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EXTENDED ABSTRACT

Feasibility of reusing fine waste generated on the cutting process of GFRP in concrete

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September 2008

1. Introduction

Fibre reinforced polymers (FRPs) are composite materials that present light weight, ease of installation, possibility of being produced with any desired shape and high durability. Owing to these properties, FRPs are being increasingly used in several industries, including construction [1]. However, the growing use of these materials involves large and increasing volumes of FRP waste.

One of the main difficulties with thermosetting FRPs is the recycling at the end of the life cycle, because they simply cannot be remelted, in contrast to thermoplastic FRPs [2]. For this reason, unfortunately, the reuse and recycling of thermosetting FRP waste is still not a common practice and, currently, landfill is the most common disposal method for these materials [2].

The mechanical recycling of FRP waste is a relatively recent research issue, although it has already been object of different investigations referred in the technical literature. Among other solutions, the possible application of grinded FRP waste in new FRP composites [3] and also in base course bitumen macadam for road construction [4] has already been evaluated. In these and other investigations conducted in order to study possibilities of reusing FRP grinded waste, the most commonly used grinding equipment are knife mills.

The present paper reports on an investigation that was conducted in order to contribute to the provision of additional sustainable solutions to the FRP waste, studying the possibilities of using glass fibre reinforced polymer (GFRP) waste in concrete. The experimental program included preliminary trials on several knife mills in order to obtain coarse GFRP aggregates. However, these trials did not allow obtaining good quality coarse aggregates. As an alternative, it was decided to analyse the effect of using the waste produced in the cutting process of GFRP (GFRPW) in concrete production. Fig. 1 illustrates the GFRPW used in the experiments that can be classified as a filler admixture. Different concrete mixes were produced with increasing proportion of GFRPW, as a replacement of the fine aggregate. The influence of this GFRW filler admixture on the properties of fresh and hardened concrete was analysed and is reported in this paper.

2. Experimental program

2.1. Studies on the possibilities of using GFRP waste as coarse aggregates

In order to investigate the possibility of obtaining good quality FRP coarse aggregates for concrete production, grinding trials were carried out using two knife mills: an ERWICH mill (Fig. 2) and a RETSCH mill (Fig. 3). The main difference between these equipments lies in the rotor´s shape, with the latter having a helix shape. A set of preliminary trials was performed on off-cuts from GFRP pultruded profiles, with a fibre/resin ratio of about 65%. The recycled material obtained in these trials is illustrated in Fig. 4.

Fig. 1: Waste generated in the cutting process of GFRP (GFRPW)

Fig. 2: ERWICH grinder´s rotor: cylindrical shape

Fig. 3: RETSCH grinder´s rotor: helical shape

Fig. 4: Grinded material

It was concluded that the obtained particles were not suitable to be used as coarse aggregates, since they had an elongated shape that would confer concrete an anisotropic behaviour. Since the main cause for this elongated shape of the particles was the fibrous nature of the FRP materials, it was decided to grind pieces of moulded GFRP grating, which presents a fibre/resin ratio of only 30%. Using the moulded grating's waste it was possible to obtain some rounded particles, suitable to be used as aggregates. However, globally, the results were quite similar to those previously obtained with the pultruded profile. Consequently, it was concluded that using those equipments, it would not be possible to obtain good quality coarse aggregates for concrete production.

A different approach was then adopted for the research and it was decided to investigate the feasibility of reusing the fine waste generated in the cutting process of GFRP pieces (such as the pultruded profiles and the moulded gratings) in concrete production.

2.2. Materials

2.2.1. Waste generated in the cutting process of FRP materials (GFRPW)

According to the standard NP EN 12620 [5], the GFRPW can be classified as a filler admixture, since about 96% of its particles have less than 63 μm. Because of its reduced dimension and high silica content, which makes the cutting waste particularly harmful to the exposed workers, all GFRP saws incorporate a vacuum cleaning system. This system allows storing the GFRP cutting waste in bags. Since the application of this waste only requires its collection from the storing bags, this solution can be framed in the reuse level of the waste hierarchy.

