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Review

A Critical Review on the Application of Recycled Carbon Fiber to Concrete and Cement Composites

Manan Bhandari [1] and Il-Woo Nam [2,*]

[1] Department of Advanced Convergence, Handong Global University, Pohang 37554, Republic of Korea; 22238004@handong.ac.kr
[2] School of Spatial Environment System Engineering, Handong Global University, Pohang 37554, Republic of Korea
* Correspondence: namiru@handong.edu

Abstract: Carbon fiber (CF) exhibit extraordinary properties, such as high specific and tensile strength, high elastic modulus, light weight, and weather resistance, which has led to a rapid increase in the use of CF in sectors such as aerospace, sports equipment, energy storage, automotive, construction, and wind energy applications. However, the increase in CF applications has led to a massive production of CF waste. As CF is non-biodegradable, it results in CF accumulation in landfills. CF waste is a rapidly growing ecological hazard because of its high energy consumption and expensive production methods. The properties of carbon fibers can be preserved even after recycling given the development of recycling technology; therefore, multiple studies have been conducted to demonstrate the effect of recycled carbon fiber (RCF) in different composites such as cement-based composites. This review presents the results of studies conducted on the application of RCF to cement composites and analyzes those results to investigate the effect of RCF on the properties of cement composites such as mechanical properties (compressive strength, flexural strength, and tensile strength), fracture characteristics (fracture toughness and fracture energy), electrical properties, and workability. Overall, the studies demonstrated a positive trend in the application of RCF to cement composites.

Keywords: recycled carbon fiber; cement composite; carbon fiber

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1. Introduction

The history of carbon fibers (CFs) dates back to the eighteenth century, when Sir Joseph Wilson Swan discovered them in 1860 [1,2]. Earlier forms of CFs were cellulose-based, and plants such as cotton and bamboo were used to produce CF filaments [1]. Petroleum-based CFs were developed by Bacon in 1958 [1]. CF production using the polyacrylonitrile (PAN) method was first reported in the 1960s by Dr. Akio Shindo [1]. Today, 90% of global CF production is realized through the PAN method [3]. Modern-day CFs have excellent properties such as a high elastic modulus per mass density, high tensile strength, high specific strength, high temperature resistance, and excellent electrical properties [3,4].

CF is a lightweight material suitable for applications in the fields of automation, aeronautics, electrical appliances, wind turbines, sports equipment, and energy storage [1,3–5]. The global demand for CF was 117,000 tons in 2022 [6,7] and is expected to reach 120,000 tons by 2030 [8]. Further advancements in CF production techniques are expected to increase its adoption in different industries. More CF waste production is imminent with an increase in CF usage. Almost 30% of CF is estimated to become waste during its production [8–10]. Approximately 62,000 tons of waste and unused CF are estimated to be accumulated annually in landfills [8].

Given the ever-increasing use of CF and its numerous composites and the concurrent increase in CF waste, numerous studies have been conducted on utilizing recycled carbon fibers (RCF) in different sectors and applications, including in electromagnetic shielding and as thermoelectric and lithium-ion battery materials [4]. The utilization of CF waste in civil engineering applications, particularly in cement composites, has also gained considerable attention. The application of CF to cement composites has already shown significant improvements in the properties of cement composites; RCF has excellent potential for use in cement composites instead of virgin carbon fibers (VCF) because it retains its strength even after recycling [11–13]. Multiple studies have reported that RCF can retain its mechanical strength up to a range of 90–98% compared to that of the VCF [14–16]; this further validates RCF as an eco-friendly and economical alternative to VCF.

The use of CFs in the automobile and aerospace industry has significantly increased over the years, as their lightweight characteristic aids lower fuel consumption. The aerospace sector has been the leading global consumer of CF. In 2020, the total CF global demand by the aerospace sector reached ~26,000 tons [6]. The wind energy sector is another major consumer of CF. In 2021, ~30,000 tons of CF was consumed by the wind energy sector [17]. With such high consumption, both the aerospace and wind energy sectors produce significant amounts of waste, and it is estimated that 23,600 tons of CF waste will be produced by the aerospace industry in 2035 [8], while the wind energy sector is estimated to contribute 483,000 tons [8]. CF is a non-biodegradable material that takes a long time to degrade. CF waste is disposed in landfills, which leads to land pollution. Further, when disposed of through combustion, it results in massive air pollution. CF production is expensive in terms of energy consumption and economics; it is estimated that 1 kg of CF production requires ~195–595 MJ/kg of energy [6,18–20]. However, the recycling cost of CF is only ~38 MJ/kg energy [6,18–20]. It is estimated that for less than 5 $/kg, RCF can be obtained from CF scrap, which is only 15% of the cost for producing VCF [21]. Hence, recycling waste CF is an economical and environmentally friendly choice. Extensive research on new technologies to recycle CF more cost-effectively while maintaining its original properties can further help reduce and reutilize CF waste.

This review deals with various aspects of CF, such as CF waste production, the necessity of CF recycling, and various methods of recycling waste CF. Furthermore, the literature regarding the effect of RCF on cement composite properties, such as mechanical, fractural, microstructural, and electrical properties, was reviewed. The main objective of this review is to demonstrate the positive aspects of RCF utilization as a cement composite filler material that can help decrease global CF waste while simultaneously producing high-performance cement composites.

2. Recycling Process of CF

One of the widespread applications of CF is in fiber-reinforced polymers. Carbon fiber-reinforced polymer (CFRP) production combines CF with matrices such as epoxy resin, polystyrene, polyester, and vinyl ester. Several studies have been conducted, and businesses have been established to utilize waste CFRP. In general, CFRP can be recycled mechanically, thermally, or chemically (Figure 1).

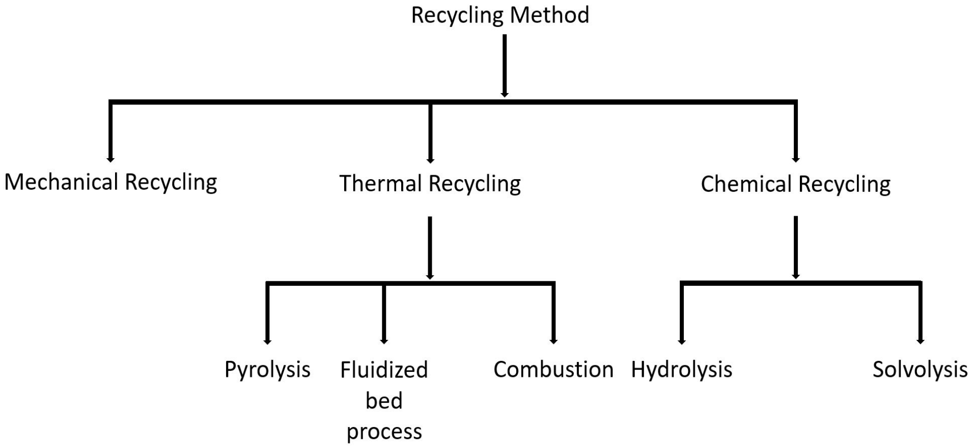

Figure 1. Recycling methods of fiber-reinforced polymers (cf. [22]).

