Journal of
Composites Science

MDPI

Article

Specific Design of a Self-Compacting Concrete with Raw-Crushed Wind-Turbine Blade

Manuel Hernando-Revenga [1], Víctor Revilla-Cuesta [1,*], Nerea Hurtado-Alonso [2], Javier Manso-Morato [1] and Vanesa Ortega-López [1]

[1] Department of Civil Engineering, University of Burgos, 09001 Burgos, Spain; mhrevenga@ubu.es (M.H.-R.); jmanso@ubu.es (J.M.-M.); vortega@ubu.es (V.O.-L.)
[2] Department of Construction, University of Burgos, 09001 Burgos, Spain; nhurtado@ubu.es
* Correspondence: vrevilla@ubu.es; Tel.: +34-947-497117

Abstract: Wind-turbine blades pose significant disposal challenges in the wind-energy sector due to the increasing demand for wind farms. Therefore, this study researched the revaluation of Raw-Crushed Wind-Turbine Blade (RCWTB), obtained through a non-selective blade crushing process, as a partial substitute for aggregates in Self-Compacting Concrete (SCC). The aim was to determine the most adequate water/cement (w/c) ratio and amount of superplasticizing admixtures required to achieve adequate flowability and 7-day compressive strength in SCC for increasing proportions of RCWTB, through the production of more than 40 SCC mixes. The results reported that increasing RCWTB additions decreased the slump flow of SCC by 6.58% per 1% RCWTB on average, as well as the compressive strength, although a minimum value of 25 MPa was always reached. Following a multi-criteria decision-making analysis, a w/c ratio of 0.45 and a superplasticizer content of 2.8% of the cement mass were optimum to produce SCC with up to 2% RCWTB. A w/c ratio of 0.50 and an amount of superplasticizers of 4.0% and 4.6% were optimum to produce SCC with 3% and 4% RCWTB, respectively. Concrete mixes containing 5% RCWTB did not achieve self-compacting properties under any design condition. All modifications of the SCC mix design showed statistically significant effects according to an analysis of variance at a confidence level of 95%. Overall, this study confirms that the incorporation of RCWTB into SCC through a careful mix design is feasible in terms of flowability and compressive strength, opening a new research avenue for the recycling of wind-turbine blades as an SCC component.

Keywords: self-compacting concrete; wind-turbine blade; glass fiber-reinforced polymer; concrete design; water/cement ratio; admixtures; flowability; slump flow; mechanical performance; compressive strength

check for updates

Citation: Hernando-Revenga, M.; Revilla-Cuesta, V.; Hurtado-Alonso, N.; Manso-Morato, J.; Ortega-López, V. Specific Design of a Self-Compacting Concrete with Raw-Crushed Wind -Turbine Blade. *J. Compos. Sci.* **2024**, *8*, 540. https://doi.org/10.3390/jcs8120540

Academic Editors: Ying-Liang Chen and Pai-Haung Shih

Received: 8 November 2024
Revised: 5 December 2024
Accepted: 16 December 2024
Published: 19 December 2024

1. Introduction

Concrete is an artificial composite material obtained by mixing a hydraulic binder, usually Portland cement, with aggregates, water, and in certain cases admixtures [1]. Cement, water and the finest fraction of the aggregates are responsible for creating a cement paste that is capable of adequately dragging all the concrete components, thus providing proper workability [2]. When mixed with water, cement undergoes an exothermic hydration process, creating a hardened cementitious matrix that surrounds the aggregates when setting ends. Such cementitious matrix unifies the whole and binds the aggregates together, providing strength. Its microstructure largely determines the mechanical and durability properties of concrete [3]. Besides, aggregates provide volume, stiffness, and tensile strength to concrete [4]. Finally, the admixtures play a fundamental role in modifying both the fresh and the hardened properties of concrete, thus improving workability, setting time, strength, waterproof, and durability, among others [5].

Concrete has a wide range of applications in the construction sector, being used in buildings, infrastructures, pavements, hydraulic works, and for both structural (beams and columns) and non-structural (furniture and curbs) precast elements [6,7]. Each of these applications has a number of specific requirements, the design and dosage of concrete being achieved through means of mathematical modelling and experimental testing to meet such specifications [1,8]. The two most important properties in concrete performance are workability and compressive strength, which guarantee successful placement and adequate in-service strength behavior [9,10]. Despite this, attention must also be paid to other relevant properties such as tensile strength, flexural strength, elastic stiffness, permeability, durability and fire resistance, among others, which vary depending on each specific concrete application [11,12].

Self-Compacting Concrete (SCC) represents a significant evolution in concrete technology. This concrete type exhibits rheological properties that allow it to flow and compact under its own weight without the need for vibration or external forces [13]. This behavior is achieved through careful raw-material proportioning, mainly regarding the aggregate fines, and the addition of superplasticizing admixtures. On the one hand, aggregate fines enable a compact cement paste to be formed, which is able to uniformly drag all the coarse-aggregate particles [14]. A granulometry with high-fine content also prevents blockage when the SCC goes through the reinforcements [15,16]. On the other hand, superplasticizing admixtures coat the aggregate particles, reducing the internal friction enabling the concrete to flow homogeneously [13]. This high flowability is what allows SCC to completely and successfully fill any formwork, even those with a complex geometry [10], to properly encase heavy reinforcement without leaving gaps [17]. Additionally, the absence of vibration reduces energy consumption, thereby reducing the carbon footprint of concrete and contributing to a higher sustainability within the construction sector [18,19]. However, this performance will only be adequate if SCC demonstrates excellent stability and resistance to segregation, in a way that a homogeneous mixture is guaranteed when concreting [20].

In addition to its high flowability, SCC offers numerous substantial advantages that are making it increasingly popular in the construction sector, leading to its use in a growing number of applications [21]. First, the absence of vibration prevents the segregation of the concrete constituents, which results in a more homogeneous surface finish that is free of pores and imperfections [22]. Second, this absence of pores in the surface finish and the greater packing density of SCC contribute to a higher resistance to the penetration of any aggressive external agents within the concrete, therefore reducing reinforcement corrosion, improving durability and lowering maintenance costs [23,24]. Third, the ease of placement of SCC and the elimination of the need for vibration notably reduce the time and labor required for the execution of the works, thus increasing in-situ productivity and output in precast-concrete plants [25]. Finally, noise is also minimized due to the elimination of the need for vibration [26]. Therefore, although the initial cost of SCC may be slightly higher than that of conventional concrete, the long-term benefits enumerated often offset such economical difference [27].

Fibers can be incorporated into any concrete type, which modifies concrete performance in various dimensions. Fibers mainly improve toughness, ductility and waterproof of concrete, which in turn lead to a greater resistance to cracking, tensile stresses and impacts [28]. However, fibers can also negatively influence other properties such as workability and compressive strength [29,30]. Therefore, it is essential to carefully select the proportion of fibers to be added, and to adapt the concrete composition to their addition, mainly through the water/cement (w/c) ratio and aggregates' gradation, in such a way that those detrimental effects are counterbalanced [31].

Concrete can incorporate various types of fibers, each one with different characteristics and applications. The most common fibers are steel, polypropylene, and glass fibers [32]. Steel fibers impart high tensile and bending strengths to concrete, making them ideal for structural applications where high load capacities are required [33]. Polypropylene fibers improve the toughness and ductility of concrete, reducing the formation and propagation of cracks. These fibers are especially useful in applications where impacts or cyclic loads are expected, such as pavements [34]. Finally, glass fibers, offering a balanced combination of strength and durability, are commonly used in environments in which high resistance to alkalinity and chemical agents is required [35]. Therefore, selecting the appropriate fiber type depends on the specific performance requirements of the concrete and the in-service conditions it will face [36]. Additionally, the use of recycled fibers is another possibility that is currently becoming increasingly widespread [7], as they offer the advantages of conventional fibers while reducing the environmental impact of fiber manufacturing [37].

The combination of the properties of SCC with those provided by the fibers allows for fiber-reinforced SCC with excellent performance in various applications such as floors, pavements, precast elements, and structures subjected to cyclic loads [28,31–35]. The development of SCC containing recycled fibers can be even more interesting, as such type of fibers are able to provide the described behaviors while reducing the overall environmental impact [38]. Another type of recycled fiber is that derived from the crushing of Glass Fiber-Reinforced Polymer (GFRP) [39], which is used in the manufacture of components such as wind-turbine blades, and which does not yet have a widely accepted recycling pathway [40]. However, wind-turbine blades are not only made of GFRP, but also of balsa wood and polymers [41]. The simultaneous crushing of all the blade constituents yields a material called Raw-Crushed Wind-Turbine Blade (RCWTB), which is composed of GFRP fibers and polymer and balsa-wood particles [42]. The author's research group is committed to the revaluation of RCWTB as a raw material in concrete. To date, this waste has been successfully employed as a raw material for the development of concrete with conventional workability [43]. Consequently, the development of SCC containing RCWTB is the next step in this research line.

A previous initial approach revealed that conventional SCC design was not suitable when RCWTB was incorporated due to its complex composition, which caused large decreases in flowability and compressive strength when added to this concrete type [44]. Therefore, this paper reports the design and optimization of an SCC composition exclusively developed for the incorporation of RCWTB to this concrete type. An initial SCC-mix design usually applied in precast-concrete plants was first adopted following the experience of the author's research group [25], to later define the adjustments of water and superplasticizing admixtures necessary to achieve an adequate balance between flowability and compressive strength when adding different percentages of this waste. Over forty SCC mixes were designed for this purpose. This research aims to mitigate the environmental impact of both the concrete industry and the wind-energy sector. First, by producing SCC, which enables energy savings by eliminating vibration [13]. Second, by using RCWTB as a raw material in concrete, thus revaluing a material that is currently being landfilled or incinerated, causing a considerable environmental impact at the end of the service life of wind turbines [45,46].

2. Materials and Methods

2.1. Raw Materials

2.1.1. Conventional Materials

The present SCC was made with conventional materials similar to those used in the production of precast-concrete elements, including superplasticizers [25].

Portland cement type II with a 28-day compressive strength of 42.5 MPa that contained 6–20% limestone in its composition was used. This cement type is labelled CEM II/A-L 42.5R according to EN 197-1 [47]. The use of this type of cement is currently quite extended, as it is considered optimal for its use in most concrete applications [48].

Water was supplied by the local network of the city of Burgos, Spain. More precisely, the water was taken from the large-structures workshop located at the La Milanera campus of the University of Burgos.

Two different third-generation superplasticizing admixtures were added, allowing the development of SCC mixtures with a lower water/cement ratio while maintaining an adequate flowability [49].

Four different fractions of natural aggregates were used to guarantee proper aggregate packing and fresh flowability [50]. Particle gradation of the aggregates is reflected in Figure 1, and consisted of (density and 24-h water absorption as per EN 1097-6 [47]):

- Siliceous gravel sized 4/12 mm, with a density of 2.66 kg/dm^3 and a 24-h water-absorption level of 0.66% wt.
- Siliceous sand sized 0/4 mm, with a density of 2.65 kg/dm^3 and a 24-h water-absorption of 0.74% wt.
- Limestone sand sized 0/2 mm, with a density of 2.64 kg/dm^3 and a 24-h water-absorption level of 0.52% wt.
- Limestone filler sized < 0.063 mm, with a density of around 2.77 kg/dm^3.

