especially in the case of FW admixture, requires higher contents of binder matrix for a proper wetting and cohesive bonding of aggregates. This feature is believed to be the main reason for the observed inflexion points in the behaviour trend of the mortar materials (at approximately 8% in waste content for compression and 4% for bending).

Although not shown in this paper, a less brittle failure was observed for GFRP admixed mortars, both in bending and in compression. Improved ductility with increasing GFRP waste content was more pronounced in compression than in bending, with higher retention of load capacity after peak load.

### 3.3.2. *Effect of GFRP waste type*

'GFRP Waste Type' factor also has a significant influence on mechanical strength of modified PMs, contributing with 12% and 17% to the global variation of compressive and flexural strength responses, respectively. As shown in response graphs of Figs. 4 and 5 regarding the main effect of this factor, PMs modified with CW clearly show improved mechanical behaviour over FW admixed mortars. This feature is also highlighted in response graphs of interaction effects and is more pronounced regarding compressive than flexural behaviour. In general, the addition of CW recyclates leads to higher increases in loading capacities than homologous amounts of FW admixtures. For GFRP waste contents of 4% and 8% respectively, increases of 16.0% and 22.3% on average mechanical properties of CW admixed formulations were found, compared with increases of 8.3% and 1.3% on homologous values of FW trial formulations (the average increases of mechanical properties are computed as average increases of compressive plus flexural strengths). Moreover, for 12% waste addition, FW test series even shows a decrease of 8.7% on mechanical properties with regard to the control formulation, whereas for the CW12 trial formulation they remained higher. While focusing only on the waste type effect, the results clearly show that 4% and 8% in waste content addition constitute the turning points in the trend of the behaviour of these materials for, respectively, FW and CW based formulations (either in bending or in compression). The higher sensitivity of FW admixed mortars to increasing amounts of GFRP waste might be explained, once again, by the distinct specific surface areas and geometric characteristics of CW and FW recyclates (FW admixtures, with finer particles, require higher contents of resin binder to attain the same level of wetting).

Magnified images of GFRP recyclates obtained by a high-resolution metallographic microscope (Fig. 6) also shows that the CW recyclates comprise a wide range of fibre lengths varying between 25 mm and few micrometres, whereas the maximum fibre length of FW is about 5 mm; thus, CW has a higher reinforcing effect than FW. This feature generally leads to strengthening of the host material, provided strong interface bonding is ensured. In general terms and taking into account the distinct geometric characteristics of FW and CW recyclates, it can be stated that whereas FW acts more like a filler extension for sand aggregates of modified mortar (leading to a less void-volume of resultant material), CW acts as an effective reinforcing material, promoting improved mechanical strength and less brittle behaviour of modified mortars.

The results highlight the importance of sieving and sorting operations during and after recycling of process FRP wastes. Relevant properties of the recyclates that will affect the performance of final composite are dictated by these key operations. In the research studies carried out by Rikards et al. [55] and Palmer et al. [13], which constitute some of the few thorough investigations that take into consideration fibre and filler fractions, with various combinations of recyclate grades and replacement percentages, this feature is also stressed. With a well-designed combination of

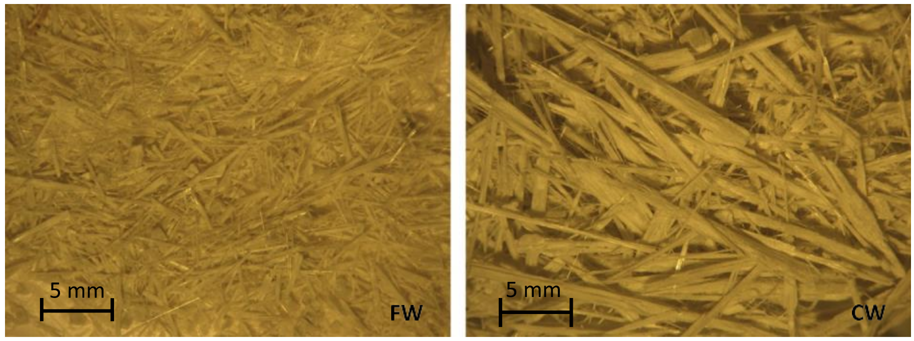


Fig. 6. Magnified images of FW and CW recyclates obtained by metallographic microscopy (magnification: 5x).

powder and fibre fractions, better properties on the final composites can be achieved due better packing of overall aggregate system, without compromising both workability and wettability of the mixture.

### 3.3.3. *Effect of 'GFRP Waste Content' by 'GFRP Waste Type' interaction*

The interaction effect between the two factors was only considered significant on flexural behaviour of modified PMs. According to response graph of Fig. 5, the observed interaction is mainly due to significant differences on flexural behaviours of FW and CW trial formulations when waste content is increased from 4% to 8%. This feature is easily noticeable by the different and opposite slopes of straight lines CW4–CW8 and FW4–FW8; while both pairs of straight lines between points CW0–CW4/CW8–CW12 and FW0–FW4/FW8–FW12 are nearly parallels. Still, one point must be stressed: as no real differences exist between CW0 and FW0 trial formulations, the effect of 'GFRP Waste Type' on global variance of target responses, as well as the effect of its interaction with 'GFRP waste content', are weakened, masking somehow the real effects.

## 4. Conclusions

The viability of the incorporation of mechanically recycled GFRP wastes into polymer based mortars was investigated and assessed. Four different levels of GFRP waste content with two different size grades were considered, and their influences on flexural and compressive strengths of modified PMs were statistically analysed. Considering the results of the trial formulations analysed in this study, the following conclusions may be drawn:

- The partial replacement of sand aggregates by GFRP waste materials, up to 8% in total weight content, has an incremental effect on both flexural and compressive strengths of resultant PMs, regardless of the GFRP waste size grade. Increasing the amount of GFRP recyclates leads to progressive decrease in mechanical properties of admixed PMs, and above 12% waste content, loading capacities tend to drop below those of unmodified PMs. The influence of GFRP waste content is more pronounced in compression than in bending, with turning points in the behaviour trends of these materials at 8% and 4% waste content, respectively.
- PMs modified with coarse waste (CW) show improved mechanical behaviour over those with fine waste (FW), both in bending and in compression. Waste content of 4% and 8% constitute the turning points in the behaviour trends of mortar materials for FW and CW based formulations, respectively. The best combination of factors' levels that maximise both flexural and compressive strengths of modified PMs is achieved for 8% weight of sand replacement by CW recyclates.
- The observed dissimilar behaviour of trial formulations, depending on the mechanical strength response (bending or compression) and size grade of GFRP recyclates (CW or FW), can be attributed to intrinsic differences between the geometric characteristics of FW and CW admixtures; whereas FW acts more like a filler extension for sand aggregates of modified mortars, CW acts as an effective reinforcing material.

The findings of this study showed that a viable technological solution for GFRP waste management can be achieved, thus opening the door to selective recycling of GFRP waste and its (re)use in a cost-effective end-use application, as reinforcing material for polymer based mortars.

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