2.1. Mechanical Recycling

Mechanical recycling is a simple technique in which waste CF composites are broken down into different sizes using mechanical processes such as shredding, crushing, ball milling, grinding, and grounding [4,8,22–25]. This method does not produce toxic byproducts unlike thermal and chemical recycling, which makes it the most eco-friendly form of recycling [8]. However, a significant disadvantage of mechanically recycled CFRP is that it cannot maintain the structural integrity of the CF, which has a negative effect on its strength [4,22–25]. Research conducted by Li and Englund [26] reported a prepared composite incorporating mechanically recycled CFs by means of compression molding. They concluded that these panel composites only retained up to 10%, 50%, and 25% of flexural strength, flexural stiffness, and tensile stiffness, respectively, compared with the original CF composite. Despite being an eco-friendly process, mechanical recycling is unsuitable for mass recycling because it cannot maintain the mechanical properties of CF.

2.2. Thermal Recycling

Thermal recycling treats CFRP at high temperatures to separate plastic matrices from fibers [4,22–25]; it is a suitable form of recycling owing to the high thermal stability of CF, because temperatures in the range 450–700 °C are required to degrade plastic matrices [22,24,25]. This method results in longer and cleaner RCF, a major advantage [22]. Thermal recycling can be classified into pyrolysis, fluidized bed process (FBP), and combustion/incineration [22]. Combustion is not preferred because ash is produced as a byproduct [24]. However, ash could potentially be utilized in a cement composite since numerous studies have shown a positive effect of different forms of ash in cement composite [27,28].

Pyrolysis (Figure 2) is the most efficient thermal method of recycling fiber composites, where fiber is heated at a high temperature of 350–700 °C in an inert atmosphere with a lack of oxygen [8,29,30]. It is the most commercially used method to recycle CF waste [30] because the RCF obtained from it shows retention up to 90% of the original CF mechanical strength [19]. The quality of the recovered RCF significantly depends on parameters such as the temperature, heating rate, pressure, and residence time [31]. The RCF obtained from the pyrolysis process showed a high retention of mechanical strength compared to that obtained from mechanical recycling [25]; however, toxic gas production and char on the RCF surface are the drawbacks of pyrolysis [24,25]. The char on the surface of the RCF is the subject of studies since it can affect the mechanical characteristics of the RCF itself. However, to the best of the authors' knowledge, research on the effects of the char adhered to the RCF surface on mechanical properties of not only the RCF itself but of RCF-added cement composites has scarcely been carried out and is subject to future studies.

FBP is a novel thermal recycling method (Figure 3), wherein a rapid stream of hot air between 450 and 550 °C is deployed to decompose chopped scrap fiber composites [22,24,25,29]. In this process, CFRP is chopped into ~25 mm and fed into a bed, which comprises fine silica sand of 0.85 mm size; then, hot air stream in the range of 450–550 °C fluidizes the waste CFRP without damaging the structural integrity of CF [22,24,25,29]. Temperature is an important factor in the FBP process. Low temperatures make it difficult for polymer matrices to fully break down from the CF surface, whereas, high temperatures can harm the mechanical qualities of CFs [24]. The works of Piñero-Hernanz et al. [17], Verma et al. [23], Pimenta et al. [25], and Borjan et al. [31] present a detailed summary of the thermal recycling of CFRP.

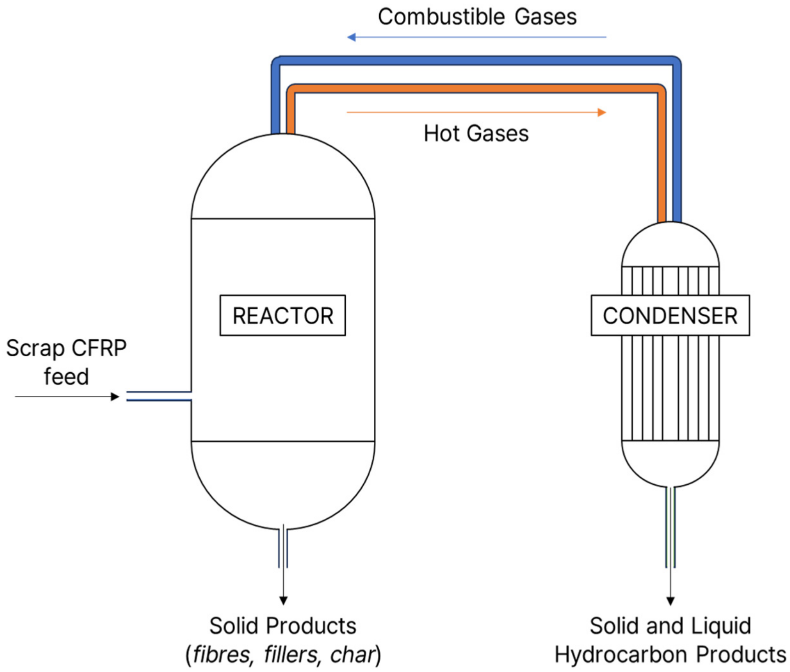

Figure 2. Pyrolysis method of recycling (cf. [19]).

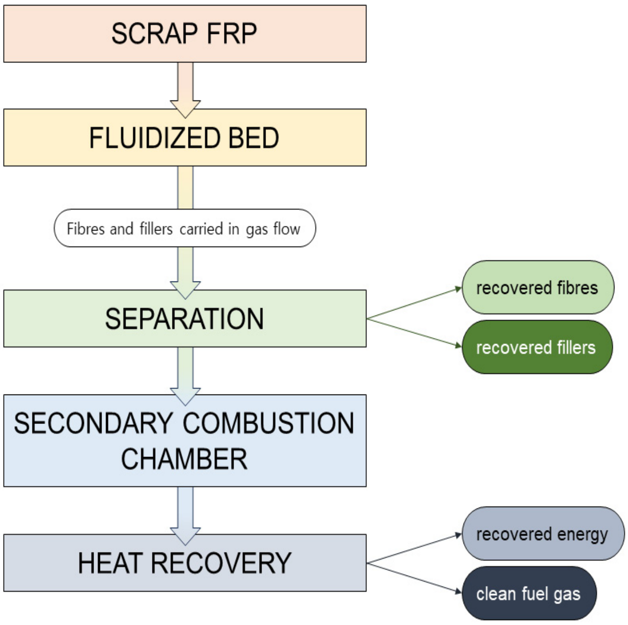

Figure 3. Schematic of the fluidized bed process (cf. [14]).

2.3. Chemical Recycling

Chemical recycling separates polymer matrices from CF using acids, bases, and solvents [22,24]. This method maintains the structural integrity of CFs while consuming less energy than that required for thermal recycling [29]. CFs can retain resins and long fibers in addition to maintaining their mechanical properties [25].

Hydrolysis and solvolysis are the two primary chemical recycling methods that use water and solvents, respectively [22,29]. In solvolysis, plastic matrices are decomposed using a solvent (water, alcohol, or ammonia) [30]. Water and alcohol are more eco-friendly than other chemicals that produce toxic waste which is difficult to dispose. Solvolysis can be further classified into two types, which are higher pressure/temperature (i.e., higher than 200 °C) and lower pressure/temperature (i.e., under 200 °C) solvolysis [29,31].