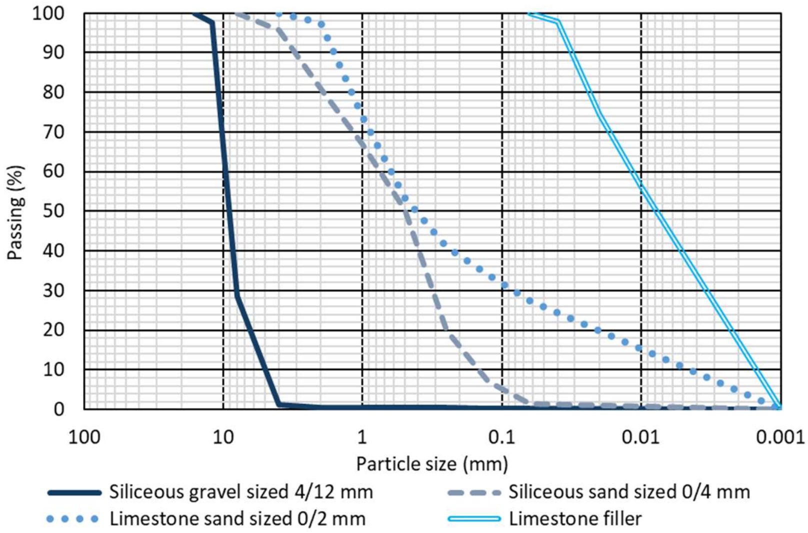


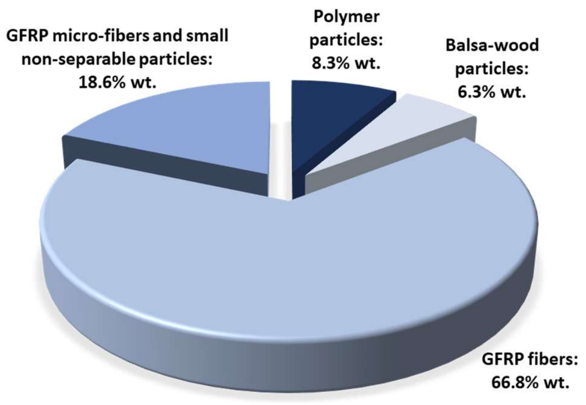
Figure 1. Granulometry of the aggregates.

2.1.2. Raw-Crushed Wind-Turbine Blade (RCWTB)

Wind-turbine blades are composed of different materials, among which GFRP, balsa wood and polymers stand out for their higher proportions [41]. Pieces of wind-turbine blades with dimensions from 20 × 20 cm up to 30 × 30 cm containing these materials were crushed by using a knife mill. Particles with a size less than 10 mm were required in order to guarantee a proper distribution of the waste within the SCC [42]. Therefore, any resulting particles exceeding a size greater than 10 mm were crushed again until they reached the required dimensions. The processed material obtained was labelled as RCWTB and added to the SCC mixes.

RCWTB had a real density of 1.63 kg/dm^3 and an apparent density of around 247 kg/m^3. It was composed of GFRP fibers (density of 2.04 kg/dm^3); balsa wood (density of 0.33 kg/dm^3) and polymers in the form of roughly spherical particles with an average size of around 5 mm; and micro-fibers in the form of fluffs interspersed with tiny balsa-wood and polymer particles that could not be mechanically separated from the micro-fibers. The weight percentages of each RCWTB constituent obtained through a manual screening and selection process can be observed in Figure 2a, while Figure 2b shows the appearance of the RCWTB. Furthermore, Table 1 shows the chemical composition of the RCWTB components obtained by Energy Dispersive X-ray (EDX) analyses.

Characterization of the GFRP fibers was also conducted. The length of these fibers was measured with a caliper, an average length of 13.07 mm being obtained. Their equivalent diameter was also evaluated, and an average value of 0.73 mm was yielded. Additionally, their tensile strength was determined by conducting pure-tensile tests in which loading was applied in the direction parallel to the longitudinal axis of the fibers, resulting in an average result of 270 MPa.



(**a**)

(**b**)

Figure 2. RCWTB: (**a**) composition; (**b**) appearance.

Table 1. Chemical composition of RCWTB components following EDX analyses.

Component	Carbon	Oxygen	Silicon	Calcium	Others
GFRP fibers	53.49	22.79	4.96	4.37	14.39
Balsa wood	61.36	18.70	3.90	0.95	15.09
Polymers	60.57	13.41	9.49	0.47	16.06

2.2. Mix Design

As mentioned at the final part of the introduction, the aim of this study is to develop an SSC mix design in which RCWTB is incorporated in a satisfactory way in terms of flowability and compressive strength [51]. For this purpose, the starting point was a reference SCC composition that did not incorporate any type of residue and that is commonly used in precast-concrete industries according to the authors' experience [25]. This initial composition of SCC was characterized by the following aspects:

- A cement content of 320 kg/m^3.
- Values of the w/c ratio of 0.45 (145 kg/m^3 of water) and 0.50 (160 kg/m^3 of water), which covered all the usual range of w/c ratios in precast-concrete plants [52].
- Superplasticizing-admixture contents of 2.2% and 2.8% of the cement mass (6.9 kg/m^3 and 9.0 kg/m^3 of superplasticizing admixtures, respectively). These two values corresponded to the lower and upper limits of the range within the amount of this type of admixture is found when SCC is produced industrially [52].
- Aggregate contents were determined by an optimal adjustment of the overall gradation to Fuller's curve with an exponent of 0.35. This optimization enabled to fix adequate aggregate proportions to reach self-compactability [50]. Such adjustment is shown in Figure 3. This process yielded contents of 555 kg/m^3 of siliceous gravel sized 4/12 mm, 610 kg/m^3 of siliceous sand sized 0/4 mm, 625 kg/m^3 of limestone sand sized 0/2 mm, and 170 kg/m^3 of limestone filler sized < 0.063 mm.

Taking this SCC composition as guidance, incremental additions of RCWTB were introduced in steps of 1% by volume replacing the siliceous gravel, siliceous sand and limestone sand. Such replacement was conducted by maintaining the initial aggregate proportions. Limestone filler was not partly substituted by RCWTB because of its critical role for obtaining adequate self-compactability according to different studies in the literature [53–55]. An adjustment by volume dependent on the density of each SCC component was considered when adding the RCWTB.

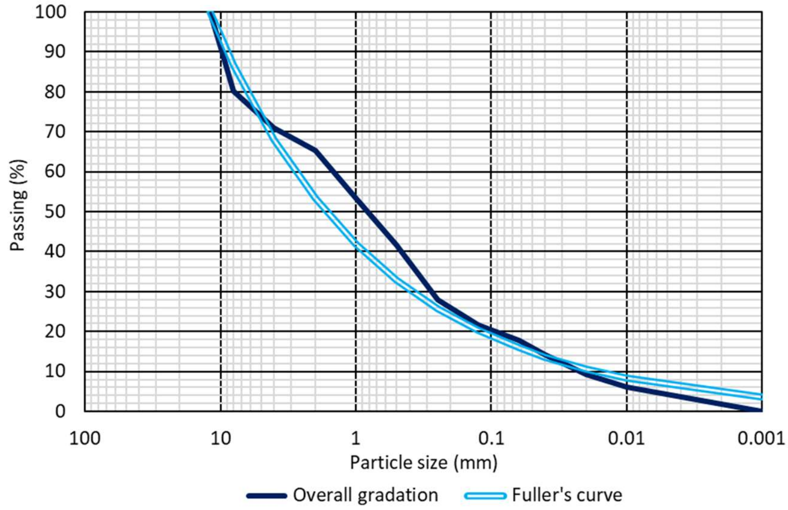


Figure 3. Overall gradation of the aggregates.

This incremental process continued until the RCWTB addition reached a point where the mix lost its self-compacting capability. From this threshold RCWTB content and dosage, the behavior of the SCC was evaluated by increasing both the w/c ratio in steps of 0.05 and the superplasticizing admixtures in steps of 0.6% of the cement mass. The cement content and the aggregate proportions were not modified to guarantee proper strength and aggregate packing of the SCC [50]. In agreement with concrete specialists of a precast-concrete facility, no limitation was established for the w/c ratio. However, it was specified that the maximum superplasticizer content applied in practice was 6.4% of the cement mass, which thus served as the upper boundary for this research.

The SCC mixtures were labelled as *W%*, where the symbol % represented the value of the percentage of RCWTB added to the SCC. Therefore, the result of this research was the development of SCC compositions suitable for each RCWTB content. In accordance, the detailed composition of all the SCC mixtures prepared is shown in Section 3, which is destined to the exposition of the results obtained in the study.

2.3. Experimental Plan

A three-stage mixing process was applied during the production of all the SCC mixes. The aim was to ensure a uniform distribution of the RCWTB within the SCC, regardless of the waste content added [42,56]. Before starting the mixing process, all the fractions of aggregates, RCWTB, and cement were weighed following the mix design. Subsequently, the water was weighed by removing 0.50 kg, which was used to dilute the superplasticizing admixtures. The mixing water was divided into two batches that accounted for 30% and 70% of its remaining weight. The stages that comprised this process were as follows:

- In the first step of mixing, all aggregates, RCWTB and 30% water were poured into a planetary mixer and mixed for three minutes.
- The second step consisted of adding the cement with 70% water, followed by mixing for another three minutes.
- In the last mixing stage, the superplasticizing admixtures diluted in 0.50 l of water were added. The last three minutes of mixing were then conducted.

Immediately after the batching process was completed, slump-flow measurements were performed according to EN 12350-8 [47] by measuring the spreading diameter of the SCC in two perpendicular directions. When self-compactability was not reached, the slump test was conducted as per EN 12350-2 [47], in which the vertical displacement of the concrete due to its own weight was evaluated. Then, three cylindrical specimens of 10 cm in diameter and 20 cm in height were made, in which compressive-strength tests after 7 days of curing in a humid chamber were performed following EN 12390-3 [47]. For this purpose, the specimens were subjected to an increasing stress at a rate of 0.6 MPa/s until failure was reached.

Finally, a three-way ANalysis Of VAriance (ANOVA) was calculated to elucidate the significance of the impact of the three factors evaluated (RCWTB content, w/c ratio, and percentage of admixtures) in both properties of SCC at a confidence level of 95%. This practice is usual in such kind of research [57,58]. Optimization through Multi-Criteria Decision-Making (MCDM) algorithms was also conducted to define the optimum mix design for each RCWTB amount added to SCC. TOPSIS algorithm was applied, as their use is common in concrete optimization [25,59].

3. Results and Discussion

The stages related to the design of SCC containing RCWTB carried out in this research can be divided into four groups:

- Group 1. In the first group of mixes, amounts of 0%, 1%, 2% and 3% of RCWTB were added to an SCC with a conventional design. According to all the aspects explained in the mix design section, w/c ratios of 0.45 and 0.50 and contents of superplasticizing admixtures (ad.) of 2.2% and 2.8% of the cement mass were considered for each RCWTB amount. Therefore, four SCC mixes were produced for each RCWTB content (0.45 w/c and 2.2% ad.; 0.45 w/c and 2.8% ad.; 0.50 w/c and 2.2% ad.; and 0.50 w/c and 2.8% ad.), yielding sixteen different mixes.
- Group 2. 3% RCWTB with water and admixture contents indicated for Group 1 did not enable to achieve a slump flow higher than 550 mm, minimum required value to consider this concrete as self-compacting according to EN 206 [47]. Therefore, the w/c ratio was increased up to 0.55 and the content of superplasticizer admixtures up to 3.4% of the cement mass. These six mixes conformed the second group.
- Group 3. From the experience of increasing the w/c ratio to 0.55, it was found that the water started to segregate from the mix, providing the adjustment unsuitable for achieving stable SCC with 3% RCWTB. Consequently, SCC with 3% RCWTB was designed by fixing the w/c ratio at both 0.45 and 0.50 while increasing the amount of superplasticizing admixtures. Admixture proportions of 3.4, 4.0%, 4.6%, 5.2%, 5.8% and 6.4% of the cement mass were considered. The twelve SCC mixes developed following these criteria comprised the third group.
- Group 4. In the last group of mixes, 4% and 5% of RCWTB were added to an SCC with a w/c ratio of 0.50, as it was previously demonstrated to be the most adequate w/c ratio when 3% RCWTB was added to SCC. The minimum content of superplasticizing admixtures for each RCWTB amount was the one that allowed reaching self-compactability with the immediately lower RCWTB content. Admixture proportions up to 6.4% of the cement mass were added in increasing steps of 0.6%, resulting in nine different mixes.

3.1. Group 1: RCWTB Content Between 0% and 3%; w/c Ratio Between 0.45 and 0.50; Admixture Amount Between 2.2% and 2.8% of the Cement Mass

The composition of the mixtures in this first group is detailed in the following tables: Table 2 (*W0* mixes, 0% RCWTB), Table 3 (*W1* mixes, 1% RCWTB), Table 4 (*W2* mixes, 2% RCWTB), and Table 5 (*W3* mixes, 3% RCWTB).

