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Review

## A Critical Review of Research on Reuse of Mechanically Recycled FRP Production and End-of-Life Waste for Construction

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Received: 25 April 2014; in revised form: 28 May 2014 / Accepted: 4 June 2014 /

Published: 17 June 2014

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**Abstract:** For the last three decades, fiber reinforced polymer (FRP) composite materials have been widely used in major engineering industries. Managing FRP waste is becoming an important issue due to the growth in the production of FRP composite materials. In this article, the issue of FRP waste management is discussed and the commonly used methods for the handling of FRP waste are reviewed. One potentially viable use of FRP waste is in the partial replacement of fillers or aggregates in cementitious materials (particularly portland cement mortar and concrete). A number of important prior investigations performed on the use of FRP waste in concrete and mortar are reviewed. The results from most of those investigations suggest that FRP aggregates significantly reduce the strength of cementitious materials with little significant effect on durability. Recommendations for future research in this area are provided for producing stronger mortars and concretes incorporating FRP production and end-of-life waste.

**Keywords:** aggregate; concrete; fiber reinforced polymer; filler; mechanical properties; recycling; reuse

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### 1. Introduction

Fiber-reinforced polymer (FRP) composite materials are used extensively and increasingly in major industries including aerospace, marine, construction, electrical, automotive, domestic appliances, furniture, and sports equipment. FRP composite materials used in these industries typically consist of glass, carbon, or aramid fibers, which are either continuous or discrete, encased in a matrix of

thermosetting resins that have fiber concentrations typically in the range of 12%–60% by volume [1], and inorganic fillers (also known as “extenders”) typically in the range of zero to 20% by volume. Some types of polymer composites such as bulk molding compounds (BMC) can contain fillers (usually calcium carbonate, talcum, or mica powders) with up to 50% of the composite weight (which for BMC materials is close to the volume fraction) [2]. FRP composite materials have important advantages over many traditional construction engineering materials (such as steel and concrete, and timber (wood) in certain circumstances). Those advantages typically include lower densities (*i.e.*, light weight), higher mechanical properties in certain directions, ease of production in different shapes, ease of installation, and greater durability in harsh chemical and aqueous environments. Disadvantages relative to conventional construction materials typically include higher costs, lower temperature resistance and fire performance, lack of standard profiles and parts, lack of accepted material and design specifications, and difficulty of recycling. According to the American Composite Manufacturers Association (ACMA), one of the first known FRP products was produced less than a century ago (in the mid-1930s) in an experimental production of a boat hull using fiberglass fabric and polyester resin [3]. The use of FRP components for civil engineering structures started to become popular in the mid-1990s [4]. The use of FRP in the marine industry started about six decades ago and has led to increasing number of reinforced plastic recreational and working boats, the vast majority being fiberglass (glass fiber reinforced polyester). The International Council of Marine Industry Associations (ICOMIA) has estimated that there are more than 6 million recreational boats in Europe alone [5]. Because FRP composite materials are highly durable, end-of-life disposal has not been a major issue to-date. However, the number of the FRP-incorporated vessels and structural members that are approaching the end of their service or functional lives is increasing rapidly resulting in a growing rate of waste accumulation. Another source of FRP waste is the scrap from the production process of FRP materials, parts and sections; in all production processes portions of the raw material and the final product are rendered unusable. The total combined volume of end-of-life and production waste generated by the glass thermoset composites market in Europe is expected to reach 304,000 tonnes (metric tons) by 2015 [6].

It is predicted that in the U.S. the demand for FRP will climb to nearly 2 million tonnes in 2017 [7]. According to the European Composites Industry Association (EuCIA), in 2013 approximately 1.02 million tonnes of glass fiber reinforced polymer (GFRP) composite materials were manufactured in Europe [8]. In 2010, Osmani and Asokan [9] reported that in the United Kingdom alone the annual production of GFRP waste was around 55,000 tonnes with an expected annual production increases of 10%. Most of the production and end-of-life disposal waste is landfilled. According to Osmani and Asokan, in the United Kingdom, about 90% of the GFRP waste is landfilled [9].

