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Comparative Study of Physico-Mechanical Properties of Polypropylene Fibre-Reinforced Gypsum Composites

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Abstract. Nowadays, the growing demand of plastic is leading to an uncontrolled waste production that threats the Planet's health. Over 8 million tonnes of plastic debris go into the ocean annually because of poor end-life management. Single-use products represent one of the main sources of plastic pollution, due to its low recycling rate related to its large production. Among them, personal hygiene disposable products (e.g., non-degradable wet wipes) represent a hazardous concern to marine ecosystem because of their dumping into the sea, dragged away by wastewater currents. Classified as non-woven textiles, non-degradable wet wipes are made from polymeric fibres, mainly polypropylene (PP), that complicate their degradation in contact with water. The incorrect disposal society makes of this waste causes devasting blockages in sewerage network, with alarming environmental and economic consequences. In this sense, alternative solutions to promote the recycling of this waste are needed in support of governmental regulations. Thus, from construction sector and committed to the Circular Economy's objectives set by the European Green Deal, the present work evaluates the feasibility of using PP waste fibres from disposable wet-wipes, as alternative to commercial PP reinforcement fibres, to produce eco-friendly reinforced gypsum-based products. Two types of reinforced-gypsum composites were prepared by adding commercial polypropylene (PPF) and waste polypropylene (PPWF) fibres, respectively. Different addition levels of fibre (2, 2.5, 3 and 3.5% by weight of gypsum) were selected to develop each group of gypsum blends. Then, composites were subjected to an experimental campaign based on dry density, mechanical behaviour (flexural and compressive strength) and deformability pre-failure, following the guidelines stablished by standards and comparing the results with the control material. The results showed a slight decrease of density as the percentage of PPWF rose, when compared to reference gypsum. Despite of the fact that lower values of mechanical strength were got by composites containing PPWF compared to those reinforced by PPF, a significant improvement of flexural strength (up to ~19.5%) was reached by mixtures with 2.5wt% PPWF content, in relation to control material. On the other hand, a decrease on compressive strength of composites with PPWF addition was observed, unlike the performance showed by gypsums with PPF content up to 2.5 wt% (~4.5% increase). However, all the data were over the minimum strength values stablished by standard. Furthermore, greater plastic deformation was developed by fibre-reinforced gypsum before to reach the failure point, in comparison with control gypsum which presented a brittle failure. Finally, it could be inferred the effectiveness of commercial PPF to enhance the mechanical properties of gypsum composites, just as the feasibility of using recycled WPPF as eco-friendly replacement to obtain gypsums for construction applications with both mechanical and environmental improvements, so promoting circular economy development.

INTRODUCTION

The growing trend for global plastic production reached 367 million tonnes (Mt) in 2020 (15% in Europe), according to data published by Plastic the Facts 2021 [1]. At the European level, 53% of plastic postconsumer waste was collected in 2020, of which 42% was destined for energy recovery, 34.6% recycled, and the remaining 23.4% landfilled. Single used products represent one of the main sources of plastic pollution (130 million tonnes were discarded throughout the world in 2019) [2], due to their low recycling rate related to their high production. Most of them are dumped in landfills or thrown directly into the environment, resulting in more than 8 million tons of plastic debris entering the ocean annually. Among them, the incorrect end-life management of personal hygiene disposable

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products like non-degradable wet wipes, represents a hazardous concern that has gained considerable relevance in recent years. Classified as non-woven textiles, non-degradable wet wipes are made from plastic, mainly polypropylene (PP) fibres, that complicate their degradation in contact with water (up to 500 years) [3]. Thus, the misused society make of toilets to rejected non-degradable wet wipes, provokes devasting blockages in sewerage networks, as well as the dumping of tonnes of waste into the sea. The dangerous environmental and economic consequences derived from this problem reveal that alternative solutions from the main economic sectors are needed to promote the correct recycling of this waste, in support of current governmental regulations. One possible answer from the construction sector to solve this problem is to take advantage of fibrous waste strength properties to replace the use of commercial polymeric reinforcement fibres to produce new construction materials with enhanced mechanical, thermal, acoustic and environmental behaviour.