In Figure 4a, the slump flows of the mixes that reached self-compactability are presented. If the mixes did not perform as such, the slumps were measured, which are recorded in Figure 4b. Analyzing the trends of the three factors (w/c ratio, amount of superplasticizing admixtures, and RCWTB content), the next insights can be highlighted:

- A clear improvement (16.28% on average) in the slump flow was observed when increasing the w/c ratio from 0.45 to 0.50. This was due to the development of a greater amount of cement paste surrounding the aggregate particles and the RCWTB. Besides, this phenomenon resulted in a decrease in the internal friction between the SCC components, which allowed them to flow more easily [60].

- Regarding the increase in the admixture percentage, there was no clear trend, as opposed to the w/c ratio. The influence of increasing admixture content varied depending on the w/c ratio, with no consistent behavior observed. Thus, the slump flow was improved by 5.11% on average for a w/c ratio of 0.45, while the slump flow decreased by 1.34% on average when a w/c ratio of 0.50 was considered in the SCC. The SCC mixture segregated more quickly, inhibiting the attainment of a high value of slump flow when the maximum admixture percentage and w/c ratio were simultaneously applied, as also found in other experiences with alternative raw materials in SCC [61,62]. The use of superplasticizing admixtures allowed for the reduction of water while maintaining workability [63]. Therefore, low w/c ratios yielded the highest efficiency when increasing the admixtures up to 2.8% wt. of the cement mass for the studied RCWTB contents.
- The described efficiency of increasing the percentage of admixtures was not found when the amount of RCWTB rose. For a w/c ratio of 0.45, increasing the admixture percentage from 2.2% to 2.8% of the cement mass resulted in an increase of the slump flow of 33 mm for 0% RCWTB and only 5 mm for 2% RCWTB. The GFRP fibers within this waste hindered the flow of the other SCC components [64], mainly the coarse aggregate particles, which an increasing admixture proportion could not counterbalance, as in similar research [65].
- The increase in the percentage of RCWTB in general caused a decrease in the slump flow. The most pronounced reduction was found in the mixes with a w/c ratio of 0.45 and 2.8% of admixtures, for which 2% RCWTB reduced the slump flow by 17.21% compared to the *W0* mix. This reduction was driven by two primary factors. On the one hand, the GFRP fibers increased the specific surface area of the SCC components to be covered by the cementitious paste [30]. On the other hand, the GFRP fibers hindered the flow of the rest of the SCC components [64]. The decrease in the slump flow that suffered the *W3* mixes was so great that self-compactability could not be reached with the water admixture contents considered in this first group when adding that RCWTB amount.

Table 2. Mix design (kg/m^3) of the *W0* mixes (0% RCWTB).

Component	0.45 w/c; 2.2% ad.	0.50 w/c; 2.2% ad.	0.45 w/c; 2.8% ad.	0.50 w/c; 2.8% ad.
Cement	320	320	320	320
Water	145	160	145	160
Admixtures	6.9	6.9	9.0	9.0
Filler	170	170	170	170
Sand 0/2 mm	625	625	625	625
Sand 0/4 mm	610	610	610	610
Gravel 4/12 mm	555	555	555	555
RCWTB	0	0	0	0

w/c: water/cement ratio; ad.: amount of superplasticizing admixtures.

Table 3. Mix design (kg/m^3) of the *W1* mixes (1% RCWTB).

Component	0.45 w/c; 2.2% ad.	0.50 w/c; 2.2% ad.	0.45 w/c; 2.8% ad.	0.50 w/c; 2.8% ad.
Cement	320	320	320	320
Water	145	160	145	160
Admixtures	6.9	6.9	9.0	9.0
Filler	170	170	170	170
Sand 0/2 mm	620	620	620	620
Sand 0/4 mm	605	605	605	605
Gravel 4/12 mm	550	550	550	550
RCWTB	11	11	11	11

w/c: water/cement ratio; ad.: amount of superplasticizing admixtures.

Table 4. Mix design (kg/m^3) of the *W2* mixes (2% RCWTB).

Component	0.45 w/c; 2.2% ad.	0.50 w/c; 2.2% ad.	0.45 w/c; 2.8% ad.	0.50 w/c; 2.8% ad.
Cement	320	320	320	320
Water	145	160	145	160
Admixtures	6.9	6.9	9.0	9.0
Filler	170	170	170	170
Sand 0/2 mm	615	615	615	615
Sand 0/4 mm	600	600	600	600
Gravel 4/12 mm	545	545	545	545
RCWTB	22	22	22	22

w/c: water/cement ratio; ad.: amount of superplasticizing admixtures.

Table 5. Mix design (kg/m^3) of the *W3* mixes (3% RCWTB) for 0.45–0.50 w/c and 2.2–2.8% ad.

Component	0.45 w/c; 2.2% ad.	0.50 w/c; 2.2% ad.	0.45 w/c; 2.8% ad.	0.50 w/c; 2.8% ad.
Cement	320	320	320	320
Water	145	160	145	160
Admixtures	6.9	6.9	9.0	9.0
Filler	170	170	170	170
Sand 0/2 mm	605	605	605	605
Sand 0/4 mm	595	595	595	595
Gravel 4/12 mm	540	540	540	540
RCWTB	33	33	33	33

w/c: water/cement ratio; ad.: amount of superplasticizing admixtures.

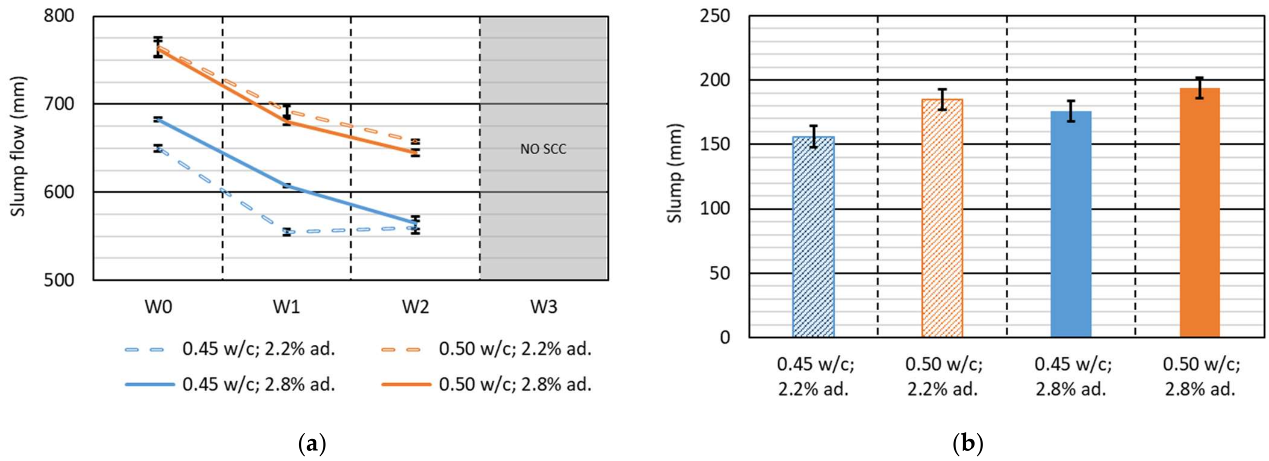


Figure 4. Workability of the mixes of the Group 1: (**a**) slump flow; (**b**) slump of the *W3* mixes (w/c: water/cement ratio; ad.: amount of superplasticizing admixtures).

Since the *W3* mixes were not self-compacting for the w/c ratios and the amounts of superplasticizing admixtures considered in the first group of mixes, their slumps were therefore measured (Figure 4b). Expectedly, the slump increased with higher w/c ratios and admixture proportions, as widely reported in the scientific literature related to design of both conventional concrete and SCC [66]. A 14.22% increase in the slump flow was achieved when increasing the w/c ratio from 0.45 to 0.50, while the improvement of the slump was of 8.84% when varying the admixture content from 2.2% to 2.8% of the cement mass.

The results of the 7-day compressive strength of the mixes of the first group of concrete mixes are detailed in Figure 5. Notably, an average reduction in compressive strength of 12.88% and 4.18% was obtained for the increase in the w/c ratio and the content of admixtures, respectively. This reduction was more pronounced with the increase of the w/c ratio, as led to an increase of residual water in the mix, and therefore augmented the porosity of the cementitious matrix [67]. Moreover, the increase in the percentage of

RCWTB also produced a decrease in strength, which reached a value of 20.21% when 3% RCWTB was incorporated to concrete. This situation was caused by the lower density and strength found in RCWTB in comparison with the substituted aggregates [68]. Additionally, the authors' research group found that the particles of polymers and balsa wood within this waste create weak Interfacial Transition Zones (ITZ) due to their reduced adhesion to the cementitious matrix [69]. Finally, the stitching effect of the GFRP fibers in the RCWTB was not very effective in improving the performance of concrete under compression stresses [43]. It is important to note that the waste content was the factor that altered the strength the most, although the loss of the self-compactability when 3% RCWTB was added counterbalanced such negative effect, as can be noted in the last column in Figure 5.

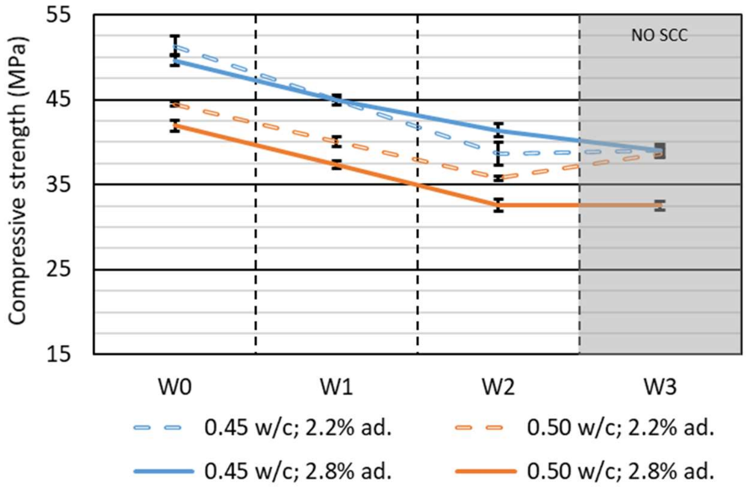


Figure 5. Compressive strength of the mixes of the Group 1 (w/c: water/cement ratio; ad.: amount of superplasticizing admixtures).

3.2. Group 2: 3% RCWTB; w/c Ratio Between 0.45 and 0.55; Admixture Amount Between 2.8% and 3.4% of the Cement Mass

As stated before, self-compactability with 3% RCWTB was not achieved by considering w/c ratios of 0.45 and 0.50 and superplasticizing-admixture amounts between 2.2% and 2.8% of the cement mass. Therefore, the w/c ratio was increased up to 0.55 and the amount of admixtures up to 3.4%, without modifying the waste content in the concrete to evaluate the most suitable way to develop SCC with this specific RCWTB amount. These mix designs comprised the second group of concrete mixes, whose composition is detailed in Table 6 (*W3* mixes, 3% RCWTB).

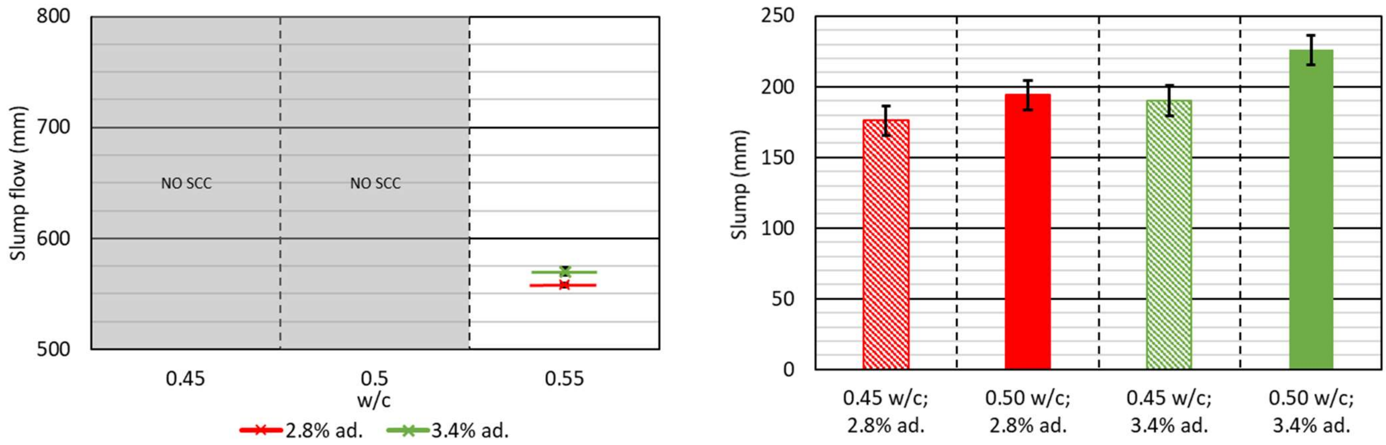
Table 6. Mix design (kg/m^3) of the *W3* mixes (3% RCWTB) for 0.45–0.55 w/c and 2.8–3.4% ad.