Since unlike many of the widely used materials—particularly metals, wood, and concrete—recycling and reusing FRP waste is more difficult and expensive. Finding an application for minimally recycled FRP waste will be particularly valuable as it reduces the amount of FRP waste disposed of in landfill sites and the associated high costs. One of those potential applications is using FRP waste as a partial replacement of filler (aggregate) in portland cement mortar and concrete. In this review article, (1) the currently used methods for FRP waste recovery and recycling are discussed, (2) past work on incorporating recycled FRP in cementitious materials is reviewed, and (3) suggestions are made for further investigations to study the viability of using FRP waste in concrete.

## 2. Fiber-Reinforced Polymer (FRP) Waste Management Methods

FRP waste can sometimes be directly used in construction. For example, the scrap generated from the production of glass fibers reinforced polymer (GFRP) reinforcing bars (typically in the form of short rebars, or defected rebars with poorly bonded glass fibers) can be used in less-structurally-sensitive concrete such as flatwork and slabs on ground. In addition to the direct reuse of FRP waste, there are three main ways to manage FRP waste: (1) landfilling, (2) incineration, and (3) recycling. Landfilling remains the most popular solution to manage FRP waste [10]. Producing FRP and manufacturing FRP members leaves a notable amount of waste. In highly efficient processes such as pultrusion, waste (scrap) is in the range of 3%–5%, while in less efficient hand lay-up processes, it typically approaches 15% [11,12]. In aerospace production, CRFP pre-preg scrap can approach 40% [12]. An average value of 10% is reported in [11]. Landfilling costs are predicted to increase sufficiently to discourage waste disposal in the future [13]. The high costs of landfilling FRP waste increases the overall cost of FRP products. At the time of preparing this article, the cost of FRP waste management (including pickup and landfilling the scraps) in the U.S. was in the range of \$45–\$200 per tonne. In addition, landfilling is the least sustainable option. In several European Union countries, including Germany, landfilling regulations for FRP waste are very strict [14].

Incineration is a less-commonly adopted method for disposal of thermoset polymer composites including FRP composite waste [15,16]. Incineration allows some energy recovery from the heat produced during the combustion process due to the high calorific value of FRP materials [17]. However, the cost of FRP incineration is higher than landfilling. In general, incineration facilities charge more for incinerating FRP waste because both the high calorific content and the toxic emissions tend to overload the system, meaning they can only process a limited amount of waste [13]. An additional problem with the incineration of GFRP is that about 50%–70% of the residue material is mineral and is left as ash, which still needs to be landfilled. A co-processing method known as the “cement-kiln” method that shares similarities with incineration has been introduced in Germany [14,18]. In this method, size-reduced GFRP waste is fed to a cement production kiln as a raw material for the production of cement clinker and as a secondary fuel. In the kiln, the organic resin burns, providing energy, and the mineral (from the fibers and the fillers) constituent turns into calcium oxide, which is the primary component of portland cement, and provides feedstock for the cement clinker.

Considering the increasing costs, environmental issues, and legislative limitations associated with landfilling and incinerating FRP waste, recycling and reusing waste is becoming an increasingly viable alternative for managing FRP waste. Recycling FRP can be categorized into two main groups: (1) reclaiming the fibers from the polymeric matrix, and (2) mechanical recycling [19]. Fiber reclamation consists of recovering the fibers from the FRP, typically by employing an aggressive thermal or chemical process to break-down the thermoset matrix so that the fibers can be released and collected. Fiber reclamation processes can be attractive options for recycling carbon fiber reinforced polymer (CFRP) materials for two reasons: (1) carbon fibers have high chemical stability [10], and usually their superior mechanical properties are not significantly affected during reclamation, and (2) reclamation processes are costly and have economic justification only for extracting expensive filaments such as carbon fibers. Several companies have been reclaiming and reusing high-value carbon fiber from CFRP waste [20]. Companies such as Boeing and Airbus have invested in efforts to

recycle carbon composites in order to develop methods that are as robust as those for aluminum, steel and other metals and achieve high recycling percentages [21]. While recently some successful efforts have been made for reclaiming glass fibers from GFRP waste, it is not yet economical to reclaim lower cost glass fibers [22–24].

