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Fiber-reinforced polymer waste in the construction industry: a review

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Abstract

Fiber-reinforced polymer composites, reaching a production of approximately 2.78 million tons in 2022 in Europe, display unique properties, yet at their end of service they are disposed of by conventional methods such as landfill and incineration. Here we review the recycling of fiber-reinforced polymer wastes in the construction industry, with emphasis on fiber reinforced polymer composites, recycling methods, and applications of carbon and glass fiber polymer composites in civil engineering. Recycling methods include mechanical, thermal, and chemical techniques. Applications comprise the use in fine fillers, coarse and fine aggregates, macro-fiber, alkali-activated materials, geopolymers, asphalt composites, and cement composites. We discuss workability, mechanical properties including compressive, flexural, and tensile properties, durability, and surface modification. Future applications include three dimensional concrete printing, self-sensing cement composites, self heating and energy harvesting cement composites, and electromagnetic shielding. We propose a waste management hierarchy, considering the source of composites and their intended applications, to improve circularity.

Keywords: Fiber-reinforced polymer; Recycling techniques; Construction materials; Surface modification

1. Introduction

The production of concrete demands a substantial amount of natural resources. According to a report from the European Cement Association, in 2019, approximately 4.1 gigatons of cement binder were produced globally (Cembureau 2020). For every ton of cement produced, approximately 1.27 tons of limestone are required (Tiong *et al.* 2018), leading to a significant demand for limestone resources on Earth. Furthermore, the civil engineering industry relies heavily on vast mineral raw materials, with the total consumption of sands, gravels, and stones accounting for roughly 40% of the annual global consumption (Dixit *et al.* 2010). On the other hand, the environmental impact and high energy consumption associated with concrete manufacturing have raised growing concerns among scientists and policymakers (Salami *et al.* 2022; Ho *et al.* 2023; Li *et al.* 2024b). The production of Portland cement, the most widely used hydraulic binder in concrete, is one of the leading contributors to carbon footprints, accounting for 5% to 10% of anthropogenic carbon dioxide emissions worldwide (Poudyal and Adhikari 2021; Baena-Moreno *et al.* 2023; Li *et al.*

2023b). To address these environmental challenges, the utilization of recycled materials can play a crucial role in reducing resource consumption and energy usage in building construction (Gao *et al.* 2001; Osman *et al.* 2022; Osman *et al.* 2024). Recently, the global consumption of fiber-reinforced polymer has experienced rapid growth. According to the Market Report of Industrievereinigung Verstärkte Kunststoffe e. V (Witten and Mathes 2024), fiber-reinforced polymer composite production in Europe reached 2.39 million tons in 2011, steadily increasing to approximately 2.56 million metric tons by 2023. However, the extensive use of fiber-reinforced polymer products has led to the significant accumulation of end-of-life waste and subsequent environmental concerns. Over the past few decades, landfilling has been the predominant method for disposing of fiber-reinforced polymer waste (Pickering 2006). This approach is becoming less favored due to the increasingly stringent regulations, the loss of energy stored in fiber-reinforced polymer, and the potential for future cost escalations (Halliwell 2010). Incineration is a commonly used method for fiber-reinforced polymer disposal (Danish *et al.* 2022). While this method recovers energy from fiber-reinforced polymer, it poses challenges such as harmful gas emissions, significant residual ash production, and higher costs than landfilling (Halliwell 2010; Yazdanbakhsh and Bank 2014). Consequently, recycling and reusing waste fiber-reinforced polymer have garnered significant attention.

Construction materials typically exhibit brittle characteristics and limited ductility. In particular, Portland cement concrete suffers from low flexural and tensile properties (Li *et al.* 2022a; Li *et al.* 2022c). In this context, the utilization of mechanically recycled fiber-reinforced polymers or fibers extracted from end-of-life fiber-reinforced polymers has shown substantial potential for enhancing the mechanical performance of construction materials (Abdollahnejad *et al.* 2017; Danish *et al.* 2022; Li *et al.* 2022c). Moreover, unlike conventional steel reinforcements, fiber-reinforced polymer wastes or recycled fibers do not corrode, therefore, they do not necessitate thick protective layers in structural designs (Li *et al.* 2021a). This eco-friendly recycling approach not only enhances the strength and long-term serviceability of construction materials but also promotes resource conservation and effective waste management. In this article, the investigated fiber-reinforced polymer wastes intended for construction use are categorized as follows: 1) discarded fiber-reinforced polymer composites with straightforward processing requirements, 2) fibers extracted from these composites, and 3) fiber-reinforced polymer powder obtained through mechanical processing from waste fiber-reinforced polymers. We first summarized the recycling operations of end-of-life fiber-reinforced polymers in Section 2, followed by the properties of construction materials reinforced with carbon fiber-reinforced polymer and glass fiber-reinforced polymer in Sections 3 and 4, respectively. Finally, we reviewed the application of alternative recycled fiber-reinforced polymer in construction materials and provided perspective. The key components of this study are illustrated in the framework diagram shown in Fig. 1.

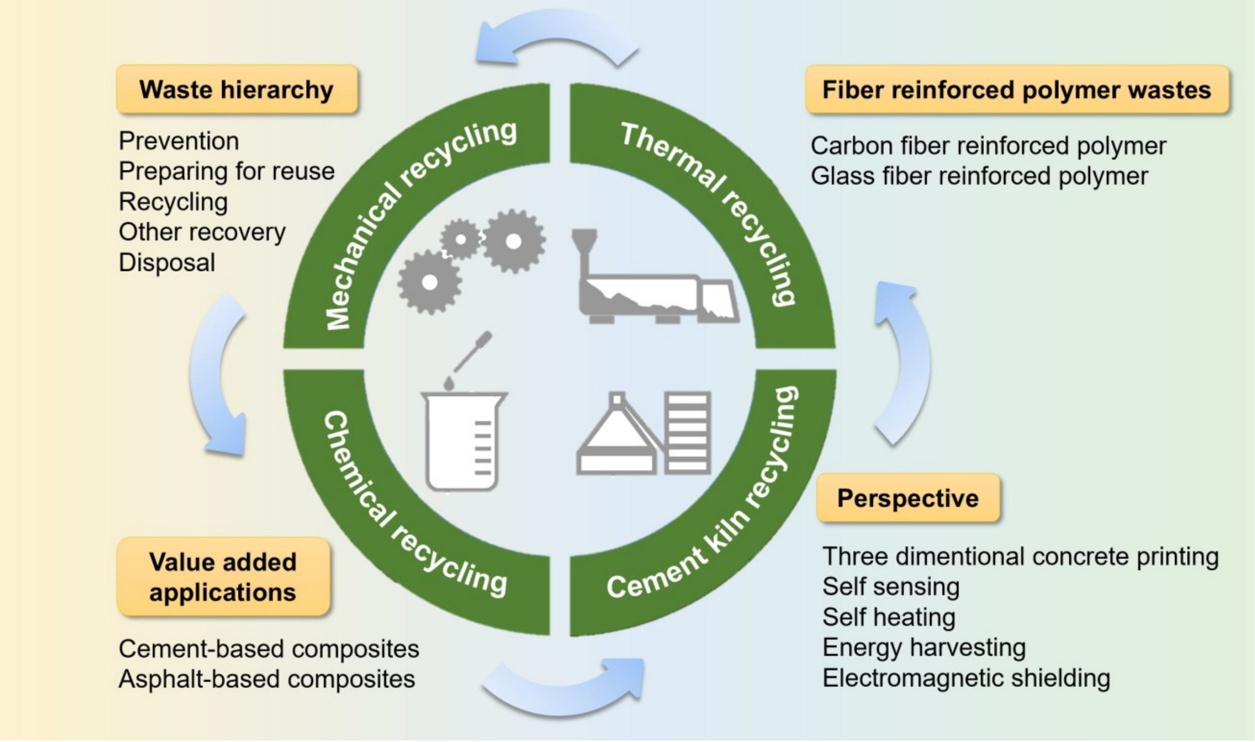

Fig. 1. Recycling methods, application routes in construction materials, and perspectives for recycled fiber-reinforced polymer. Carbon fiber-reinforced polymer and glass fiber-reinforced polymer are mainly reviewed. The waste hierarchy is introduced as a classification framework for different recycling routes of recycled fiber-reinforced polymers in the construction industry.

The prevailing review studies primarily concentrate on the application of recycled fibers or fiber-reinforced polymers in cementitious mixes, as outlined in Table 1. From the analysis of published review articles, it becomes evident that most studies either concentrate on a wide array of waste-derived fibers, including a limited number of fiber-reinforced polymers, or exclusively scrutinize a single type of fiber-reinforced polymers. However, a limited number of previous studies delve into the utilization of waste fiber-reinforced polymer products, particularly concerning specific recycling technologies (Yazdanbakhsh and Bank 2014). Furthermore, it's noteworthy that all available review studies concentrate solely on ordinary cement-based composites or their subcategories, such as hybrid fiber-reinforced cementitious mixes and self-compacting cementitious mixes. The exploration of other construction materials remains notably absent in the current research landscape. In the present study, we categorize research on building materials reinforced with recycled fiber-reinforced polymer for the first time, according to methods of reuse, recycling, and composite recovery, following waste hierarchy principles. The primary goal is to optimize waste management strategies and harness the application potential of recycled fiber-reinforced polymer as reinforcements in construction materials. Additionally, we conducted a systematic review of literature not only concerning traditional cementitious materials but also exploring the utilization of recycled fiber-reinforced polymer in other building materials such as alkali-activated composites and asphalt. This comprehensive approach aims to facilitate the effective and widespread use of waste fiber-reinforced polymer and elevate its value in the construction industry.

Table 1. Previous review articles on the utilization of discarded fiber-reinforced polymer products in construction materials.

Coverage on waste fiber-reinforced polymer	Target matrices	Recycling methods for fiber-reinforced polymer	Focus of review	Ref.
Carbon fiber-reinforced polymer and glass fiber-reinforced polymer	Portland cement	Mechanical	The effect of mechanically recycled fiber-reinforced polymer on the fresh, hardened, and durability properties of cementitious mixes	Yazdanbakhsh and Bank 2014
Carbon fiber-reinforced polymer and glass fiber-reinforced polymer	Self-compacting cementitious mixes	Mechanical, thermal, and chemical	The effect of waste-originated fibers on the fresh, hardened properties, and durability of self-compacting cementitious mixes	Thakare *et al.* 2021
Partial carbon fiber-reinforced polymer and glass fiber-reinforced polymer	Hybrid fiber-reinforced cementitious mixes	Indeterminate	The effect of recycled fibers on the fresh, hardened properties, and durability of hybrid fiber-reinforced cementitious mixes	Balea *et al.* 2021
Glass fiber-reinforced polymer	Concrete	Mechanical	The effect of mechanically recycled large-sized fiber-reinforced polymer on the fresh and hardened properties of concrete	Yazdanbakhsh *et al.* 2018b
Carbon fiber-reinforced polymer	Cementitious materials	Mechanical, thermal, and chemical	The effect of recycled carbon fiber-reinforced polymer on the fresh, hardened properties, and durability of cementitious mixes	Danish *et al.* 2022

2. Fiber reinforced polymer composites

Fiber-reinforced polymer composites have found extensive applications in various daily life and industry sectors, including marine, civil engineering, automotive, aerospace, and sports equipment (Reynolds and Pharaoh 2010). Their widespread use is attributed to numerous advantages, such as high directional strength, lightweight properties, flexibility to create complex composite shapes, and excellent durability even in harsh environments (Yazdanbakhsh and Bank 2014). Fiber-reinforced polymer composites typically consist of fiber reinforcements such as carbon, glass, basalt, aramid fibers, thermoplastic matrices like polypropylene, polyamides, or thermoset matrices such as polyester, vinylester, epoxy, and inorganic fillers like mica, calcium carbonate, talcum powders (Reynolds and Pharaoh 2010). For structural applications of fiber-reinforced polymer composites, the fiber volume fractions are usually designed within the range of 0.55 to 0.72 (Hensher 2016). Notably, in this article, we review two primary types of fiber-reinforced polymer waste separately: carbon fiber-reinforced polymer and glass fiber-reinforced polymer. This separation is based on the diverse commercial value and thermal sensitivity of the fibers, as well as the different adaptability of recycling methods for each type of fiber.

2.1. Carbon fiber reinforced polymer composite

From 2010 to 2018, the demand for carbon fiber-reinforced polymers experienced a substantial increase, rising from 51.0 kilotons to 128.5 kilotons. Projections estimated the demand to reach approximately 197.0 kilotons by the year 2023 (Sauer and Kuhnel 2019). This composite material, known for its high specific strength, has garnered significant attention in the aerospace industry. Boeing, for instance, employed carbon fiber-reinforced polymer for nearly 50% of the airframe construction of the Boeing 787, while Airbus incorporated carbon fiber-reinforced polymer composites for approximately 25% of the A380 and 53% of the A350 airframes (Vieira *et al.* 2017). However, this rapid growth in carbon fiber-reinforced polymer usage has raised both economic and environmental concerns. It is estimated that around 6,000 to 8,000 commercial planes will be retired by 2030 (McConnell 2010), each potentially generating over 20 tons of carbon fiber-reinforced polymer waste (Roberts 2007).

Notably, the production of virgin carbon fiber is an energy-intensive process, consuming between 183 to 286 gigajoules of energy per ton of carbon fiber product (Song *et al.* 2009; Chen *et al.* 2024). This process also releases volatile organic compounds and hazardous gases (Grzanka 2014). In contrast, the energy consumption for recycling carbon fiber from carbon fiber-reinforced polymer, regardless of the recycling method used, is significantly lower (Pakdel *et al.* 2020). Additionally, if 2,000 tons of carbon fiber-reinforced polymer scraps were recycled annually and converted into fibers, it could represent an estimated total value of $20 million, based on a rate of $11 per kilogram of recycled carbon fiber (McConnell 2010). Therefore, considering both sustainability and economic perspectives, recycling carbon fiber-reinforced polymer waste and reusing recyclates is worthwhile.

Carbon fiber-reinforced polymer composites are classified into two primary types: carbon fiber-thermoset and carbon fiber-thermoplastic, each with distinct recycling approaches. In the case of carbon fiber-thermoset composites, the challenge lies in separating carbon fibers from thermoset polymers, as thermoset materials are not readily recyclable. Conversely, carbon fibers within carbon fiber-thermoplastic composites can undergo recycling alongside thermoplastic constituents through processes like melting, reshaping, or dissolution, due to the inherent recyclability of thermoplastic materials (Roux *et al.* 2017; Li *et al.* 2023a).

2.2. Glass fiber reinforced polymer composite

Glass fiber-reinforced polymer composites continue to dominate the composites market, capturing over 95% of the market share (Witten and Mathes 2024). In 2019, the European market for glass fiber-reinforced polymer products reached an approximate total of 1.14 million tons (Witten and Mathes 2020). This composite material finds widespread use across various sectors, including infrastructure, transportation, power supply, sports, and more. Notably, the majority of recreational boats in the marine industry are constructed using glass fiber-reinforced polymer (Yazdanbakhsh and Bank 2014), with an expected average service life of 35 years (Dejhala and Legović 2018). It has been reported that there are approximately 23 million pleasure boats worldwide, and about 2% of them reach the end of their service life each year (Dejhala and Legović 2018). Furthermore, glass fiber-reinforced polymer is a primary material in the wind power industry (Naqvi *et al.* 2018). In Europe, the utilization of glass fiber-reinforced polymer in wind power blade construction experienced rapid growth, increasing from 50 kilotons in 2000 to 130 kilotons in 2010, and continuing to grow progressively to approximately 150 kilotons nowadays (Naqvi *et al.* 2018). Projections suggest that Europe will generate approximately 11 million tons of wind blade waste by 2050 (Liu and Barlow 2017).

In contrast to carbon fiber, the energy consumption for manufacturing glass fiber is relatively lower, ranging from 13 to 32 gigajoules per ton (Song *et al.* 2009). This lower energy consumption makes it less sustainable to employ energy-intensive recycling techniques, such as thermal and chemical processes, to recover inexpensive virgin glass fiber (Jani *et al.* 2022). Thus, mechanical recycling methods appear to be the most suitable approach for addressing outdated glass fiber-reinforced polymers due to their economic feasibility and eco-friendliness (Dorigato 2021; Pegoretti 2021).

3. Current recycling methods

Recycled fibers derived from end-of-service-life fiber-reinforced polymer exhibit notable variations in both mechanical and surface characteristics, contingent upon the chosen recycling methods (Oliveux *et al.* 2015; Pakdel *et al.* 2020). This section provides an overview of state-of-the-art recovery techniques for fiber-reinforced polymers which are summarized in Table 2. The recycling routes for waste fiber-reinforced polymer composites are comprehensively covered, particularly in the field of civil engineering, and they can be categorized into three main categories: mechanical, chemical, and thermal approaches (Oliveux *et al.* 2015). In addition to outdated fiber-reinforced polymers, this review article also considers the offcuts or residues of dry fibers generated in the production process due to their similar mechanical properties to virgin fibers (Pakdel *et al.* 2020). Furthermore, this section presents the challenges and applicability of each method for different types of fibers.

3.1. Mechanical recycling

Mechanical recycling stands as an energy-efficient and eco-friendly approach to recycle end-of-life fiber-reinforced polymer composites (Jani *et al.* 2022). In the widely adopted recycling procedure, discarded fiber-reinforced polymers undergo initial shredding or crushing into smaller segments, achieved with specialized machines like the multiple shaft shredder. This is followed by a grinding process, which allows the recyclates to be categorized into fiber-rich and resin-rich components through sieving (Pegoretti 2021). In several research studies, waste fiber-reinforced polymers were either simply cut or crushed to serve as coarse aggregates in concrete (Ogi *et al.* 2005; Shahria Alam *et al.* 2013; Yazdanbakhsh *et al.* 2016). Additionally, waste fiber-reinforced polymers were specially processed into 'needle' shapes for reinforcing cementitious composites (Yazdanbakhsh *et al.* 2018a; Fu *et al.* 2021). Moreover, large fiber-reinforced polymer components, such as wind turbine blades, can be simply processed and then applied to various infrastructures (Martinez-Marquez *et al.* 2022) (depicted in Fig. 2).

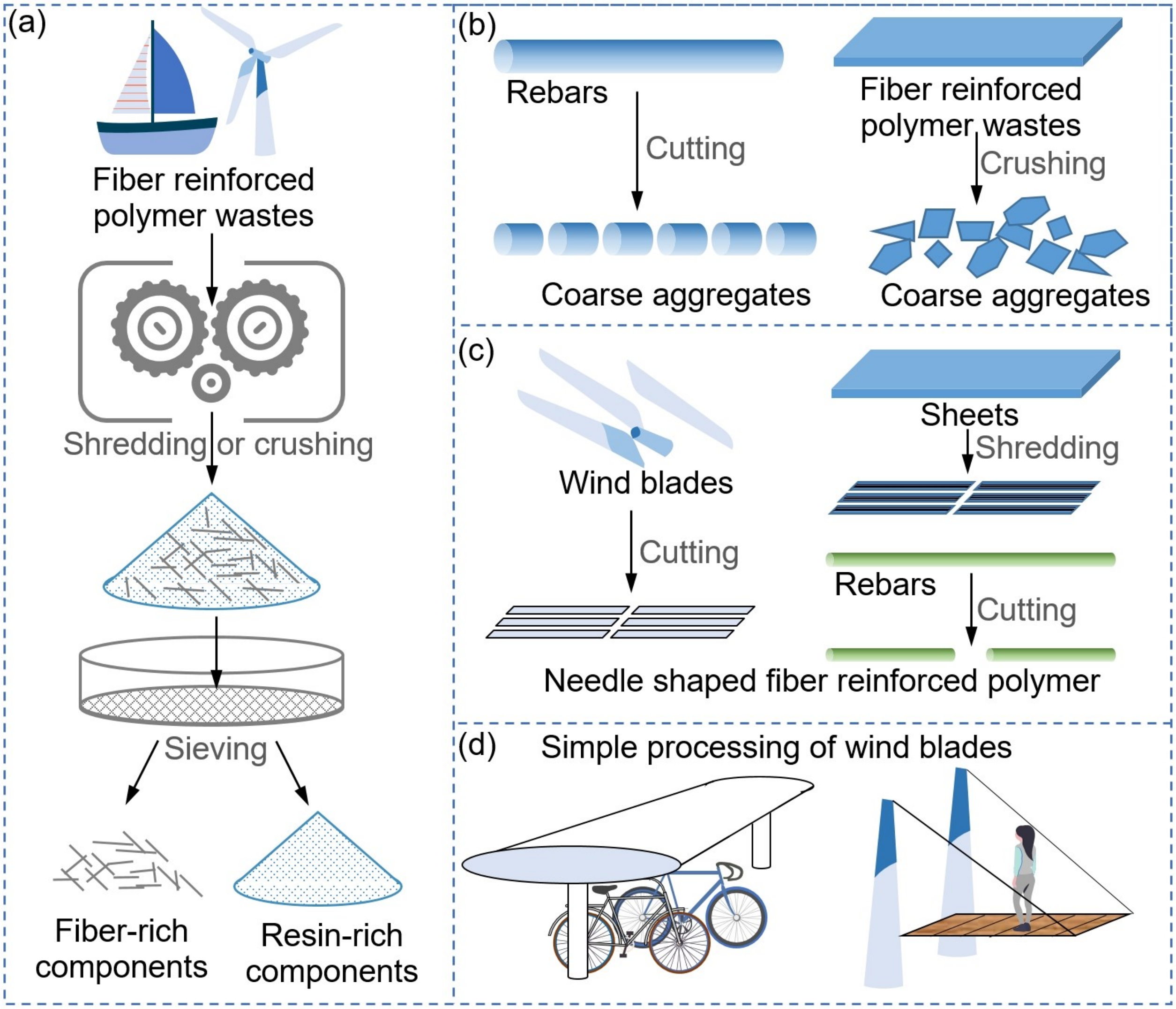

Fig. 2. (a) Recycled fiber-reinforced polymers are initially shredded or crushed into smaller segments using machines like multiple shaft shredders. The recyclates are then ground, followed by a sieving process that allows for classification into fiber-rich and resin-rich components; (b) Fiber-reinforced polymer wastes can be simply cut or crushed into segments to be used as coarse aggregates in concrete; (c) Fiber-reinforced polymers can also be processed into needle-shaped elements; (d) Large fiber-reinforced polymer components, such as wind blades, can be specially processed to serve as various types of urban infrastructure.

Mechanical recycling is notably cost-effective, particularly in Europe, where its processing cost is lower than that of incineration and landfills (Fonte and Xydis 2021). Rybicka *et al.* (2016) have reported that mechanical grinding stands as the most mature technique for recycling glass fiber-reinforced polymer. The mechanical recycling of glass fiber-reinforced polymer has garnered increasing attention from scientific researchers due to its cost-effectiveness, making it suitable for low-value glass fiber (Pakdel *et al.* 2020). However, the grinding process for carbon fiber-reinforced polymer composites presents challenges and can lead to machinery failures. Additionally, the grinding process may significantly reduce the value of recycled carbon fiber, rendering it a less popular method in carbon fiber recycling (Rybicka *et al.* 2016). Overall, the mechanical process is more suitable for recycling glass fiber-reinforced polymer, and the specific recycling method should be determined according to practical needs. In contrast, carbon fibers are preferably completely extracted from the polymer matrices instead of being mechanically recycled due to their high value. For polymer composites containing both carbon and glass fibers, such as wind turbine blades, it is recommended to separate the different fiber zones before proceeding with the recycling process.

3.2. Thermal recycling

The thermal process is used to decompose the cross-linked polymer matrices to retrieve the embedded fibers, especially in thermoset matrices. The thermal process primarily consists of three methods: pyrolysis, microwave-assisted pyrolysis, and the fluidized bed process (Oliveux *et al.* 2015), all of which are elaborated upon in the subsequent section.

In recent years, the pyrolysis process has garnered increasing interest in the recovery of carbon fiber and has achieved widespread industrial applications on a large scale (Pakdel *et al.* 2020). In the general pyrolysis process, the polymeric matrices of fiber-reinforced polymer wastes undergo degradation under inert conditions, with minimal or no oxygen present, at controlled pressure and elevated temperatures typically exceeding 350°C (Meyer *et al.* 2009; Oliveux *et al.* 2015). Following the thermal treatment, various degradation products are generated, including gases such as CH_4, CO_2, CO, and H_2, aromatic compounds like toluene, benzene, phenols, and ethyl benzene, and solid mixtures including composites' fillers, fibers, and potentially char-like substances (Oliveux *et al.* 2015; Naqvi *et al.* 2018). It's worth noting that the residual pyrolytic char on fiber surfaces can hinder interfacial bonding when reclaimed fibers are embedded in new matrices (Oliveux *et al.* 2015). Therefore, post-pyrolysis oxidation with air is necessary to eliminate these char layers originating from resin decomposition (Naqvi *et al.* 2018). Furthermore, the obtained liquids and gases can be effectively reused as secondary fuels or resources (López *et al.* 2013). For the purpose of obtaining high-value, hydrogen-rich gases, in addition to carbon fibers, thermal or thermalcatalytic treatments can be applied to the vapors and gases released during polymeric resin decomposition (Lopez-Urionabarrenechea *et al.* 2021), as shown in Fig. 3.

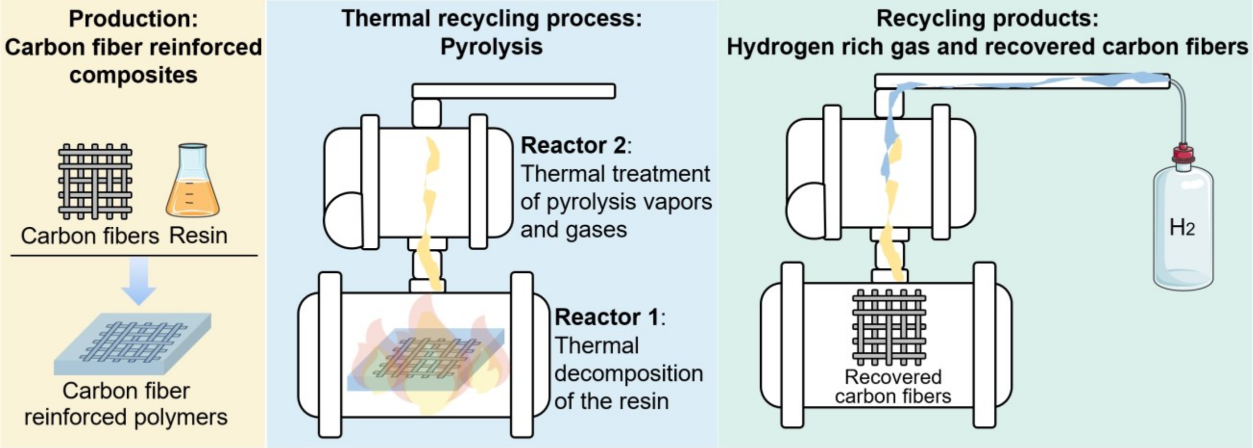

Fig. 3. The upgraded pyrolysis process to recover carbon fibers from carbon fiber-reinforced polymer wastes consists of several phases. The manufactured carbon fiber-reinforced polymer undergoes thermal decomposition, during which the released vapors and gases are thermally treated. Finally, hydrogen-rich gas and recovered carbon fibers are obtained. Adapted from Lopez-Urionabarrenechea *et al.* (2021).

The microwave-assisted pyrolysis approach, developed over the last two decades, employs microwaves as the heat source to degrade carbon fiber-reinforced polymer or glass fiber-reinforced polymer composites within an inert atmosphere such as nitrogen (Lester *et al.* 2004; Åkesson *et al.* 2012). In this relatively new method, certain gases and oils can also be recovered during pyrolysis (Oliveux *et al.* 2015). In comparison to conventional recycling thermolysis, microwave-assisted pyrolysis is regarded as more energy-efficient, highly effective, and notably faster; particularly, microwave-assisted pyrolysis enables cleaner surfaces of fibers (Deng *et al.* 2019).

Recently, a novel method utilizing superheated water steam has been investigated for reclaiming carbon fibers from carbon fiber-reinforced polymers (Wada *et al.* 2016). This innovative approach introduces superheated water steam into the pyrolysis recycling process, with temperatures surpassing the boiling point of water, to effectively decompose the polymer composites. This method offers high heat transfer efficiency and thermal capacity, facilitating efficient degradation of resin and resulting in clean fiber surfaces with high polarities (Kim *et al.* 2017; Cai *et al.* 2020).

The fluidized bed recycling technique has been employed to separate embedded fibers from composite scraps, typically performed within a silica bed using a hot air stream at temperatures ranging from 450°C to 550°C, dependent on the type of polymeric matrices (Pakdel *et al.* 2020). In this process, the recovered fibers and produced gases are transported by the stream, while additives and fillers remain in the bed and are subsequently oxidized in an afterburner (Pakdel *et al.* 2020; Dorigato 2021). It's worth noting that the thermal energy generated during the composite decomposition can sometimes be harnessed to facilitate the procedure (Dorigato 2021). However, this method has limited applications concerning fiber recycling, especially for carbon fiber. The carbon fiber recycled from a fluidized bed tends to experience more significant strength deterioration compared to pyrolysis. Additionally, fiber strength can be compromised due to attrition caused by the presence of sand. Unlike pyrolysis, this method cannot recover valuable oil compounds from the resin (Oliveux *et al.* 2015).

Among all the recycling routes, the thermal approach, especially pyrolysis, exhibits the highest technology readiness level for recycling discarded carbon fiber-reinforced polymers (Rybicka *et al.* 2016). The energy consumption of thermal recycling presents only about ~16% of the total energy consumed in manufacturing new carbon fiber (Rani *et al.* 2021). Whereas, it is not recommended to extract glass fiber from glass fiber-reinforced polymer composites using the thermal process due to the severe loss of strength in the recovered glass fiber and the relatively low cost of glass fiber itself (Jani *et al.* 2022).

Different fibers exhibit varying temperature sensitivities in the thermal process, dependent on their types and even specific brands. Carbon fiber, for instance, exhibits a higher tolerance to elevated temperatures than glass fiber, which has a lower temperature limit (Oliveux *et al.* 2015). Previous studies have reported that heat treatment can reduce the amorphous carbon content of carbon fibers, as some amorphous carbon can transform into highly thermally-stable crystalline graphite at high temperatures (He *et al.* 2019; Yang *et al.* 2019). Li *et al.* (2023c) have also demonstrated an improvement in the thermal stability of carbon fiber following the pyrolysis process. However, the pyrolyzed carbon fiber also exhibited a decrease in tensile behavior, likely attributable to the disruption of surface crystallites induced by surficial defects (Guozhan and Stephen J. 2016; Li *et al.* 2023c). Pyrolysis recycling and fluidized bed processing appear to retain approximately 80% of the mechanical strength of recycled carbon fiber from carbon fiber-reinforced polymer wastes at 550°C; In contrast, glass fiber retains only about 50% of its strength at a temperature of 450°C (Pickering *et al.* 2000; Hyde *et al.* 2006; Pickering 2006). All in all, glass fiber-reinforced polymer is not appropriate to be recycled using a thermal process. However, conventional and microwave-assisted pyrolysis, as well as superheated steam treatment, hold great promise for recovering carbon fibers from composite wastes.

3.3. Chemical recycling

Chemical recycling technologies have garnered significant attention from researchers worldwide for chemically reclaiming the reinforcing fibers and certain decomposition products of the matrices from fiber-reinforced polymers within an appropriate solvent (Pegoretti 2021). Typically, chemical recycling methods encompass solvolysis recycling under mild conditions or at supercritical conditions involving high temperatures exceeding 200°C and elevated pressures (Oliveux *et al.* 2015), as well as electrochemical recycling (Zhu *et al.* 2019).

Supercritical fluid recycling is regarded as an eco-friendly, green approach due to its low toxicity (Kumar and Krishnan 2020). Supercritical fluids exhibit intermediate properties between gases and liquids, characterized by high diffusivities, elevated mass transport coefficients, low viscosities, and pressure-dependent solvent power (Hyde *et al.* 2006; Liu *et al.* 2024). During the recycling process, the properties of the solvent and reaction rates can be controlled by adjusting the pressure (Wu *et al.* 1991). Supercritical water, for instance, is widely employed to separate carbon fiber from the resin matrix under stringent conditions, with pressures exceeding 221 bar and temperatures surpassing 374°C (Oliveux *et al.* 2015). Other solvents such as methanol, ethanol, acetone, and propanol, which possess lower critical pressure and temperature, have also been utilized in supercritical fluid processing (Oliveux *et al.* 2015). This technology has been reported to enable the decomposition of resin in carbon fiber-reinforced polymer recycling at rates exceeding 95% (Morin *et al.* 2012). Following supercritical fluid recycling, the primary degradation product of fiber-reinforced polymer composites is phenol, along with some gases including O_2, H_2, CO_2, and some alkanes (Oliveux *et al.* 2015) (Fig. 4a).

Additionally, a mild solvolysis process can be conducted with stirring at ambient pressure and temperatures below 200°C to recover both the fibers and resin matrices (Oliveux *et al.* 2015). In this method, oxidizing chemicals, along with swelling agents, acids, catalysts, and heat, are often employed (Pakdel *et al.* 2020). The widely accepted chemical degradation procedures consist of two main phases: first, the cured resins are expanded using swelling agents, allowing catalysts to infiltrate the cross-linked networks. Then, the chemical bonds of the resin matrix are cleaved into soluble molecules, enabling the fibers to be reclaimed (Liu *et al.* 2017) (Fig. 4b). However, the frequent use of acidic media such as acetic (Li *et al.* 2012), nitric (Dang *et al.* 2002), and sulphuric acids (Feraboli *et al.* 2012), as well as alkali solutions like potassium hydroxide (Liu *et al.* 2012), raises environmental concerns and health risks. An environmentally friendly oxidant, hydrogen peroxide, has recently gained traction for degrading thermosetting polymers, as it releases potent oxidizing species and produces no side products other than water (Liu *et al.* 2012; Pakdel *et al.* 2020). Schamel *et al.* (2021) developed an eco-friendly approach to degrade the cross-linked epoxy network and recover the internal carbon fiber. This process utilizes reusable N-methyl-2-pyrrolidone as a swelling agent, and thermolysis is carried out in hydrogen peroxide at temperatures below 200°C and atmospheric pressure.

