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Raw-crushed wind-turbine blade: Waste characterization and suitability for use in concrete production

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ABSTRACT

Many of the first wind-turbine installations are reaching the end of their useful life, so their blades have to be replaced. Inexpensive, sustainable, and straightforward recycling solutions are therefore needed. The conversion of turbine blades into raw materials for concrete solutions is proposed in this paper, through a novel recycling process entailing non-selective cutting, crushing, and sieving of the blade walls, without component separation. The material, Raw-Crushed Wind-Turbine Blade (RCWTB), consists of fiberglass-composite fibers, polyurethane, and balsa-wood particles. It serves as concrete fibers and aggregates, according to its physical and microscopic characterizations. A customized concrete mix design and a five-stage mixing procedure with up to 6% RCWTB achieved suitable workability levels. The compressive strength of the RCWTB concrete was 40 MPa, and it had a higher load-bearing capacity and a lower carbon footprint than ordinary concrete. The results encourage research on the overall performance of RCWTB concretes.

1. Article approach

In view of wind-turbine ageing and estimates for wind farm decommissioning over forthcoming years (AEE, 2022; WE, 2022), the wind-energy sector will be prioritizing wind-turbine blade recycling. The complex and varied composition of blades made from glass- or carbon-fiber composites, wood, polyurethane, and resins means that their recycling has been under research for several years (Liu and Barlow, 2017), but there is currently no widely accepted solution (Leon, 2023). The scientific literature contains a few solutions to this problem that are at a preliminary-analysis stage. These solutions include the adaptation of the blades to serve as urban furniture (Joustra et al., 2021), the chemical separation of blade components for individual revaluation (Fonte and Xydis, 2021), and the mechanical processing of blades for use as raw material in the manufacture of concrete and many other products (Yazdanbakhsh et al., 2018; Baturkin et al., 2021).

In this research, a novel preliminary approach to the recovery of dismantled wind-turbine blades is provided, different from all those available in the literature, as it addresses the revaluation through a simple mechanical treatment of all the components of the wind-turbine blades simultaneously (Yazdanbakhsh et al., 2018; Pławecka et al., 2021; Xu et al., 2022). This processing involves cutting and non-selective crushing for use in concrete production as aggregate and fiber additions. An inexpensive, rapid, and low-technical waste treatment process is proposed, producing a residue that the authors will refer to as Raw-Crushed Wind-Turbine Blade (RCWTB). The varied composition (Joustra et al., 2021) of blades contains some fractions that can replace natural aggregate and others that can function as recycled fibers. In this way, the wind-turbine blade materials may not only be recovered, but can improve both concrete sustainability (Souza et al., 2022) and, through fiber additions, load-bearing capacity (Zia et al., 2022).

This paper covers the basic aspects for the successful production of concrete with RCWTB and answers the initial question of the suitability of this way for the recycling of wind-turbine blades, serving as a starting point in this research field. Therefore, the key general aspects for the suitable use of sustainable concrete aggregates and fibers are reviewed in this paper (Section 2), thus being defined the functions to be performed by the different wind-turbine-blade components. The current situation of the wind-energy sector is then addressed, as is the need for recycling wind-turbine blades, and the approach adopted in this research is described (Section 3). Then, the production and characterization of RCWTB (Section 4) and the design and necessary mixing process of the concrete produced with additions of RCWTB (Section 5) are all discussed, aspects that are fundamental for the effective use of

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RCWTB as a raw material in concrete. Finally, an initial approach to the hardened behavior and the production viability of the concrete produced with this residue is presented (Section 6) before the conclusions are set out (Section 7).

The final objective is to define whether the proposed solution for the recovery of the wind-turbine blades is feasible in terms of sustainability and fresh and hardened performance of concrete, so as to serve as a basis for further research on concrete made with RCWTB. In addition, it describes the key aspects for researchers and companies to initiate research related to RCWTB concrete, which the authors of this paper think will be essential in the coming years given the situation facing the wind-energy sector (Leon, 2023).

2. Sustainable aggregate and fiber in concrete

Concrete is one of the most widely used materials in the civil-engineering sector. It is used both for making non-structural elements, such as pipes, and urban furniture, as well as structural elements, such as buildings or bridges (Cuadrado et al., 2012; Faneca et al., 2020; Kirthiga and Elavenil, 2022). Its widespread use is attributable to its low cost, easy transport when fresh, versatility when set in formworks of different shapes, and excellent performance in terms of compressive strength (García et al., 2012; Structural Code, 2021). Proper design of concrete is essential to ensure an adequate balance between its fresh and hardened behavior, so concrete exhibits all the above advantages. To do so, the proportions of its three fundamental components (cement, water, and aggregates) must be balanced for the particular purpose of the concrete that is to be produced (Nepomuceno et al., 2018).

Concrete is also criticized because of its low levels of sustainability (Souza et al., 2022; Vashistha et al., 2022). The production of both aggregate and cement has a very negative impact on the environment (Hossein et al., 2022). On the one hand, aggregate is extracted from large rock massifs (quarries) after blasting, cutting, and crushing (Zhao et al., 2020; Kumar and Yarrakula, 2022) and from riverbanks (gravel pits) (Colas et al., 2021). In both cases, natural environments and local habitats are affected and the visual impact is disturbing (Drew et al., 2002). On the other hand, cement production implies high levels of atmospheric emissions of CO_2, in so far as an approximate estimate is that the production of one ton of cement will emit between 0.9 and 1 ton of CO_2 (He et al., 2022). Assuming that 1 m^3 of concrete will typically have a cement content of between 300 kg/m^3 and 320 kg/m^3, then the atmospheric emissions per cubic meter of concrete in relation to cement alone will on average amount to 300 kg of CO_2 *per* cubic meter of concrete, without factoring in the greenhouse-gas emissions due to concrete manufacture and transport (Zhang et al., 2022).

In one of the most formidable research challenges within the civil-engineering sector, the search to increase the sustainability of concrete manufacturing sets out to counter the high carbon emissions of concrete manufacturing (Alberto López Ruiz et al., 2022). Different waste streams that are used to produce green concretes of lower environment impact, yet with comparable behaviors to conventional concrete, have been researched mainly throughout the 21st century (Pellegrino et al., 2019; Martínez-Lage et al., 2020). An approach to sustainability that also has the advantage of recovering the waste streams rather than dumping waste in ever larger landfill sites (Hoang et al., 2022), as long as proper waste management is essential to maximize the use of waste in concrete (Yazdani et al., 2021).

However, concrete must be properly designed for the above strategy to be successful, *i.e.*, using the correct content of recycled material and adjusting the proportions of all other components accordingly (Pellegrino et al., 2019). Thus, for example, it has been found that when steel slag is used as aggregate, it is advisable to increase the fines content within the mix, so as to compensate for the high density of that aggregate and the difficulty of the fresh mix evenly dragging the heavier aggregate particles within it (Santamaría et al., 2017). Similarly, the use of recycled concrete aggregate leads to the need to increase the water content of concrete to compensate for its higher water-absorption levels (Xiong et al., 2021). The high fineness of ground granulated blast furnace slag when used as a binder in substitution of ordinary Portland cement leads to the need to reduce the coarse-aggregate content, thereby ensuring adequate workability (Revilla-Cuesta et al., 2022b). The densification of silica fume requires the use of a staged mixing process when manufacturing concrete to ensure its proper hydration and uniform distribution within the concrete mix (Pedro et al., 2018). Finally, the content of fly ash should always be precisely defined, so that the concrete is valid for common building applications despite the reduction in compressive strength that it causes (Etxeberria, 2021). In fact, a proper mix design allows even designing special concrete types with a wide range of wastes (Toghroli et al., 2018; Shariati et al., 2019; Sandhu and Siddique, 2022).