Component	0.45 w/c; 2.8% ad.	0.50 w/c; 2.8% ad.	0.55 w/c; 2.8% ad.	0.45 w/c; 3.4% ad.	0.50 w/c; 3.4% ad.	0.55 w/c; 3.4% ad.
Cement	320	320	320	320	320	320
Water	145	160	175	145	160	175
Admixtures	9.0	9.0	9.0	10.9	10.9	10.9
Filler	170	170	170	170	170	170
Sand 0/2 mm	605	605	605	605	605	605
Sand 0/4 mm	595	595	595	595	595	595
Gravel 4/12 mm	540	540	540	540	540	540
RCWTB	33	33	33	33	33	33

w/c: water/cement ratio; ad.: amount of superplasticizing admixtures.

Workability test results of the mixes in the second group are detailed in Figure 6. When self-compactability was reached, the slump flow was measured, as can be seen in

Figure 6a. For those instances where the mix design was not adequate to achieve SCC conditions, the slump was measured through the Abrams-cone test, whose values are depicted in Figure 6b.



(**a**) (**b**)

Figure 6. Workability of the mixes of the Group 2: (**a**) slump flow (0.55 w/c); (**b**) slump (0.45–0.50 w/c) (w/c: water/cement ratio; ad.: amount of superplasticizing admixtures).

A notable increase in the workability of concrete was found when raising the w/c ratio from 0.45 to 0.55. For an amount of admixtures of 2.8% of the cement mass, the concrete exhibited a slump of around 170–190 mm for w/c ratios of 0.45 and 0.50, but it reached a slump flow of approximately 560 mm when a w/c ratio of 0.55 was considered. This phenomenon was also found when adding an admixture content of 3.4%. As discussed for the mixes in the first group, the recorded increase in workability was due to the increased amount of cement paste coating the aggregates and the RCWTB. It reduced the internal friction between the aggregate particles and the RCWTB components, which in turn facilitated their relative displacements and flow, as found by other authors [60].

The effects of increasing contents of superplasticizing admixtures on workability of the concrete could also be easily perceived. The slump obtained in the mixes with w/c ratios of 0.45 and 0.50 increased by 12.22% on average when the quantity of admixtures was 3.4% of the cement mass compared to the mixes with 2.8% admixture. The slump flow reached with a w/c ratio of 0.55 (SCC mixes) was also augmented. Superplasticizing admixtures reduced the water demand of the cement for proper hydration, which increased the amount of free water within the concrete. This phenomenon facilitated the flow of the particles of the different aggregates and the RCWTB constituents, as supported by the literature related to SCC fresh performance [63].

Based on the behavior described in the preceding paragraphs, it can be deduced that the use of a w/c ratio of 0.55 and high amounts of superplasticizing admixtures could be optimal for the development of SCC with 3% RCWTB. Nevertheless, an accelerated segregation process of the mixing water was noted when workability tests were conducted in the mixes with a w/c ratio of 0.55, regardless of the admixture content. This phenomenon is shown in Figure 7 for a w/c ratio of 0.55 and an admixture content of 2.8%. Concrete workability was improved with an increased proportion of admixtures without causing segregation [67], as opposed to the effects of higher water content. Therefore, it was considered that a 0.55 w/c ratio was not advisable to develop a suitable SCC containing 3% RCWTB. To avoid this issue, a maximum value of 0.50 was then set for the w/c ratio to develop a proper SCC when adding 3% RCWTB, and consequently the content of superplasticizing admixtures had to be adjusted. Such w/c ratio is widely used in the concrete industry when developing many types of concrete mixes for different applications in the construction sector [70]. Another possibility could be the use of thickeners, such as carboxymethyl cellulose, which limit stratification and segregation of SCC when the water content is increased [13]. This is an aspect that could be evaluated in future research.

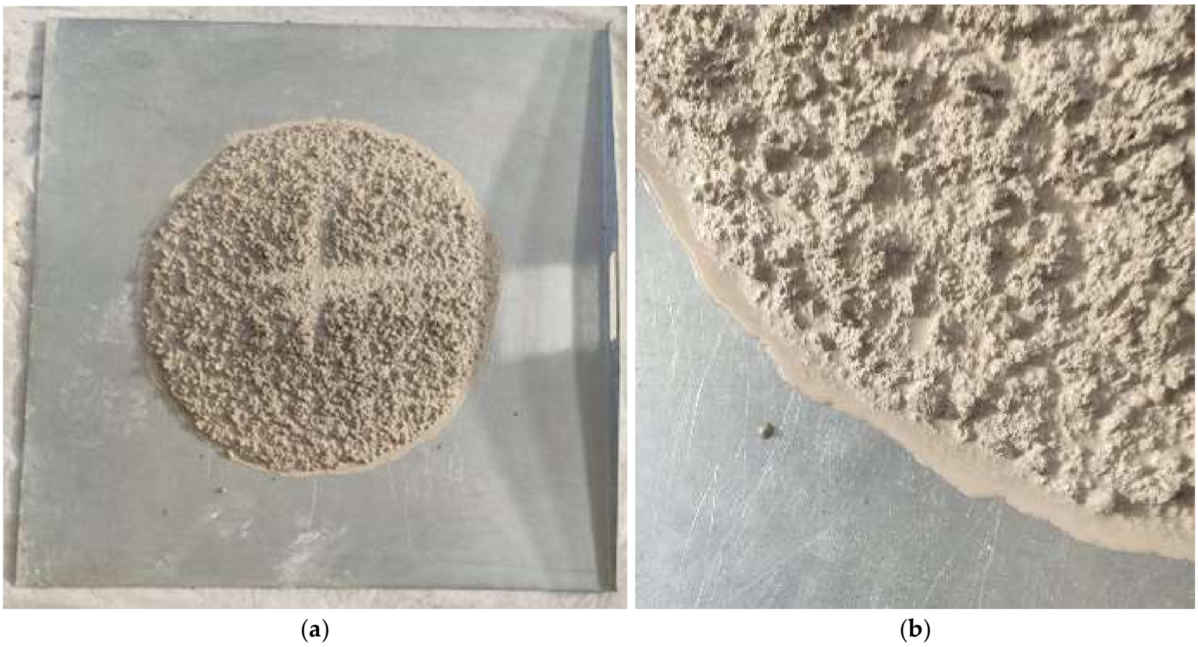


Figure 7. Water segregation in SCC with 3% RCWTB, 0.55 w/c ratio and 2.8% admixture: (**a**) slump-flow test; (**b**) detail of water segregation.

Figure 8 describes the behavior of the concrete mixes in terms of compressive strength. In general, it decreased as w/c ratios and superplasticizing-admixture contents increased (average reductions of 13.39% and 0.60%, respectively), along with higher variability in strength values. As previously discussed for the mixes of the first group, the compressive strength worsened to a greater extent with increasing the w/c ratios, since it led to a higher content of residual water within the concrete, which increased the porosity of the cementitious matrix and weakened it [67]. However, the enhanced aggregate-packing structure derived from the addition of higher proportions of admixtures partly counterbalanced such negative effects [71]. Notably, despite of the phenomena described, a compressive strength of 25 MPa was always reached, which is the minimum required value to use the concrete in structural applications according to design standards [52].

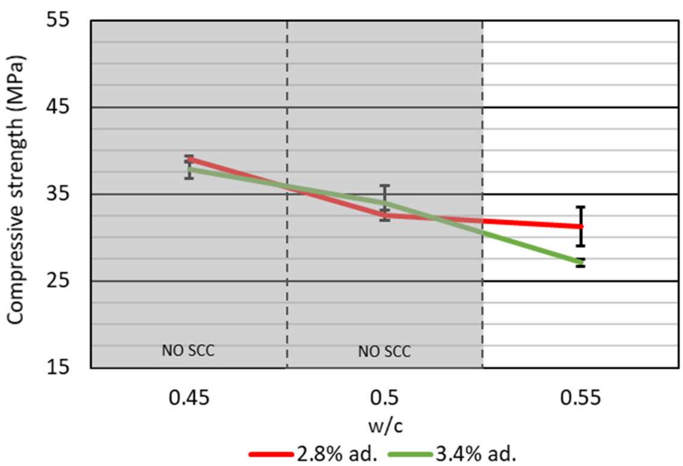


Figure 8. Compressive strength of the mixes of the Group 2 (w/c: water/cement ratio; ad.: amount of superplasticizing admixtures).

3.3. Group 3: 3% RCWTB; w/c Ratio Between 0.45 and 0.50; Admixture Amount Between 3.4% and 6.4% of the Cement Mass

In accordance with the conclusions reached in the second group of mixes, SCC containing 3% RCWTB was developed by fixing the w/c ratio at 0.45 and 0.50 and increasing the superplasticizing-admixture content in 0.6% steps up to 6.4% of the cement mass, which is the maximum recommended amount according to the design followed in a precast-concrete plant, as previously discussed. Third-group concrete compositions are detailed in Table 7 (*W3* mixes, 3% RCWTB, 0.45 w/c ratio) and Table 8 (*W3* mixes, 3% RCWTB, 0.50 w/c ratio).

Table 7. Mix design (kg/m^3) of the *W3* mixes (3% RCWTB) for 0.45 w/c and 3.4–6.4% ad.

Component	0.45 w/c; 3.4% ad.	0.45 w/c; 4.0% ad.	0.45 w/c; 4.6% ad.	0.45 w/c; 5.2% ad.	0.45 w/c; 5.8% ad.	0.45 w/c; 6.4% ad.
Cement	320	320	320	320	320	320
Water	145	145	145	145	145	145
Admixtures	10.9	12.8	14.7	16.6	18.6	20.5
Filler	170	170	170	170	170	170
Sand 0/2 mm	605	605	605	605	605	605
Sand 0/4 mm	595	595	595	595	595	595
Gravel 4/12 mm	540	540	540	540	540	540
RCWTB	33	33	33	33	33	33

w/c: water/cement ratio; ad.: amount of superplasticizing admixtures.

Table 8. Mix design (kg/m^3) of the *W3* mixes (3% RCWTB) for 0.50 w/c and 3.4–6.4% ad.

Component	0.50 w/c; 3.4% ad.	0.50 w/c; 4.0% ad.	0.50 w/c; 4.6% ad.	0.50 w/c; 5.2% ad.	0.50 w/c; 5.8% ad.	0.50 w/c; 6.4% ad.
Cement	320	320	320	320	320	320
Water	160	160	160	160	160	160
Admixtures	10.9	12.8	14.7	16.6	18.6	20.5
Filler	170	170	170	170	170	170
Sand 0/2 mm	605	605	605	605	605	605
Sand 0/4 mm	595	595	595	595	595	595
Gravel 4/12 mm	540	540	540	540	540	540
RCWTB	33	33	33	33	33	33

w/c: water/cement ratio; ad.: amount of superplasticizing admixtures.