Compared to the other methods, chemical recycling is the least environmentally friendly process because of its toxic waste production, particularly when using low-temperature solvolysis [25]. Another disadvantage of chemical recycling is that its commercial application is economically challenging. Further, epoxy resins obtained from chemical recycling show a loss of adhesion [25]. The studies by Pimenta et al. [25], Butenegro et al. [29], Morin et al. [30], and Borjan et al. [31] present a detailed summary of solvolysis along with reviewing multiple works of the literature conducted over the years on the application of different types of chemical recycling of CFRP.

3. Physical and Chemical Properties of RCF

The properties of RCFs depend on the recycling method. Due to harsh recycling processes, irregular shape, and the presence of polymer on its surface, RCFs obtained from mechanical recycling exhibits poor mechanical properties compared to those obtained from thermal and chemical recycling. Table 1 summarizes the properties of RCFs used in cement composites.

Table 1. Properties of RCFs used in cement composites.

Diameter (μm)	Tensile Strength (MPa)	Elastic Modulus (GPa)	Density (g/cm^3)	Length (mm)	Electrical Resistivity ($\Omega\cdot$m)	Carbon Content (wt. %)	Elongation at Break (%)	Reference
-	4950	240	-	-	-	-	1.5	[32]
7	3500	230	1.85	6		94 (>92)	-	[33]
7.5	3150	200	1.80	-	0.103 [a]/0.34 [b]	-	-	[34]
7.5	3150	200	1.80	-	0.103 [a]/0.34 [b]	-	-	[34]
7	4150	252	1.80	12	0.103 [a]/0.34 [b]	-	-	[34]
7	4200	240	1.76	12	0.016	-	-	[34]
6.9	3620	207.75	1.77	14.9 [c]/7.2 [d]	-	-	-	[35]
7.5	3150	200	1.80	20	0.103 [a]/0.34 [b]	-	-	[36]
7	4150	252	1.76	12	0.016	-	-	[36]
7	3790	237	0.4	0.0954	-	>95	-	[37]
7	3500	230	1.70/2.0	6	-	-	-	[38]
10	4.90	230	-	40/50	-	-	2.10	[39]
7	4150	252	1.80	6/12	-	100	-	[40]
7	3790	237	1.80	6	-	-	-	[41]
7	-	-	0.4	0.08/0.1	-	>95	-	[42]
-	4940	230	-	35	-	-	1.40	[43]
7	-	-	1.85	6	-	94	-	[44]
7 ± 2	3500	230	1.7/2.0	0.1 ± 0.02	-	94 (>92)	1.5	[45]
6.7 ± 0.8	-	-	1.81	1.5 ± 1.2	-	-	-	[46]
7	3530	230	1.76	20	-	-	1.5	[47]
7 ± 2	3500	230	1.7/2.0	6.0 ± 0.5	0.0015	94 (>92)	-	[48]

0.103 [a]: electrical resistivity across the lengthwise section, 0.34 [b]: electrical resistivity across the cross section, 14.9 [c]: mean length, and 7.2 [d]: standard deviation length.

4. Effect of RCF on Properties of Cement Composites

4.1. Mechanical Properties

4.1.1. Compressive Strength

Previous studies have suggested that the addition of RCF significantly improves the compressive strength of cement composites (Table 2) [33,34,36,37,45,46,49–52]. Patrinou et al. [45] have shown that adding milled RCF at 1% and 2.5% by cement weight improved the compressive strengths of the cement pastes by 143.7% and 185.9%, respectively. Similarly, Patchen et al. [46] concluded that RCF increased the compressive strength of ultrahigh performance concrete (UHPC) by 42.5% compared to a plain UHPC composite.

Studies have shown that the type of RCF [36], the physical properties of RCF (aspect ratio, length, and size) [53], dispersion method [34], and the dosage of RCF [45] significantly affect the compressive strength.

Patrinou et al. [45] concluded that the compressive strength of cement composites increased with an increase in RCF dosage. Li et al. [54] demonstrated that concrete composite with 10% of RCF dosage exhibited better compressive strength compared to concrete composites with 5% and 15% of RCF dosages. Similarly, Mastali et al. [53] have investigated the influence of RCF dosage on cement composites by adding 0.5%, 1%, 1.5%, and 2% of RCF volume to a cement composite. They observed an increase in the compressive strength of the cement composite with RCF dosage content [53]. Further, they showed the effect of RCF size on cement composites by adding RCF of lengths 10, 20, and 30 mm to a cement composite; the cement composite with an RCF of 30 mm length showed the highest compressive strength [53]. They concluded that an increase in the dosage and length of the RCF tended to limit crack propagation, which resulted in an increase in compressive strength [53].

Another critical parameter affecting RCF-added cement composites is the surface modification of the RCF. Wang et al. [50] demonstrated that cement mortar with 1 mol/L NaOH solution-treated RCF had better compressive strength than mortar containing RCF that was not treated. They concluded that when treatment is performed using an NaOH solution by removing the residual epoxy, it leads to a rougher RCF surface, which helps better bonding with the cement matrix [50].

Studies by Faneca et al. [34] have shown that the mixing process affects RCF dispersion on cement composite compressive strength and conclude that the wet-mix process enables the proper dispersion of RCF. Therefore, it exhibits a higher compressive strength than RCF-added cement composites which follow a dry-mix process. Segura et al. [36] have shown that monofilament RCF resulted in a more noticeable improvement in the strength of UHPC compared to the UHPC with a fibrillated sheet RCF.

Further, Patchen et al. [46] reported that RCF showed positive results compared to other type of fibers, and that the RCF-added cement composite performed better than cement composites with Hexcel CF and steel fiber-added cement composites. They concluded that the ability of RCFs to disperse and bond with the cement matrix makes them more suitable for preparing UHPC instead of Hexcel CFs and steel fibers [46].

Thus, the addition of RCFs improved the compressive strength of cement composites. The compressive strength enhancement can be attributed to the crack-bridging/branching capability of RCF [53]. Multiple studies have shown that the presence of epoxy on the RCF surface negatively affects the compressive strength of cement composites; however, few studies have been conducted on the effect of parameters such as water content ratio, RCF size, curing period, recycling method of CF, and the dispersion method of RCF. Further investigation of the effects of various parameters on RCF will further validate RCF as an ecofriendly substitute for VCF.

Table 2. Comparison of the enhanced extent of compressive strength in a cement composite with RCF.

Authors	RCF Type	Matrix	Mixing Amount of RCF	Improvements
Patrinou et al. [45]	Milled RCF	Cement paste	1%, 2.5% by weight of cement	Improvement by 143.7% (~22 MPa) and 185.9% (~25.5 MPa) compared to that of plain cement paste (~9 MPa).
Patchen et al. [46]	RCF obtained by pyrolysis	UHPC	0.016% by weight of cement mix ^{c}	RCF-added composite shows 42.5% (135.3 MPa) improvement compared to plain UHPC (87.9 MPa).

