Applications of Wind Turbine Blade Recycling Materials

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The rapid growth of the wind energy industry has resulted in a significant increase in Wind Turbine Blade (WTB) waste, posing challenges for recycling due to the composite materials used in their construction. Each recycling technique employs distinct approaches, all to reclaim the valuable fibres in these blades. Mechanical recycling yields resin-rich, fibre-rich, and other qualities of byproducts, while pyrolysis generates fibres, fillers, gas, and oil.

Keywords: recycling technologies ; mechanical properties ; wind turbine blades

1. Introduction

The wind energy sector is experiencing a rapid evolution due to the global demand for a clean energy supply to combat climate change and the energy crisis [1]. In 2021, wind energy supplied 744 GW (7% of global electricity demand), while in Europe, it provided 437 TWh of electricity (15% of EU-27 + UK electricity demand) [2][3][4].

By 2050, wind power is expected to supply more than one-third of the world's electricity demand [5], while in Europe, it is projected to cover 50% [2][3]. The European Union's goal of elevating the proportion of renewable energy to 27% by 2030 and achieving a substantial reduction in greenhouse gas emissions, ranging from 80% to 95% by 2050, underscores the pivotal significance of wind energy in the forthcoming energy landscape.

The wind industry faces a complex challenge as the number of wind turbines that need to be decommissioned continues to increase. The expected lifetime of a wind turbine is 20–25 years, and there are growing opportunities for repowering, which involves replacing the old models/components with newer and more efficient ones [1][6][7][8][9].

Several studies have estimated the amount of waste generated by Wind Turbine Blades (WTB) to find alternative waste management strategies [1][10][11][12]. Liu and Barlow (2017) estimate that the end-of-life waste stream will generate 2.9 million tonnes in 2050, with 43 million tonnes of cumulative blade waste [10]. The regional distribution shows that China will be responsible for most of the waste (40%), followed by Europe (25%), the rest of the world (19%), and the USA (16%). However, Lichtenegger et al. (2020) [11] forecast 325,000 tonnes of WTB waste, while Liu and Barlow's estimate amounts to 495,000 tonnes [10][11]. In Germany, WTB waste is projected to reach 67,000 tonnes by 2050. Cooperman et al. (2021) [12] predict an estimated cumulative waste quantity of 2.2 million tonnes by 2050 in the United States. This projection of accumulated waste is lower than that of Liu and Barlow (3.8 million tonnes) [12]. The US states that may collect the highest amount of EOL blade waste by 2050 are Texas, with over 450,000 tonnes, followed by New York, with approximately 200,000 tonnes. California and Iowa are the following US states with almost 150,000 tonnes. In Canada, the accumulated waste will be 275,000 tonnes in 2050 [1].

The significant increase in decommissioned WTBs emphasises the necessity to develop and implement efficient waste processing systems for a more sustainable supply chain [3][4][5]. Recycling these blades lowers greenhouse gas emissions and reduces the energy costs associated with producing new fibres [1][2]. Nevertheless, recycling WTBs poses a formidable challenge due to their complex composite structure comprising multiple materials, resulting in a more intricate and demanding recycling process [2][4][5].

Wind turbine blades are composed of various materials, including reinforcement fibres (primarily glass and carbon fibres), a polymer matrix (consisting of thermosetting resins like epoxies and polyurethanes), a sandwich core (often made from materials like balsa wood or foams, including polyvinyl chloride), structural adhesives (such as epoxies and polyurethanes), coatings (like polyester and polyurethane), and specific metal components for lightning protection and structural support [4][5]. These blades typically consist of approximately 60–65% reinforcement fibres and 30–35% polymer matrices by weight, making up most of their weight, and reaching up to 90% of the total blade weight [7]. The core materials contribute around 4–5%, and the combined percentage of adhesives and additional materials typically remains under 5% [7].

The disposal of wind turbines offers various alternatives, which include landfilling, incineration, and recycling [1][4][5]. Landfilling is the most economically efficient option, although it does have significant environmental repercussions [1]. This is primarily due to the materials employed in their construction, which are non-biodegradable and, therefore, unable to degrade naturally [6][13]. As a result, incineration could be more environmentally friendly and economically viable for recycling. Consequently, current research is concentrated on developing innovative recycling technologies and processes specifically tailored to wind turbine blades to address the challenges associated with their disposal more sustainably [1][6][13]. At present, there exist three fundamental methodologies for the recycling of composite waste, namely mechanical recycling [14][15][16][17][18], thermal recycling involving pyrolysis [18][19][20], microwave pyrolysis [21][22], gasification fluidised beds [23][24][25][26][27], and chemical recycling utilising the solvolysis process [28][29][30][31][32][33]. The best recycling technique in terms of the physical and mechanical properties of the recycled compounds, operational costs, and energy consumption needs to be identified. These authors' work presents the first systematic review of quantitative data on all available wind-blade recycling processes, evaluating the performance of the recycled material on an economic, technical, and environmental level.

2. Applications of Wind Turbine Blade Recycling Materials

2.1. 3D Printing Reinforced Filaments

Some authors have developed new fused filament fabrication (FFF) filaments that utilize glass fibres from old blades to create structurally rigid parts using 3D printing [34][35]. This innovative process requires a mechanical recycling technique that combines grinding and double sieving to develop value-added FFF from scrap blades. However, FFF parts typically lack strength and stiffness due to their pure thermoplastic material composition, significantly limiting their structural performance [34].