Table 1 presents the results of the chemical analysis of the GFRPW, which was conducted at Secil laboratories. As expected, there is a high content of silicon dioxide. The waste also presents high loss on ignition and a high content of aluminium oxide.

Table 1: Chemical characterization of the waste generated in the cutting process of GFRP

Designation	Existence (%)
Loss on ignition (L.O.I.)	42,960
Na_2O	0,538
MgO	0,563
Al_2O_3	18,733
SiO_2	23,665
P_2O_5	0,118
SO_3	0,056
Cl^-	0,041
K_2O	0,119
CaO	11,780
TiO_2	0,620

Designation	Existence (%)
Cr	0,019
Fe^2O^3	0,347
Zn	0,021
As	0,023
Br	0,178
Sr	0,081
Zr	0,008
Sb	0,048
Ba	0,028
Pb	0,042
MnO	0,012

The tested GFRPW has a specific density of 1,84 g/cm^3. A laser granulometry test was carried out in order to compare the grading curves of both cement and GFRPW particles (Fig. 5). As it can be seen, the dimensions of the waste particles are very similar to the cement ones. The Blaine specific surface area of the waste particles is 5307 cm^2/g (calculated from the particle size distribution).

2.2.2. Cement

Concrete mixtures were produced with cement type CEM II/B-L 32,5N. As for the GFRPW, a laser granulometry test was carried out (Fig. 5). The cement used in concrete production has a specific density of 3,01 g/cm^3 and a Blaine specific surface area of 5540 cm^2.

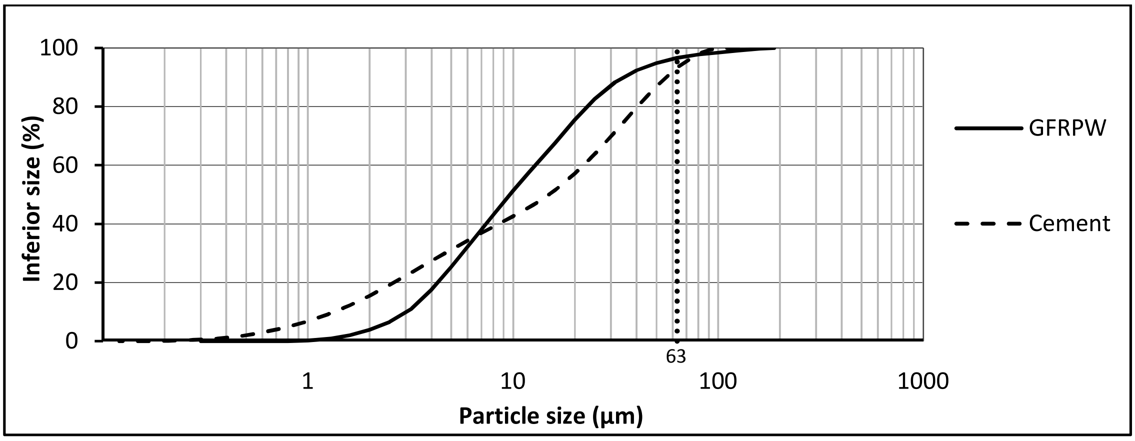

Fig. 5: Comparison of GFRPW and cement particles size.

2.2.3. Aggregates

Concrete mixtures were produced using a coarse aggregate (CA) obtained from crushed limestone and two fine aggregates (FA1 and FA2) extracted from sedimentary deposits (sand). The properties evaluated for both coarse and fine aggregates are presented in Table 2, as well as the corresponding test specifications. The grading curves of the aggregates are presented in Fig. 6.