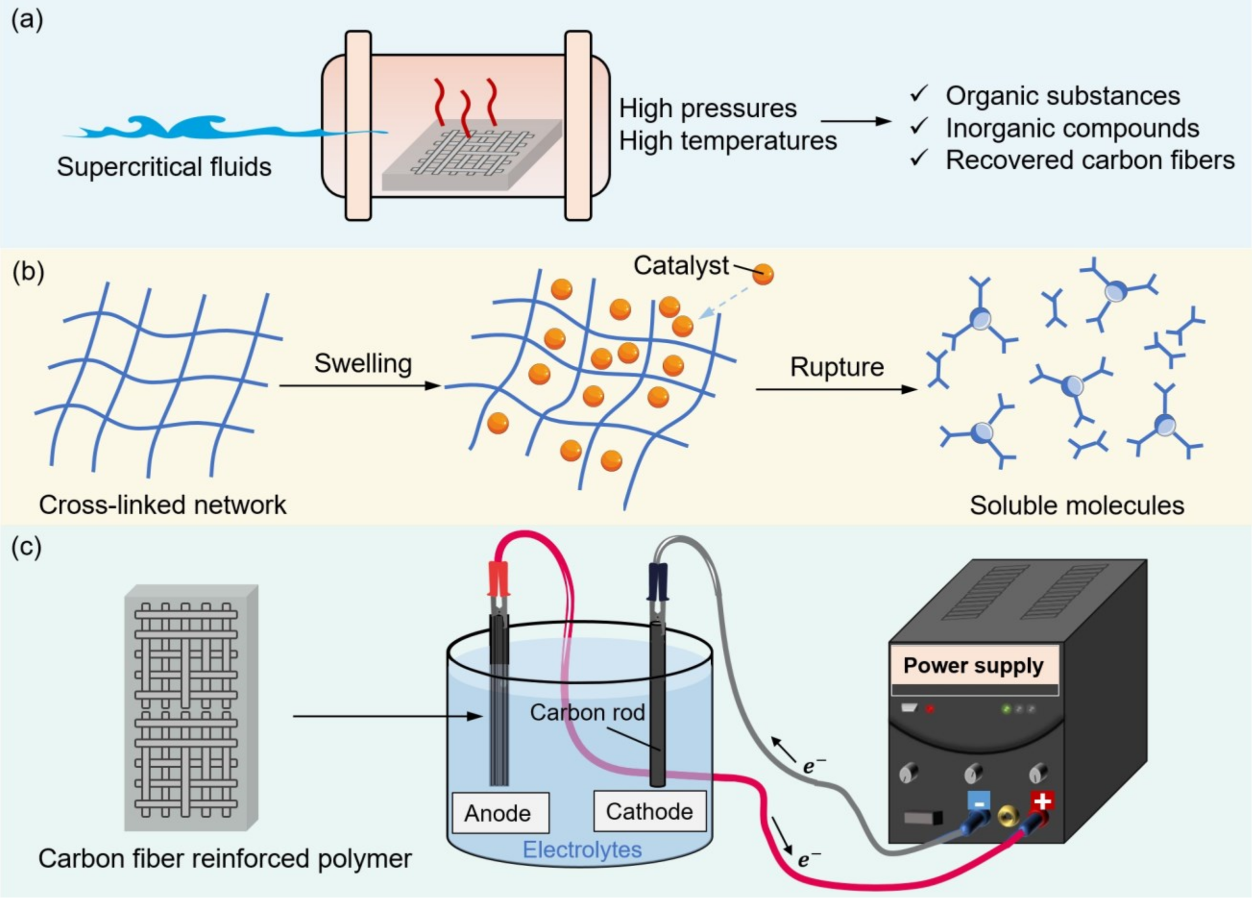

Fig. 4. (a) Supercritical fluid recycling can be used to recover the carbon fibers under controlled pressure at high temperatures; (b) The chemical decomposition process consists of two main stages: the resin matrices are swollen in liquid, and the catalysts infiltrate the cross-linked networks. Then, the chemical bonds of the resins are cleaved into soluble molecules, enabling the recovery of carbon fibers. Adapted from Liu *et al.* (2017); (c) The carbon fibers can be electrochemically recovered from carbon fiber-reinforced polymer composites. Adapted from Oshima *et al.* (2020).

In recent years, a sustainable and cost-effective electrochemical method has been developed for extracting recycled carbon fibers from end-of-service-life carbon fiber-reinforced polymer composites (Sun *et al.* 2015; Zhu *et al.* 2019; Pei *et al.* 2021) (Fig. 4c). In this electrochemical recycling process, the carbon fiber-reinforced polymer strip used as the anode can be decomposed in various electrolytes, e.g., NaOH, Na_2CO_3, KCl, KOH, NaCl, NaCl/KOH, and dimethyl sulfoxide (Sun *et al.* 2015; Zhu *et al.* 2019; Oshima *et al.* 2020; Pei *et al.* 2021), under a direct current electric field. Researchers have extensively explored different temperatures, currents, and electrolyte concentrations to optimize the resin removal rate and the residual strengths of the recovered carbon fibers. It's important to note that these parameters must be carefully controlled to avoid a drastic drop in residual tensile strengths (Zhu *et al.* 2019).

In summary, solvolysis and electrochemical recycling offer a wide range of parameters, demonstrating significant potential in the recovery of fiber-reinforced polymer wastes. Unlike pyrolysis, chemical methods prevent the generation of char on recycled fibers, resulting in cleaner fibrous products (Oliveux *et al.* 2015; Pei *et al.* 2021). However, supercritical fluid recycling is considered energy-intensive and expensive, requiring specific reactors capable of withstanding high-temperature and high-pressure conditions (Dorigato 2021). In contrast, electrochemical recycling and mild solvolysis demand lower temperatures, making them easier to control (Oliveux *et al.* 2015). Previous studies have shown that both solvolysis and electrochemical approaches can maintain approximately 80-100% of the residual strength for recycled carbon fiber (Zhu *et al.* 2019; Pakdel *et al.* 2020; Pei *et al.* 2021); while chemically recovered glass fiber through solvolysis exhibits a larger fiber strength loss of approximately 50% (Kao *et al.* 2012; Oliveux *et al.* 2012).

3.4. Waste hierarchy for fiber reinforced polymer composite wastes

Current and future environmental protection and waste management policies emphasize the proper recycling and recovery of all end-of-life engineering materials (Yang *et al.* 2012). To promote a circular economy, reduce environmental impacts, and enhance resource utilization efficiency, the concept of a "waste hierarchy" was introduced in the European waste directive (Zhang *et al.* 2022a). This hierarchy outlines the preferred order for waste management and was originally proposed by Dutch politician Ad Lansink in 1979 (Zhang *et al.* 2022a). A significant milestone in the field of waste material management came with the introduction of the latest European Waste Framework Directive 2008/98/European Commission (Gharfalkar *et al.* 2015). This directive established a clear and comprehensive waste hierarchy as a legislative framework (Gharfalkar *et al.* 2015). It encompasses five waste treatment operations: prevention, preparing for reuse, recycling, other recovery, and disposal (Gharfalkar *et al.* 2015). When viewed in the context of a product's life cycle, these measures can be further categorized into three stages: pre-use, use, and post-use phases (Zhang *et al.* 2022a), as shown in Fig. 5.

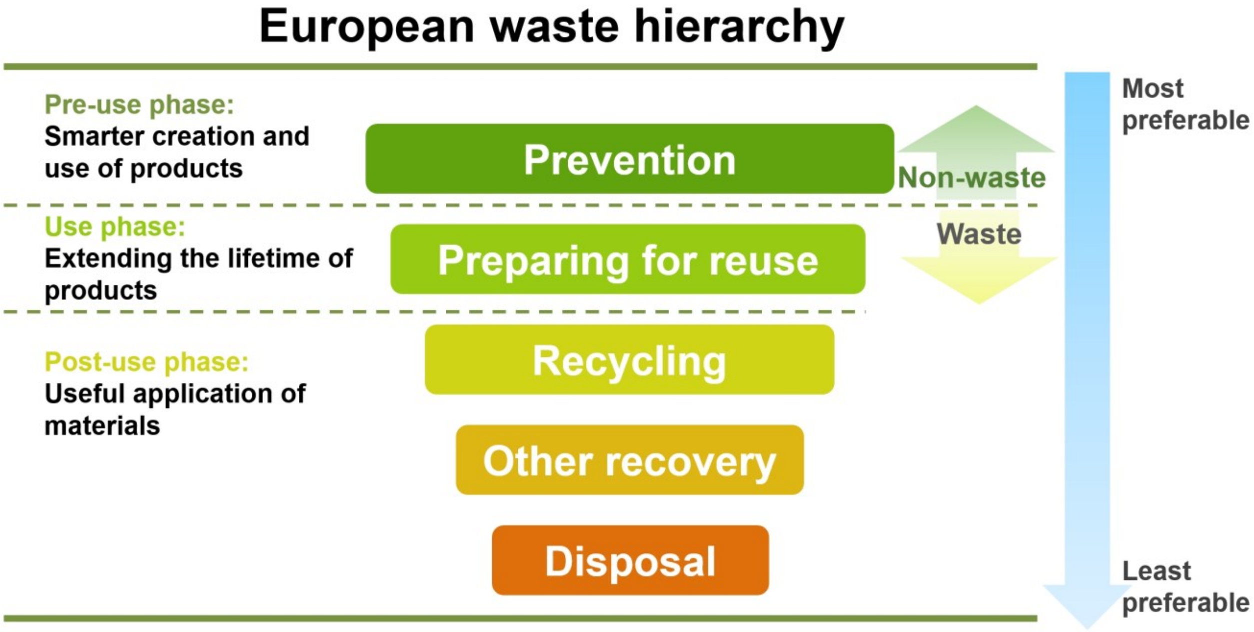

Fig. 5. The European Waste Framework Directive 2008/98/European Commission comprises five steps including prevention, preparing for reuse, recycling, other recovery, and disposal. The ‘reuse’ operation is suitable for ‘non-waste’, while the other operations are described to be applicable to ‘waste’. The waste hierarchy considers different stages of product use, including the pre-use phase, use phase, and post-use phase. Adapted from Zhang *et al.* (2022a).

However, research on the allocation of recycling processes for fiber-reinforced polymer composites based on the waste management hierarchy remains relatively scarce (Rybicka *et al.* 2016). No reported categorization of recycling routes for fiber-reinforced polymer wastes has been reported in the construction field. Consequently, the construction sector requires a waste hierarchy specific to fiber-reinforced polymer recycling methods to minimize resource depletion, reduce environmental impact, and maximize the efficiency of fiber-reinforced polymer reinforcement utilization. While various versions of waste management hierarchies have been issued by authorities or proposed by researchers (Zhang *et al.* 2022a), this study has chosen to use the most representative Waste Framework Directive 2008/98/European Commission, in conjunction with principles from the circular economy theory, as the foundation for classification. This choice is made due to its applicability and comprehensive nature in addressing the specific needs of fiber-reinforced polymer recycling in the construction sector.

To identify suitable waste management solutions, the implementation of a waste hierarchy becomes imperative for various recycling pathways of waste fiber-reinforced polymer products within the construction sector. Table 2 categorizes the three leading recycling technologies for fiber-reinforced polymer wastes and their applications in civil engineering, considering the Waste Framework Directive 2008/98/European Commission and circular economy principles. Within mechanical recycling, simple processing, such as repurposing discarded wind blades for structural use (Martinez-Marquez *et al.* 2022), aligns with the "Preparing for reuse" category. This falls within the "Use phase" of the product lifecycle (Zhang *et al.* 2022a), as seen in Fig. 2. Other mechanical recycling methods like grinding, cutting or crushing, and special processing are categorized as "recycling" since they create new construction materials without recovering energy or fuels and backfilling operations (Gharfalkar *et al.* 2015). Thermal recycling methods, including pyrolysis, microwave-assisted pyrolysis, and fluidized bed techniques, are classified under "Other recovery", because they enable the recovery of thermal energy and/or fuels in the process (Gharfalkar *et al.* 2015), as discussed in Section 3.2. Chemical recycling technologies, such as solvolysis at mild and supercritical conditions, are also placed in the "Other recovery" category due to their potential to reclaim valuable products from the resin. In contrast, electrochemical recycling falls under "recycling" because it doesn't recover resin monomers or energy.

Cement kiln recycling is considered one of the most suitable and sustainable pathways for recycling end-of-life glass fiber-reinforced polymer composites (Krauklis *et al.* 2021; Mao *et al.* 2023; Shen *et al.* 2023). In this process, the inorganic components of glass fiber-reinforced polymers, such as fibers and fillers, are converted into raw materials for cement production, while the organic part serves as an additional energy source during combustion (Fonte and Xydis 2021; Krauklis *et al.* 2021). Consequently, cement kiln co-processing is categorized as "Other recovery," although its impact on cement quality remains a subject of debate (Oliveux *et al.* 2015).

Another recycling method worth mentioning is the high voltage fragmentation method, which has been tentatively employed to disintegrate glass fiber-reinforced polymer and carbon fiber-reinforced polymer composites. In this process, repetitive pulse electrical discharges are applied under high voltages exceeding 100 kV (Mativenga *et al.* 2016; Roux *et al.* 2017). While high voltage fragmentation has shown slight improvements in resin removal ratios and the strength of recycled fibers compared to mechanical methods (Rouholamin *et al.* 2014; Mativenga *et al.* 2016), it has not gained widespread popularity due to its exceptionally high electricity consumption (Shuaib and Mativenga 2017). As a result, this method is not further discussed in this study and is not included in the table.

Table 2. Present and potential recycling routes of fiber-reinforced polymer wastes in the construction industry.

Classification	Recycling technologies	Waste types	Applications in construction	Waste hierarchy

Mechanical recycling	Simple processing	Wind blades (Martinez-Marquez *et al.* 2022)	Playground, public seating, bus stop, and bicycle shelter (Martinez-Marquez *et al.* 2022)	Preparing for reuse
	Grinding, milling	Carbon fiber-reinforced polymer (Norambuena-Contreras *et al.* 2016), glass fiber-reinforced polymer (Asokan *et al.* 2009)	Carbon fiber-reinforced polymer (Norambuena-Contreras *et al.* 2016) or glass fiber-reinforced polymer (Asokan *et al.* 2009) as fine aggregates	Recycling
	Cutting or crushing	Carbon fiber-reinforced polymer (Ogi *et al.* 2005), glass fiber-reinforced polymer (Shahria Alam *et al.* 2013), high density polyethylene reinforced polymer (Jha *et al.* 2014)	Carbon fiber-reinforced polymer (Ogi *et al.* 2005) or glass fiber-reinforced polymer (Yazdanbakhsh *et al.* 2016) as coarse aggregates	Recycling
	Special processing	Carbon fiber-reinforced polymer (Rangelov *et al.* 2016), glass fiber-reinforced polymer (Fu *et al.* 2021)	Needle-shape carbon fiber-reinforced polymer (Rangelov *et al.* 2016) or glass fiber-reinforced polymer (Fu *et al.* 2021) as macro-fiber	Recycling
	Cutting or chopping	Carbon fiber wastes (Belli *et al.* 2020), glass fiber (Novais *et al.* 2017) wastes	Carbon fiber wastes (Belli *et al.* 2020) or glass fiber (Novais *et al.* 2017) wastes as fiber reinforcement	Recycling
Thermal recycling	Pyrolysis	Carbon fiber-reinforced polymer (Li *et al.* 2022c), glass fiber-reinforced polymer (Criado *et al.* 2014)	Pyrolyzed carbon fiber (Li *et al.* 2022c) or glass fiber (Criado *et al.* 2014) as fiber reinforcement	Other recovery
	Microwave-assisted pyrolysis	Carbon fiber-reinforced polymer (Li *et al.* 2021b; Li *et al.* 2023d)	Carbon fiber-reinforced polymer (Li *et al.* 2021b; Li *et al.* 2023d) as fiber reinforcement	Other recovery
	Fluidized bed	Carbon fiber-reinforced polymer (Yip *et al.* 2002), glass fiber-reinforced polymer (Zheng *et al.* 2009)	—	Other recovery
Chemical recycling	Solvolysis in mild conditions	Carbon fiber-reinforced polymer (Li *et al.* 2023a), glass fiber-reinforced polymer (Zhao *et al.* 2023)	Recovered carbon fiber as fiber reinforcement (Li *et al.* 2023a)	Other recovery
	Supercritical fluids	Carbon fiber-reinforced polymer (Kulikova *et al.* 2022), glass	—	Other recovery

		fiber-reinforced polymer (Oliveux *et al.* 2013)		
	Electrochemical recycling	Carbon fiber-reinforced polymer (Zhu *et al.* 2019), carbon fiber-reinforced cementitious composites (Chen *et al.* 2019)	—	Recycling
Cement kiln recycling	Co-incineration in cement kilns	Carbon fiber-reinforced polymer and glass fiber-reinforced polymer (Sommer and Walther 2021)	Energy and material source in cement production (Sommer and Walther 2021)	Other recovery

4. Application of recycled carbon fiber reinforced polymer

4.1. Mechanically recycled carbon fiber reinforced polymer as reinforcement in construction materials

After the mechanical recycling process, the obtained recycled carbon fiber-reinforced polymer exhibits substantial variations in morphology and shape. These disparities significantly influence the reinforcement effectiveness within cement composites and the bonding characteristics with the matrix. Consequently, it becomes imperative to categorize recycled carbon fiber-reinforced polymer based on its distinct forms. In this context, we identify three primary classifications of carbon fiber-reinforced polymer waste: carbon powder, carbon fiber-reinforced polymer coarse aggregate, and needle-shaped carbon fiber-reinforced polymer characterized by its notably high slenderness ratio, as shown in Fig. 6.

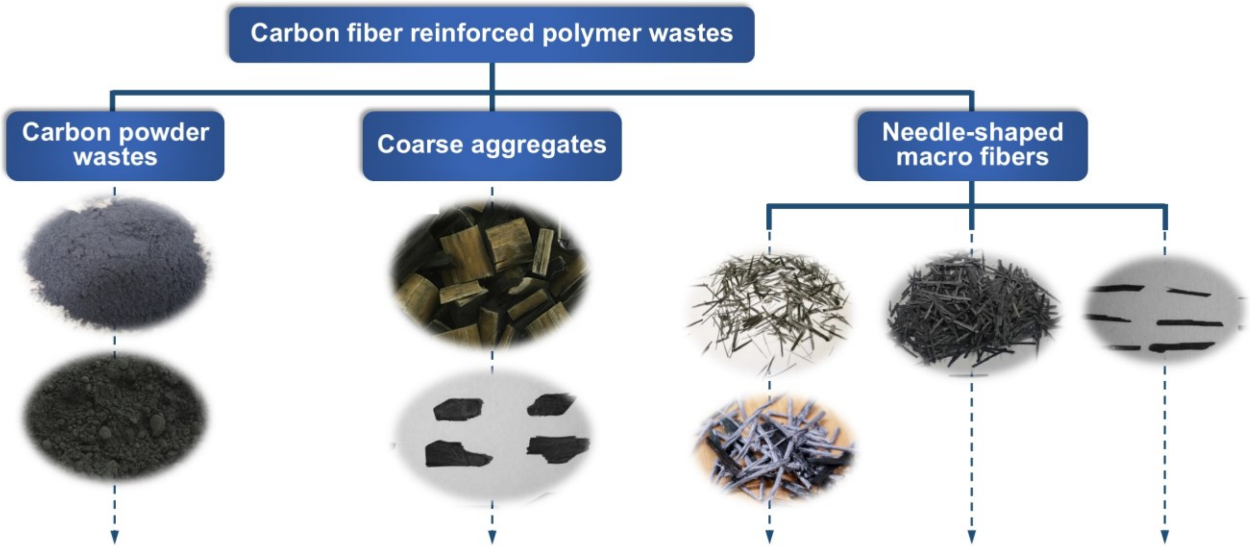

Fig. 6. Mechanically recycled carbon fiber-reinforced polymers are classified according to their unique morphologies. Carbon powder wastes can be used as fillers in construction materials, recycled carbon fiber-reinforced polymers can serve as coarse aggregates in concrete, and needle-shaped carbon fiber-reinforced polymers can be utilized as macro fibers to reinforce building materials. Adapted from Ogi *et al.* (2005); Thomas *et al.* (2014); Rodin III *et al.* (2018b); Clark *et al.* (2020); Nassiri *et al.* (2021); Xiong *et al.* (2021).

4.1.1. Carbon powder waste as fine filler

Due to the inherent high value-added characteristics, the length of recycled carbon fibers has been typically retained during the recycling of carbon fiber-reinforced polymer wastes. In recent years, there has been a growing interest in exploring the potential of carbon powder wastes derived from the cutting process of carbon fiber-reinforced polymer scraps for reinforcement in cement composites. Notably, Norambuena-Contreras *et al.* (2016) pioneered the utilization of carbon powder waste as fine fillers in cement paste, employing dosages ranging from 1.5% to 5.5% by the weight of clinker. They also subjected virgin carbon powder wastes to high-temperature treatment exceeding 200°C to reduce the content of powdered resin impurities. Their investigations revealed certain noteworthy findings, including an increase in porosity, a reduction in bulk density, and a proportional decline in abrasion resistance of the matrices with increasing carbon powder waste content. Moreover, both untreated and treated carbon powder waste led to augmented flexural strength but reduced compressive properties, as shown in Fig. 7. Intriguingly, heat treatment of carbon powder waste resulted in improved mechanical performance due to reduced resin contents and lowered porosity in the matrices (Norambuena-Contreras *et al.* 2016).

Furthermore, Clark *et al.* (2020) introduced fine particle fiber-powder generated during the cutting of conductor core rods into cementitious paste at a concentration of 6 wt.%. Their study observed a decrement in compressive strength but an enhancement in the hardness of the particle fiber-powder reinforced cement composite. Upon subjecting the composite to aging in ocean saltwater, the particle fiber-powder reinforced cement composite exhibited comparable strength to neat samples, showcasing the potential application of this hybrid carbon fiber and glass fiber reinforced polymer waste in corrosive environments.

To sum up, we observed that the inclusion of carbon powder waste in cement composites adversely affects compressive performance, which can be mitigated by heat treatment. However, adding carbon powder waste seems to be beneficial for improving the flexural strength of cementitious materials. It's worth noting that despite these promising developments, research on the use of carbon powder wastes in construction materials remains relatively limited, warranting further investigations and exploration of its full potential.

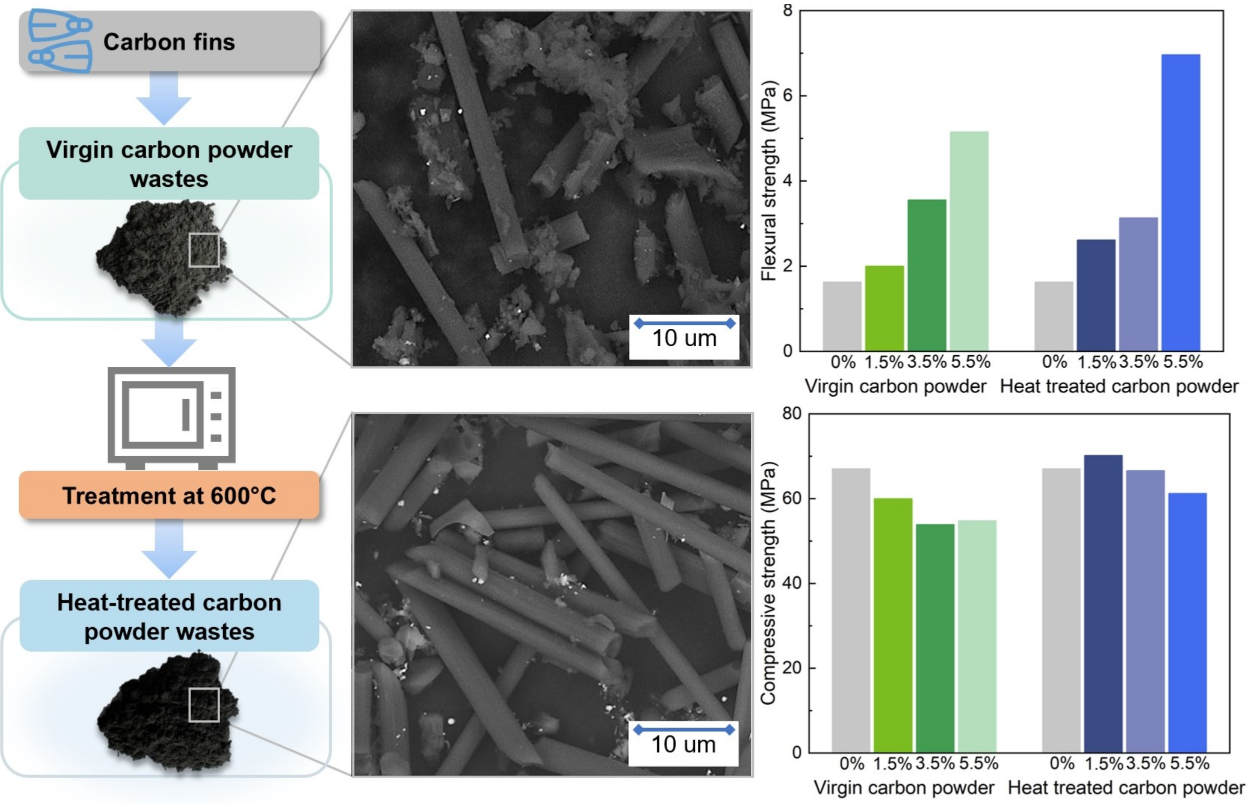

Fig. 7. The virgin and heat-treated carbon powder wastes are incorporated into cement paste. Both untreated and heat-treated carbon powder wastes can improve flexural strength, while reducing compressive properties. Heat treatment of carbon powder waste leads to improved mechanical performance of cement composites. Adapted from Norambuena-Contreras *et al.* (2016).

4.1.2. Recycled carbon fiber reinforced polymer as coarse aggregate

The role of carbon fiber-reinforced polymer wastes as coarse aggregates in cement-based composites has received limited attention in research. In a study conducted by Clark *et al.* (2020), crushed conductor core rod chips, accounting for 6 wt.% of the composite mixture, were integrated as coarse aggregates. The results of this study indicated a detrimental effect on the compressive behavior of the composites, both before and after curing in a simulated seawater environment. This adverse impact was attributed to the presence of polymer resin-bound chips, which initiated cracks within the composite matrices.

In a study conducted by Ogi *et al.* (2005), crushed carbon fiber-reinforced polymer pieces of varying sizes were introduced into concrete as coarse aggregates at different dosages ranging from 5% to 10% by weight. The research revealed that small or medium sized carbon fiber-reinforced polymer pieces contributed to an increase in compressive and flexural strengths as the proportion of carbon fiber-reinforced polymer additives in the large specimens increased. However, Singh *et al.* (2022) reported a decrease in compressive and splitting tensile strengths of pervious concrete that contained carbon fiber-reinforced polymer pieces with sizes exceeding 7 mm. Interestingly, they also found that the inclusion of carbon fiber-reinforced polymer wastes led to an enhancement in the flexural properties of the control mixture by approximately 1.5% to 5.5%, depending on the dosage of carbon fiber-reinforced polymer. It is worth noting that in both studies, the carbon fiber-reinforced polymer additives exhibited a flaky appearance with relatively small thickness. This irregular shape likely had a significant impact on the interaction between carbon fiber-reinforced polymer aggregates and the surrounding matrices, and further investigation is warranted to elucidate the mechanisms behind this enhancement. As a whole, we observed that the use of recycled carbon fiber-reinforced polymer as coarse aggregates is likely to reduce the compressive and splitting tensile behavior of cement composites. However, in the case of flaky shapes of carbon fiber-reinforced polymer aggregates, the flexural properties can be enhanced.

4.1.3. Specially shaped recycled carbon fiber reinforced polymer as macro fiber

Upon reviewing open publications, it becomes apparent that the inclusion of carbon powder and coarse aggregates derived from carbon fiber-reinforced polymer waste tends to have a detrimental effect on the strength of cement composites. However, one aspect often overlooked is the influence of the shapes of mechanically recycled carbon fiber-reinforced polymer additives. To fully harness the unidirectional high strength of carbon fibers, recycled carbon fiber-reinforced polymer can undergo processing into elongated elements, often referred to as macro fibers. This approach serves to enhance the post-peak load-carrying capacity of cementitious matrices (Yazdanbakhsh 2021). For a more comprehensive understanding, Table 3 provides detailed information on selected studies pertaining to the use of needle-shaped glass fiber-reinforced polymer in cement-based composites.

4.1.3.1. Workability

The influence of adding fibers from waste carbon fiber-reinforced polymer on the fluidity of cementitious mixes was investigated by several researchers. For instance, Xiong *et al.* (2021) incorporated macro fibers made of waste carbon fiber-reinforced polymer, measuring 35×2×0.2 mm, into concrete at dosages ranging from 0.5 to 1.5 vol.%. They observed a gradual reduction by up to 22% in slump values with the increase of volume fraction, attributed to the presence of a three-dimensional web composed of macro fibers. In a study by Mastali *et al.* (2017), an evaluation of the fresh-state properties of self-compacting concrete reinforced with macro fibers from recycled carbon fiber-reinforced polymer revealed a declining trend in flowability as both fiber length and dosage increased. Overall, we found that in most cases, the introduction of macro fibers derived from carbon fiber-reinforced polymer wastes had an adverse effect on the flowability of the fresh cement mixture.

4.1.3.2. Mechanical properties

The utilization of needle-shaped recycled carbon fiber-reinforced polymer reinforcements generally yields improvements in the mechanical performance of cement composites, particularly in terms of flexural strength (Nguyen *et al.* 2016; Rangelov *et al.* 2016; Rodin III *et al.* 2018b). For instance, Rangelov *et al.* (2016) conducted research on the mechanical properties of pervious concrete reinforced with macro fibers from waste carbon fiber-reinforced polymer, using fibers of varying sizes and dosages. Their results indicated a significant enhancement in the compressive and tensile properties of concrete materials after 28 days of curing, with more pronounced increases observed at higher fiber volumes of above 1 vol.% and longer lengths of above 0.8 mm. Similarly, Mastali *et al.* demonstrated that the mechanical performance of self-compacting concrete can be significantly improved with increasing proportions and lengths of macro fibers from recycled carbon fiber-reinforced polymer in terms of compressive, flexural, and tensile strength, as well as impact resistance (Mastali and Dalvand 2016; Mastali *et al.* 2017). The incorporated macro fibers are capable of transferring stress to the surrounding matrices, resisting crack propagation and promoting the formation of multiple cracks under loading (Mastali and Dalvand 2016). This mechanism was supported by scanning electron microscopy images, which showed a failure mode at the interface between recycled carbon fiber and matrices dominated by debonding. This fiber bridging action can offset the adverse effects of the increased porosity in cementitious matrices, contributing to improved strength properties (Mastali *et al.* 2017).

However, there have been instances where the addition of carbon fiber-reinforced polymer fibers had a negative impact on strength development (Wang *et al.* 2019a; Nassiri *et al.* 2021). In the work of Prieto *et al.* (2021), a reduction in the maximum and ultimate strengths of concrete reinforced with fibers from recycled carbon fiber-reinforced polymer was observed compared to the plain matrix. They also noted that the addition of fibers of recycled carbon fiber-reinforced polymer increased ductility and improved flexural and impact resistance in the concrete, while reducing premature cracking and surface flaking of cement composites (Prieto *et al.* 2021). It's important to note that the needle-shaped recycled carbon fiber-reinforced polymer reinforcements under investigation exhibit significant variations in terms of length, width, and thickness, which could lead to discrepancies in the reinforcing efficiency of fibers of recycled carbon fiber-reinforced polymer and the resulting strength of cement-based composites. This shape effect warrants further investigation in future studies. Based on previous findings, we observed that the application of macro fibers made from waste carbon fiber-reinforced polymer in cement matrices aided in improving flexural strength. Additionally, adding macro fibers can contribute to enhancing compressive behavior in the majority of cases, despite reports of worse compressive behavior in some instances.

4.1.3.3. Durability

Research efforts focused on enhancing the durability of cement composites reinforced with needle-shaped recycled carbon fiber-reinforced polymer are relatively scarce. Wang *et al.* (2019a) introduced 1 vol.% of flaky macro fibers from recycled carbon fiber-reinforced polymer into cement mortars and examined the drying shrinkage behavior of the composites. Their findings indicated that including fibers of recycled carbon fiber-reinforced polymer reduced the drying shrinkage of mortars at 35 days compared to plain samples. This reduction can be attributed to the interfacial adhesion between the fiber and matrix, which partially inhibits the development of shrinkage trends.

Rangelov *et al.* (2016) investigated the durability of pervious concrete incorporating fibers of recycled carbon fiber-reinforced polymer at volume fractions ranging from 0.5% to 1.5%. Their results suggested that the addition of fibers at various dosages increased the infiltration rates, despite a reduction in porosity. This improvement in infiltration rates can be explained by the enhancement of void connectivity. Additionally, they utilized macro fibers from recycled carbon fiber-reinforced polymer to partially substitute the coarse aggregates of concrete, with substitutions up to 2 vol.%, resulting in increased infiltration rates and porosity (Nassiri *et al.* 2021). Nevertheless, for higher fiber contents of 3-5 vol.%, the infiltration of pervious concrete generally decreased, likely due to the deterioration of void connectivity (Rodin III *et al.* 2018b). Further research in this area is needed to fully understand the complex interplay between additives of recycled carbon fiber-reinforced polymer and the durability of cement composites. Overall, we observed that mixing macro fibers of recycled carbon fiber-reinforced polymer into cement composites could result in increased porosity and infiltration rates, but a decline in shrinkage behavior.

4.1.3.4. Application in alkali activated material and geopolymer

Mechanically recycled carbon fiber-reinforced polymers have found applications in alkali-activated materials and geopolymers. Manzi *et al.* (2020) produced alkali-activated composites reinforced with needles made of recycled carbon fiber-reinforced polymer at varying contents of 3, 6, 9, and 12 wt.%, using metakaolin and incinerator bottom ash as binders. Their findings revealed that the inclusion of fibers of recycled carbon fiber-reinforced polymer led to a reduction in the flowability of fresh mortars and increased water absorption, although it had little effect on compressive strength. However, due to the strong adhesion between carbon fiber-reinforced polymer and matrices, the bending strength and fracture energy of fiber-reinforced alkali-activated materials progressively improved with increasing fiber amounts (Manzi *et al.* 2020). Saccani *et al.* (2019) employed fibers from recycled carbon fiber-reinforced polymer to reinforce fly ash- and metakaolin-based geopolymers at 1.3-4.5% volume fractions. Their results showed that adding fibers decreased workability and water absorption as fiber dosages increased, while it had a positive effect on improving flexural and compressive behavior.

In summary, we found that the addition of macro fibers made from carbon fiber-reinforced polymer waste showed a positive effect on the mechanical properties of alkali-activated composites and geopolymers. However, the inclusion of recycled carbon fiber-reinforced polymer diminished the flowability of fresh mixes. Despite these findings, the investigation into the application of recycled carbon fiber-reinforced polymer in alkali-activated materials (Nazar *et al.* 2023c) or geopolymer composites (Nazar *et al.* 2023b) substantially lags behind.

Table 3. Applications of specially-shaped recycled carbon fiber-reinforced polymer as macro-fibers in cement-based composites.