Fiber-reinforced concrete contains fibers that bridge the concrete matrix, adding to its compressive strength, and cement content can, in some cases, be reduced (Lämmlein et al., 2021). Nevertheless, the bridging effect of the fibers mainly increases the tensile and flexural strength of the concrete and provides post-cracking toughness (Amran et al., 2022). Furthermore, the fibers act as rigid elements embedded in the cementitious matrix, thereby reducing concrete shrinkage (Ortega-López et al., 2022). However, some disadvantages are associated with the use of fibers. On the one hand, their uniform distribution in the concrete mass is hard to achieve, so it is generally necessary to use multi-stage mixing processes to ensure it (Jiang et al., 2022). On the other hand, the fibers hinder the flow of the aggregate particles in the fresh state, which reduces concrete workability (Li and Kim, 2019). However, it should be noted that, once properly designed and mixed, a fiber-reinforced self-compacting concrete may even be developed with high-density aggregates such as steel slags (Qasrawi, 2020; Ortega-López et al., 2022). A further step in recent research into the sustainability of fiber-reinforced concrete has been to propose the use of recycled fibers rather than standard steel or polypropylene fibers (Gu and Ozbakkaloglu, 2016). Thus, there is research on the use of steel fibers from waste tires (Aiello et al., 2009), recycled synthetic fibers (Frhaan et al., 2022), basalt fibers (Zheng et al., 2021), and even recycled carpet fibers (Ahmed et al., 2021), and recycled polypropylene fibers from COVID-19 single-use face masks (Kilmartin-Lynch et al., 2021). The feasibility of their joint used with sustainable aggregates has also been addressed (Toghroli et al., 2020). The key research point to be defined is the optimum content and the intended use of each type of fiber (Ahmed et al., 2021).

It may be noted that the use of any sustainable aggregate or fiber in concrete requires detailed characterizations and, as said, the definition of a proper concrete mix design and mixing process. Both can be adjusted to optimize the properties of the sustainable raw material (waste/by-product) while, at least partially, compensating the negative aspects. Those first steps were considered before the non-selective crushing of wind-turbine blades was addressed to produce aggregate and fiber residues for inclusion in concrete mixes.

3. Current situation of the wind-energy sector. Recycling need of wind-turbine blades

The wind-energy sector is one of the main sources of electricity production in the world, with an installed power of 743 GW (WWEA, 2022). Its widespread use is mainly due to two reasons. On the one hand, its high sustainability, as the second least polluting renewable energy, emitting only 12 g CO_2-eq/kWh, behind only hydroelectric energy (Moomaw et al., 2011). On the other hand, the generation of electricity at affordable prices, between 0.03 €/kWh and 0.08 €/kWh (WE, 2022). The main producers of wind energy in the world are, in this order, China, the United States, Germany, India and Spain (WWEA, 2022). Spain's fifth position, with an installed capacity of 25 GW in 2020, is due to its firm commitment to wind energy, in view of the steady wind currents over its mountainous terrain and northern and southern mesetas (AEE, 2022).

The first wind farms were built at the end of the 20th century in those countries that initially opted for this type of energy. However, it was not until the beginning of the 21st century that wind energy was definitively consolidated, at which point the installation of wind turbines steadily rose (WE, 2022). As shown in Fig. 1a, wind energy was pioneered in Spain where the first wind turbines date back to 1998. Since that time, the installed power and the number of wind turbines continuously increased until 2012, at which point the creation of new wind farms stopped, due to the reduction of new sites suitable for their installation (AEE, 2022). At this point, Spain decided to opt for a regenerative wind policy, *i.e.,* increasing installed wind power by replacing aging wind turbines at the end of their useful life with more powerful ones (AEE, 2022).

The useful life of a wind turbine is approximately 25 years, according to wind-energy sector experts (AEE, 2022). This useful life is possible thanks to the development of advanced procedures and algorithms for the prediction of the performance of the wind turbines in the design stage (Shariati et al., 2021) and for their structural and vibration monitoring when in service (Katebi et al., 2020). Nevertheless, given the state of aging of wind turbines within various Spanish regions, a high number of wind turbines will have to be dismantled in forthcoming years. As detailed in Fig. 1b, around 1000 wind turbines and a maximum estimate of around 2500 wind turbines are set to be dismantled in 2023 and in 2029, respectively (AEE, 2022; WE, 2022). This situation is occurring simultaneously in other countries where this type of energy has been pioneered such as Denmark and Germany, and will inevitably occur in the future in other countries with high installed wind power but with newer wind turbines, as shown for the case of Europe in Fig. 1c (Sommer and Walther, 2021).

Undoubtedly, dismantled wind turbines will have to be recycled, thus complying with the regulatory and social requirement of sustainability and circular economy (Beauson et al., 2022). The recycling of a wind turbine is divided into parts. Its metallic tower and nacelle can easily find a second life (Zhao et al., 2023). The concrete foundation can be reused and enlarged for a new wind turbine and demolished to obtain aggregate for concrete (Etxeberria, 2021). However, wind-farm-management companies are grappling with the main question of how to approach the decommissioning of wind-turbine blades, as there are various options for their recycling, though many are still at a research stage (Leon, 2023), due to the complex composition of a wind-turbine blade, in which composites, polymers and even wood can be found (Fonte and Xydis, 2021).

Scientific research is therefore ongoing within this area. One approach under study is to subject the wind-turbine blade to different treatments such as solvolysis, pyrolysis, or gasification, in order to separate its different components, thereby giving them a second life (Rani et al., 2021). However, the cost of these processes is high, approximately €540 per ton of waste, and their sustainability in terms of gas emissions is questionable (Fonte and Xydis, 2021). Other researchers have experimented with selective mechanical cutting to separate the different components (Beauson et al., 2022). Once separated and cut, the different components can either be cut again into smaller regular-shaped pieces (Yazdanbakhsh et al., 2018) or crushed to obtain fibers (Rahimizadeh et al., 2020). Both components can be used either as sustainable aggregates or as sustainable fibers in concrete production, respectively, the very few available studies offering promising results (Yazdanbakhsh et al., 2018; Pławecka et al., 2021; Xu et al., 2022). However, selective cutting is problematic, in so far as it has to be adjusted to the varying composition and component distributions of each blade (Rani et al., 2021). The crushing of the fragments obtained from the non-selective cutting of wind-turbine blades and the use of the resulting waste material in concrete has also been addressed in the scientific literature (Baturkin et al., 2021). However, it has been conducted with little depth and without establishing a systematic crushing process to obtain concrete with adequate behavior when adding this waste.