Table 2: Properties of coarse and fine aggregates

Property	Specification	CA	FA2	FA1
Specific dry density (Kg/m^3)	NP EN 1097-6	2570	2540	2590
Saturated surface specific dry density (Kg/m^3)	NP EN 1097-6	2610	2560	2600
Water absorption (%)	NP EN 1097-6	1,5	0,5	0,4
Bulk density (Kg/m^3)	NP EN 1097-6	1440	1520	1410
Microfines content (%)	NP EN 933-1	1,0	1,2	0,6
Fineness modulus	NP1379	1,95	3,29	6,33

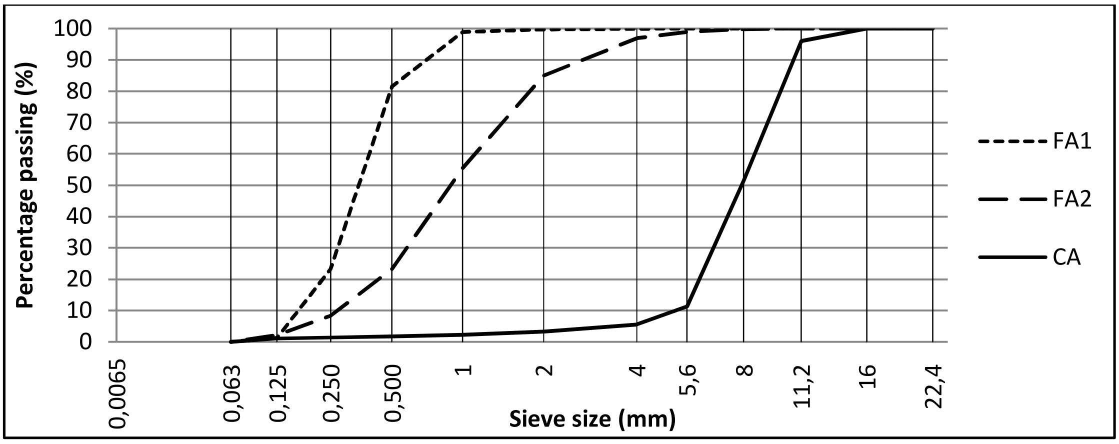

Fig. 6: Grading curves of the aggregates

2.3. General description of the performed tests

Five different concrete mixtures were produced with replacement rates of 0% (reference mixture), 5%, 10%, 15% and 20% (in terms of volume) of fine aggregate (sand) by GFRPW. These proportions were calculated in relation to the overall quantity of fine aggregate (FA1+FA2), although only the finest aggregate (FA1) was replaced. All concrete mixtures were set with a constant slump of 150±10 mm, which was achieved by adjusting the water/cement ratio. The composition of all concrete mixes is shown in Table 3.

Table 3: Composition of the concrete mixes (Kg per m^3 of concrete)

Concrete mixture	CA	FA2	FA1	Cement	GFRPW	Water	Superplasticizer
B0	1103,4	412,6	242,2	398,6	0,0	159,4	4,0
B5	1108,0	414,3	210,0	400,2	23,5	156,1	4,0
B10	1103,4	412,6	176,0	398,6	46,8	159,4	4,0
B15	1094,4	409,2	141,8	395,4	69,7	166,1	4,0
B20	1077,1	402,7	107,3	389,0	91,5	178,9	3,9

The water needed to achieve the fixed slump value and the specific density of fresh concrete were measured for all mixes. With regard to hardened concrete, mechanical behaviour tests (compressive strength, tensile splitting strength and elasticity modulus) and durability tests (water absorption by immersion, water absorption by capillarity and abrasion resistance) were performed.

Table 4 lists the tests performed within the experimental campaign, as well as the test specifications and specimen sizes.

All specimens were demoulded 24 h after casting and placed in a moist room (20℃). The mechanical properties were tested at the age of 28 days. Specimens used for the water absorption by immersion tests were immersed at the age of 28 days. Specimens used for the water absorption by capillarity tests, as well as those used in the abrasion resistance tests, were obtained by cutting the specimens used in the water absorption by immersion tests. Abrasion resistance was evaluated at the age of 51 days and the drying process (10 days at 65ºC) for the water absorption by capillarity tests started at the age of 45 days.