Related to the use of commercial fibres as reinforcement of binder materials, several studies have been conducted on cement mortars containing mainly PP, glass, or steel fibres. Xu et al.[4] studied the influence of different lengths and dosages of PP fibres on the mechanical, porosity and ultimate toughness properties of cement composites. Other studies compared the effectiveness of using PP fibres instead of mineral fibres (i.e., carbon, basalt), achieving lower crack propagation, just as increased strength and stiffness of samples [5-6]. Furthermore, the reduction in shrinkage of recycled mortars and the improvement of their mechanical strength by using PP, glass and steel fibres were analysed by Saiz-Martínez et al. [7].

On the other hand, alternative eco-friendly solutions to commercial fibre-reinforced cement mortars based on the addition of waste fibres, have recently been proposed [8-9]. Brazao et al. [10] developed cement-based mortar composites containing high contents of textile, acrylic, and glass waste fibres. As a result, improvements on deformability and impact resistance were shown, as well as crack reduction of the reinforced mortars, corresponding the best behaviour to textile fibres. In this line, Baricevic et al. [11] focused their work on the contribution of glass, basalt and carbon fibres sourced from waste in the manufacture of high-performance technical textiles, to the fresh and hardened properties of fibre-reinforced mortars. Positive effects on flexural strength, toughness, and volumetric deformations were obtained. The possibility of using recycled plastic fibres was also explored by several authors [12]. Among them, the study conducted by Araya-Letelier et al. [13] assessed the implementation of recycled PP fibres from rejected sweeps as fibre-reinforcement in cement-based mortars. Furthermore, the impact behaviour and microstructure of cement mortar containing waste carpet fibres after exposure to high temperatures was analyzed by the Xuan et al. [14], with encouraging results compared to adding commercial PP fibres.

Concerning to the addition of fibres in gypsum composites, some interesting studies have been published. Gencel et al. [15-16] proposed the addition of commercial PP fibres up to 1% together with the partial replacement of the gypsum matrix by diatomite and vermiculite aggregates, obtaining significant improvements in the mechanical behaviour of these new lightweight gypsum composites. In this line, Alameda et al. [17] and Álvarez et al. [18] analysed the feasibility of using new reinforcement fibres (i.e., PP, glass, basalt and wood) to improve the mechanical performance of lighter gypsums with plastic addition. The addition of new PP fibres as reinforcement to produce gypsum-based products such as blocks and panels was studied by Flores et al. [19] and Barakat et al. [20], respectively. In both cases, a decrease in porosity was found, as well as an increase in the mechanical strength, durability, and cracking capacity of the gypsum products. Some other notable studies were conducted by Suárez et al. [21] related to the influence of the size, surface finish and length of polymer fibres on the fracture behaviour of fibre-reinforced gypsum composites. Moreover, Zhu et al. [22] evaluated the possibility of replacing the widespread use of PP reinforcement fibre with PVA fibres, developing a comparable study based on the mechanical strength and thermal properties of the gypsum material.

Similarly, the use of recycled fibres as an alternative to commercial ones has been researched in several works. Gonçalves et al. [23] benchmarked the addition of commercial E glass and recycled glass fibres to reinforce gypsum matrix. The results showed a notable enhancement in flexural strength in both cases, but a more plastic deformation when virgin fibres were used. Other interesting works sought to find a solution to plastic pollution and reduce the amount of raw material needed to make gypsum-based material by using recycled plastic fibres for the same purpose. Erdem et al. [24] researched the effects of PET fibres from discarded bottles on physico-mechanical properties of gypsum composites. As could be observed in other studies, the impact resistance and toughness of the samples improved, but the flexural strength was slightly reduced. Recycling of polyethylene (PE) fishing nets waste as fibre reinforcement in gypsum was proposed by Bertelsen et al. [25]. As a result, a significant increase in the postcrack performance should be pointed out, instead of the reduction of mechanical properties, which makes this material viable to be used to manufacture non-structural elements. Furthermore, in previous works by Romero-Gómez et al. [26] used PP waste as a partial replacement for the gypsum matrix, achieving enhanced results in flexural strength.