Hence, the approach of this research is to process wind-turbine blades through mechanical grinding, so that the resulting residue may be used as an addition in concrete mixes. It involves minimum economic and energetic costs and no thermal or chemical treatment whatsoever. In addition, non-selective cutting and crushing of blades, *i.e.*, with no previous separation of components, offers a very fast and low-cost pretreatment that may easily be standardized. The residue, referred to here as Raw-Crushed Wind-Turbine Blade (RCWTB), is an integral mix of all the components of the particular wind-turbine blade (glass/carbon fibers, wood, plastics and resins). Thus, the novelty of this research is to conduct a first approach on the suitability of using in concrete the material obtained from the joint crushing of all the components of the wind-

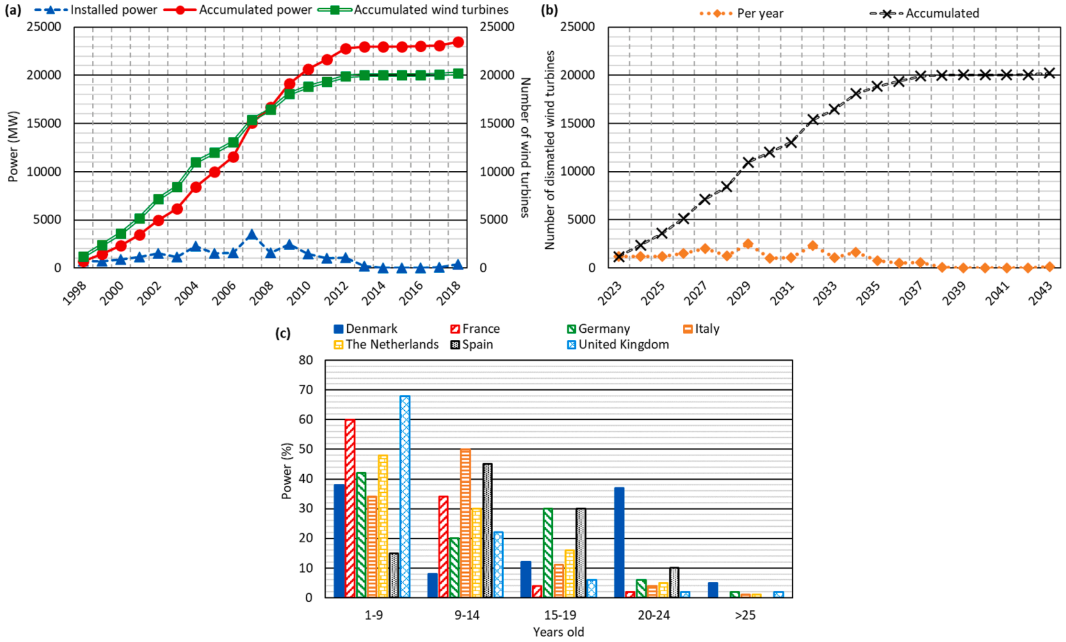

Fig. 1. Situation of the wind-energy sector (AEE, 2022; WE, 2022): (a) evolution of wind-energy sector in Spain over recent years; (b) number of wind turbines to be dismantled in Spain over forthcoming years; (c) age of wind turbines within the main European wind-power-generating countries.

turbine blade, without separating them from each other.

4. Production and characterization of Raw-Crushed Wind-Turbine Blade (RCWTB)

4.1. Waste production

Wind-turbine blades are designed by aeronautical engineers to offer minimal wind resistance, so that the wind can rotate the blades with minimal effort (Haselbach et al., 2022). The first wind turbines that were installed had 20-to-35 m-long blades and weighed between 1.2 and 2 tons. It is this type of blade, under study in this paper, that will be dismantled and recycled in Spain up until 2030 (AEE, 2022; WE, 2022). An example is shown in Fig. 2a. However, it should be noted that, over time, the power of wind turbines and their blade lengths have been increasing. Blade lengths of 55 m or more are now quite common.

The wind-turbine blades analyzed in the present study have a circular or slightly elliptical section (Fig. 2b) through which they are joined to the nacelle, generally with a bolted joint. This metallic area can be recycled in the same way as any metal (Zhao et al., 2023). The blade section becomes slimmer until it assumes an aerodynamic shape; a representative section profile of a wind-turbine blade is shown in Fig. 2c. This profile basically consists of a thin side wall, joined by transverse stiffeners that prevent both lateral and local buckling (Haselbach et al., 2022). The section decreases as it approaches the tip, since the stresses it must withstand due to wind action are progressively lower. Towards the end, the section becomes narrower, and the side wall becomes thinner.

Except for the metallic circular joint with the nacelle, wind-turbine blades are basically composed of a composite made of glass and carbon fibers and polymeric resins that provide mechanical resistance to stress. Light-weight balsa wood and polyurethane also increase bending strength, and indirectly allow reducing the weight of the blade. Moreover, a surface coating resin (Joustra et al., 2021) and, in some cases, PVC stiffeners are used (Joustra et al., 2021). Parts of the blade section may be formed by only one of these components in the case of a section close to the tip, where the side wall is very thin, as shown in the scheme of Fig. 2c. However, in those areas where the side wall of the blade requires greater thickness, it is made up of sandwich panels (right of the Fig. 2c), in which the composite is interspersed with balsa wood and polyurethane, which increases bending strength and lightens the whole structure. These areas are the largest and the most common in any type of blade (Joustra et al., 2021).

In this study, sandwich panels located in the central part of a wind-turbine blade close to the stiffeners were cut and crushed. The central area of the blade was chosen, because it has sandwich panels with a high composite content. The idea was to analyze a material with all the components, in order to evaluate the waste obtained through a non-selective cutting process while at the same time taking advantage of