Table 4: Description of performed tests, specifications and specimen sizes

Test			**Specification**	**Specimen size**
Fresh state		Slump	NP EN 12350-2	-
		Specific density of fresh concrete	NP EN 12350-6	-
Hardened state	Mechanical properties	Compressive strength	NP EN 12390-3	10×10×10 cm^3
		Tensile splitting strength	NP EN 12390-6	Ø15×30 cm^3
		Elasticity modulus	LNEC E397	Ø15×30 cm^3
	Durability related properties	Water absorption by immersion	LNEC E394	10×10×10 cm^3
		Water absorption by capillarity	LNEC E393	5×5×10 cm^3
		Abrasion resistance (wear test)	DIN 52108	7×7×5 cm^3

3. Results and analysis

3.1. Fresh state properties

As previously mentioned, the produced concrete mixtures were set with a constant slump, obtained by adjusting the water/cement ratio (w/c). The w/c ratio, the slump and the specific density of the different concrete mixtures in the fresh state (SD_{FS}) are presented in Table 5.

Table 5: Fresh state properties

Concrete mixture	**Slump (mm)**	**SD_{FS} (Kg/m^3)**	**w/c**
B0	149	2420	0,40
B5	157	2380	0,39
B10	159	2350	0,40
B15	140	2320	0,42
B20	149	2280	0,46

As expected, it can be seen that the specific density in the fresh state decreased with the GFRPW content in the mix. This was basically because the specific density of the GFRPW is about 70% of the specific density of the substituted fine aggregate (FA1).

The most important characteristics of ultrafine particles (<63 µm) influencing the water requirement of concrete are the specific surface area and the morphological characteristics, such as shape and texture. Since the ultrafine particles have a high specific surface area, for high incorporation rates of ultrafines, the water need increases significantly [6]. On the other hand, the morphological characteristics of the particles, like a rounded shape and a small roughness of the particle surface, might have a beneficial effect on workability, thus reducing the w/c ratio [7]. Therefore, for reduced ultrafines content, the water need might be reduced. However, when the replacement rate increases, the high specific surface of the particle leads to an increase in the water need. On other words, some ultrafine particles present a water requirement optimization. With this respect, in the experiments carried out by Almeida [8], in which 10% of the fine aggregate (in volume) was replaced by recycled stone slurry (ultrafine particles), a decrease in the w/c ratio from 0,36 (reference mixture) to 0,32 was measured.

The variation of the w/c ratio with the GFRPW content is presented in Fig. 7, where three distinct behaviour zones can be distinguished. In zone I (from 0% to 5% of GFRPW content), it can be seen that the w/c ratio decreases with the GFRPW content. This means that the GFRPW shape and texture do have a positive effect on the workability, which is more significant than the increase of water need associated with the high specific surface of the waste particles. In zone II (from 5% to 10% of GFRPW content), the specific surface effect starts to become more relevant and, therefore, the w/c ratio increases with the GFRPW content; however, in this zone, the w/c ratio is still lower than the w/c of the reference composition. In zone III (from 10% to 20% of GFRPW content) the specific surface effect starts to dominate and, consequently, the w/c ratio becomes higher than the w/c value of the reference composition B0, with this tendency increasing with the waste content.

