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Mechanical and environmental advantages of the revaluation of raw-crushed wind-turbine blades as a concrete component

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A R T I C L E I N F O

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A B S T R A C T

The large number of wind farms that will have to be dismantled in coming years is prompting a search for reliable wind-turbine-blade recycling methods, but there is not yet a broad consensus on the most appropriate. Jointly crushing all the blade components produces a material that is referred to as Raw-Crushed Wind-Turbine Blade (RCWTB), formed by fibers from the crushing of Glass Fiber-Reinforced Polymer (GFRP) composite, and spherical balsa-wood and polyurethane particles. The incorporation of this inexpensive and easy-to-produce material in concrete could help to solve the problem of blades recycling, but this approach has not been extensively evaluated in the literature. In the present study, the overall addition of RCWTB up to 6 % by volume in concrete was analyzed in terms of mechanical performance and carbon footprint. The results showed that the incorporation of RCWTB might be beneficial for both the mechanical behavior of concrete and its sustainability rating. RCWTB at 1.5 % improved compressive strength in a conventional concrete design, yielding values above 50 MPa at 28 days. Furthermore, this content reduced the carbon footprint *per* unit of compressive strength by 0.12 $kgCO_2eq/(MPa{\cdot}m^3)$. Similarly, 6.0 % RCWTB improved flexural strength, reaching values higher than 6 MPa, and reducing the carbon footprint *per* unit of flexural strength by 7.5 %. The waste had no significant negative effect on the temporal development of the mechanical performance of concrete. Furthermore, if all the wind-turbine blades annually dismantled in Spain, the world's fifth largest wind-energy producer, were crushed and converted into RCWTB, it could all be recycled at rates of 0.6–2.2 % within the total annual volume of commercial concrete produced in Spain. These figures show that RCWTB production is a feasible solution for recycling decommissioned wind-turbine blades, as it can be successfully used for manufacturing sustainable concretes with suitable mechanical and environmental performance levels.

1. Introduction

Fiber-reinforced concrete is a leading-edge technology nowadays that is used in numerous civil-engineering projects [1]. The addition of fibers to concrete and their bridging effect within the cementitious matrix have several positive consequences. First, fibers increase concrete strength, especially in bending, as the external load must additionally overcome the bond between the fibers and the

Abbreviations: (ANOVA), analysis of variance; (GFRP), glass fiber-reinforced polymer; (RCWTB), raw-crushed wind-turbine blade; (UPV), ultrasonic pulse velocity.

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matrix, or break the fibers, before any breakage of the concrete element [2]. It even means that concrete components with fiber reinforcements, such as pavements, require no additional reinforcements [3]. Second, fibers reduce cracking, hindering the entry of aggressive external agents [4], which is beneficial for concrete durability. Third, fibers increase impact resistance [5] and add post-cracking strength, so that when the concrete element fails, it is still capable of bearing load [6]. Fourth, fibers are stiff elements embedded within the cementitious matrix that reduce concrete shrinkage [7]. However, fibers also decrease concrete workability, acting as obstacles to the flow of concrete, and increasing friction between its components [8]. The main challenge is therefore to ensure that the fibers simultaneously provide all the above-mentioned advantages and suitable fresh behavior, enabling proper placement and compaction of the fiber-reinforced concrete.

Steel fibers have traditionally been the fibers of choice, which are thought to offer the best performance. Their high modulus of elasticity means that they can support loading at the same time as the concrete in which they are embedded [6]. However, they have the drawback of high CO_2 manufacturing emissions [9], which has led to the search for greener alternatives. Thus, synthetic fibers can be used, generally polypropylene in different forms, such as high-toughness, homopolymers, and polyolefin fibers [10], although basalt fibers [4], glass fibers [11], and carbon fibers [2] are also common. These fibers provide the aforementioned advantages of lower environmental impact, but are less effective than steel fibers, due to their lower modulus of elasticity. A further step towards sustainability has been taken with the utilization of fibers from different recycled elements, such as end-of-life tires [12], and recycled steel and polypropylene fibers [13,14]. Scientific research has mainly been focused on defining the optimal amount of recycled fibers for a suitable concrete performance, at the same time as reducing the environmental damage of fibers, and recovering waste products, thereby partly contributing to the circular economy. However, a complete circular economy can only be achieved if the concrete made with different wastes can be recycled at the end of its useful life [15], a research line that should be pursued to a greater extent.

The wind-energy sector is currently facing a major challenge, as the earliest wind farms that were built are reaching the end of their useful life [16]. This situation is already occurring in the countries that have pioneered wind energy, such as Denmark, Spain, and Germany [17]. It is expected that 25,000 tons of blades a year will be decommissioned in Europe alone up until 2025, and 52,000 tons a year by 2030 [16]. A solution must therefore be found for the management, recycling, and recovery of the blades, so as to reduce further dumping in landfill sites and to reuse their raw materials [18]. However, it is no easy solution, because the blades, generally made of Glass Fiber-Reinforced Polymer (GFRP), balsa wood, and polyurethane [19], are the most complex wind-turbine component in terms of their composition.

At present, the main approach to the recycling of wind-turbine blades consists of their thermal and/or chemical treatment. Pyrolysis or solvolysis are used to separate the components for subsequent individual treatment [20]. However, these high-cost processes also involve high energy consumption and greenhouse gas emissions, resulting in significant environmental impacts [21]. Another recycling possibility is the mechanical treatment of the blades, to produce a raw material of great potential from both economic and environmental perspectives for other applications, such as concrete manufacturing [22]. Still, research on the use of chopped, shredded, and crushed blades within the manufacture of concrete is very scarce.

- Crushed wind-turbine blades have in one study [23] been converted into powder for use as a filler. This solution led to a worsening of concrete behavior, as it increased porosity and decreased mechanical strength.
- Other authors have proposed the machining of the blades, mainly the composite part, to obtain cubes or cylinders to replace the aggregates, and plain and serrated needles for use as fibers [24,25]. The results revealed that the needles were the machined element that performed best in concrete, the toughness increase they caused was comparable to that of conventional fibers [25]. It was attributable to the structure of the blade's GFRP composite, that primarily consisted of unidirectionally oriented glass fibers within a polymer matrix, which if loaded in the fiber direction showed high stiffness and ultimate stress levels [18].
- Finally, other preliminary approaches can be found in recent literature [24,26] that involve crushing the GFRP composite to produce fibers that are similar to commercial ones. These studies contain successful reports of having increased the flexural strength of concrete, aspect also noted in mortars [27,28]. However, once the composite has been crushed, a major disadvantage is that separate treatment of the other blade's components, namely balsa wood and polyurethane, is required, each of which need separate recovery processes.

In the present study, a step forward is taken in the use of crushed wind-turbine blades as raw material in concrete. Therefore, the production of concrete with the crushed GFRP composite is proposed without separating it from the other components, obtaining a product composed of GFRP-composite fibers together with spherical-shaped particles of balsa wood and polyurethane that can serve as aggregate. The material is referred to here as Raw-Crushed Wind-Turbine Blade (RCWTB). The advantage of this simple, inexpensive, and innovative approach is that it can be easily implemented with conventional crushing machinery [29].