Various factors, including the filament material (e.g., polylactic Acid (PLA)), extrusion and manufacturing processes, and design parameters, influence the mechanical properties of FFF-manufactured parts [34][35][36]. A 3D printer nozzle diameter of 0.4 mm is used in all studies. Simultaneously, the double-sieving process guarantees the availability of fibres shorter than 0.4 mm, a critical requirement for highly processable filaments [20][35][37].

However, using fibres recovered from mechanical recycling presents challenges, such as traces of old resin that may weaken the interface between fibres and matrices (scrap blades are generally reinforced epoxy composites). The fibre's surface still contains remnants of epoxy, which possess multiple 1,2-epoxy groups per molecule and are highly reactive to various substances such as PLA [35]. However, these difficulties can be overcome by leveraging the beneficial interactions between the functional groups of PLA and epoxy through hydrogen bonding. These reactions elongate molecular chains, enhancing the interfacial strength between PLA and fibres recovered without necessitating costly thermal or chemical treatment processes to eliminate the previous resin. Additionally, the matrix residue on the fibre's surface augments its unevenness, thereby contributing to the mechanical interactions between the fibres and PLA molecules [35].

In contrast, Moslehi et al. (2022) [37] treated the fibres with a silane-coupling agent to improve the interface between the matrix and the fibre (15 wt% Recycled Glass Fibre Reinforced Filament (RGFRF)). The incorporation of 1,2,3,4-butane tetracarboxylic acid (0.425 wt% BTCA) and the application of a silane treatment (0.6 wt% silane) onto the fibres recovered resulted in a significant improvement in strength, with a 30% increase in the elongation at break and impact strength of the composite being observed, as noted in a previous study [37]. A comparison between PLA/S RGFRF and neat PLA revealed a considerable enhancement in both tensile strength and tensile modulus, with an increase of 36% and 45%, respectively. This indicates the potential of modified glass fibres to enhance the strength and rigidity of PLA [38]. Furthermore, when comparing PLA/S RGFRF, which consists of fibres modified with organic silane, to PLA/RGFRF, it was found that the tensile strength and modulus were improved by 20% and 10%, respectively. It is worth mentioning that although the addition of modified fibres led to a reduction in the elongation at the break of PLA, this reduction was less pronounced compared to the composite with non-modified fibres. This can be attributed to the improved compatibility between SR-GFs and PLA achieved through silane modification. The decreased elongation at break in the composite can be attributed to the higher rigidity of glass fibres, which exhibit less flexibility than the polymeric matrix and consequently limit the deformation of the polymer [37]. **Table 1** summarises the crucial findings from the study involving various PLA variants. The data is methodically arranged in ascending tensile strength order for improved clarity.

Table 1. Summary of tensile characteristics: modulus, elongation at break, and strength of different PLA variants.

Reinforced Filaments	Tensile Strength [GPa]	Young's Modulus [GPa]	Elongation Break [%]	Study
PLA	**0.013**	**3.1**	**5**	[37]
PLA/15 wt% RGFRF	**0.026**	**4.1**	**3**	[37]
PLA	**0.051**	**3.3**	**-**	[35]
PLA-5 wt% RGFRF	**0.054**	**3.6**	**-**	[35]
PLA/15 wt% RGFRF-0.6 wt% silane-0.425% BTCA	**0.056**	**4.6**	**31**	[37]
PLA/15 wt% RGFRF-0.6 wt% silane	**0.066**	**4.5**	**3.4**	[37]

Rahimizadeh et al. (2019) [39] demonstrated that reinforced filaments with 25% fibre content could increase the specific stiffness of PLA samples by up to 74%. However, this increase comes at the cost of a reduced specific tensile strength and failure strain by 42% and 65%, respectively. The study explored the use of virgin and recycled glass fibres and found that fibres recovered partially covered with epoxy particles led to an 18% increase in specific modulus and a 19% increase in tensile strength compared to virgin fibres [39]. However, adding fibres harmed the ductility and ultimate strength of the samples due to the development of excessive stress concentration regions caused by fibre aggregation and resin particles with sharp corners on the surfaces of the fibres recovered.

Recent studies have shown that the recycled feedstock filament for FFF has superior tensile properties compared to that of pure polymer filaments, according to research by Rahimizadeh et al. (2020) [35] and Tahir et al. (2021) [40]. Rahimizadeh et al. (2020) [35] revealed that ground fibres with a 20 mm gauge length had strength like virgin fibres. However, increasing the gauge length to 40 mm and 60 mm resulted in a brittle failure mode and lower average strength. The primary determinant of the mechanical properties of fibres is the distribution of surface imperfections. Generally, shorter fibres exhibit fewer flaws, while longer fibres are more prone to external surface defects, which can increase the likelihood of microcrack formation [35].

Interestingly, the stiffness of the fibres after undergoing mechanical recycling was comparable to that of pristine threads when measured at various gauge lengths, indicating no deterioration in stiffness. In contrast to strength, longer gauge lengths are suggested to result in a higher modulus, as per research findings [41]. This is attributed to a more substantial decrease in ductility than ultimate strength. While the stiffness of the processed fibres displayed some variability, it is noteworthy that the average stiffness values remained remarkably consistent across various gauge lengths, as indicated in reference [36].