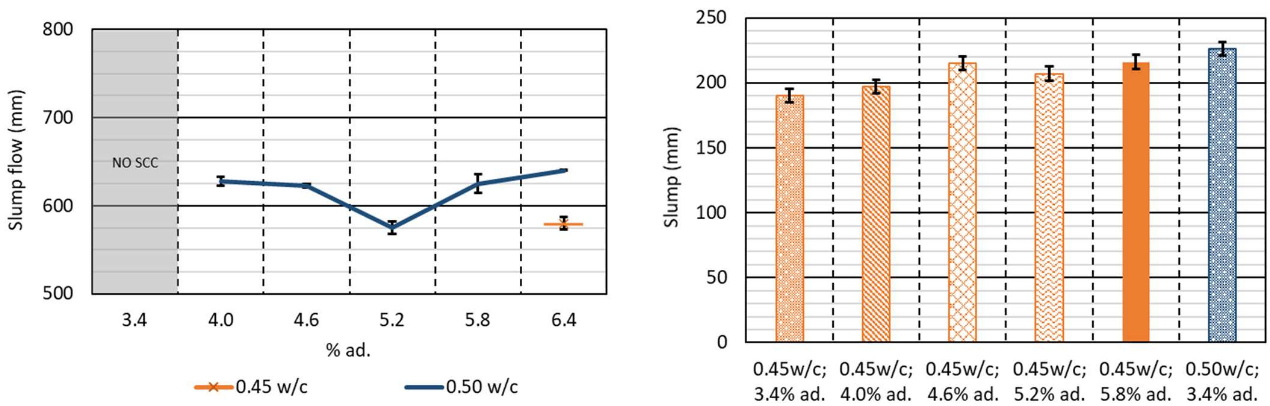
Figure 9 depicts the workability of the mixes of the third group: Figure 9a graphed the slump flows of SCC mixes and Figure 9b shows the achieved slump of non-SCC mixes. It can be noted that the *W3* mixes always led to a lower flowability than RCWTB contents of up to 2% (Figure 4), due to irregular shape of the particles of balsa wood and polymers and the interposition of the GFRP fibers in the flow of the other SCC components.

The increase of the w/c ratio from 0.45 to 0.50 notably augmented workability. First, a 3.4% amount of superplasticizers did not lead to self-compactability for any w/c ratio, but when a 0.50 w/c was used the slump achieved increased by 18.95% compared to a 0.45 w/c ratio (first and last columns in Figure 9b). Second, a w/c ratio of 0.50 allowed for SCC with 3% RCWTB when implementing contents of admixtures from 4.0%, while SCC with a w/c ratio of 0.45 was only achieved for 6.4% admixture. Finally, the slump flow of SCC with 6.4% admixture was 10.34% higher when a w/c ratio of 0.50 was considered.

Higher amounts of superplasticizing admixtures in general resulted in increased workability for both w/c ratios considered:

- Self-compactability was not achieved for a w/c ratio of 0.45 and admixture contents up to 5.8% of the cement mass, though the slump of concrete improved by 13.68%. Furthermore, SCC with a slump flow of 580 mm was only obtained for a superplasticizing-admixture amount of 6.4% of the cement mass. This increase in superplasticizers reduced cement's water demand, which allowed to increase the free water of the mix and thus its workability [59].

- Only an admixture content of 3.4% did not lead to self-compactability when considering a w/c ratio of 0.50 (slump of around 225 mm). For the remaining admixture contents, SCC was obtained, although two different trends were found. On the one hand, a reduction of the slump flow of up to 8.37% was noted in the mixes with admixture contents from 4.0% to 5.2%. The increase of free water generated by the admixtures and their inadequate interaction with RCWTB led to a premature segregation of the mixing water [65]. On the other hand, the trend completely changed from a superplasticizing-admixture content of 5.2% of the cement mass, as the slump flow increased by 11.30% for an admixture content of 6.4%. Therefore, higher admixture contents led to better results in terms of flowability when adding 3% RCWTB to SCC. Finally, it should be noted that the mix with 6.4% admixture exhibited a slump flow 1.99% higher than that of the mix with 4.0% admixture. The increase in the superplasticizing-admixture proportion successfully compensated the negative effect of the premature segregation of the mixing water found at lower admixture levels, as established in specific literature related to the effects of the admixtures in concrete [2].



(a) (b)

Figure 9. Workability of the mixes of the Group 3: (**a**) slump flow (0.45 w/c for 6.4% ad.; 0.50 w/c from 4.0% ad.); (**b**) slump (0.45 w/c up to 5.8% ad.; 0.50 w/c for 3.4% ad.) (w/c: water/cement ratio; ad.: amount of superplasticizing admixtures).

Figure 10 shows the results of the 7-day compressive strength of the mixes, where two clear trends can be perceived. First, increasing the w/c ratio from 0.45 to 0.50 caused an average reduction of 15.43% in the compressive strength. Second, the increase in the admixture content also led to a loss of strength, average reductions of 15.35% and 25.80% being obtained for w/c ratios 0.45 and 0.50, respectively. It seems clear that higher amounts of residual water augmented the porosity and weakened the cementitious matrix [67]. As a result of these two trends, admixture contents of 5.8% and 6.4% did not accomplish a compressive strength of 25 MPa when combined with a w/c ratio of 0.50, rendering those mixes as not being adequate for structural applications [52]. Finally, the SCC mixes with 3% RCWTB had a lower compressive strength than the mixes with lower waste amounts (Figure 5). Similar to conventional concrete [43], the particles of balsa wood and polymers present in the RCWTB created weak ITZ, while the GFRP fibers did not perform in an effective way when applying compression stresses to concrete.

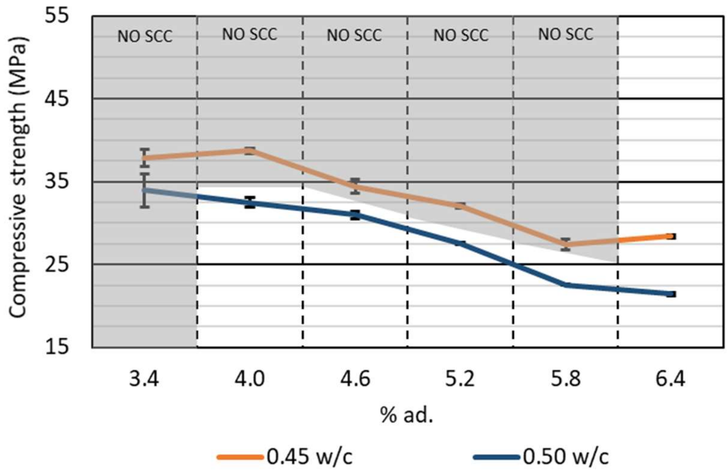


Figure 10. Compressive strength of the mixes of the Group 3 (w/c: water/cement ratio; ad.: amount of superplasticizing admixtures).

3.4. Group 4: RCWTB Content Between 4% and 5%; 0.50 w/c Ratio; Admixture Amount Between 4.0% and 6.4% of the Cement Mass

The mixtures with more than 3% RCWTB were developed with 0.50 w/c ratio and admixture contents up to 6.4% were considered. The minimum admixture content for 4% and 5% RCWTB was 4.0% and 4.6%, respectively, as the lower limit for admixtures was determined by the mix that achieved self-compactability with the immediately lower RCWTB content. The compositions of all the mixtures within this fourth group are detailed in Table 9 (*W4* mixes, 4% RCWTB) and Table 10 (*W5* mixes, 5% RCWTB).

Table 9. Mix design (kg/m^3) of the *W4* mixes (4% RCWTB) for 0.50 w/c and 4.0–6.4% ad.

Component	0.50 w/c; 4.0% ad.	0.50 w/c; 4.6% ad.	0.50 w/c; 5.2% ad.	0.50 w/c; 5.8% ad.	0.50 w/c; 6.4% ad.
Cement	320	320	320	320	320
Water	160	160	160	160	160
Admixtures	12.8	14.7	16.6	18.6	20.5
Filler	170	170	170	170	170
Sand 0/2 mm	600	600	600	600	600
Sand 0/4 mm	585	585	585	585	585
Gravel 4/12 mm	535	535	535	535	535
RCWTB	44.3	44.3	44.3	44.3	44.3

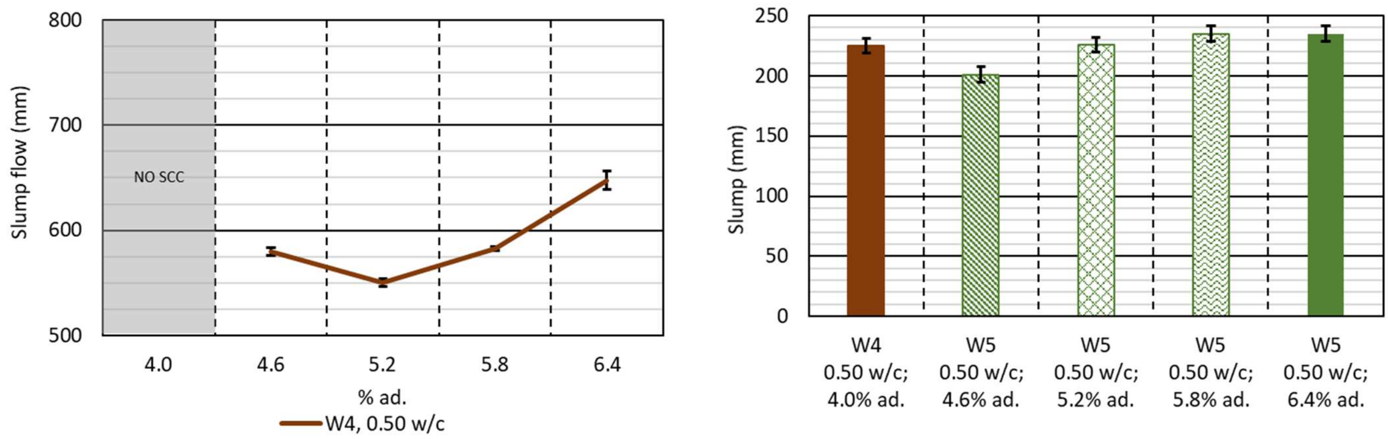
w/c: water/cement ratio; ad.: amount of superplasticizing admixtures.

Table 10. Mix design (kg/m^3) of the *W5* mixes (5% RCWTB) for 0.50 w/c and 4.0–6.4% ad.

Component	0.50 w/c; 4.6% ad.	0.50 w/c; 5.2% ad.	0.50 w/c; 5.8% ad.	0.50 w/c; 6.4% ad.
Cement	320	320	320	320
Water	160	160	160	160
Admixtures	14.7	16.6	18.6	20.5
Filler	170	170	170	170
Sand 0/2 mm	595	595	595	595
Sand 0/4 mm	580	580	580	580
Gravel 4/12 mm	525	525	525	525
RCWTB	55.3	55.3	55.3	55.3

w/c: water/cement ratio; ad.: amount of superplasticizing admixtures.

The fresh properties (slump flow or slump) of the mixes of this fourth group are shown in Figure 11, in the same way as previous figures.



(**a**) (**b**)

Figure 11. Workability of the mixes of the Group 4: (**a**) slump flow (*W4* mixes from 4.6% ad.); (**b**) slump (*W4* mix with 4.0% ad.; *W5* mixes) (w/c: cement/cement ratio; ad: amount of superplasticizing admixtures).

As the w/c ratio was fixed at a value of 0.50, the amount of superplasticizing admixtures and the RCWTB content were the two factors that influenced the fresh performance of concrete. The following aspects did stand out:

- SCC containing 4% RCWTB was developed when the admixture content was at least 4.6% of the cement mass. Additionally, the slump flow results obtained for *W4* when increasing the admixture proportion exhibited the same behavior trend as that of SCC from *W3* with 0.50 w/c ratio. Thus, the slump flow decreased by 5.17% when increasing the admixtures from 4.6% to 5.2% of the cement mass, and then increased by 17.72% when reaching 6.4% admixture. While superplasticizing admixtures favored a premature segregation of the free water when used up to 5.2% of the cement mass [2], higher amounts of superplasticizers reduced that segregation and interacted better with the RCWTB, allowing higher slump flows to be obtained [65].
- SCC was not achieved for 5% RTCWB, although the slump increased by 5.47% on average with increasing percentages of admixtures. Superplasticizers reduced the water consumed by cement during its hydration, which facilitated the relative displacement and flow of the particles compositing the concrete [72], yet not being enough to reach self-compactability.
- The addition of RCWTB reduced the workability of concrete in all cases, whether or not self-compactability was reached. Thus, 5% RCWTB did not allow SCC to be developed for admixture quantities for which SCC containing 4% RCWTB was successfully produced. Furthermore, the *W4* mixes showed lower slump flows than the *W3* mixes with exactly the same w/c ratio and admixture content (Figure 9). The GFRP fibers in this residue hindered the displacement and flow of the coarse-aggregate particles [64]. In addition, RCWTB increased the specific surface area of the SCC components to be covered by the cement paste [30].

