Raw-crushed wind-turbine blade as an effective addition to enhance recycled concrete properties

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ABSTRACT: Many wind-turbine blades are approaching the end of their operational life, and they must be replaced soon. As a result, there is a pressing need for cost-effective, sustainable, and simple recycling methods. This paper proposes a recycling process that transforms turbine blades into raw materials for concrete production. Raw-crushed wind-turbine blade (RCWTB) obtained from dismissed wind-turbine blades was incorporated in mixes containing recycled aggregates to improve fresh and early-age mechanical properties. The RCWTB is composed of glass fibers, polymeric particles, and balsa wood; based on its physical and microscopic properties, it works as both concrete fibers and aggregates. As a key finding, incorporating this waste material was observed to improve the early-age properties of concrete containing recycled aggregates. Plastic shrinkage decreased up to 47% and flexural strength reached 14% higher values, while compressive strength remained almost unchanged.

Keywords: Recycled concrete, Raw-crushed wind-turbine blades, Plastic shrinkage, Flexural strength, Compressive strength.

1. INTRODUCTION

Cementitious concrete is the most consumed substance in the world for anthropogenic use after water (Gagg, 2014). It is considered responsible for 4-8% of the global carbon emissions (Watts, 2019), while, in terms of raw material consumption, it requires a huge amount of aggregates, i.e. sand and gravel, which occupy up to 80-85% over the total concrete volume (Ahmed Shaikh et al., 2019). Considering the global population growth, the demand for aggregates has been growing as well at a yearly rate of about 5.2%, with a resulting consumption of 51.79 billion metric tons in 2019 (Tejas & Pasla, 2023).

Parallelly, the production of construction and demolition waste (C&DW) has been greatly increasing (Alqahtani et al., 2021) and finding a sustainable solution for its disposal is still a challenge, as around 35% of total C&DW is landfilled (Kabirifar et al., 2020).

One of the most viable solutions is replacing the conventional aggregates with recycled ones obtained from recovering C&DW. Even if such a solution shows undoubtedly environmental advantages, it remains still limited due to inferior properties of the resulting conglomerate (B. Wang et al., 2021). Nevertheless, there are several methods to improve the properties of concretes including recycled aggregates (RAs), among them the removal or strengthening of the mortar attached to the original aggregate (Tam et al., 2021; B. Wang et al., 2021), the addition of supplementary cementing materials (Y. Wang et al., 2023), and the incorporation of fibers are the most viable ones (Chan et al., 2020). This last solution, i.e. the incorporation of fibers, greatly improves the tensile strength and limits the formations and propagation of micro-cracks, contributing to enhance durability (Gao et al., 2020). However, the material and the source of the fibers should be considered, because the incorporation of virgin fibers in recycled aggregate concrete (RAC) may jeopardize the environmental benefits of employing RAs.

In this context, the wind-energy sector represents an important source of glass fibers-reinforced polymer (GFRP), a composite material consisting of glass fibers embedded in a polymeric epoxy resin, as this is the main component of wind-turbine blades (Revilla-Cuesta et al., 2023). Currently, wind power satisfies around 20% of Europe's electricity demand, but such a value is unevenly distributed, as Denmark relies on wind energy for 56% of its electricity, while Ireland depends on it for 36%, the UK for 29%, the Netherlands for 27%, and Spain for 27% (*Wind Energy Today*, n.d.). Wind may be the no. 1 source of power in Europe by 2027 according to the Internation Energy Agency (*Wind Energy Today*, n.d.). In Spain, approximately 1,000 were dismantled in 2023 with an expected increase to a maximum estimate of about 2,500 wind turbines dismantled *per* year by 2029 (Revilla-Cuesta et al., 2023).