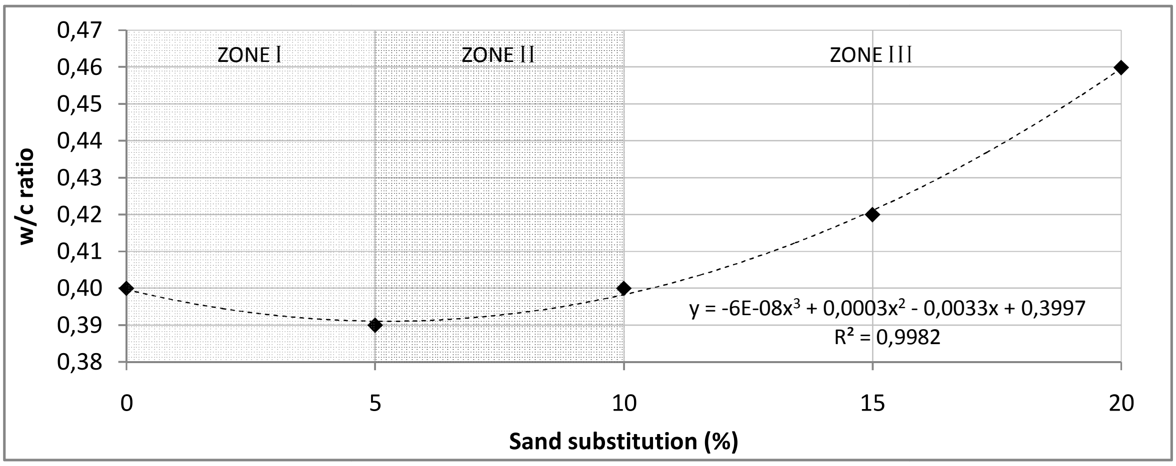

Fig. 7: Water/cement ratio as a function of the sand substitution percentage

3.2. Hardened state properties

3.2.1. Durability related properties

The results of the water absorption by immersion (Ai) and the wear loss (Δe), related to the abrasion resistance tests, are presented in Table 6. The water absorption by capillarity (Ac) tests results are presented in Table 7. The average values are presented together with the corresponding standard deviations.

The variations on the wear loss and the water absorption by immersion are presented in Fig. 8.

Table 6: Results of water absorption by immersion and wear loss (abrasion resistance) tests (average ± standard deviation)

Concrete mixture	**A_i (%)**	**A_i var. (%)**	**Δe**	**Δe var. (%)**
B0	12,9 ± 0,04	-	1,37 ± 0,19	-
B5	12,7 ± 0,12	-1,9	1,94 ± 0,25	+41,6
B10	13,6 ± 0,23	+5,4	1,73 ± 0,21	+26,1
B15	14,8 ± 0,03	+14,8	1,88 ± 0,05	+37,4
B20	15,9 ± 0,17	+22,7	2,15 ± 0,32	+57,2

Table 7: Results of water absorption by capillarity tests (average ± standard deviation)

Concrete mixture	**$A_{C,\ 3h}$**	**$A_{C,\ 6h}$**	**$A_{C,\ 24h}$**	**$A_{C,\ 48h}$**	**$A_{C,\ 72h}$**
B0	**1,67**E-03±**0,25**E-03	**2,27**E-03±**0,17**E-03	**3,79**E-03±**0,22**E-03	**4,38**E-03±**0,21**E-03	**4,52**E-03±**0,31**E-03
B5	**1,37**E-03±**0,33**E-03	**1,87**E-03±**0,25**E-03	**3,18**E-03±**0,25**E-03	**4,30**E-03±**0,27**E-03	**4,96**E-03±**0,17**E-03
B10	**1,46**E-03±**0,15**E-03	**1,94**E-03±**0,11**E-03	**3,02**E-03±**0,14**E-03	**3,99**E-03±**0,27**E-03	**4,65**E-03±**0,41**E-03
B15	**1,65**E-03±**0,10**E-03	**2,09**E-03±**0,12**E-03	**3,82**E-03±**0,18**E-03	**4,85**E-03±**0,30**E-03	**5,43**E-03±**0,39**E-03
B20	**1,95**E-03±**0,08**E-03	**2,58**E-03±**0,03**E-03	**4,40**E-03±**0,23**E-03	**5,20**E-03±**0,34**E-03	**5,91**E-03±**0,64**E-03