The compressive strength of the *W4* and *W5* mixes measured at 7 days is shown in Figure 12. Consistent with other groups of mixes analyzed in this study, the increase of the admixture amount caused a reduction in the compressive strength. For the *W4* mixes, a reduction of 13.00% between admixture proportions of 4.0% and 6.4% was recorded, these mixes exhibiting similar levels of compressive strength than the SCC *W3* mixes (Figure 10). In the *W5* mixes, a reduction of 31.98% was measured from an admixture content of 4.6% to an amount of 6.4%. In fact, the mixes with admixture amounts of 5.8% and 6.4% of the cement mass did not reach the minimum value for use in structural applications of 25 MPa [52]. This negative effect of RCWTB on compressive strength was due to the replacement of the aggregates with weaker particles of balsa wood and polymers contained in this residue, which also decreased the bond in the ITZ [69]. However, the loss of self-compactability that occurred when adding 5% RCWTB to concrete could partly counteract that phenomenon [73].

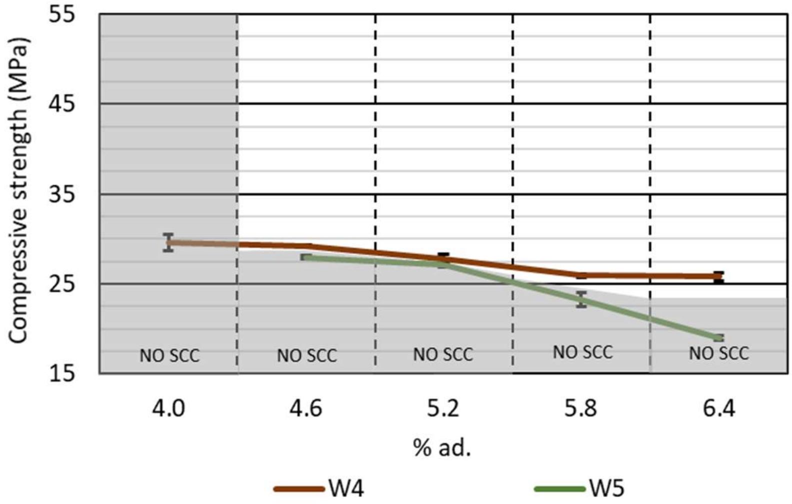


Figure 12. Compressive strength of the mixes of the Group 4 (w/c: water/cement ratio; ad.: amount of superplasticizing admixtures).

3.5. Statistical Evaluation Through an ANOVA

The results obtained in this study were statistically validated according to an ANOVA performed at a confidence level of 95%, as in other research in the literature [58]. This procedure was used to define whether each of the three factors analyzed (RCWTB content, w/c ratio and superplasticizing-admixture amount) significantly affected the two properties evaluated, slump flow and 7-day compressive strength. For this purpose, all the experimental replicates were used [57], i.e., all the values of slump flow and compressive strength recorded in the mixes that reached self-compactability, not only the average results. Table 11 shows the results of such ANOVA. On the one hand, a *p*-value below 0.05 indicates that the effect of a factor was significant for the SCC performance. On the other hand, homogeneous groups indicate the values of the factors that statistically led to the same behavior in the SCC.

Table 11. ANOVA results.

Property	*p*-Value			Homogeneous Groups		
	RCWTB	w/c	ad.	RCWTB	w/c	ad.
Slump flow	0.0000	0.0000	0.0000	0%, 1%, and 2% 3% and 4%	None	2.2% and 2.8% 3.4% and 4.0% 4.6%, 5.2%, and 5.8%
Compressive strength	0.0000	0.0000	0.0000	2%, 3%, and 4%	None	2.8%, 3.4%, and 4.0%

RCWTB: content of RCWTB; w/c: water/cement ratio; ad.: amount of superplasticizing admixtures.

All three factors had a significant influence on the performance of SCC both in terms of slump flow and compressive strength. These results therefore justified the need to study the behavioral variations of SCC produced with different RCWTB contents and changing w/c ratios and admixture contents, which has been addressed in this research. The homogeneous groups also revealed interesting aspects:

- Each w/c ratio led to a different SCC behavior in terms of slump flow and compressive strength, underscoring the importance of carefully controlling this design parameter [74], especially when RCWTB is added.

- The incorporation of RCWTB only affected the slump flow of the SCC in a relevant way when it was added in a proportion equal to or higher than 3%. Over this threshold, conventional SCC design was not valid due to the interposition of the GFRP fibers in the flow of the rest of the SCC components [31]. In terms of compressive strength, however, RCWTB amounts above 2% always led to equivalent performance.
- The superplasticizing-admixture content could be divided into three groups that led to equivalent fresh behavior of the SCC. First, the admixture contents corresponding to a conventional design (2.2% and 2.8%). Second, intermediate contents of 3.4% and 4.0%. Finally, high contents (4.6%, 5.2% and 5.8%). Conventional admixture contents were adequate when adding up to 2% RCWTB, while the proportion of admixtures had to be increased to values generally above 4.0% of the cement mass for RCWTB contents of 3.0% or higher. It is common that the addition of wastes to SCC leads to higher amounts of superplasticizers in the mix design to maintain flowability [63]. The levels of compressive strength were equivalent for admixture amounts between 2.8% and 4.0%.

3.6. MCDM Optmization

To conclude the study, the optimal w/c ratio and superplasticizing-admixture amount for each RCWTB content level at which SCC was successfully produced, was determined. The aim was to define the most adequate mix design to get a balanced flowability and strength performance in SCC. For this purpose, a MCDM analysis was performed using the TOPSIS algorithm, which is common in concrete optimization [59], and considering the slump flow and the 7-day compressive strength as the decision factors. These two factors were rated as equally important, so that each of them represented a 50% weight in the decision.

The results obtained are shown in Figure 13, which aligned closely with all the aspects discussed throughout the paper. On the one hand, the optimum w/c ratio when adding up to 2% RCWTB to SCC was 0.45, while the optimum admixture content was 2.8% (Figure 13a). Therefore, a conventional SCC design was valid up to the *W*2 mixes, the best option being to maintain a low w/c ratio to avoid a high loss of compressive strength [51] and a high enough admixture content to maximize flowability [63]. On the other hand, it was necessary to use intermediate w/c ratios (0.50 in this case) to compensate for the negative effects of the GFRP fibers on the flowability of the SCC for RCWTB contents from 3%. However, this resulted in a decrease in compressive strength, so that the minimum admixture contents that allowed self-compactability to be achieved (4.0% for 3% RCWTB and 4.6% for 4% RCWTB) were optimal to avoid excessive strength losses [75].

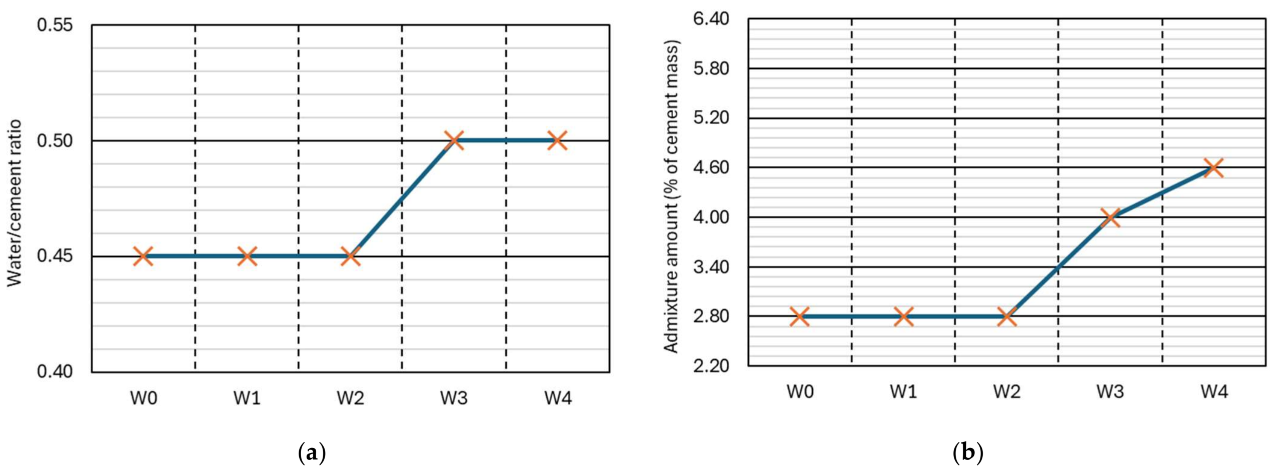


Figure 13. MCDM analysis of the SCC mixes: (**a**) optimum w/c ratios; (**b**) optimum amounts of superplasticizing admixtures.

4. Conclusions and Future Research Lines

The urgent need in the wind-energy sector to find a sustainable way to recycle wind-turbine blades has led to the exploration of various possibilities to repurpose this waste material. This research introduces a non-selective crush and sieve of wind-turbine blades to generate Raw-Crushed Wind-Turbine Blade (RCWTB), which contains a high proportion of GFRP fibers but also particles of balsa wood and different polymers. Such waste can be incorporated in Self-Compacting Concrete (SCC). The research is focused on defining an SCC design that yields proper flowability and compressive strength when incorporating this waste. This research dimension has been addressed in this paper, the key conclusions regarding the design of SCC incorporating RCWTB being the following:

- Increasing the water/cement (w/c) ratio was necessary to achieve self-compactability with higher RCWTB contents. A w/c ratio of 0.45 and 0.50 was adequate for up to 2% RCWTB, while for higher contents, a 0.50 w/c ratio was required. A w/c ratio of 0.55 caused premature segregation of SCC.
- Higher proportions of superplasticizers were needed to achieve self-compactability with larger RCWTB contents. The effectiveness of conventional amounts of admixtures decreased at high RCWTB levels. An admixture content of 2.8% of the cement mass is recommended up to 2% RCWTB, and 4–6% for higher RCWTB amounts.
- Compressive strength decreased with increased RCWTB due to the presence of weak balsa-wood and polymer particles, and increasing w/c ratios and admixture proportions. However, a minimum strength of 25 MPa was always achieved, suitable for structural applications such as slabs, beams, pavements, and precast elements, among others, according standards [47].
- Following a multi-criteria decision-making analysis, the optimal w/c ratio was 0.45 for up to 2% RCWTB, and 0.50 for higher contents. The optimal admixture content was 2.8% of the cement mass up to 2% RCWTB, 4.0% for 3% RCWTB, and 4.6% for 4% RCWTB.
- SCC could not be developed with 5% RCWTB, even with admixture amounts up to 6.4%. The irregular shape and surface roughness of balsa-wood and polymer particles, as well as the GFRP fibers interfered with the flow of the other components, which could not be counterbalanced by adjusting the w/c ratio and admixture content.

Overall, it is determined that the addition of RCWTB to SCC is possible through a careful mix design, which depends on the percentage of waste incorporated into the concrete mix. This approach enables a balance between an adequate slump flow and a proper compressive strength required for structural use. However, the authors suggest that further research steps are needed for a comprehensive evaluation performance of SCC with RCWTB produced following the key aspects of design found in this research:

- First of all, it would be necessary to evaluate the passing ability of the SCC mixes produced. For this, it is not enough with an adequate flowability [76], but also an adequate segregation resistance that guarantees the cohesion of the mixture when flowing [77], and an adequate packing structure that is capable of properly dragging all the aggregate particles of the SCC [78]. In this way, the proportion of aggregate fines could be accurately adjusted according to fresh requirements [77], while not affecting and even improving the mechanical performance of SCC [79–81]. Thus, an SCC containing RCWTB that would be valid for a wide range of applications could be developed from the point of view of the fresh performance.
- Second, an overall analysis of the mechanical, durability, environmental, including toxicity, and economic performance of SCC would be needed. In this way, it is guaranteed that the performance of SCC containing RCWTB is adequate in all performance dimensions [37], not only in terms of fresh behavior and compressive strength, although it is the basic strength property of concrete [51].