Table 2. *Cont.*

Authors	RCF Type	Matrix	Mixing Amount of RCF	Improvements
Belli et al. [33]	RCF	Cement mortar	0.05% by volume of cement	Decrease in compressive strength by 10% (27.90 MPa) compared to that of plain cement mortar (31 MPa).
Li et al. [55]	Chemically recycled RCF	Cement-based matrix	1.0% by weight of cement	Improvement of 66% (~22 MPa) and 76% (~23 MPa) in RCF treated with hydrogen peroxide at concentrations of 30% and 50%, respectively, compared to that of the plain cement matrix (~13 MPa).
Li et al. [54]	RCF obtained by microwave assisted pyrolysis	Early strength concrete	5%, 10%, and 15% by weight of cement	Improvement by 4.86% (25.89 MPa), 14.22% (28.25 MPa), and 13.77% (28.09 MPa) compared to that of plain concrete (24.69 MPa).
Segura et al. [36]	Monofilament RCF and fibrillated RCF sheets	UHPC	0.2%, 0.4%, 0.6%, 0.8%, 1.0%, 1.2%, and 1.4% by volume of cement	Monofilament RCF of dosage 1.4% added UHPC shows highest improvement up to 70 MPa, meanwhile fibrillated RCF sheets of dosage 1.2% added UHPC show highest improvement up to 55 MPa)

Cement mix ^{c}: mix of cement, silica flume, sand, and ground quartz.

4.1.2. Flexural Strength, Tensile Strength, and Other Properties

Concrete has poor flexural and tensile strengths, and fibers such as steel, carbon, glass, and basalt have been utilized to improve the flexural and tensile properties of concrete. Incorporating the environmentally friendly alternative RCF in cement composite achieves significant improvements in flexural strength [33,36,45,46,51,56,57] and tensile strength [43,46,50].

Patrinou et al. [45] have shown that adding 2% RCF improves cement paste flexural strength by 210.3%. They concluded that the improvement in flexural strength was caused by the crack-bridging capacity of RCF on the cement matrix. Nguyen et al. [56] reported that the addition of a 1.5% dosage of RCF with high-range water-reduction (WH) additive to cement mortar resulted in an improvement in flexural strength by 11.5%, which was attributed to bonding between RCF and calcium silicate hydrate (C-S-H) mineral. Similarly, Baričević et al. [51] have shown that adding a 1% dosage of RCF to cement mortar improved flexural strength by 15% compared to that of plain cement mortar.

The dosage content and physical qualities of RCFs are crucial for the flexural strength of cement composites. Patrinou et al. [45] concluded that flexural strength increased with dosage and reported that 2% RCF dosage is an optimum concentration for improving flexural strength. Their study indicated that a further increase in the RCF dosage up to 2.5% regressed flexural strength because of the agglomeration of RCF [45]. Li et al. [54] have investigated the flexural strength of early strength concrete by adding a 5%, 10%, and 15% dosage of RCF. Their investigation concluded that a 10% addition of RCF improved the flexural strength of cement composites.

Studies by Nguyen et al. [58] and Mastali et al. [53] have shown that the addition of 1.5% dosage of RCF achieved the maximum flexural strength when a flexural strength test was performed on cement mortar with the addition of 0.5%, 1%, and 1.5% dosages of RCF. The RCF-added cement composite outperformed the other fiber-added cement composites. Baričević et al. [51] reported that with the same amount, adding RCF shows higher flexural strength compared to that when glass and basalt fiber are added to the cement mortar. Patchen et al. [46] also showed that an RCF-added cement composite outperformed Zoltek CFs in terms of flexural strength. Mastali et al. [53] have investigated the influence of RCF size on cement composites flexural strength by adding RCF of lengths 10, 20, and 30 mm to a cement composite; the cement composite with an RCF of 30 mm length showed the highest flexural strength [53]. They concluded that the larger sized fiber resulted in planar fibers aligning, which in turn improves the flexural strength of the cement composite [53].

The overall improvement in the flexural strength of cement composites is attributed to the high tensile strength of RCF [51,59]. The dosage content and physical properties such as the aspect ratio and length of the RCF play a significant role in the flexural strength of cement composites [33,36,45,46,51,56,57].

The use of RCF also improves the tensile strength of cement composites. For example, Li et al. [54] have investigated the splitting tensile strength of early strength concrete by adding a 5%, 10%, and 15% dosage of RCF and concluded that, comparatively, a 10% addition of RCF showed a significant improvement in the splitting tensile strength of cement composites. Wang et al. [50] have shown that incorporating RCF into cement composites improved tensile strength by 65.3% compared to that of cement-only samples. Zaid et al. [43] have shown that adding 6% RCF to cement composites improved tensile strength by 20.1%. Further, they included recycled aggregates (RA) in cement composites along with 6% RCF, which improved the tensile strength to 17.8% compared to that of plain samples [43]. Patchen et al. [46] have shown that adding 0.016% by weight of the cement mix achieved a 27.8% increase in tensile strength compared to that of the plain samples. They reported that the same amount of RCF-added cement composite showed a higher split tensile strength than cement composites with added steel fibers, Hexcel CFs, and Zoltek CFs [46]. The overall improvement in the RCF-added cement composite can be attributed to the crack-bridging effect of the RCF and its ability to interlock with the cement matrix [50]. To the best of our knowledge, studies examining the impact of the length of RCF on the tensile strength of RCF-added cement composites have not yet been conducted. Further research is needed on the effect of RCF size on the tensile strength of cement composites, as the influence of fiber size has been demonstrated in the tensile strength of VCF-added cement composites [60].

Properties such as stiffness [56] and elastic modulus [39,61] also improved with the addition of RCF. Nguyen et al. [56] have investigated the effect of RCF and chemical additives, such as a water-reduction admixture (21WH) and lignin sulfonate, on cement mortar stiffness. A combination of 1.5% of RCF and 21WH achieved a 20.5% increase in stiffness compared to that of the plain cement mortar [56].

In conclusion, the additives positively improved the flexural and tensile strengths of cement composites (Table 3). The enhancement of the flexural and tensile strengths can be attributed to the crack-bridging/branching capability of the RCF. However, further studies are required to demonstrate the effects of water content ratio, RCF size, curing period, CF recycling method, and dispersion method on improving the flexural and tensile strengths of RCF-added cement composites.

Table 3. Comparison of enhanced flexural and tensile strength extents in cement composite with RCF.

Authors	RCF Types	Matrix	Amount of RCF	Test Performed	Improvements
Nguyen et al. [56]	RCF + WH	Cement mortar	1.5% by weight of cement	Flexural, Stiffness	11.5% (8.58 MPa) and 20.5% (4.89 MPa) improvements in flexural strength and stiffness, respectively, compared to those of plain mortar (7.69 MPa and 4.05 MPa).
Baričević et al. [51]	RCF obtained from high-performance textiles	Cement mortar	1% by weight of cement	Flexural	15% improvement compared to that of plain mortar.

