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SUITABILITY OF CONCRETE PRODUCED WITH HIGH CONTENTS OF CRUSHED WIND-TURBINE BLADE

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ABSTRACT

Some of the first-installed wind turbines will have to be replaced soon, as they are approaching the end of their life span. These wind-turbine blades must be recycled, so their suitability to be added into concrete mixes as fibers is studied. Thus, a less-polluting fiber-reinforced concrete can be achieved, maintaining its mechanical behavior. To recycle numerous wind-turbine blades at an adequate rate, large amounts of waste need to be added into concrete. This study aims to find out the suitability of adding high amounts of this waste material (0% vol., 5% vol., and 10% vol.). Testing yielded a slight decrease in fresh density and a higher occluded air content, yet largely maintaining its suitability for structural use according to the compressive strength. The results showed that concrete with a high content of crushed wind-turbine blade is suitable for structural use, being it an effective solution to said current sustainability problems.

Keywords

Sustainability, concrete, high content crushed wind-turbine blade, fresh performance, compressive strength

INTRODUCTION

Concrete is one of the most used materials worldwide (GCCA, 2021). Its ability to adapt to any shape thanks to its fresh state characteristics and the new advances in formwork structures, as well as concrete's inherent compression-related mechanical properties, make for a great material to be used almost in any kind of site (ANEFHOP, 2022). Besides, concrete can be used in different ways to fulfill the required needs of any project or building. Reinforced concrete is used when the element being built will be under flexural or tensile stresses (Eurocode 2, 2010), as plain concrete is not able to resist high tensile loads by itself. Mass concrete is used when required in high volumes, and it is usually under high compressive loads or lower flexural stress (Ministry of Infrastructures, 2021), such as in pavements (Fuente-Alonso *et al.*, 2017; Hutchinson *et al.*, 1987), foundations, walls or barriers, and dams (Calavera, 2008). Another way of using concrete is by adding fibers into the mixture, resulting in fiber-reinforced concrete (FRC).

Nowadays, numerous kinds and materials of fibers are under study, having a widespread range of options of FRC to use depending on the boundary conditions (Zhao *et al.*, 2023). These fibers tend to enhance the flexural and tensile strength of the concrete when added in the correct amount, as they stitch the concrete matrix and avoid brittle fracture (Amran *et al.*, 2022). In addition, fibers also help with the effects of shrinkage (Ortega-López *et al.*, 2022), as they aid maintain the original dimensions of concrete elements and counterbalance the lengthening and shortening of the cementitious matrix. However, these fibers also tend to reduce the workability and flowability of the concrete (Revilla-Cuesta *et al.*, 2023), hindering its real-life implementation without a proper design of the mix.

Seeking exploitation of these beneficial properties of FRC, ongoing research is looking into developing more sustainable fiber materials while enhancing all mechanical properties of concrete as much as possible, without them becoming detrimental to its fresh state performance (Soltanzadeh *et al.*, 2022). Some kinds of fibers have already been studied and evaluated for longer periods of time, such as steel fibers, plastic fibers, glass fibers, natural fibers, and carbon fibers (Zhao *et al.*, 2023). Other types of fibers that are recently being under studied are recycled or sustainable fibers (Ahmed *et al.*, 2021), such as metallic fibers from used tires (Soltanzadeh *et al.*, 2022) and fibers produced from dismantled wind-turbine blades (Revilla-Cuesta *et al.*, 2023; Yazdanbakhsh *et al.*, 2017, 2018).These last ones, fibers produced from crushed dismantled wind-turbine blades, are under study in the current paper.

Some of the first installed windfarms are approaching their disassembling phase, as they are reaching the end of their expected lifespan (World Wind Energy Association, 2022). These windfarms are expected to be equipped with newer, more powerful turbines, in the manner that the wind-energy sector is becoming one of the most powerful ones, generating 15.3% of Europe’s electricity just by itself (WindEurope, 2023). Therefore, there is an increasing need to recycle these older wind turbines (Asociación Empresarial Eólica, 2022). Large amounts of turbines will be required to be recycled in the next few years, up to 2500 before 2029 (Asociación Empresarial Eólica, 2022; World Wind Energy Association, 2022), and especially their blades. Wind-turbine blades are the one of the few components of the wind turbines that are not metallic. They are made from a mixture of materials (Joustra *et al.*, 2021), such as glass or carbon fibers infused with polymeric resins, balsa wood, polyurethane, and coating resins for their surface, which create a composite material that is difficult to treat and recycle.