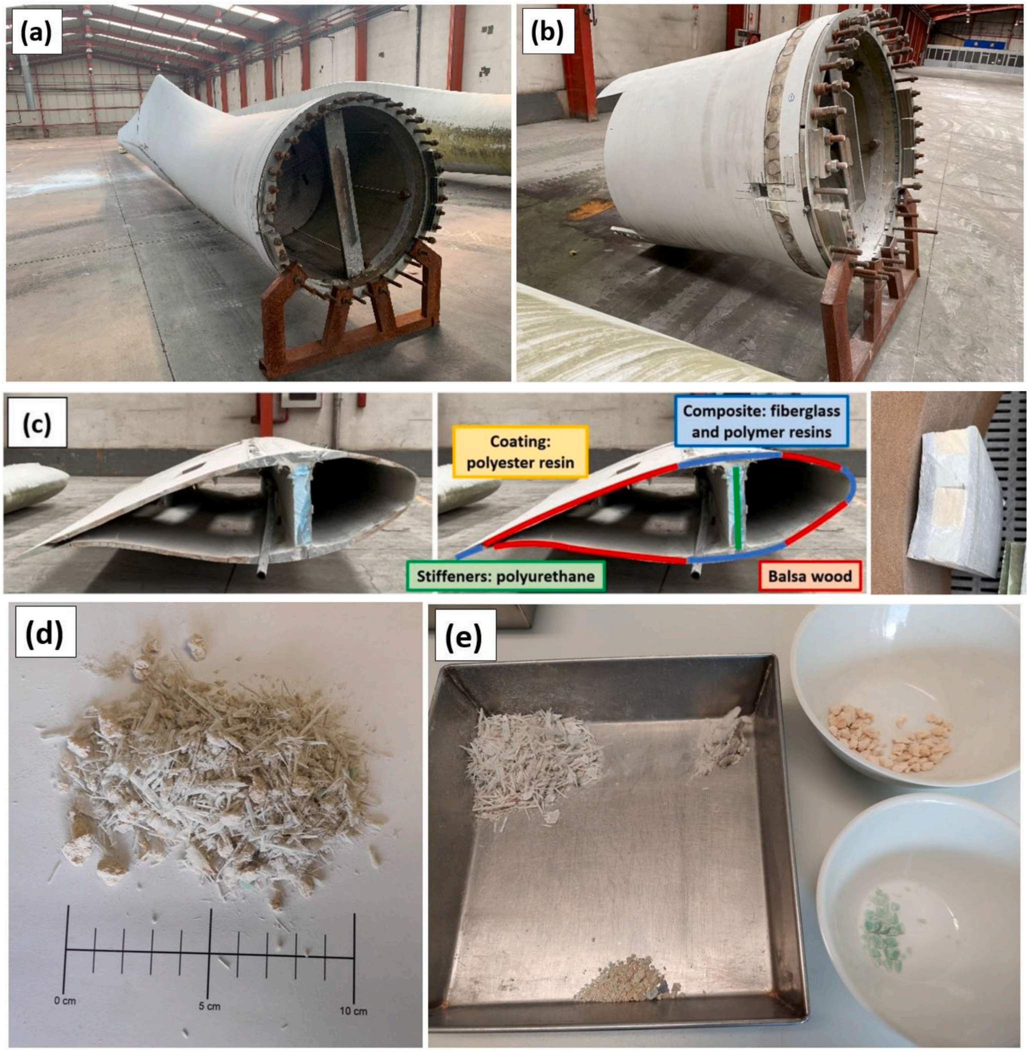

Fig. 2. Wind-turbine blade: (a) general view, (b) starting section with metal joint; (c) generic section with component identification; (d) material resulting from the crushing of the wind-turbine blade, i.e., RCWTB; (e) separate components of RCWTB.

the composite, the most beneficial material for concrete behavior from a mechanical approach. For other cement-based materials, the predominance of the content of balsa wood or polyurethane could be beneficial (Kuznetsova and Seleznev, 2023).

The production process consisted of the non-selective cutting of the sandwich panels (between 20 × 20 cm and 30 × 30 cm) -*i.e.*, without separating composite, wood, and polyurethane- their crushing and sieving. The blade was first cut into 1-m long pieces as soon as it was removed from the wind turbine, which were then transported to a suitable warehouse for a second cut, thus obtaining the sandwich panels for crushing. This solution was considered the most suitable in terms of transport and ease of operation in agreement with collaborating companies. Subsequently, a knife mill commonly used for plastic crushing was adjusted to produce fragments between 5 and 15 mm in size. Subsequently, the material was sieved and once again crushed whenever larger than 10 mm. The composite was disaggregated in the form of fibers during this process, while obtaining approximately spherical particles of polyurethane and balsa wood. The resulting material, RCWTB, is shown in Fig. 2d. The energy consumption during the whole process (cutting, crushing and screening) was estimated at 1.23 kWh/t, considering the power of the machines, their time of use and the amount of RCWTB produced. This energy consumption was approximately 0.50 kWh/t lower than the usual energy consumption in a quarry for crushed-aggregate production (Petit et al., 2018). This simple recycling treatment of wind-turbine blades would simply require the correct location of the crushing plants within the waste-management chain currently existing in the wind-energy sector.

4.2. *Characterization and physical properties of RCWTB*

Having obtained the RCWTB, the next step was to perform its physical characterization. For this purpose, its saturated-surface-dry density was measured with a pycnometer, both the whole residue and its separate components, as well as its overall bulk density was measured with the volumetric method. The EN 1097-6 and EN 1097-3 (EN-Euronorm, 2023) standards were used as a reference, which contain specific measurement procedures to test each property in aggregates. In addition, the residue composition was determined after mechanical separation, and sieving and weighing, and so too were the length, equivalent diameter and tensile strength of the fibers. Average fiber length was determined by averaging the length measured by caliper of three groups of at least 100 fibers obtained from the total set by quartering. Average equivalent diameter was calculated by defining a circular cross-section with the same area as their actual cross-section for the fibers of those three groups. Finally, the tensile strength was determined on some fibers by applying a pull at a rate of 5 kN/s until failure. All these properties, shown in Table 1, were recorded with the objective of defining the suitability of this material for concrete production.

In relation to the whole material, a real density of approximately 1.6 kg/dm^3 was obtained, similar to the value of a lightweight aggregate, as conventional aggregate exhibits a density of around 2.4–2.5 kg/dm^3 (Etxeberria, 2021). Staged mixing processes were therefore used to achieve adequate component distribution within the concrete mass (Mazian et al., 2022). This type of mixing is also common when fibers are added after all other components have formed a homogeneous mixture towards the end of mixing (Ortega-López et al., 2022). The very low bulk density, at around 0.25 t/m^3, reflects the spongy nature of the RCWTB, a small mass of which occupies a large volume, making it costly to transport. It would therefore be a suitable material for use in concrete production near the point of crushing, as in precast-concrete applications (Revilla-Cuesta et al., 2022a).

Five components were identified after a detailed analysis of the material (Fig. 2e): fibers, polyurethane, balsa wood, micro-fibers, and small non-separable particles. In percentages by weight, fibers and micro-fibers were the most abundant elements, also due to their higher density. These two components came from the crushing of the fiberglass composite. The fibers had an average length of about 13 mm and an equivalent diameter of 0.73 mm, values that are similar to some commercial micro-fibers used in concrete with a length of 13 mm (Ortega et al., 2022). Their tensile strength was around 270 MPa. The micro-fibers were thread-like, agglomerating in forms that could be called "fluffs". These micro-fibers comprised part of the fiberglass that had disintegrated and the coating gel. Balsa wood and polyurethane were found in the form of approximately spherical brown or green particles with an average size of 5 mm. The most remarkable aspect was the low density of the balsa wood, which justifies its use as a light-weight material in the manufacture of the wind-turbine blades (Joustra et al., 2021). Finally, the so-called non-separable small particles were such small fragments of polyurethane, fiberglass, and mainly balsa wood that their mechanical separation was impossible. Overall, the physical characterization of the RCWTB confirmed its dual composition of both fibers and particles, which may be used in concrete as fibers and as aggregate, respectively. These aspects should be considered when designing concretes with RCWTB.

4.3. *Scanning Electron Microscope (SEM) analysis*

The micro-structural analysis of the RCWTB was performed with Scanning Electron Microscopy (SEM) and its elemental chemical composition was determined with Energy-Dispersive X-ray (EDX) spectroscopy. Fig. 3 shows SEM images and EDX spectra for the fibers, wood, and polyurethane. The chemical composition of balsa good and polyurethane (Fig. 3f and i) was clearly organic based, with a predominance of carbon and oxygen. The fibers were fragments of the fiberglass composite, so they had a composition based on carbon and oxygen, from the polymeric resins of this composite, and silica, the basic component of glass (Fig. 3c).

The fibers (Fig. 3a and b) presented the typical appearance of a fiberglass composite formed of thread-like fibers bonded together with a polymer resin. However, it was observed that this composite had been crushed in two aspects. On the one hand, the ends of the fibers were not regular, but in general had an irregular shape (left of Fig. 3a). On the other hand, in some areas the fiberglass was covered by a thick layer of polymer resin, as can be seen in the upper part of Fig. 3b. Both aspects, rather than negative points, were considered to increase fiber roughness and thereby improve fiber adhesion within the cementitious matrix, as

Table 1
Properties of RCWTB.