Currently, the authors of this study are engaged in developing research on the use of RCWTB material in concrete production, with the primary target of determining whether it is a feasible strategy to solve the problem of recovering and recycling wind-turbine blades. In a previous work, after presenting the need for its recycling, the waste product was characterized, and a customized mixing process was defined for concrete produced with RCWTB [29]. The same framework is assumed and briefly referred to in this paper, the aim of which is to further the analysis of concrete mixes with added amounts of RCWTB and their mechanical and environmental performance. To the best of the authors' knowledge, there are no studies in which the behavior of concrete incorporating RCWTB or any similar materials have been addressed.

2. Materials and methods

2.1. Raw materials

The concrete mixes were produced with conventional raw materials that were locally available.

- Ordinary Portland cement with a density of 3.00 kg/dm^3 and with limestone additions of between 6 % and 20 %, which was used to make the concrete more sustainable. Its designation according to EN 197–1 [30] was CEM II/A-L 42.5 R.
- Three fractions of siliceous crushed aggregate whose gradation is shown in Fig. 1: sand 0/2 mm (density of 2.62 kg/dm^3 and 24-h water absorption of 0.52 %), fine gravel 2/6 mm (density of 2.58 kg/dm^3 and 24-h water absorption of 1.83 %), and coarse gravel 6/22 mm (density of 2.59 kg/dm^3 and 24-h water absorption of 1.66 %).
- Water from the supply network of Burgos, the Spanish city where the study was conducted.
- Two plasticizing admixtures intended to achieve a higher concrete workability with a lower water/cement ratio, thus maximizing concrete strength.

The RCWTB was obtained by crushing rectangular panels cut from the central area of a wind-turbine blade, with sides measuring roughly 20–30 cm, that were composed of GFRP composite, balsa wood, and polyurethane layers. The panels were crushed using a knife mill and subsequently sieved, to produce the RCWTB composed of GFRP-composite fibers and approximately spherical particles of balsa wood and polyurethane uniformly sized between 2 and 5 mm. The average length of the GFRP-composite fibers was measured in several samples with a caliper, for which a value of 13.1 mm was obtained, similar to that of some commercially available fibers. The whole material exhibited a density of 1.63 kg/dm^3, determined by adapting the aggregate-density test (EN 1097–6 [30]), and a fiber content of 66.8 % by weight, defined by sieving and manual separation. Fig. 2 shows an example of the transverse section of a wind-turbine blade and the resulting RCWTB after its crushing. A more in-depth characterization of this waste and the methods used for conducting it can be found in another paper of the authors [29]. However, it should be noted that the composition of wind-turbine blades is highly variable, depending on the manufacturer and even the area of the blade [31]. Therefore, the characteristics of the RCWTB obtained from other blades and areas may differ from those of the waste used in this research, being an aspect that should be further analyzed.

2.2. Mix design

The reference concrete without RCWTB was designed and produced with the above-mentioned conventional raw materials. The objective was to achieve a slump class S3 (slump between 10 and 15 cm), thus guaranteeing suitable workability for placement, and at the same time an adequate strength for general use. For this purpose, the concrete design was based on the Eurocode 2 [32], which was later empirically adjusted. Finally, a cement content of 320 kg/m^3, a water/cement ratio of 0.40, and a plasticizer content of 1.0 % of the cement mass was established. The contents of the three aggregate fractions were fixed, so that the joint gradation was adjusted to the Fuller curve, as shown in Fig. 1.

The waste was added in amounts of 1.5 %, 3.0 %, 4.5 %, and 6.0 % by volume due to the low density of this waste, which were transformed into weights when defining the composition of the concrete mixes. This waste was added as an overall addition to produce the RCWTB mixes, so the content of all the other components *per* cubic meter of concrete was reduced. In this way, the fibers in the RCWTB were expected to improve mechanical performance, while diminishing the use of cement that is known to possess the largest carbon footprint of all concrete materials [33]. The amount of water and plasticizer was increased by 0.93 % and 10.55 % *per* 1 % RCWTB to preserve the slump class.

The composition of the mixes is shown in Table 1. In this table, the comparative mix design provides the composition of the concrete mixes by weight, showing that the quantity of any other component was not modified when adding RCWTB, which led to an

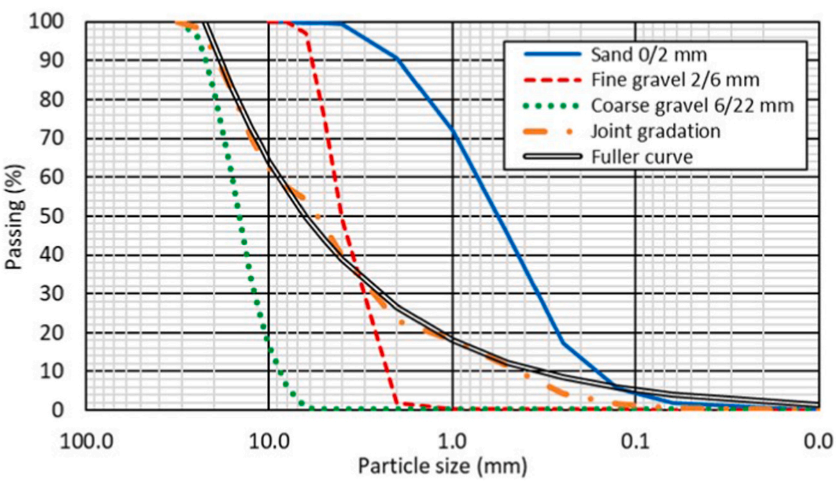


Fig. 1. Gradation of aggregates and concrete mixes.

Fig. 2. Transverse section of a wind-turbine blade (up) and raw-crushed wind-turbine blade (down).

Table 1
Mix design.

Component	Comparative					kg/m^3				
	M0.0	M1.5	M3.0	M4.5	M6.0	M0.0	M1.5	M3.0	M4.5	M6.0
Cement	320	320	320	320	320	318	312	306	300	295
Water	128	133	137	142	146	127	129	131	133	134
Plasticizer 1	2.20	2.62	3.04	3.46	3.88	2.19	2.56	2.91	3.25	3.57
Plasticizer 2	1.10	1.31	1.52	1.73	1.94	1.09	1.28	1.45	1.62	1.79
Sand 0/2 mm	500	500	500	500	500	497	488	478	469	461
Fine gravel 2/6 mm	600	600	600	600	600	597	585	574	563	553
Coarse gravel 6/22 mm	900	900	900	900	900	895	878	861	845	829
RCWTB	0.0	24.5	49.0	73.5	98.0	0.0	23.9	46.9	69.0	90.3

Table 2
Hardened-state experimental plan.

Test	Specimen type	Standard [30]
Hardened density	10x10x10-cm cubic	EN 12390-7
Compressive strength	10x20-cm cylindrical	EN 12390-3
Modulus of elasticity	10x20-cm cylindrical	EN 12390-13
Poisson's coefficient	10x20-cm cylindrical	EN 12390-13
Ultrasonic pulse velocity	10x10x10-cm cubic	EN 12504-4
Splitting tensile strength	10x20-cm cylindrical	EN 12390-6
Flexural strength	7.5x7.5x27-cm prismatic	EN 12390-5

increase in the mix volume. The mix design in kg/m^3 shows the quantities of the different raw materials needed to produce one cubic meter of concrete. The five mix designs were labelled with the letter *M* followed by the percentage of RCWTB they incorporated.