In the present study, to meet these recycling rate requirements, different amounts of these fibers will be added into the concrete mix in higher percentages than usual (0% vol., 5% vol. and 10% vol.) (*EHE-08: Structural Concrete Regulations.*, 2010; Eurocode 2, 2010), in order to evaluate the fresh-state performance and

compressive properties of the manufactured FRC. Cement content will remain the same throughout the mixtures, while the crushed wind-turbine blade will be added as a cement addition. These raw materials will be detailed below, as well as the mix design and the results of the experimental campaign, regarding the fresh performance (slump test, occluded air content and fresh density) and the hardened state, characterized by the compressive strength behavior.
Through the present research, it is thought to evaluate the suitability of incorporating higher-than-usual amounts of recycled fibers from crushed wind-turbine blades into the concrete mix, so adding crushed wind-turbine blade into concrete can became a feasible and sustainable option to both the concrete manufacturing industry and the wind-energy sector. Hence, resulting in an important aid towards a greener and circular economy.

MATERIALS AND METHODS

Raw Materials

The present research used CEM II/A-L 42.5 R, according to EN 197-1 (EN-Euronorm, 2020), as it does incorporate low percentages of limestone content instead of it being just clinker; regular water, and two different admixtures to ensure proper workability (EN-Euronorm, 2020).
Different siliceous and limestone aggregates were used as raw materials in the concrete mix. A limestone fine 0/2 mm sand was used, and the siliceous aggregates were of the 0/4 mm, 4/12 mm and 12/22 mm fractions. The gradation of each one the aggregates and their combined gradation can be seen in **Figure 1**.
Following EN 1097-6 (EN-Euronorm, 2020), the limestone 0/2 mm sand had a 2.62 kg/dm^3 density and 0.52% vol. 24-h water absorption. The siliceous 0/4 mm sand had a 2.63 kg/dm^3 apparent density and 0.13% vol. 24-h water absorption; the siliceous fine 4/12 mm gravel had a 2.65 kg/dm^3 apparent density and 0.33% vol. 24-h water absorption; and the siliceous coarse 12/20 mm gravel had a 2.62 kg/dm^3 apparent density and 0.55% vol. 24-h water absorption.

Raw-Crushed Wind-Turbine Bade

Finally, the crushed wind-turbine blades were added into the mix as a cement addition, in different percentages in volume while keeping the quantities of the cement constant.
The need for recycling this part of the wind turbine is increasing drastically, as the dismantling of large windfarms is taking place at a vivid pace (WindEurope, 2023). The large wind-energy companies are looking for a solution to this issue, as a widely accepted solution has not emerged yet (Leon, 2023). The recycling of wind-turbine blades is not an easy task: the composition of the blade makes it difficult to use in any other applications (Fonte and Xydis, 2021) and the actual variable cross section of the blade makes the composition of the blade change along its axis (Haselbach *et al.*, 2022).