Ref.	Matrix	Carbon fiber-reinforced polymer source	Production process	Resin ratio	Carbon fiber-reinforced polymer size	Carbon fiber-reinforced polymer dosage	Water/binder ratio	Curing condition	Flowability	Compressive strength	Flexural strength	Tensile strength	Impact resistance	Characterization analysis
Nguyen *et al.* 2016	Mortar	Reclaimed carbon fiber, carbon fiber-reinforced polymer waste, or prepreg carbon fiber waste	Shearing	—	Reclaimed carbon fiber 0.05-15 mm; carbon fiber-reinforced polymer waste 3, 6 mm; prepreg carbon fiber waste≈20 mm	Reclaimed carbon fiber, 0.5, 1, 1.5 wt.%; carbon fiber-reinforced polymer waste, 2, 3 wt.%; prepreg carbon fiber waste, 1, 2 wt.%	—	7, 28 d in water tank at room temperature	—	Increase	Increase	—	—	Scanning electron microscope, fracture toughness, drying shrinkage
Wang *et al.* 2019b	Mortar	Cured carbon fiber composite material	Shredding, hammer-milling	96% carbon fiber, 4% epoxy resin	0.05-12 mm length; 0.8 mm maximum width	1 vol.%	0.5	7, 28 d, 23±2°C, relative humidity>90 %	—	Decrease (saturated pore solution/0.5 h; saturated pore solution/2h); increase (saturated pore solution/0.5 h/triisopropanolamine; montmorillonite nanoclay	—	21.8-84.3 % increase (splitting tensile)	—	Scanning electron microscope, fourier transform infrared spectroscopy, thermal gravimetric analysis

										emulsion/2h)				
Wang *et al.* 2019a	Mortar	Cured carbon fiber composite material	Shredding, hammer-milling	96% carbon fiber, 4% epoxy resin	0.05-12 mm length; 0.8 mm maximum width	1 vol.%	0.5	7, 28 d, 23±2°C, relative humidity>90 %	—	Decrease	—	Increase (splitting tensile)	—	Scanning electron microscope, thermal gravimetric analysis, free drying shrinkage
Mastali and Dalvand 2016	Self-compacting mortar	Carbon fiber-reinforced polymer laminates	Shredding	—	20 mm length; 0.11 mm thickness	0.25, 0.75, 1.25 vol.%	0.35	28d in water; 23°C	Decrease	31.1-65.1 % increase	31.2-66.9 % increase	—	320-648 % increase (ultimate crack impact resistance)	Scanning electron microscope
Mastali *et al.* 2017	Self-compacting mortar	Carbon fiber-reinforced polymer sheets	Shredding	—	10, 20, 30 mm length; 0.11 mm thickness	0.5, 1, 1.5, 2 vol.%	0.38	28d in water; 20°C	Decrease	Increase	Increase; increase (toughness)	—	Increase	Scanning electron microscope, atomic force microscopy, backscattered electron, energy dispersive

														X-ray spectroscopy, ultrasonic pulse velocity
Ogi *et al.* 2005	Concrete	T700S, Toray	—	—	Small (3.4×0.4 mm), medium (9.9×2.2 mm), large (21×7.7 mm); 0.05-0.2 mm thickness	0.013, 0.02, 0.026 vol.%	0.45	14 d; steam curing	Decrease	Increase, decrease (large)	Increase, decrease (small); increase (fracture work)	—	—	Scanning electron microscope, pullout tests
Prieto *et al.* 2021	Concrete	Carbon fiber-reinforced polymer used in U-shaped flexural test	Manually extracted from wooden elements	—	48 mm length, 0.04 mm thickness, 2 mm width	Recycled carbon fibers in quantities of 3 kg/m^3 and 6 kg/m^3	0.46	28 d, 20±2°C; relative humidity>90 %	—	6.0-10.5 % decrease	Increase	—	Increase (fracture energy)	—
Xiong *et al.* 2021	Concrete	Waste carbon fiber-reinforced polymer sheets	Shredding	—	35 mm length; 2 mm width	0.5, 1.0, 1.5 vol.%	0.4	28 d; 20±2°C; relative humidity>90 %	Decrease	0.1-5.5 % increase	6.1-38.7 % increase	—	Increase (first and ultimate cracking impa	CO_2 emission

													ct resistance, impact energy)	
Lamba *et al.* 2023	Concrete	From already-used carbon fiber-reinforced polymer sheets	—	—	30 mm	0.2, 0.4, 0.6, 0.8, 1 vol.%	0.239	28 d in water	—	Increase	—	—	—	Ultrasonic pulse velocity, X-ray diffraction
Rodin III *et al.* 2018b	Pervious Concrete	Cured carbon fiber composite material	Grinding, screening	—	0.6-5mm	3, 4, 5 vol.%	0.27	7, 28 d	—	Increase (4 vol.%); decrease (3, 5 vol.%)	Increase (modulus of rupture); increase (toughness)	Increase (splitting tensile)	—	Infiltration, porosity
Rangelov *et al.* 2016	Pervious Concrete	Coarse and flaky cured carbon fiber composite material	Shredding, hammer-milling	—	Combined: <3.35 mm; 2 mm<large<3.35 mm; 0.841 mm<medium<2 mm; small<0.841 mm	0.5, 1, 1.5 vol.%	0.24	7, 28 d in closed (capped) molds at 21°C	—	~10.8 % increase; 6.8-46.6% increase (modulus of elasticity)	—	~44.4 % increase (splitting tensile)	—	Infiltration, porosity
Nassiri *et al.* 2021	Pervious Concrete	Carbon fiber-reinforced polymer from the	Hammer milling, screening	—	11.6 mm length; 0.81 mm width	0.5, 1, 2 vol.%, replacing coarse aggregate	0.34	7, 28 d in full sealed conditions	—	Decrease	Decrease (0.5 vol.%); increase (1, 2 vol.%)	Decrease (splitting tensile)	Comparable	Infiltration, porosity, surface abrasion, freeze-thaw cycling,

		aerospace industry												scaling resistance
Manzi *et al.* 2020	Alkali-activated Binders	Pre-preg off-cuts from carbon fiber-reinforced polymer production	—	30±8 wt.%	150-450 μm average thickness; 13±2 mm length; 5-10 mm lateral size, multiple layers	3, 6, 9, 12 wt.% of powders by mass	0.36, 0.28	28 d at 25±1° C; relative humidity 98±1 %	Decrease	Comparable	Increase	—	—	Scanning electron microscope, free drying shrinkage, water absorption, porosity
Saccani *et al.* 2021	Alkali-activated binders	Pre-preg off-cuts from carbon fiber-reinforced polymer production	—	—	300±20 μm average thickness, 5±1 mm or 10±1 mm length; 3-6 mm lateral size (multiple layers)	4.6 vol.%	0.07, 0.1	28 d; 23±2° C; relative humidity 70±5 %	—	Decrease	Increase	—	—	Fourier transform infrared spectroscopy, water absorption, pullout tests
Saccani *et al.* 2019	Geopolymer	Scraps from carbon fiber-reinforced polymer production	—	30±8 wt.%	8-12 μm or 150-450 μm thickness (single layer or multiple layers)	1.3, 2.5, 4.5 vol.%	0.3, 0.4	28 d; 25±1° C; relative humidity 98±2 %	Decrease	Increase	Increase	—	—	Scanning electron microscope, optical observation, water absorption

4.2. Recovered carbon fiber from pyrolysis as reinforcement in construction materials

In contemporary times, pyrolysis recycling stands out as the sole technology that has achieved industrial-scale implementation. The product of pyrolysis recycling, recycled carbon fiber, holds immense promise for application in cementitious materials. Previous research has predominantly investigated recycled carbon fiber materials produced by leading carbon fiber-reinforced polymer recycling companies, including ELG Carbon Fiber Ltd. (Faneca *et al.* 2018; Akbar *et al.* 2021), CAR FiberTec GmbH (Faneca *et al.* 2018), CFK Valley Stade Recycling GmbH & Co. KG (Kimm *et al.* 2020), Nantong Fuyuan Carbon Fiber Recycling Co., LTD (Li *et al.* 2022c), and Thermolysis Co., Ltd. (Li *et al.* 2021b; Li *et al.* 2023d), as detailed in Table 4.

In 2018, Faneca *et al.* (2018) pioneered the utilization of pyrolyzed carbon fibers to reinforce both ultra-high-performance concrete and conventional concrete within volume fractions ranging from 0.1% to 1.4%. Their findings indicated a reduction in slump flow as the fiber content increased. For ultra-high-performance concrete, comparable or improved mechanical properties were achieved, particularly when using the wet mix approach for incorporating recycled carbon fiber. Conversely, the dry mix approach has a detrimental effect on flexural and compressive strength. In conventional concrete matrices, the addition of recycled carbon fiber resulted in a decrease in compressive performance due to the introduction of pores caused by reduced flowability. However, adding recycled carbon fiber led to an upward trend in the flexural strength of conventional concrete composites with increasing fiber content (Faneca *et al.* 2018).

In most cases, adding recycled carbon fiber derived from pyrolysis favors strengthening the flexural and compressive performance of cementitious composites (Kimm *et al.* 2020; Akbar *et al.* 2021; Li *et al.* 2022c). Kimm *et al.* (2020) blended 0.25% to 2% recycled carbon fiber into mortars and observed a substantial increase in flexural strength, reaching up to 111% improvement at the 1% recycled carbon fiber content compared to plain matrices. Similarly, Akbar *et al.* identified the optimal fiber content as 1 vol.%, resulting in the highest flexural, compressive, and splitting tensile resistance among cement pastes reinforced with recycled carbon fiber at various dosages ranging from 0.25 to 1.5 vol.% (Akbar and Liew 2020a; Akbar *et al.* 2021). They also noted a decrease in density as recycled carbon fiber content increased (Akbar and Liew 2020a).

More recently, Li *et al.* (2023c) introduced 1 wt.% recycled carbon fiber from pyrolysis into limestone calcined clay cement. They observed that the addition of recycled carbon fiber significantly improved the flexural properties of the plain cement matrix and cement composite containing 25% limestone calcined clay cement. Incorporating recycled carbon fiber benefits the enhancement of compressive strength in plain matrix, while exhibiting little effect on limestone calcined clay cement composites. When compared to virgin carbon fiber, recycled carbon fiber exhibited inferior bond behavior with cementitious matrices and a reduced reinforcing effect in composites, primarily due to the absence of surficial sizing, as seen in Fig. 8. Consequently, the surface chemistry of recycled carbon fiber played a pivotal role in load transferring and the overall performance of fiber-reinforced composites, warranting further investigation.

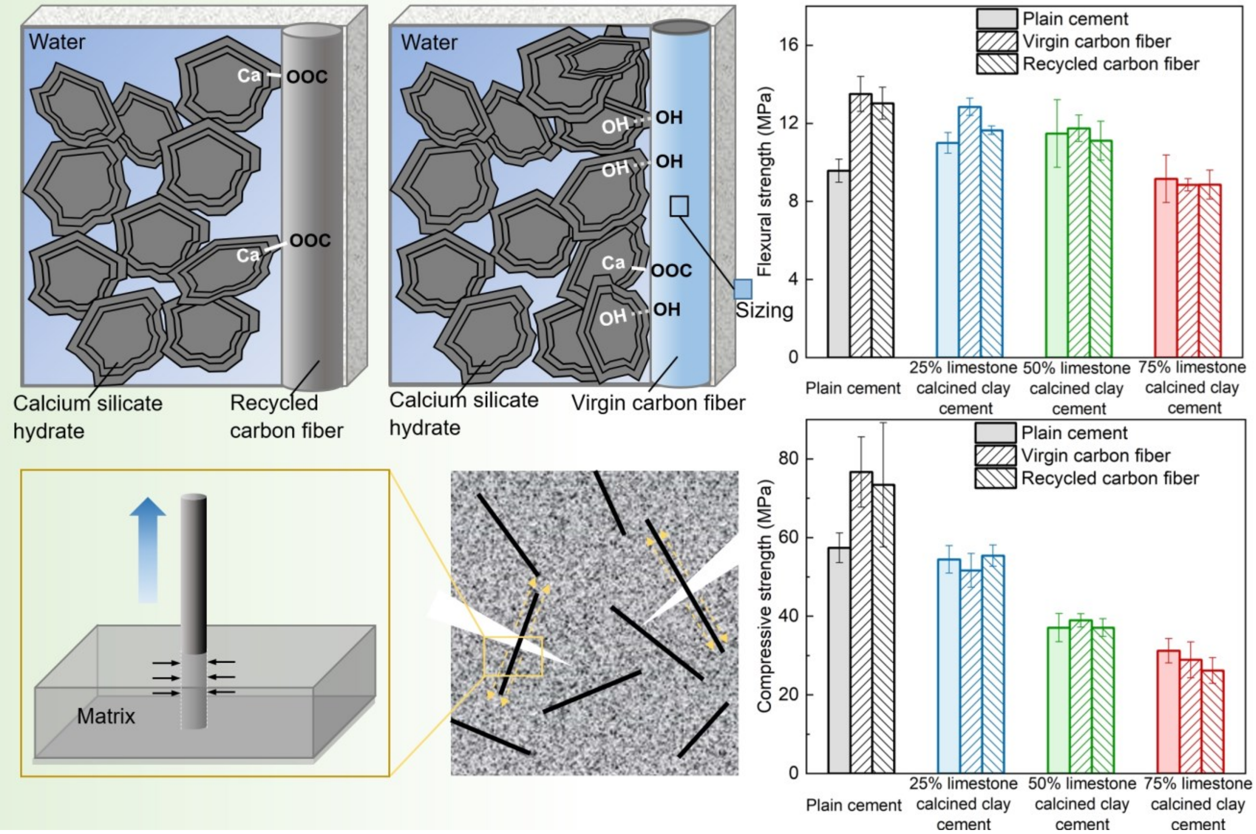

Fig. 8. Adding recycled carbon fiber obtained from pyrolysis enhances the flexural and compressive strength of plain cement and cement composites containing 25% limestone calcined clay cement after a curing period of 28 days. The bond performance of virgin carbon fiber with cementitious matrices is better than that of recycled carbon fiber due to the presence of surficial sizing. Ionic bonds and hydrogen bonds can form between functional groups on the fiber surfaces and cement matrices. Adapted from Li *et al.* (2023c).

Moreover, the incorporation of pyrolyzed carbon fibers had a favorable impact on the residual mechanical properties of cement composites subjected to elevated temperatures. Akbar and Liew (2020b) subjected cement composites containing 0.5 to 1.5 vol.% recycled carbon fiber to temperatures ranging from 200°C to 900°C. They observed that the addition of recycled carbon fiber contributed to the improvement of residual strength in plain pastes up to 800°C, with the most significant reinforcement observed at a fiber dosage of 1%. The enhanced residual mechanical properties, including compressive, flexural, and splitting tensile strength, were attributed to the release of high-pressure steam passing through the channels on the recycled carbon fiber surfaces. However, at temperatures of 900°C, the fibers were completely degraded, leaving behind empty tunnels, which had a detrimental impact on the composite performance (Akbar and Liew 2020b). Whereas, Zegardło (2022) reported a substantial increase in residual flexural and compressive strengths of concrete containing recycled carbon fiber after annealing at 1000°C compared to plain matrices. They asserted that recycled carbon fiber remained after heat treatment and could continue to serve as reinforcement in the structures. Overall, the use of recycled carbon fiber derived from pyrolysis in cement-based composites did not exhibit significant differences in flowability, mechanical properties, or electrical behavior (Faneca *et al.* 2018) compared to virgin carbon fibers. However, there is a lack of publications that provide insights into the durability of cementitious composites with the addition of pyrolyzed carbon fiber.

Li *et al.* (2022c) were the first to utilize 1 wt.% short recycled carbon fiber obtained from pyrolysis to enhance one-part alkali-activated materials, with ground granulated blast-furnace slag and fly ash serving as precursors. They demonstrated that the addition of recycled carbon fiber led to substantial improvement in the flexural and compressive performance of the alkali-activated materials, by up to 19% and 25%, respectively. This enhancement was attributed to the effective reinforcing action of the fibers through a bridging effect. However, there is currently a lack of research on the impact of adding pyrolyzed carbon fibers on the durability of alkali-activated composites.

In the last few years, carbon fibers recovered through microwave-assisted pyrolysis have been tentatively introduced into cement-based materials. In the studies conducted by Li *et al.*, recycled carbon fibers obtained from microwave-assisted pyrolysis were incorporated into concrete at varying dosages ranging from 0.5% to 1.5% by cement mass (Li *et al.* 2021b; Li *et al.* 2023d). They observed a reduction in the workability of fresh concrete mixes as the fiber content increased. However, at 7 and 28 days, significant improvement in flexural and compressive strengths, as well as impact resistance, was recorded relative to plain matrices. The most optimal mechanical performance was achieved with a dosage of 1 wt.%. Interestingly, the addition of microwave-assisted pyrolysis-recycled carbon fibers had a similar impact on concrete properties when compared to the original carbon fibers. In summary, the reinforcing effect of recycled carbon fiber from microwave-assisted pyrolysis closely resembles that of the pyrolyzed carbon fibers discussed earlier. On the whole, we observed that despite of inferior workability incorporating pyrolyzed carbon fiber is in favor of improving both flexural and compressive performance of cement-based materials under room and elevated temperatures, with an optimal dosage of 1%. The addition of pyrolyzed carbon fiber is also advantageous for the strength development of alkali-activated materials.

Table 4. Applications of pyrolyzed carbon fiber in cement-based composites.

Ref.	Matrix	Carbon fiber source	Production condition	Carbon fiber length	Carbon fiber dosage	Water/binder ratio	Curing condition	Flowability	Compressive strength	Flexural strength	Tensile strength	Impact resistance	Characterization analysis
Faneca *et al.* 2018	Concrete, ultra-high performance concrete	ELG Carbon Fiber Ltd, UK	Pyrolysis	40, 20, 12, 12 mm	0.1-1.4 vol.%	0.45 (concrete); 0.14 (ultra-high performance concrete)	28 d; 20±2°C; relative humidity 95±5 %	Decrease	Decrease (concrete); comparable (ultra-high performance concrete)	Increase (concrete); comparable and increase (ultra-high performance concrete)	—	—	Electrical resistivity
Kimm *et al.* 2020	Mortar	CFK Valley Stade Recycling GmbH & Co. KG, Wischhafen, Germany	Pyrolysis	14.9 mm mean length, 6.9 μm diameter	0.25, 0.5, 1, 2 vol.%	0.33	28 d in water; 22±3°C	—	—	53.0-110.7% increase, 30.8-161.5% increase (elongation at break)	—	—	Optical observation
Kimm *et al.* 2021	Mortar	carboNXT pure CFK Valley Stade Recycling GmbH & Co. KG, Wischhafen, Germany	Pyrolysis	10-30 mm length, 27 mm mean length; 7 μm diameter	0.25, 0.5, 0.75, 1 vol.%	0.33	28 d (7d in water, 20 d at 22±3°C)	—	—	13.3-38.9% increase, 7.7-53.8% increase (elongation at break)	—	—	Optical observation

Akbar and Liew 2020b	Paste	ELG Carbon Fiber Ltd, UK	Pyrolysis	7 µm diameter; 80-100 µm length, 95.4 µm mean length	0.5, 1, 1.5 vol.%	0.35	28 d; 25±2°C; relative humidity 95%	—	Increase (25-800°C), decrease (900°C)	Increase (25-900°C)	Increase (25-800°C), decrease (900°C) (splitting)	—	Scanning electron microscope, X-ray diffraction, thermal gravimetric analysis, X-ray photoelectron spectroscopy, optical observation
Akbar and Liew 2020a	Paste	ELG Carbon Fiber Ltd, UK	Pyrolysis	7 µm diameter; 80-100 µm length, 95.4 µm mean length	0.25, 0.5, 0.75, 1, 1.25, 1.5 vol.%	0.35	28 d in a sealed curing chamber; 20±2°C	—	—	Increase (fracture energy, elastic modulus, toughness)	—	—	Scanning electron microscope, X-ray diffraction, fourier transform infrared spectroscopy
Akbar *et al.* 2021	Paste	ELG Carbon Fiber Ltd, UK	Pyrolysis	7 µm diameter; 80-100 µm length, 95.4 µm mean length	0.25, 0.5, 0.75, 1, 1.25, 1.5 vol.%	0.35	7, 28 d; 20±3°C; relative humidity 95%	—	Increase (7, 28 d)	Increase (28 d)	—	—	Scanning electron microscope, electron dispersive spectroscopy, X-ray diffraction, fourier transform infrared spectroscopy, thermal gravimetric analysis
Zegardło 2022	Concrete	Manufacturer of carbon composites	Pyrolysis	0.4-10 cm	0.194 vol.%	0.45	28 d	—	Increase (room temperature, after 1000°C)	Increase (room temperature, after 1000°C)	—	—	Scanning electron microscope, optical observation

Li *et al.* 2022c	Alkali-activated composites	China Nantong Fuyuan Carbon Fiber Recycling Co., LTD (FUY)	Pyrolysis	0.51 mm average length	1 wt.% by weight of solid precursors	0.32	3, 28 d	—	21.4-24.9% increase (28 d)	8.0-19.0% increase (28 d)	—	—	Scanning electron microscope, energy dispersive X-ray spectroscopy, X-ray spectroscopy, X-ray diffraction, thermal gravimetric analysis, pullout tests
Li *et al.* 2023d	Concrete	Thermolysis Co.,Ltd., Kaohsiung, Taiwan	Microwave-assisted pyrolysis	24 mm	0.5, 1, 1.5 wt.%	0.6	7 d	Decrease	4.9-14.4% increase	19.7-56.5% increase	8.8-12.6% increase (splitting)	80-2221% increase	Scanning electron microscope, electron dispersive spectroscopy, optical observation
Li *et al.* 2021b	Concrete	Thermolysis Co.,Ltd., Kaohsiung, Taiwan	Microwave-assisted pyrolysis	20-30 mm	0.5, 1, 1.5 wt.%	0.6	28 d	Decrease	5.0-36.7% increase	20.0-46.3% increase	—	60.0-2305.4% increase	Scanning electron microscope, single filament tensile tests, optical observation

4.3. Chemically-recovered carbon fiber as reinforcement in cement based composite

Research into the utilization of chemically recycled carbon fibers in construction materials remains limited. Kulikova *et al.* (2022) employed a solvolysis method under supercritical conditions to recover carbon fibers from carbon fiber-reinforced phenol-formaldehyde resin. The solvolysis process was carried out at temperatures ranging from 20 to 220°C and pressures from atmospheric to 4 bar, with varying durations from 1 to 24 hours. Various inorganic oxidizers and organic solvents were employed in the recycling process. Subsequently, the obtained recycled carbon fibers from solvolysis recycling were introduced into concrete at different lengths ranging from 3 to 9 mm and contents ranging from 0.2 to 0.6 wt.%. The results demonstrated that the addition of recycled carbon fiber positively enhanced the flexural strength of concrete. Notably, recycled carbon fiber measuring 3 mm in length exhibited superior mechanical properties. In contrast, longer fibers exceeding 6 mm had a detrimental effect on compressive performance due to their uneven distribution within the matrix.

In a recent study conducted by Li *et al.* (2023a), carbon fibers were successfully reclaimed from epoxide-based carbon fiber-reinforced polymer using a chemical recycling method; see Fig. 9. This approach involved the use of N-methyl-2-pyrrolidone as a swelling agent and hydrogen peroxide for thermolysis, carried out at 175°C. The process aimed to achieve a higher degree of depolymerization of the recycled carbon fiber, resulting in reduced epoxide residues on the fiber surfaces and improved interfacial adhesion between the fibers and cementitious matrices. When these completely recycled fibers were incorporated into mortar samples, a significant enhancement in both flexural and compressive strengths was observed, with increases of up to 48% and 76%, respectively, compared to unreinforced samples. Despite having lower oxygen content, the recycled carbon fiber exhibited superior reinforcing capabilities in cement-based materials compared to virgin fibers. In summary, we observed the positive effect of chemically recycled carbon fibers in strengthening the mechanical performance of cementitious materials, and these findings suggest promising applications for chemically recycled carbon fiber in civil engineering. However, further research in this area is necessary to explore and optimize these recycling methods for practical use in construction materials.

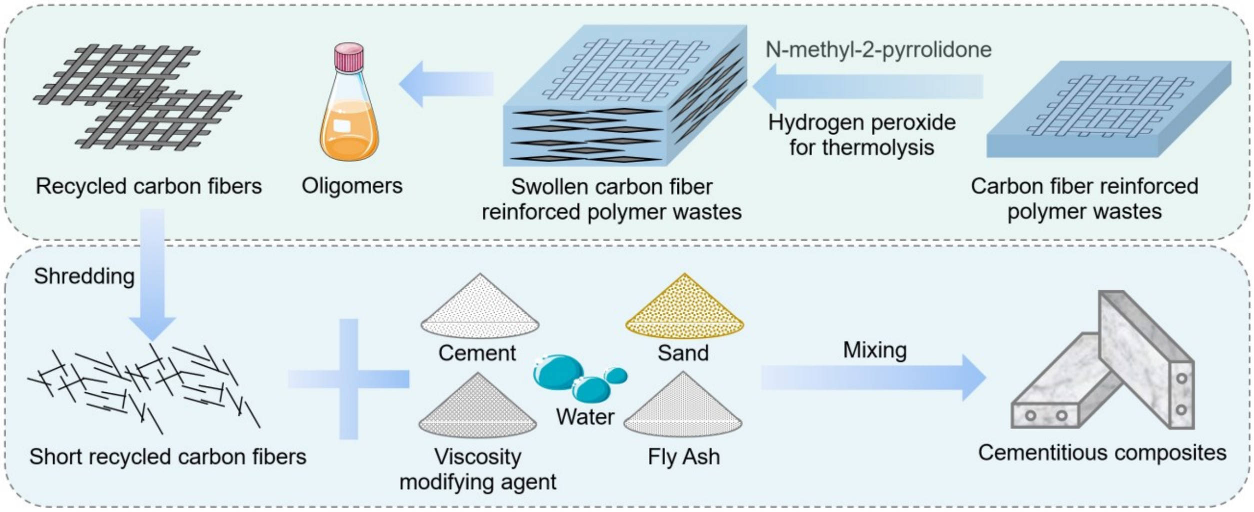

Fig. 9. The carbon fibers are chemically recovered using N-methyl-2-pyrrolidone as a swelling agent and hydrogen peroxide for thermolysis at 175°C. Subsequently, the recycled carbon fibers are shredded and incorporated into the cement mortar. This incorporation enhances both flexural and compressive strengths compared to unreinforced mortar. Adapted from Li *et al.* (2023a).

4.4. Carbon fiber waste from carbon fiber reinforced polymer production as reinforcement in cement based composite

Carbon fiber wastes are residual materials generated during the manufacturing of carbon fiber-reinforced polymer. These materials are typically trimmed and collected before the impregnation with resins, and as a result, carbon fiber wastes possess properties similar to those of pristine carbon fibers. While the term "recycled carbon fiber" is commonly used in the literature to describe this material, we will use the term "carbon fiber waste" in this section to distinguish this type of fiber reinforcement from other carbon fibers recycled from carbon fiber-reinforced polymer products. Commercially available carbon fiber waste, typically with a length of 6 mm, procured from Procotex Belgium SA, has been frequently employed in mortar (Belli *et al.* 2020; Belli *et al.* 2023) and concrete composites (Mobili *et al.* 2022b; Mobili *et al.* 2023). Additionally, waste carbon fiber sheets (Zaid and Zamir Hashmi 2021) or waste carbon fiber blankets (de Souza Abreu *et al.* 2020) have also been utilized as reinforcements in cement composites, as summarized in Table 5.

The incorporation of carbon fiber waste in cementitious mixtures generally leads to a reduction in fluidity, and this workability reduction becomes more pronounced with increasing carbon fiber waste content (de Souza Abreu *et al.* 2020; Zaid and Zamir Hashmi 2021; Mobili *et al.* 2022a). This decrease in workability is attributed to the network structures formed by the fibers, which impede the flow of the mixtures. Additionally, cement particles tend to adhere to the surface of carbon fiber wastes due to their large surface area, further increasing the viscosity of the mixtures (Aflaki Samani and Jabbari Lak 2019; Zaid and Zamir Hashmi 2021). Therefore, it is recommended to use superplasticizers in cement composites containing carbon fiber waste to compensate for the loss in flowability (de Souza Abreu *et al.* 2020).

Most of research studies have reported an improvement in the compressive strength of cementitious composites when reinforced with carbon fiber waste (de Souza Abreu *et al.* 2020; Zaid and Zamir Hashmi 2021; Mobili *et al.* 2022b). For instance, Zaid and Zamir Hashmi (2021) used discarded carbon fibers with a length of 3.5 cm at various contents of 2, 4, and 6 vol.% to reinforce concrete, and they observed an increasing trend in composite strength with higher carbon fiber waste contents. This gradual improvement in compressive strength with increasing carbon fiber waste content was also noted by Aflaki Samani and Jabbari Lak (2019). It is widely accepted that carbon fiber waste can hinder the propagation of micro-cracks and provide nucleation sites for the growth of calcium silicate hydrate gel, thereby promoting the development of strength in cement composites containing carbon fiber waste (Mobili *et al.* 2022a; Mobili *et al.* 2022b). However, there have been cases where the addition of carbon fiber waste led to a reduction in compressive performance (Belli *et al.* 2023; Mobili *et al.* 2023). For example, Mobili *et al.* (2023) incorporated 0.05 vol.% carbon fiber waste with a length of 6 mm into concrete and observed a decrease in compressive strength after 28 days of curing, primarily due to an increase in the total pore volume.

Regarding flexural and (splitting) tensile behavior, adding carbon fiber waste to cementitious mixes consistently leads to comparable or superior performance compared to unreinforced samples. Belli *et al.* (2020) introduced carbon fiber waste into mortar composites at dosages ranging from 0.05 vol.% to 1.6 vol.%, and their results showed an increasing trend in both flexural and splitting tensile strengths as more carbon fiber waste was added, attributed to the bridging effect of the fibers. Similarly, Zaid and Zamir Hashmi (2021) and Aflaki Samani and Jabbari Lak (2019) observed a regular increase in flexural and splitting tensile strengths with higher fiber dosages. Furthermore, the ductility and energy absorption capacity of carbon fiber waste-reinforced concrete also improved. The addition of carbon fiber waste helps restrain crack expansion in the matrices and enhances bonding between the aggregate and cement (Aflaki Samani and Jabbari Lak 2019; de Souza Abreu *et al.* 2020).

There are conflicting findings regarding the water absorption and porosity of cement composites with the addition of carbon fiber waste. Some researchers have claimed that incorporating carbon fiber waste reduces capillary water absorption and the total porosity volume (Belli *et al.* 2020; Mobili *et al.* 2022a; Belli *et al.* 2023), since fiber additives can optimize the microstructure of cement matrices and facilitate the formation of hydration products (Belli *et al.* 2020). However, other scientists have suggested that the air trapped within carbon fiber bundles might be introduced into the mixtures during mixing, leading to the creation of voids and an increase in water absorption (Mobili *et al.* 2022b). Mobili *et al.* (2023) proposed that the increased porosity caused by carbon fiber waste addition could accelerate the carbonation process and increase chloride penetration in the cementitious matrices, potentially compromising the durability of carbon fiber waste-reinforced concrete. Further research is needed to clarify these conflicting findings. On a different note, there is a consensus that the electrical impedance (Mobili *et al.* 2022b; Mobili *et al.* 2023) and electrical resistivity (Belli *et al.* 2020; Mobili *et al.* 2022a; Belli *et al.* 2023) of cement composites are reduced by the incorporation of carbon fiber waste. This finding opens up the potential for the use of these composites in multifunctional self-sensing applications (Belli *et al.* 2023).

Overall, we found that carbon fiber waste can be utilized in cementitious matrices without significant differences compared to original fibers. Adding carbon fiber waste could reduce the fluidity of fresh mixes, while being advantageous for strength development in terms of compressive, flexural, and splitting tensile performance due to the fibers' bridging effect. However, there remain controversial conclusions regarding the durability properties of carbon fiber waste-reinforced cement composites, which need further exploration.

Table 5. Applications of carbon fiber waste in cement-based composites.

Ref.	Matrix	Carbon fiber source	Carbon fiber length	Carbon fiber dosage	Water/binder ratio	Curing condition	Flowability	Compressive strength	Flexural strength	Tensile strength	Characterization analysis
Belli *et al.* 2020	Mortar	APPLY CARBON SA	6 mm	0.05, 0.1, 0.2, 0.4, 0.8, 1.2, 1.6 vol.%	0.5	14 d; 20±1°C; relative humidity 50±5%	—	Increase	Increase, increase (toughness), 21.0-26.6% decrease (elastic modulus)	Increase (splitting)	Scanning electron microscope, water absorption, drying shrinkage, electrical resistivity, porosity
Belli *et al.* 2018	Mortar	APPLY CARBON SA	6 mm	0.05, 0.2 vol.%	0.5	7d at 20±1◦C, relative humidity 95±5%, 21 d at 20±1◦C, relative humidity 65±5%	—	Decrease	Decrease (0.05 vol.%), increase (0.2 vol.%)	—	Scanning electron microscope, electrical resistivity, optimal observation
Belli *et al.* 2023	Mortar	APPLY CARBON SA	6 mm	0.05, 0.2 vol.%	0.5	7d at 20±1◦C, relative humidity 95±5%, 21 d at 20±1◦C, relative humidity 65±5%	Increase (0.05 vol.%), decrease (0.2 vol.%)	Decrease	Decrease (0.05 vol.%), increase (0.2 vol.%)	—	Scanning electron microscope, water absorption, electrical resistivity, porosity, dry density
Mobili *et al.* 2022b	Concrete	Procotex Belgium SA	6 mm	0.05 vol.%	0.44	1, 7, 28 d in polyethylene sheets; 20±1°C; relative humidity 90±5%	—	4.1% increase (28 d)	—	—	Density, capillary water absorption, electrical impedance, chloride penetration, free chloride content, accelerated carbonation

Mobili *et al.* 2022a	Mortar	Procotex Belgium SA	6 mm	0.2 vol.%	0.45	28 d; 20±1°C; relative humidity 50±5%	Decrease	Comparable (28 d)	Increase (28 d), comparable (modulus of elasticity, 28 d)	—	Density, capillary water absorption, porosity, density, electrical resistivity
Mobili *et al.* 2023	Concrete	Procotex Belgium SA	6 mm	0.05 vol.%	0.42	1, 7, 28d in polyethylene films; 20±1◦C; relative humidity> 95%	—	Decrease	—	Comparable (28 d)	Density, capillary water absorption, electrical impedance, chloride penetration, water penetration, free chloride content, accelerated carbonation
Zaid and Zamir Hashmi 2021	Concrete	Leftover sheets of other researchers	3.5 cm	2, 4, 6 wt.% by weight of total matrix	0.5	28 d in water; 24°C	Decrease	Increase	Increase	Increase (splitting)	Scanning electron microscope, optimal observation
Aflaki Samani and Jabbari Lak 2019	Concrete	Waste carbon fiber sheets of other researchers at Najafabad University	2 cm	0.1, 0.2, 0.3 vol.%	0.45	28 d in water; 23°C	Decrease	8.7-29.6% increase	11.1-35.2% increase	6.7-43.4% increase (splitting)	Scanning electron microscope, optimal observation
de Souza Abreu *et al.* 2020	Concrete	Carbon fiber blanket	40-50 mm	2 wt.% by weight of cement	0.5	28 d	Decrease	14.8% increase; 5.8% decrease (modulus of elasticity)	—	20.7% increase	Scanning electron microscope, optimal observation, water absorption, void index, specific mass

4.5. Surface modification of recycled carbon fibers

Carbon fibers are known for their non-polar, hydrophobic surfaces, which can limit the effective interaction between the fibers and water-based mineral matrices in construction materials (Li *et al.* 2024a). This limitation hinders the full utilization of the high-strength properties of carbon fibers in building components (Li *et al.* 2022d). Consequently, this section provides an overview of recent advancements in the surface modification of recycled carbon fibers. The modifications are categorized based on the recycling technologies employed, and details can be found in Table 6.

Efforts have been dedicated to enhancing the surface properties of mechanically recycled carbon fibers to improve their performance in cement-based materials. Wang *et al.* (2019a) conducted a study in which they immersed recycled carbon fiber composite scraps with length of 0.05-12 mm and a maximum width of 0.8 mm in 1-3 mol/L NaOH solutions for 24 hours. These treated recycled carbon fibers were then incorporated into cement mortar at a volume fraction of 1%. The research showed that recycled carbon fiber treated with 1 mol/L NaOH led to improved compressive strength but reduced splitting tensile strength compared to samples reinforced with untreated recycled carbon fiber. The NaOH solution effectively removed resin residues from the fiber surfaces and enhanced their bonding with cement. However, highly concentrated NaOH solutions could damage the recycled carbon fiber, leading to a negative impact on mechanical performance (Wang *et al.* 2019a). In their extended research (Wang *et al.* 2019b), recycled carbon fiber-reinforced polymers were subjected to different surface treatments, including soaking in pore solution or montmorillonite nanoclay emulsion for 0.5 or 2 hours. Triisopropanolamine was added to the pore solution group with a treatment duration of 0.5 hours. The research indicated that the pore solution/Triisopropanolamine- and montmorillonite nanoclay emulsion-treated recycled carbon fiber-reinforced polymer significantly increased the splitting tensile and compressive strengths of cement mortars at 28 days compared to untreated samples. This improvement is attributed to the enhanced adhesion between the fibers and hydration products. However, prolonged SPS treatment damaged the surfaces of the recycled carbon fiber-reinforced polymers and resulted in reduced composite strength (Wang *et al.* 2019b).