Wind turbine blades are primarily made of a GFRP composite. This material provides both adequate mechanical strength and durability. However, the blades also incorporate lightweight materials, e.g. balsa wood and polymers sandwiched with GFRP, which enhance the blades bending strength while reducing their overall weight (Revilla-Cuesta et al., 2024). Additionally, the blade surface is coated with a polymeric resin, and polyvinyl chloride stiffeners may be used in certain cases. The difficulty of separating these components makes blade recycling a significant research challenge. Crushing wind-turbine blades is a way to recycle and revalue such a waste, the resulting material consists of GFRP fibers mixed roughly with minor quantities of balsa wood and polymers (Ortega-López et al., 2024).

In this work, raw-crushed wind-turbine blade (RCWTB) is used as an addition to improve the detrimental effects of coarse recycled aggregates (CRAs) in concrete manufacturing. The specific aim is to analyze whether the RCWTB allows for improving the behavior of RAC, mainly focusing on shrinkage, compressive strength and flexural strength in different curing conditions.

2. EXPERIMENTAL PROGRAM

2.1 Materials characterization

Five aggregate types were employed to reach a suitable gradation, the saturated surface-dry density (SSD density) and 24-hour water absorption (WA) were determined according to BS EN 1097-6:

- Siliceous 12/22 (SSD density=2.60 kg/dm^3; WA=0.55%);
- Siliceous 4/12 (SSD density=2.63 kg/dm^3; WA=0.33%);
- Siliceous 0/4 (SSD density=2.62 kg/dm^3; WA=0.13%);
- Limestone 0/2 (SSD density=2.66 kg/dm^3; WA=0.10%);
- Recycled (CRA) 4/22 (SSD density=2.44 kg/dm^3; WA=6.12%).

The CRAs were obtained from crushing concrete elements produced with siliceous aggregate having characteristics compressive strength equal to 45 MPa. The gradation curves are displayed in Figure 1.

A cement type CEM II/A-L 42.5 R according to BS EN 197-1 was employed which includes limestone as partial clinker replacement. Water from the main supply network of Burgos (Spain) was used. To reach an adequate workability, two superplasticizers were added: the former consists of a modified polycarboxylate with a water-base, the latter is composed of a modified polycarboxylate.

The RCWTB was prepared by crushing rectangular panels of wind turbine blades. The content of GFRC-composite fibers was 66.8% by weight, the length and diameter of which were evaluated in multiple samples, yielding average values of 13.1 and 0.73 mm, respectively, resulting in a mean aspect ratio *l/d* of around 18. RCWTB has SSD density equal to 1.63 kg/m^3 determined with the aggregate procedure (BS EN 1097-6). Figure 2 shows the aspect of the aggregate and the RCWTB used in this work.