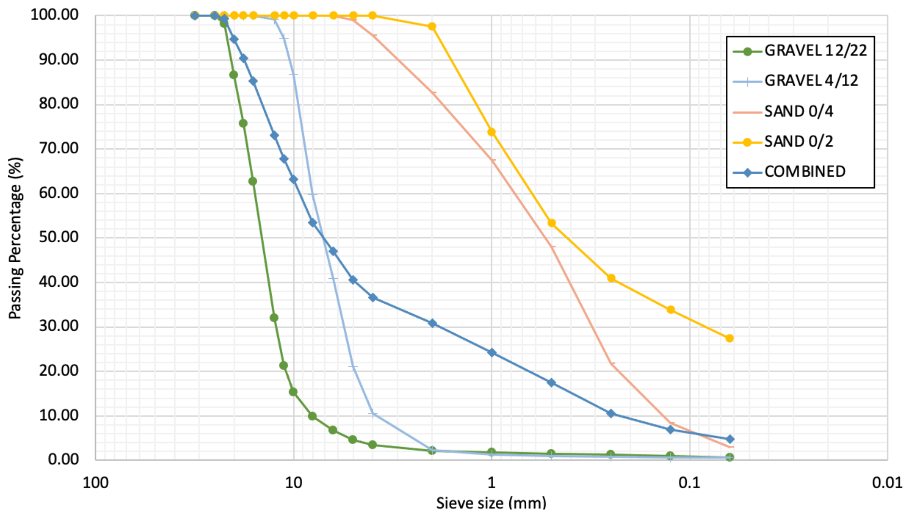

Figure 1. Aggregate gradation.

These blades that are being dismantled are made of a composite material of glass and carbon fibers mixed with polymeric resins (Joustra *et al.*, 2021) to strengthen it and make it able to bear the loads that will be suffered during its lifespan. To make the blade lighter, balsa wood and polyurethane are implemented where the loads are less demanding, in the form of sandwich panels, with resin coating in their outermost layer and PVC stiffeners where needed (Joustra *et al.*, 2021).
Authors have taken different approaches towards this issue. The use of separating processes such as solvolysis, pyrolysis or gasification (Rani *et al.*, 2021) are not cost-effective nor sustainable, as they have high costs per ton of recycled waste, they do not perform as well as expected, and they produce high amounts of greenhouse gases (Fonte and Xydis, 2021). Other option that is more sustainable and cost-effective comes from the non-selective cutting of the whole blade through knife-mills. The blade is taken down from the turbine (**Figure 2a**) and cut into smaller rectangular pieces (**Figure 2b**) that are introduced into the mills in a two-step crushing process, with an intermediate sieving of the by-product to ensure its properties, resulting in a composite material with fibers, microfibers and other non-separable particles (**Figure 2c**). This material under study is known as Raw-Crushed Wind-Turbine Blade (RCWTB) (Revilla-Cuesta *et al.*, 2023).
This RCWTB material has been physically characterized, in its most important characteristics following EN 1097-6 and EN 1097-3 (EN-Euronorm, 2020) have been studied profusely in other paper (Revilla-Cuesta *et al.*, 2023). The overall real density of RCWTB was 1.63 kg/dm^3, but its apparent density was 0.25 kg/dm^3, showing its great volume for lower mass (Revilla-Cuesta *et al.*, 2023). The composition of the RCWTB was made up from around 69% wt. of fibers with an average length of 13.07 ± 4.66 mm, showing the varying length of the crushed fibers. Then, there was an 8% wt. made of polyurethane spheres, a 6% wt. from balsa-wood spheres, and a 14% wt. of microfibers from the cutting and crushing of the pieces. Finally, there was a 5% wt. of small non-separable particles (Revilla-Cuesta *et al.*, 2023).