Tahir et al. (2021) [40] compared three different fibre categories: virgin, ground, and pyrolyzed, using experimental and analytical micromechanical models. The results showed that both fibres recovered (ground and pyrolyzed) had higher strength and stiffness values than virgin fibres. The specific stiffness of 3D-printed reinforced specimens improved by 39.5%, 43.1%, and 69.6% for 10% fibre content using virgin, ground, and pyrolyzed fibres, respectively [42]. However, adding fibres harmed the sample ductility and ultimate strength, resulting in a significant average drop of 29.3%, 13.4%, and 17.9% for 10% fibre content using virgin, ground, and pyrolyzed fibres, respectively [42]. Nevertheless, the tensile strength of 3D-printed samples reinforced with the three distinct fibre categories was observed to be lower when compared to the strength of pure PLA samples. This decrease in strength can be attributed to the relatively shorter fibre lengths, with an average measurement of 0.226 mm, falling below the critical threshold of 0.87 mm for ground fibres. As a result, the study recommends repeating the experiment employing fibre categories characterised by lengths closer to the essential point. This adjustment is necessary to precisely ascertain the tensile properties of reinforced 3D-printed samples [42].

Rahimizadeh et al. (2021) [36] investigated the effect of ground fibres above the critical length on the strength of 3D-printed parts, with 3, 5, and 10 wt% of recycled content. The study found that 3D-printed parts with 5 wt% of recycled content had a 20% increase in specific strength compared to pure PLA specimens. However, increasing the recycled content to 10 wt% resulted in a slight reduction in tensile strength, likely due to low surface quality. Samples with up to 5 wt% of recycled content exhibited higher ductility than pure PLA parts due to the low fibre volume fraction of the recycled and the favourable interactions between the fibres and PLA.

Furthermore, Rahimizadeh et al. (2021) [36] compared the properties of 3D-printed samples reinforced with long glass fibres and short recycled glass fibres. The results showed that samples reinforced with long fibres had higher tensile properties, which could be attributed to two factors [36]. In the first step, the researchers employed micromechanical characterisation to determine the appropriate parameters for manufacturing and recycling, resulting in longer fibres in the final product. Subsequently, multiple classification operations were conducted post-grinding to minimize the presence of epoxy powder particles and preserve the epoxy residues on the surface of the reclaimed extended glass fibres. The preservation of these surface epoxy residues proves crucial in enhancing the mechanical performance of the fibres, as it establishes an interface that is 26% stronger compared to that formed between fibres with a smooth surface (Rahimizadeh et al. (2021) [36]). This finding suggests that surface epoxy residues significantly contribute to the overall strength improvement of the recycled composites. By ensuring the preservation of these residues during the manufacturing process, the composites can be produced with enhanced mechanical properties, making them suitable for various industrial applications. The study highlights the importance of proper manufacturing and recycling parameters and the preservation of surface epoxy residues in producing recycled composites with improved mechanical properties.

Table 2 presents a summary of the mechanical properties and their corresponding standard deviations for FFF 3D printing filaments with varying fibre contents, as explored in previous research. To enhance clarity, the data has been meticulously organized in ascending order of specific strength.

Table 2. Summary of the mechanical properties of FFF 3D printing filament composed of polylactic acid with varying weight percentages of recycled glass fibre-reinforced filament.

Reinforced Filaments	Specific Strength (MPa·cm^3/g)	Specific Stiffness (GPa·cm^3/g)	Failure Strain (%)	Study
PLA-25 wt% RGFRF	24	4.4	0.01	[27]
PLA-15 wt% RGFRF	26	3.9	0.01	[27]
PLA-20 wt% RGFRF	26	4.1	0.01	[27]
Virgin glass fibre-reinforced coupon	27	3.2	0.02	[27]
Virgin glass fibre [3]	27	3.2	1.50	[42]
PLA-5 wt% RGFRF [3]	28	2.6	1.10	[42]
PLA-10 wt% RGFRF	34	3.5	0.01	[27]
Recycled glass fibre-reinforced coupon	34	3.5	0.01	[27]
PLA-10 wt% RGFRF [1]	34	3.5	1.40	[37]
PLA-10 wt% RGFRF [3]	34	3.4	1.40	[42]
PLA3	39	2.3	2.00	[42]
PLA-5 wt% RGFRF	41	2.8	0.02	[27]
PLA-5 wt% RGFRF1	41	2.8	1.80	[37]
PLA-10 wt% RGFRF	42	3.7	1.20	[37]
PLA-10 wt% RGFRF [2]	43	3.7	1.60	[37]
PLA-0 wt% RGFRF	45	2.8	0.02	[27]
PLA-0 wt% RGFRF	45	2.8	2.10	[37]
PLA-3 wt% RGFRF	51	3.4	2.20	[37]
PLA-5 wt% RGFRF	54	3.7	2.10	[37]
PLA-5 wt% RGFRF [2]	54	3.7	2.10	[37]

[1] Short fibres; [2] Long fibres; [3] 20 mm.

Adding recycled glass fibre-reinforced filament to PLA can increase the filament's specific stiffness but decrease the failure strain and specific strength. The strength of the filament decreases with the increasing weight percentage of the reinforced filament while the specific stiffness increases. This trend can be seen in both studies in the table that were conducted by Rahimizadeh et al. in 2019 [39] and 2021 [35]. The decrease in particular strength can be attributed to the addition of the reinforced filament, leading to the dilution of the polymer matrix, which decreases the filament's strength. However, the increase in specific stiffness can be attributed to the fact that the reinforced filament provides a reinforcement effect, which improves the stiffness of the filament. Another important observation is that the failure strain of the filament decreases with the increasing weight percentage of the reinforced filament. This means that the filament becomes more brittle and less ductile with the addition of the reinforced filament. This trend can be seen in both studies presented in the table. Lastly, it is important to note that the length of the fibres used can also affect the mechanical properties of the filament. It can be observed that longer fibres lead to a higher specific stiffness, as seen in the study conducted by Rahimizadeh et al. in 2021 [36].