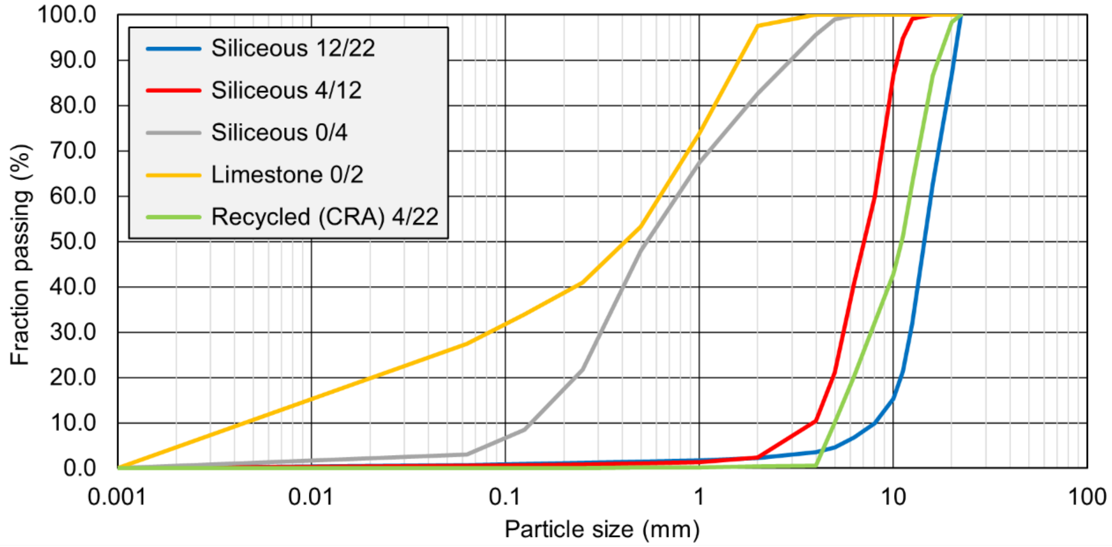

Figure 1. Gradation curves of the aggregates

a) b) c)

d) e) f)

Figure 2. Materials employed in this experimental campaign: a) Siliceous 12/22; b) Siliceous 4/12; c) Siliceous 0/4; d) Limestone 0/2; e) Recycled (CRA) 4/22; f) RCWTB.

2.2 Mix design

Six concrete batches were cast for this experimental campaign, three of them were prepared as term of comparison with recycled aggregate amounts 0%, 50% and 100%, without including RCWTB; the others have the same proportions but including 6% RCWTB over the total aggregate volume.

The cement dosage was kept constant at 320 kg/m^3 in all the mixes, whereas the water content was slightly adjusted to maintain the same effective water/cement ratio according to the recycled aggregate content, due to their higher water demand than that of natural aggregates. The total superplasticizer content was maintained constant and equal to 1% of the cement mass. The mix proportions are shown in Table 1.

Table 1. Mix design (in kg/m^3)

	0CRA/ 0RCWTB	50CRA/ 0RCWTB	100CRA/ 0RCWTB	0CRA/ 6RCWTB	50CRA/ 6RCWTB	100CRA/ 6RCWTB
Cement	320	320	320	320	320	320
Water	130	140	150	130	140	150
W/C ratio	0.41	0.44	0.47	0.41	0.44	0.47
Plasticizer 1: 20HE	1.07	1.07	1.07	1.07	1.07	1.07
Plasticizer 2: 5790	2.13	2.13	2.13	2.13	2.13	2.13
Siliceous 12/22	780	390	0	733	367	0
Siliceous 4/12	555	277	0	522	261	0
Siliceous 0/4	385	385	385	362	362	362
Limestone 0/2	280	280	280	263	263	263
Recycled (CRA) 4/22	0	623	1246	0	586	1171
RCWTB	0	0	0	75	75	75

2.2 Testing program

Fresh and hardened concrete properties were measured in this work. The samples were subjected to two curing conditions, i.e. ambient and moist, to detect possible variation in strength evolution due to hydration (Atiş et al., 2005). Slump, air content and fresh density were determined in the fresh state according to BS EN 12350-2, BS EN 12350-7 and BS EN 12350-6, respectively.

Plastic shrinkage was measured over three days from casting following the procedure developed from some of the authors (Ortega-López Vanesa et al., 2022). The measurement was performed on a 1-m long gutter, the concrete remained fixed from one end, while freely moving in the opposite one. The free one was equipped with a digital comparator to measure the displacement and, hence, shrinkage.

A series of fifteen 75x75x75 mm prismatic samples and fifteen 100x200 mm cylindrical samples were cast *per* batch and left in the lab environment (20±2 °C and 50±5% humidity) for 24 hours. Three cylinders and three prisms were tested to measure compressive and flexural strength, respectively, after one day from casting. Later, six cylinders and six prisms were put in a moist chamber (20±2 °C and 90±5% humidity), and the remaining samples in an ambient curing room (20±2 °C and 60±5% humidity). Three cylinders and three prisms *per* curing environment were tested to measure compressive and flexural strength at an age of both three and seven days according to the European standards BS EN 12390-3 and BS EN 12390-5, respectively.