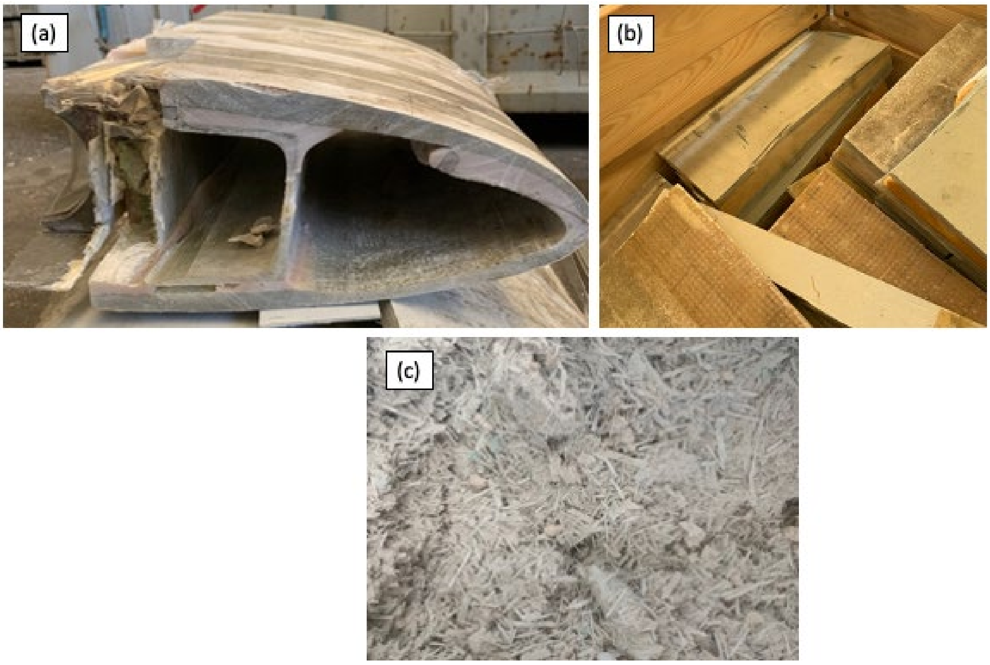

Figure 2. Raw-Crushed Wind-Turbine Blade. (a) Cross section of a blade after dismantling. (b) Regular pieces cut from the blade. (c) Fiber-like components resulting from crushing and sieving.

In order to carry out the non-selective cutting and crushing, it has been estimated that the energy cost of the whole process (machine power and duration of the operations) is 1.23 kWh per metric ton of RCWTB (Revilla-Cuesta *et al.*, 2023). At the current price of energy in Spain (0.20 €/kWh), that would result in 0.25 € per metric ton of ready-to-use RCWTB. For comparison, that is 41% cheaper than usual energy consumption for crushed aggregate production in quarry (Petit *et al.*, 2018).

Mix Design

The concrete mixture was designed to incorporate three different amounts of RCWTB. Firstly, a reference mix without RCWTB was manufactured and labelled as W0, as it had 0% vol. of RCWTB. Then, a mixture with 5% vol. (W5) and a mixture with 10% vol. (W10) of RCWTB as cement additions were made. Cement remained constant in all mixes of the resulting FRC.

Usual recommendations to structural concrete manufacturing were followed in the design (Eurocode 2, 2010; Ministry of Infrastructures, 2021). The cement content was 320 kg/m^3, the initial water/cement ratio was 0.40 and the original plasticizer content was 1% wt. of the cement content. The W0 mix incorporated no RCWTB, while the W5 mix had 37.59 kg/m^3 of RCWTB and the W10 had 74.36 kg/m^3 of RCWTB. As of the aggregates, the W0 mix incorporated 780 kg/m^3 of siliceous coarse 12/22 mm gravel, 555 kg/m^3 of siliceous fine 4/12 mm gravel, 385 kg/m^3 of siliceous 0/4 mm sand, and 280 kg/m^3 of limestone fine 0/2 mm sand. These aggregate contents varied when adding RCWTB while keeping the content of cement constant.

Dosage of the Content of Water and Plasticizer

The addition of fibers usually hinders workability and flowability of the concrete in its fresh state (Garcia-Llona *et al.*, 2022). To counterbalance these negative impacts, the water content and the plasticizer content were adapted when adding RCWTB to meet the requirements of a slump test performed after the mixing process.

As these fibers sew the concrete mix and do not allow the aggregates to get dragged by the cement paste (Revilla-Cuesta *et al.*, 2023), it was not possible to achieve the desired slump just by adding water into the mixture without affecting the quality of the concrete through a higher water/cement ratio. As in **Table 1**, the different contents of water and each plasticizer can be seen. The concrete was manufactured in 45-liter batches, where these materials were added and then the dosage was calculated proportionally for a standard 1-m^3 batch, as a method of comparison between the mixtures. The full-scale study of these types of concretes is studied in other papers (Santamaría *et al.*, 2023).

Table 1. Variation of water and plasticizer contents regarding.

	45 l batch of concrete			**1 m^3 of concrete**		
	W0	**W5**	**W10**	**W0**	**W5**	**W10**
Added water (kg)	0.000	0.630	1.100	0.000	12.04	20.69
Added Plasticizer 1 (kg)	0.000	0.000	0.012	0.000	-0.014	0.225
Added Plasticizer 2 (kg)	0.000	0.000	0.025	0.000	-0.028	0.471

For the W0 reference mix, the slump was adequate, so there was no need for higher contents of water or plasticizer. Regarding the W5 mix, there was a need for more water, which helped achieve the desired slump. Therefore, the overall quantity of plasticizer decreased, as water took up a higher amount of the cubic meter of concrete, resulting in a 0.44 water/cement ratio. As per the W10, both water and plasticizer content were higher than in any other mixes. The water content and the plasticizer content were almost doubled for the 45-liter batch, which resulted in less overall water in the W10 mix, thus not affecting as much to the water/cement ratio that ended up being around 0.48.