Saccani *et al.* (2021) employed needle-shaped carbon fiber-reinforced polymer scraps, soaked them in a 0.2 mol/L sulfuric acid solution for 1 hour, and then mixed them into alkali-activated mortars at a volume fraction of 4.6%. This acid treatment enriched the external epoxy layers with permanent dipoles and hydroxyl groups, facilitating the formation of hydrogen bonds between recycled carbon fiber-reinforced polymer and the alkali-activated mortar while roughening the epoxy surfaces. As a result, a stronger interaction between the two phases was achieved, leading to improved flexural and compressive properties (Saccani *et al.* 2021).

When it comes to pyrolyzed carbon fiber, there is limited information available regarding the modification of fiber surfaces to enhance their bonding with cement-based matrices. Li *et al.* (2022c) conducted pioneering research by applying electrochemical oxidation treatment to recycled carbon fiber obtained from pyrolysis. The treatment involved immersing the recycled carbon fiber in a NaOH solution at either 1 or 3 V for 15 min. This process effectively removed surface impurities from the recycled carbon fiber and introduced functional groups onto their surfaces, significantly improving the interfacial interaction between the inert recycled carbon fiber and alkali-activated materials, as depicted in Fig. 10. As a result of this enhanced bond, the flexural strength of the composite materials increased by approximately 10% compared to composites with untreated fibers (Li *et al.* 2022c). In another study, Kimm *et al.* (2021) used oxygen plasma to modify pyrolyzed carbon fibers at a pressure of 0.3-0.5 mbar with a power of 50 W. Interestingly, the incorporation of 0.5 vol.% recycled carbon fiber into mortars led to a reduction in flexural strength but an enhancement in ductility of the cementitious composite. However, the exact reasons for these changes were not specified.

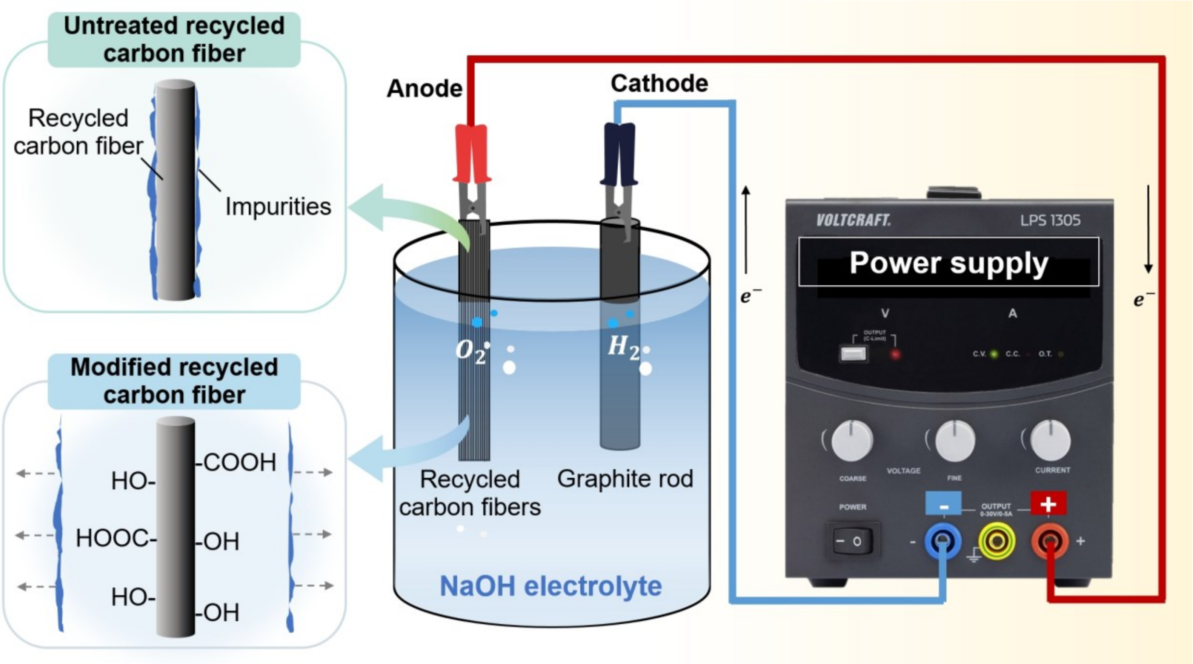

Fig. 10. The recycled carbon fibers are anodically modified under 1 V or 3 V for 15 minutes. During this process, surface impurities are eliminated, and functional groups are introduced onto the fiber surfaces, significantly enhancing the interfacial bonding between the recycled carbon fiber and alkali-activated matrices. Electrochemical modification significantly improves the fiber bridging effect and the flexural strength of the fiber-reinforced composite. Adapted from Li *et al.* (2022c).

However, the impact of surface modification on the properties of cement composites containing chemically recovered carbon fibers has not yet been reported so far. Notably, after recycling treatment, the surface properties of carbon fibers can differ dramatically based on the specific treatment conditions. Yan *et al.* (2016) chemically recovered carbon fibers from carbon fiber-reinforced polymer using supercritical 1-propanol along with 1 wt.% KOH at 320°C and reported an increase in surface oxygen compared to virgin fibers. In contrast, Li *et al.* (2023a) recycled waste carbon fiber-reinforced polymer using N-methyl-2-pyrrolidone and hydrogen peroxide at 175°C, and they observed a lower oxygen ratio on fiber surfaces. However, fully recovered carbon fibers demonstrated better affinity towards cement matrices despite having less oxygen.

Based on these findings, we observed that both acidic and alkaline treatments are effective in modifying the surfaces of mechanically recycled carbon fiber-reinforced polymers, thereby enhancing their bond behavior with mineral matrices and their reinforcing effect on the flexural and compressive properties of the fiber-added composites.To ensure superior interaction between fiber and matrices, appropriate surface modification is needed for pyrolyzed carbon fibers with inert surfaces. The surface states of recycled carbon fibers vary significantly according to the specific recycling techniques, which influences the determination of the appropriate surface modification. Under certain treatment parameters, the chemical recycling process of carbon fibers from polymer matrices can achieve both fiber recovery and surface modification. Regardless of the recycling methods used, fiber modification treatments remain crucial for hydrophobic recovered carbon fibers. Further research in this field is needed to enhance stress transfer efficiency from fibers to the matrix in cement composites.

Table 6. Impact of surface modification on mechanical properties of recycled carbon fiber-reinforced cement-based matrices.

Treatment	Treatment condition	Recycled carbon fiber type	Recycled carbon fiber size	Recycled carbon fiber content	Matrix	Water/binder ratio	Curing condition of the matrix	Increase in flexural strength [%]	Increase in splitting tensile strength [%]	Increase in compressive strength [%]	Ref.
NaOH solution	In NaOH 1 mol/L, 24 h	Flaky, cured carbon fiber-reinforced polymer from shredding, hammer-milling	0.05-12 mm length; 0.8 mm maximum width	1 vol.%	Mortar	0.5	7 d; 23 ± 2°C; relative humidity>90%	—	-17.6	0.9	Wang *et al.* 2019a
	In NaOH 1 mol/L, 24 h	Flaky, cured carbon fiber-reinforced polymer from shredding, hammer-milling	0.05-12 mm length; 0.8 mm maximum width	1 vol.%	Mortar	0.5	28 d; 23 ± 2°C; relative humidity>90%	—	-21.1	5.2	Wang *et al.* 2019a
Saturated pore solution or montmorillonite nanoclay emulsion	In saturated pore solution, 0.5 h; saturated pore solution, 0.5 h/triisopropanolamine; montmorillonite nanoclay emulsion, 2 h	Flaky, cured carbon fiber-reinforced polymer from shredding, hammer-milling	0.05-12 mm length	1 vol.%	Mortar	0.5	7 d; 23 ± 2°C; relative humidity>90%	—	-20.7 (saturated pore solution, 0.5 h); 0.6 (saturated pore solution, 0.5 h/triisopropanolamine); 5.3 (montmorillonite nanoclay emulsion, 2 h)	-7.7 (saturated pore solution, 0.5 h); 19.4 (saturated pore solution, 0.5 h/triisopropanolamine); 19.1 (montmorillonite nanoclay emulsion, 2 h)	Wang *et al.* 2019b
	In saturated pore solution, 0.5 h; saturated pore solution, 0.5 h/triisopropanolamine;	Flaky, cured carbon fiber-reinforced polymer from	0.05-12 mm length	1 vol.%	Mortar	0.5	28 d; 23 ± 2°C; relative humidity>90%	—	-16.4 (saturated pore solution, 0.5 h); 8.3 (saturated pore solution,	-3.4 (saturated pore solution, 0.5 h); 20.6 (saturated pore solution,	Wang *et al.* 2019b

	montmorillonite nanoclay emulsion, 2 h	shredding, hammer-milling							0.5 h/triisopropanolamine); 11.6 (montmorillonite nanoclay emulsion, 2 h)	0.5 h/triisopropanolamine); 22.1 (montmorillonite nanoclay emulsion, 2 h)	
Sulfuric acid solution	In 0.2 mol/L H_2SO_4, 1 h	Flaky pre-preg off-cuts from the production of carbon fiber-reinforced polymer	5±1 mm length; 300±20 μm thickness, 3-6 mm lateral size	4.6 vol.%	Alkali-activated binders (metakaolin)	0.1	28 d; 23±2°C; relative humidity 70±5%	16.8	—	3.2	Saccani *et al.* 2021
	In 0.2 mol/L H_2SO_4, 1 h	Flaky pre-preg off-cuts from the production of carbon fiber-reinforced polymer	5±1 mm length; 300±20 μm thickness, 3-6 mm lateral size	4.6 vol.%	Alkali-activated binders (fly ash)	0.07	28 d; 23±2°C; relative humidity 70±5%	19.1	—	6.7	Saccani *et al.* 2021
	In 0.2 mol/L H_2SO_4, 1 h	Flaky pre-preg off-cuts from the production of carbon fiber-reinforced polymer	10±1 mm length; 300±20 μm thickness, 3-6 mm lateral size	4.6 vol.%	Alkali-activated binders (metakaolin)	0.1	28 d; 23±2°C; relative humidity 70±5%	22.4	—	8.1	Saccani *et al.* 2021
	Immersion in 0.2 mol/L H_2SO_4, 1 h	Flaky pre-preg off-cuts from the production of carbon fiber-reinforced polymer	10±1 mm length; 300±20 μm thickness, 3-6 mm lateral size	4.6 vol.%	Alkali-activated binders (fly ash)	0.07	28 d; 23±2°C; relative humidity 70±5%	32.3	—	10.3	Saccani *et al.* 2021
Electrochemical	In 0.0025 mol/L NaOH, 3 V/15 min	Recycled carbon fiber from pyrolysis	0.51 mm length	1 wt.% by weight of	Alkali-activated	0.32	28 d in bags	10.2	—	-2.9	Li *et al.*

modification				solid precursors	composite						2022c
Oxygen plasma	In O_2 at 50 W; 0.3-0.5 mbar; 5-10 cm^3/min; 5 min/each side of 3-5 cm thick layer of recycled carbon fiber	Recycled carbon fiber from pyrolysis	10-30 mm length, 27 mm mean length; 7 µm diameter	0.5 vol.%	Mortar	0.33	28 d (7 d in water, 20 d at 22±3°C)	-18.4 (flexural strength); 42.9 (elongation at break)	—	—	Kimm *et al.* 2021

5. Application of recycled glass fiber reinforced polymer in civil engineering

5.1. Mechanically-recycled glass fiber reinforced polymer as reinforcement in construction materials

To gain a deeper understanding of the reinforcing efficiency of mechanically recycled composites, the shape features of glass fiber-reinforced polymer additives were compared and summarized, and their impact on the properties of cement-based composites was thoroughly reviewed. The recycled glass fiber-reinforced polymer composites can be roughly divided into three categories: glass fiber-reinforced polymer powder, glass fiber-reinforced polymer coarse blocks, and slender glass fiber-reinforced polymer elements. Notably, slender glass fiber-reinforced polymer elements exhibited various morphologies, including strips, rebars, and fibers extracted from ground glass fiber-reinforced polymer scraps or shredded glass fiber-reinforced polymer sheets; refer to Fig. 11. In this section, their influences and reinforcing mechanisms are discussed separately in an attempt to provide guidelines for future mechanical recycling endeavors.

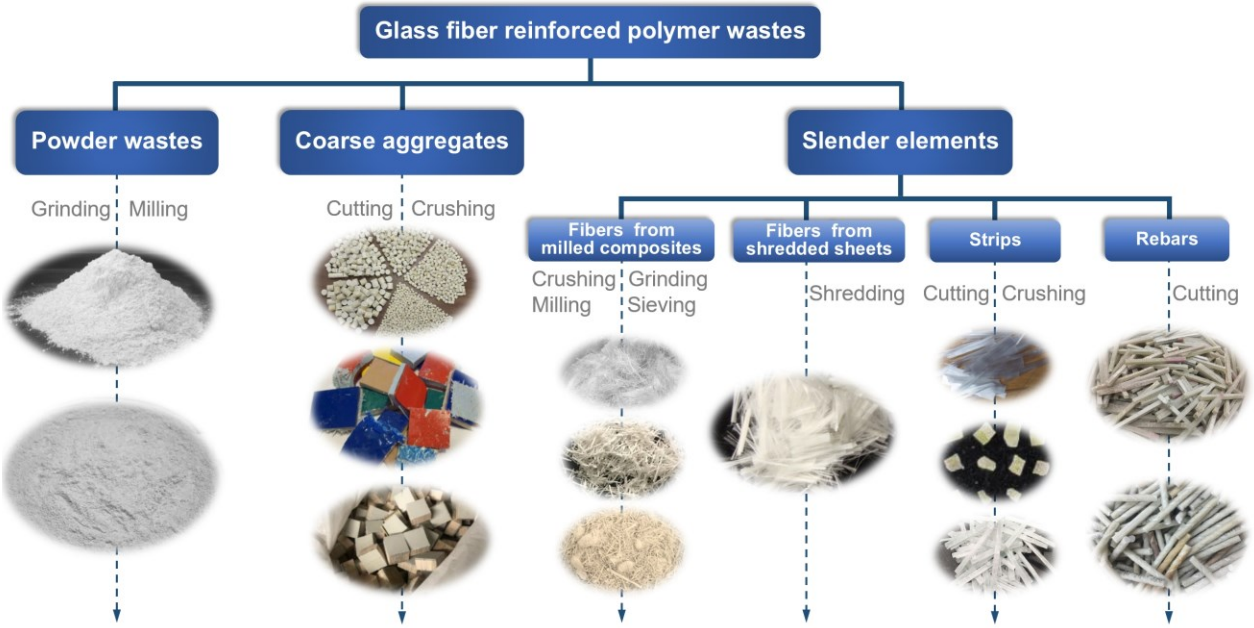

Fig. 11. Mechanically recycled glass fiber-reinforced polymers are classified according to their unique morphologies. Glass fiber-reinforced polymer powders can be used as fillers in construction materials, recycled glass fiber-reinforced polymers can also serve as coarse aggregates in concrete, and slender elements of glass fiber-reinforced polymers can be utilized as macro fibers to reinforce building materials. Adapted from Asokan *et al.* (2010); Shahria Alam *et al.* (2013); Tittarelli and Shah (2013); Castro *et al.* (2014); Mastali *et al.* (2016); Yazdanbakhsh *et al.* (2016); Abdollahnejad *et al.* (2017); Rodin III *et al.* (2018a); Yazdanbakhsh *et al.* (2018a); Baturkin *et al.* (2021); Singh *et al.* (2022); Yuan *et al.* (2022).

5.1.1. Recycled glass fiber reinforced polymer as fine aggregate

In the open literature, the powder-like glass fiber-reinforced polymer wastes are typically obtained by shredding and milling, and they are then incorporated into cementitious composites to partially substitute the fine aggregates. However, it's important to note that the glass fiber-reinforced polymer powder or dust consists primarily of a resin matrix with a small fraction of glass fibers, as detailed in Table 7. Many researchers have focused on finding ways to reuse ground glass fiber-reinforced polymer wastes in cement-based materials.

5.1.1.1. Fresh state properties

Most studies have reported that the addition of recycled glass fiber-reinforced polymer dust or powder has a positive effect on the workability of freshly mixed mortar or concrete (Tittarelli 2013; Tittarelli and Shah 2013; Ma *et al.* 2022). For example, Tittarelli and Shah (2013) added recycled glass fiber-reinforced polymer dust to mortar at a ratio of 30% by cement volume and observed a decrease in viscosity and yield stress, indicating improved flowability. A similar trend was observed by Ma *et al.* (2022), where they incorporated 3-9% recycled glass fiber-reinforced polymer powder into concrete composites by weight of cement, resulting in increased workability. This improvement is attributed to the specific characteristics of the added recycled glass fiber-reinforced polymer dust, such as low surface roughness and a rounded shape (Correia *et al.* 2011; Tittarelli and Shah 2013). These inclusions can act as lubricants by filling spaces between sand particles (Ma *et al.* 2022). However, there are contrasting findings in some studies. Sebaibi *et al.* (2012) used recycled glass fiber-reinforced polymer powder from glass fiber-reinforced unsaturated polyester as a sand substitute in mortar at a dosage of 7.13 vol.% and observed a significant decrease in slump flow. According to García *et al.* (2014), recycled glass fiber-reinforced polymer mixtures that include fibers, granular filler, splinters, and dusty waste have irregular geometry and a high specific surface area, which can impair the fluidity of cement mortar. The workability of cementitious materials is highly dependent on the content of recycled glass fiber-reinforced polymer added. In the study by Correia *et al.* (2011), a low fraction of recycled glass fiber-reinforced polymer powder improved flowability, while higher content above 10 vol.% negatively affected fluidity, as the high specific surface area played a dominant role. Additionally, a reduced particle size of recycled glass fiber-reinforced polymer powder contributed to improved flowability due to a more regular shape and a resulting more significant lubricating effect (Zhou *et al.* 2022).

In terms of setting times, current research has generally reached a consensus that the addition of recycled glass fiber-reinforced polymer powder extends the initial and final setting times of cement composites as recycled glass fiber-reinforced polymer dosages increase (Tittarelli and Shah 2013; Ma *et al.* 2022) or as particle size decreases (Zhou *et al.* 2022). Tittarelli and Shah (2013) suggested that the organic solvents and monomers present in recycled glass fiber-reinforced polymer dust on the surface of cement grains can hinder the hydration of cement, leading to prolonged setting times. They also noted that pre-heat treatment of recycled glass fiber-reinforced polymer dust can alleviate the extended setting times by reducing the presence of organics. Another contributing factor to delayed setting times is the expansion of matrices and the larger pore volume caused by the addition of fine recycled glass fiber-reinforced polymer powder (Zhou *et al.* 2022).

To sum up, we found that adding recycled glass fiber-reinforced polymer powder could facilitate the fluidity of fresh cementitious mixtures in most cases, although it also showed detrimental influence in some investigations. The change in workability highly depends on the dosage, geometry, and surface roughness of the recycled glass fiber-reinforced polymer powder. Additionally, recycled glass fiber-reinforced polymer additives delayed the setting times of cement-based composites due to the hindrance of hydration induced by the organic components.

5.1.1.2. Compressive properties

The majority of studies have found that adding waste glass fiber-reinforced polymer powder to cementitious materials led to a decrease in compressive strength with increasing recycled glass fiber-reinforced polymer powder content (Asokan *et al.* 2009; Tittarelli and Moriconi 2010; Tittarelli 2013; Tittarelli and Shah 2013).

For example, Sebaibi *et al.* (2012) added 7.13 vol.% recycled glass fiber-reinforced polymer powder to cementitious composites to partially replace fine aggregates and observed a reduction in compressive strength by approximately 20%, along with a 26% decrease in modulus of elasticity. The decline in elastic modulus can be attributed to the reduced content of sand in the mixture (Sebaibi *et al.* 2012). Tittarelli and Moriconi (2010) replaced 10-20 vol.% of the aggregate in mortar and 25-50 vol.% of calcareous filler in self-compacting concrete with recycled glass fiber-reinforced polymer powder. They reported a consistent decrease in compressive strength for both matrices with the addition of recycled glass fiber-reinforced polymer. This decline in mechanical strength can be attributed to the weaker interfacial interaction of plastic particles with cement compared to sand or calcareous fillers (Tittarelli and Moriconi 2010). In addition, the particle size of recycled glass fiber-reinforced polymer powder also had an impact on mortar strength, with finer particles leading to a more significant decrease in compressive performance, especially at higher recycled glass fiber-reinforced polymer powder dosages (Zhou *et al.* 2022).

However, a few studies have also shown an improvement in compressive strength with the addition of recycled glass fiber-reinforced polymer additives (Asokan *et al.* 2010; Zhou *et al.* 2022). Asokan *et al.* (2010) fabricated concrete reinforced with recycled glass fiber-reinforced polymer powder, replacing 5-15 wt.% of fine aggregates, and cured the samples under various conditions. They found that the compressive strength of recycled glass fiber-reinforced polymer-containing concrete was improved by 6-21%, mainly due to the inclusion of superplasticizer, which enhanced the bonding between recycled glass fiber-reinforced polymer particles and matrices by affecting the formation of a polymer film (Asokan *et al.* 2010). The curing conditions also played a significant role in the compressive properties of recycled glass fiber-reinforced polymer powder-reinforced cement composites, including wet curing, air curing, and oven curing (Tittarelli and Shah 2013). Asokan *et al.* (2009) showed that, compared to samples cured in water, the compressive strength of recycled glass fiber-reinforced polymer powder-modified concrete cured in an oven at 50 ± 2°C was enhanced, despite the lower strength in plain matrices without recycled glass fiber-reinforced polymer. This enhancement was attributed to the generation of a polymer film during hydration, which could interact with hydration products and form a co-matrix (Van Gemert *et al.* 2005; Asokan *et al.* 2009). Additionally, the source of recycled glass fiber-reinforced polymer wastes could strongly affect the compressive strength of cement-based composites (García *et al.* 2014).

In a word, incorporating glass fiber-reinforced polymer powder has an adverse influence on the compressive strength of cement composites, with strength decreasing as the dosage increases and the powder diameter decreases. However, by applying superplasticizers or suitable curing conditions, the compressive strength of cement-based materials can be enhanced. The influence of recycled glass fiber-reinforced polymer powder addition and various factors on compressive properties is summarized in Fig. 12.

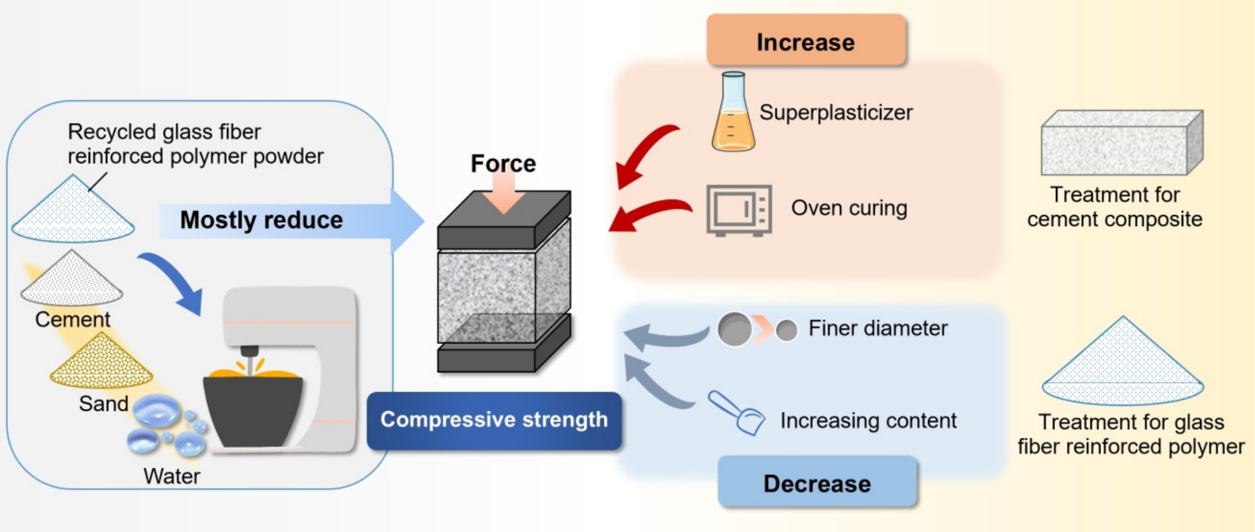

Fig. 12. Adding recycled glass fiber-reinforced polymer powder to cement composites often leads to a reduction in compressive strength. Higher powder content and smaller particle size tend to decrease compressive strength. However, the inclusion of superplasticizer and oven curing has a positive effect on compressive strength.

5.1.1.3. Flexural and tensile properties

Sebaibi *et al.* (2012) investigated the flexural properties of cement mortar, incorporating 7.13 vol.% of recycled glass fiber-reinforced polymer dust. Their findings unveiled a remarkable 33% enhancement in flexural strength. The authors postulated that fibers within the 100-400 μm length range, present in the powder, played a beneficial role in cement composites subjected to mechanical loading. Furthermore, in the study conducted by Zhou *et al.* (2022), it was observed that low fineness and high recycled glass fiber-reinforced polymer powder content had a positive impact on the flexural strength of mortars. Conversely, Ma *et al.* (2022) noted a substantial decrease in flexural performance, dropping from 6.5 MPa to 3.8 MPa in concrete, with the addition of recycled glass fiber-reinforced polymer powder ranging from 3 to 9 wt.%. A similar reduction was reported by García *et al.* (2014), although the extent of the decrease varied depending on the sources of recycled glass fiber-reinforced polymer. Based on previous studies, we found that the conclusions on the effect of adding recycled glass fiber-reinforced polymer powder on the flexural properties of cement composites are inconsistent, necessitating in-depth investigation in future studies.

However, only a limited number of studies have addressed the influence of adding recycled glass fiber-reinforced polymer powder on tensile properties (Asokan *et al.* 2010; Correia *et al.* 2011; Sebaibi *et al.* 2014). Sebaibi *et al.* (2014) conducted uniaxial tensile tests on mortar containing 7.13 vol.% of recycled glass fiber-reinforced polymer powder, revealing a notable 51% improvement in tensile strength and a 15% increase in tensile energy absorption when compared to plain matrices. Similarly, Asokan *et al.* (2010) reported a gradual increase in the splitting tensile strength of concrete with an increasing addition of recycled glass fiber-reinforced polymer powder under both water and oven curing conditions. This phenomenon can be attributed to the presence of glass fibers in the powder and the interaction between the polymeric powder and the cement matrix. However, the study by Correia *et al.* (2011) reported contrary results, where the splitting tensile strengths were reduced with increasing glass fiber-reinforced polymer powder from 5 to 20%. In general, the information on the influence of glass fiber-reinforced polymer powder on the tensile performance of cement-based composites is very scarce and needs further investigation.

5.1.1.4. Durability

The durability of cement-based materials containing recycled glass fiber-reinforced polymer is closely linked to the method of incorporating recycled glass fiber-reinforced polymer powder. When recycled glass fiber-reinforced polymer fillers are directly integrated into matrices, the water absorption of recycled glass fiber-reinforced polymer-cement composites tends to increase significantly (Ma *et al.* 2022; Zhou *et al.* 2022). Zhou *et al.* (2022) observed an elevated water absorption capacity and reduced density with increasing content and fineness of recycled glass fiber-reinforced polymer additives. However, when recycled glass fiber-reinforced polymer powder is introduced as a substitute for fine aggregates, it commonly leads to a reduction in the water absorption of cementitious composites (Asokan *et al.* 2010; Tittarelli and Moriconi 2010; Tittarelli 2013; Tittarelli and Shah 2013). This decrease can be attributed to the need for water to bypass the non-sorptive recycled glass fiber-reinforced polymer powder, thereby slowing down the propagation of the imbibition front due to increased tortuosity (Tittarelli and Moriconi 2010; Tittarelli and Shah 2013). It is worth noting that Correia *et al.* (2011) reported that a low proportion of sand replacement by glass fiber-reinforced polymer inclusions can slightly reduce the water absorption of concrete due to a filler effect and reduced porosity. Conversely, a higher substitution percentage of above 5 vol.% by recycled glass fiber-reinforced polymer resulted in increased water absorption.

The addition of recycled glass fiber-reinforced polymer powder generally leads to a decrease in the drying shrinkage of cement-based materials (Asokan *et al.* 2010; Tittarelli and Moriconi 2010; Zhou *et al.* 2022), primarily due to the constraining effect exerted by micro-fibers (Zhou *et al.* 2022). Tittarelli and Shah (2013) discovered that the inclusion of glass fiber-reinforced polymer dust recycled from a shipyard initially heightened the autogenous shrinkage of mortar but gradually reduced restrained shrinkage as recycled glass fiber-reinforced polymer content increased. Volumetric expansion caused by the addition of recycled glass fiber-reinforced polymer dust was reported in (Ma *et al.* 2022; Zhou *et al.* 2022), attributed to the reaction of recycled glass fiber-reinforced polymer with pore solution, leading to gas production.

In general, we observed that the direct addition of recycled glass fiber-reinforced polymer powder into the cement matrix as fillers increased water absorption. However, when the recycled glass fiber-reinforced polymer powder was used as a replacement for fine aggregates within a certain dosage, the water absorption of cementitious composites was often diminished. Moreover, adding recycled glass fiber-reinforced polymer powder favored the reduction in the drying shrinkage of cement composites.

5.1.1.5. Application in geopolymer

Pławecka *et al.* (2021) conducted research employing three distinct types of recycled glass fiber-reinforced polymer powder obtained from wind turbine rotors to produce geopolymers with additive contents ranging from 5-30 wt.%. Their findings indicated a diminishing trend in compressive and flexural strength as the recycled glass fiber-reinforced polymer content increased. This reduction was attributed to the increased porosity caused by the presence of recycled glass fiber-reinforced polymer powder, leading to a reduction in the active cross-sectional area and, consequently, a decrease in flexural capacity. The bridging effect of microfibers with insufficient length could not compensate for this decline. The increased pore volume in geopolymers also resulted in reduced density and increased water absorption (Pławecka *et al.* 2021).

Similar reductions in compressive strength were observed by Zhang *et al.* (2021). They introduced 20 wt.% recycled glass fiber-reinforced polymer powder with diameters below 80 μm into a geopolymer mixture and observed a degradation in composite strength due to the high demand for solution caused by the extensive surface area of fine powder and an excessive quantity of microfibers. However, their results demonstrated an enhancing effect of recycled glass fiber-reinforced polymer dust on flexural properties, with this reinforcement becoming more significant with larger particle sizes (Zhang *et al.* 2021). Altogether, we observed that the incorporation of recycled glass fiber-reinforced polymer powder can adversely affect the compressive properties of geopolymers, while its role in bending strength remains controversial. In general, research on using recycled glass fiber-reinforced polymer additives in alkali-activated materials or geopolymers remains limited.

5.1.1.6. Application in asphalt based composite

In recent years, there has been a growing interest in the use of recycled glass fiber-reinforced polymer powder in asphalt-based composites (Lin *et al.* 2022; Lan *et al.* 2023; Nie *et al.* 2023; Zhen *et al.* 2023). Lin *et al.* (2022) incorporated waste glass fiber-reinforced polymer powder as an additive in asphalt mastics at filler-bitumen ratios ranging from 0.8 to 1.2. They observed improvements in moisture resistance and aging resistance of asphalt mastics. Additionally, the medium and high-temperature performance, fatigue resistance, and rutting resistance were enhanced, attributed to the anti-stripping effect of glass fiber-reinforced polymer powder. However, the inclusion of recycled glass fiber-reinforced polymer had a detrimental effect on the low-temperature cracking resistance of asphalt, mainly due to the high volume fraction of glass fiber-reinforced polymer powder, which reduced the integrity of the bitumen phase. Similarly, Zhen *et al.* (2023) reported a positive impact of recycled glass fiber-reinforced polymer powder on high-temperature resistance but noted a reduction in low-temperature crack resistance.

On the contrary, Nie *et al.* (2023) found an improvement in the low-temperature properties of asphalt by incorporating 1-4 wt.% recycled glass fiber-reinforced polymer powder, along with increased toughness and elasticity. To maximize the benefits of recycled glass fiber-reinforced polymer powder in asphalt-based materials, pretreatment with a silane coupling agent is highly recommended (Nie *et al.* 2023). In general, utilizing recycled glass fiber-reinforced polymer powder has exhibited advantageous effects on the serviceability and durability of asphalt-based composites, which merit further exploration.