The concrete mixes were produced using a customized five-stage mixing process, to achieve an adequate workability of the concrete when RCWTB was added. This process, described in more detail elsewhere [29], consisted of the addition of the aggregates and 30 % of the water, and mixing for 3 min; the addition of the cement and the rest of the water, with a second mixing for 3 min; the addition of half the plasticizers in 0.25 L of water and a third mixing for 2 min; the addition of RCWTB and a fourth mixing for 2 min; and the addition of the rest of the plasticizers in 0.25 L of water, and a fifth and final mixing for 5 min.

2.3. Experimental plan

After concrete manufacture, the slump, fresh-density and air-content tests were conducted in a fresh-concrete sample in accordance with EN 12350–2, EN 12350–6, and EN 12350–7, respectively [30]. Simultaneously, three specimens were prepared for each hardened-state test (Table 2 and Fig. 3), which were conducted at 7, 28, 56, and 90 days, except for the hardened-density test, which was only performed at 28 days. These tests were conducted to analyze the mechanical behavior of the mixtures over time. All specimens were demolded 24 h after the manufacture of the concrete and held in a moist room at a humidity of 90 ± 5 % and a temperature of 20 ± 2 °C up until the different test ages.

The study was completed with two further objectives. On the one hand, an ANalysis Of VAriance (ANOVA) of the significance of the two factors that influenced the mechanical behavior of concrete (time and RCWTB content). On the other hand, an environmental evaluation of the concrete mixes, based on the calculation of their carbon footprints and an assessment of the suitability of this solution for the recycling of wind-turbine blades within Spain, home to the authors of this study, where wind-turbine decommissioning is currently a major concern [34,35].

3. Results and discussion: fresh and mechanical behavior

3.1. Fresh properties

The values of the three fresh properties of the five mixes are shown in Table 3. The results showed that.

- Concrete slump increased with RCWTB, despite the poorer workability that was generally associated with the use of fibers within concrete that interfere with the flow of the other components [8]. It is thought to be mainly due to the proper adjustment of the contents of water and plasticizer. However, the lower density of the polyurethane and balsa-wood particles in comparison with the natural aggregate may also mean that they were more easily dragged within the cement paste, as found regarding other wastes [36]. All the mixes showed a slump class S3 as *per* EN 206 [30], so the influence of workability can be disregarded when analyzing the effect of RCWTB on the mechanical behavior of concrete.

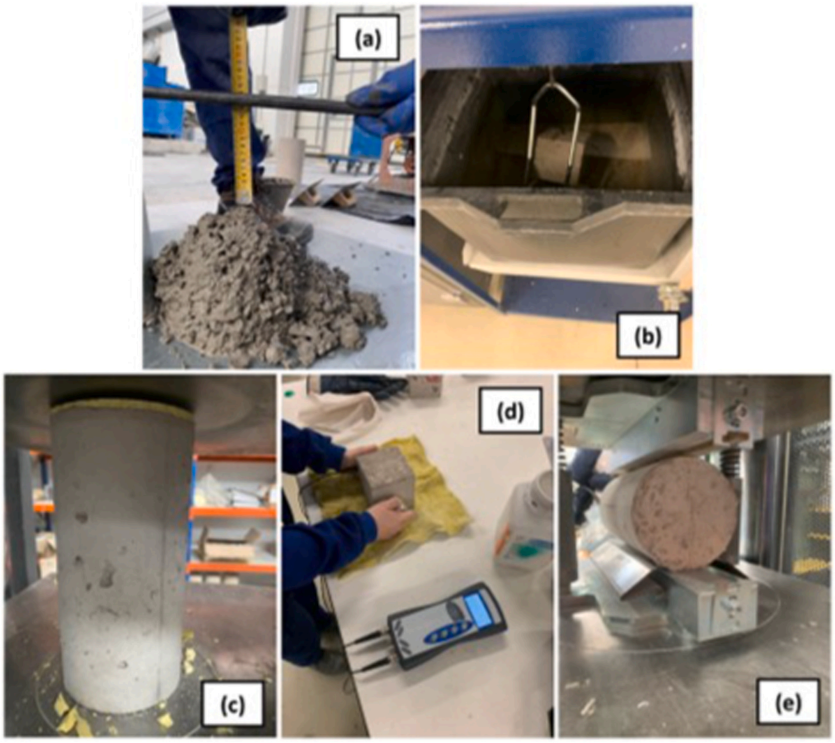


Fig. 3. Experimental set-up of tests: (a) slump; (b) hardened density; (c) compressive strength; (d) ultrasonic pulse velocity; (e) splitting tensile strength.

Table 3
Fresh properties.

Property	M0.0	M1.5	M3.0	M4.5	M6.0
Slump (cm)	10.0	10.5	13.0	13.5	12.0
Fresh density (kg/dm^3)	2.43 ± 0.02	2.37 ± 0.02	2.35 ± 0.01	2.30 ± 0.01	2.28 ± 0.01
Air content (% vol.)	1.8 ± 0.0	2.0 ± 0.0	2.0 ± 0.1	2.2 ± 0.2	2.6 ± 0.2

- As expected, the fresh density diminished 6.2 % for additions of 6.0 % RCWTB. A behavior that the replacement of cement and natural aggregates (around 3.00 kg/dm^3 and 2.60 kg/dm^3, respectively) with RCWTB (1.63 kg/dm^3) undoubtedly explained. Moreover, the increased amounts of both water and plasticizer, less dense components of concrete, also contributed to this result [37].
- Air content also clearly increased with additions of RCWTB. Thus, the value obtained for mix *M6.0* was 1.44 times higher than that of the reference concrete. The fibers present in the RCWTB were believed to favor air retention, as has been found with conventional fibers [38]. Furthermore, the porosity may increase in the interfacial transition zones, due to the presence of polyurethane and, especially, balsa-wood particles with a high surface porosity [39].

3.2. Hardened density

The hardened density followed the same trend as the fresh-density values (Table 4), showing a linear decrease (R^2 coefficient of 96.2 %) with RCWTB content, due to the lower density of this waste, the increase in water and plasticizer content, and the higher occluded-air content of the concrete mass after adding RCWTB. The mix performance was consistent with research findings on waste-plastic concrete [40]. Thus, mix *M6.0* presented a 5.4 % lower density than the reference mix, a reduction which was lower than that of the fresh density (6.2 %). It could be due to the higher water-retention capacity of the polyurethane and balsa-wood particles compared to the natural aggregate, which could very likely have reduced water evaporation [41]. An aspect that was also observed in the loss of density from the fresh to the hardened state (fourth row of Table 4), as it was smaller with increasing RCWTB contents.

3.3. Compressive strength

The results on compressive strength are shown in Fig. 4. The compressive strengths of all the mixes exceeded 40 MPa at 28 days and were over 45 MPa at 90 days, making them suitable in general for structural applications [32].

Globally, the use of RCWTB led to a decrease in compressive strength, which was partly caused by the increase in the water/cement ratio when adding this waste. Furthermore, this effect may have been reinforced by the poorer adhesion of polyurethane and balsa wood within the cementitious matrix [42]. The compressive-strength decreases of the *M3.0* and *M6.0* mixes were therefore around 9.5 % and 20.0 % with respect to the reference mix, respectively, regardless of age. However, two exceptions could be distinguished in this overall trend.