In conclusion, optimising the weight percentage and length of the reinforced fibres can improve the mechanical properties of FFF 3D printing filaments. However, it is important to note that adding the reinforced filament can decrease specific strength and failure strain, making the filament more brittle.

2.2. Reinforced Concrete

The use of GFRP waste from EOL wind turbines for fibre extraction as a replacement for synthetic macro fibres in concrete is supported by several studies, including those by Fu et al. (2021) [41], Yazdanbakhsh et al. (2018) [43], and Rodin et al. (2018) [44]. These studies have consistently shown that adding GFRP fibres can significantly enhance the mechanical properties of concrete, resulting in more resilient and longer-lasting structures that can withstand the demands of infrastructure and construction projects.

Specifically, GFRP fibres have been shown to enhance the tensile and flexural strength, durability, and resistance to cracking of concrete in studies such as Fu et al. (2021) [41], Yazdanbakhsh et al. (2018) [43], and Rodin et al. (2018) [44]. Baturkin et al. (2021) [45] found that using it as fibre reinforcement improved the flexural capacity without sacrificing compressive strength. Haider et al. (2021) [46] found that recycled GFRP used as mortar also exhibited improved toughness. At the same time, Fu et al. (2021) [41] and Xu et al. (2022) [47] found that macro fibres with hybrid lengths improved flexural performance, including flexural strength, deformation capacity, and toughness. However, Fu et al. [41] did not report the negative impact on compression behaviour that Xu et al. [47] observed. **Table 3** summarises the mechanical properties of the concrete samples tested in the laboratory, including the compressive strength and modulus of elasticity. Overall, these studies demonstrate the potential of recycled and waste GFRP materials as a substitute for traditional reinforcement materials in concrete. However, a careful selection of the specific form and recycling technique is necessary to achieve the desired mechanical properties. For instance, the size and shape of the recycled GFRP can vary depending on the mechanical process used, which can affect the properties of GFRP. Therefore, carefully selecting the recycling technique used to extract GFRP fibres from waste materials is crucial to achieving the desired mechanical properties for concrete reinforcement. Yazdanbakhsh et al. (2018) [43] found that the size and shape of the recycled GFRP varied depending on the mechanical technique used. A recycling technique that preserves the composite nature of GFRP by creating large needles with cross-sections of 6 mm by 6 mm and a length of 100 mm, both in the plain and grooved varieties produced, has yielded superior mechanical properties when compared to alternative recycling techniques. To be more specific, the study by Yazdanbakhsh et al. (2018) [43] found that the replacement of 5% and 10% of the coarse aggregate by volume with plain needles led to a significant increase in the average equivalent flexural strength of concrete, from 1.1 MPa to 14.0 MPa and 32.3 MPa, respectively. When grooved needles were used, the average comparable flexural strength for 5% and 10% replacements was 12.6 and 24.7, respectively [43].

Table 3. Mechanical properties of concrete with varying weight percentages of glass fibre-reinforced polymer. “PLN” and “GRV” represent plain and grooved needles.

Specimen	Compressive Strength (MPa)		Modulus of Elasticity (GPa)	Study
	7 Days Strength	28 Days Strength		
CC-54 wt% GFRPV [2]	**0.0**	**9.0**	**-**	[45]
CC-40 wt% GFRP	**12.0**	**18.0**	**-**	[45]
CC-27 wt% GFRPV [1]	**15.0**	**27.0**	**-**	[45]
CC-2.5 wt%GFRP	**-**	**29.1**	**18.7**	[47]
CC-1.5 wt% GFRP	**-**	**31.6**	**19.9**	[47]
CC-0.5 wt% GFRP	**-**	**32.6**	**21.4**	[47]
CC-20 wt% GFRP	**25.0**	**33.0**	**-**	[45]
CC-control	**-**	**33.8**	**18.9**	[47]

Specimen	Compressive Strength (MPa)		Modulus of Elasticity (GPa)	Study
	7 Days Strength	28 Days Strength		
CC-10 wt% SSD-3.52 wt% GRV	**-**	**34.4**	**24.7**	[43]
CC-5 wt% SSD-1.76 wt% PLN	**-**	**35.5**	**29.1**	[43]
CC-control	**-**	**36.0**	**25.9**	[43]
CC-10 wt% SSD-3.52 wt% PLN	**-**	**36.1**	**27.4**	[43]
CC-5 wt% SSD-1.76 wt% GRV	**-**	**38.6**	**27.6**	[43]
CC-5 wt% GFRP-20 wt% FA	**33.9**	**41.2**	**-**	[46]
CC-5 wt% SF	**29.7**	**44.0**	**-**	[46]
CC-control	**44.0**	**51.0**	**-**	[45]
CC-control	**44.8**	**51.0**	**-**	[46]
CC-5 wt% GFRP	**46.6**	**52.9**	**-**	[46]
CC-20 wt% FA	**39.4**	**53.7**	**-**	[46]
CC-5 wt% GFRP-5 wt% SF	**42.4**	**56.2**	**-**	[46]
CC-control	**45.7**	**-**	**29.2**	[41]
CC-1.5 wt% GFRP	**47.4**	**-**	**29.6**	[41]
CC-1.0 wt% GFRP	**47.5**	**-**	**30.2**	[41]
CC-0.5 wt% GFRP	**47.7**	**-**	**30.2**	[41]

[1] 20% for cement replacement and 7% for sand replacement; [2] 40% for cement replacement and 14% for sand replacement.