1114 Table 7. Applications of recycled glass fiber-reinforced polymer as fine aggregates in cement-based composites.

Ref.	Matrix	Glass fiber-reinforced polymer source	Production condition	Resin ratio	Glass fiber-reinforced polymer size	Glass fiber-reinforced polymer dosage	Water/binder ratio	Curing condition	Flowability	Compressive strength	Flexural strength	Tensile strength	Characterization analysis
Asokan *et al.* 2009	Concrete	Hambleside Danelaw Rooflights and Cladding Limited, United Kingdom	Grinding	95% powder, 5% fiber	0.02-600 µm	Replacing 5, 15, 30, 50 wt.% fine aggregate	0.5, 0.55, 0.57, 0.68, 0.71	14, 28, 180 d in water at 20±2°C; in oven at 50±2°C	—	Powder: decrease (28 d in water, 5-50 wt.%); increase (28 d in oven, 5-15 wt.%), decrease (28 d in oven, 30-50 wt.%)	—	—	Density
Asokan *et al.* 2010	Concrete	Hambleside Danelaw Rooflights and Cladding Limited, United Kingdom	Grinding	95% powder, 5% fiber	0.02-600 µm	Replacing 5, 15 wt.% fine aggregate	0.34, 0.37, 0.38	28 d in water at 20±2°C; in oven at 50±2°C	—	6.1-14.3% increase (water), 9.1-20.7% increase (oven)	—	7.0-9.6% increase (water), 6.5-29.7% increase (oven) (splitting)	Scanning electron microscope, energy dispersive X-ray spectroscopy, density, drying shrinkage, initial surface absorption, total water absorption, optimal observation

Correia *et al.* 2011	Concrete	—	Cutting pultruded profiles	—	<63 µm	Replacing 5, 10, 15, 20 vol.% sand	0.39-0.46	28d in a moist room; 20°C	—	19.3-47.5% decrease; 2.9-31.4% decrease (modulus of elasticity)	—	2.6-46.8% decrease (splitting)(powder)	Water absorption, optimal observation
Tittarelli and Moriconi 2010	Mortar and self compacting concrete	Industrial by-product from a shipyard	—	80 vol.% polyester resin; 20 vol.% glass fiber	5-400 µm	Replacing 10, 15, 20 vol.% sand (mortar); replacing 25, 50 vol.% calcareous filler (self compacting concrete)	0.5 (mortar); 0.6 (self compacting concrete)	2, 7, 28 d wet-curing at room temperature	—	Decrease	Decrease (mortar); increase (self compacting concrete)	—	Capillary water absorption, drying shrinkage
Tittarelli and Shah 2013	Mortar	Industrial by-product from a shipyard	—	80 vol.% polyester resin; 20 vol.% glass fiber	5-400 µm	Replacing 5, 10 vol.% sand	0.4	2, 7, 28, 90 d; wet curing at 23±2°C, relative humidity 100%; air curing at 23±2°C, relative humidity 50±5%; oven curing at 50±2°C	Increase	Decrease (2-90 d, wet, air, oven curing)	Decrease (modulus of rupture, wet curing)	—	Capillary water absorption, autogenous and restrained shrinkage

Tittarelli 2013	Mortar	Industrial by-product from a shipyard	—	80 vol.% polyester resin; 20 vol.% glass fiber	5-400 µm	Replacing 2.5, 5 vol.% sand	1.1	28 d; 20±2°C; relative humidity 65±5%	Increase	Decrease	Increase	—	Permeability, thermal conductivity, capillary water absorption, efflorescence tests
Sebaibi *et al.* 2012	Mortar	Glass fiber-reinforced unsaturated polyester	Grinding	25.95 wt.% polymer, 62.05 wt.% $CaCO_3$, 11.99 wt.% glass fiber	5 µm	Replacing 7.13 vol.% sand	0.17	28 d in water; 20±2°C	Decrease	20.3% decrease; 25.6% decrease (modulus of elasticity)	33.5% increase	—	Scanning electron microscope, mercury intrusion porosimetry
Sebaibi *et al.* 2014	Mortar	Glass fiber-reinforced unsaturated polyester	Grinding	25.95 wt.% polymer, 62.05 wt.% $CaCO_3$, 11.99 wt.% glass fiber	5 µm	Powder: replacing 7.13 vol.% sand	0.17	28 d in water; 20±2°C	Decrease	—	—	51.7% increase (uniaxial)	Scanning electron microscope, mercury intrusion porosimetry
García *et al.* 2014	Mortar	Streamlined fairings on trains, electrical panelboards, hulls for pleasure boats, pultruded glass fiber-reinforced polymer profiles	Hammer milling	—	—	Replacing 5, 10 wt.% sand	0.5	28d; 20°C; relative humidity 100%	Decrease	Decrease (7 d)	Decrease (7, 28 d)	—	Scanning electron microscope, shrinkage, fiber-alkali reactivity
Baturkin *et al.* 2021	Concrete	Disassembled wind turbines	Ball milling	29% resin, 7% wood, 64% glass fiber	3 µm average	Replacing 10, 20, 30 wt.% cement (unprocessed	0.5 (unprocessed);	28, 90 d in lime-saturated water	—	26-67% decrease	9-17% decrease	—	Density, X-ray diffraction, X-ray fluorescence

						); replacing 10 wt.% cement (processed)	0.48 (processed)						spectrometry, pyrolysis
Zhou *et al.* 2022	Mortar	Box, lid, glass fiber-reinforced polymer offcuts	Grinding	—	<303 μm (box), <194 μm (lid) and <140 μm (offcuts)	Adding 2, 4, 6 wt.% by weight of cement	0.4	28 d; 20±2°C; relative humidity> 95%	Increase	Increase (4, 6 wt.% box; 2, 4 wt.% lid); decrease (offcuts; 2 wt.% box; 6 wt.% lid)	Increase (box; 6 wt.% lid); decrease (offcuts; 2, 4 wt.% lid)	—	Scanning electron microscope, thermal gravimetric analysis, X-ray diffraction, fourier transform infrared spectroscopy, bulk density, water absorption, drying shrinkage, porosity
Ma *et al.* 2022	Concrete	Waste off-cuts of glass fiber-reinforced polymer	Crushing	—	10-1000 μm	Adding 3, 6, 9 wt.% by weight of cement	0.4	28d; 20±2°C; relative humidity>95 %	Increase	Decrease	Decrease	—	Scanning electron microscope, X-ray diffraction, micro computed tomograph, expansion, initial/final setting time, bulk density, water absorption, hydration heat
Rodin III *et al.*	Mortar	Wind turbine blades	Shredding and	43% polyester	<0.42mm	Replacing 1, 3, 5 vol.% sand	0.35 (Phase I),	7 d (Phase I), 7, 28, 90 d (Phase II) in	—	Decrease	Decrease	—	Density, alkali-silicate

2018a			hammer milling	resin, 57% glass fiber			0.4 (Phase II)	fog room; 23°C; relative humidity 98%					reaction expansion, Scanning electron microscope, optimal observation
Zhang *et al.* 2021	Geopolymer	In-house produced glass fiber-reinforced polymer flat panels	Grinding and sieving	35 wt.% average	<40 µm, 40 µm, 80 µm	Adding 3, 5, 20 wt.% by weight of binder	29-44 wt.%	7, 28,56 d in chamber	—	Decrease (28 d)	Increase (28 d)	—	Scanning electron microscope, electron dispersive spectroscopy, X-ray diffraction, micro computed tomograph
Pławecka *et al.* 2021	Geopolymer	Rotor blade aerodynamic part (I); turbine blade monolithic part (II); rotor blade aerodynamic part (III)	Crushing	Glass fiber content: 72.35% (I); 56.89% (II); 70.87% (III)	50 -1000 µm (I); 50 -400 µm (II); 100 - 1000 µm (III)	Adding 20 wt.% by weight of fly ash	0.05, 0.15, 0.3 (powder: fly ash)	28 d; 20°C; relative humidity 50%	—	Decrease	Decrease	—	Scanning electron microscope, electron dispersive spectroscopy, density, Absorption, optimal observation

5.1.2. Recycled glass fiber reinforced polymer as coarse aggregate

In the existing body of literature, researchers have explored the potential use of recycled glass fiber-reinforced polymer as a replacement for coarse natural aggregates in concrete composites. Yazdanbakhsh *et al.* (2017) manufactured glass fiber-reinforced polymer recycled aggregates by cutting waste glass fiber-reinforced polymer rebars with diameters ranging from 6 to 19 mm into short pieces. They incorporated these glass fiber-reinforced polymer recycled aggregates into concrete as a substitute for coarse natural aggregates at dosages of 5 and 10 vol.%. Their findings indicated that using 5 vol.% glass fiber-reinforced polymer recycled aggregates did not significantly affect the flowability of the concrete. However, higher replacement ratios led to a 7% reduction in slump. Furthermore, compared to the control samples, replacing coarse aggregate with recycled aggregate of glass fiber-reinforced polymer resulted in a decrease in compressive strength of 3-6%, primarily due to the weaker interlock between glass fiber-reinforced polymer recycled aggregate and the matrix. However, the use of glass fiber-reinforced polymer aggregate had no significant influence on the modulus of elasticity of the concrete (Yazdanbakhsh *et al.* 2017). In another study (Yazdanbakhsh *et al.* 2016), cut recycled glass fiber-reinforced polymer rebars with diameters ranging from 6 to 25 mm were employed to replace natural aggregates in normal- and high-strength concrete at levels of 40-100 vol.%. They observed a similar decrease in compressive strength for both types of concrete, with reductions of 13% and 21% for substitution levels of 40% and 100%, respectively (Yazdanbakhsh *et al.* 2016). Additionally, both studies reported a deterioration in splitting tensile strength when natural aggregate was replaced with glass fiber-reinforced polymer recycled aggregate (Yazdanbakhsh *et al.* 2016; Yazdanbakhsh *et al.* 2017).

Shahria Alam *et al.* (2013) conducted a partial replacement of natural aggregates in concrete with glass fiber-reinforced polymer scrap squares at levels ranging from 25 to 50 vol.%. Their findings indicated that as the proportion of recycled glass fiber-reinforced polymer aggregate increased, both the flexural and compressive strengths of the concrete decreased. This reduction in strength was attributed to the characteristics of glass fiber-reinforced polymer recycled aggregate, which had a low absorption capacity, leading to a higher amount of free water within the matrix. Additionally, the weak bonding between glass fiber-reinforced polymer recycled aggregate and hydration products contributed to the decline in strength.

Baturkin *et al.* (2021) reported a gradual decline in both flexural and compressive behavior when replacing natural aggregate in concrete with glass fiber-reinforced polymer recycled aggregate at increasing dosages ranging from 33 to 100 vol.%, as depicted in Fig. 13. They also replaced 10-30 wt.% of cement with recycled glass fiber-reinforced polymer powder and observed that the detrimental effect on strength caused by recycled glass fiber-reinforced polymer was more pronounced compared to using recycled glass fiber-reinforced polymer in aggregate form. This decrease in strength could be attributed to the reduced cement content and the presence of retarding agents from the wooden components of recycled glass fiber-reinforced polymer. However, when the glass fibers extracted from ground recycled glass fiber-reinforced polymer composites were used as additional reinforcement in concrete at the dosages of 1-1.75 vol.%, it led to comparable compressive performance and improved flexural behavior compared to reference samples.

By and large, we found that the incorporation of recycled glass fiber-reinforced polymer pieces as coarse aggregates in concrete had an adverse effect on mechanical performance. Further research is needed to explore methods for roughening the smooth surfaces of polymeric composites or enhancing the interaction between glass fiber-reinforced polymer recycled aggregate and the surrounding cementitious matrices to mitigate this negative impact.

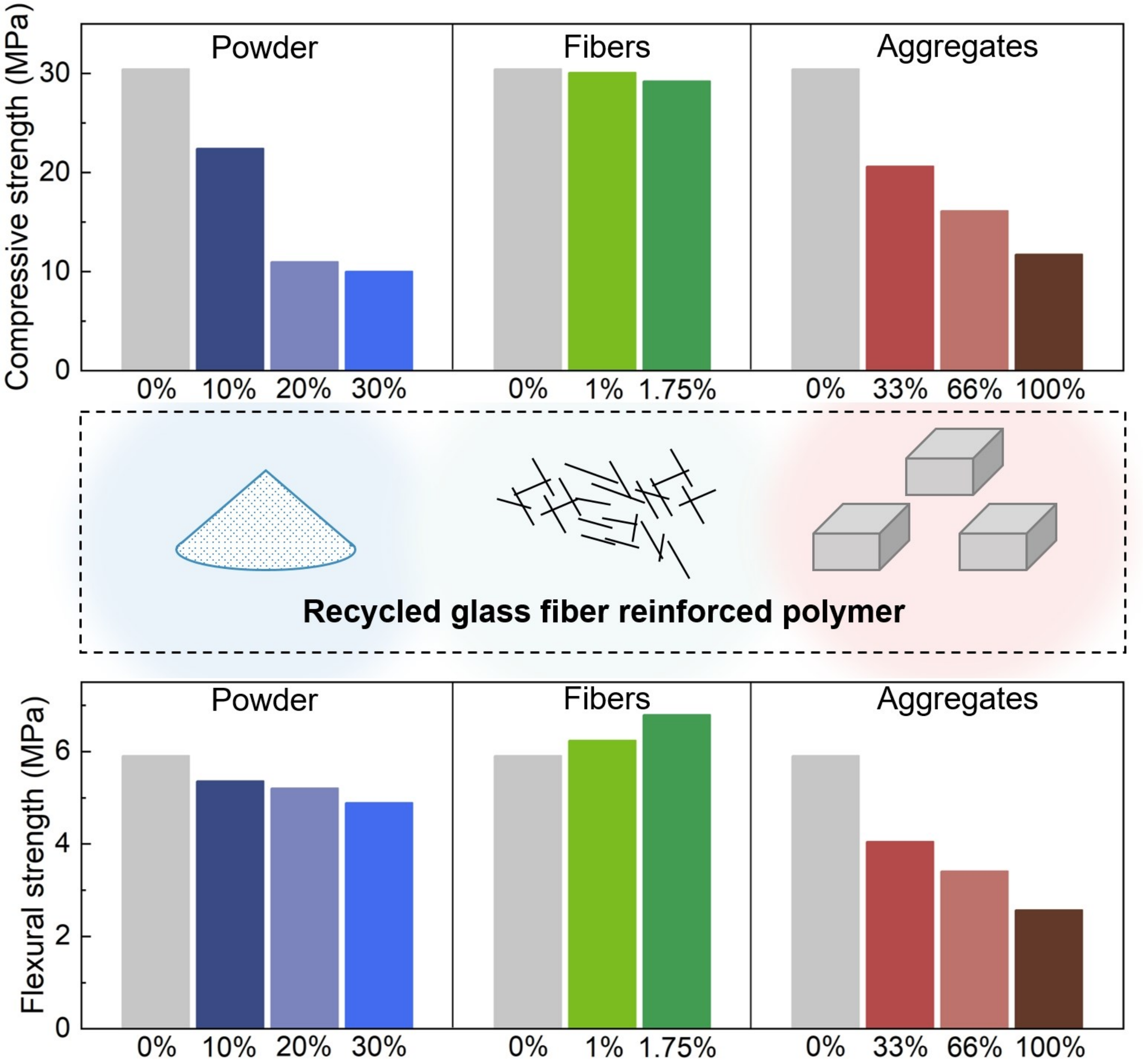

Fig. 13. Glass fiber-reinforced polymer additives are incorporated into concrete in various forms, including powder, fibers, and aggregates. The inclusion of aggregates and powder generally has a detrimental effect on mechanical properties. However, adding glass fiber-reinforced polymer fibers has little impact on compressive strength and can significantly improve the flexural strength of concrete. Adapted from Baturkin *et al.* (2021).

5.1.3. Specially shaped recycled glass fiber reinforced polymer as macro fiber

Recognizing the detrimental impact of both powdered and aggregate forms of recycled glass fiber-reinforced polymer on the mechanical properties of cementitious composites, researchers have embarked on shaping mechanically recycled glass fiber-reinforced polymer scraps to maximize their reinforcing potential within cement matrices. Building upon previous studies, recycled glass fiber-reinforced polymer can be crafted into various forms, including cylindrical, flaky, and slender shapes, or in the form of fibers extracted from milled or crushed composites, as depicted in Fig. 15.

5.1.3.1. Workability

The flowability of mortar and concrete containing slender recycled glass fiber-reinforced polymer was studied by several researchers. For instance, Fu *et al.* (2021) introduced 0.5-1.5 vol.% recycled glass fiber-reinforced polymer strips created by cutting wind blades into concrete and observed a significant reduction in slump diameter of up to 53% with increasing content of recycled glass fiber-reinforced polymer. The inclusion of recycled glass fiber-reinforced polymer strips resulted in a decrease in free water in the cement mixture due to their larger total surface area. This, in turn, increased the shear strength of the fresh-state matrices, thereby reducing fluidity (Fu *et al.* 2021; Yuan *et al.* 2022). Similarly, Yazdanbakhsh *et al.* replaced coarse aggregates in concrete with slender recycled glass fiber-reinforced polymer of regular shape at dosages of 5 and 10 vol.%, and their findings indicated that the incorporation of slender glass fiber-reinforced polymer reinforcements reduced the slump due to the increased specific surface area (Yazdanbakhsh *et al.* 2018a; Yazdanbakhsh and Tian 2019). Likewise, the addition of recycled glass fiber obtained from shredded glass fiber-reinforced polymer sheets or milled wind blades led to a decrease in the workability of fresh cement blends, with the extent of the decrease being proportionally related to the fiber content and length (Mastali *et al.* 2016; Mastali *et al.* 2018; Zhou *et al.* 2021; Xu *et al.* 2022). Altogether, we observed that it is a common phenomenon that the workability of cementitious mixtures is adversely affected by the addition of needle-shaped recycled glass fiber-reinforced polymer in its various forms.

5.1.3.2. Compressive properties

The impact of macro fibers of recycled glass fiber-reinforced polymer on the compressive properties of cement composites exhibited significant variation depending on the fibers' geometry. In the case of fibers recycled from glass fiber-reinforced polymer through shredding or grinding, some studies reported a favorable influence of recycled glass fiber on compressive strength. Haider *et al.* (2021) employed various sizes of recycled glass fibers derived from discarded wind turbine blades to replace 1-7 vol.% of sand in mortar partially. They observed an enhancement in compressive strength attributable to the bridging action of recycled glass fibers and the substantial fiber content of 77-79% in additives. Additionally, Zhou *et al.* (2021) demonstrated improved strength in cement mortar containing 5 wt.% recycled glass fibers from diverse sources, emphasizing the positive correlation between the reinforcing effect and the surface hydrophilicity of recycled glass fibers.

Conversely, other researchers have documented an adverse effect of recycled glass fibers from the ground or shredded glass fiber-reinforced polymer on the strength of cement composites (Dehghan *et al.* 2017; Rodin III *et al.* 2018a; Xu *et al.* 2022). Dehghan *et al.* (2017) introduced fibers derived from recycled glass fiber-reinforced polymer with four types of resin into concrete as a substitute for 5 wt.% of coarse aggregates. They illustrated a decline in compressive properties, with variations depending on the sources of glass fiber-reinforced polymer. Similarly, Xu *et al.* (2022) incorporated 0.5, 1.5, and 2.5 vol.% recycled glass fibers obtained from crushed turbine blades into concrete composites, resulting in reductions of 4%, 7%, and 14% in compressive strength, respectively. This reduction was attributed to the weak bond between recycled glass fibers and matrices. Concurrently, they observed increased toughness and Poisson's ratio in concrete due to the crack-bridging action of fibers (Xu *et al.* 2022). Analysis of Table 8 allows for a reasonable deduction: a low fraction of resin content in recycled glass fiber-reinforced polymer additives exhibits a strong correlation with the enhancement of compressive strength. Furthermore, the dimensions and length-to-width ratio of recycled glass fibers appear to play a pivotal role in compressive performance, warranting further detailed investigations (Zhou *et al.* 2021).

Mastali *et al.* (2018) employed recycled glass fibers obtained from shredded glass fiber-reinforced polymer sheets, ranging in lengths from 10 to 30 mm and with contents varying from 0.5 to 2 vol.%, as reinforcements in self-compacting mortar. They reported a progressive enhancement in composite strength with longer recycled glass fiber lengths and larger volume fractions, amounting to an increase of up to 45%. Similar trends were observed in porosity results, which paralleled the compressive outcomes. This boost in compressive strength can be attributed to the bridging action of fibers and their ability to resist crack propagation (Mastali *et al.* 2016; Mastali *et al.* 2018).

By incorporating recycled glass fiber-reinforced polymer strips from recycled wind blades or slender flaky glass fiber-reinforced polymer waste into concrete, compressive strength can also be augmented (Fu *et al.* 2021; Singh *et al.* 2022; Yuan *et al.* 2022). Fu *et al.* (2021) demonstrated that using 0.5-1.5 vol.% recycled glass fiber-reinforced polymer strips as reinforcement in concrete led to a modest improvement in compressive strength, approximately in the range of 3.6-4.4%. Additionally, the modulus of elasticity increased by 1.4-3.4%. This improvement can be attributed to the fact that the addition of recycled glass fiber-reinforced polymer reduces the water-to-cement ratio by absorbing some free water and can effectively constrain crack development through interaction with the concrete matrices.

Yazdanbakhsh *et al.* conducted an investigation into the mechanical properties of concrete, focusing on the replacement of coarse aggregates with various slender glass fiber-reinforced polymer rebars (Yazdanbakhsh *et al.* 2017; Yazdanbakhsh *et al.* 2018a; Yazdanbakhsh and Tian 2019). These rebar elements included needles, (grooved) wind blade fibers, and small fibers, with volumetric ratios of 5% and 10%. Their findings revealed that most of the reinforced samples experienced only a marginal reduction in compressive performance, falling within 9% when compared to plain matrices. A similar minor decline, caused by substituting 5-10% of coarse aggregate with recycled glass fiber-reinforced polymer needles, was also observed by Cheng *et al.* (2023). However, as the replacement levels increased to 15 vol.%, a more substantial decrease in compressive strength, approximately 10%, was recorded. This slight negative impact on compressive properties was attributed to the regular shapes and round, smooth surfaces of the recycled glass fiber-reinforced polymer needles (Cheng *et al.* 2023). Building upon prior studies (Yazdanbakhsh *et al.* 2017; Yazdanbakhsh *et al.* 2018a; Yazdanbakhsh and Tian 2019; Cheng *et al.* 2023), it was observed that lower replacement levels of aggregate with rod-shaped recycled glass fiber-reinforced polymer favored an enhancement in the modulus of elasticity due to crack-bridging action. Conversely, higher substitution ratios, exceeding 10%, resulted in a descending trend in modulus of elasticity, primarily due to the lower elastic modulus of recycled glass fiber-reinforced polymer itself.

When cracks intersect needles in concrete under loading conditions, the needles will initially debond due to the high interfacial shear stress and detach from one side of the crack (Yazdanbakhsh *et al.* 2018a). For fibers intersecting the crack surface obliquely, they must undergo bending near the crack surfaces during the debonding process. High modulus fibers, like steel fibers, will undergo plastic deformation and bending in this process (Fig. 14a). In the case of needle reinforcements with high flexural stiffness and shear and tensile strengths, local spalling and crumbling would occur on at least one side of the crack during the debonding process (Yazdanbakhsh *et al.* 2018a) (Fig. 14b). Therefore, the high modulus and strength of the recycled glass fiber-reinforced polymer needles enable efficient bridging action. To enhance the efficient transfer of loads from the smooth needles to the matrix, surface modification emerges as a promising avenue for future studies.

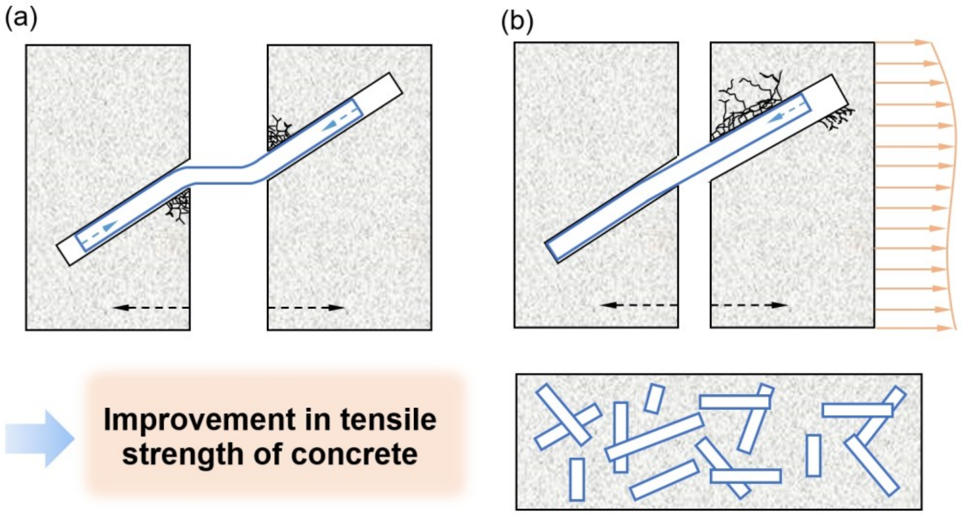

Fig. 14. The incorporation of recycled glass fiber-reinforced polymer needles can improve the tensile strength of concrete. (a) When the concrete undergoes external loading, the crack propagates and intersects the glass fiber-reinforced polymer needles, resulting in debonding on one side of the needles. The inclined needles will bend on the crack surface during pullout as the crack opening grows. (b) The very rigid, high-strength glass fiber-reinforced polymer needles will cause local failure and disintegration of the matrix during crack development in concrete. Adapted from Yazdanbakhsh *et al.* (2018a).

As a whole, there exist controversial outcomes in the compressive strengths of cement composites when using fibers extracted from shredded or ground glass fiber-reinforced polymer as reinforcements. We observed that the reinforcing effect of fibers seems to have a negative correlation with their resin content. Furthermore, the incorporation of fibers derived from glass fiber-reinforced polymer sheets through shredding, or recycled glass fiber-reinforced polymer strips, led to improvements in the compressive properties of mortar or concrete. Nevertheless, the use of glass fiber-reinforced polymer rebars in concrete lowered the composite strength due to their regular shapes and smooth surfaces.

5.1.3.3. Flexural and tensile properties

Previous studies have consistently demonstrated the positive impact of incorporating recycled glass fibers extracted from milled glass fiber-reinforced polymer scraps on the flexural and tensile performance of cementitious composites. Asokan *et al.* (2009) conducted experiments showcasing that the inclusion of 5 wt.% waste fibers from recycled glass fiber-reinforced polymer in architectural cladding panels led to a substantial improvement in bending strength. For panels with 8 mm and 12 mm thickness, the bending strength increased by 33% and 58%, respectively. In a similar vein, Xu *et al.* (2022) incorporated recycled glass fibers ranging from 0.5 to 2.5 vol.% with lengths spanning from 28 to 82 mm into concrete. The results showed a significant augmentation of flexural strength, ranging from 4% to 38%, as well as a remarkable increase in flexural toughness, which ranged from 15 to 37 times, in proportion to the recycled glass fiber content. Additionally, their direct-tensile tests indicated that tensile strength and toughness both increased with higher recycled glass fiber proportions, reaching up to 10% and 73%, respectively (Xu *et al.* 2022). As well, an improvement in the splitting tensile strength of concrete containing recycled glass fiber was reported by Dehghan *et al.* (2017).

When it comes to recycled glass fibers derived from glass fiber-reinforced polymer sheets, the addition of these fibers to cement mortar has demonstrated a substantial enhancement in various mechanical properties, encompassing flexural strength, flexural toughness, and impact resistance (Mastali *et al.* 2016; Mastali *et al.* 2018). Additionally, Fu *et al.* have emphasized a positive correlation between the dosage of flaky, rectangular recycled glass fiber-reinforced polymer strips used in concrete composites and both flexural strength and flexural toughness and splitting tensile strength (Fu *et al.* 2021; Yuan *et al.* 2022). Even after splitting failure, glass fiber-reinforced polymer strips exhibit crack-bridging capabilities through fiber pullout action. Nevertheless, it's worth noting that the irregular shapes of flaky, elongated glass fiber-reinforced polymer wastes have been reported to have a negative impact on the flexural and splitting tensile strength of concrete (Singh *et al.* 2022).

The incorporation of rod-shaped glass fiber-reinforced polymer elements has been observed to have a minor detrimental effect on the bending strength of concrete; however, it appears to contribute positively to the improvement in flexural toughness (Yazdanbakhsh *et al.* 2018a; Yazdanbakhsh and Tian 2019). Interestingly, no consistent pattern has emerged regarding the influence of glass fiber-reinforced polymer needles on the splitting tensile strength, as findings vary among studies (Yazdanbakhsh *et al.* 2017; Yazdanbakhsh *et al.* 2018a; Yazdanbakhsh and Tian 2019).

On the whole, we observed that the incorporation of needle-shaped recycled glass fiber-reinforced polymer in various forms favored the improvement in the flexural properties of cement composites, except for the glass fiber-reinforced polymer rebars. In most cases, macro fibers made of recycled glass fiber-reinforced polymer postively influenced the tensile strength of concrete. However, research on their impact on paste or mortar matrices is still needed in future studies.

5.1.3.4. Durability

Research on the durability effects of concrete reinforced with slender recycled glass fiber-reinforced polymer elements remains quite limited. Dehghan *et al.* (2017) conducted a study on the dry shrinkage of concrete containing four types of recycled glass fiber-reinforced polymer fibers produced using a hammer mill grinding system. They observed a slight increase in drying shrinkage compared to plain matrices. This phenomenon was attributed to the relatively low stiffness of recycled glass fiber-reinforced polymer fibers and the introduction of pores due to the fibrous masses. In contrary, in another investigation by Zhou *et al.* (2021), the researchers took measures to prevent the formation of additional pores by removing fiber balls and employed three types of recycled glass fiber-reinforced polymer fibers with high stiffness in cement-based mixtures. Consequently, the reinforced mortar exhibited slightly lower levels of drying shrinkage. Furthermore, Singh *et al.* (2022) demonstrated increased permeability in concrete reinforced with flaky recycled glass fiber-reinforced polymer, and this permeability showed a positive correlation with the higher porosity observed. In summary, we found that the conclusions regarding shrinkage behavior are inconsistent, and there is a clear need for further exploration into the durability of cement composites reinforced with slender recycled glass fiber-reinforced polymer elements.

5.1.3.5. Application in geopolymer composite and polymer concrete

Limited research has been conducted on the impact of fibers of recycled glass fiber-reinforced polymer on the properties of geopolymer composites. Abdollahnejad *et al.* (2017) employed recycled glass fibers with varying lengths and contents to reinforce fly ash-slag geopolymer mixtures. They noted that as the dosage of recycled glass fibers increased, the compressive strength gradually decreased, while flexural performance improved progressively. Additionally, they found that higher recycled glass fiber content in the geopolymer matrix led to a gradual reduction in the rate of drying shrinkage, attributed to the bridging action (Nazar *et al.* 2023a) of recycled glass fibers. In a study by Zhang *et al.* (2021), recycled glass fibers obtained from ground glass fiber-reinforced polymer waste were blended into an inorganic polymer matrix, resulting in a 17-49% increase in compressive strength with the addition of fibers. This improvement can be explained by the fibers' reactive composition, which includes Al_2O_3, SiO_2, and CaO, and the rough surfaces induced by polymer residues, contributing to both chemical and physical interactions at the fiber-matrix interface. These interactions benefited the increase in compression strength. Furthermore, the addition of recycled glass fibers also enhanced the flexural resistance of geopolymer compared to the benchmarks (Zhang *et al.* 2021). Previous studies have also reported the advantageous effects of recycled glass fibers on the mechanical behavior of foamed geopolymer (Zhang *et al.* 2023) and geopolymer-stabilized silty clayey dredged materials (Zhang *et al.* 2022b).

The utilization of recycled glass fibers in polymer concrete has been explored by Castro *et al.* (Castro *et al.* 2013; Castro *et al.* 2014). They partially replaced sand aggregates with recycled glass fibers at contents ranging from 4 to 15 wt.% and observed an improvement in compressive and flexural capacity for concrete-polymer composites, both with and without silane additives. By and large, we observed that the use of macro fibers from recycled glass fiber-reinforced polymer appears to be a promising choice for reinforcing geopolymer composites and polymer concrete. This direction is worth considering for further, in-depth exploration.

5.1.3.6. Application in asphalt based material

The application of needle-shaped recycled glass fiber-reinforced polymer in asphalt-based materials also shows a significant promise for improving performance. Yang *et al.* (2020) incorporated macro-fibers made of recycled glass fiber-reinforced polymer with varying lengths up to 12 mm and diameters ranging from 0.125 mm to 0.71 mm into bitumen composites. They reported the advantageous effects of glass fiber-reinforced polymer additives on various aspects of performance, including creep and recovery behavior, water resistance, rutting resistance, stiffness, and resistance to low-temperature cracking in bitumen. The researchers noted that the inclusion of fibers of recycled glass fiber-reinforced polymer facilitated the formation of a three-dimensional network within the matrices, limiting crack propagation through the bridging function of the fibers. In the study conducted by Lan *et al.* (2023), fine aggregates in the asphalt mixture were replaced by needle-shaped recycled glass fiber-reinforced polymer produced from wind blades at contents ranging from 0.1% to 0.3% by weight. Their results indicated that the addition of recycled glass fiber-reinforced polymer led to improvements in both the high- and low-temperature performance of asphalt mortar. Furthermore, the optimal performance of asphalt mixtures was achieved when simultaneously using recycled glass fiber-reinforced polymer powder and fibers (Lan *et al.* 2023). As a whole, we observed that needle-shaped recycled glass fiber-reinforced polymer can be used as sustainable reinforcements for tailoring the properties of asphalt-based materials and for effective waste management.

Table 8. Application of needle-shaped recycled glass fiber-reinforced polymer as macro-fiber in cement-based composites.