- On the one hand, mix *M1.5* showed a 5.7 % lower compressive strength than mix *M.0.0* at 7 days, while at 28 days both mixes showed the same strength, and at 90 days the strength of mix *M1.5* was 8.3 % higher. It proved that the RCWTB fibers were capable of increasing the final compressive strength of concrete mixtures with comparable mix designs, since the two mixes (*M0.0* and *M1.5*) presented a very similar cement content and water/cement ratio (Table 1). A similar behavior had already been observed with other recycled fibers [13,43]. However, the increase in the case of the RCWTB fibers occurred mainly at advanced ages, which was presumably due to the more progressive intensification in the adhesion between those fibers and the cementitious matrix [10].
- On the other hand, the differences between the compressive strengths of mixes *M4.5* and *M6.0* were negligible at all ages. It appears that above a certain threshold, the RCWTB fibers can compensate for the loss of strength due to the factors discussed above (cement content, water/cement ratio and adherence of polyurethane and balsa wood). Similar patterns have been observed with other wastes, for which the decrease in the compressive strength they cause stabilizes from a certain content [44,45].

The other factor for analysis was the evolution of compressive strength over time. In general, all the mixes showed a very similar temporal evolution, with compressive strengths at 28 and 56 days of 86–90 % and 94–97 % of the strength at 90-days, respectively. However, it could be observed that mix *M1.5* underwent a higher strength increase at advanced ages, while mixes *M4.5* and *M6.0* developed lower initial strengths (7-day compressive strength of around 72 % compared to 80 % for the other mixes). Both aspects were explained in terms of RCWTB fiber adhesion within the cementitious matrix that developed more slowly over time [46], so that the fibers began to add compressive strength at advanced ages when RCWTB was added at low contents, and to compensate for the factors that decreased compressive strength when added in high amounts. All the mixes showed continuous strength evolution, so that the polyurethane and balsa-wood particles appeared to have no critical long-term effect on compressive strength.

Table 4
Hardened density.

Property	M0.0	M1.5	M3.0	M4.5	M6.0
Hardened density (kg/dm^3)	2.40 ± 0.03	2.35 ± 0.02	2.33 ± 0.01	2.28 ± 0.01	2.27 ± 0.02
Loss of density due to RCWTB additions (%)[a]	0.0	2.1	2.9	5.0	5.4
Loss of density from fresh to hardened state (%)[a]	1.2	0.8	0.9	0.9	0.4

[a] Values calculated with the medium values of the fresh and hardened densities of each mix.

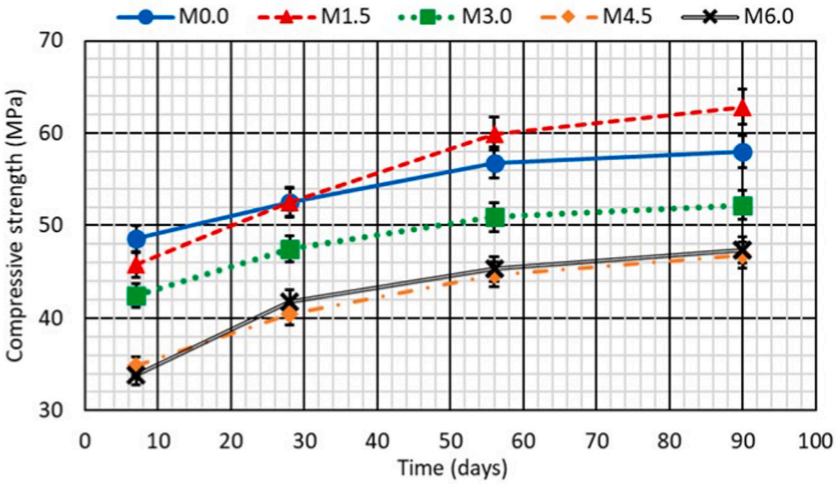


Fig. 4. Compressive strength.

3.4. Modulus of elasticity

The modulus of elasticity for each mix at each age was calculated from the increase in longitudinal strain when applying 5 % and 30 % of the compressive strength, as specified in EN 12390–13 [30]. Table 5 shows these longitudinal strains at 28 days as an example, while the values of the modulus of elasticity of all the mixes at all ages are shown in Fig. 5.

The 90-day elastic modulus at over 30 GPa, the minimum value usually adopted in structural design according to the standards [32], was adequate for mixes *M0.0*, *M1.5* and *M3.0*. At the same age, the elastic modulus of mixes *M4.5* and *M6.0* almost reached 30 GPa. All the mixtures showed similar trends for their elasticity moduli over time, *i.e.*, the elasticity moduli at 7, 28, and 56 days were always 92 %, 98 %, and 99 % of the 90-day modulus of elasticity, with the highest increase in elastic stiffness occurring at early ages. The eventual increase in RCWTB fiber adhesion within the cementitious matrix, discussed in the previous section [10], had no influence on the modulus of elasticity, which is a property that evaluates concrete behavior under compressive stress before cracking [47]. On the other hand, the presence of balsa wood and polyurethane particles had no negative effect on the temporal development of elastic stiffness, as the concrete mixes with those particles showed the same evolution as the *M0.0* reference mix.

The trends of the modulus of elasticity were more consistent than those for compressive strength. Thus, the addition of RCWTB always led to a decrease in the modulus of elasticity, which was approximately proportional to the added RCWTB (8 % for mix *M1.5*, 17 % for mix *M3.0* and 31 % for mix *M4.5*), and was remarkably similar at all ages. The explanation was that the very slender RCWTB fibers embedded in the concrete had little or no effect on the elastic shortening of the cementitious matrix after the application of a compressive load, while any such shortening increased after reducing the cement content and raising the water/cement ratio. The same behavior has also been documented with other fiber types, which do not improve the compressive behavior of concrete unless there are cracks that they can bridge [2], or they are made of a material with high elastic stiffness such as steel [48]. In addition, the presence of balsa-wood and polyurethane particles, which are more deformable than natural aggregates, might also favor this behavior [40]. The above is valid for all the mixes with the exception of mix *M6.0*, which presented a modulus of elasticity that was 2 GPa higher than that of the *M4.5* mix. As observed with the compressive strength, the addition of RCWTB appeared to worsen the behavior of the concrete, reaching a threshold where the fibers compensated for the deterioration caused by the modification of the concrete composition.

3.5. Poisson's coefficient

Poisson's coefficient, which evaluates the elastic deformability of a material in the direction perpendicular to the applied load [49], was determined in the same specimens as the modulus of elasticity by dividing the increases in transverse and longitudinal strains when applying 5 % and 30 % of the compressive strength. The values of these strains at 28 days are shown in Table 5. This coefficient (Fig. 6) was always between 0.19 and 0.22, at all times very close to 0.20, a value traditionally considered for concrete [32].

RCWTB additions generally led to a decrease in the Poisson's coefficient, the reduction of which at 90 days with respect to mix *M0.0*

Table 5
Strains (με) for the calculation of the moduli of elasticity and Poisson's coefficients at 28 days.