Fu et al. (2021) [41] demonstrated that including macro fibres significantly enhanced the flexural performance of concrete beams. This improvement encompassed flexural strength, deformation capacity, and toughness. These macro fibres possess a typical thickness like that of a lamina (e.g., 0.4–1.0 mm), a width of several millimetres, and a length ranging from 30 to 100 mm. Consequently, their aspect ratio (i.e., length-to-thickness ratio) falls within the range of 30–120, which resembles that of standard steel fibres employed in concrete [41]. The flexural strength experienced a substantial increase of 135% compared to the reference beams when 1.5% macro fibres were incorporated into the concrete specimens.

Furthermore, the residual flexural strengths at deflections of 1/600 and 1/150 of the span (i.e., f600 and f150) also displayed an augmentation with adding fibres. Similarly, the average toughness of the control group specimens was a mere 0.97 J, whereas samples with 1.0% and 1.5% macro fibres exhibited toughness values of 151.3 J and 182.4 J, respectively [41].

The examination outcomes indicate that, like discoveries about macro fibres of predetermined lengths [48], including hybrid-length macro fibres can enhance concrete beams' flexural strength and toughness. Additionally, this enhancement becomes more pronounced as the fibre volume ratio increases [41][47]. Similarly, Xu et al. (2022) [47] reported that using macro fibres with hybrid lengths in a concrete mix can improve concrete performance, including flexural strength and toughness. The investigation revealed a notable increase in flexural strength for the various groups with fibre volume ratios of 0.5%, 1.5%, and 2.5%. Specifically, the flexural strength exhibited an augmentation of 4.34%, 13.30%, and 37.85%, respectively, compared to the control group. Furthermore, as the fibre volume ratio increased, the enhancement in flexural strength became more pronounced. In addition, the flexural toughness for the groups with fibre volume ratios of 0.5%, 1.5%, and 2.5% experienced a significant improvement, with a respective increase of 15.5, 22.7, and 36.8 times compared to that of the control group. Remarkably, the flexural toughness of the groups with fibre volume ratios of 0.5%, 1.5%, and 2.5% demonstrated a substantial enhancement of 15.5, 22.7, and 36.8 times, respectively, compared to the control group. However, incorporating macro fibres negatively impacted the concrete's compression behaviour, resulting in a significant loss of 54% [47].

Haider et al. (2021) [46] conducted a study on producing recycled GFRP in three different sizes through hammer milling of 12.7 mm and screening. The researchers found no significant trend in the size or quantity of GFRP on the compressive strength of the mortar. However, almost all GFRP mortars exhibited significantly improved flexural strength due to their high modulus [46]. In addition, it is observed that the fracture toughness of GFRP mortars shows a progressive increase as the proportion of GFRP in all size categories rises. Notably, large GFRP proportions, specifically 5% and 7% by volume, manifest exceptional toughness indices characterised by strain-hardening behaviour after the peak and an approximate equivalent flexural ratio of 60% and 70%. A comprehensive examination of the micrographs depicting the GFRP–mortar interfaces reveals the successful integration and anchoring of GFRP shreds within the mortar matrix. Furthermore, the failure modes observed in the experiments encompassed both pullout and fracture phenomena, indicating the successful incorporation and bond formation between the GFRP and mortar components [46].

Baturkin et al. (2021) [45] evaluated the impacts of incorporating GFRP in concrete as a powder, aggregate, or fibre on its performance. They attempted 10–30% cement replacement rates, coarse aggregate replacement levels of 33–100%, and fibre addition rates of 1–1.75 vol.% [45]. When introduced in powder form, adding GFRP led to a notable extension in the time taken for the concrete to set. Furthermore, it caused a significant decline in both compressive and flexural strengths. This reduction can be attributed to wood-based polysaccharides interfering with the kinetics of cement hydration. However, when the wooden components were eliminated, mixtures containing 10% GFRP powder as a replacement for cement demonstrated comparable compressive strength to that of the control mixture (without GFRP) after 90 days [45]. In the case of GFRP incorporated as a fibre reinforcement in concrete, an improvement in the flexural capacity of up to 15% was achieved without any noticeable decrease in the compressive strength. Conversely, when GFRP was added as aggregates, lower compressive and flexural strengths were observed. This is due to the smooth surface of GFRP, which leads to reduced adhesion with the matrix and the creation of a weak interfacial transition zone [45].

Table 3 provides a concise summary of the mechanical properties of concrete samples containing varying weight percentages of GFRP, encompassing compressive strength and modulus of elasticity. To improve clarity, the data has been systematically arranged in ascending order based on compressive strength (28 days strength).

Based on the studies summarised, incorporating GFRP materials in concrete can reduce the compressive strength and modulus of elasticity, especially at higher weight percentages. However, the reduction can be limited by carefully selecting the form and recycling technique of GFRP and other supplementary materials such as fly ash. Using grooved needles instead of plain needles can also improve the properties of the GFRP-reinforced concrete. Overall, the results suggest that GFRP materials have the potential to be a viable alternative to traditional reinforcement materials in concrete, but further research is needed to optimise their properties and ensure their long-term durability.