Mixing Process

To achieve the desired fresh state characteristics, a specific mixing process had to be determined (Revilla-Cuesta *et al.*, 2023), so the hydration of the cement content would be optimal and the RCWTB would be homogeneously distributed in the whole mix.

A three-stage mixing process was determined. Before the mixing process began, the mixer was lightly dampened and the water content was divided into three parts: one of them contained 0.50 liters of water, and the other two contained 30% wt. and 70% wt. of the remaining water content, separately. Regarding the mixing process, firstly, the aggregates with 30% wt. of the water content were added and mixed for five minutes. Then, the cement and the RCWTB contents were added with 70% wt. of the water and mixed for three minutes. Finally, the plasticizers were diluted in the 0.50 liters of water and added into the mix for another five minutes. To ensure workability, a slump test was performed after this mixing process.

Experimental campaign.

As mentioned above, after the mixing process a slump test was performed, according to EN 12350 (EN-Euronorm, 2020) and trying to achieve a S3 slump (EN 206 (EN-Euronorm, 2020), 100-150 mm). After the slump testing, the fresh density (EN 12350-6) was evaluated and the occluded air content (EN 12350-7) was measured (EN-Euronorm, 2020). Afterwards, six cylindrical specimens were manufactured for compressive strength testing (EN 12390-3) with a diameter of 100 mm and a height/diameter ratio of 2 (EN-Euronorm, 2020). The compressive strength was evaluated at 7 and 28 days of curing in humid chamber (95% or higher relative humidity and 20 ± 2 ºC of temperature), with three specimens to be tested at each age.

RESULTS AND DISCUSSION

Slump

The results of the slump test can be seen in **Figure 3**. An Abrams Cone was used to perform the tests, and a S3 slump (100-150 mm) was achieved in every mix, according to EN 206 (EN-Euronorm, 2020). As it can be perceived, the slump decreased as the RCWTB content increased, recording the highest slump in the W0 and the lowest in the W10 mix despite of the water and plasticizer that was added to counter the negative effects of fibers in the fresh state. Thus, the need for a specific mixing process and the adjustment of said water and plasticizer amounts (Revilla-Cuesta *et al.*, 2023).

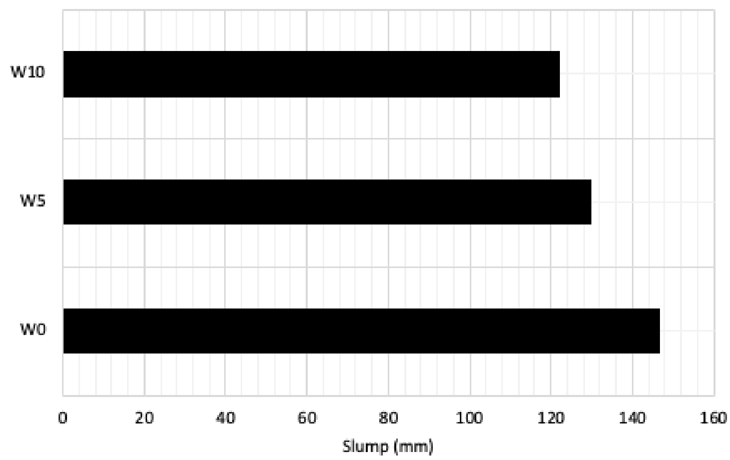

Figure 3. Slump testing results

Fresh Density

The fresh density was evaluated by weighing the seven-liter container by itself and then weighing it filled with concrete after its vibration in the shaking table, according to EN 12350-6 (EN-Euronorm, 2020). The results showed an almost linear trend, where the fresh density results decreased as the RCWTB increased. The W0 reference mix recorded a fresh density of 2.42 kg/dm^3, common value for plain concrete (EN-Euronorm, 2020). Then, the W5 mix had a fresh density of 2.36

kg/dm^3 and the W10 had a fresh density of 2.24 kg/dm^3.
The variation of the fresh state density compared to the reference mix was 2.66% lower for the W5 mix and 7.26% lower for the W10 mix, phenomenon that is explain by the addition of the low-density RCWTB into the concrete mix, which lightens the mixture while maintaining its volume (Revilla-Cuesta *et al.*, 2023).