- Multi-criteria optimization could then be conducted by accounting all the properties of SCC [58,59]. Thus, the optimal RCWTB content in SCC could be defined, point from which the analysis of real elements manufactured with such type of mixes could be addressed [52].

Author Contributions: Conceptualization, M.H.-R. and V.R.-C.; methodology, V.R.-C. and V.O.-L.; software, M.H.-R. and V.R.-C.; validation, N.H.-A. and J.M.-M.; formal analysis, M.H.-R. and V.R.-C.; investigation, M.H.-R., V.R.-C., N.H.-A. and J.M.-M.; resources, V.O.-L.; data curation, M.H.-R. and V.R.-C.; writing—original draft preparation, M.H.-R. and V.R.-C.; writing—review and editing, J.M.-M., N.H.-A. and V.O.-L.; visualization, J.M.-M., N.H.-A. and V.O.-L.; supervision, V.R.-C. and V.O.-L.; project administration, V.O.-L.; funding acquisition, V.O.-L. All authors have read and agreed to the published version of the manuscript.

Funding: This research work was supported by MICIU, AEI, EU, ERDF and NextGenerationEU/PRTR [grant numbers PID2023-146642OB-I00; 10.13039/501100011033; TED2021-129715B-I00; FPU21/04364]; the Junta de Castilla y León (Regional Government) and ERDF [grant number UIC-231; BU033P23; BU066-22]; and, finally, the University of Burgos [grant number SUCONS, Y135.GI].

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Hoang, Q.G.; Vu, Q.V. Estimation the Initial Cement Dosage of Concrete from Mechanical Behavior and Chemical Analysis. *Civ. Eng. Arch.* **2020**, *8*, 580–585. [CrossRef]
2. Ferraris, C.F.; Obla, K.H.; Hill, R. The Influence of Mineral Admixtures on the Rheology of Cement Paste and Concrete. *Cem. Concr. Res.* **2001**, *31*, 245–255. [CrossRef]
3. Elahi, A.; Basheer, P.A.M.; Nanukuttan, S.V.; Khan, Q.U.Z. Mechanical and Durability Properties of High Performance Concretes Containing Supplementary Cementitious Materials. *Constr. Build. Mater.* **2010**, *24*, 292–299. [CrossRef]
4. Silva, R.V.; de Brito, J.; Dhir, R.K. Tensile Strength Behaviour of Recycled Aggregate Concrete. *Constr. Build. Mater.* **2015**, *83*, 108–118. [CrossRef]
5. Nagrockienė, D.; Girskas, G.; Skripkiūnas, G. Properties of Concrete Modified with Mineral Additives. *Constr. Build. Mater.* **2017**, *135*, 37–42. [CrossRef]
6. Özalp, F.; Yilmaz, H.D.; Kara, M.; Kaya, Ö.; Şahin, A. Effects of Recycled Aggregates from Construction and Demolition Wastes on Mechanical and Permeability Properties of Paving Stone, Kerb and Concrete Pipes. *Constr. Build. Mater.* **2016**, *110*, 17–23. [CrossRef]
7. Merli, R.; Preziosi, M.; Acampora, A.; Lucchetti, M.C.; Petrucci, E. Recycled Fibers in Reinforced Concrete: A Systematic Literature Review. *J. Clean. Prod.* **2020**, *248*, 119207. [CrossRef]
8. Habibi, A.; Ghomashi, J. Development of an Optimum Mix Design Method for Self-Compacting Concrete Based on Experimental Results. *Constr. Build. Mater.* **2018**, *168*, 113–123. [CrossRef]
9. Krząkała, J.; Łaziński, P.; Gerges, M.; Pyrzowski, Ł.; Grządziela, G. Influence of Actual Curing Conditions on Mechanical Properties of Concrete in Bridge Superstructures. *Materials* **2023**, *16*, 54. [CrossRef]
10. Cu, Y.T.H.; Tran, M.V.; Ho, C.H.; Nguyen, P.H. Relationship between Workability and Rheological Parameters of Self-Compacting Concrete Used for Vertical Pump up to Supertall Buildings. *J. Build. Eng.* **2020**, *32*, 101786. [CrossRef]
11. Reddy Suda, V.B. Compressive Strength, Flexural Strength and Modulus of Elasticity Relationships of Ternary Blended Concrete. In *IOP Conference Series: Earth and Environmental Science*; IOP Publishing: Bristol, UK, 2022; Volume 1086, p. 012046. [CrossRef]
12. Novak, J.; Kohoutkova, A. Mechanical Properties of Concrete Composites Subject to Elevated Temperature. *Fire Saf. J.* **2018**, *95*, 66–76. [CrossRef]
13. Schwartzentruber, L.D.; Le Roy, R.; Cordin, J. Rheological Behaviour of Fresh Cement Pastes Formulated from a Self Compacting Concrete (SCC). *Cem. Concr. Res.* **2006**, *36*, 1203–1213. [CrossRef]
14. Santamaría, A.; Orbe, A.; Losañez, M.M.; Skaf, M.; Ortega-Lopez, V.; González, J.J. Self-Compacting Concrete Incorporating Electric Arc-Furnace Steelmaking Slag as Aggregate. *Mater. Des.* **2017**, *115*, 179–193. [CrossRef]
15. Autier, C.; Azema, N.; Taulemesse, J.-M.; Clerc, L. Mesostructure Evolution of Cement Pastes with Addition of Superplasticizers Highlighted by Dispersion Indices. *Powder Technol.* **2013**, *249*, 282–289. [CrossRef]
16. Sáez-Pérez, M.P.; Verdú-Vazquez, A.; Patón-Aguilera, M. Diseño de Hormigón Autocompactante Con Aditivos Sintéticos de 4 a Generación. *DYNA* **2019**, *94*, 455–459. [CrossRef]
17. Vanhove, Y.; Djelal, C.; Schwendenmann, G.; Brisset, P. Study of Self Consolidating Concretes Stability during Their Placement. *Constr. Build. Mater.* **2012**, *35*, 101–108. [CrossRef]
18. Long, G.; Gao, Y.; Xie, Y. Designing More Sustainable and Greener Self-Compacting Concrete. *Constr. Build. Mater.* **2015**, *84*, 301–306. [CrossRef]

19. Long, W.-J.; Gu, Y.; Liao, J.; Xing, F. Sustainable Design and Ecological Evaluation of Low Binder Self-Compacting Concrete. *J. Clean. Prod.* **2017**, *167*, 317–325. [CrossRef]
20. Bui, V.K.; Montgomery, D.; Hinczak, I.; Turner, K. Rapid Testing Method for Segregation Resistance of Self-Compacting Concrete. *Cem. Concr. Res.* **2002**, *32*, 1489–1496. [CrossRef]
21. Aslani, F.; Ma, G.; Yim Wan, D.L.; Muselin, G. Development of High-Performance Self-Compacting Concrete Using Waste Recycled Concrete Aggregates and Rubber Granules. *J. Clean. Prod.* **2018**, *182*, 553–566. [CrossRef]
22. Murthy, N.K.; Rao, N.; Reddy, I.R.; Reddy, M.V.S. Mix Design Procedure for Self-Compacting Concrete. *IOSR J. Eng.* **2012**, *2*, 33–41. [CrossRef]
23. Zong, L.; Zhang, S.P.; Liang, P.X. Experiment Study on the Durability of Dry-Mixing Self-Compacting Concrete. *Adv. Mat. Res.* **2011**, *250–253*, 493–496.
24. Volaš, J.; Broćeta, G.; Krndija, M.L.; Šupić, S.; Pantić, V.; Malešev, M.; Radonjanin, V.; Cumbo, A.; Savić, A.; Lazić, Ž. Effect of the HRWRA Quantity on Durability Properties of Self-Compacting Concrete. In Proceedings of the International Conference on Contemporary Theory and Practice in Construction XVI, Banja Luka, Bosnia and Herzegovina, 13–14 June 2024; Volume 16, pp. 351–362.
25. Revilla-Cuesta, V.; Fiol, F.; Perumal, P.; Ortega-López, V.; Manso, J.M. Using Recycled Aggregate Concrete at a Precast-Concrete Plant: A Multi-Criteria Company-Oriented Feasibility Study. *J. Clean. Prod.* **2022**, *373*, 133873. [CrossRef]
26. Rasekh, H.; Joshaghani, A.; Jahandari, S.; Aslani, F.; Ghodrat, M. 2—Rheology and Workability of SCC. In *Self-Compacting Concrete: Materials, Properties and Applications*; Siddique, R., Ed.; Woodhead Publishing: Sawston, UK, 2020; pp. 31–63, ISBN 978-0-12-817369-5.
27. Paul, V.K.; Khursheed, S.; Jain, S. Benefit Cost Analysis of Self Compacting Concrete over Conventional Reinforced Cement Concrete. *Int. J. Res. Eng. Technol.* **2017**, *6*, 64–74.
28. Zhu, D.; Mobasher, B.; Peled, A. Experimental Study of Dynamic Behavior of Cement-Based Composites. *J. Sustain. Cem. Based Mater.* **2013**, *2*, 1–12. [CrossRef]
29. Wu, Z.; Shi, C.; He, W.; Wu, L. Effects of Steel Fiber Content and Shape on Mechanical Properties of Ultra High Performance Concrete. *Constr. Build. Mater.* **2016**, *103*, 8–14. [CrossRef]
30. Zeyad, A.M. Effect of Fibers Types on Fresh Properties and Flexural Toughness of Self-Compacting Concrete. *J. Mater. Res. Technol.* **2020**, *9*, 4147–4158. [CrossRef]
31. Li, K.F.; Yang, C.Q.; Huang, W.; Zhao, Y.B.; Wang, Y.; Pan, Y.; Xu, F. Effects of Hybrid Fibers on Workability, Mechanical, and Time-Dependent Properties of High Strength Fiber-Reinforced Self-Consolidating Concrete. *Constr. Build. Mater.* **2021**, *277*, 122325. [CrossRef]
32. Ghamari, A.; Kurdi, J.; Shemirani, A.B.; Haeri, H. Experimental Investigating the Properties of Fiber Reinforced Concrete by Combining Different Fibers. *Comp. Concr.* **2020**, *25*, 509–516. [CrossRef]
33. Yoo, D.-Y.; Lee, J.-H.; Yoon, Y.-S. Effect of Fiber Content on Mechanical and Fracture Properties of Ultra High Performance Fiber Reinforced Cementitious Composites. *Compos. Struct.* **2013**, *106*, 742–753. [CrossRef]
34. Hatami Jorbat, M.; Hosseini, M.; Mahdikhani, M. Effect of Polypropylene Fibers on the Mode I, Mode II, and Mixed-Mode Fracture Toughness and Crack Propagation in Fiber-Reinforced Concrete. *Theor. Appl. Fract. Mech.* **2020**, *109*, 102723. [CrossRef]
35. Kwan, W.H.; Cheah, C.B.; Ramli, M.; Chang, K.Y. Alkali-Resistant Glass Fiber Reinforced High Strength Concrete in Simulated Aggressive Environment. *Mater. Constr.* **2018**, *68*, 147. [CrossRef]
36. More, F.M.D.S.; Subramanian, S.S. Impact of Fibres on the Mechanical and Durable Behaviour of Fibre-Reinforced Concrete. *Buildings* **2022**, *12*, 1436. [CrossRef]
37. Manso-Morato, J.; Hurtado-Alonso, N.; Revilla-Cuesta, V.; Skaf, M.; Ortega-López, V. Fiber-Reinforced Concrete and Its Life Cycle Assessment: A Systematic Review. *J. Build. Eng.* **2024**, *94*, 110062. [CrossRef]
38. Mastali, M.; Dalvand, A.; Sattarifard, A.R.; Illikainen, M. Development of Eco-Efficient and Cost-Effective Reinforced Self-Consolidation Concretes with Hybrid Industrial/Recycled Steel Fibers. *Constr. Build. Mater.* **2018**, *166*, 214–226. [CrossRef]
39. Tao, Y.; Hadigheh, S.A.; Wei, Y. Recycling of Glass Fibre Reinforced Polymer (GFRP) Composite Wastes in Concrete: A Critical Review and Cost Benefit Analysis. *Structures* **2023**, *53*, 1540–1556. [CrossRef]
40. Rani, M.; Choudhary, P.; Krishnan, V.; Zafar, S. A Review on Recycling and Reuse Methods for Carbon Fiber/Glass Fiber Composites Waste from Wind Turbine Blades. *Compos. Part B Eng.* **2021**, *215*, 108768. [CrossRef]
41. Joustra, J.; Flipsen, B.; Balkenende, R. Structural Reuse of Wind Turbine Blades through Segmentation. *Comp. Part C Open Access* **2021**, *5*, 100137. [CrossRef]
42. Revilla-Cuesta, V.; Skaf, M.; Ortega-López, V.; Manso, J.M. Raw-Crushed Wind-Turbine Blade: Waste Characterization and Suitability for Use in Concrete Production. *Resour. Conserv. Recycl.* **2023**, *198*, 107160. [CrossRef]
43. Revilla-Cuesta, V.; Manso-Morato, J.; Hurtado-Alonso, N.; Skaf, M.; Ortega-López, V. Mechanical and Environmental Advantages of the Revaluation of Raw-Crushed Wind-Turbine Blades as a Concrete Component. *J. Build. Eng.* **2024**, *82*, 108383. [CrossRef]
44. Hernando-Revenga, M.; Revilla-Cuesta, V.; Chica, J.A.; Ortega-López, V.; Manso, J.M. Initial Approach to Self-Compacting Concrete with Raw-Crushed Wind-Turbine Blade: Fresh, CFD and Mechanical Analysis. *Appl. Sci.* **2024**, *14*, 9946. [CrossRef]
45. Baturkin, D.; Hisseine, O.A.; Masmoudi, R.; Tagnit-Hamou, A.; Massicotte, L. Valorization of Recycled FRP Materials from Wind Turbine Blades in Concrete. *Resour. Conserv. Recycl.* **2021**, *174*, 105807. [CrossRef]