2.3. New Thermoset Polymer Composites from Fibres Pyrolyzed

Some studies provide valuable insights into the potential of using recycled glass fibres in new composite materials and demonstrate the feasibility of using microwave pyrolysis as a recycling technique for composites. The research conducted by Åkesson et al. [49] investigated the feasibility of extracting glass fibres from previously utilized reinforced composites through microwave pyrolysis and assessing their potential for incorporation into fresh composites. In the first study, Åkesson et al. (2012) [49] conducted a study to assess the mechanical properties of composites made with recovered glass fibres and polypropylene (PP) to enhance the adhesion between the recovered glass fibres and the polymer matrix in composite materials produced through microwave pyrolysis. Examining SEM micrographs demonstrated a diminished level of adhesion between the recuperated fibres and the polymer matrix. The incorporation of maleic anhydride-grafted PP (MA-PP) exhibited a notably influential impact on the mechanical characteristics, resulting in an elevation of flexural strength from 46 MPa to 62 MPa and a rise in flexural modulus from 2.4 GPa to 3.4 GPa. Nevertheless, the augmentation of the weight percentage of MA-PP led to a decline in the strength and modulus of the composites. The mechanical properties of the composites experienced an enhancement up to a specific threshold with the escalation in MA-PP concentration and subsequently deteriorated at higher concentrations. The lower molecular weight of MA-PP compared to polypropylene may explain the reduced bending properties at high weight percentages of MA-PP. Including coupling agents in the formulation resulted in an augmentation of the tensile strength and modulus of the composites. However, this enhancement came at the expense of a decrease in maximum elongation. The recovered fibres were weaker than virgin fibres, even with coupling agents. Using chalk as a filler resulted in a tensile strength of 26 MPa and a modulus of 2.6 GPa [50].

In the second study [51], the researchers aimed to evaluate the potential of the recovered glass fibres from a WTB obtained through microwave pyrolysis as a reinforcement for thermoset composites. Non-woven fibre mats were fabricated by manually blending recycled glass fibres with bicomponent fibres, followed by a heat treatment to facilitate fibre bonding. The polyester resin was then applied to the mats via hand lay-up and cured using compression moulding, resulting in composites with varying proportions of recycled and virgin glass fibres. The decline in tensile strength can be remedied by employing a hybrid composite that combines recycled glass fibres with virgin fibres. Experimental analysis has demonstrated that composites containing 25 wt% of fibres recovered exhibited favourable mechanical properties, characterised by a flexural strength of 157 MPa and a flexural modulus of 12 GPa.

Nonetheless, compared to composites consisting solely of 100 wt% virgin fibres, the flexural strength experienced a decrease from approximately 189 MPa to 157 MPa, while the flexural modulus decreased from roughly 16 MPa to 12 MPa. This observation implies that the reinforcing influence of mats derived from reclaimed fibres was relatively modest, potentially due to alterations in the surface characteristics of the fibres after pyrolysis. The adhesion between the fibres and matrix could have been higher due to the degraded glass fibre sizing. One potential solution is to improve adhesion by heating the fibres with oxygen to remove the char and adding a new sizing, which could lower tensile strength [51].

Table 4 offers a succinct summary of the flexural strength and flexural modulus values for the different composites prepared using recovered fibres obtained through microwave pyrolysis, as reported in Akesson's studies. To enhance clarity, the data has been meticulously organized in ascending order according to flexural strength.

Table 4. Flexural strength and flexural modulus of composites prepared using the recovered fibres.

Composites	Flexural Strength [MPa]	Flexural Modulus [MPa]	Study
GFRP 0 wt% MA-PP	**46**	**45**	[49]
PP	**47**	**2**	[49]
GFRP 20 wt% MA-PP	**52**	**51**	[49]
GFRP 2 wt% MA-PP	**56**	**56**	[49]
GFRP 10 wt% MA-PP	**56**	**56**	[49]
GFRP 100 wt%	**61**	**-**	[51]
GFRP 5 wt% MA-PP	**62**	**62**	[49]
GFRP 50 wt%	**104**	**-**	[51]
GFRP 25 wt%	**157**	**-**	[51]
vGF 100 wt%	**189**	**-**	[51]

The composites with glass fibres and MA-PP had higher flexural strength and flexural modulus values compared to a PP composite. The 100% virgin glass fibre composite had the highest flexural strength value. The studies suggest that using recovered fibres obtained through microwave pyrolysis in composites can improve their mechanical properties and be a sustainable and eco-friendly alternative to traditional composites made of virgin materials. The studies suggest that using recovered fibres obtained through microwave pyrolysis in composites can improve their mechanical properties, particularly when combined with glass fibres and MA-PP. These findings could have important implications for developing sustainable and eco-friendly composites with comparable or better mechanical properties than traditional composites made of virgin materials.

References

1. Heng, H.; Meng, F.; McKechnie, J. Wind turbine blade wastes and the environmental impacts in Canada. Waste Manag. 2021, 133, 59–70.
2. European Wind Energy Association (EWEA). Working Group on Grid Code Requirements, Position Paper, European Grid Code Requirements for Wind Power Generation; EWEA: Brussels, Belgium, 2020.
3. WindEurope. Accelerating Wind Turbine Blade Circularity; WindEurope: Brussels, Belgium, 2020.
4. WindEurope. Wind Energy in Europe—2021 Statistics and the Outlook for 2022–2026; WindEurope: Brussels, Belgium, 2022.
5. International Renewable Energy Agency (IRENA). Future of Wind: Deployment, Investment, Technology, Grid Integration and Socio-Economic Aspects (A Global Energy Transformation Paper); IRENA: Abu Dhabi, United Arab Emirates, 2019.
6. Majewski, P.; Florin, N.; Jit, J.; Stewart, R.A. End-of-life policy considerations for wind turbine blades. Renew. Sustain. Energy Rev. 2022, 164, 112538.