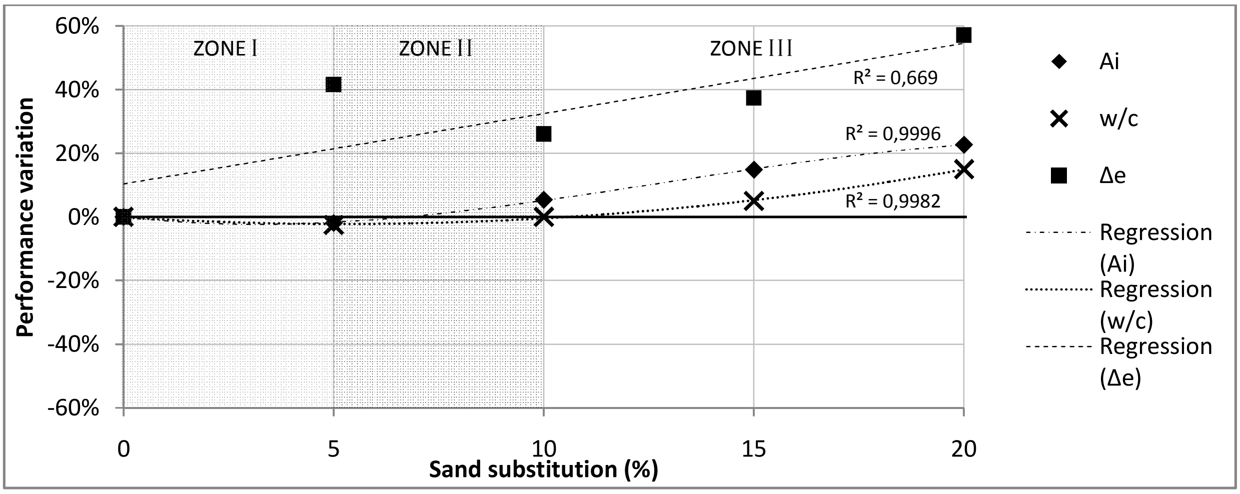

Fig. 8: Performance variation as a function of the sand substitution percentage: water absorption by immersion (Ai), w/c ratio and wear loss (Δe)

The wear loss followed an increasing trend with the GFRPW content. This result is in agreement with other investigations on concrete with ultrafines, where the abrasion resistance is reported to be the property that suffers the highest reduction as a consequence of the incorporation of these particles [9].

The results of water absorption by immersion tests are presented for the different behaviour zones identified in the previous section:

- ZONE I: The reduction on the water absorption by immersion reveals that the concrete with a GFRPW content from 0% to 5% has a less porous structure than the reference concrete and, therefore, presents a better performance in what concerns with durability. This porosity decrease is related to the w/c ratio reduction induced by the GFRPW.
- ZONE II: For a GFRPW content between 5% and 10%, an increasing trend with the waste content was observed. For the B10 mix, the water absorption by immersion was higher than that for the B0 mix, even though there was no variation on the w/c ratio. This aspect shows that the GFRPW does have a negative effect on porosity for sand substitution ratios above 5%, which are not related to the water need.
- ZONE III: For a GFRPW content higher than 10%, the water absorption by immersion significantly increases with the waste content. This result was predictable given the increase on the mixing water of the compositions framed in this zone.

Figure 9 presents the relationship between the water absorption by capillarity (as a result of the ratio between the water absorption in mass and the specimens' sectional surface) and the time´s square root for the different concrete mixes.

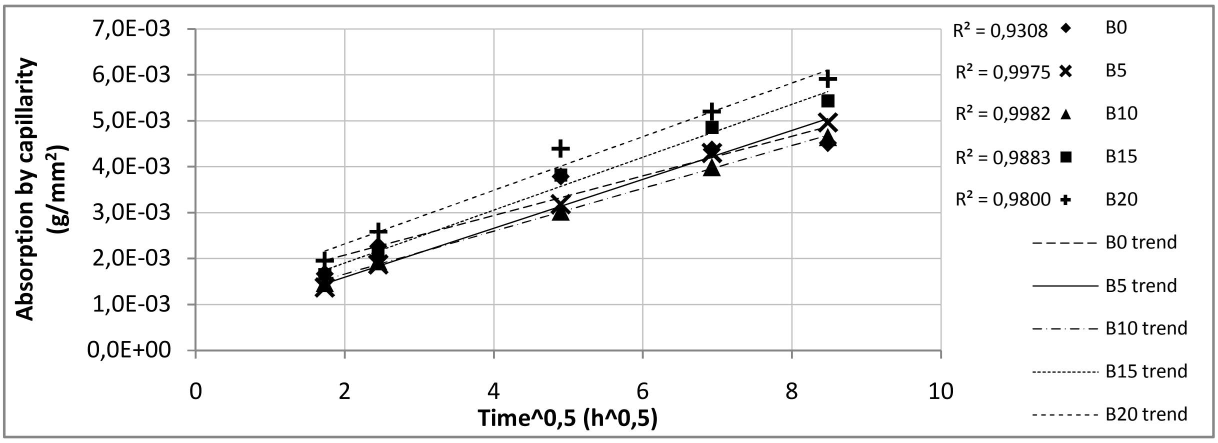

Fig. 9: Variation of water absorption by capillarity with the time's square root for the different concrete compositions