Table 3. *Cont.*

Authors	RCF Types	Matrix	Amount of RCF	Test Performed	Improvements
Patrinou et al. [45]	Milled RCF	Concrete	2% by weight of cement	Flexural	210.3% (7.2 MPa) improvement compared to that of plain concrete (2.3 MPa).
Patchen et al. [46]	RCF obtained by pyrolysis	UHPC	0.016% by weight of cement mix ^{c}	Flexural, Tensile	8.9% (10.7 MPa) lower than that of plain concrete composite (11.7 MPa). 27.8% (6.89 MPa) increase in tensile strength compared to that of the plain sample (5.21 MPa).
Wang et al. [50]	NaOH solution-treated RCF	Cement mortar	1% by volume of cement	Tensile	RCF without surface treatment shows a 65.30% improvement and RCF treated with 1 mol/L NaOH solution shows a 30.6% improvement compared to that of the plain mortar.
Zaid et al. [43]	RCF	Concrete, concrete with RA	6% by weight of cement	Tensile	20.1% (5.6 MPa) improvement without RA and 17.8% (5.3 MPa) improvement with RA compared to that of the control sample (3.9 MPa).
Akbar et al. [61]	Milled RCF	Cement paste	0.25% by volume of cement	Elastic modulus	30% improvement compared to that of plain mortar.
Li et al. [54]	RCF obtained by microwave-assisted pyrolysis	Early strength concrete	5%, 10%, and 15% by weight of cement	Flexural, Tensile	19.70% (5.53 MPa), 56.50% (7.23 MPa), and 53.25% (7.08 MPa) increase in flexural strengths compared to that of plain concrete (4.62 MPa). 8.80% (3.09 MPa), 22.54% (3.48 MPa), and 16.19% (3.3 MPa) increase in tensile strengths compared to that of plain concrete (2.84 MPa).
Li et al. [55]	Chemically recycled RCF	Cement-based matrix	1.0% by a cement weight	Flexural	34% (~7 MPa) and 48% (~8 MPa) improvement for RCF treated with hydrogen peroxide with concentrations of 30% and 50%, respectively, compared to the plain cement matrix (5.5 MPa).

Cement mix ^{c}: mix of cement, silica flume, sand, and ground quartz.

4.2. Fracture Characteristics

Fracture characteristics are used to investigate and assess the formation of cracks in cement composites [62]. Fibers such as steel, carbon, glass, and basalt improve the fracture characteristics of cement composites [62]. The use of RCF also achieves a significant improvement in the fracture characteristics of cement composites [51,56,58,61].

In 2016, Nguyen et al. [56] demonstrated that adding 1.5% RCF into cement mortar improved its fracture energy by 164% compared to that of plain cement mortar. Further investigation by Nguyen et al. [58] have shown that the addition of 1.5% RCF improved the fracture toughness and fracture energy of cement mortar in comparison to that of plain cement mortar. Akbar et al. [61] reported that the addition of 0.25% and 1% dosages of milled recycled CFs to cement paste increased the fracture toughness by 168% and 325%, respectively, compared with the plain cement sample; the addition of a 1% dosage of RCF increased the fracture energy 14 times compared to that of the plain cement sample. The improvement in the fractural characteristics of cement composites with the addition of RCF was attributed to the bonding between RCF and the calcium silicate hydrate mineral (C-S-H) [56,58].

The addition of RCF achieved better improvements compared to that with other forms of fiber-added cement composites. Baričević et al. [51] suggested that the superiority of RCF to glass and basalt fiber caused by its higher aspect ratio helps in crack bridging [51]. Baričević et al. (2022) [51] have investigated the effect of RCF size on cement composite properties; they found that adding textile waste RCFs of 5 mm and 10 mm lengths improved the specific energy by 100% and 263%, respectively, compared to that of plain samples.

Thus, adding RCF achieved positive effects on the fracture characteristics of cement composites (Table 4). The crack-bridging/branching capability of RCF enhances its fracture properties; however, only a limited number of studies have been conducted on the ability of RCF to improve the fractural characteristics of cement composites. Studies on the impact of RCF on the cement fractural characteristics that consider the water content ratio, size of the RCF, curing period, recycling method of CF, and dispersion method will further aid in understanding RCF's potential in cement composites.

Table 4. Comparison of the enhancements in fracture properties in cement composites with RCF.

Authors	RCF Type	Matrix	Mixing Amount of RCF	Fractural Characteristics	Improvements
Baričević et al. [51]	RCF obtained from high-performance textiles	Cement mortar	0.65% by weight of cement	Specific energy	100% and 263% increase compared to that of plain cement mortar with the addition of RCF (length of 5 mm and 10 mm).
				Fracture toughness	7% improvement compared to that of plain cement mortar.
Li et al. [55]	Chemically recycled RCF	Cement-based matrix	1.0% by weight of cement	Fracture energy	179% and 206% improvements for RCF treated with hydrogen peroxide with concentrations of 30% and 50%, respectively.
Nguyen et al. [56]	RCF	Cement mortar	1.50% by weight of cement	Fracture energy	164% increase compared to that of plain cement mortar.
Akbar et al. [61]	Milled RCF	Cement paste	0.2%, 1%, 1.25%, and 1.5% by weight of cement	Fracture energy	Increase by 125.88% (7.68 N/m), 1298.53% (47.55 N/m), 1202.06% (44.27 N/m), and 886.471% (33.54 N/m), respectively, compared to that of the plain composite (3.4 N/m).
				Fracture toughness	168%, 325%, 255%, and 237% increase, respectively, compared to that of the plain cement paste.

4.3. Electrical Properties

Cement composites are poorly conductive and intrinsically piezoresistive materials. Adding conductive materials such as CF improves the electrical properties and piezoresistive sensing capabilities of cement composites [63]. When added to cement composites, the CF strands overlap and form a conductive path, decreasing the electrical resistivity of the cement composite [4]. Studies have concluded that the use of RCF improves the electrical properties of cement composites as described in Table 5 [33,34,36,38,45,47,64,65].

Table 5. Comparison of the enhancements in electrical properties in cement composites with RCF.

Authors	RCF Type	Matrix	Mixing Amount of RCF	Electrical Characteristics	Improvements
Mobili et al. [64]	RCF	Cement mortar	0.05% and 0.2% by volume of cement	Electrical resistivity	47% and 67% decrease compared to that of plain mortar.
Mobili et al. [64]	RCF	Gasification char-added cement mortar	0.05% and 0.2% by volume of cement	Electrical resistivity	68% and 80% decrease compared to that of plain mortar.
Mobili et al. [65]	RCF	Cement mortar	0.2% by volume of cement	Electrical resistivity	83% decrease compared to that of plain mortar.
Belli et al. [33]	RCF	Cement mortar	0.2% of RCF and 4% GNP by volume of cement	Electrical resistivity	92% decrease compared to that of plain mortar.

Patrinou et al. [45] demonstrated that adding RCF to cement paste decreases resistivity compared to that of plain cement paste. Further, they concluded that the change in resistivity depended on the RCF dosage [45]. Their study found that the percolation threshold is at 1.0% of RCF, and increasing the RCF dosage further increased the resistivity [45].