7. Jensen, J.; Skelton, K. Wind turbine blade recycling: Experiences, challenges and possibilities in a circular economy. Renew. Sustain. Energy Rev. 2018, 97, 165–176.
8. Sommer, V.; Stockschläder, J.; Walther, G. Estimation of glass and carbon fiber reinforced plastic waste from end-of-life rotor blades of wind power plants within the European Union. Waste Manag. 2020, 115, 83–94.
9. Lefeuvre, A.; Garnier, S.; Jacquemin, L.; Pillain, B.; Sonnemann, G. Anticipating in-use stocks of carbon fibre reinforced polymers and related waste generated by the wind power sector until 2050. Resour. Conserv. Recycl. 2019, 141, 30–39.
10. Liu, P.; Barlow, C.Y. Wind turbine blade waste in 2050. Waste Manag. 2017, 62, 229–240.
11. Lichtenegger, G.; Rentizelas, A.A.; Trivyza, N.; Siegl, S. Offshore and onshore wind turbine blade waste material forecast at a regional level in Europe until 2050. Waste Manag. 2020, 106, 120–131.
12. Cooperman, A.; Eberle, A.; Lantz, E. Wind turbine blade material in the United States: Quantities, costs, and end-of-life options. Resour. Conserv. Recycl. 2021, 168, 105439.
13. Beauson, J.; Laurent, A.; Rudolph, D.; Jensen, J.P. The complex end-of-life of wind turbine blades: A review of the European context. Renew. Sustain. Energy Rev. 2022, 155, 111847.
14. Beauson, J.; Madsen, B.; Toncelli, C.; Brøndsted, P.; Bech, J.I. Recycling of shredded composites from wind turbine blades in new thermoset polymer composites. Compos. Part A Appl. Sci. Manuf. 2016, 90, 390–399.
15. Mamanpush, S.H.; Tabatabaei, A.T.; Li, H.; Englund, K. Physical properties data of extruded composites from recycled wind turbine blade material. Data Brief 2019, 25, 104030.
16. Fonte, R.; Xydis, G. Wind turbine blade recycling: An evaluation of the European market potential for recycled composite materials. J. Environ. Manag. 2021, 287, 112269.
17. Beauson, J.; Lilholt, H.; Brøndsted, P. Recycling solid residues recovered from glass fibre-reinforced composites—A review applied to wind turbine blade materials. J. Reinf. Plast. Compos. 2014, 33, 1542–1556.
18. Cousins, D.S.; Suzuki, Y.; Murray, R.E.; Samaniuk, J.R.; Stebner, A.P. Recycling glass fiber thermoplastic composites from wind turbine blades. J. Clean. Prod. 2019, 209, 1252–1263.
19. Palmer, J.; Ghita, O.; Savage, L.; Evans, K. Successful closed-loop recycling of thermoset composites. Compos. Part A Appl. Sci. Manuf. 2009, 40, 490–498.
20. 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.
21. Rani, M.; Choudhary, P.; Krishnan, V.; Zafar, S. Development of sustainable microwave-based approach to recover glass fibers for wind turbine blades composite waste. Resour. Conserv. Recycl. 2022, 179, 106107.
22. Pender, K.; Yang, L. Regenerating performance of glass fibre recycled from wind turbine blade. Compos. Part B Eng. 2020, 198, 108230.
23. Pender, K.; Yang, L. Investigation of catalyzed thermal recycling for glass fiber-reinforced epoxy using fluidized bed process. Polym. Compos. 2019, 40, 3510–3519.
24. Pickering, S.J.; Turner, T.A.; Meng, F.; Morris, C.N.; Heil, J.P.; Wong, K.H.; Melendi-Espina, S. Developments in the fluidised bed process for fibre recovery from thermoset composites. In Proceedings of the 2nd Annual Composites and Advanced Materials Expo, CAMX 2015, Dallas, TX, USA, 26–29 November 2015; pp. 2384–2394.
25. Yip, H.L.H.; Pickering, S.J.; Rudd, C.D. Characterisation of carbon fibres recycled from scrap composites using fluidised bed process. Plast. Rubber Compos. 2002, 31, 278–282.
26. Pickering, S.; Kelly, R.; Kennerley, J.; Rudd, C.; Fenwick, N. A fluidised-bed process for the recovery of glass fibres from scrap thermoset composites. Compos. Sci. Technol. 2000, 60, 509–523.
27. Bashir, S.; Yang, L.; Anderson, R.; Tang, P.; Liggat, J.; Thomason, J. A simple chemical approach to regenerating the strength of thermally damaged glass fibre. Compos. Part A Appl. Sci. Manuf. 2017, 102, 76–87.
28. Henry, L.; Schneller, A.; Doerfler, J.; Mueller, W.M.; Aymonier, C.; Horn, S. Semi-continuous flow recycling method for carbon fibre reinforced thermoset polymers by near- and supercritical solvolysis. Polym. Degrad. Stab. 2016, 133, 264–274.
29. Khalil, Y. Sustainability assessment of solvolysis using supercritical fluids for carbon fiber reinforced polymers waste management. Sustain. Prod. Consum. 2019, 17, 74–84.
30. Prinçaud, M.; Aymonier, C.; Loppinet-Serani, A.; Perry, N.; Sonnemann, G. Environmental Feasibility of the Recycling of Carbon Fibers from CFRPs by Solvolysis Using Supercritical Water. ACS Sustain. Chem. Eng. 2014, 2, 1498–1502.