Even though several works have analysed the feasibility of adding new and recycled PP fibres as reinforcement in binder matrixes, no previous studies have compared the results of the usage of commercial polypropylene fibres (PPF) and polypropylene waste fibres (PPWF) at the same percentage in the blends, as partial replacement of gypsum matrix. Thus, PPWFs from disposable nondegradable wet wipes and commercial PPFs were used to produce gypsum-based composites. In this work, a comparative experimental campaign based on dry density, mechanical properties (flexural and compressive strength) and pre-failure deformation behaviour of both types of gypsum composites has been developed.

MATERIALS AND METHODS

Materials

The materials used to prepare the gypsum-based composites evaluated in this work are listed below:

- Controlled setting gypsum for construction (B1), according to the standard EN 13279-1[27].
- Regular tap water in accordance with Council Directive 98/83/EC.
- Commercial polypropylene fibres (PPF), for mortar reinforcement. Monofilament SikaFibers M-12 with 12 mm long and 31µm of diameter were employed (FIGURE ***1*** 1a).
- Polypropylene waste fibres (PPWF), sourced from non-degradable wet wipes. Fibres with a variable length between 15-30mm and width 2-3 mm were used (Figure 1b).

(a)

(b)

FIGURE 1. PPF (a) and PPWF (b) fibres added to gypsum blends.

Samples Preparation

Samples were prepared following the guidelines established by standard EN 13279-2 [28]. A water /gypsum ratio (W/G) of 0.55 was fixed for all the mixtures, which limited the maximum percentage of fibre addition to 3.5wt%, in order to maintain a correct workability of the blends without using additives. Therefore, the fibre addition levels used were 2, 2.5, 3 and 3.5% by weight of gypsum (wt%).

The mixtures were prepared manually according to the proportions of material summarized in Table 1, but there were some differences between the following procedures related to the types of fibre added. On the one hand, PPF were dry mixes with gypsum powder before hydration to ensure a correct dispersion of the fibres through the matrix. On the other hand, an amount of water, deducted from the total water required for the mix (corresponding to the PPWF absorption capacity) was added to the dry PPWF before mixing them with gypsum powder. After that, wet PPWFs were added to gypsum powder and mixed for 2 minutes after incorporating the rest of water needed to matrix hydration. In both cases, once all the components were added to the blend, that was mixed for 2 minutes until a homogeneous state.

TABLE 1. Mix composition for six prismatic samples 40x40x160mm

Sample Series	Gypsum [g]	Water [g] (total)	Water [g] (Gypsum mix)	Water [g] (Fibre mix)	W / G ratio	PPF [g]	PPWF [g]
G/CM	1800	990	-	-	0.55	-	-
G/PPF/2	1764	970	-	-	0.55	36	-
G/PPF/2.5	1755	965	-	-	0.55	45	-
G/PPF/3	1746	960	-	-	0.55	54	-
G/PPF/3.5	1737	955	-	-	0.55	63	-
G/PPWF/2	1764	970	867	103	0.55	-	36
G/PPWF/2.5	1755	965	837	129	0.55	-	45
G/PPWF/3	1746	960	806	154	0.55	-	54
G/PPWF/3.5	1737	955	775	180	0.55	-	63

A total of 24 prismatic samples of 40x40x160 mm^3 were prepared for each type of fibre evaluated (i.e. six prismatic specimens for each series of mixture), as well as the control specimen (G/CM). Those specimens were designed to test the physico-mechanical properties of the new gypsum composites.

Test Methods

Concluded the specimen preparation, the resulting samples were cured and tested according to the standard EN 13279-2 [28]. After being stored for seven days in a dry chamber at a temperature of 24ºC and a relative humidity of 50 ± 1%, the samples were placed in an oven at 40 ± 2 ◦C to constant mass and cooled to laboratory temperature in a desiccator.

Then, the dry density of the new composites was calculated by measuring the mass and volume of the test samples and expressed as the main value of the six measures per series. Flexural strength was determined by subjecting six samples for mixture to three-point bending test, as well as the resulting 12 test sections were undergone compressive strength test. The automatic multi-test press MCO-30 equipment, with a 300 KN load capacity was used to develop flexural and compressive strength. A progressive centered load with a speed of 10 N/s and 20 N/s, respectively, was applied until sample failure.