Glass fiber-reinforced polymer shape	Matrix	Glass fiber-reinforced polymer source	Production condition	Resin ratio	Glass fiber-reinforced polymer size	Glass fiber-reinforced polymer dosage	Water/binder ratio	Curing condition	Flowability	Compressive strength	Flexural strength	Tensile strength	Characterization analysis	Ref.
Fiber-like shape	Mortar	Hambleside Danelaw Rooflights and Cladding Limited, United Kingdom	Grinding, sieving	—	20 mm	Adding 5 wt.% by weight of cement	0.33	28 d in water at 20±2°C	—	—	58% (12 mm thickness) increase, 33% (8 mm thickness) increase	—	Density	Asokan *et al.* 2009
	Concrete	Four commercially produced glass fiber-reinforced polymers	Grinding, hammer milling	Fiber content: 54.3, 43.1, 41.1, 42.0 vol.%	21.7, 17.2, 21.2, 19.5 mm	Replacing 5 wt.% coarse aggregate	0.45	7, 28 d in lime-saturated water	Increase (bisphenol-A, novolac-based, flame retardant epox	Decrease	—	Increase (unsaturated polyester, bisphenol-A, flame retardant epoxy vinyl ester),	Backscattered electron, energy dispersive X-ray spectroscopy, water absorption, density, accelerated mortar bar test, drying shrinkage, alkali-silica reaction	Dehghan *et al.* 2017

									y vinyl ester), decrease (unsaturated polyester)			decrease (novolac-based epoxy vinyl ester)(splitting)		
	Mortar	Wind turbine blades	Shredding, hammer milling	57% glass fiber, 43% polyester resin	0.42 mm<a<0.841 mm (small), 1.41 mm<a<2 mm (medium), 2 mm<a<2.38 mm (large)	Replacing 1, 3, 5 vol.% sand	0.35 (Phase I), 0.4 (Phase II)	7 d (Phase I); 7, 28, 90 d (Phase II) in fog room at 23°C and relative humidity 98%	—	Increase (7 d; large), decrease (7 d; small, medium)	Increase (7 d; small, large), decrease (7 d; medium); increase (toughness)	—	Scanning electron microscope, density	Rodin III *et al.* 2018a
	Mortar	Recycled glass fiber-reinforced polymer fiber from box, lid, offcut	Shredding, vibratory screening, hydrauli	Resin content 23.6% (box), 33.4% (lid),	3.1 mm (box), 9.5 mm (lid), 6.8 mm (offcut)	Adding 5 wt.% by weight of binder	0.4	28 d; 20°C; relative humidity 95%	Decrease	Increase	Increase, decrease (box)	—	Scanning electron microscope, X-ray diffraction, thermal gravimetric analysis, fourier transform infrared spectroscopy,	Zhou *et al.* 2021

			c selection, aerodynamic separation	45.2% (offcut)									drying shrinkage, micro computed tomography	
	Concrete	Disassembled wind turbines	Cutting, chipping	29% resin, 7% wood, 64% glass fiber	—	Adding 1, 1.75 vol.%	0.5 (unprocessed); 0.48 (processed)	28, 90 d in lime-saturated water	—	1-4% decrease	6-15% increase	—	Density, X-ray diffraction, X-ray fluorescence spectrometry, pyrolysis	Baturkin *et al.* 2021
	Mortar	Wind turbine blades	Milling, screening, sizing	resin content 21-23%	0.67 mm (small), 1.07 mm (medium), 2.56 mm (large)	Replacing 1, 2, 3 vol.% sand	0.4	7, 28 d	Decrease	Increase (28 d)	Increase (28 d), increase (toughness)	—	Scanning electron microscope, thermal gravimetric analysis, fourier transform infrared spectroscopy	Haider *et al.* 2021
	Concrete	Wind blade	Cutting, screening	—	47.2 mm (length), 3.64 mm (width), 0.97 mm (thickness)	Adding 0.5, 1.5, 2.5 vol.% by volume of matrix	0.48	28 d in plastic films	Decrease	3.8-13.9% decrease	4.3-37.9% increase; 1539-3678% increase (toughness)	Increase (direct-tensile test)	Optical observation	Xu *et al.* 2022
	Geopolymer	Wind turbine blade	Cutting, crushing, sieving		1.45-4.75 mm	Adding 2, 4, 6 wt.%	Various ratios	Room temperature	Decrease	Increase (unconfined)	—	—	Setting times, density, drying shrinkage, thermal	Zhang *et*

	mortar							/relative humidity 40-50%					conductivity, porosity	*al.* 2023
	Geopolymer	In-house produced glass fiber-reinforced polymer flat panels	Grinding, sieving	35 wt.% epoxy resin	160 µm, 250 µm, 500 µm, 710 µm, 1 mm, 2.5 mm	Adding 3 wt.% by weight of binder	29-44 wt.%	7, 28, 56 d in the chamber	—	Increase (28 d)	Increase (28 d)	—	Scanning electron microscope, electron dispersive spectroscopy, X-ray diffraction, micro computed tomography	Zhang *et al.* 2021
	Polymer concrete	Leftovers of pultrusion profiles	Shredding, milling	55% (glass fiber), 16% ($CaCO_3$), 29% (resin)	Average particle (or fiber) diameter of 390 µm or 950 µm, fineness modulus of 1.64 or 2.69, for fine or coarse pultrusion waste	Replacing 4, 8, 12 wt.% sand	—	24 h at 23°C/ relative humidity 50%, curing 8 h/30°C plus 3 h/80°C	—	Increase (4, 8, 12 wt.% coarse pultrusion waste, 4, 8 wt.% fine pultrusion waste); decrease (12 wt.% fine pultrusion waste)	Increase (4, 8, 12 wt.% coarse pultrusion waste, 4 wt.% fine pultrusion waste); decrease (8, 12 wt.% fine pultrusion waste)	—	Optical observation	Castro *et al.* 2013
	Polymer concrete	Leftovers of glass fiber-reinforced polymer	Shredding	55% (glass fiber), 16% ($CaCO_3$),	Average particle (or fiber) diameter of 390 µm or	Replacing 5, 10, 15 wt.% sand	—	7 d/23°C	—	8.9-13.0% increase (coarse pultrusion waste); 2.3-12.2%	4.1-11.5% increase (coarse pultrusion waste); 4.3-10.3%	—	Scanning electron microscope, optical observation	Castro *et al.* 2014

		pultrusion profiles		29% (resin)	950 µm, fineness modulus of 1.64 or 2.69, for fine or coarse pultrusion waste					increase (fine pultrusion waste)	increase (fine pultrusion waste)			
Fibers from glass fiber-reinforced polymer sheets	Self-compacting mortar	Unusable glass fiber-reinforced polymer sheets	Shredding	—	20 mm	Adding 0.2, 0.75, 1.25 vol.%	0.34	28 d in water at 23°C	Decrease	Increase	Increase, increase (toughness)	—	Scanning electron microscope, backscattered electron, atomic force microscopy, energy dispersive X-ray spectroscopy, impact resistance (increase)	Mastali *et al.* 2016
	Self-compacting mortar	Leftover unusable glass fiber-reinforced polymer sheets	—	—	10, 20, 30 mm	Adding 0.5, 1, 1.5, 2 vol.%	0.38	28 d in water at 20°C	Decrease	Increase	Increase, increase (toughness)	—	Scanning electron microscope, backscattered electron, atomic force microscopy, energy dispersive X-ray spectroscopy, ultrasonic pulse velocity, impact resistance (increase)	Mastali *et al.* 2018

Strips	Concrete	Wind blade	Cutting	—	89.7 mm (length), 3.04 mm (width), 0.79 mm (thickness)	Adding 0.5, 1.0, 1.5 vol.% by volume of matrix	0.47	3 months under indoor conditions	Decrease	3.7-4.4% increase, 1.4-3.4% increase (modulus of elasticity)	15.7-120.3% increase, 8385-20993% increase (toughness)	21.3-52.4% increase (splitting)	Optical observation	Fu *et al.* 2021
	Concrete	Wind blade	Cutting	—	62.85 mm (length), 5.17 mm (width), and 0.62 mm (thickness)	Adding 1.0, 1.5, 2.0 vol.% by volume of matrix	0.47	28 d in plastic film	Decrease	Increase (1.5, 2.0 vol.%), decrease (1.0 vol.%); decrease (modulus of elasticity)	Increase, increase (toughness)	Increase (splitting)	Optical observation	Yuan *et al.* 2022
	Concrete	Glass fiber-reinforced polymer wastes	Crushing	—	10.90 mm (length) and 9.13 mm (width)	Adding 0.33, 0.65, 1 vol.%	0.3	7 d in water under ambient conditions	—	Increase	Decrease	Decrease (splitting)	Porosity, density, permeability, ultrasonic pulse velocity, dynamic modulus of elasticity	Singh *et al.* 2022
	Self-compacting mortar and fly	Unusable glass fiber-reinforced polymer sheets	Shredding	—	10, 20, 30 mm	Adding 0.5, 1, 1.5, 2 vol.%	30 wt.% (alkali activator/powder)	28 d at room temperature	—	Decrease	Increase	—	Scanning electron microscope, drying Shrinkage, optical observation	Abdollahnejad *et al.* 2017

	ash-slag geopolymer mortar													
Rebar	Concrete	—	—	—	100 mm (length), 6 mm (diameter), 17 (aspect ratio)	Replacing 5, 10, 15 vol.% coarse aggregate	0.47	28 d	—	3.4-9.5% decrease; modulus of elasticity: increase (5, 10 vol.%), decrease (15 vol.%)	—	—	Optical observation	Cheng *et al.* 2023
	Concrete	Glass fiber-reinforced polymer rebars produced by Hughes Brothers	Cutting by diamond saw	70 wt.% (fiber content); resin type: vinyl ester resin)	100 mm (length), 6 mm (diameter), 17 (aspect ratio)	Replacing 5, 10 vol.% coarse aggregate	0.45	28 d at room temperature, relative humidity 98%	0-7.1% increase	5.5-8.7% decrease; modulus of elasticity: increase (5 vol.% rebar), decrease (10 vol.% rebar)	—	22.2-33.0% increase (splitting); increase (postpeak toughness)	Optical observation	Yazdanbakhsh *et al.* 2017
	Concrete	Shell of wind	Cutting by table saw	—	6 mm×6 mm (square cross-	Replacing 5, 10 vol.%	0.49	28d	Decrease	Comparable	0-10% decrease, increase	0-13.7% decrea	Optical observation	Yazdanbakhsh

	turbine blade	with a diamond blade		section), 100 mm (length)	coarse aggregate					(toughness)	se (splitting)		*et al.* 2018a
Concrete	Cut pultruded glass fiber-reinforced polymer rebars, cut pieces of a wind turbine blade, pultruded glass fiber-reinforced polymer fibers	Cutting by table saw	Fiber content: >70 wt.%	Length 40 mm, diameter 1.5 mm (pultruded glass fiber-reinforced polymer fiber); length 100 mm, side length 6 mm (wind blade fiber); diameter 6 mm, length 100 mm (glass fiber-reinforced polymer needle)	Replacing 5, 10 vol.% coarse aggregate	0.49	28 d at room temperature, relative humidity 98%	Decrease	1.4-8.8% decrease; 3.4% increase (5 vol.% needle)	0-0.1% decrease, increase (toughness)	6.7-24.5% increase (5, 10 vol.% needle, 5, 10 vol.% pultruded fiber); 4.0-5.4% increase (5, 10 vol.% wind blade fiber) (splitting)	Optical observation	Yazdanbakhsh and Tian 2019

5.2. Recovered glass fiber from pyrolysis as reinforcement in cement based composite

The application of glass fiber recovered from glass fiber-reinforced polymer waste through thermal recycling in construction materials remains restricted due to the severe degradation in fiber strength and its low intrinsic value (Jani *et al.* 2022). Despite these challenges, Criado *et al.* (2014) conducted an investigation into the effects of pyrolyzed glass fiber as a partial replacement for cement in mortar at the dosages of 5-15 wt.%; see Fig. 15. Their findings indicated that as the substitution levels of ordinary portland cement by pyrolyzed glass fiber increased, both compressive and flexural strengths experienced a gradual decline, ranging from 6% to 46% and 11% to 35%, respectively. This reduction in mechanical properties can be attributed to several factors. High dosages of recovered glass fiber can easily form agglomerations, leading to stress concentrations. Additionally, an increased fiber amount can elevate the viscosity of the fresh mixture and introduce air bubbles into the matrix during mixing. Consequently, this results in increased porosity and less uniform dispersion of recovered glass fiber, ultimately deteriorating the composite's strength. Furthermore, they delved into the impact of recovered glass fiber on the corrosion behavior of reinforced mortar. They noted that the addition of 5% to 10% of recovered glass fiber had a slight negative effect on rebar corrosion behavior, while higher amounts of fiber additives significantly accelerated the corrosion process. This acceleration was attributed to chloride contamination and an increase in porosity. On the whole, we observed that the utilization of pyrolyzed glass fiber in cementitious materials had a negative effect on compressive and flexural performance. The challenges related to the mechanical properties of recovered glass fibers must be addressed.

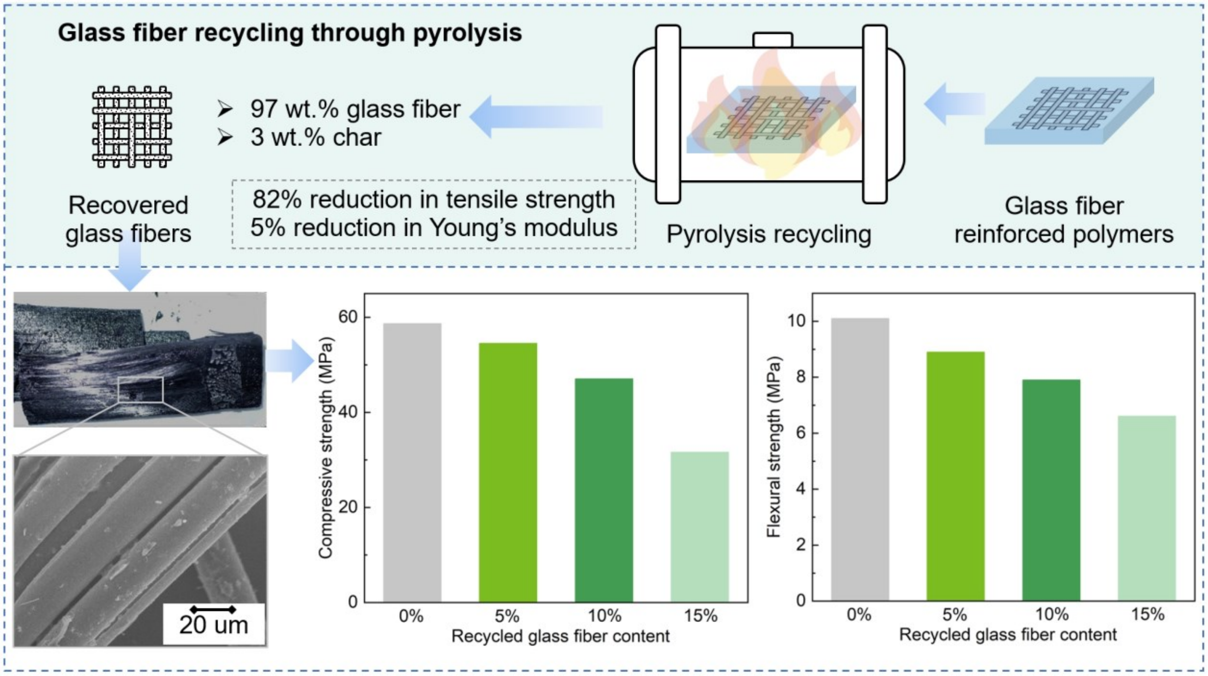

Fig. 15. Glass fibers are recovered from the glass fiber-reinforced polymer wastes through pyrolysis. The decomposition products are composed of 3 wt.% char and 97 wt.% recycled glass fibers. The pyrolysis process results in the reduction in tensile strength and Young's modulus of reclaimed glass fibers in comparison to the original glass fibers. Adding pyrolyzed glass fiber in cementitious materials leads to the decline in compressive and flexural strength with increasing proportion of recovered glass fibers. Adapted from Criado *et al.* (2014).

5.2.1. Fiber strength regeneration

Based on previous publications, it has been widely noted that the mechanical strength of glass fiber tends to experience significant degradation, typically in the range of 40% to 80%, after exposure to heat conditioning (Thomason *et al.* 2016a). For instance, Criado *et al.* (2014) observed that glass fibers subjected to pyrolysis exhibited a dramatic reduction in tensile strength, decreasing by as much as 82% compared to their virgin counterparts. Young's modulus also saw a decrease, albeit by a smaller margin, approximately 5%. In a study conducted by Thomason *et al.* (2014), it was demonstrated that the tensile strength of boron-free E-glass fibers, both with and without sizing, could decrease by as much as approximately 70% after undergoing heat conditioning at 600°C for 15 min. This thermally-induced loss of strength significantly hinders the broader application of recovered glass fibers and diminishes their commercial value.

To combat the issue of strength degradation in thermal recycling, scientists have developed techniques for regenerating the strength of glass fibers. Sakka (1956) found that the tensile strength of glass fibers declined when reheated at elevated temperatures; however, the fiber's strength could be restored to its original level by using hydrofluoric acid etching, which removed a thin surface layer. Aslanova (1960) also reported this strength recovery in glass fibers. They explained that the heating and cooling process induced the development of strength-reducing defects due to the crystallization of the fiber surface. These defects could be mitigated by hydrofluoric acid treatment, resulting in comparable or even higher strength in thermally-treated glass fibers compared to virgin fibers. Yang *et al.* (2015) further highlighted the strength recovery potential of a 1% hydrofluoric acid aqueous solution for thermally-weakened glass fibers. They observed a progressive enhancement in tensile strength, reaching nearly tripled values with increasing treatment times from 0.5 to 2.5 min.

In research funded by the Engineering and Physical Sciences Research Council under the project of Regenerated Composite Value Reinforcement, Thomason *et al.* extensively investigated the role of alkaline solutions, particularly NaOH solutions, in regenerating the strength of thermally-recycled glass fibers (Thomason *et al.* 2016b; Bashir *et al.* 2017). They found that exposure to high temperatures caused a degradation of glass fiber strength by approximately 70-80%. However, immersing damaged glass fibers in hot NaOH or KOH solutions for within 30 min at concentrations of 1.5-5 M could double or even triple the fiber strength (Thomason *et al.* 2016b; Bashir *et al.* 2017). Notably, due to the corrosive nature of NaOH solutions, a short treatment time and low molarity should be employed to optimize the efficiency of strength recovery (Bashir *et al.* 2017). Additionally, the application of silane sizing can further improve the tensile properties of the fibers and regenerate surface functionality (Thomason *et al.* 2016b). By and large, applying acidic or alkaline treatments holds great promise for regenerating the tensile properties of thermally recycled glass fiber. This could impart higher value to the glass fibers recovered from pyrolysis and enable their application in construction materials.

5.3. Glass fiber waste from glass fiber reinforced polymer production as reinforcement in geopolymer composite

Glass fiber wastes generated during the production of glass fiber-reinforced polymer materials can be considered as pristine glass filaments since they have not been impregnated with polymer matrices and retain their original properties. Research on the utilization of glass fiber waste materials in cementitious matrices remains still very scarce.

However, Novais *et al.* (2017) have conducted investigations into the impact of glass fiber waste on the performance of geopolymer composites. They proposed that by incorporating 0.1-3 wt.% of glass fiber wastes, which have lengths ranging from 6 to 20 mm, into the matrix, both compressive and tensile strengths can be significantly improved, up to approximately 162% and 77%, respectively, when compared to an unreinforced matrix. Furthermore, the inclusion of glass fiber waste has been shown to enhance post-cracking ductility and reduce the porosity of the geopolymer. In another study (Senff *et al.* 2020), researchers demonstrated that the addition of 1-2 wt.% of glass fiber wastes to geopolymer foams led to a reduction in flowability, total porosity, and water absorption, along with a slight increase in density. The introduction of these fibers effectively connected adjacent pores and reinforced the microstructure of the foams. Furthermore, glass fiber waste had a minor impact on thermal conductivity. In a separate investigation, Novais *et al.* (2018) reinforced geopolymer beams using glass fiber waste obtained from wind blade production in fabric form. They incorporated 1-3 layers of fabric within the matrices and observed a remarkable improvement in flexural resistance, up to 144%. Additionally, the inclusion of fabrics enhanced ductility but resulted in a lower apparent density (Novais *et al.* 2018).

Overall, we observed that glass fiber waste, having comparable properties to virgin glass fibers, has been merely applied in geopolymer composites and has achieved improved mechanical strength. Their incorporation can also lead to a decline in flowability, porosity, and water absorption of geopolymers, as well as an increase in ductility. Given the high-strength properties of glass fiber waste, these reinforcements can be practically applied to various cement-based materials to effectively enhance their mechanical performance.

5.4. Surface modification for recycled glass fiber reinforced polymer composites

In the case of mechanically recycled glass fiber-reinforced polymer used in cement-based materials, whether in the form of powder, coarse aggregates, or needle-shaped reinforcement, it is often the polymeric content of glass fiber-reinforced polymer additives that directly contacts the matrices rather than the glass fibers themselves. This limitation significantly restricts the force transfer between the two phases and the effective reinforcing action of glass fiber-reinforced polymer.

It has been reported that finely-ground recycled glass fiber-reinforced polymer dust added to cement composites can react with the alkaline pore solution and release gases such as NH_3, H_2, and CH_4 within the matrix. This phenomenon leads to the expansion of the matrix, retards cement hydration, increases porosity, and ultimately has a negative impact on composite strength while raising water absorption (Zhou *et al.* 2022). To mitigate the expansion caused by the recycled glass fiber-reinforced polymer dust, Ma *et al.* (2022) pre-soaked the glass fiber-reinforced polymer dust in a 5% NaOH solution for 4 hours and incorporated 3-9 wt.% of both treated and untreated polymeric powder as filler in concrete. They found that the expansion could be eliminated at various dosages of recycled glass fiber-reinforced polymer additives because no gas was generated after pretreatment in the NaOH solution due to the dissolution of reactive elements present in recycled glass fiber-reinforced polymer. Moreover, surface modification of glass fiber-reinforced polymer powder slightly increased the workability of fresh-state mortar and facilitated the hydration process at a later stage. Therefore, NaOH treatment significantly reduced the porosity of the matrix, which effectively compensated for the strength loss induced by the glass fiber-reinforced polymer addition. This led to higher density matrices compared to untreated glass fiber-reinforced polymer-reinforced samples (Ma *et al.* 2022), as depicted in Fig. 16.

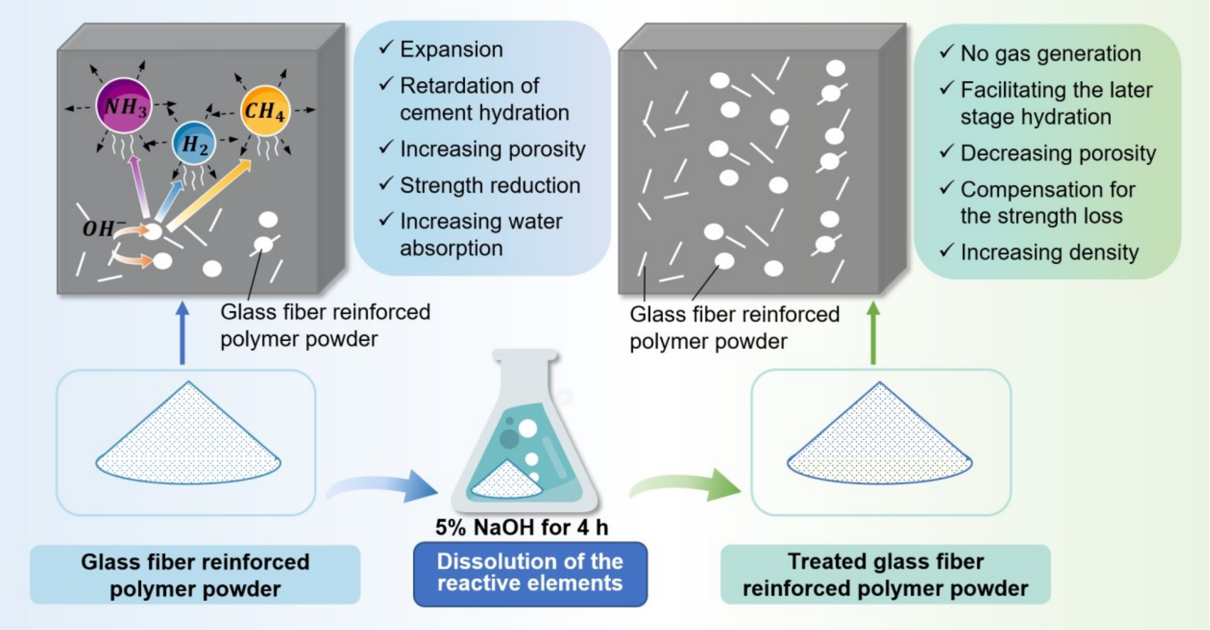

Fig. 16. The recycled glass fiber-reinforced polymer dust can react with the alkaline pore solution in the cement matrices and produce gases, leading to the expansion of the matrix, retardation of cement hydration, increased porosity, strength reduction, and increased water absorption. Immersing finely-ground glass fiber-reinforced polymer dust in NaOH solution can prevent gas release by removing reactive elements. This pre-soaking treatment facilitates later-stage hydration, reduces porosity, mitigates strength loss, and increases the density of cement composites containing glass fiber-reinforced polymer dust.

When shredded glass fiber-reinforced polymer with cracks and delamination was incorporated into cement composites, the unprotected recycled glass fibers were exposed to the strong alkaline environment, which impaired the fiber strength and compromised the reinforcing effect of recycled glass fiber in the cement matrices (Kimm *et al.* 2020). The use of complete glass fiber-reinforced polymer as reinforcement is a feasible alternative option, but the interface between the glass fiber-reinforced polymer and cementitious matrices needs to be modified. To address this issue, Kimm *et al.* (2020) modified the surfaces of glass fiber-reinforced polymer strips using hydrolyzed silane and sand coating (Fig. 17). Pullout experiments demonstrated that the silane treatment had a negative impact on interfacial adhesion. This was because the silanol groups likely crosslinked with the calcium silicate hydrate phase, potentially generating a hydrophobic silicone resin layer through water release. In contrast, the sand coating on the surfaces improved the shear strength at the interface between glass fiber-reinforced polymer and concrete. This improvement was attributed to the high surface area of the sand particles, which facilitated enhanced interaction with the aggregates (Kimm *et al.* 2020).

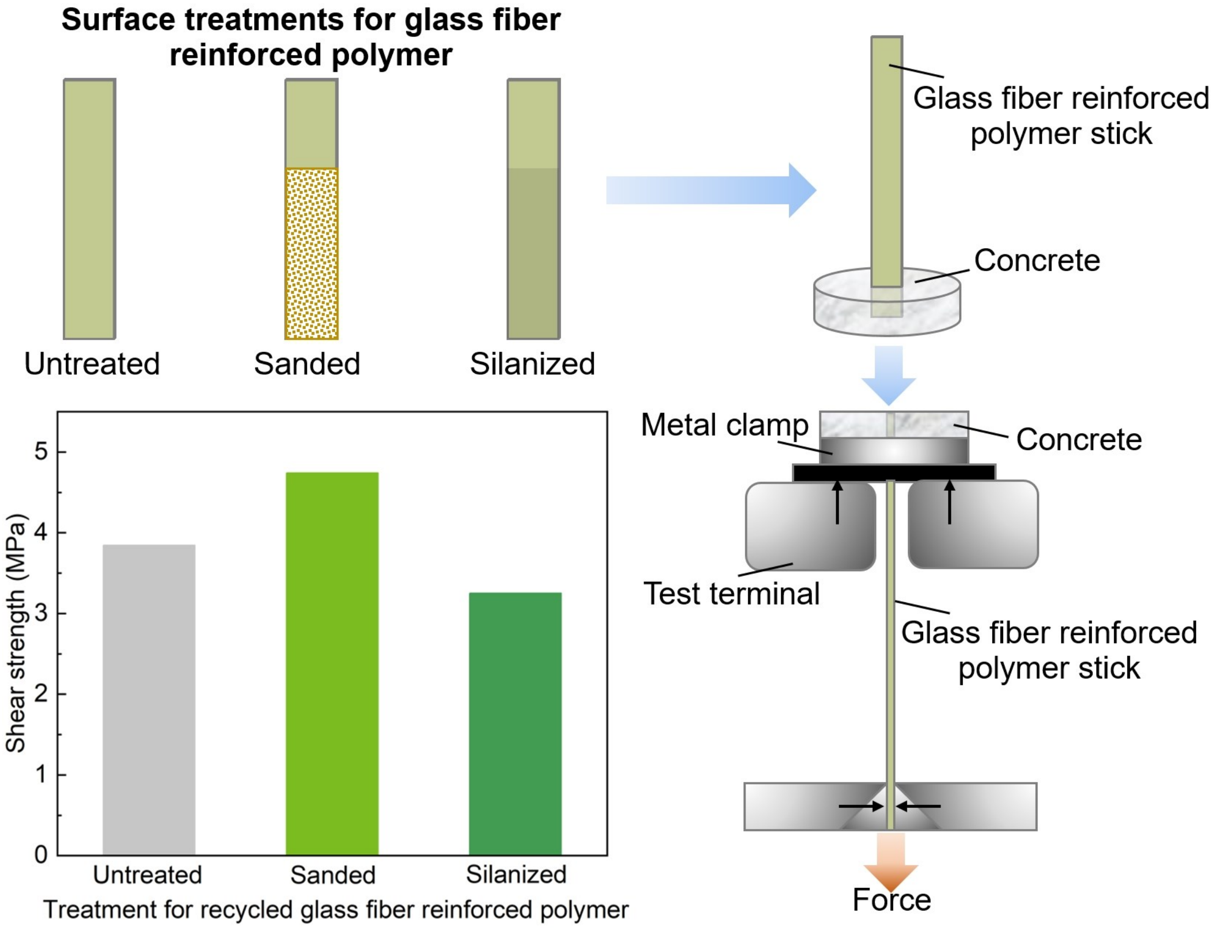

Fig. 17. The glass fiber-reinforced polymer strips are sanded and silanized to modify the surfaces. The untreated and modified strips are embedded in the concrete for pullout tests. The results of the pullout experiments show that the sand adhered to the surfaces of the strips improves the surface area and enhances the interfacial shear strength. In contrast, the silanization treatment generates a hydrophobic silicone resin layer between the concrete and the glass fiber-reinforced polymer strips, resulting in a decline in bond behavior. Adapted from Kimm *et al.* (2020).

Overall, we observed that the reactive elements in the glass fiber-reinforced polymer dust are harmful to the strength of cement composites, which can be mitigated by alkaline solution treatment. Increasing the roughness of the glass fiber-reinforced polymer strips contributed to improved bond behavior with cement-based matrices. Numerous researchers have utilized waste glass fiber-reinforced polymer in cement-based composites in various forms in previous studies. However, there is a substantial lack of information regarding the durability of recycled glass fibers in alkaline cementitious composites and the interfacial bond behavior between glass fiber-reinforced polymer and the surrounding matrices. In an effort to enhance the efficiency of load transfer and increase the added value of glass fiber-reinforced polymer as reinforcements, comprehensive investigations into surface treatments are warranted in future studies.

5.5. Innovative application of wind blade in contemporary construction practice

The end-of-service-life wind blades can be repurposed or re-designed instead of being discarded in landfills. Due to their graceful curves and substantial internal spaces, they can be easily cut and processed for various applications.

Several research projects and industry initiatives have focused on reusing wind turbine blades. For instance, Superuse Studios designed a large, circular, and sustainable playground of 1200 m^2 named Playground Wikado, utilizing five blades for this purpose (Martinez-Marquez *et al.* 2022). This project successfully reduced carbon emissions by approximately 90% compared to a conventional playground (Martinez-Marquez *et al.* 2022). However, safety concerns must be addressed, as the sharper parts of rotor blades and potentially hazardous chemicals from glass fibers and coatings could pose risks to users (Medici *et al.* 2020). Superuse Studios has also implemented playgrounds and seating furniture projects in Terneuzen (Karavida and Peponi 2023). Another Re-Wind project by Superuse Studios involves creating ergonomic urban furniture from nine blades at Willemsplein, Rotterdam (Martinez-Marquez *et al.* 2022). Furthermore, waste wind blades have been repurposed into a bicycle shelter in Aalborg Harbor, Denmark, taking advantage of their substantial hollow space (Martinez-Marquez *et al.* 2022). GP Renewables Group has achieved sustainable design and application of end-of-life rotor blades, resulting in various captivating architectural structures, including sun loungers, pedestrian bridges, and benches (Karavida and Peponi 2023).

Based on construction cases, we found that repurposing wind turbine blades as infrastructure through architectural design and simple processing in urban construction is appealing. This approach has low costs and provides aesthetic value and urban furniture functionality. However, design and certification guidelines or standards for reused glass fiber-reinforced polymers are lacking. Scaling up the application of these composites is also challenging, as it depends on social acceptance and the intended reuse purposes (Joustra *et al.* 2021).

6. Utilizing alternative recycled fiber reinforced polymer materials in civil engineering applications

So far, the application of waste fiber-reinforced polymer in construction materials has predominantly focused on carbon fiber-reinforced polymer and glass fiber-reinforced polymer, with limited attention given to other fiber-reinforced polymer scraps. Only a few scientists have made efforts to reuse basalt fiber-reinforced polymer and high-density polyethylene plastic. Dong *et al.* (2019) employed rod-shaped basalt fiber-reinforced polymer wastes to reinforce seawater sea-sand concrete by replacing 5-20 vol.% of coarse aggregate. They observed that the diameter of basalt fiber-reinforced polymer played a minor role in compressive strength, while a high replacement ratio of 20% significantly improved compression behavior by up to 16%, mainly due to moisture absorption by basalt fiber-reinforced polymer bars. The addition of recycled basalt fiber-reinforced polymer resulted in a slight decrease in flexural strength but a noticeable increase in splitting tensile strength by 2-32% (Dong *et al.* 2019). Kowalik and Ubysz (2021) subjected basalt bars to treatment at 250°C to decompose the polymer resin, followed by a shredding process. Adding the obtained recycled basalt fibers to concrete at a 1% dosage yielded comparable strength with only a minor decrease. Additionally, high-density polyethylene plastic waste strips have been tentatively applied in pavements, demonstrating their beneficial effect in reducing the thickness of flexible pavement and improving the California Bearing Ratio and subgrade modulus (Jha *et al.* 2014).

This suggests promising prospects for the use of high density polyethylene waste as soil reinforcement in sub-base and highway-base applications, contributing to resource circularity and enhancing economic value.

In summary, we found that despite the compromised mechanical properties observed in some cases when using basalt fiber-reinforced polymer in cement-based materials, recycled basalt fiber-reinforced polymer bars showed the potential to enhance the mechanical behavior of concrete. The use of high-density polyethylene plastic also appears promising in road construction. Future studies can investigate the influence of shape factor, content, and surface treatment of fiber-reinforced polymer reinforcements on the properties of various construction materials.

7. Perspective

7.1. Recycled carbon fiber and recycled glass fiber enhanced three dimensional concrete printing

The integration of automation into three-dimensional concrete printing technology has witnessed rapid development in recent years; see Fig. 18. This technology enables the manufacturing of complex structures with free-form designs (Paolini *et al.* 2019) while significantly reducing the need for formwork and manual labor (Tay *et al.* 2017), ultimately enhancing construction efficiency (Weng *et al.* 2020). Previous studies have reported that three-dimensional concrete printing technology can lead to a reduction of 50-70% in manufacturing time, 50-80% in labor costs, and 30-60% in construction waste generation (Zhang *et al.* 2019). Various production methods for three-dimensional concrete printing have been employed, including shotcrete (Kloft *et al.* 2020), particle-bed processes (Yu *et al.* 2022), and extrusion-based layer deposition (Paolini *et al.* 2019), with material extrusion being the most commonly used approach. To achieve continuous material extrusion, it is crucial to consider the fresh-state properties of cementitious materials, including extrudability, pumpability, and buildability (Mohan *et al.* 2021).

The incorporation of fiber reinforcement in three-dimensional concrete printing has garnered increasing interest with the goal of enhancing the compressive, flexural, and tensile strengths, as well as the ductility of concrete (Paolini *et al.* 2019; Liu *et al.* 2023). Recent research has involved three-dimensional printing of cementitious mortar incorporated with short recycled carbon fibers with a length below 150 μm, and it reported an optimal dosage of 1.5 vol.% that improved compressive and flexural strength while ensuring feasible buildability and extrudability (Liu *et al.* 2023). It's worth noting that, for virgin carbon fiber-reinforced cement paste, some fiber blockage has been reported during the extrusion process through a 2-4 mm nozzle (Rutzen *et al.* 2021). This aspect deserves more attention in future studies of recycled carbon fiber-augmented three-dimensional printing. Further research is anticipated in the use of recycled carbon fibers or recycled glass fibers in the three-dimensional printing of cementitious materials, particularly in concrete composites.

7.2. Self sensing cement composite

The field of structural health monitoring in civil engineering has experienced rapid development in recent decades. Structural health monitoring techniques enable the early detection of structural failures, leading to reduced maintenance costs and enhanced structural safety (Belli *et al.* 2023). An emerging and promising option in this realm is the use of smart cement-based composites with self-sensing capabilities, allowing for real-time monitoring of their own conditions, including damage, temperature, strain, and stress (Chung 2004a). Researchers have achieved this by incorporating conductive materials into the cementitious matrix, which enhances conductivity through tunneling and contacting conduction phenomena (Han *et al.* 2015).

Carbon fiber-reinforced composites exhibit piezo-resistivity, primarily due to slight fiber pull-out during crack formation, resulting in increased electrical resistivity at the carbon fiber-cement interface (Wen and Chung 2006). The orientation of fibers under strain also influences conductivity (Taya *et al.* 1998). In studies by Belli *et al.*, 0.2 vol.% of carbon fiber wastes, along with used foundry sand or graphene nanoplatelet fillers, were incorporated into the mortar, demonstrating high piezo-resistivity while maintaining comparable mechanical properties (Belli *et al.* 2018; Belli *et al.* 2023). Additionally, the use of pyrolyzed carbon fibers in concrete has been shown to enhance the signal-to-noise ratio and piezo-resistive response (Segura *et al.* 2019). The utilization of recycled carbon fibers holds significant promise for the development of smart, self-sensing cement-based materials. This approach not only reduces construction costs by substituting expensive carbonaceous materials but also achieves acceptable mechanical performance.

7.3. Self-heating and energy harvesting cement composites

The self-heating effect of cement composites is advantageous for building heating and de-icing applications, including bridges, airport runways, and highways (Chung 2004b), as shown in Fig. 18. To facilitate resistance heating, structural elements must possess suitable electrical resistivity to ensure that the current remains within the desired range (Chung 2004b). Recent research has demonstrated the practical self-heating performance of concrete containing recycled carbon fiber, achieving temperature increases of 2-4°C above ambient levels after 30 min of voltage application (Faneca *et al.* 2020). Given the relatively lower cost of recycled carbon fiber compared to virgin carbon fibers and their excellent conductivity, incorporating recycled carbon fiber as additives in self-heating cement materials holds significant commercial and research potential.

In contrast to the self-heating cement, energy-harvesting cement composites allow for the conversion of thermal energy into electrical energy, rather than releasing thermal energy into the environment (Singh *et al.* 2021); see Fig. 18. These thermoelectric-based cement composites rely on the Seebeck effect, where charge carriers move from areas of high temperature to low temperature, generating a voltage difference (Chung 2000). Consequently, when a temperature difference exists between the outer and inner surfaces of cementitious composites, energy can be harvested (Singh *et al.* 2021). Previous research has shown that adding 0.5-1.0 wt.% of short carbon fibers to cement paste can enhance the reversibility and linearity of the Seebeck effect in the composite (Wen and Chung 1999). Wei *et al.* (2014) reported that cement paste containing 1 wt.% carbon fibers achieved energy harvesting of up to 8.4×10^{-6} J/m^2 during 420 min of solar irradiation, raising the sample surface temperature rapidly to 68°C. These carbon fiber-reinforced cement composites hold great promise for capturing outdoor urban energy during the summer. Incorporating cost-efficient recycled carbon fiber can reduce the overall cost of these thermoelectric-based cement composites, increasing their commercial viability.

7.4. Electromagnetic shielding

The electromagnetic wave shielding can be interpreted as the absorption or reflection of electromagnetic waves by applying conductive materials (Hemming 1992), as shown in Fig. 18. This technology has received increasing attention in the fields of construction, telecommunications, electronics, and the military, with the aim of providing protection from electromagnetic interference, preventing eavesdropping, reducing false echo, and contributing to the development of stealth technology (Nam *et al.* 2018). Furthermore, the electromagnetic shielding can be used for electromagnetic pulse protection in the event of a high-altitude nuclear explosion (Chung 2012). Flexible graphite has been reported to possess high electromagnetic interference shielding effectiveness, reaching up to 130 dB at 1 GHz (Luo and Chung 1996). Other conductive carbonaceous materials, including carbon fibers (Chiou *et al.* 1989; Wang *et al.* 2008) and carbon nanofibers (Fu and Chung 1996), have been shown to be effective as additives in cementitious materials for electromagnetic interference shielding. Cement paste containing 1 vol.% carbon fibers could provide up to 30 dB at 1 GHz of shielding effectiveness, with polyacrylonitrile-based carbon fibers exhibiting better shielding behavior than pitch-based carbon fibers (Muthusamy and Chung 2010). The use of recycled carbon fibers for electromagnetic interference shielding shielding has not been investigated so far but holds great promise, considering environmental and economic aspects.