46. Corinaldesi, V.; Donnini, J.; Nardinocchi, A. Lightweight Plasters Containing Plastic Waste for Sustainable and Energy-Efficient Building. *Constr. Build. Mater.* **2015**, *94*, 337–345. [CrossRef]
47. *EN 197-1*; EN-Euronorm. European Committee for Standardization: Brussels, Belgium.
48. de Azevedo, A.R.G.; Alexandre, J.; Xavier, G.D.C.; Pedroti, L.G. Recycling Paper Industry Effluent Sludge for Use in Mortars: A Sustainability Perspective. *J. Clean. Prod.* **2018**, *192*, 335–346. [CrossRef]
49. Banfill, P.F.G. Additivity Effects in the Rheology of Fresh Concrete Containing Water-Reducing Admixtures. *Constr. Build. Mater.* **2011**, *25*, 2955–2960. [CrossRef]
50. Nepomuceno, M.C.S.; Pereira-De-Oliveira, L.A.; Lopes, S.M.R.; Franco, R.M.C. Maximum Coarse Aggregate's Volume Fraction in Self-Compacting Concrete for Different Flow Restrictions. *Constr. Build. Mater.* **2016**, *113*, 851–856. [CrossRef]
51. Elemam, W.E.; Abdelraheem, A.H.; Mahdy, M.G.; Tahwia, A.M. Optimizing Fresh Properties and Compressive Strength of Self-Consolidating Concrete. *Constr. Build. Mater.* **2020**, *249*, 118781. [CrossRef]
52. Fiol, F.; Revilla-Cuesta, V.; Skaf, M.; Thomas, C.; Manso, J.M. Scaled Concrete Beams Containing Maximum Levels of Coarse Recycled Aggregate: Structural Verifications for Precast-Concrete Building Applications. *Struct. Concr.* **2023**, *24*, 3476–3497. [CrossRef]
53. Zhu, W.; Gibbs, J.C. Use of Different Limestone and Chalk Powders in Self-Compacting Concrete. *Cem. Concr. Res.* **2005**, *35*, 1457–1462. [CrossRef]
54. Benjeddou, O.; Soussi, C.; Jedidi, M.; Benali, M. Experimental and Theoretical Study of the Effect of the Particle Size of Limestone Fillers on the Rheology of Self-Compacting Concrete. *J. Build. Eng.* **2017**, *10*, 32–41. [CrossRef]
55. Benaicha, M.; Belcaid, A.; Alaoui, A.H.; Jalbaud, O.; Burtschell, Y. Effects of Limestone Filler and Silica Fume on Rheology and Strength of Self-compacting Concrete. *Struct. Concr.* **2019**, *20*, 1702–1709. [CrossRef]
56. Ortega, J.J.; Ruiz, G.; Poveda, E.; González, D.C.; Tarifa, M.; Zhang, X.X.; Yu, R.C.; Vicente, M.Á.; de la Rosa, Á.; Garijo, L. Size Effect on the Compressive Fatigue of Fibre-Reinforced Concrete. *Constr. Build. Mater.* **2022**, *322*, 126238. [CrossRef]
57. Cantero, B.; Bravo, M.; de Brito, J.; Sáez del Bosque, I.F.; Medina, C. Water Transport and Shrinkage in Concrete Made with Ground Recycled Concrete-Additioned Cement and Mixed Recycled Aggregate. *Cem. Concr. Compos.* **2021**, *118*, 103957. [CrossRef]
58. Cantero, B.; Neves, R.; Sequeira, L.; de Brito, J.; Bravo, M. Optimisation of the Performance of Alkali-Activated Mortars Using CDW Binders from Different Sources. *Constr. Build. Mater.* **2024**, *442*, 137677. [CrossRef]
59. Warda, M.A.; Ahmad, S.S.E.; Mahdi, I.M.; Sallam, H.E.-D.M.; Khalil, H.S. The Applicability of TOPSIS- and Fuzzy TOPSIS-Based Taguchi Optimization Approaches in Obtaining Optimal Fiber-Reinforced Concrete Mix Proportions. *Buildings* **2022**, *12*, 796. [CrossRef]
60. Qiu, J.; Guo, Z.; Yang, L.; Jiang, H.; Zhao, Y. Effects of Packing Density and Water Film Thickness on the Fluidity Behaviour of Cemented Paste Backfill. *Powder Technol.* **2020**, *359*, 27–35. [CrossRef]
61. Ibrahim, H.A.; Abbas, W.A. Fresh Properties of Self-Consolidating Expired Cement-Fly Ash Cold Bonded Lightweight Aggregate Concrete with Different Mineral Admixtures. *Eng. Tech. J.* **2023**, *41*, 734–744. [CrossRef]
62. Safiuddin, M.; West, J.S.; Soudki, K.A. Properties of Freshly Mixed Self-Consolidating Concretes Incorporating Rice Husk Ash as a Supplementary Cementing Material. *Constr. Build. Mater.* **2012**, *30*, 833–842. [CrossRef]
63. Li, L.G.; Kwan, A.K.H. Effects of Superplasticizer Type on Packing Density, Water Film Thickness and Flowability of Cementitious Paste. *Constr. Build. Mater.* **2015**, *86*, 113–119. [CrossRef]
64. Saba, A.M.; Khan, A.H.; Akhtar, M.N.; Khan, N.A.; Rahimian Koloor, S.S.; Petrů, M.; Radwan, N. Strength and Flexural Behavior of Steel Fiber and Silica Fume Incorporated Self-Compacting Concrete. *J. Mater. Res. Technol.* **2021**, *12*, 1380–1390. [CrossRef]
65. Prakash, R.; Raman, S.N.; Divyah, N.; Subramanian, C.; Vijayaprabha, C.; Praveenkumar, S. Fresh and Mechanical Characteristics of Roselle Fibre Reinforced Self-Compacting Concrete Incorporating Fly Ash and Metakaolin. *Constr. Build. Mater.* **2021**, *290*, 123209. [CrossRef]
66. Mansor, A.M.; Borg, R.P.; Hamed, A.M.; Gadeem, M.M.; Saeed, M.M. The Effects of Water-Cement Ratio and Chemical Admixtures on the Workability of Concrete. In *IOP Conference Series: Materials Science and Engineering*; IOP Publishing: Bristol, UK, 2018; Volume 442, p. 012017. [CrossRef]
67. Salain, I. Effect of Water/Cement and Aggregate/Cement Ratios on Consistency and Compressive Strength of Concrete Using Volcanic Stone Waste as Aggregates. *Civ. Eng. Arch.* **2021**, *9*, 1900–1908. [CrossRef]
68. Gu, L.; Ozbakkaloglu, T. Use of Recycled Plastics in Concrete: A Critical Review. *Waste Manag.* **2016**, *51*, 19–42. [CrossRef] [PubMed]
69. Trento, D.; Faleschini, F.; Revilla-Cuesta, V.; Ortega-López, V. Improving the Early-Age Behavior of Concrete Containing Coarse Recycled Aggregate with Raw-Crushed Wind-Turbine Blade. *J. Build. Eng.* **2024**, *92*, 109815. [CrossRef]
70. Kim, Y.-Y.; Lee, K.-M.; Bang, J.-W.; Kwon, S.-J. Effect of W/C Ratio on Durability and Porosity in Cement Mortar with Constant Cement Amount. *Adv. Mater. Sci. Eng.* **2014**, *2014*, 273460. [CrossRef]
71. Wang, L.; Ma, Y.; Li, L. Uncovering the Role of Superplasticizer in Developing Nano-Engineered Ultra-High-Performance Concrete. *Front. Mater.* **2023**, *10*, 1177189. [CrossRef]
72. Kwan, A.K.H.; Ng, I.Y.T. Optimum Superplasticiser Dosage and Aggregate Proportions for SCC. *Mag. Concr. Res.* **2009**, *61*, 281–292. [CrossRef]
73. Domone, P.L. A Review of the Hardened Mechanical Properties of Self-Compacting Concrete. *Cem. Concr. Compos.* **2007**, *29*, 1–12. [CrossRef]

74. Nematollahzade, M.; Tajadini, A.; Afshoon, I.; Aslani, F. Influence of Different Curing Conditions and Water to Cement Ratio on Properties of Self-Compacting Concretes. *Constr. Build. Mater.* **2020**, *237*, 117570. [CrossRef]
75. Casagrande, C.A.; Jochem, L.F.; Onghero, L.; Ricardo de Matos, P.; Repette, W.L.; Gleize, P.J.P. Effect of Partial Substitution of Superplasticizer by Silanes in Portland Cement Pastes. *J. Build. Eng.* **2020**, *29*, 101226. [CrossRef]
76. Lai, M.H.; Griffith, A.M.; Hanzic, L.; Wang, Q.; Ho, J.C.M. Interdependence of passing ability, dilatancy and wet packing density of concrete. *Constr. Build. Mater.* **2021**, *270*, 121440. [CrossRef]
77. Lai, M.; Hanzic, L.; Ho, J.C.M. Fillers to improve passing ability of concrete. *Struct. Concr.* **2019**, *20*, 185–197. [CrossRef]
78. Huang, Z.; Zhang, B.; Ho, J.C.M.; Ren, F.; Lai, M. Improving passing ability of ultra-heavy-weight concrete by optimising its packing structure. *Mag. Concr. Res.* **2024**, *76*, 1266–1278. [CrossRef]
79. Lai, M.H.; Lin, J.L.; Cui, J.; Ren, F.M.; Kitipornchai, S.; Ho, J.C.M. A novel packing-coupled stress-strain model for confined concrete. *Eng. Struct.* **2024**, *303*, 117415. [CrossRef]
80. Lai, M.H.; Lu, Z.Y.; Luo, Y.T.; Ren, F.M.; Cui, J.; Wu, Z.R.; Ho, J.C.M. Pre- and post-fire behaviour of glass concrete from wet packing density perspective. *J. Build. Eng.* **2024**, *86*, 108758. [CrossRef]
81. Lai, M.H.; Xie, Y.M.; Zhang, B.X.; Ren, F.M.; Kitipornchai, S.; Ho, J.C.M. Iron sand heavy-weight concrete—Pre- and post-fire characteristics from wet packing density perspective. *Constr. Build. Mater.* **2024**, *435*, 136728. [CrossRef]