Mobili et al. [64] incorporated 0.05 and 0.2 vol% of RCF in cement mortar and observed that electrical resistivity decreased by 47% and 67% compared to that of plain mortar. Further, they concluded that gasification char mixed with 0.05 vol% RCF and 0.2 vol% RCF further decreases the resistivity by 68% and 80%, respectively. Mobili et al. [64] further reported that alternating current (AC) is preferred over direct current (DC) while measuring the CF-added cement composite resistivity to preventing electrodes from being polarized or degrading the material characteristics over time via ion migration. In another study, Mobili et al. [65] have shown that the addition of 0.2 vol% RCF decreased the electrical resistivity by 83% compared to that of the plain mortar. Further, they concluded that adding graphitization char with RCF achieved resistivity as low as 90% compared to that of the plain cement mortar [65]. Similarly, Belli et al. [33] have shown that 0.2 vol% of RCF mixed with 4% of graphene nanoplatelets (GNP) on mortars achieved pronounced piezoresistivity and a 92% decrease in electrical resistivity compared to the mortar-only composite (80 Ω·m). Segura et al. [36] demonstrated the potential of RCF in cement-based sensing composites. The addition of RCF to a cement composite showed piezoresistive characteristics with the potential for self-sensing. They concluded that the fiber dispersion and waviness of the RCF significantly affected the piezoresistive characteristics [36]. However, a limited number of studies have investigated the addition of RCF to cement composite for piezoresistive sensing capabilities. Studies have shown that the incorporation of various conductive materials, such as VCF [66], carbon nanomaterial [67], and nickel powder [68], has a positive effect on the sensing capabilities of cement composites. RCF, being potentially eco-friendly and economical, could serve as an alternative for developing self-sensing cement composites. The addition of RCFs positively affected the electrical properties of cement composites. The use of RCF for developing sensors has considerable potential in the future and requires further study.

4.4. Workability

The fluidity of fresh concrete before hardening is referred to as the workability of cement. One challenge in using CF in cement composites is their effect on the workability of cement composites [46,69]. Multiple studies have been conducted over the years on the workability of cement composites with added RCFs. For example, Li et al. [54] have shown that the slump values of fresh RCF-added concrete composites is at 150 mm, 80 mm, and 35 mm with additions of 5%, 10%, and 15% RCF, respectively. Faneca et al. [34] have investigated the workability of four different dosages of cement composites with added

RCFs. At a high dosage of 1.4%, RCF-added cement composites showed a decrease in workability. They concluded that fibrillated sheet-type RCF showed better dispersion in cement composites than single fiber types in cement composites [34]. Similar results were demonstrated by Segura et al. [36], who revealed that fibrillated sheet-type RCF-added cement composites exhibited better dispersion than monofilament RCF-added cement composites. Further, they showed that, in addition to the type of RCF, the number of fibers per unit volume affect the workability of cement composites [36]. Baričević et al. [51] have shown that 5 mm and 10 mm RCF-added cement composites showed flow values of 119 mm and 111 mm, respectively. They reported that the two main parameters that affected the workability of RCF-added cement composites were the aspect ratio and dosage of RCF in the mixture [51]. Further, they concluded that the dispersion technique was essential for proper workability [51].

In general, workability tests primarily measure the ease of handling and mixing cement composites by considering the flow of material. However, workability tests do not consider parameters such as shear stress, shear rate, viscosity of fluid, and yield stress, which are the primary governing factors for the flow of cement composites [70,71]. These parameters, which govern the flow, are known as rheological parameters, and the tests that deals with the flow and deformation of cement composites under these parameter are known as rheological tests [71]. For a comprehensive investigation into the fluidity of RCF-added cement composites, rheological tests based on shear stress and viscosity should be conducted.

4.5. Microstructural Properties

The microstructural properties of RCF-added cement composites were studied at the micro level. Scanning electron microscopy (SEM) is a typical method used to monitor microstructural properties. SEM observations show that RCF improves the microstructural properties of cement composites. Nguyen et al. [56] reported that RCF exhibits good bonding between C-S-H minerals. Samani and Lak [32] conducted SEM on a fracture surface, showing proper dispersion of RCF in the mortar and the crack-bridge effect of RCF on the mortar matrix.

Wang et al. [50] compared an untreated RCF-containing cement composite with an alkali-treated RCF-containing cement composite [50]. As shown in Figure 4a, their SEM images showed that the untreated RCF did not properly bond within the cement matrix, and when treated with a 1 mol/L NaOH solution, the RCF surface bonded with the cement hydration product, as shown in Figure 4b,c [50]. The SEM images, as shown in Figure 4g, indicate that the treatment with 3 mol/L NaOH resulted in fiber breakage [50]. Wang et al. [49] reported the same result; their SEM images show that the untreated RCF did not properly bond with the cement matrix due to presence of epoxy on the RCF surface, as shown in Figure 5a. However, when treated with a saturated (simulated concrete) pore solution (SPS) for 0.5 h, the RCF surface roughened without damaging it, hence creating a tight bond with the cement matrix, as shown in Figure 5c–f [49]. In the SEM images shown in Figure 5g–i, the RCF surface shows a needle-shaped ettringite when treated with montmorillonite nanoclay emulsion (mNCE), which helps in creating a tight bond between RCF and the cement matrix [49]. Similarly, when first treated with (SPS) for 0.5 h and later with triisopropanolamine (TIPA), a dense layer of cement hydration products is created, as shown in Figure 5j [49].

Akbar et al. [37] obtained an SEM image of cement composite incorporating an RCF of 1% total volume. The RCF diverted the crack paths and caused crack branching when a load was applied to the cement composite [37]. Further, they concluded that the RCF exhibited a pullout effect and improved the tensile strength [37]. Zaid et al. [43] demonstrated that crack bridging became visible when the RCF fibers were dispersed uniformly. Mobili et al. [64] conducted an SEM observation, which showed that RCF was more bonded with the cement matrix than VCF. Further, they observed that the flexural strength of the RCF-containing cement composite depended on the bonding between the cement and RCF.