Finally, the deformation behaviour was evaluated using the elasticity modulus and the stress-strain curves obtained from the compressive strength test.

RESULTS AND DISCUSSIONS

The values obtained for the different test methods applied to characterize the new reinforced gypsum composites are summarized in Table 2.

TABLE 2. Summary table with the results obtained for the physico-mechanical tests.

Sample Series	Density [Kg/cm^3]	Flexural Strength [MPa]	Compressive Strength [MPa]	E [MPa]
G/CM	1205	3.73	8.45	859
G/PPF/2	1199	6.88	8.82	963
G/PPF/2.5	1195	8.28	8.73	853
G/PPF/3	1183	8.20	7.65	647
G/PPF/3.5	1182	7.86	7.27	489
G/PPWF/2	1203	4.35	4.75	784
G/PPWF/2.5	1202	4.45	4.13	391
G/PPWF/3	1196	3.85	3.41	316
G/PPWF/3.5	1194	3.42	3.15	311

Dry density

With respect to the data observed in Figure 2, the density values of the gypsum composites, in all cases, decreased slightly as the percentage of fibre addition increased. Compared to the control material, a more pronounced density reduction was observed in samples with PPF content (~2% decrease when a percentage of 3.5 wt% PPF was added). Regarding to PPWF-containing gypsums, the density reduction was ~1% (G/PPWF/3.5), compared to the reference sample. The declining trend observed in both cases could be attributed to the partial replacement of gypsum matrix by PPF/PPWF fibres with lower density (around 2650 kg/m^3 vs. 910/1000 kg/m^3, respectively).

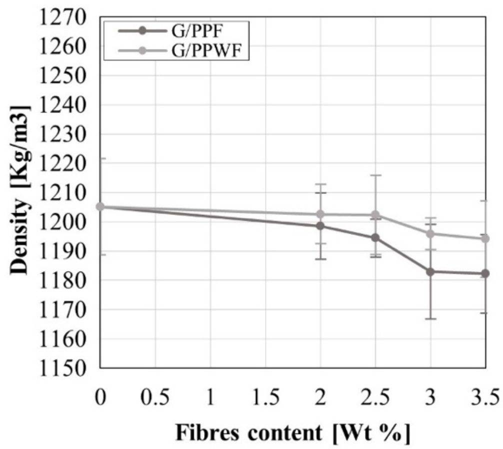


FIGURE 2. Dry Density comparative results

Flexural Strength

Encouraging results were obtained for the flexural strength test, as can be observed in Figure 3. In all cases, the addition of fibres led to an increase in flexural strength. Although composites reinforced with PPF presented higher flexural strength values (up to ~121% increase), the incorporation of PPWF into gypsum mixtures improved the flexural strength behaviour by up to ~19.5%, compared to the control material. In both cases, the highest improvement in flexural strength (8.28MPa for G/PPF/2.5 and 4.45MPa for G/PPWF/2.5) corresponds to composites with a 2.5wt% fibre content. So, it can be inferred that the 2.5wt% PPF/PPWF replacement level is a peak, from which a decreasing trend was observed as the percentage of fibre addition rose. Also, it should be noted that all values were well within the 1MPa limit as per standard EN 13279-2.