Occluded Air Content

The results of the occluded air content testing can be seen in **Figure 4**. This fresh-state tests also showed a clear trend, as the higher RCWTB contents caused higher occluded air contents as well. The W5 recorded a 50% higher occluded air content than the reference mix, and the W10 showed a 100% higher value than the reference mix.
Despite the high variation among the mixes, all the obtained values for the occluded air testing were within usual range (López-Gayarre *et al.*, 2009). This showed that the higher the RCWTB, more air got trapped inside the concrete mix, resulting a more porous cementitious matrix. This cementitious matrix was then of less quality, showing worse results in the hardened state, as will be seen in the upcoming section. Besides, the porosity of the balsa wood spheres could also have affected negatively to the occluded air content because of its low density. Therefore, the porosity of the balsa wood could have been interpreted as if they were of the concrete. Subsequently, the more RCWTB that was added, the balsa wood content was increased, resulting in a higher occluded air content in the W5 and W10 mixes.

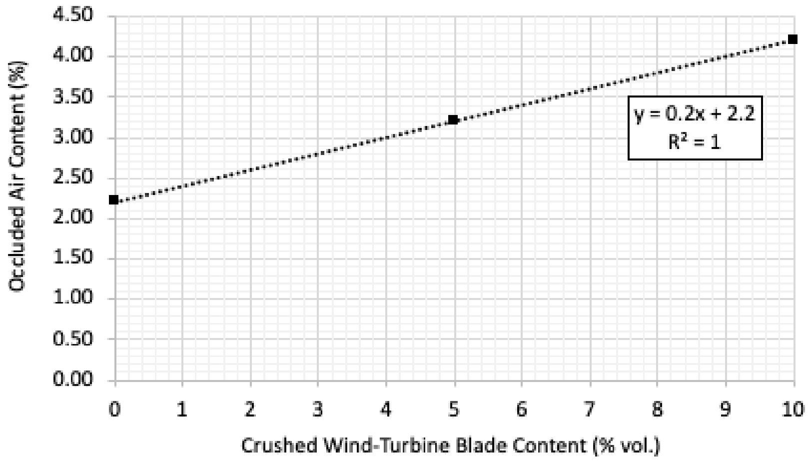

Figure 4. Occluded air content results.

Compressive Strength

After 7 and 28 days, the compressive strength specimens underwent testing, showing their results in **Figure 5a**. Their compressive strength variation with the reference mix can be seen in **Figure 5b**. All the mixes showed results above the limit for structural applications (Eurocode 2, 2010), but the results tended to slightly decrease as the RCWTB content increased.
For the 7-day testing, the W0 and W5 showed similar results, with a minimal variation of around 1.10%. On the other hand, the W10 mix showed lower results, with a loss of around 13.50% compared to the reference mix. These results can be explained by the worsening of the quality of the cementitious matrix, as the balsa wood and polyurethane spheres experimented worse adhesion to the matrix than natural aggregate (Revilla-Cuesta *et al.*, 2023), and the increasing water/cement

ratio (Ortega-López *et al.*, 2022) and plasticizer content (Hosseinzadeh *et al.*, 2023), that was more detrimental that the beneficial bridging effects of the fibers (Garcia-Llona *et al.*, 2022).