Value	M0.0	M1.5	M3.0	M4.5	M6.0
Longitudinal strain for 5 % compressive strength	39	40	44	49	48
Longitudinal strain for 30 % compressive strength	359	387	391	413	403
Transverse strain for 5 % compressive strength	7	4	22	31	26
Transverse strain for 30 % compressive strength	74	78	91	105	96

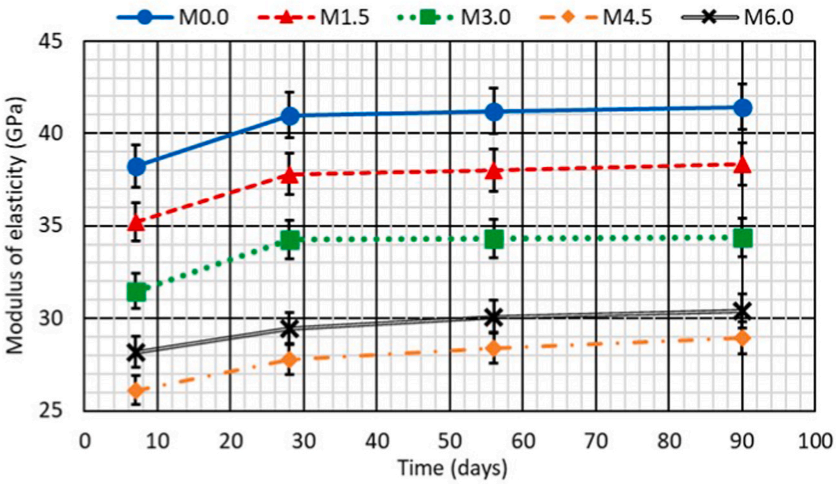


Fig. 5. Modulus of elasticity.

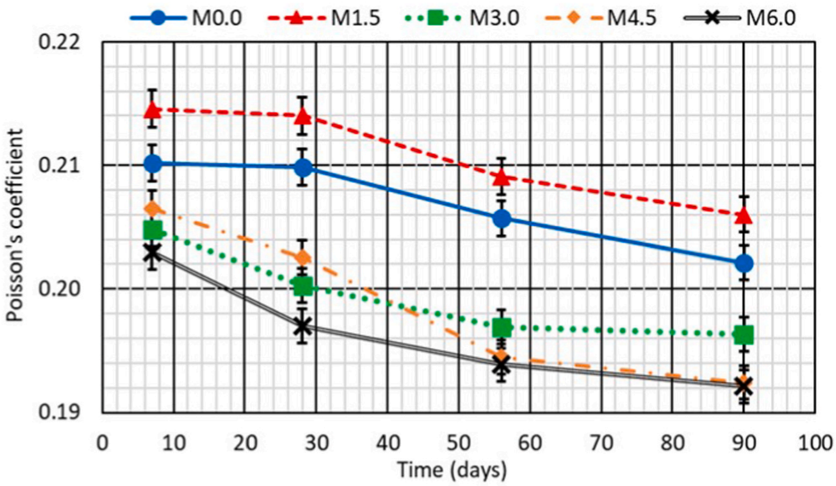


Fig. 6. Poisson's coefficient.

was 2.9 % for mix *M3.0* and 5.0 % for mixes *M4.5* and *M6.0*. Research has found that fiber bridging of the cementitious matrix reduces the transverse deformability of concrete and limits the bulging of concrete specimens when they are subjected to compressive stresses [50]. The fibers can even remove the creep step between the zones of elastic- and plastic-behavior, reflected in the stress-strain curve of concrete in the transverse direction [6], due to the vertical-splitting cracking that appears during loading [51]. In this case, RCWTB fibers matched this behavior in the elastic regime, limiting the bulging of the specimen and reducing the Poisson's coefficient. It can be noted that the fibers were effective at reducing transverse deformability as they worked in tension [1], unlike for longitudinal strain under compression, as discussed in the previous section. On the other hand, it is likely that the particles of balsa wood and polyurethane had the opposite effect, increasing the transverse deformability of concrete, due to their lower adherence within the cementitious matrix [42], and their greater flexibility [40]. This behavior can be observed in mix *M1.5*, which had a higher Poisson's coefficient than the *M0.0* reference mix (2 % higher at 90 days). The low fiber content of the concrete mix meant that the decrease in transverse deformability due to the fibers was smaller than the increase produced by the particles of polyurethane and balsa wood.

Regarding the temporal evolution of the Poisson's coefficient, all the mixes showed a conventional evolution, so that this coefficient decreased slightly over time, with reductions as usual of 6–7% from 7 to 90 days [51]. The decrease was more pronounced in the mixtures with high RCWTB contents at early ages, due to the contribution of the RCWTB fibers that limited transversal deformability from the outset [49]. In mixes *M0.0* and *M1.5*, the decrease in the Poisson's coefficient was more delayed, as it was mainly linked to the development of stiffness within the mix, a typical behavior in concretes without fibers [44].

3.6. Ultrasonic pulse velocity

The Ultrasonic Pulse Velocity (UPV) test results are depicted in Fig. 7. The UPV values always corresponded to a good-quality

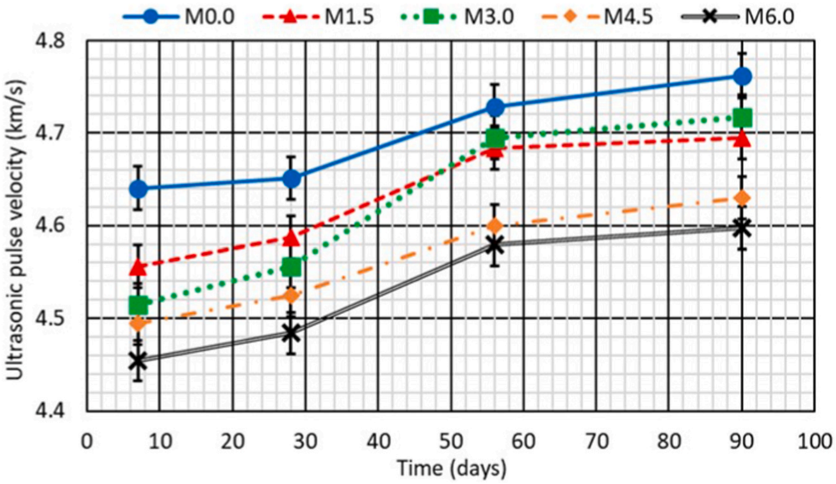


Fig. 7. Ultrasonic pulse velocity.

concrete, between 4.2 and 5.4 km/s [52]. It once again shows the validity of RCWTB as a global addition in the production of concrete that is suitable for structural and non-structural use.

Increasing the RCWTB content in concrete caused a decrease in UPV, but only in the order of 2–4% at 90 days for all mixes. It was a slight decrease, thought to be due to the lower density of the concrete (Table 4) and the possible increase in porosity (Table 3, air content) caused by the addition of RCWTB, properties with which UPV is closely related [13]. Moreover, the 7-day UPV reading accounted for 96–97 % of the 90-day UPV, leaving UPV almost constant over time, regardless of the RCWTB content of the concrete. The larger variations of the compressive-behavior mechanical properties, compared to the UPV, suggested that the common practice of estimating these properties through the UPV [53,54] should be used with caution.

3.7. Splitting tensile strength

The values of splitting tensile strength are shown in Fig. 8. Two groups of mixtures with very similar strength values at all ages could be distinguished (maximum differences of 0.1 MPa).