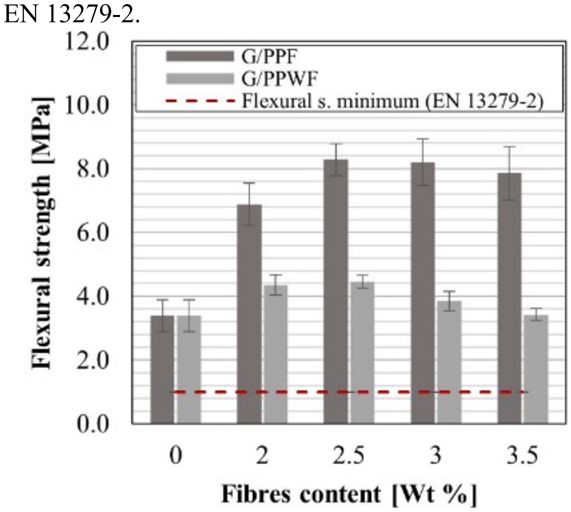


FIGURE 3. Comparison of flexural strength results

Compressive Strength

Figure 4 shows the results of the compressive strength test of the composites evaluated. A notable difference in compressive performance was detected related to the type of fibre used. For PPF-containing gypsum, an improvement of up to ~4.5% was achieved using 2wt% fibre content, compared to reference gypsum. From this point on, the compressive strength showed a downward linear trend with values below the control material data after exceeding the 3 wt% PPF replacement level. On the other hand, the higher the percentage of PPWF addition was added to the blends, the lower the compressive strength values were achieved in relation to the reference material. The maximum fall of 62.7% was reached by G/PPWF/3.5 composites. Despite the declining linear trend showed by PPWF-containing composites, all the resistance values were higher than the minimum 2MPa requirement set by standard EN 13279-2 [28].

The relation between compressive strength and density of the new composites can be observed in Figure 5. The widespread reduction of density pointed out an increase of gypsum matrix void. This meant the compactness of PPWF-containing composites deteriorated as the percentage of fibre rose, because of a weak fibre-matrix bond. However, the incorporation of PPF up to 2.5wt% replacement level led to the development of lighter composites with enhanced compressive strength performance. So, it can be inferred that the good cohesion between PPF-matrix observed until reach this optimal content, got worse when higher levels of PPF addition were used.

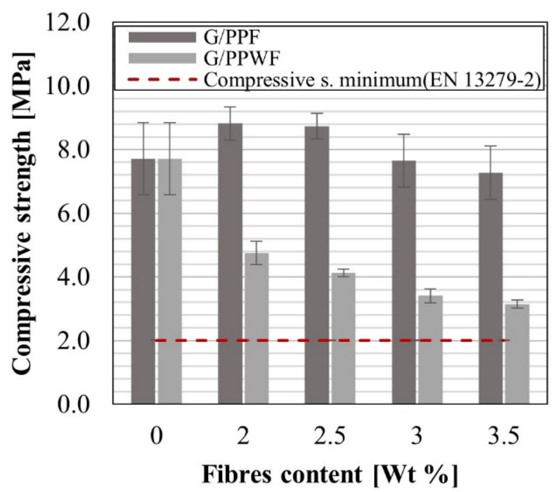


FIGURE 4. Comparative results of compressive strength

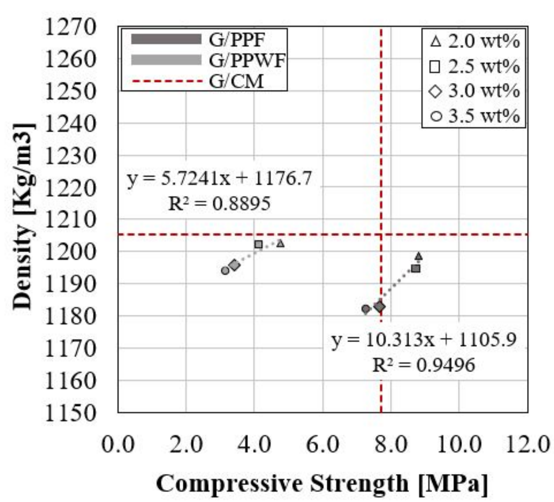
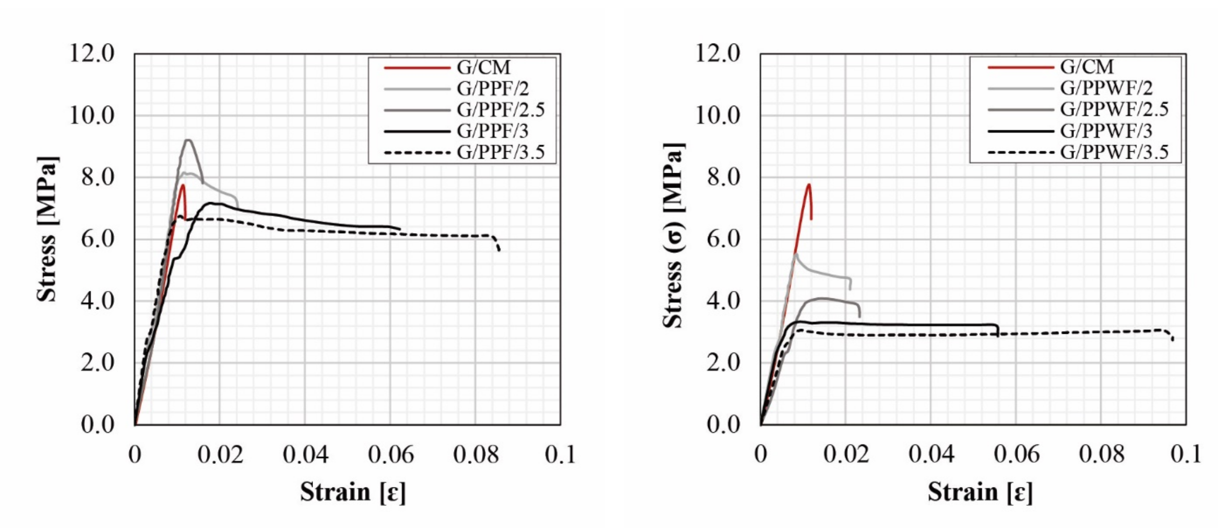