	Real density (kg/dm^3)	Apparent density (kg/m^3)	Composition (% wt.)	Length (mm)	Equivalent diameter (mm)	Tensile strength (MPa)
Overall	1.63±0.03	246.64±12.20	–	–	–	–
Fibers	2.04±0.05 *	–	66.8±3.1	13.07±4.66	0.73±0.14	270±3
Polyurethane		–	8.3±0.3	–	–	–
Balsa wood	0.33±0.02	–	6.3±0.2	–	–	–
Micro-fibers	–	–	13.8±0.5	–	–	–
Small non-separable particles	–	–	4.8±0.4	–	–	–

* Density measured in both components, fibers, and polyurethane, together.

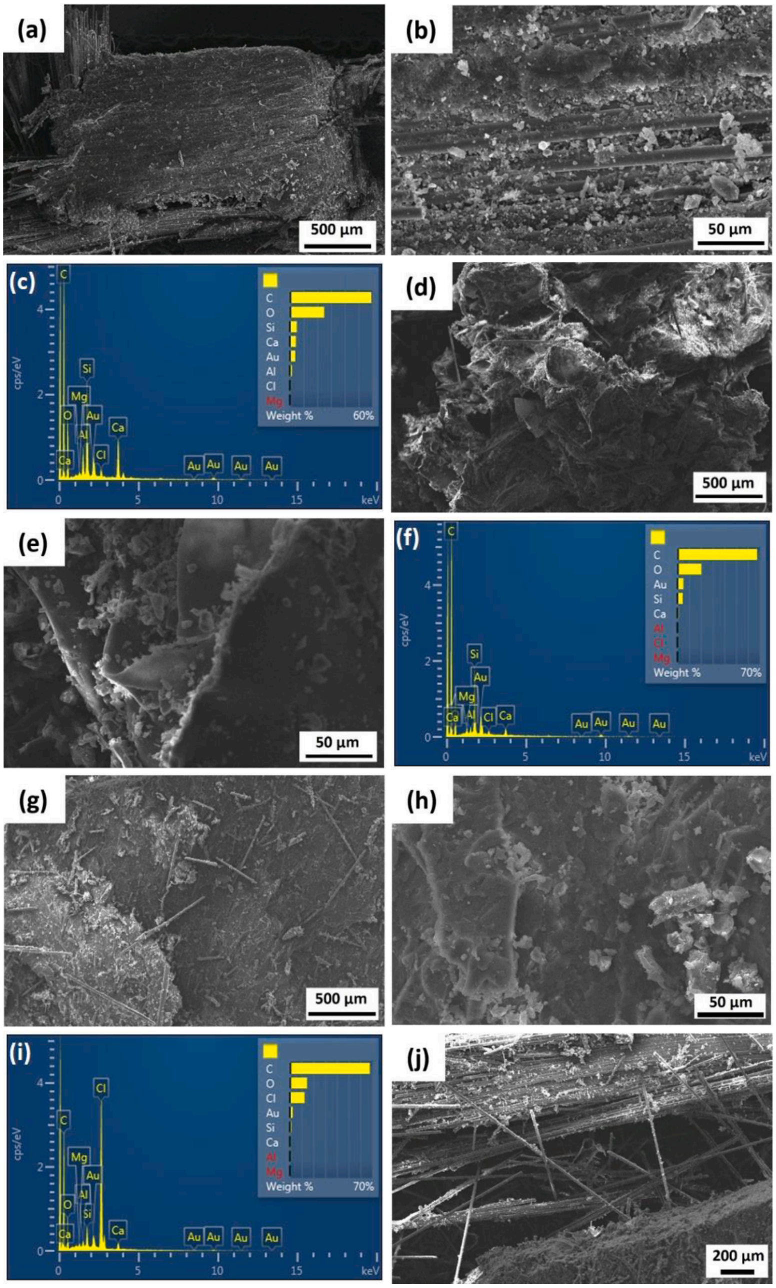

Fig. 3. SEM images and EDX spectra of RCWTB: (a–c) fibers; (d–f) balsa wood; (g–i) polyurethane; (j) micro-fibers.

conventional fibers, which usually exhibit a rough surface (Frhaan et al., 2022). The elimination of the polymer resin in some cases led to the glass fibers not being bonded to each other, thus resulting in the so-called micro-fibers (Fig. 3j).

The balsa wood presented a very irregular surface topography (Fig. 3d), visible in numerous surface pores and a three-dimensional laminar shape with dispersed orientation (Fig. 3e). The adhesion of the balsa wood lamellae within the cementitious matrix was considered to be positive, as those protrusions embedded within the cementitious matrix slightly compensated the weak bonding of balsa wood due to its low density within the interfacial transition zone. The polyurethane (Fig. 3g and h) presented a more regular and smooth surface, its bond with the cementitious matrix being similar to that of other recycled plastics used in concrete, unable to form interfacial transition zones as dense and resistant as natural aggregates (Abdullahi et al., 2022).

5. Design of mixes with Raw-Crushed Wind-Turbine Blade (RCWTB)

A mix design and a mixing process adapted to the characteristics of the RCWTB, thus being different to those of conventional concrete, have to be defined that make its use as a raw material in concrete production effective. The aim is to achieve concrete with a uniform distribution of the RCWTB and an adequate workability. These aspects are addressed in this section.

5.1. Initial mix design

A concrete mix containing no RCWTB was initially designed as a reference and for comparative purposes, to analyze the feasibility of using RCWTB. Labelled with the letter *R* (*R*eference mix), the mix had standard design values for a concrete with average fresh and mechanical characteristics, and could therefore be considered as conventional concrete (Structural Code, 2021): 320 kg/m^3 of cement CEM II/A-L 42.5 R, according to EN 197-1 (EN-Euronorm, 2023), a water-to-cement ratio of 0.40, and a plasticizer content of 1% of the cement mass. That type of cement, frequently used within the area of the study, consisted of Portland clinker with between 6% and 20% limestone as an addition to reduce its carbon footprint (Etxeberria, 2021). On the other hand, siliceous crushed aggregate divided into three fractions (0/2 mm, 2/6 mm, and 6/22 mm) was used, with a low fines content <0.063 mm in the 0/2 mm sand fraction, so plasticizers were added to ensure adequate workability (Fuente-Alonso et al., 2017). The composition of this concrete is shown in Table 2.

Having defined the reference concrete, two concrete mixes were designed with different contents of RCWTB. In view of its characteristics, described in the previous section, the use of RCWTB was proposed as a global addition in the manufacture of concrete, adding it at a certain percentage of the mix volume. In this way, the balsa-wood and polyurethane particles could serve as aggregate substitutes, while the bridging effect of the fibers and micro-fibers could strengthen the concrete. The RCWTB was also used as an overall addition to increase mix sustainability. If the concrete composition per cubic meter is analyzed (Table 2), this way of adding the RCWTB also reduced the cement content, thus lowering the consumption of the most environmentally harmful concrete component (He et al., 2022).

It was decided to add a low content (1.5% of the mix volume) and a high content (6.0% of the mix volume) of RCWTB, thereby achieving fiber contents within the concrete that were similar to those used in other studies of the authors (Fuente-Alonso et al., 2017; Ortega-López et al., 2022). These two concrete mixtures were labelled *L* and *H*, for their *L*ow content and *H*igh content of RCWTB, respectively. In Table 2 it can also be seen that, in this initial composition, the addition of RCWTB was not accompanied by the modification of the proportion of any other component. The first objective was to define the most suitable mixing process.