As it can be seen in Fig. 9, there was a tendency of the mixes with higher GFRPW rates, to have higher values of water absorption by capillarity. However, for the initial periods, B0 mix presented a higher water absorption by capillarity than the B5, B10 and B15 mixes, although this trend is not so clear for longer periods. On the other hand, the B5 mix, which had lower values of w/c ratio and lower water absorption by immersion, presented lower water absorption by capillarity than the other mixes only for the initial periods. Therefore, results of water absorption by capillarity tests are not in total agreement with the w/c ratio neither with the water absorption by immersion ones. The explanation for this might be the fact that the specimens used in the water absorption by capillarity tests were obtained by cutting the specimens used in the water absorption by immersion tests and, therefore, they were previously submitted to immersion and drying procedures. Additionally, specimens' size does not fulfil all requirements of the test specification. For these reasons, the information on the porous structure of the concrete with GFRPW incorporation driven by the water absorption by capillarity tests is not as significant as that provided by the water absorption by immersion tests. Nevertheless, it is important to notice an increase of the water absorption by capillarity on the mixes with higher GFRPW content.

3.2.2. Mechanical properties

Table 8 presents the average values and corresponding standard deviations in the compressive strength ($f_{cm,28d}$), tensile splitting strength ($f_{ctm,28d}$) and elasticity modulus ($E_{cm,28d}$) of the different concrete mixes, as well as the respective variations when compared to the reference concrete (B0). Fig. 10 presents the performance variation for those properties as a function of the sand substitution percentage.

Table 8: Results of mechanical properties tests (average ± standard deviation)

Concrete mixture	$f_{cm,28d}$ (MPa)	$f_{cm,28d}$ var. (%)	$f_{ctm,28d}$	$f_{ctm,28d}$ var. (%)	$E_{cm,28d}$ (GPa)	$E_{cm,28d}$ var. (%)
B0	65,7 ± 2,55	-	3,42 ± 0,03	-	41,7 ± 1,35	-
B5	53,0 ± 3,84	-19,4	3,33 ± 0,44	-2,7	40,5 ± 0,57	-3,0
B10	51,1 ± 0,34	-22,2	3,20 ± 0,16	-6,5	35,8 ± 0,35	-14,1
B15	45,4 ± 0,94	-30,9	2,28 ± 0,10	-33,5	32,3 ± 1,31	-22,6
B20	34,5 ± 3,15	-47,5	1,82 ± 0,07	-46,9	28,6 ± 0,92	-31,5