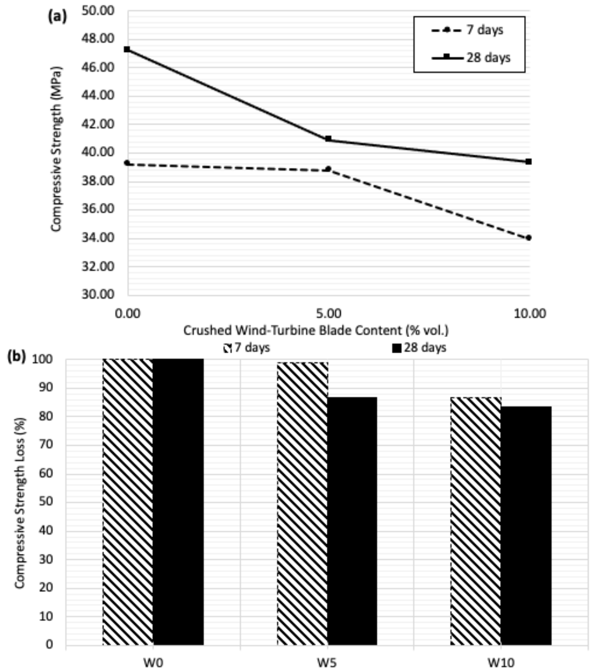

Figure 5. Compressive strength behavior. (a) Results of compressive strength testing after 7 and 28 days in humid chamber. (b) Loss of compressive strength compared to the reference mix (W0) after 7 and 28 days in humid chamber.

Besides, the 28-day compressive strength yielded similar results, yet the W0 mix showed a higher compressive strength than the other mixes, as hydration of the matrix occurred, resulting in a higher quality concrete. The W5 mix, as fibers and balsa wood tend to accumulate water and affect the interstitial transition zone, showed a 13.36% loss of compressive strength and the W10 showed a 16.71% loss, both compared to the reference mix, showing that the compressive strength after a certain amount of RCWTB amount behaved asymptotically and did not affect its behavior drastically, widely ensuring the required compressive strength behavior for any structural application regarding higher amounts of added RCWTB.

CONCLUSIONS

In this research, FRC was manufactured by incorporating high amounts of Raw-Crushed Wind-Turbine Blade (RCWTB) into the concrete mix, as an attempt to ensure the suitability of the addition of this recycled material into the concrete mix. By this work, a more sustainable concrete was obtained, as it aimed to aid the wind-energy sector with its environmental issues while largely maintaining the most important characteristics of concrete in its fresh and hardened state. The following statements can be drawn from this study:

- The mixing process needed to be adjusted specifically for each concrete mix. To achieve the desired characteristics, the mixing process needed more steps than for plain concrete, as it was required to achieve a homogeneous distribution of the fibers throughout the concrete mix and ensure proper hydration of the cement.

- The water and plasticizer contents had to be adjusted for each individual amount of RCWTB that was added into the concrete mix. By this careful procedure, the mixes had the desired fresh state characteristics, yet not resulting largely detrimental to the concrete quality or its actual cementitious matrix and ensuring a correct behavior in combination with the recycled fibers.
- The fresh density and the occluded air content showed equivalent trends, with not major variations from the reference mix. The variations that did occur could be explained by the addition of RCWTB contents and the increasing water and plasticizer content. As the density of the residue was significantly lower than the concrete actual density, the overall fresh density decreased slightly. Besides, the addition of balsa wood spheres and polyurethane spheres present in RCWTB resulted in less quality interstitial transition zones, also explained by higher quantities of plasticizer.
- The compressive strength remained alike to the reference mix, with variations lower than 17% in all cases. The compressive strength of the reference mix was close to the other mixes incorporating high amounts of RCWTB when tested at 7 days of curing in humid chamber. When tested after 28 days of curing in humid chamber, the reference mix achieved slightly higher results, as the quality of the concrete was increased because of a lower water/cement ratio, but the variations yielded that there only was a 3.34% difference in compressive strength between both percentages of RCWTB added. Thus, showing the viability of introducing higher amounts of RCWTB into the mixes, as the bridging effect of the fibers helped counterbalance the existence of a lower quality cementitious matrix and the detrimental effect of the particles of balsa wood and polyurethane.

The present study yielded that it is feasible to incorporate higher amounts of RCWTB into the concrete mix, as confirmed by the results of the designed experimental campaign regarding its fresh-state performance and its compressive behavior. Thus, helping achieve a more sustainable material by recycling a by-product from the wind-farming sector and helping reduce the global issues they are facing, aiming towards a greener and more efficient circular economy.

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