- The first group consisted of mixes *M0.0*, *M1.5,* and *M3.0*, with an average splitting tensile strength of 3.98 MPa at 28 days, and 4.32 MPa at 90 days. Splitting tensile strength is strongly conditioned by the bond between the aggregate and the cementitious matrix [40], so it could have been negatively affected by the polyurethane and balsa-wood particles present in the RCWTB. However, it is also thought that this negative effect may have been offset by the presence of fibers that sewed the cementitious matrix and enhanced the tensile strength [43]. Furthermore, the decrease in the cement content and the increase in the water/cement ratio were very small in all three mixtures, so they had no adverse effect either, as reported in the literature [6]. Finally, the evolution of the splitting tensile strength over time, with smaller increments between ages as time progressed, showed that its development was

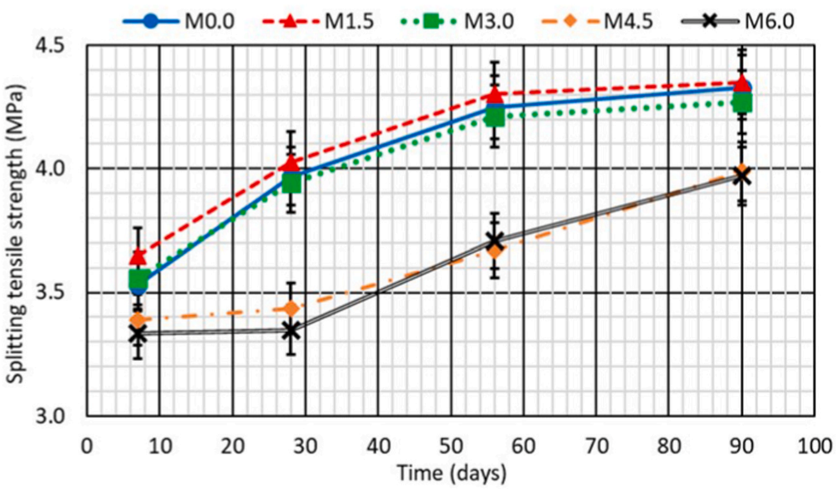


Fig. 8. Splitting tensile strength.

linked to the hydration of the cementitious matrix and its consequent strength development, as with all hydraulic concretes [55]. Overall, the presence of up to 3 % by volume of RCWTB as a global addition had no effect on the splitting tensile strength.

- The second group was formed of mixes *M4.5* and *M6.0*, which presented average splitting-tensile-strength values of 3.39 MPa at 28 days and 3.98 MPa at 90 days. These mixtures showed a noticeable decrease in strength with respect to the mixtures of the first group. Based on the hypothesis of compensation between the positive and negative effects of RCWTB discussed for the first group of mixes, it was suggested that the decrease in cement and the increase in the water/cement ratio had already reached a critical value that inevitably led to a lower strength [44]. However, this loss of strength decreased over time (reductions of 15 % at 28 days and 8 % at 90 days). Any such RCWTB additions were considered to add sufficient fiber content, so as to begin to contribute effectively to concrete tensile strength [43]. Thus, the temporal increase in the bond between the fibers and the cementitious matrix over time [46], which was also observed in the compressive strength, led to the fact that under tensile stresses, the improvements attributable to the RCWTB fibers showed an upward trend over time. Once again, it was noted that the presence of polyurethane and balsa-wood particles had no effect on long-term strength development.

3.8. Flexural strength

Flexural-strength behavior (Fig. 9) can be described as a combination of the aspects discussed in relation to compressive strength and splitting tensile strength. The addition of RCWTB therefore led to a slight decrease in flexural strength up to contents of 3.0 %. Beyond that threshold, the fiber bridging effect started once again to increase the flexural strength of the mixes. A behavior that can be analyzed on the basis of mixes *M3.0* and *M6.0*.

- Mix *M3.0* showed the highest decrease in flexural strength at a value of 5 % after 28 days, a lower loss than for the compressive-behavior properties. The decreased content of cement, the increase in the water/cement ratio, and the reduced adhesion of the polyurethane and balsa-wood particles may have adversely affected the area of the concrete specimen under compressive stresses [24,40]. Nevertheless, the presence of RCWTB fibers improved the behavior of concrete in the traction zone, as deduced from the splitting tensile strength results. Thus, the deterioration of the bending-tensile behavior of concrete when adding RCWTB was lower than under compression.
- Mix *M6.0* showed a slightly higher flexural strength than the *M0.0* reference mix at all ages (around 0.05–0.1 MPa). As with the splitting tensile strength, that amount of RCWTB provided sufficient fiber content to make positive contributions to the flexural behavior of the concrete, a key aspect when using recycled fibers in concrete [43,56]. In that way, all the negative effects of the RCWTB that affected the compressed zone of the concrete during the test could be compensated. Undoubtedly, additions of RCWTB improved the flexural strength of the mixes, which underlines the suitability of this waste material as an overall addition, especially in concrete components under bending stresses, as briefly suggested elsewhere [24].

The temporal development of flexural strength followed conventional patterns within all the mixes, unlike the splitting tensile strength, such that the increase in strength was lower as time passed [49]. However, the effect of the RCWTB fibers could be detected, even though the most notable increase in strength occurred at early ages in all concrete mixtures, because the higher the amount of added RCWTB, the more pronounced the enhancement of strength at advanced ages. A behavior that the incremental adhesion over time between fiber and cementitious matrix might presumably explain [46].

3.9. ANOVA statistical validation

An ANOVA at a confidence level of 95 % completed the results analysis, in which the two factors that affected the mechanical behavior of concrete (RCWTB content and time) and their interaction were considered. The results reported in Table 6 showed that.

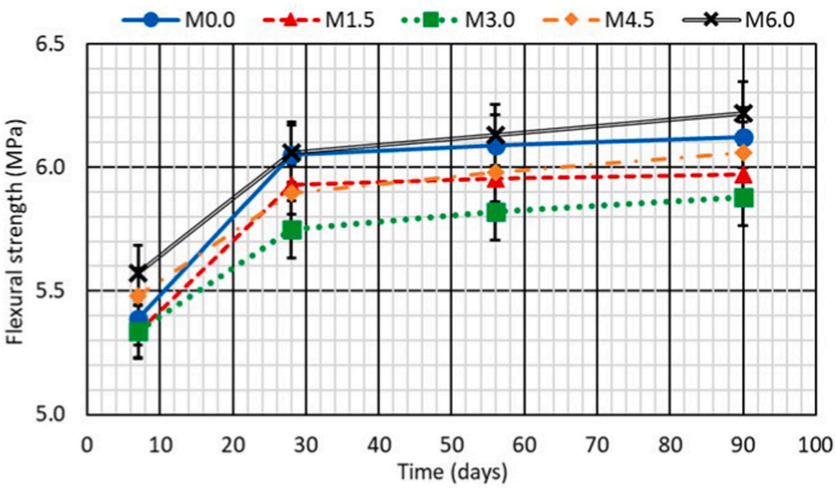


Fig. 9. Flexural strength.

Table 6
ANOVA results (α = 0.05).