5.2. *Definition of the mixing process*

Once the mix compositions had been defined, a three-stage mixing process was adopted (Fig. 4a). This mixing process was selected because of its successful use in other research on fiber-reinforced concrete by the authors (Ortega-López et al., 2022). It basically consisted of the simultaneous addition of all the components of the mixture except the RCWTB and the plasticizers, which were added at two later points when the other components had already been homogeneously mixed. A homogeneous mixture in principle will mean less likelihood of excessive interference between the movements of the different components during the slump test (Santamaría et al., 2017). As shown in Fig. 5a, mix *R* presented a slump of 6.0 cm with this mixing process, and the addition of RCWTB led to the loss of approximately 0.60 cm of slump *per* 1% of RCWTB, while the slump of mix *H* was only 2.5 cm.

In view of the very low slump values, which might imply very energetic vibrating for concrete placement (Ram Kumar and Ramakrishna, 2022), a four-stage mixing process was implemented (Fig. 4b). It was identical to the three-stage mixing process, although the aggregates and cement were separately added. This step was intended to let the aggregate absorb all the water it needed before the other components were added, so as to ensure the availability of sufficient water for a fluid cement paste within which the other components could easily be dragged (Revilla-Cuesta et al., 2022b). The slump values were increased in all the mixes when implementing this mixing process, with a slump of 9.0 cm for mix *R* and 5.5 cm for mix *H*, reaching a slump class S2, between 50 and 90 mm according to EN 206 (EN-Euronorm, 2023), in all cases. However, the slump loss was very similar to the one in the three-stage mixing process, 0.63 cm *per* 1% of RCWTB (Fig. 5a). It was thought that although this mixing process increased the overall workability, the distribution of the RCWTB was still not completely homogeneous within the concrete mass, so that it interfered with the dragging of some aggregate particles (Ahmed et al., 2021).

A third mixing process consisting of five stages was introduced, to achieve a more homogeneous distribution of the RCWTB fibers in the concrete mass (Fig. 4c). This process was almost identical to the four-stage mixing process, except for the addition of the plasticizers in two equal parts, before and after the addition of the RCWTB. The addition of the first half of the plasticizer was to obtain a more fluid cement paste that would allow a more homogeneous distribution of the RCWTB when added, while the second half sought to compensate for the decrease in workability caused by the addition of the waste. For mixes *R* and *L*, with low contents of RCWTB, the slump increase was very small with respect to the previous mixing process, although the slump increase of mix *H* was 3 cm, *i.e.*, 54% (Fig. 5a), because the slump loss was only 0.25 cm *per* 1% of residue. The slump loss reported in other studies on fiber additions (Fuente-Alonso et al., 2017; Frhaan et al., 2022) was similar and was considered adequate as a concrete with a slump class S2 was obtained when using high contents of RCWTB. A five-stage mixing process, quite different from that used in conventional concrete, was therefore recommended to maximize the workability of the concrete produced with this waste by reaching a uniform distribution of RCWTB in the concrete mass.

5.3. *Adjustment of water and plasticizer content*

Having defined a suitable mixing process, it was possible to achieve a slump class S2 with the addition of 6.0% of RCWTB. However, this workability level was insufficient for some applications (Revilla-Cuesta et al., 2022a). It was therefore decided to look for a procedure to increase the workability of the concrete to a slump class S3 according to EN 206 (EN-Euronorm, 2023), *i.e.*, a slump between 100 and 150 mm, which is a widely accepted workability level in practice (Structural Code, 2021).

The search for this increase in workability was experimentally conducted through trial mixes in which the proportion of some concrete components were modified, while maintaining the pre-defined five-stage mixing process (Fig. 4c). At the same time, steps were taken so that

Table 2
Composition of concrete mixes.

	Definition of the mixing process						Adjustment of the content of water and plasticizers					
	Comparative			kg/m^3			Comparative			kg/m^3		
	R	L	H	R	L	H	R	L	H	R	L	H
Cement	320	320	320	318	314	300	320	320	320	318	312	295
Water	128	128	128	127	125	120	128	133	146	127	129	134
Plasticizer 1	2.20	2.20	2.20	2.19	2.16	2.07	2.20	2.62	3.88	2.19	2.56	3.57
Plasticizer 2	1.10	1.10	1.10	1.09	1.08	1.03	1.10	1.31	1.94	1.09	1.28	1.79
Sand 0/2 mm	500	500	500	497	490	469	500	500	500	497	488	461
Fine gravel 2/6 mm	600	600	600	597	588	563	600	600	600	597	585	553
Coarse gravel 6/22 mm	900	900	900	895	882	845	900	900	900	895	878	829
Raw-crushed wind-turbine blade	0.0	24.5	98.0	0.0	24.0	92.0	0.0	24.5	98.0	0.0	24.0	90.0
Volume (liters)	1005	1020	1065	1000	1000	1000	1005	1025	1086	1000	1000	1000