31. Wu, M.-S.; Jin, B.C.; Li, X.; Nutt, S. A recyclable epoxy for composite wind turbine blades. Adv. Manuf. Polym. Compos. Sci. 2019, 5, 114–127.
32. Murray, R.E.; Penumadu, D.; Cousins, D.; Beach, R.; Snowberg, D.; Berry, D.; Suzuki, Y.; Stebner, A. Manufacturing and Flexural Characterization of Infusion-Reacted Thermoplastic Wind Turbine Blade Subcomponents. Appl. Compos. Mater. 2019, 26, 945–961.
33. Sokoli, H.U.; Simonsen, M.E.; Søgaard, E.G. Investigation of degradation products produced by recycling the solvent during chemical degradation of fiber-reinforced composites. J. Reinf. Plast. Compos. 2017, 36, 1286–1296.
34. Dickson, A.N.; Abourayana, H.M.; Dowling, D.P. 3D Printing of Fibre-Reinforced Thermoplastic Composites Using Fused Filament Fabrication—A Review. Polymers 2020, 12, 2188.
35. Rahimizadeh, A.; Tahir, M.; Fayazbakhsh, K.; Lessard, L. Tensile properties and interfacial shear strength of recycled fibers from wind turbine waste. Compos. Part A Appl. Sci. Manuf. 2020, 131, 105786.
36. Rahimizadeh, A.; Kalman, J.; Fayazbakhsh, K.; Lessard, L. Mechanical and thermal study of 3D printing composite filaments from wind turbine waste. Polym. Compos. 2021, 42, 2305–2316.
37. Moslehi, A.; Ajji, A.; Heuzey, M.; Rahimizadeh, A.; Lessard, L. Polylactic acid/recycled wind turbine glass fiber composites with enhanced mechanical properties and toughness. J. Appl. Polym. Sci. 2022, 139, 51934.
38. Wang, G.; Zhang, D.; Wan, G.; Li, B.; Zhao, G. Glass fiber reinforced PLA composite with enhanced mechanical properties, thermal behavior, and foaming ability. Polymer 2019, 181, 121803.
39. Rahimizadeh, A.; Kalman, J.; Fayazbakhsh, K.; Lessard, L. Recycling of fiberglass wind turbine blades into reinforced filaments for use in Additive Manufacturing. Compos. Part B Eng. 2019, 175, 107101.
40. Tahir, M.; Rahimizadeh, A.; Kalman, J.; Fayazbakhsh, K.; Lessard, L. Experimental and analytical investigation of 3D printed specimens reinforced by different forms of recyclates from wind turbine waste. Polym. Compos. 2021, 42, 4533–4548.
41. Fu, B.; Liu, K.; Chen, J.; Teng, J. Concrete reinforced with macro fibres recycled from waste GFRP. Constr. Build. Mater. 2021, 310, 125063.
42. Naik, D.L.; Fronk, T.H. Weibull distribution analysis of the tensile strength of the kenaf bast fiber. Fibers Polym. 2016, 17, 1696–1701.
43. Yazdanbakhsh, A.; Bank, L.C.; Rieder, K.-A.; Tian, Y.; Chen, C. Concrete with discrete slender elements from mechanically recycled wind turbine blades. Resour. Conserv. Recycl. 2018, 128, 11–21.
44. Rodin, H.; Nassiri, S.; Englund, K.; Fakron, O.; Li, H. Recycled glass fiber reinforced polymer composites incorporated in mortar for improved mechanical performance. Constr. Build. Mater. 2018, 187, 738–751.
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.
46. Haider, M.; Nassiri, S.; Englund, K.; Li, H.; Chen, Z. Exploratory Study of Flexural Performance of Mechanically Recycled Glass Fiber Reinforced Polymer Shreds as Reinforcement in Cement Mortar. Transp. Res. Rec. J. Transp. Res. Board 2021, 2675, 1254–1267.
47. Xu, G.-T.; Liu, M.-J.; Xiang, Y.; Fu, B. Valorization of macro fibers recycled from decommissioned turbine blades as discrete reinforcement in concrete. J. Clean. Prod. 2022, 379, 134550.
48. Zhu, Y.-D.; Li, X.; Fan, L.; Li, L.; Wang, J.; Yang, W.-J.; Wang, L.; Yao, X.-Y.; Wang, X.-L. Indoor air quality in the primary school of China—Results from CIEHS 2018 study. Environ. Pollut. 2021, 291, 118094.
49. Åkesson, D.; Foltynowicz, Z.; Christéen, J.; Skrifvars, M. Microwave pyrolysis as a method of recycling glass fibre from used blades of wind turbines. J. Reinf. Plast. Compos. 2012, 31, 1136–1142.
50. Mariak, A.; Kurpińska, M. The effect of macro polymer fibres length and content on the fibre reinforced concrete. MATEC Web Conf. 2018, 219, 03004.
51. Åkesson, D.; Krishnamoorthi, R.; Foltynowicz, Z.; Christéen, J.; Kalantar, A.; Skrifvars, M. Glass Fibres Recovered by Microwave Pyrolysis as a Reinforcement for Polypropylene. Polym. Polym. Compos. 2013, 21, 333–340.

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