FIGURE 5. Compressive Strength vs. Density of the composites evaluated

Deformation Behavior

Regarding the influence of PP fibre addition on the deformation behaviour of gypsum composites, it can be observed that the modulus of elasticity (Table 2) of PPWF reinforced gypsum composites was reduced by increasing the level of fibre addition, compared to the reference value. However, PPF-containing composites presented a higher modulus of elasticity when percentages of addition lower than 2.5wt% were used; after that content, the values were above the reference. This fact indicates that G/PPF/2 and G/PPF/2.5 composites are stiffer than the control material, supporting the improvement of composites compactness up to reach the optimal content (2wt%).

On the other hand, after analysing the pre-failure performance of new composites by the stress-strain curves obtained from the compressive strength test (Figure 6), it could be deduced a more ductile failure of fibre-reinforced composites, benhmarked to the brittle failure shown by the reference material. When comparing the influence of both types of fibres, PPF-reinforced composites showed the greatest tenacity, due to the optimal balance between higher values of compressive strength and deformation pre-failure. However, more plastic deformation was performed by PPWF-reinforced composites when 3.5 wt% fibre content was added.



(a) (b)

FIGURE 6. Stress-Strain curves from the compressive strength test: a) G/PPF composites; b) G/PPWF composites.

CONCLUSION

In this work, the effectiveness of using new and recycled polypropylene (PP) fibres as reinforcement of gypsum-based composites, partially replacing the raw material, was evaluated. After analyzing the physico, mechanical and deformation performance of the new gypsum composites, the following conclusions were drawn:

- The incorporation of PPF and PPWF into gypsum mixtures leads to a slight decrease in the density of composites in the dry state as the percentage of fibre content increases, compared to the reference material. The lowest density values were achieved with PPF-containing composites.
- The flexural strength of fibre-reinforced composites was significantly enhanced, peaking at 2.5wt% fibre content. Higher values of flexural strength were reached by PPF-containing composites. Also, the addition of up to 2.5wt% PPF shows an enhancement of compressive strength. However, the use of PPWF leads to a decrease in compressive resistance, which is greater in mixtures with a higher level of fibre addition.
- Gypsum-based composites reinforced with PPF and PPWF exhibit a more ductile behavior before failure, compared to the control gypsum, which shows a brittle failure.

Finally, it can be inferred the feasibility of using PPF as partial replacement of the binder matrix to improved mechanical performance of gypsum composites. Likewise, encouraging results on the substitution of these commercial fibres by PPWF from waste wet wipes were demonstrated. As a result, new lighter, environmentally friendly PPWF-containing gypsums with improved flexural strength performance and acceptable compressive strength values within the minimum standard requirement were developed. Thus, a more sustainable material as substitute for commercial gypsum in buildings, included in a circular economy model was proposed, by decreasing the use of raw material (i.e. gypsum) and offering a new recycling way to an pollutant waste (i.e. wet wipes).

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