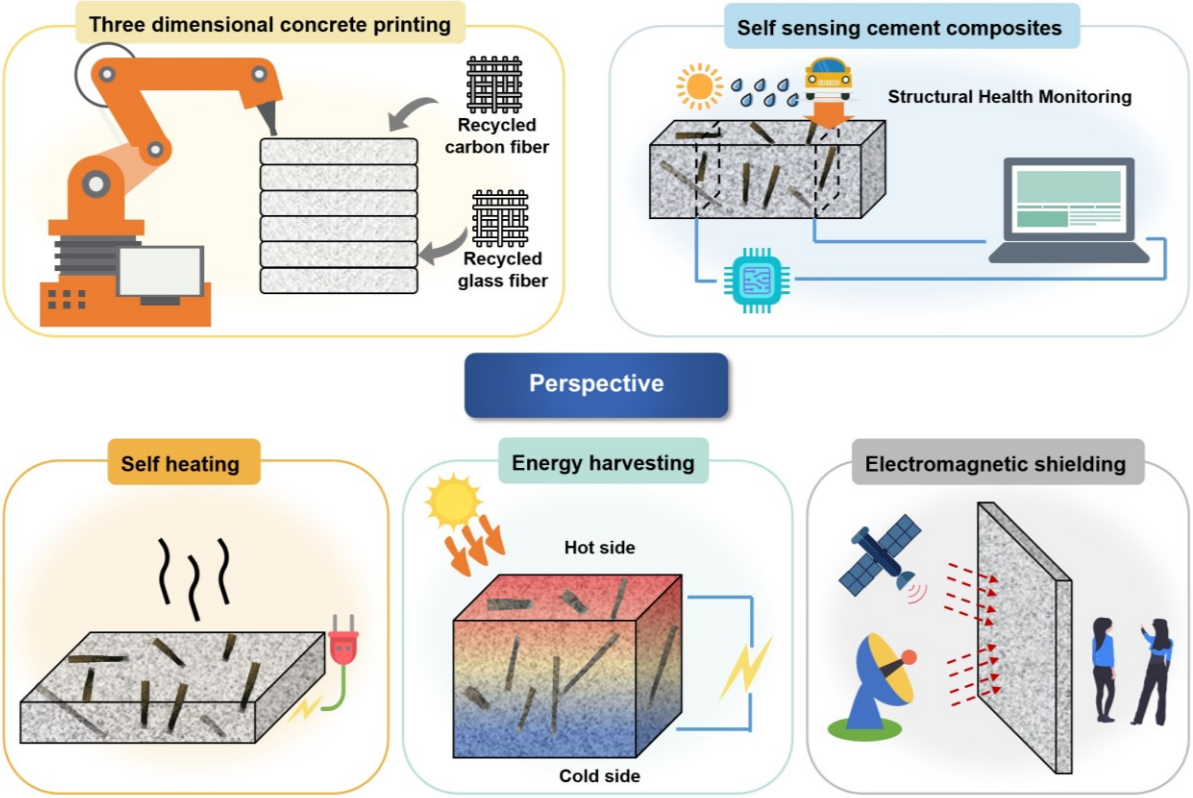

Fig. 18. The use of recycled fibers from recycled fiber-reinforced polymers holds great promise in the field of smart construction. Recycled carbon fibers and recycled glass fibers can be used to enhance three-dimensional concrete printing. Recycled carbon fibers can also be utilized to fabricate self-sensing cement, self-heating cement, and energy-harvesting cement. Adding recycled carbon fibers to the cement matrices can provide the function of electromagnetic interference shielding.

8. Conclusion

Based on Market Report of Industrievereinigung Verstärkte Kunststoffe e. V (Witten and Mathes 2024), the global composites market reached 13 million tons in 2023. However, the rapid increase in demand for fiber-reinforced polymer incurs substantial amounts of discarded composites. Common disposal methods, including landfills and incineration, can produce hazardous substances and threaten the ecosystem. Consequently, the application of fiber-reinforced polymer composites, especially carbon fiber-reinforced polymer and glass fiber-reinforced polymer wastes, in the field of the construction industry appears to be a win-win strategy, considering both economic and environmental aspects. This article provides an overview of the use of discarded fiber-reinforced polymer wastes obtained from mechanical, thermal, and chemical recycling processes in cement-based and asphalt-based composites. Given that fiber-reinforced polymer reinforcements take various forms, such as powder, blocks, fiber-like shapes, rebar, and strips, and they possess diverse surface states and resin contents, the existing studies are categorized according to their properties, along with an introduction to the waste management hierarchy. To our best knowledge, no study to date has comprehensively categorized the application routes based on the shapes and sources of recycled fibers or powder in construction materials.

Carbon powder wastes and carbon fiber-reinforced polymer blocks, obtained through mechanical processing of end-of-life carbon fiber-reinforced polymer composites, generally had a negative impact on the strength development of cement-based composites. On the other hand, the inclusion of needle-shaped recycled carbon fiber-reinforced polymer reinforcements showed a positive effect on the mechanical performance of cement composites, especially in terms of flexural properties. The addition of recycled carbon fiber obtained through conventional and microwave-assisted pyrolysis holds great promise for improving the mechanical properties of cement-based materials under normal and elevated temperatures. However, due to the hydrophobic nature of carbon fiber surfaces and their poor bonding with mineral-based composites, surface modification treatments are essential for enhancing the load transfer between recycled carbon fiber or recycled carbon fiber-reinforced polymer and the matrices.

The use of glass fiber-reinforced polymer coarse aggregates or glass fiber-reinforced polymer powder, which consists mostly of resin and glass fibers, appears to have a detrimental effect on the mechanical properties of cementitious composites. However, the strength loss in glass fiber-reinforced polymer powder-reinforced cement composites can be partially mitigated by using superplasticizers, oven curing, or carefully selecting particle sizes. Enhancing the reinforcing efficiency of glass fiber-reinforced polymer additives is promising through special shaping of the composites or by extracting the glass fibers from the polymer matrices through milling or grinding. It's important to note that reducing the resin content in recycled glass fiber-reinforced polymer can improve the mechanical strength of matrices. Additionally, the length-to-width ratio of recycled glass fibers strongly influences the properties of cement composites, and further systematic investigation is needed in this area. To better utilize glass fiber-reinforced polymer's reinforcing properties, surface modification can be applied to glass fiber-reinforced polymer powder or needle-shaped composites. Furthermore, recent reports have demonstrated that recycled wind turbine blades can be easily repurposed into playground equipment or city furniture, making full use of their graceful shape and large internal space.

The review has highlighted several research gaps that should be addressed in the near future. There is a need for further investigation into the impact of mechanically recycled carbon fiber-reinforced polymer and recycled carbon fiber obtained from pyrolysis on the durability of cement matrices. Additionally, current research on recycled carbon fiber has primarily focused on Portland cement-based matrices, with limited information on their use in Mg-rich cement-based, asphalt-based, or alkali-activated composites.

Exploring the potential of surface modification techniques, such as electrochemical treatments (Li *et al.* 2020; Li *et al.* 2022b; Li *et al.* 2022e), oxidation (Li *et al.* 2019), and plasma (Li *et al.* 2021a), to improve the interfacial interaction of recycled carbon fiber with mineral matrices should be a focus for future research efforts.

Indeed, there is room for more research and attention to be directed towards the carbon fiber and glass fiber wastes generated in the production of fiber-reinforced plastics. These fibers, when not impregnated with resin, still possess valuable properties, yet research in this area is currently lacking compared to other forms of recycling. The use of glass fibers from pyrolysis has been limited due to the significant strength loss during thermal processing. However, the development of glass fiber strength regeneration approaches using acid or alkaline solutions offers an attractive option to enhance the value and broaden the applications of thermally-degraded glass fibers in the construction industry. Furthermore, emerging hybrid approaches like microwave-assisted chemical recycling are energy-efficient and eco-friendly options for recycling, and the recovered fibers can find applications as reinforcement in mineral-based or asphalt-based composites. These avenues represent promising opportunities for further research and development.

Efficient recycling of end-of-service-life fiber-reinforced polymer materials in the construction field can be achieved through the establishment of a well-defined waste management hierarchy. This hierarchy should help optimize the selection of recycled carbon fiber-reinforced polymer and glass fiber-reinforced polymer wastes based on practical demand and upgrade the value of the fibers. To implement such a hierarchy effectively, several steps can be taken: 1) Sieving and Sorting: After the recycling process of discarded fiber-reinforced polymer composites, sieving and sorting operations should be carried out. These operations can be tailored to separate materials based on factors such as fiber fraction of the powder, length-width ratio of fiber-reinforced polymer fiber, recycled fiber strength, and surface properties. Image analysis technology can be employed to assist in the classification process. 2) Standardization: The incorporation ratio and shape of recycled fiber-reinforced polymer materials should not solely rely on empirical knowledge but should also be standardized. Developing clear standards and guidelines for the use of recycled fiber-reinforced polymer materials will make it easier for government decision-makers to promote their use in construction projects. By implementing these steps, the recycling of fiber-reinforced polymer materials can become more efficient, environmentally friendly, and economically viable, contributing to a sustainable construction industry to meet the net-zero emission target globally.

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References

Abdollahnejad Z, Mastali M, Mastali M, Dalvand A (2017) Comparative study on the effects of recycled glass–fiber on drying shrinkage rate and mechanical properties of the self-compacting mortar and fly ash–slag geopolymer mortar. *Journal of Materials in Civil Engineering* **29**(8): 04017076. https://doi.org/10.1061/(ASCE)MT.1943-5533.0001918

Aflaki Samani M, Jabbari Lak S (2019) Experimental investigation on the mechanical properties of recycled aggregate concrete reinforced by waste carbon fibers. *International Journal of Environmental Science and Technology* **16**(8): 4519-4530. https://doi.org/10.1007/s13762-018-1855-z

Akbar A, Kodur V, Liew K (2021) Microstructural changes and mechanical performance of cement composites reinforced with recycled carbon fibers. *Cement and Concrete Composites* **121**: 104069. https://doi.org/10.1016/j.cemconcomp.2021.104069

Akbar A, Liew K (2020a) Assessing recycling potential of carbon fiber reinforced plastic waste in production of eco-efficient cement-based materials. *Journal of Cleaner Production* **274**: 123001. https://doi.org/10.1016/j.jclepro.2020.123001

Akbar A, Liew K (2020b) Influence of elevated temperature on the microstructure and mechanical performance of cement composites reinforced with recycled carbon fibers. *Composites Part B: Engineering* **198**: 108245. https://doi.org/10.1016/j.compositesb.2020.108245

Åkesson D, Foltynowicz Z, Christeen J, Skrifvars M (2012) Microwave pyrolysis as a method of recycling glass fibre from used blades of wind turbines. *Journal of Reinforced Plastics and Composites* **31**(17): 1136-1142. https://doi.org/10.1177/0731684412453512

Aslanova M (1960) The effect of different factors on the mechanical properties of glass fibers. *Glass and Ceramics* **17**(11): 563-569. https://doi.org/10.1007/BF00670102

Asokan P, Osmani M, Price AD (2009) Assessing the recycling potential of glass fibre reinforced plastic waste in concrete and cement composites. *Journal of Cleaner Production* **17**(9): 821-829. https://doi.org/10.1016/j.jclepro.2008.12.004

Asokan P, Osmani M, Price AD (2010) Improvement of the mechanical properties of glass fibre reinforced plastic waste powder filled concrete. *Construction and Building Materials* **24**(4): 448-460. https://doi.org/10.1016/j.conbuildmat.2009.10.017

Baena-Moreno FM, Leventaki E, Riddell A, Wojtasz-Mucha J, Bernin D (2023) Effluents and residues from industrial sites for carbon dioxide capture: a review. *Environmental Chemistry Letters* **21**(1): 319-337. https://doi.org/10.1007/s10311-022-01513-x

Balea A, Monte MC, Blanco A, Negro C (2021) Recycled fibers for sustainable hybrid fiber cement based material: A review. *Materials* **14**(9): 2408. https://doi.org/10.3390/ma14092408

Bashir S, Yang L, Anderson R, Tang P, Liggat J, Thomason J (2017) A simple chemical approach to regenerating the strength of thermally damaged glass fibre. *Composites Part A: Applied Science and Manufacturing* **102**: 76-87. https://doi.org/10.1016/j.compositesa.2017.07.023

Baturkin D, Hisseine OA, Masmoudi R, Tagnit-Hamou A, Massicotte L (2021) Valorization of recycled FRP materials from wind turbine blades in concrete. *Resources, Conservation and Recycling* **174**: 105807. https://doi.org/10.1016/j.resconrec.2021.105807

Belli A, Mobili A, Bellezze T, Cachim PB, Tittarelli F (2023) Commercial and recycled carbon-based fillers and fibers for self-sensing cement-based composites: Comparison of mechanical strength, durability, and piezoresistive behavior. *Journal of Building Engineering* **73**: 106836. https://doi.org/10.1016/j.jobe.2023.106836

Belli A, Mobili A, Bellezze T, Tittarelli F (2020) Commercial and recycled carbon/steel fibers for fiber-reinforced cement mortars with high electrical conductivity. *Cement and Concrete Composites* **109**: 103569. https://doi.org/10.1016/j.cemconcomp.2020.103569

Belli A, Mobili A, Bellezze T, Tittarelli F, Cachim P (2018) Evaluating the self-sensing ability of cement mortars manufactured with graphene nanoplatelets, virgin or recycled carbon fibers through piezoresistivity tests. *Sustainability* **10**(11): 4013. https://doi.org/10.3390/su10114013

Cai G, Wada M, Ohsawa I, Kitaoka S, Takahashi J (2020) Tensile properties of recycled carbon fibers subjected to superheated steam treatment under various conditions. *Composites Part A: Applied Science and Manufacturing* **133**: 105869. https://doi.org/10.1016/j.compositesa.2020.105869

Castro ACM, Carvalho JP, Ribeiro MC, Meixedo JP, Silva FJ, Fiúza A, Dinis ML (2014) An integrated recycling approach for GFRP pultrusion wastes: recycling and reuse assessment into new composite materials using Fuzzy Boolean Nets. *Journal of Cleaner Production* **66**: 420-430. https://doi.org/10.1016/j.jclepro.2013.10.030

Castro AM, Ribeiro M, Santos J, Meixedo JP, Silva FJ, Fiúza A, Dinis M, Alvim MR (2013) Sustainable waste recycling solution for the glass fibre reinforced polymer composite materials industry. *Construction and Building Materials* **45**: 87-94. https://doi.org/10.1016/j.conbuildmat.2013.03.092

Cembureau (2020) Activity report, Cembureau-The European Cement Association. (Brussels) https://cembureau.eu/media/m2ugw54y/cembureau-2020-activity-report.pdf

Chen L, Zhang Y, Chen Z, Dong Y, Jiang Y, Hua J, Liu Y, Osman AI, Farghali M, Huang L (2024) Biomaterials technology and policies in the building sector: a review. *Environmental Chemistry Letters*: 1-36. https://doi.org/10.1007/s10311-023-01689-w

Chen P-y, Pei C, Zhu J-H, Su M, Xing F (2019) Sustainable recycling of intact carbon fibres from end-of-service-life composites. *Green Chemistry* **21**(17): 4757-4768. https://doi.org/10.1039/C9GC01847F

Cheng C-S, Xu Y-B, Xiao C-Y, Fu B, Gao R-F, Kuang Y-D (2023) Behavior of confined concrete with recycled glass fiber-reinforced polymer needles as coarse aggregates under axial compression. *Journal of Building Engineering* **71**: 106453. https://doi.org/10.1016/j.jobe.2023.106453

Chiou J-M, Zheng Q, Chung D (1989) Electromagnetic interference shielding by carbon fibre reinforced cement. *Composites* **20**(4): 379-381. https://doi.org/10.1016/0010-4361(89)90663-0

Chung D (2000) Cement reinforced with short carbon fibers: a multifunctional material. *Composites Part B: Engineering* **31**(6-7): 511-526. https://doi.org/10.1016/S1359-8368(99)00071-2

Chung D (2004a) Electrically conductive cement-based materials. *Advances in cement research* **16**(4): 167-176. https://doi.org/10.1680/adcr.2004.16.4.167

Chung D (2004b) Self-heating structural materials. *Smart materials and structures* **13**(3): 562. https://doi.org/10.1088/0964-1726/13/3/015

Chung D (2012) Carbon materials for structural self-sensing, electromagnetic shielding and thermal interfacing. *Carbon* **50**(9): 3342-3353. https://doi.org/10.1016/j.carbon.2012.01.031

Clark E, Bleszynski M, Valdez F, Kumosa M (2020) Recycling carbon and glass fiber polymer matrix composite waste into cementitious materials. *Resources, Conservation and Recycling* **155**: 104659. https://doi.org/10.1016/j.resconrec.2019.104659

Correia JR, Almeida NM, Figueira JR (2011) Recycling of FRP composites: reusing fine GFRP waste in concrete mixtures. *Journal of Cleaner Production* **19**(15): 1745-1753. https://doi.org/10.1016/j.jclepro.2011.05.018

Criado M, García-Díaz I, Bastidas J, Alguacil FJ, López F, Monticelli C (2014) Effect of recycled glass fiber on the corrosion behavior of reinforced mortar. *Construction and Building Materials* **64**: 261-269. https://doi.org/10.1016/j.conbuildmat.2014.04.049

Dang W, Kubouchi M, Yamamoto S, Sembokuya H, Tsuda K (2002) An approach to chemical recycling of epoxy resin cured with amine using nitric acid. *Polymer* **43**(10): 2953-2958. https://doi.org/10.1016/S0032-3861(02)00100-3

Danish A, Mosaberpanah MA, Salim MU, Amran M, Fediuk R, Ozbakkaloglu T, Rashid MF (2022) Utilization of recycled carbon fiber reinforced polymer in cementitious composites: A critical review. *Journal of Building Engineering* **53**: 104583. https://doi.org/10.1016/j.jobe.2022.104583

de Souza Abreu F, Ribeiro CC, da Silva Pinto JD, Nsumbu TM, Buono VTL (2020) Influence of adding discontinuous and dispersed carbon fiber waste on concrete performance. *Journal of Cleaner Production* **273**: 122920. https://doi.org/10.1016/j.jclepro.2020.122920

Dehghan A, Peterson K, Shvarzman A (2017) Recycled glass fiber reinforced polymer additions to Portland cement concrete. *Construction and Building Materials* **146**: 238-250. https://doi.org/10.1016/j.conbuildmat.2017.04.011

Dejhala R, Legović D (2018) Disposal of worn out fiberglass recreational boats. *Pomorski zbornik*(2): 143-153. https://hrcak.srce.hr/199120

Deng J, Xu L, Zhang L, Peng J, Guo S, Liu J, Koppala S (2019) Recycling of carbon fibers from CFRP waste by microwave thermolysis. *Processes* **7**(4): 207. https://doi.org/10.3390/pr7040207

Dixit MK, Fernández-Solís JL, Lavy S, Culp CH (2010) Identification of parameters for embodied energy measurement: A literature review. *Energy and buildings* **42**(8): 1238-1247. https://doi.org/10.1016/j.enbuild.2010.02.016

Dong Z, Wu G, Zhu H (2019) Mechanical properties of seawater sea-sand concrete reinforced with discrete BFRP-Needles. *Construction and Building Materials* **206**: 432-441. https://doi.org/10.1016/j.conbuildmat.2019.02.029

Dorigato A (2021) Recycling of thermosetting composites for wind blade application. *Advanced Industrial and Engineering Polymer Research* **4**(2): 116-132. https://doi.org/10.1016/j.aiepr.2021.02.002

Faneca G, Ikumi T, Torrents J, Aguado A, Segura I (2020) Conductive concrete made from recycled carbon fibres for self-heating and de-icing applications in urban furniture. *Materiales de Construcción* **70**(339): e223-e223. https://doi.org/10.3989/mc.2020.17019

Faneca G, Segura I, Torrents J, Aguado A (2018) Development of conductive cementitious materials using recycled carbon fibres. *Cement and Concrete Composites* **92**: 135-144. https://doi.org/10.1016/j.cemconcomp.2018.06.009

Feraboli P, Kawakami H, Wade B, Gasco F, DeOto L, Masini A (2012) Recyclability and reutilization of carbon fiber fabric/epoxy composites. *Journal of Composite Materials* **46**(12): 1459-1473. https://doi.org/10.1177/0021998311420604

Fonte R, Xydis G (2021) Wind turbine blade recycling: An evaluation of the European market potential for recycled composite materials. *Journal of Environmental Management* **287**: 112269. https://doi.org/10.1016/j.jenvman.2021.112269

Fu B, Liu K, Chen J, Teng J (2021) Concrete reinforced with macro fibres recycled from waste GFRP. *Construction and Building Materials* **310**: 125063. https://doi.org/10.1016/j.conbuildmat.2021.125063

Fu X, Chung D (1996) Submicron carbon filament cement-matrix composites for electromagnetic interference shielding. *Cement and Concrete Research* **26**(10): 1467-1472. https://doi.org/10.1016/0008-8846(96)00146-9

Gao W, Ariyama T, Ojima T, Meier A (2001) Energy impacts of recycling disassembly material in residential buildings. *Energy and Buildings* **33**(6): 553-562. https://doi.org/10.1016/S0378-7788(00)00096-7

García D, Vegas I, Cacho I (2014) Mechanical recycling of GFRP waste as short-fiber reinforcements in microconcrete. *Construction and Building Materials* **64**: 293-300. https://doi.org/10.1016/j.conbuildmat.2014.02.068

Gharfalkar M, Court R, Campbell C, Ali Z, Hillier G (2015) Analysis of waste hierarchy in the European waste directive 2008/98/EC. *Waste management* **39**: 305-313. https://doi.org/10.1016/j.wasman.2015.02.007

Grzanka R (2014) The greening of carbon fibre. *Reinforced Plastics* **58**(3): 44-46. https://doi.org/10.1016/S0034-3617(14)70143-2

Guozhan J, Stephen J. P (2016) Structure–property relationship of recycled carbon fibres revealed by pyrolysis recycling process. *Journal of materials science* **51**: 1949–1958.

Haider MM, Nassiri S, Englund K, Li H, Chen Z (2021) Exploratory study of flexural performance of mechanically recycled glass fiber reinforced polymer shreds as reinforcement in cement mortar. *Transportation Research Record* **2675**(10): 1254-1267. https://doi.org/10.1177/03611981211015246

Halliwell S (2010) FRPs—The environmental agenda. *Advances in Structural Engineering* **13**(5): 783-791. https://doi.org/10.1260/1369-4332.13.5.783

Han B, Ding S, Yu X (2015) Intrinsic self-sensing concrete and structures: A review. *Measurement* **59**: 110-128. https://doi.org/10.1016/j.measurement.2014.09.048

He H, Yang F, Ge Y, Ran L, Peng K, Yi M (2019) Effect of crystallinity of PAN-based carbon fiber surfaces on the formation characteristics of silicon carbide coating. *Materials Research Express* **6**(8): 085603. https://doi.org/10.1088/2053-1591/ab198c

Hemming LH (1992) 'Architectural electromagnetic shielding handbook: a design and specification guide.' (Wiley-IEEE Press) https://doi.org/10.1109/9780470544181

Hensher DA (2016) 'Fiber-reinforced-plastic (FRP) reinforcement for concrete structures: properties and applications.' (Elsevier) https://doi.org/10.1016/C2009-0-09136-3

Ho H-J, Iizuka A, Lee C-H, Chen W-S (2023) Mineral carbonation using alkaline waste and byproducts to reduce CO2 emissions in Taiwan. *Environmental Chemistry Letters* **21**(2): 865-884. https://doi.org/10.1007/s10311-022-01518-6

Hyde JR, Lester E, Kingman S, Pickering S, Wong KH (2006) Supercritical propanol, a possible route to composite carbon fibre recovery: a viability study. *Composites Part A: Applied Science and Manufacturing* **37**(11): 2171-2175. https://doi.org/10.1016/j.compositesa.2005.12.006

Jani HK, Kachhwaha SS, Nagababu G, Das A (2022) A brief review on recycling and reuse of wind turbine blade materials. *Materials Today: Proceedings*. https://doi.org/10.1016/j.matpr.2022.02.049

Jha J, Choudhary A, Gill K, Shukla SK (2014) Behavior of plastic waste fiber-reinforced industrial wastes in pavement applications. *International Journal of Geotechnical Engineering* **8**(3): 277-286. https://doi.org/10.1179/1939787914Y.0000000044

Joustra J, Flipsen B, Balkenende R (2021) Structural reuse of high end composite products: A design case study on wind turbine blades. *Resources, Conservation and Recycling* **167**: 105393. https://doi.org/10.1016/j.resconrec.2020.105393

Kao C, Ghita O, Hallam K, Heard P, Evans K (2012) Mechanical studies of single glass fibres recycled from hydrolysis process using sub-critical water. *Composites Part A: Applied Science and Manufacturing* **43**(3): 398-406. https://doi.org/10.1016/j.compositesa.2011.11.011

Karavida S, Peponi A (2023) Wind Turbine Blade Waste Circularity Coupled with Urban Regeneration: A Conceptual Framework. *Energies* **16**(3): 1464. https://doi.org/10.3390/en16031464

Kim K-W, Lee H-M, An J-H, Chung D-C, An K-H, Kim B-J (2017) Recycling and characterization of carbon fibers from carbon fiber reinforced epoxy matrix composites by a novel super-heated-steam method. *Journal of Environmental Management* **203**: 872-879. https://doi.org/10.1016/j.jenvman.2017.05.015

Kimm M, Pico D, Gries T (2020) Investigation of surface modification and volume content of glass and carbon fibres from fibre reinforced polymer waste for reinforcing concrete. *Journal of Hazardous Materials* **390**: 121797. https://doi.org/10.1016/j.jhazmat.2019.121797

Kimm M, Sabir A, Gries T, Suwanpinij P Potential of using recycled carbon fibers as reinforcing material for fiber concrete. Proceedings of Fibre Reinforced Concrete: Improvements and Innovations: RILEM-fib International Symposium on FRC (BEFIB) in 2020 10, 2021. pp. 949-960. (Springer) https://doi.org/10.1007/978-3-030-58482-5_83

Kloft H, Krauss H-W, Hack N, Herrmann E, Neudecker S, Varady PA, Lowke D (2020) Influence of process parameters on the interlayer bond strength of concrete elements additive manufactured by Shotcrete 3D Printing (SC3DP). *Cement and Concrete Research* **134**: 106078. https://doi.org/10.1016/j.cemconres.2020.106078

Kowalik T, Ubysz A (2021) Waste basalt fibers as an alternative component of fiberconcrete. *Materials Today: Proceedings* **38**: 2055-2058. https://doi.org/10.1016/j.matpr.2020.10.140

Krauklis AE, Karl CW, Gagani AI, Jørgensen JK (2021) Composite material recycling technology—state-of-the-art and sustainable development for the 2020s. *Journal of Composites Science* **5**(1): 28. https://doi.org/10.3390/jcs5010028

Kulikova Y, Sliusar N, Korotaev V, Babich O, Larina V, Ivanova S (2022) Recovery and use of recycled carbon fibers from composites based on phenol-formaldehyde resins. *Recycling* **7**(2): 22. https://doi.org/10.3390/recycling7020022

Kumar S, Krishnan S (2020) Recycling of carbon fiber with epoxy composites by chemical recycling for future perspective: a review. *Chemical Papers* **74**(11): 3785-3807. https://doi.org/10.1007/s11696-020-01198-y

Lamba N, Raj R, Singh P (2023) Mechanical response of recycled carbon fiber reinforced polymer fibers in high-strength concrete. *Materials Today: Proceedings* **78**: 603-607. https://doi.org/10.1016/j.matpr.2022.11.477

Lan T, Wang B, Zhang J, Wei H, Liu X (2023) Utilization of waste wind turbine blades in performance improvement of asphalt mixture. *Frontiers in Materials* **10**: 1164693. https://doi.org/10.3389/fmats.2023.1164693

Lester E, Kingman S, Wong KH, Rudd C, Pickering S, Hilal N (2004) Microwave heating as a means for carbon fibre recovery from polymer composites: a technical feasibility study. *Materials Research Bulletin* **39**(10): 1549-1556. https://doi.org/10.1016/j.materresbull.2004.04.031

Li H, Liebscher M, Curosu I, Choudhury S, Hempel S, Davoodabadi M, Dinh TT, Yang J, Mechtcherine V (2020) Electrophoretic deposition of nano-silica onto carbon fiber surfaces for an improved bond strength with cementitious matrices. *Cement and Concrete Composites* **114**: 103777. https://doi.org/10.1016/j.cemconcomp.2020.103777

Li H, Liebscher M, Ly KH, Ly PV, Köberle T, Yang J, Fan Q, Yu M, Weidinger IM, Mechtcherine V (2022a) Effect of electrophoretic deposition of micro-quartz on the microstructural and mechanical properties of carbon fibers and their bond performance toward cement. *Journal of Materials Science* **57**(48): 21885–21900. https://doi.org/10.1007/s10853-022-07989-w

Li H, Liebscher M, Michel A, Quade A, Foest R, Mechtcherine V (2021a) Oxygen plasma modification of carbon fiber rovings for enhanced interaction toward mineral-based impregnation materials and concrete matrices. *Construction and Building Materials* **273**: 121950. https://doi.org/10.1016/j.conbuildmat.2020.121950

Li H, Liebscher M, Micusik M, Yang J, Sun B, Yin B, Yu M, Mechtcherine V (2022b) Role of pH value on electrophoretic deposition of nano-silica onto carbon fibers for a tailored bond behavior with cementitious matrices. *Applied Surface Science* **600**: 154000. https://doi.org/10.1016/j.apsusc.2022.154000

Li H, Liebscher M, Ranjbarian M, Hempel S, Tzounis L, Schröfl C, Mechtcherine V (2019) Electrochemical modification of carbon fiber yarns in cementitious pore solution for an enhanced interaction towards concrete matrices. *Applied Surface Science* **487**: 52-58. https://doi.org/10.1016/j.apsusc.2019.04.246

Li H, Liebscher M, Yang J, Davoodabadi M, Li L, Du Y, Yang B, Hempel S, Mechtcherine V (2022c) Electrochemical oxidation of recycled carbon fibers for an improved interaction toward alkali-activated composites. *Journal of Cleaner Production* **368**: 133093. https://doi.org/10.1016/j.jclepro.2022.133093

Li H, Liebscher M, Yang J, Zhang Y, Mechtcherine V (2024a) Influence of electrophoretic deposition of micro-or nanosized silica particles on the microstructure of carbon fibers and their bond behavior with cementitious matrices. *Materials and Structures* **57**(5): 107. https://doi.org/10.1617/s11527-024-02355-5

Li H, Liebscher M, Zhao D, Yin B, Du Y, Yang J, Kaliske M, Mechtcherine V (2022d) A review of carbon fiber surface modification methods for tailor-made bond behavior with cementitious matrices. *Progress in Materials Science* **132**: 101040. https://doi.org/10.1016/j.pmatsci.2022.101040

Li H, Schamel E, Liebscher M, Zhang Y, Fan Q, Schlachter H, Köberle T, Mechtcherine V, Wehnert G, Söthje D (2023a) Recycled carbon fibers in cement-based composites: Influence of epoxide matrix depolymerization degree on interfacial interactions. *Journal of Cleaner Production* **411**: 137235. https://doi.org/10.1016/j.jclepro.2023.137235

Li H, Wang L, Zhang Y, Yang J, Tsang DC, Mechtcherine V (2023b) Biochar for sustainable construction industry. In 'Current Developments in Biotechnology and Bioengineering'. pp. 63-95. (Elsevier) https://doi.org/10.1016/B978-0-323-91873-2.00015-7

Li H, Yang J, Wang L, Li L, Xia Y, Köberle T, Dong W, Zhang N, Yang B, Mechtcherine V (2023c) Multiscale assessment of performance of limestone calcined clay cement (LC3) reinforced with virgin and recycled carbon fibers. *Construction and Building Materials* **406**: 133228. https://doi.org/10.1016/j.conbuildmat.2023.133228

Li H, Yang J, Wang L, Zhang N, Wang Q, Mechtcherine V (2024b) Recycling of biomass combustion ash into SCMs and aggregates. In 'Treatment and Utilization of Combustion and Incineration Residues'. pp. 269-295. (Elsevier) https://doi.org/10.1016/B978-0-443-21536-0.00022-8

Li H, Zhao D, Liebscher M, Yin B, Yang J, Kaliske M, Mechtcherine V (2022e) An experimental and numerical study on the age depended bond-slip behavior between nano-silica modified carbon fibers and cementitious matrices. *Cement and Concrete Composites* **128**: 104416. https://doi.org/10.1016/j.cemconcomp.2022.104416

Li J, Xu P-L, Zhu Y-K, Ding J-P, Xue L-X, Wang Y-Z (2012) A promising strategy for chemical recycling of carbon fiber/thermoset composites: self-accelerating decomposition in a mild oxidative system. *Green Chemistry* **14**(12): 3260-3263. https://doi.org/10.1039/C2GC36294E

Li Y-F, Li J-Y, Ramanathan GK, Chang S-M, Shen M-Y, Tsai Y-K, Huang C-H (2021b) An experimental study on mechanical behaviors of carbon fiber and microwave-assisted pyrolysis recycled carbon fiber-reinforced concrete. *Sustainability* **13**(12): 6829. https://doi.org/10.3390/su13126829

Li Y-F, Li J-Y, Syu J-Y, Yang T-H, Chang S-M, Shen M-Y (2023d) Mechanical Behaviors of Microwave-Assisted Pyrolysis Recycled Carbon Fiber-Reinforced Concrete with Early-Strength Cement. *Materials* **16**(4): 1507. https://doi.org/10.3390/ma16041507

Lin J, Guo Z, Hong B, Xu J, Fan Z, Lu G, Wang D, Oeser M (2022) Using recycled waste glass fiber reinforced polymer (GFRP) as filler to improve the performance of asphalt mastics. *Journal of Cleaner Production* **336**: 130357. https://doi.org/10.1016/j.jclepro.2022.130357

Liu J, Tran P, Van VN, Gunasekara C, Setunge S (2023) 3D printing of cementitious mortar with milled recycled carbon fibres: Influences of filament offset on mechanical properties. *Cement and Concrete Composites* **142**: 105169. https://doi.org/10.1016/j.cemconcomp.2023.105169

Liu P, Barlow CY (2017) Wind turbine blade waste in 2050. *Waste Management* **62**: 229-240. https://doi.org/10.1016/j.wasman.2017.02.007

Liu T, Zhang M, Guo X, Liu C, Liu T, Xin J, Zhang J (2017) Mild chemical recycling of aerospace fiber/epoxy composite wastes and utilization of the decomposed resin. *Polymer Degradation and Stability* **139**: 20-27. https://doi.org/10.1016/j.polymdegradstab.2017.03.017

Liu Y, Liu J, Jiang Z, Tang T (2012) Chemical recycling of carbon fibre reinforced epoxy resin composites in subcritical water: synergistic effect of phenol and KOH on the decomposition efficiency. *Polymer degradation and stability* **97**(3): 214-220. https://doi.org/10.1016/j.polymdegradstab.2011.12.028