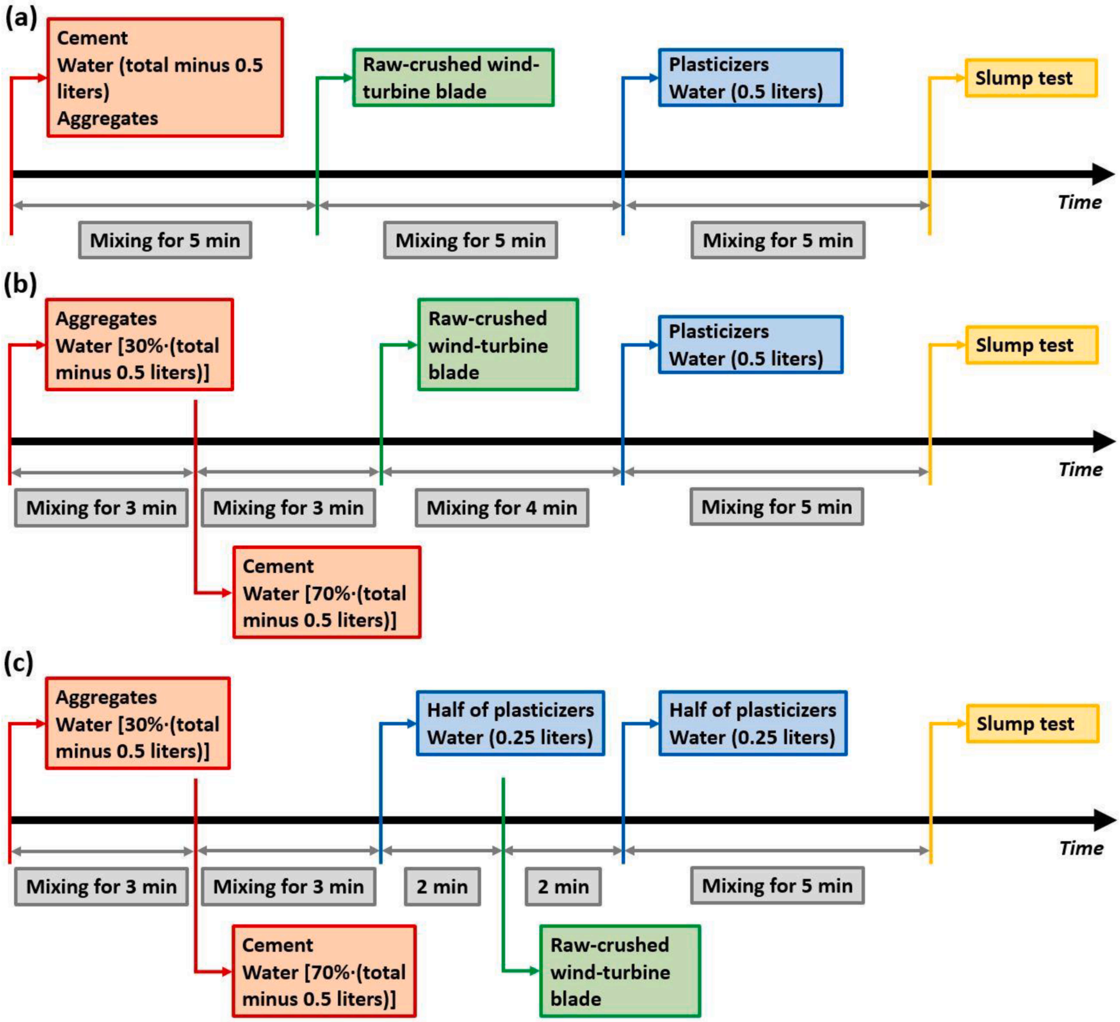

Fig. 4. Mixing processes: (a) three-stage mixing process; (b) four-stage mixing process; (c) five-stage mixing process.

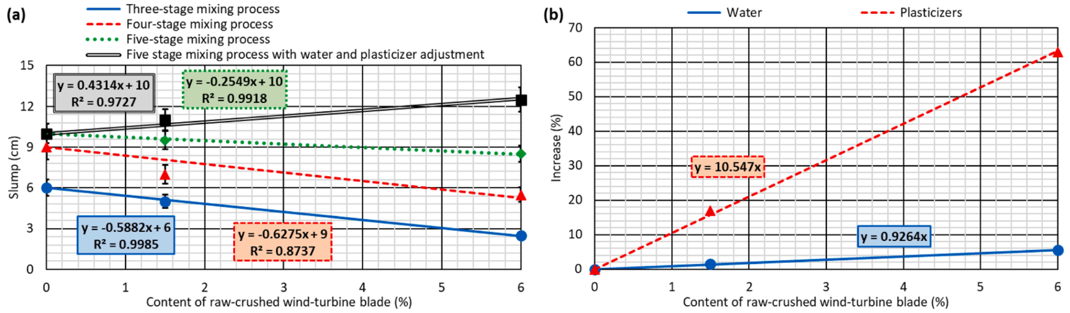

Fig. 5. Fresh performance of concrete mixes with RCWTB: (a) slump; (b) water and plasticizer adjustment.

the modification of any other component had no effect on the expected decrease in concrete strength, due to the addition of RCWTB. After various attempts, it was found that the simultaneous increase of the content of water and plasticizer was the most suitable solution. Thus, as shown in Fig. 5b, the water and plasticizer content of the concrete mix was increased by 0.93% and 10.55% *per* 1% of residue, respectively, for the production of 1 m^3 of concrete. The composition of the mixes after adjustment for water and plasticizer is shown in Table 2. The plasticizer content was increased more than the water content because the increase in water content resulted in segregations and negatively affected the mechanical strength.

Mix *H*, with 6.0% of RCWTB, had a water-to-cement ratio of 0.45 and a plasticizer content of 1.82% in the cement mass (Table 2), which recorded the mean slump value of slump class S3: 12.5 cm. In addition, these dosage adjustments led to a slump increase of 0.43 cm for each 1% of RCWTB, thus ensuring that the addition of this waste did not negatively affect concrete workability. As regards other waste types, the definition of an adequate content of water and admixtures and an adapted mixing process are key to reach a suitable fresh performance, aspects that should be simultaneously considered when producing concrete with that residue (Nepomuceno et al., 2018; Pellegrino et al., 2019). However, further research is needed on the validity of these procedures for RCWTB concrete production at industrial volumes, as the scale change may result in slight variations in performance (Revilla-Cuesta et al., 2022a).

6. Compressive behavior and carbon footprint of concrete with Raw-Crushed Wind-Turbine Blade (RCWTB)

Once the final composition of the concrete mixes with RCWTB and the five-stage mixing process for their manufacture had been defined, three 10 × 20 cm cylindrical specimens of each mix were prepared to determine their 28-day compressive strength according to EN 12390-3 (EN-Euronorm, 2023). In addition, the load and the longitudinal strain of the specimens during this test were continuously recorded using a load cell and strain gauges, thus obtaining the stress-strain curves under compression. The objective of these tests was to perform a first evaluation of the strength and deformational behavior of the concrete made with this waste. In addition, the carbon footprint of all the mixtures was determined from the sum of the partial carbon footprints of their components, which are available in other studies in the literature (Hossain et al., 2016; Yang et al., 2019), suitably weighted according to the composition of the concrete, as explained in other researches of the authors (Revilla-Cuesta et al., 2021). In this way, the sustainability of the mixes was also estimated. From these tests, it was intended to evaluate the suitability of the addition of RCWTB to concrete. All the results are shown in Fig. 6.

Regarding the compressive strength of the mixes (Fig. 6a), reference conventional-concrete mix *R* presented a compressive strength of 52.3 MPa, adequate for most application types. This strength was practically identical to that of mix *L*, which showed that the bridging effect of the fibers and micro-fibers (Garcia-Llona et al., 2022) compensated the decrease in strength due to the small reduction of 6 kg/m^3 of cement and the increase of the water-to-cement ratio to 0.41, following the addition of 1.5% of RCWTB. However, the addition of 6.0% of RCWTB led to a strength decrease of 20.4%, losing approximately 4.53% compressive strength *per* 1% of added residue as from a residue content of 1.5% (Fig. 6b). One explanation is the decrease in cement content and the increase in the water-cement ratio, with values of 295 kg/m^3 and 0.45 (Table 2), respectively, for mix *H* (Ortega-López et al., 2022). Another possibility is that this strength loss was due to the lower adhesion of the polyurethane and balsa-wood particles to the cementitious matrix compared to natural aggregate (Gu and Ozbakkaloglu, 2016). However, the favorable effect of the fibers within the residue, which bridged the cementitious matrix and therefore lessened the strength decrease rather more than had been expected, should also be noted (Yazdanbakhsh et al., 2018; Baturkin et al., 2021).

In terms of deformability under compression, the analysis of the stress-strain curves (Fig. 6c) showed that the addition of RCWTB increased the deformability and the load-bearing capacity of concrete. The modulus of elasticity decreased by around 27% when adding 6% RCWTB regarding the reference concrete mix. Furthermore, while mix *R* containing 0.0% of RCWTB underwent abrupt failure under a breaking load, recording strain levels of 1800 με, mix *H* withstood external stress and recorded strain levels of around 600 με, after reaching strain levels of around 2500 με when it broke. It is clear that the fibers and micro-fibers contained in this residue adhered well to the cementitious matrix, bridging the cracks in such a way that the concrete could still withstand some load after failure and almost doubling the maximum strain levels it experienced, which are among the main objectives of fiber-reinforced concrete (Li and Kim, 2019; Ahmed et al., 2021). Overall, the suitability of RCWTB concrete for common structural building applications can be accepted from this first approach to its strength and deformational behavior under compression (Mohammadhassani et al., 2013; Structural Code, 2021), although further research is needed.