3. RESULTS AND DISCUSSION

3.1 Slump, air content and fresh density

Table 2 summarizes the results for slump, air content and fresh density. As a general observation, the workability was found to decrease when CRAs were employed in place of conventional aggregates and when RCWTB was included. Indeed, CRAs have an irregular shape and rougher texture, which hinder concrete flow (Lavado et al., 2020); similarly, the use of fibers also interferes with the other concrete components (Ravichandran et al., 2022).

For the same reasons, air content increased, and fresh density decreased for higher CRAs and RCWTB additions.

Table 2. Fresh test results: slump, air content and fresh density.

	0CRA/ 0RCWTB	50CRA/ 0RCWTB	100CRA/ 0RCWTB	0CRA/ 6RCWTB	50CRA/ 6RCWTB	100CRA/ 6RCWTB
Slump (cm)	15	17	5	15	13	1
Air content (% vol.)	2.4	2.1	3.2	3.0	3.7	4.1
Fresh density (kg/dm^3)	2.46	2.37	2.33	2.39	2.32	2.29

3.2 Plastic shrinkage

Table 2 summarizes the results for the plastic shrinkage tests. All samples mostly shrank during the first ten hours of the curing process, after which the contraction clearly slows down. All concrete batches showed a shrinkage lower than 0.7 mm/m over 72 hours of fry curing, except 100CRA/0RCWTB, which faced a notably higher contraction, i.e. 1.07 mm/m.

CRAs incorporation usually greatly affects shrinkage, for their intrinsic higher flexibility and water absorption (Bai et al., 2020), but the addition of RCWTB helped reducing plastic shrinkage, especially for higher CRAs replacement, which may be due to the frictional behavior of the GFRP with rough CRA particles (Ahmed & Lim, 2021). The GFRP contained in the RCWTB clearly developed the bridging effect traditionally found in fiber-reinforced concrete produced with commercial fibers. Therefore, RCWTB additions resulted in a well-bonded matrix that hindered high dilatations and contractions.

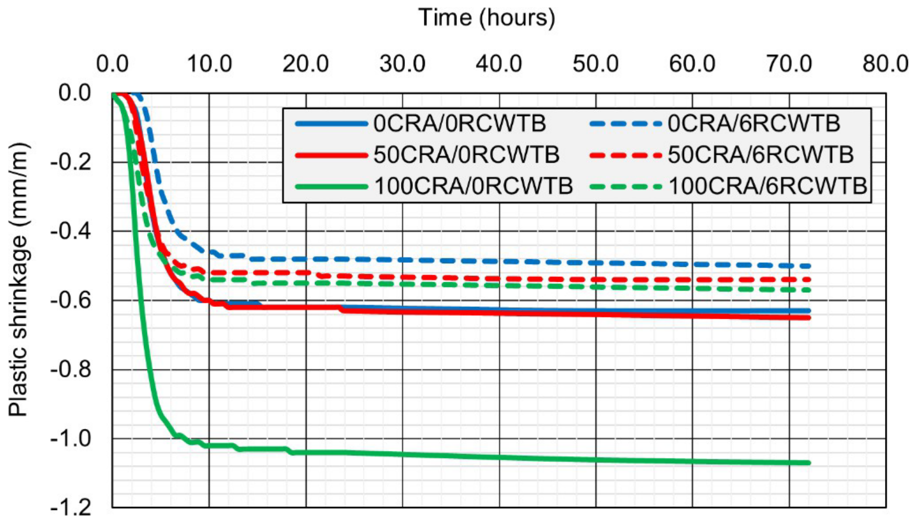

Figure 3. Result of the plastic shrinkage test.

3.3 Mechanical properties

3.3.1 Compressive strength

The results of the compressive tests are displayed in Figure 4a and 4b for ambient and moist curing, respectively. As a first observation, all samples demonstrated values of 7-day compressive strength greater than 40 MPa for both curing conditions, proving their suitability for structural applications according to the European standard 1992-1-1.