Property	Factor: RCWTB content (% vol.)			Factor: time (days)		Interaction
	p-value	Homogeneous groups		*p*-value	Homogeneous groups	
Slump	0.0155	0.0 and 1.5	3.0 and 4.5	–	–	–
Fresh density	0.9071	All		–	–	–
Air content	0.0158	0.0, 1.5, and 3.0		–	–	–
Hardened density	0.7320	All		–	–	–
Compressive strength	0.0000	0.0 and 1.5	4.5 and 6.0	0.0000	None	0.0676
Modulus of elasticity	0.0000	None		0.0008	28, 56 and 90	0.9999
Poisson's coefficient	0.0000	None		0.0000	None	0.1215
Ultrasonic pulse velocity	0.0014	1.5 and 3.0	4.5 and 6.0	0.0002	None	0.9997
Splitting tensile strength	0.0000	0.0, 1.5 and 3.0	4.5 and 6.0	0.0000	None	0.2857
Flexural strength	0.0302	0.0 and 6.0	1.5 and 4.5	0.0000	28, 56 and 90	0.9340

- The effect of RCWTB content on all properties was significant, except for fresh and hardened density. Any small increase in the RCWTB content had a significant impact on the modulus of elasticity and Poisson's coefficient. In statistical terms, the mixes with low RCWTB contents (0.0 %, 1.5 %, and 3.0 %) formed homogeneous groups, so those additions could be said to have similar effects on the rest of the mechanical properties. The mixes with high RCWTB contents (4.5 % and 6.0 %) also constituted homogeneous groups. An anomalous behavior was found in flexural strength, in which the *M0.0* reference mix showed the same behavior as mix *M6.0*, as the fibers counterweighted the negative effects of RCWTB additions that modified the concrete composition, as has also been found in other studies [12].
- Consistent with expectations, behavior over time generally presented a significant effect on all the mechanical properties. Nevertheless, both the modulus of elasticity and flexural strength at 28 days were statistically unaltered at 56 and at 90 days.
- Finally, the interaction between both factors was not significant. Therefore, the effect of RCWTB additions was analogous at all concrete ages, and the use of RCWTB never modified the temporal development of strength.

4. Results and discussion: environmental analysis

The carbon footprint of each concrete mix, cf, was calculated according to Equation (1), which accounts for the content of each concrete component *per* m^3 in kg (a_i), see Table 1, and the individual carbon footprint (cf_i) of each component in $kgCO_2eq/kg$, researched in the literature [57–59] and, in the case of RCTWB, roughly calculated through the CO_2 emissions during blade processing due to energy consumption and transportation needs. The other CO_2-emitting factors during concrete manufacture, such as concrete mixing and concrete transportation, were considered identical for all the mixes, thus obtaining a comparative carbon-footprint value

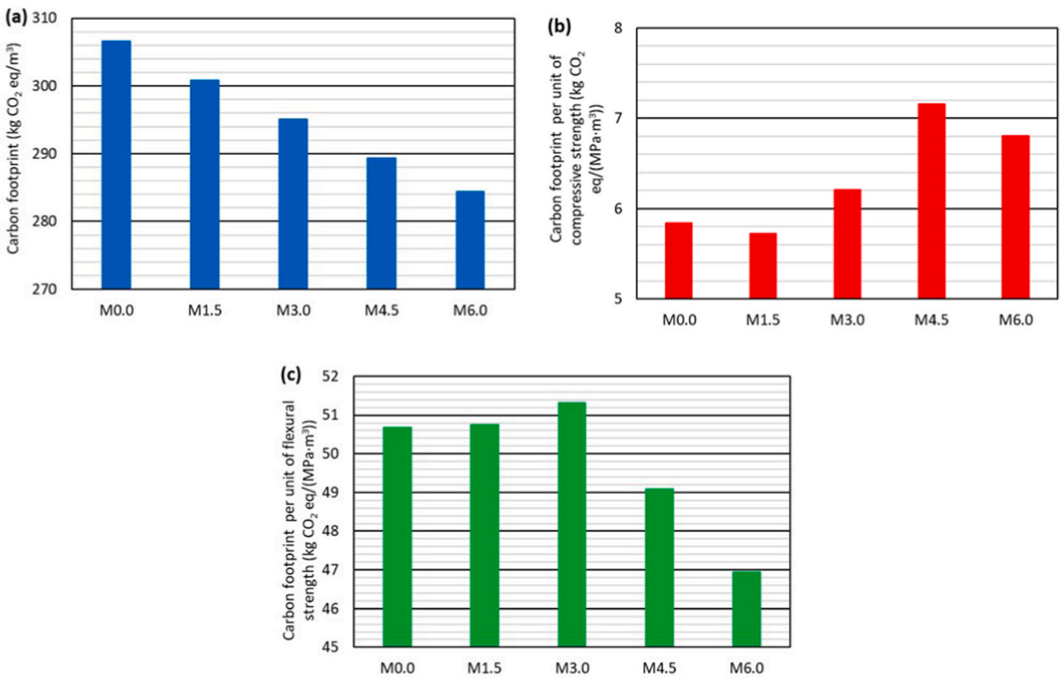


Fig. 10. Carbon footprint: (a) overall value; (b) *per* unit of compressive strength; (c) *per* unit of flexural strength.

only based on concrete composition [60]. As mentioned in the mix design, RCWTB was used as an overall addition, which led to a reduction in the cement content *per* m^3 of concrete, from 318 kg/m^3 in mix *M0.0*–295 kg/m^3 in mix *M6.0*. Cement is the component with the largest carbon footprint in concrete [33]. The overall addition of RCWTB therefore lowered the carbon footprint (kg CO_2 eq/m^3) of the mixes, as shown in Fig. 10a. Thus, the use of RCWTB not only maintained satisfactory mechanical properties in concrete, but also had clear environmental benefits.

$$cf = \sum_i a_i \cdot cf_i \tag{1}$$

It is also of interest to analyze this information in terms of the carbon footprint of each mix *per* unit of strength [61]. Values that are shown in Fig. 10 for 28-day compressive strength and 28-day flexural strength.

- In relation to compressive strength (Fig. 10b), mix *M1.5* showed a lower carbon footprint than the reference mix: 5.84 kgCO_2eq/(MPa·m^3) vs. 5.72 kgCO_2eq/(MPa·m^3). The RCWTB fibers compensated the slight decrease in cement content, even slightly increasing the compressive-strength values. In applications requiring adequate compressive performance, the use of 1.5 % RCWTB was therefore the option that offered the best strength-to-sustainability ratio.
- In the analysis of flexural strength (Fig. 10c), it was noted that the carbon footprint *per* unit of strength showed minimal increases with respect to the reference mix, up to a content of 3.0 % RCWTB. However, the RCTWB fibers started to act beneficially under tensile stresses from that content onwards, which led to that sustainability value decreasing very noticeably: 50.7 kgCO_2eq/(MPa·m^3) for the *M0.0* mix and 46.9 kgCO_2eq/(MPa·m^3) for the *M6.0* mix. When producing a concrete component to withstand significant bending stresses, the use of high RCWTB contents enables the required concrete performance to be achieved at a lower environmental impact.

5. Results and discussion: solution viability for the recycling of wind-turbine blades

In the previous sections, the results of adding RCWTB overall additions to concrete mixes has been described in terms of adequate fresh and mechanical behavior, while simultaneously reducing the carbon footprint *per* unit of strength. This analysis can additionally explore the feasibility of recycling wind-turbine blades in that manner.

Spain is the fifth largest producer of wind energy in the world (wind-energy power of 25 GW), behind only China, the United States, Germany, and India [62]. It is therefore an ideal geographical framework for this analysis. Based on information from different specialist organizations [16,17,63], the maximum potential annual production of RCWTB in Spain has been equated with the total output of concrete considered sufficient for its consumption.