Liu Y, Shi J, Jin H, Guo L (2024) Chemical recycling methods for managing waste plastics: A review. *Environmental Chemistry Letters* **22**(1): 149-169. https://doi.org/10.1007/s10311-023-01664-5

Lopez-Urionabarrenechea A, Gastelu N, Jiménez-Suárez A, Prolongo SG, Serras-Malillos A, Acha E, Caballero BM (2021) Secondary raw materials from residual carbon fiber-reinforced composites by an upgraded pyrolysis process. *Polymers* **13**(19): 3408. https://doi.org/10.3390/polym13193408

López FA, Rodríguez O, Alguacil FJ, García-Díaz I, Centeno TA, García-Fierro JL, González C (2013) Recovery of carbon fibres by the thermolysis and gasification of waste prepreg. *Journal of analytical and applied pyrolysis* **104**: 675-683. https://doi.org/10.1016/j.jaap.2013.04.012

Luo X, Chung D (1996) Electromagnetic interference shielding reaching 130 dB using flexible graphite. *MRS Online Proceedings Library* **445**: 235-238. https://doi.org/10.1557/PROC-445-235

Ma G, Zhou B, Zhang M, Sanjayan J (2022) Understanding and eliminating of expansion caused by recycled glass fiber reinforced plastic powder in concrete. *Construction and Building Materials* **347**: 128542. https://doi.org/10.1016/j.conbuildmat.2022.128542

Manzi S, Lancellotti I, Masi G, Saccani A (2020) Alkali-activated binders from waste incinerator bottom ashes and metakaolin reinforced by recycled carbon fiber composites. *Frontiers in Materials* **7**: 583400. https://doi.org/10.3389/fmats.2020.583400

Mao L, Jiang H, Zhang W, Peng M, Hu L (2023) Occurrence of a leachable pentavalent chromium species in cement co-processed with tanning sludge. *Environmental Chemistry Letters* **21**(6): 3083-3087. https://doi.org/10.1007/s10311-023-01634-x

Martinez-Marquez D, Florin N, Hall W, Majewski P, Wang H, Stewart RA (2022) State-of-the-art review of product stewardship strategies for large composite wind turbine blades. *Resources, Conservation & Recycling Advances*: 200109. https://doi.org/10.1016/j.rcradv.2022.200109

Mastali M, Dalvand A (2016) The impact resistance and mechanical properties of self-compacting concrete reinforced with recycled CFRP pieces. *Composites Part B: Engineering* **92**: 360-376. https://doi.org/10.1016/j.compositesb.2016.01.046

Mastali M, Dalvand A, Sattarifard A (2016) The impact resistance and mechanical properties of reinforced self-compacting concrete with recycled glass fibre reinforced polymers. *Journal of Cleaner Production* **124**: 312-324. https://doi.org/10.1016/j.jclepro.2016.02.148

Mastali M, Dalvand A, Sattarifard A (2017) The impact resistance and mechanical properties of the reinforced self-compacting concrete incorporating recycled CFRP fiber with different lengths and dosages. *Composites Part B: Engineering* **112**: 74-92. https://doi.org/10.1016/j.compositesb.2016.12.029

Mastali M, Dalvand A, Sattarifard AR, Abdollahnejad Z (2018) Effect of different lengths and dosages of recycled glass fibres on the fresh and hardened properties of SCC. *Magazine of Concrete Research* **70**(22): 1175-1188. https://doi.org/10.1680/jmacr.17.00180

Mativenga PT, Shuaib NA, Howarth J, Pestalozzi F, Woidasky J (2016) High voltage fragmentation and mechanical recycling of glass fibre thermoset composite. *CIRP Annals* **65**(1): 45-48. https://doi.org/10.1016/j.cirp.2016.04.107

McConnell VP (2010) Launching the carbon fibre recycling industry. *Reinforced Plastics* **54**(2): 33-37. https://doi.org/10.1016/S0034-3617(10)70063-1

Medici P, van den Dobbelsteen A, Peck D (2020) Safety and health concerns for the users of a playground, built with reused rotor blades from a dismantled wind turbine. *Sustainability* **12**(9): 3626. https://doi.org/10.3390/su12093626

Meyer LO, Schulte K, Grove-Nielsen E (2009) CFRP-recycling following a pyrolysis route: process optimization and potentials. *Journal of composite materials* **43**(9): 1121-1132. https://doi.org/10.1177/0021998308097737

Mobili A, Cosoli G, Bellezze T, Revel GM, Tittarelli F (2022a) Use of gasification char and recycled carbon fibres for sustainable and durable low-resistivity cement-based composites. *Journal of Building Engineering* **50**: 104237. https://doi.org/10.1016/j.jobe.2022.104237

Mobili A, Cosoli G, Giulietti N, Chiariotti P, Bellezze T, Pandarese G, Revel G, Tittarelli F (2023) Biochar and recycled carbon fibres as additions for low-resistive cement-based composites exposed to accelerated degradation. *Construction and Building Materials* **376**: 131051. https://doi.org/10.1016/j.conbuildmat.2023.131051

Mobili A, Cosoli G, Giulietti N, Chiariotti P, Pandarese G, Bellezze T, Revel GM, Tittarelli F (2022b) Effect of gasification char and recycled carbon fibres on the electrical impedance of concrete exposed to accelerated degradation. *Sustainability* **14**(3): 1775. https://doi.org/10.3390/su14031775

Mohan MK, Rahul A, De Schutter G, Van Tittelboom K (2021) Extrusion-based concrete 3D printing from a material perspective: A state-of-the-art review. *Cement and Concrete Composites* **115**: 103855. https://doi.org/10.1016/j.cemconcomp.2020.103855

Morin C, Loppinet-Serani A, Cansell F, Aymonier C (2012) Near-and supercritical solvolysis of carbon fibre reinforced polymers (CFRPs) for recycling carbon fibers as a valuable resource: State of the art. *The journal of supercritical fluids* **66**: 232-240. https://doi.org/10.1016/j.supflu.2012.02.001

Muthusamy S, Chung D (2010) Carbon-Fiber Cement-Based Materials for Electromagnetic Shielding. *ACI materials journal* **107**(6). https://doi.org/10.14359/51664047

Nam I, Choi J, Kim C, Lee H-K (2018) Fabrication and design of electromagnetic wave absorber composed of carbon nanotube-incorporated cement composites. *Composite Structures* **206**: 439-447. https://doi.org/10.1016/j.compstruct.2018.07.058

Naqvi S, Prabhakara HM, Bramer E, Dierkes W, Akkerman R, Brem G (2018) A critical review on recycling of end-of-life carbon fibre/glass fibre reinforced composites waste using pyrolysis towards a circular economy. *Resources, conservation and recycling* **136**: 118-129. https://doi.org/10.1016/j.resconrec.2018.04.013

Nassiri S, AlShareedah O, Rodin III H, Englund K (2021) Mechanical and durability characteristics of pervious concrete reinforced with mechanically recycled carbon fiber composite materials. *Materials and Structures* **54**(3): 107. https://doi.org/10.1617/s11527-021-01708-8

Nazar S, Yang J, Amin MN, Husnain M, Ahmad F, Alabduljabbar H, Deifalla AF (2023a) Investigating the Influence of PVA and PP Fibers on the Mechanical, Durability, and Microstructural Properties of One-Part Alkali-Activated Mortar: An Experimental Study. *Journal of Materials Research and Technology*. https://doi.org/10.1016/j.jmrt.2023.06.115

Nazar S, Yang J, Ashraf M, Aslam F, Javed MF, Eldin SM, Xie J (2023b) Formulation and characterization of cleaner one-part novel fly ash/lime-based alkali-activated material. *Journal of Materials Research and Technology* **23**: 3821-3839. https://doi.org/10.1016/j.jmrt.2023.02.022

Nazar S, Yang J, Khan MS, Quazi MF, Li H, Rahim A (2023c) Investigating the Effects of MWCNTs on Sustainable Alkali-Activated Mortar: Physical, Rheological, and Mechanical Analysis. *Materials Today Sustainability*: 100519. https://doi.org/10.1016/j.mtsust.2023.100519

Nguyen H, Carvelli V, Fujii T, Okubo K (2016) Cement mortar reinforced with reclaimed carbon fibres, CFRP waste or prepreg carbon waste. *Construction and Building Materials* **126**: 321-331. https://doi.org/10.1016/j.conbuildmat.2016.09.044

Nie Y, Liu Q, Xiang Z, Zhong S, Huang X (2023) Performance and Modification Mechanism of Recycled Glass Fiber of Wind Turbine Blades and SBS Composite-Modified Asphalt. *Applied Sciences* **13**(10): 6335. https://doi.org/10.3390/app13106335

Norambuena-Contreras J, Thomas C, Borinaga-Treviño R, Lombillo I (2016) Influence of recycled carbon powder waste addition on the physical and mechanical properties of cement pastes. *Materials and Structures* **49**(12): 5147-5159. https://doi.org/10.1617/s11527-016-0850-4

Novais RM, Carvalheiras J, Capela M, Seabra M, Pullar R, Labrincha J (2018) Incorporation of glass fibre fabrics waste into geopolymer matrices: An eco-friendly solution for off-cuts coming from wind turbine blade production. *Construction and Building Materials* **187**: 876-883. https://doi.org/10.1016/j.conbuildmat.2018.08.004

Novais RM, Carvalheiras J, Seabra M, Pullar R, Labrincha J (2017) Effective mechanical reinforcement of inorganic polymers using glass fibre waste. *Journal of Cleaner Production* **166**: 343-349. https://doi.org/10.1016/j.jclepro.2017.07.242

Ogi K, Shinoda T, Mizui M (2005) Strength in concrete reinforced with recycled CFRP pieces. *Composites Part A: Applied Science and Manufacturing* **36**(7): 893-902. https://doi.org/10.1016/j.compositesa.2004.12.009

Oliveux G, Bailleul J-L, La Salle ELG (2012) Chemical recycling of glass fibre reinforced composites using subcritical water. *Composites Part A: Applied Science and Manufacturing* **43**(11): 1809-1818. https://doi.org/10.1016/j.compositesa.2012.06.008

Oliveux G, Bailleul J-L, La Salle ELG, Lefèvre N, Biotteau G (2013) Recycling of glass fibre reinforced composites using subcritical hydrolysis: reaction mechanisms and kinetics, influence of the chemical structure of the resin. *Polymer degradation and stability* **98**(3): 785-800. https://doi.org/10.1016/j.polymdegradstab.2012.12.010

Oliveux G, Dandy LO, Leeke GA (2015) Current status of recycling of fibre reinforced polymers: Review of technologies, reuse and resulting properties. *Progress in Materials Science* **72**: 61-99. https://doi.org/10.1016/j.pmatsci.2015.01.004

Oshima K, Matsuda S, Hosaka M, Satokawa S (2020) Rapid removal of resin from a unidirectional carbon fiber reinforced plastic laminate by a high-voltage electrical treatment. *Separation and Purification Technology* **231**: 115885. https://doi.org/10.1016/j.seppur.2019.115885

Osman AI, Farghali M, Dong Y, Kong J, Yousry M, Rashwan AK, Chen Z, Al-Fatesh A, Rooney DW, Yap P-S (2024) Reducing the carbon footprint of buildings using biochar-based bricks and insulating materials: a review. *Environmental Chemistry Letters* **22**(1): 71-104. https://doi.org/10.1007/s10311-023-01662-7

Osman AI, Fawzy S, Farghali M, El-Azazy M, Elgarahy AM, Fahim RA, Maksoud MA, Ajlan AA, Yousry M, Saleem Y (2022) Biochar for agronomy, animal farming, anaerobic digestion, composting, water treatment, soil remediation, construction, energy storage, and carbon sequestration: a review. *Environmental Chemistry Letters* **20**(4): 2385-2485. https://doi.org/10.1007/s10311-022-01424-x

Pakdel E, Kashi S, Varley R, Wang X (2020) Recent progress in recycling carbon fibre reinforced composites and dry carbon fibre wastes. *Resources, Conservation and Recycling*: 105340. https://doi.org/10.1016/j.resconrec.2020.105340

Paolini A, Kollmannsberger S, Rank E (2019) Additive manufacturing in construction: A review on processes, applications, and digital planning methods. *Additive manufacturing* **30**: 100894. https://doi.org/10.1016/j.addma.2019.100894

Pegoretti A (2021) Towards sustainable structural composites: A review on the recycling of continuous-fiber-reinforced thermoplastics. *Advanced Industrial and Engineering Polymer Research* **4**(2): 105-115. https://doi.org/10.1016/j.aiepr.2021.03.001

Pei C, Chen P-y, Kong S-C, Wu J, Zhu J-H, Xing F (2021) Recyclable separation and recovery of carbon fibers from CFRP composites: Optimization and mechanism. *Separation and Purification Technology* **278**: 119591. https://doi.org/10.1016/j.seppur.2021.119591

Pickering SJ (2006) Recycling technologies for thermoset composite materials—current status. *Composites Part A: applied science and manufacturing* **37**(8): 1206-1215. https://doi.org/10.1016/j.compositesa.2005.05.030

Pickering SJ, Kelly RM, Kennerley JR, Rudd CD, Fenwick NJ (2000) A fluidised-bed process for the recovery of glass fibres from scrap thermoset composites. *Composites Science and Technology* **60**(4): 509-523. https://doi.org/10.1016/S0266-3538(99)00154-2

Pławecka K, Przybyła J, Korniejenko K, Lin W-T, Cheng A, Łach M (2021) Recycling of mechanically ground wind turbine blades as filler in geopolymer composite. *Materials* **14**(21): 6539. https://doi.org/10.3390/ma14216539

Poudyal L, Adhikari K (2021) Environmental sustainability in cement industry: An integrated approach for green and economical cement production. *Resources, Environment and Sustainability* **4**: 100024. https://doi.org/10.1016/j.resenv.2021.100024

Prieto MI, González MdlN, Cobo A, Alonso D (2021) Comparison of the mechanical behavior of concrete containing recycled cfrp fibers and polypropylene fibers. *Applied Sciences* **11**(21): 10226. https://doi.org/10.3390/app112110226

Rangelov M, Nassiri S, Haselbach L, Englund K (2016) Using carbon fiber composites for reinforcing pervious concrete. *Construction and Building Materials* **126**: 875-885. https://doi.org/10.1016/j.conbuildmat.2016.06.035

Rani M, Choudhary P, Krishnan V, Zafar S (2021) A review on recycling and reuse methods for carbon fiber/glass fiber composites waste from wind turbine blades. *Composites Part B: Engineering* **215**: 108768. https://doi.org/10.1016/j.compositesb.2021.108768

Reynolds N, Pharaoh M (2010) An introduction to composites recycling. In 'Management, recycling and reuse of waste composites'. pp. 3-19. (Elsevier) https://doi.org/10.1533/9781845697662.1.3

Roberts T (2007) Rapid growth forecast for carbon fibre market. *Reinforced Plastics* **51**(2): 10-13. https://doi.org/10.1016/S0034-3617(07)70051-6

Rodin III H, Nassiri S, Englund K, Fakron O, Li H (2018a) Recycled glass fiber reinforced polymer composites incorporated in mortar for improved mechanical performance. *Construction and Building Materials* **187**: 738-751. https://doi.org/10.1016/j.conbuildmat.2018.07.169

Rodin III H, Rangelov M, Nassiri S, Englund K (2018b) Enhancing mechanical properties of pervious concrete using carbon fiber composite reinforcement. *Journal of Materials in Civil Engineering* **30**(3): 04018012. https://doi.org/10.1061/(ASCE)MT.1943-5533.0002207

Rouholamin D, Shyng Y, Savage L, Ghita O A comparative study into mechanical performance of glass fibres recovered through mechanical grinding and high voltage pulse power fragmentation. Proceedings of Proceedings of the ECCM16-16th European Conference on Composite Materials, Seville, Spain, 2014. pp. 22-26) http://www.escm.eu.org/eccm16/assets/0056.pdf

Roux M, Eguémann N, Dransfeld C, Thiébaud F, Perreux D (2017) Thermoplastic carbon fibre-reinforced polymer recycling with electrodynamical fragmentation: From cradle to cradle. *Journal of Thermoplastic Composite Materials* **30**(3): 381-403. https://doi.org/10.1177/0892705715599431

Rutzen M, Schulz M, Moosburger-Will J, Lauff P, Fischer O, Volkmer D (2021) 3D printing as an automated manufacturing method for a carbon fiber-reinforced cementitious composite with outstanding flexural strength (105 N/mm 2). *Materials and Structures* **54**: 1-20. https://doi.org/10.1617/s11527-021-01827-2

Rybicka J, Tiwari A, Leeke GA (2016) Technology readiness level assessment of composites recycling technologies. *Journal of Cleaner Production* **112**: 1001-1012. https://doi.org/10.1016/j.jclepro.2015.08.104

Saccani A, Manzi S, Lancellotti I, Lipparini L (2019) Composites obtained by recycling carbon fibre/epoxy composite wastes in building materials. *Construction and Building Materials* **204**: 296-302. https://doi.org/10.1016/j.conbuildmat.2019.01.216

Saccani A, Manzi S, Totaro G, Lancellotti I (2021) Alkali-activated mortars modified by epoxy-carbon fiber composites wastes. *Applied Sciences* **11**(13): 6110. https://doi.org/10.3390/app11136110

Sakka S (1956) Effects of reheating on strength of glass fibers. *Bulletin of the Institute for Chemical Research, Kyoto University* **34**(6): 316-320. https://repository.kulib.kyoto-u.ac.jp/dspace/bitstream/2433/75572/1/chd034_6_316.pdf

Salami BA, Oyehan TA, Tanimu A, Olabintan AB, Ibrahim M, Sanni-Anibire MO, Nafiu SA, Arowojolu O, Saleh TA (2022) Cement-based batteries design and performance. A review. *Environmental Chemistry Letters* **20**(3): 1671-1694. https://doi.org/10.1007/s10311-022-01389-x

Sauer M, Kuhnel M (2019) Composites market report 2019. *Carbon Composites*: 1-11. https://composites-united.com/media/3988/eng_ccev_market-report_2019_short-version.pdf

Schamel E, Wehnert G, Schlachter H, Söthje D (2021) Chemical Recycling of Carbon Fiber Reinforced Epoxy Composites Using Mild Conditions. *Chemie Ingenieur Technik* **93**(10): 1619-1628. https://doi.org/10.1002/cite.202100048

Sebaibi N, Benzerzour M, Abriak N-E, Binetruy C (2012) Mechanical and physical properties of a cement matrix through the recycling of thermoset composites. *Construction and Building Materials* **34**: 226-235. https://doi.org/10.1016/j.conbuildmat.2012.02.048

Sebaibi N, Benzerzour M, Abriak NE (2014) Influence of the distribution and orientation of fibres in a reinforced concrete with waste fibres and powders. *Construction and Building Materials* **65**: 254-263. https://doi.org/10.1016/j.conbuildmat.2014.04.134

Segura I, Faneca G, Torrents J, Aguado A (2019) Self-sensing concrete made from recycled carbon fibres. *Smart Materials and Structures* **28**(10): 105045. https://doi.org/10.1088/1361-665X/ab3d59

Senff L, Novais R, Carvalheiras J, Labrincha J (2020) Eco-friendly approach to enhance the mechanical performance of geopolymer foams: Using glass fibre waste coming from wind blade production. *Construction and building Materials* **239**: 117805. https://doi.org/10.1016/j.conbuildmat.2019.117805

Shahria Alam M, Slater E, Muntasir Billah A (2013) Green concrete made with RCA and FRP scrap aggregate: Fresh and hardened properties. *Journal of materials in civil engineering* **25**(12): 1783-1794. https://doi.org/10.1061/(ASCE)MT.1943-5533.0000742

Shen Y, Apraku SE, Zhu Y (2023) Recycling and Recovery of Fiber-reinforced Polymer Composites for End-of-Life Wind Turbine Blades Management. *Green Chemistry*. https://doi.org/10.1039/D3GC03479H

Shuaib NA, Mativenga PT (2017) Carbon footprint analysis of fibre reinforced composite recycling processes. *Procedia Manufacturing* **7**: 183-190. https://doi.org/10.1016/j.promfg.2016.12.046

Singh A, Charak A, Biligiri KP, Pandurangan V (2022) Glass and carbon fiber reinforced polymer composite wastes in pervious concrete: Material characterization and lifecycle assessment. *Resources, Conservation and Recycling* **182**: 106304. https://doi.org/10.1016/j.resconrec.2022.106304

Singh VP, Kumar M, Srivastava R, Vaish R (2021) Thermoelectric energy harvesting using cement-based composites: A review. *Materials Today Energy* **21**: 100714. https://doi.org/10.1016/j.mtener.2021.100714

Sommer V, Walther G (2021) Recycling and recovery infrastructures for glass and carbon fiber reinforced plastic waste from wind energy industry: A European case study. *Waste Management* **121**: 265-275. https://doi.org/10.1016/j.wasman.2020.12.021

Song YS, Youn JR, Gutowski TG (2009) Life cycle energy analysis of fiber-reinforced composites. *Composites Part A: Applied Science and Manufacturing* **40**(8): 1257-1265. https://doi.org/10.1016/j.compositesa.2009.05.020

Sun H, Guo G, Memon SA, Xu W, Zhang Q, Zhu J-H, Xing F (2015) Recycling of carbon fibers from carbon fiber reinforced polymer using electrochemical method. *Composites Part A: Applied Science and Manufacturing* **78**: 10-17. https://doi.org/10.1016/j.compositesa.2015.07.015

Tay YWD, Panda B, Paul SC, Noor Mohamed NA, Tan MJ, Leong KF (2017) 3D printing trends in building and construction industry: a review. *Virtual and Physical Prototyping* **12**(3): 261-276. https://doi.org/10.1080/17452759.2017.1326724

Taya M, Kim W, Ono K (1998) Piezoresistivity of a short fiber/elastomer matrix composite. *Mechanics of materials* **28**(1-4): 53-59. https://doi.org/10.1016/S0167-6636(97)00064-1

Thakare AA, Singh A, Gupta V, Siddique S, Chaudhary S (2021) Sustainable development of self-compacting cementitious mixes using waste originated fibers: A review. *Resources, Conservation and Recycling* **168**: 105250. https://doi.org/10.1016/j.resconrec.2020.105250

Thomas C, Borges P, Panzera T, Cimentada A, Lombillo I (2014) Epoxy composites containing CFRP powder wastes. *Composites Part B: Engineering* **59**: 260-268. https://doi.org/10.1016/j.compositesb.2013.12.013

Thomason J, Jenkins P, Yang L (2016a) Glass fibre strength—a review with relation to composite recycling. *Fibers* **4**(2): 18. https://doi.org/10.3390/fib4020018

Thomason J, Nagel U, Yang L, Sáez E (2016b) Regenerating the strength of thermally recycled glass fibres using hot sodium hydroxide. *Composites Part A: Applied Science and Manufacturing* **87**: 220-227. https://doi.org/10.1016/j.compositesa.2016.05.003

Thomason JL, Yang L, Meier R (2014) The properties of glass fibres after conditioning at composite recycling temperatures. *Composites Part A: Applied Science and Manufacturing* **61**: 201-208. https://doi.org/10.1016/j.compositesa.2014.03.001

Tiong HY, Lim SK, Lee YL, Lim JH Engineering properties of 1200 kg/m³ lightweight foamed concrete with egg shell powder as partial replacement material of cement. Proceedings of E3S Web of Conferences, 2018. Vol. 65, pp. 02010. (EDP Sciences) https://doi.org/10.1051/e3sconf/20186502010

Tittarelli F (2013) Effect of low dosages of waste GRP dust on fresh and hardened properties of mortars: Part 2. *Construction and Building Materials* **47**: 1539-1543. https://doi.org/10.1016/j.conbuildmat.2013.06.086

Tittarelli F, Moriconi G (2010) Use of GRP industrial by-products in cement based composites. *Cement and Concrete Composites* **32**(3): 219-225. https://doi.org/10.1016/j.cemconcomp.2009.11.005

Tittarelli F, Shah SP (2013) Effect of low dosages of waste GRP dust on fresh and hardened properties of mortars: Part 1. *Construction and Building Materials* **47**: 1532-1538. https://doi.org/10.1016/j.conbuildmat.2013.06.043

Van Gemert D, Czarnecki L, Maultzsch M, Schorn H, Beeldens A, Łukowski P, Knapen E (2005) Cement concrete and concrete–polymer composites: Two merging worlds: A report from 11th ICPIC Congress in Berlin, 2004. *Cement and Concrete Composites* **27**(9-10): 926-933. https://doi.org/10.1016/j.cemconcomp.2005.05.004

Vieira DR, Vieira RK, Chang Chain M (2017) Strategy and management for the recycling of carbon fiber-reinforced polymers (CFRPs) in the aircraft industry: a critical review. *International Journal of Sustainable Development & World Ecology* **24**(3): 214-223. https://doi.org/10.1080/13504509.2016.1204371

Wada M, Kawai K, Suzuki T, Hira H, Kitaoka S (2016) Effect of superheated steam treatment of carbon fiber on interfacial adhesion to epoxy resin. *Composites Part A: Applied Science and Manufacturing* **85**: 156-162. https://doi.org/10.1016/j.compositesa.2016.03.024

Wang C, Li K, Li H, Guo L, Jiao G (2008) Influence of CVI treatment of carbon fibers on the electromagnetic interference of CFRC composites. *Cement and Concrete Composites* **30**(6): 478-485. https://doi.org/10.1016/j.cemconcomp.2007.09.002

Wang Y, Zhang S, Li G, Shi X (2019a) Effects of alkali-treated recycled carbon fiber on the strength and free drying shrinkage of cementitious mortar. *Journal of Cleaner Production* **228**: 1187-1195. https://doi.org/10.1016/j.jclepro.2019.04.295

Wang Y, Zhang S, Luo D, Shi X (2019b) Effect of chemically modified recycled carbon fiber composite on the mechanical properties of cementitious mortar. *Composites Part B: Engineering* **173**: 106853. https://doi.org/10.1016/j.compositesb.2019.05.064

Wei J, Nie Z, He G, Hao L, Zhao L, Zhang Q (2014) Energy harvesting from solar irradiation in cities using the thermoelectric behavior of carbon fiber reinforced cement composites. *Rsc Advances* **4**(89): 48128-48134. https://doi.org/10.1039/C4RA07864K

Wen S, Chung D (1999) Seebeck effect in carbon fiber-reinforced cement. *Cement and Concrete Research* **29**(12): 1989-1993. https://doi.org/10.1016/S0008-8846(99)00185-4

Wen S, Chung D (2006) Model of piezoresistivity in carbon fiber cement. *Cement and concrete research* **36**(10): 1879-1885. https://doi.org/10.1016/j.cemconres.2006.03.029

Weng Y, Li M, Ruan S, Wong TN, Tan MJ, Yeong KLO, Qian S (2020) Comparative economic, environmental and productivity assessment of a concrete bathroom unit fabricated through 3D printing and a precast approach. *Journal of Cleaner Production* **261**: 121245. https://doi.org/10.1016/j.jclepro.2020.121245

Witten E, Mathes V (2020) The market for glass fibre reinforced plastics (GRP) in 2020. *AVK: Berlin, Germany*. https://eucia.eu/wp-content/uploads/2023/04/AVK-Market-Report-2020.pdf

Witten E, Mathes V (2024) The European market for Fiber-Reinforced Plastics / Composites 2023. *AVK: Berlin, Germany*. https://www.avk-tv.de/wp-content/uploads/2024/06/AVK_MarketReport_2024_FINAL_ENG.pdf

Wu BC, Klein MT, Sandler SI (1991) Solvent effects on reactions in supercritical fluids. *Industrial & engineering chemistry research* **30**(5): 822-828. https://doi.org/10.1021/ie00053a003

Xiong C, Li Q, Lan T, Li H, Long W, Xing F (2021) Sustainable use of recycled carbon fiber reinforced polymer and crumb rubber in concrete: Mechanical properties and ecological evaluation. *Journal of Cleaner production* **279**: 123624. https://doi.org/10.1016/j.jclepro.2020.123624

Xu G-T, Liu M-J, Xiang Y, Fu B (2022) Valorization of macro fibers recycled from decommissioned turbine blades as discrete reinforcement in concrete. *Journal of Cleaner Production* **379**: 134550. https://doi.org/10.1016/j.jclepro.2022.134550

Yan H, Lu C-x, Jing D-q, Chang C-b, Liu N-x, Hou X-l (2016) Recycling of carbon fibers in epoxy resin composites using supercritical 1-propanol. *New Carbon Materials* **31**(1): 46-54. https://doi.org/10.1016/S1872-5805(16)60004-5

Yang F, Hu G, He H, Yi M, Ge Y, Ran L, Peng K (2019) Effect of amorphous carbon on the tensile behavior of polyacrylonitrile (PAN)-based carbon fibers. *Journal of Materials Science* **54**(11): 8800-8813. https://doi.org/10.1007/s10853-018-03256-z

Yang L, Sáez E, Nagel U, Thomason J (2015) Can thermally degraded glass fibre be regenerated for closed-loop recycling of thermosetting composites? *Composites Part A: Applied Science and Manufacturing* **72**: 167-174. https://doi.org/10.1016/j.compositesa.2015.01.030

Yang Q, Hong B, Lin J, Wang D, Zhong J, Oeser M (2020) Study on the reinforcement effect and the underlying mechanisms of a bitumen reinforced with recycled glass fiber chips. *Journal of Cleaner Production* **251**: 119768. https://doi.org/10.1016/j.jclepro.2019.119768

Yang Y, Boom R, Irion B, van Heerden D-J, Kuiper P, de Wit H (2012) Recycling of composite materials. *Chemical Engineering and Processing: Process Intensification* **51**: 53-68. https://doi.org/10.1016/j.cep.2011.09.007

Yazdanbakhsh A (2021) Technical and economic implications of using recycled fiber-reinforced polymer waste as aggregate in concrete. In 'Waste and Byproducts in Cement-Based Materials'. pp. 139-150. (Elsevier) https://doi.org/10.1016/B978-0-12-820549-5.00021-8

Yazdanbakhsh A, Bank LC (2014) A critical review of research on reuse of mechanically recycled FRP production and end-of-life waste for construction. *Polymers* **6**(6): 1810-1826. https://doi.org/10.3390/polym6061810

Yazdanbakhsh A, Bank LC, Chen C (2016) Use of recycled FRP reinforcing bar in concrete as coarse aggregate and its impact on the mechanical properties of concrete. *Construction and Building Materials* **121**: 278-284. https://doi.org/10.1016/j.conbuildmat.2016.05.165

Yazdanbakhsh A, Bank LC, Chen C, Tian Y (2017) FRP-needles as discrete reinforcement in concrete. *Journal of Materials in Civil Engineering* **29**(10): 04017175. https://doi.org/10.1061/(ASCE)MT.1943-5533.0002033

Yazdanbakhsh A, Bank LC, Rieder K-A, Tian Y, Chen C (2018a) Concrete with discrete slender elements from mechanically recycled wind turbine blades. *Resources, Conservation and Recycling* **128**: 11-21. https://doi.org/10.1016/j.resconrec.2017.08.005

Yazdanbakhsh A, Bank LC, Tian Y (2018b) Mechanical processing of GFRP waste into large-sized pieces for use in concrete. *Recycling* **3**(1): 8. https://doi.org/10.3390/recycling3010008

Yazdanbakhsh A, Tian Y (2019) Shear performance of reinforced concrete beams incorporating stiff slender elements. *Construction and Building Materials* **222**: 263-277. https://doi.org/10.1016/j.conbuildmat.2019.06.158

Yip H, Pickering S, Rudd C (2002) Characterisation of carbon fibres recycled from scrap composites using fluidised bed process. *Plastics, rubber and composites* **31**(6): 278-282. https://doi.org/10.1179/146580102225003047

Yu S, Sanjayan J, Du H (2022) Effects of cement mortar characteristics on aggregate-bed 3D concrete printing. *Additive Manufacturing* **58**: 103024. https://doi.org/10.1016/j.addma.2022.103024

Yuan H, Fu X, Fan Y, Fu B, Zou Q (2022) Flexural performance of layered macro fiber reinforced concrete beams. *Construction and Building Materials* **357**: 129314. https://doi.org/10.1016/j.conbuildmat.2022.129314

Zaid O, Zamir Hashmi SR (2021) Experimental study on mechanical performance of recycled fine aggregate concrete reinforced with discarded carbon fibers. *Frontiers in Materials* **8**: 771423. https://doi.org/10.3389/fmats.2021.771423

Zegardło B (2022) Heat-resistant concretes containing waste carbon fibers from the sailing industry and recycled ceramic aggregates. *Case Studies in Construction Materials* **16**: e01084. https://doi.org/10.1016/j.cscm.2022.e01084

Zhang C, Hu M, Di Maio F, Sprecher B, Yang X, Tukker A (2022a) An overview of the waste hierarchy framework for analyzing the circularity in construction and demolition waste management in Europe. *Science of the Total Environment* **803**: 149892. https://doi.org/10.1016/j.scitotenv.2021.149892

Zhang J, Wang J, Dong S, Yu X, Han B (2019) A review of the current progress and application of 3D printed concrete. *Composites Part A: Applied Science and Manufacturing* **125**: 105533. https://doi.org/10.1016/j.compositesa.2019.105533

Zhang M, Na M, Yang Z, Shi Y, Guerrieri M, Pan Z (2022b) Study on mechanical properties and solidification mechanism of stabilized dredged materials with recycled GFRP fibre reinforced geopolymer. *Case Studies in Construction Materials* **17**: e01187. https://doi.org/10.1016/j.cscm.2022.e01187

Zhang M, Qiu X, Shen S, Wang L, Zang Y (2023) Mechanical and thermal insulation properties of rgfrp fiber-reinforced lightweight fly-ash-slag-based geopolymer mortar. *Sustainability* **15**(9): 7200. https://doi.org/10.3390/su15097200

Zhang Y, Pontikes Y, Lessard L, van Vuure AW (2021) Recycling and valorization of glass fibre thermoset composite waste by cold incorporation into a sustainable inorganic polymer matrix. *Composites Part B: Engineering* **223**: 109120. https://doi.org/10.1016/j.compositesb.2021.109120

Zhao J, Liu P, Yue J, Huan H, Bi G, Zhang L (2023) Recycling glass fibers from thermoset epoxy composites by in situ oxonium-type polyionic liquid formation and naphthalene-containing superplasticizer synthesis with the degradation solution of the epoxy resin. *Composites Part B: Engineering* **254**: 110435. https://doi.org/10.1016/j.compositesb.2022.110435

Zhen T, Zhao P, Zhang X, Si W, Ling T (2023) The Effect of GFRP Powder on the High and Low-Temperature Properties of Asphalt Mastic. *Materials* **16**(7): 2662. https://doi.org/10.3390/ma16072662

Zheng Y, Shen Z, Ma S, Cai C, Zhao X, Xing Y (2009) A novel approach to recycling of glass fibers from nonmetal materials of waste printed circuit boards. *Journal of Hazardous Materials* **170**(2-3): 978-982. https://doi.org/10.1016/j.jhazmat.2009.05.065

Zhou B, Zhang M, Ma G (2022) Multi-scale experimental study on the effect of crushed GFRP powder and dust on physical-mechanical properties of cement mortar. *Journal of Building Engineering* **57**: 104853. https://doi.org/10.1016/j.jobe.2022.104853

Zhou B, Zhang M, Wang L, Ma G (2021) Experimental study on mechanical property and microstructure of cement mortar reinforced with elaborately recycled GFRP fiber. *Cement and Concrete Composites* **117**: 103908. https://doi.org/10.1016/j.cemconcomp.2020.103908

Zhu J-H, Chen P-y, Su M-n, Pei C, Xing F (2019) Recycling of carbon fibre reinforced plastics by electrically driven heterogeneous catalytic degradation of epoxy resin. *Green Chemistry* **21**(7): 1635-1647. https://doi.org/10.1039/C8GC03672A