In general, CRAs are responsible for a strength decrease due to their intrinsic lower properties compared to conventional aggregates (B. Wang et al., 2021).

RCWTB caused a similar phenomenon, due to the presence of balsa wood and polymeric particles with low mechanical properties and poor bond with the cementitious matrix. Thus, the use of this waste mostly led to small reduction of compressive strength. For example, the incorporation of 6% RCWTB lowered the compressive strength by 6% in the concrete with 0%CRA after 7 days of dry curing, whereas a reduction of only 5% was recorded for both 50%CRA and 100%CRA replacement ratios, once again the RCWTB exhibiting a suitable interaction with CRAs.

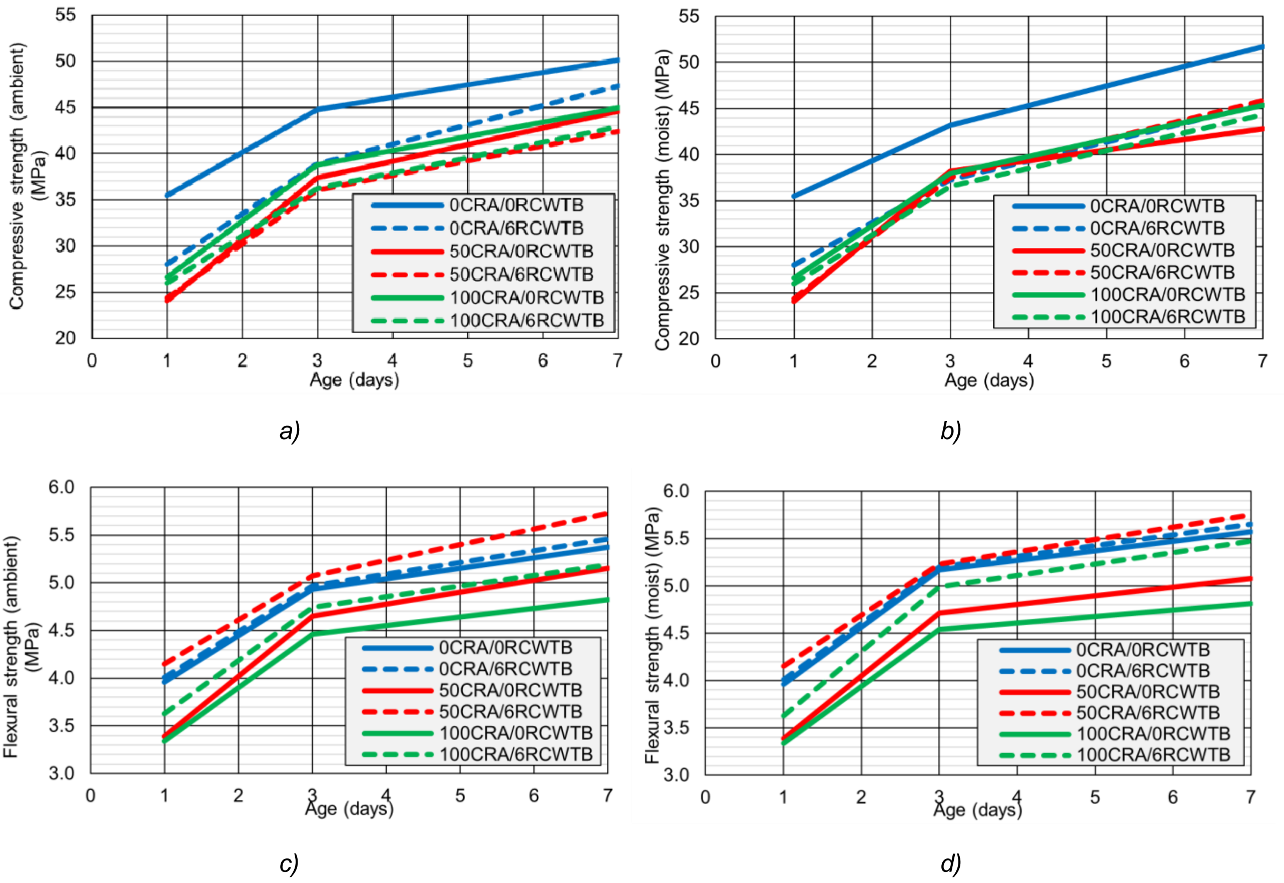

Figure 4. Strength test results: a) Compressive strength evolution under ambient curing; b) Compressive strength evolution under moist curing; c) Flexural strength evolution under ambient curing; d) Flexural strength evolution under moist curing.

3.3.2 Flexural strength

Flexural strength results are shown in Figure 4c and 4d for ambient and moist curing, respectively. After 7 days of curing all samples reached a minimum flexural strength of 4.5 MPa.