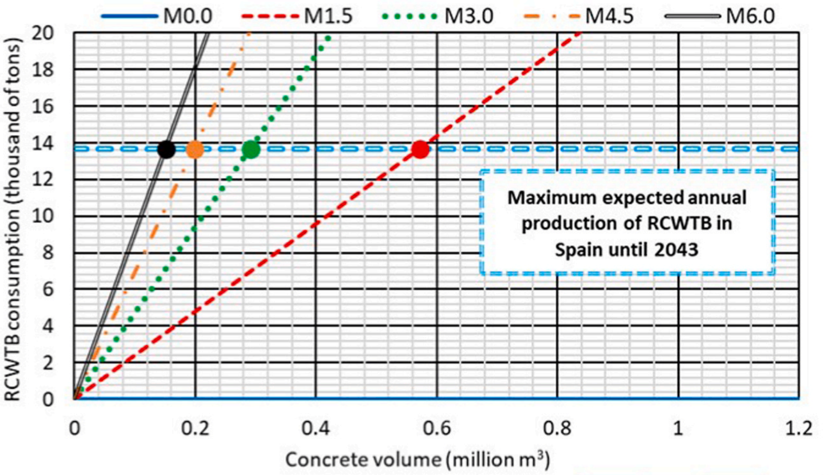
- In Spain, the maximum number of wind turbines that could be annually dismantled over the next 20 years was estimated at 2533, in 2029 [17]. As each wind turbine consists of 3 blades with an average weight of 2 tons, of which metallic elements and stiffeners could amount to approximately 10 % in weight [16], it is likewise estimated that the maximum annual production of RCWTB in Spain could be around 13.68 thousand tons.
- Total concrete production and consumption in Spain was 25.76 million m^3 in 2021, the last year for which statistics were published [63].
- RCWTB consumption *per* m^3 of concrete was 23.9 kg for mix *M1.5*, 46.9 kg for mix *M3.0*, 69.0 kg for mix *M4.5*, and 90.3 kg for mix *M6.0* (Table 1). In Fig. 11, straight lines relate concrete production with RCWTB consumption for each mix.

As shown by the cut-off points in Fig. 11, all the RCWTB that might have to be produced in Spain in the year of maximum wind-turbine dismantlement could be recycled in 0.571 million m^3 of the *M1.5* concrete mix, the mix with the best compressive strength (Fig. 4), and with 0.151 million m^3 of the *M6.0* concrete mix, the mix with the best flexural behavior (Fig. 9). At 2.22 % and 0.59 % of the total concrete produced annually in Spain, those amounts of concrete underline the feasibility of reusing and giving a second life to wind-turbine blades in the form of RCWTB, a raw material for concrete production. The use of this waste in a minimum part of the commercially produced concrete is also an economic solution, since the cost of crushing wind-turbine blades, the only mechanical process necessary for obtaining RCWTB, represents approximately one fifth of chemical-treatment costs for separating the different components of the wind turbine blades [21].

6. Conclusions

In this study, the recovery and the crushing of dismantled wind-turbine blades has been explored, to give a second life to that raw material in concrete manufacturing. To do so, a non-selective crushing process has been conducted, *i.e.*, without separating the different components of the blades, thus obtaining a waste material that is referred to here as Raw-Crushed Wind-Turbine Blade (RCWTB). The material consists of fibers from the crushing of Glass Fiber-Reinforced Polymer (GFRP) composite, and approximately spherical particles of balsa wood and polyurethane. It was used as an overall addition to concrete in volumes of 1.5 %, 3.0 %, 4.5 %, and 6.0 %. Those additions used up the waste residue and reduced the cement content. A customized mix-design resulted in an S3 slump class as *per* EN 206 [30] in all the mixes, ensuring adequate workability. The following conclusions can be drawn from the analysis of the mechanical and environmental behavior of the concrete mixtures.

- The density of RCWTB, in the order of 1.6 kg/dm^3, together with the small increase in water required to maintain concrete workability, led to a decrease in the fresh and hardened density of concrete. It also slightly increased the air content in the fresh concrete.



	M1.5	M3.0	M4.5	M6.0
Concrete volume for full RCWTB consumption in Spain (million m^3)	0.571	0.291	0.198	0.151
Percentage of annual production of concrete in Spain (25.76 million m^3)	2.22	1.13	0.77	0.59

Fig. 11. Analysis of RCWTB consumption by concrete production.

- The use of RCWTB reduced the compressive strength and the modulus of elasticity of the concrete in an approximately linear manner with the waste content. This decrease was attributed to the increase in the water/cement ratio and the reduction in cement content when adding this waste, as well as the poorer adhesion of the polyurethane and balsa wood within the cementitious matrix. However, the use of smaller additions (1.5 % by volume) of RCWTB fibers slightly increased the compressive strength. In addition, the fiber content of the concrete at 4.5 % RCWTB stabilized the compressive behavior.
- The fibers within the RCWTB reduced the transverse deformability of the concrete and its Poisson's coefficient, so that each waste content had a statistically significant effect. However, the overall results and the temporal evolution of this coefficient were within conventional limits.
- The Ultrasonic Pulse Velocity (UPV) tests yielded values within the range typically associated with good-quality concretes. However, the absence of statistical significance among the values obtained for the different mixtures suggested that caution should be exercised when using UPV as a means of estimating the mechanical properties of this type of concretes.
- RCWTB additions had no effect on the splitting tensile strength of the concrete up to a volume content of 3.0 %, after which it decreased. On the other hand, the RCWTB fibers preserved, and even minimally improved the flexural strength of concrete when added at high contents. The RCWTB fibers produced a greater increase in both strengths at advanced ages.
- The development of the mechanical properties after the addition of RCWTB was slightly delayed in the concrete over time, due to the progressive increase of the adhesion between the RCWTB fibers and the cementitious matrix, although this difference was never high enough to be significant. Polyurethane and balsa-wood particles never affected the long-term development of the mechanical properties.
- The decrease in cement content with the addition of RCWTB reduced the overall carbon footprint of concrete ($kgCO_2eq/m^3$) across all the mixes that were studied. Additionally, the carbon footprint *per* unit of strength ($kgCO_2eq/(MPa \cdot m^3)$) was reduced in compression for low RCWTB contents and in bending for high RCWTB contents. Thus, this residue enabled the development of concrete with a more favorable balance between strength and sustainability.

In summary, it has been demonstrated that RCWTB is a material that can be used in concrete production with an adequate fresh and mechanical behavior, while also contributing to greater sustainability in terms of its reduced carbon footprint. Going one step further, the results have shown that the overall addition of 1.5 % RCWTB in volume might be advisable in applications in which the concrete is primarily under compressive forces, while 6.0 % RCWTB can be recommended for concrete under high flexural stresses. Furthermore, in a country such as Spain, the world's fifth largest producer of wind energy, incorporating RCWTB as a raw material in just 0.6–2.2 % of all concrete could facilitate the complete recycling of all dismantled wind-turbine blades in the year with the highest projected levels of wind-farm decommissioning. Nevertheless, there are still many aspects to be analyzed to ensure the proper performance of this RCWTB concrete, such as its stress-strain behavior, its durability and even how the origin of the RCWTB affects concrete performance.

CRediT authorship contribution statement

Víctor Revilla-Cuesta: Conceptualization, Formal analysis, Investigation, Methodology, Validation, Writing – original draft. **Javier Manso-Morato:** Formal analysis, Investigation, Methodology, Software, Validation, Visualization. **Nerea Hurtado-Alonso:** Formal analysis, Investigation, Methodology, Software, Validation, Visualization. **Marta Skaf:** Conceptualization, Funding acquisition, Methodology, Project administration, Supervision, Writing – review & editing. **Vanesa Ortega-López:** Conceptualization, Funding acquisition, Project administration, Resources, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

As it is an experimental study, all the data generated are provided in the article through tables and graphs. The authors are pleased to provide any clarification.

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