Finally, the addition of RCWTB led to a 1.21% decrease in the carbon footprint *per* 1% of residue (Fig. 6b). So, the carbon footprints of mix *R* and mix *H* were estimated at 306.7 kg CO$_2$ eq/m^3 and at 284.5 kg CO$_2$ eq/m^3, respectively (Fig. 6a). A decrease that was mainly due to the reduction in cement content derived from the use of the RCWTB as an overall addition (Hossain et al., 2016; Sandhu and Siddique, 2022), which was aimed at the fibers in the RCWTB to provide part of the strength lost due to the decrease in cement content. Thus, the solution described in this paper is not only good for providing a solution for the recycling of wind-turbine blades, but also for increasing the sustainability of concrete, which is a priority in the construction sector (Pellegrino et al., 2019). Finally, it should be noted that reducing the cement content could lead to a reduction of the cost of concrete.

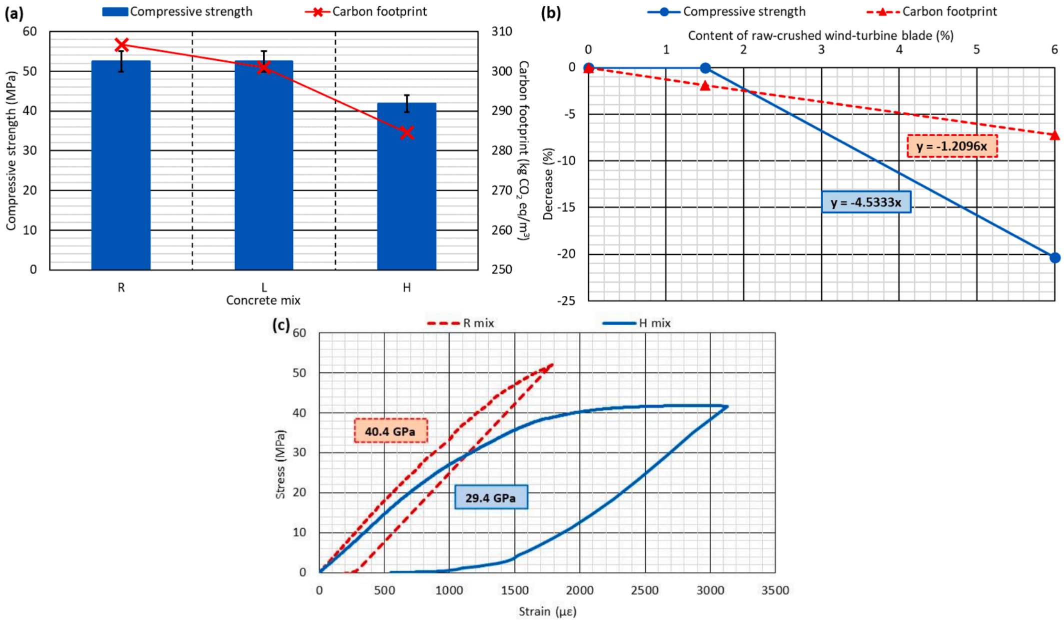

Fig. 6. Hardened behavior and carbon footprint of concrete mixes: (a) values of compressive strength and carbon footprint; (b) evolution trends of compressive strength and carbon footprint; (c) stress-strain curves under compression (the numbers are the moduli of elasticity of the mixes).

7. Conclusions

There is currently a pressing need to find a solution for the recycling of end-of life wind-turbine blades, since the first wind-turbine installations towards the end of the 20th century are nearing the end of their estimated 25-year useful life. A preliminary study has been performed of viable approaches towards the recycling of this waste as a raw material in concrete production. A procedure has been designed to manufacture suitable concrete mixtures with this waste, assessing its workability, mechanical strength and overall sustainability. The key aspect of the research has been the simplification of waste pretreatment, proposing an inexpensive, rapid, and low-technical pre-treatment valid for any type of wind-turbine blade. It consisted of the non-selective cutting of the blade wall and crushing and sieving of the panels, until a residue was obtained consisting of all the blade components, which it is referred to as Raw-Crushed Wind-Turbine Blade (RCWTB).

The study of the highly spongy final material, RCWTB, presented a real global density of about 1.6 kg/m^3, similar to that of a lightweight aggregate, and a bulk density of 0.25 t/m^3. This material was composed of glass fibers bonded by a polymeric resin, micro-fibers, *i.e.*, individual thread-like glass fibers, and spherical particles of polyurethane and balsa wood, the latter having a remarkably high surface irregularity and low density. These components could act as fibers and aggregate in the concrete, respectively.

Based on the characteristics of the processed residue, its most advantageous form of use in concrete has been as an integral addition. However, a well-designed and customized procedure has proved key to achieve proper workability. On the one hand, a five-stage mixing process was implemented where aggregates, cement and RCWTB were added to the mix at different times. In addition, plasticizers were poured in two equal parts to achieve a uniform and homogeneous distribution of the residue within the concrete mass. On the other hand, increasing the content of water and plasticizer by 0.93% and 10.55%, respectively, *per* 1% of RCWTB, was also necessary. With both measures, slump flows between 100 and 150 mm were achieved with up to 6% of RCWTB, within slump class S3 according to EN 206 (EN-Euronorm, 2023).

The analysis of the compressive behavior of the mixtures showed that the compressive strength of the concrete was maintained with the use of small percentages of RCWTB, even though compressive strength decreased by 4.53% *per* 1% of added residue at higher contents. However, adequate compressive-strength levels for using RCWTB concrete in building applications were achieved. In contrast, the deformability and load-bearing capacity of the concrete increased, due to the bridging effect of the fibers within the RCWTB. A decrease in cement content was possible thanks to the use of RCWTB as an overall addition, which led to a reduction in the carbon footprint of 1.21% for every 1% of residue, and expected economic savings.

Overall, it has been concluded that the incorporation of RCWTB in concrete mixes was beneficial for the load-bearing capacity of the resulting concrete that also presented adequate workability and compressive strength. Moreover, the sustainability associated with recycling turbine-blades is applicable not only to the concrete industry, but also to the wind-energy sector, promoting circular economy and overall sustainability on it. Further research into the behavior of concrete containing this sort of recycled waste will therefore be of interest. Thus, the first step of the future research should be to evaluate the complete mechanical behavior, long-term durability, fire resistance and leaching behavior of RCWTB concrete, for example, as well as its economic feasibility. Subsequently, it could be addressed the production of industrial volumes of these concrete mixes and conducting structural and pilot tests of full-scale elements made with them.

CRediT authorship contribution statement

Víctor Revilla-Cuesta: Conceptualization, Investigation, Methodology, Data curation, Formal analysis, Software, Writing – original draft, Writing – review & editing. **Marta Skaf:** Conceptualization, Investigation, Formal analysis, Project administration, Resources, Supervision, Writing – review & editing. **Vanesa Ortega-López:** Conceptualization, Methodology, Project administration, Funding acquisition, Resources, Visualization, Supervision. **Juan M. Manso:** Conceptualization, Methodology, Project administration, Funding acquisition, Resources, Visualization, Supervision.

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

Data will be made available on request.

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