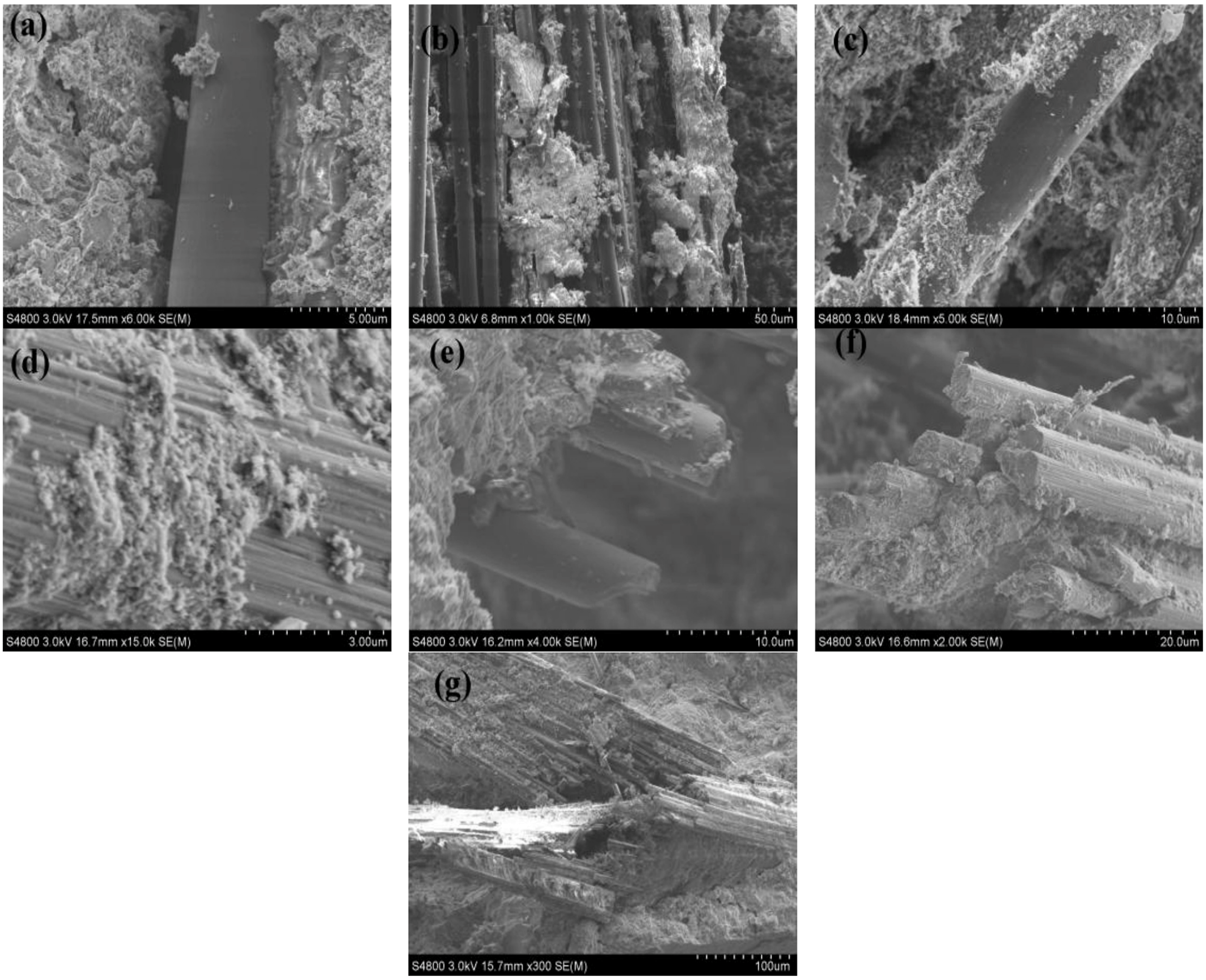

Figure 4. SEM image of RCF-added cement composite with different forms of treatment: (**a**) untreated, (**b**–**d**) treated using a 1 mol/L NaOH solution, (**e**,**f**) treated using a 2 mol/L NaOH solution, and (**g**) treated using a 3 mol/L NaOH solution [50].

For a detailed study of mineralogical changes in a cement matrix with the addition of RCF, X-ray diffraction (XRD) is preferred over SEM images. Akbar et al. [37] utilized XRD to investigate the changes in the crystalline phases of RCF-added cement composites as a function of temperature. XRD investigation showed that RCF does not undergo any chemical reaction with cement hydration products. However, due to the active nucleation sites on the surface of RCF, it promotes the hydration process. They also reported that RCF can promote the hydration process at a high temperature of 200 °C [37]. Akbar et al. [42] also reported that RCF promotes the hydration products without undergoing a chemical reaction with cement hydration products. They concluded that silica fume (SF) undergoes a chemical reaction with CH to form denser CSH gel around the RCF, which helps improve the mechanical properties of cement composites [42].

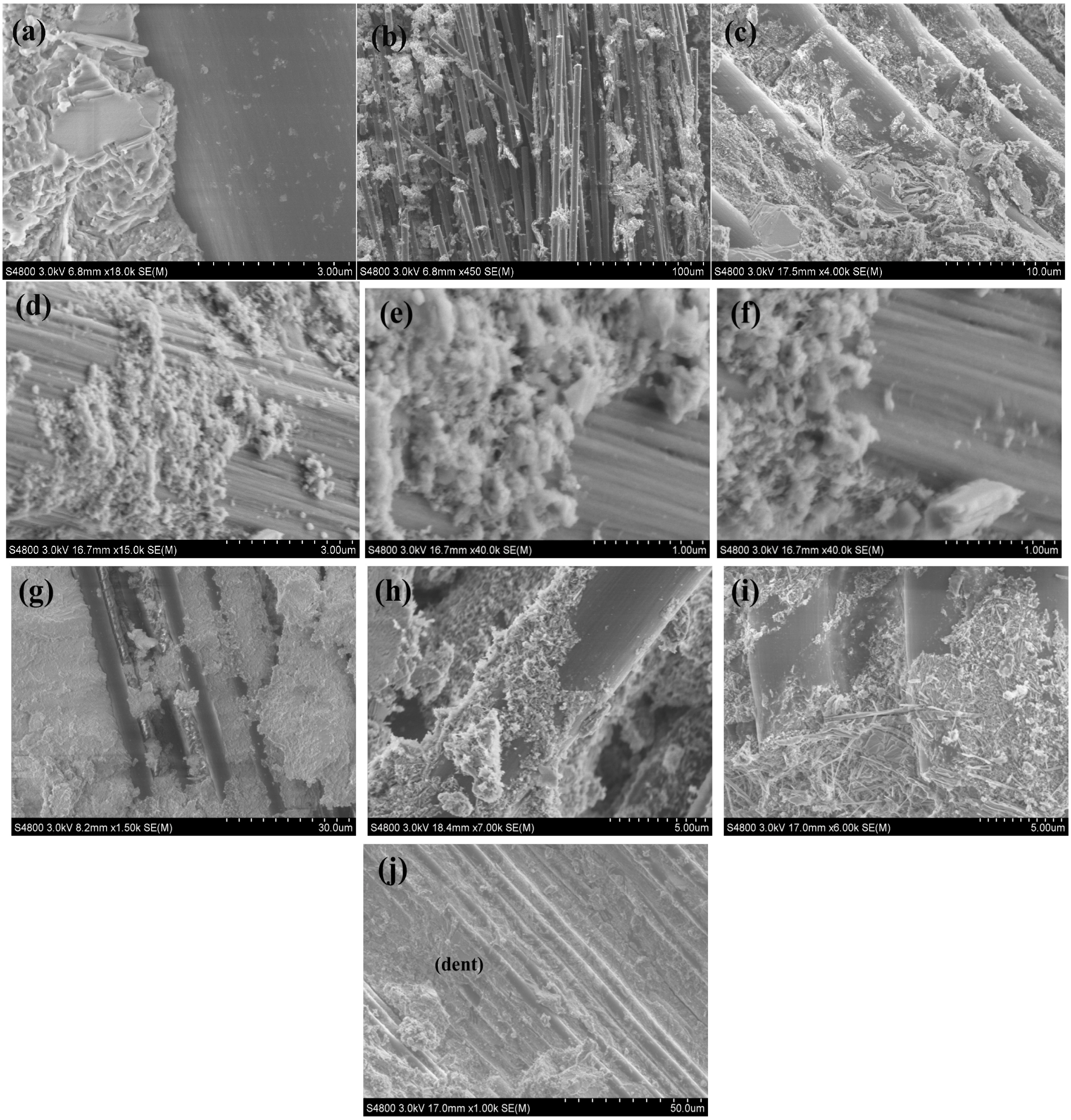

Figure 5. SEM image of chemically modified, recycled carbon fiber-added cement composite with different form of treatment: (**a**) untreated, (**b**) SPS 2.0 h, (**c**–**f**) SPS 0.5 h, (**g**–**i**) mNCE, (**j**) SPS 0.5 h/TIPA [49].