Differently from compressive strength, in this case the incorporation of RCWTB proved to be highly beneficial. Generally, no enhancement in flexural strength was recorded when RCWTB is included in conventional concretes (Revilla-Cuesta et al., 2024), but for 50% and 100% CRA content there was a notable improvement. In fact, after 7 days of dry curing, RCWTB addition allowed increasing the flexural strength by 2%, 11% and 8% moving from 0% CRA to 100% CRA. The combination of 50% CRA and RCWTB was particularly beneficial, as the 50CRA/6RCWTB overtook the flexural strength of both mixtures with 0% CRA for all curing times and conditions.

3.4 Microstructural analysis

Scanning Electron Microscopy (SEM) images were taken for both GFRP-composite fiber and polymeric particle to fully understand the behavior exhibited by mixtures with CRA and RCWTB.

The optimum adhesion of the GFRP-composite fibers to the cementitious matrix can be clearly observed in Figure 5a and 5b. Such a behavior may be favored by the irregular surface of the GFRP epoxy resin matrix (Revilla-Cuesta et al., 2023). As a confirm, in Figure 5c some tiny cementitious matrix particles remained attached to the surface of GFRP-composite fiber after slipping and failing during flexural strength testing. Instead, the polymer particles show low adhesion (Fig. 5d).