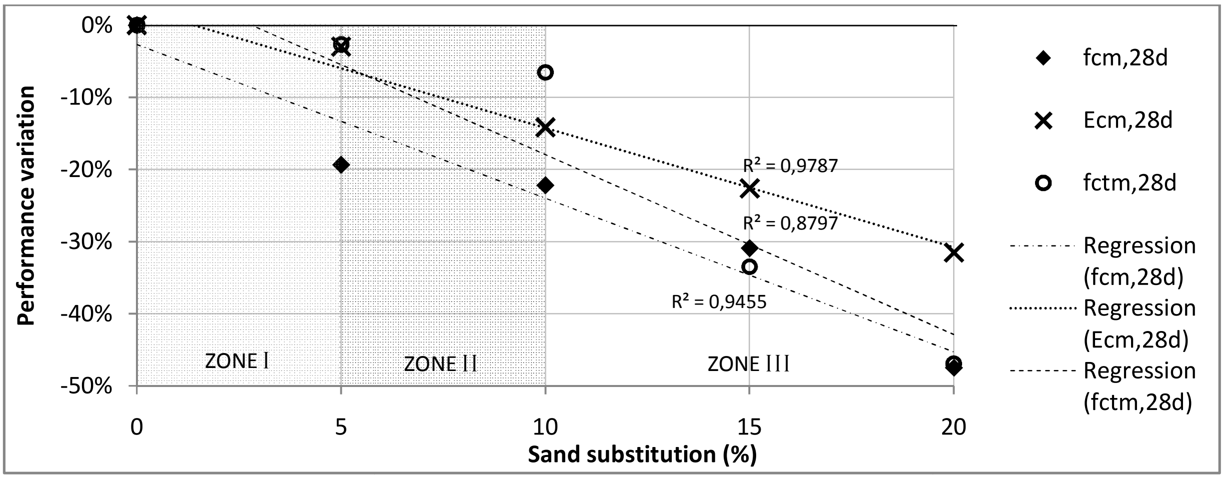

Fig. 10: Performance variation as a function of the sand substitution percentage: compressive strength, tensile splitting strength and elasticity modulus

In correspondence with the behaviour zone partition presented for the w/c ratio, the results on the mechanical properties are as follows:

- ZONE Ⅰ: Within the reference composition and that with the replacement rate of 5%, there were very little reductions in the tensile splitting strength and the modulus of elasticity. However, compressive strength experienced a more significant loss. The reductions on the mechanical properties from the B0 mix to the B5 mix, that occur in spite of the reduction in the water absorption by immersion, suggest that there is another negative effect due to the introduction of waste, in addition to the porosity change. Moreover, the fact that this reduction was higher on the compressive strength than on the other mechanical properties indicates that this property is the one which suffers more significantly the negative consequences of that effect.
- ZONE Ⅱ: In this zone, for replacement rates between 5% and 10%, there was also a decrease in the compressive strength, but at a much smaller rate. The B10 mix presented also a reduction in the tensile splitting strength but, similarly to zone Ⅰ, it was not very significant. The variation in the elasticity modulus was higher than that observed in zone Ⅰ (3,0% and 14,1% for the B5 and B10 mixes, respectively).
- ZONE Ⅲ: For substitution rates higher than 10%, the mechanical properties were quite significantly reduced. However, it must be noted that the reductions in the elasticity modulus were smaller than those suffered by both compressive and tensile splitting strengths. These losses were the result not only of the negative effects that GFRPW had already shown on zones Ⅰ and Ⅱ, but they also resulted from the w/c ratio increase.

4. Conclusions

Thermosetting FRP products are increasingly being used in several applications. However, since they cannot be remelted, most of the FRP waste is presently being sent to landfill [2]. Since this solution may cause serious environmental impacts, European legislation is increasingly becoming more severe on what concerns with landfill solution, thus promoting the development of recycling and reuse solutions. Some alternatives for the recycling of thermosetting composites have already been studied. However, the FRP industry needs to develop more innovative sustainable solutions for managing the FRP waste produced in its different lifecycle stages.

Since the knife mills tested to recycle GFRP pieces did not allow obtaining suitable coarse aggregates, the study continued with the evaluation of the feasibility of incorporating fine waste generated in the cutting process of GFRP (GFRPW) in concrete mixtures. A research was undertaken aiming to characterize concrete mixtures with sand substitution rates between 0% and 20% and a constant slump, for which the w/c ratio was adjusted.

Results showed that the substitution of 5% of the sand content by GFRPW induced lower w/c ratio and lower water absorption by immersion, which corresponds to an improvement on this durability related property. For this substitution rate, the tensile splitting strength and the modulus of elasticity suffered very little reductions (2,7% and 3,0%, respectively). However, the compressive strength had a noticeable loss (19,4%). For higher substitution rates, water need increased and, therefore, the performance in both the mechanical and durability related properties was significantly reduced.

Even though additional research is needed, it is possible to state, as a final conclusion, that the reuse of the fine waste generated in the cutting process of GFRP in concrete is feasible for applications where compressive strength is not the main requirement, such as architectural concrete or concrete pavement slabs.

5. References

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