4.6. Impact Resistance and Durability

To the best of our knowledge, only one study has evaluated the freeze–thaw durability of RCF-added cement composites [72]. Nassiri et al. [72] have investigated the durability of concrete by replacing a certain volume of aggregates with mechanically recycled CF. RCF dosages of 0.5%, 1%, and 2% of volume were incorporated, and freeze–thaw durability was evaluated according to ASTM C666 [72]. RCF additions of 1% and 2% of volume on pervious concrete showed significant improvement in its freeze–thaw durability [72].

Cement composite with a 2% volume of RCF achieved 238 freeze–thaw cycles with less than 5% mass loss [72]. They concluded that RCF and pervious concrete have excellent potential for use in cold regions [72]. The lack of research in this field makes it challenging to establish a solid argument regarding the durability of RCF-added cement composites [72].

The application of RCF to cement composites improved the impact resistance properties of the cement, as is suggested by previous studies. The ability of concrete to sustain repeated impacts and absorb energy without breaking is referred to as impact resistance [73]. Only a few studies have been conducted on the impact resistance of RCF-containing cement composites [5,54,72]. For example, Li et al. [54] conducted an impact resistance test under different impact energies on a concrete composite that contained 10% RCF of 24 mm length. At 50 J of impact energy, concrete composites with RCF showed an average impact number of 338.8, which is a 2221% increase compared to the concrete composite without RCF [54]. Similarly, Li et al., (2021) [5] conducted an impact resistance test at 50 J of impact energy on a concrete composite with a 10% dosage of RCF. The results indicated an average impact number of 356, which is a 2305% increase compared with that of a concrete composite without RCF.

5. Dispersion Methods for RCF

Good dispersion of RCF in cement composites is vital because the agglomeration of fibers can negatively affect the mechanical properties. Various technologies have been used to disperse CFs and RCFs in cement composites; however, a comparative analysis of the different dispersion processes of RCF in cement composites is yet to be performed. A novel method of RCF dispersion was achieved by mixing RCF in cement composites. Faneca et al. [34] have investigated the mixing methods of RCF into cement composites. In their study, the first batch of composites was prepared by mixing cement, aggregates, water, and additives, and then RCF was added to the mixture. This method is termed as the wet-mix method. Another batch was prepared, where, along with cement, aggregates and RCF were mixed first and, later, water and additives were added. This method is known as the dry-mix method. The batches that were prepared using the wet-mix method showed better workability and electrical properties than those prepared using the dry-mix method [34].

Admixtures such as SF have been effectively used to disperse RCF in cement matrices. Studies conducted by Akbar et al. [61] and Akbar et al. [42] have demonstrated the use of SF for realizing a better dispersion of RCF in cement composites. Ultrafine SF created mechanical separation between individual fibers by acting as a wedge, disallowing agglomeration of the fibers [42,61,74,75].

Li et al. [5] and Li et al. [54] applied a pneumatic dispersion method to disperse the RCF in cement composites. They utilized a pneumatic disperser comprising vessels with valves, through which a high-pressure airstream was applied to separate the RCF fibers [5,54]. Sizing agents, such as epoxy resins, that are attached to the RCF surface have negative effects on dispersion [42]. RCF obtained from thermal recycling pyrolysis has shown better performance in terms of removing sizing agents [42].

Numerous studies in the literature have utilized mixing techniques to ensure the proper dispersion of RCF within a cement matrix. Studies on the dispersion of RCF in cement matrices by utilization of dispersants or treatment on RCF are rarely conducted. In the case of VCF, the use of dispersants such as hydroxyethyl cellulose, carboxymethyl cellulose sodium, hydroxypropyl cellulose, and polyvinyl pyrrolidone have demonstrated improved dispersion in cement composites [76,77]. Further investigations are necessary to explore the potential of dispersants in achieving the dispersion of RCF within a cement matrix while preserving good mechanical and electrical properties.

The dispersion of VCF using a dispersant has shown weakened bonds between fibers and the cement matrix, which leads to poor mechanical and electrical properties [78]. Chemical functionalization has been proposed as a superior method for dispersion while maintaining good mechanical and electrical properties [78]. Lavagna et al. [78] proposed a limited functionalization technique aimed at improving the dispersion of VCF without causing damage to the fibers. In their study, VCF underwent an ultrasonication process with a piranha solution [78]. Following this ultrasonication process, the VCF was further dispersed in water by using an ultrasonication tip [78]. Their conclusion was that this method guarantees the proper dispersion of VCF within a cement matrix, thereby enhancing the electrical and mechanical properties of the composite compared to the untreated VCF-added composite [78]. Similar techniques could potentially be utilized for improving the dispersion of RCF in cement matrices while improving the mechanical and electrical properties of cement composites.

6. Future Prospects of Using RCF in Cement Composites

Previous studies have sufficiently demonstrated the tremendous potential of RCF inclusions in cement composites. In general, RCF–added cement composites exhibit good mechanical properties. Thus far, numerous studies have been conducted to validate RCFs as cement composite fillers. Parameters such as the water content ratio, RCF size, aspect ratio, curing period, recycling method, and dispersion method have also been investigated.

For electrical properties, RCF-added cement composites are promising as potential sensors; however, only a few studies have been conducted. Further studies on RCF and its piezoresistive characteristics at different temperatures will help identify the potential of RCF as a sensor for cement composites. In addition, the capability of RCF-added cement sensors under different environmental conditions is another topic that requires further discussion.

7. Conclusions and Discussion

This article reviewed the effect of adding RCF on the mechanical, fractural, electrical, microstructural, and workability properties of cement-based materials. There has been an increase in the use of CF in many sectors because of its excellent properties. Further, CF applications have increased waste CF, which will continue to increase without intervention. The production of CF is expensive compared to that of its competitors, such as steel. Therefore, to resolve the issue of CF waste and the consumption of resources during its production, research has been conducted on repurposing CF. One way of reusing waste CF is to add RCF to a cement composite. Several studies have been conducted on RCF-containing cement composites. The points discussed in this paper are summarized as follows.

1. The use of RCF significantly improves the mechanical properties of cement composites and can potentially be an eco-friendly alternative to VCF. The crack-bridging/branching capability of RCF has led to improvements in the mechanical properties of the cement composites.
2. Significant improvements in the fractural characteristics of cement composites such as fracture energy and toughness were achieved by adding RCF. However, further studies are required to understand the effects of RCF on cement composites.
3. Microstructural properties have indicated that RCF and cement matrices have a strong bond; however, the presence of residual epoxy in RCF reduces the bonding of RCF with a cement matrix.
4. RCF has a positive effect on the electrical properties of cement composites, and RCF-added cement composites have excellent potential as self-sensing materials.
5. The addition of RCF decreased the workability of cement composites. The crucial parameters for the proper workability of RCF-added cement composites are the dosage and aspect ratio of the RCF.
6. Although significant research has been conducted on the mechanical properties of RCF-added cement composites, studies on the effect of RCF on the durability of cement composites are limited.

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