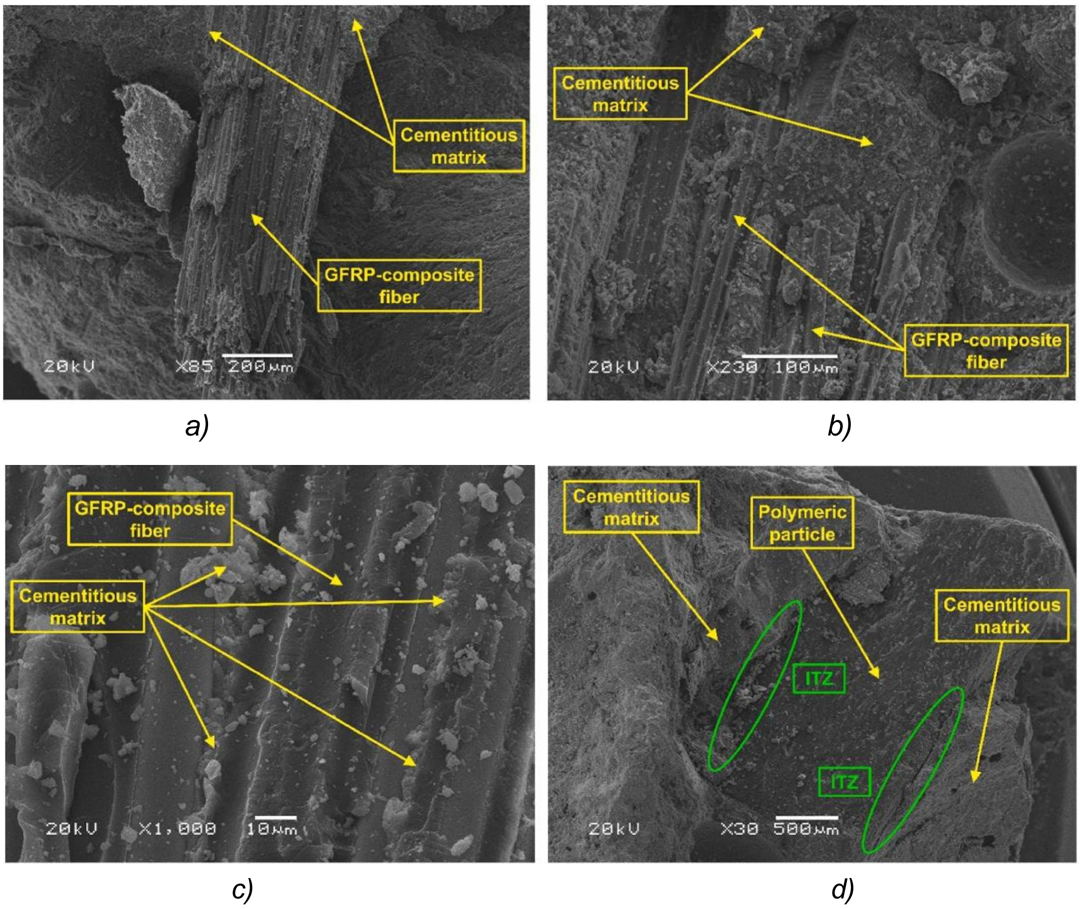

Figure 5. SEM images of ITZs between RCWTB components and the cementitious matrix.

4. CONCLUDING REMARKS

In this work, a sustainable method to improve the behavior of recycled concrete is proposed and analyzed through the incorporation of Raw-Crushed Wind-Turbine Blade (RCWTB) containing high percentages of Glass Fiber-Reinforced Polymer (GFRP). The RCWTB was included in contents equal to 0% and 6%, while the Coarse Recycled Aggregate (CRA) ranged between 0% and 100%. At the end of this study, the following conclusions can be depicted:

- Air content increased when CRA and RCWTB were included in the concrete mixtures, whereas workability and fresh density decreased. The irregular shape and rougher texture of CRA hindered concrete flow, as for the GFRP present in the RCWTB.
- The incorporation of RCWTB effectively helped at reducing plastic shrinkage, particularly in those mixes with high CRA content. The GFRP successfully acted as a rigid element within the cementitious matrix, limiting the contractions.
- The combined use of CRA and RCWTB led to concretes that exceeded 40 MPa in compressive strength after just 7 days of curing, indicating its suitability for structural applications. However, the inclusion of RCWTB slightly reduced the compressive strength of the mixtures. This reduction was due to the GFRP-composite fibers in the RCWTB being less effective under compressive stresses, and the polymeric particles for their poor adhesion to the cementitious matrix.
- All concrete mixtures achieved a minimum flexural strength of 4.5 MPa after 7 days of curing. The addition of RCWTB effectively mitigated the negative impact of CRA on flexural strength. This improvement can be attributed to the optimal adhesion of the GFRP-composite fibers within the cementitious matrix, as confirmed by scanning electron microscopy, with such an effect being more pronounced under moist curing conditions. Notably, the mixture containing 6% RCWTB and 50% CRA even displayed higher flexural strength than concrete made without CRA, likely due to the friction between some GFRP-composite fibers and CRA particles.

ACKNOWLEDGEMENTS

The present work was supported by AEI, ERDF, EU, MICINN and NextGenerationEU/PRTR; the Junta de Castilla y León and ERDF; the University of Padova. The authors sincerely thank Manuel Hernando-Revenga, Nerea Hurtado-Alonso, Javier Manso-Morato and Marcos Villalaín-Soto for delivering assistance during the lab work.

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