An overview on carbon fiber reclamation processes is presented by Pimenta and Pinho [19]. Three main methods have been used for fiber reclamation: (1) pyrolysis, (2) oxidation, and (3) chemical recycling. Pyrolysis is the thermal decomposition of organic molecules in an inert atmosphere (e.g., Nitrogen), and is one of the most widespread recycling processes for CFRP. During pyrolysis, the CFRP is heated up to 450–700 °C. In this temperature range, the polymeric matrix is volatilized into lower-weight molecules, while the fibers are minimally affected and recovered [25]. Oxidation is another well-documented thermal process in which the polymeric matrix is combusted in a hot and oxygen-rich flow of a gas such as air [10,26]. Compared to pyrolysis, this method has a higher tolerance to waste contamination, but can result in shortening and significant strength loss of fibers [19]. In chemical recycling (also known as solvolysis), FRP waste is exposed to a reactive material such an acid under low temperature (typically less than 350 °C), resulting in the decomposition and separation of the polymeric matrix material [27,28]. Chemical methods can, however, cause negative environmental impacts if they make use of hazardous materials.

Mechanical recycling started commercially in the 1970s [14]. There are different types of mechanical recycling, though all of them involve breaking down the composite material and successively reducing the particle size of recycled materials through shredding, crushing, milling, or other similar mechanical process; the resulting scrap pieces can then be segregated, by using sieves and cyclones, into powdered products (rich in resin) and fibrous products (rich in fibers) [10,29]. Mechanical recycling is the most widely used approach for recycling FRP thermoset polymeric fibrous composite materials [28,30]. Finally, there are recycling techniques that can be performed and be used for producing specific types of FRP products. For example, Adams *et al.* [28] developed a method that incorporates splitting, crushing, and hot forming of GFRP sheets obtained from boat hulls to create new GFRP plates and tubes. They showed that by using their method over 50% of the original mechanical properties, such as the Young's modulus, tensile strength, and interlaminar shear strength, can be retained.

### 3. Applications of Recycled FRP Waste in Cementitious Materials

Mechanical processing remains the most commonly-used method for processing the waste from FRP composite materials. Mechanically recycled FRP waste has a potential application as filler in portland cement mortar and concrete. Limited investigations have been performed on this topic and are discussed in this section.

#### 3.1. Durability and Physical Properties

Some of the prior studies suggest that the partial replacement of fine aggregates with mechanically recycled FRP does not affect the durability of portland cement concrete and mortar negatively. Tittarelli and Moriconi [31] investigated the alkali–silica reactivity (ASR) of ground GFRP using the chemical method prescribed by American Society for Testing and Materials (ASTM) [32]. The results

did not show any potential deleterious reactivity due to the glassy part present in the waste. Moreover, good durability of polyester, vinylester and epoxy resins against alkali attack (another durability issue) is generally reported in the literature [33]. FRP reinforcing bars (rebars) for concrete reinforcement are a well-accepted product in construction for this reason [34]. Also, Tittarelli and Moriconi found that capillary water absorption and drying shrinkage of cement-based materials with the GFRP addition resulted in significantly lower values than those of the cement-based materials manufactured without the GFRP addition. The findings from the investigations of Asokan *et al.* [35] showed that there was almost no drying shrinkage of concrete with addition of ground GFRP waste powder. Tittarelli *et al.* [36,37] reported that in mortars the risk of cracking induced by restrained drying shrinkage and capillary water absorption is significantly lower in the presence of GFRP powder. However, there are downsides to utilizing FRP waste in cementitious materials. For example, fine FRP particles can reduce the workability of concrete due to their high surface area, and in order to maintain the workability a notable change in *w/c* ratio or the addition of a significant amount of superplasticizer is required [38,39]. However, Tittarelli and Shah [6] observed that ground GFRP reduced the viscosity of cement paste and did so more effectively than fly ash. Tittarelli *et al.* [36] reported that replacing 5%–10% of sand volume with ground GFRP causes an increase in autogenous shrinkage. They also found that the addition of ground GFRP delays the setting time of cement paste. Finally, Tittarelli [37] found that the addition of GFRP dust improves thermal insulation properties. They also observed that GFRP dust reduces the salt crystallization (efflorescence) on the surface of mortar specimens which have been immersed in NaCl and Na<sub>2</sub>SO<sub>4</sub> solutions.

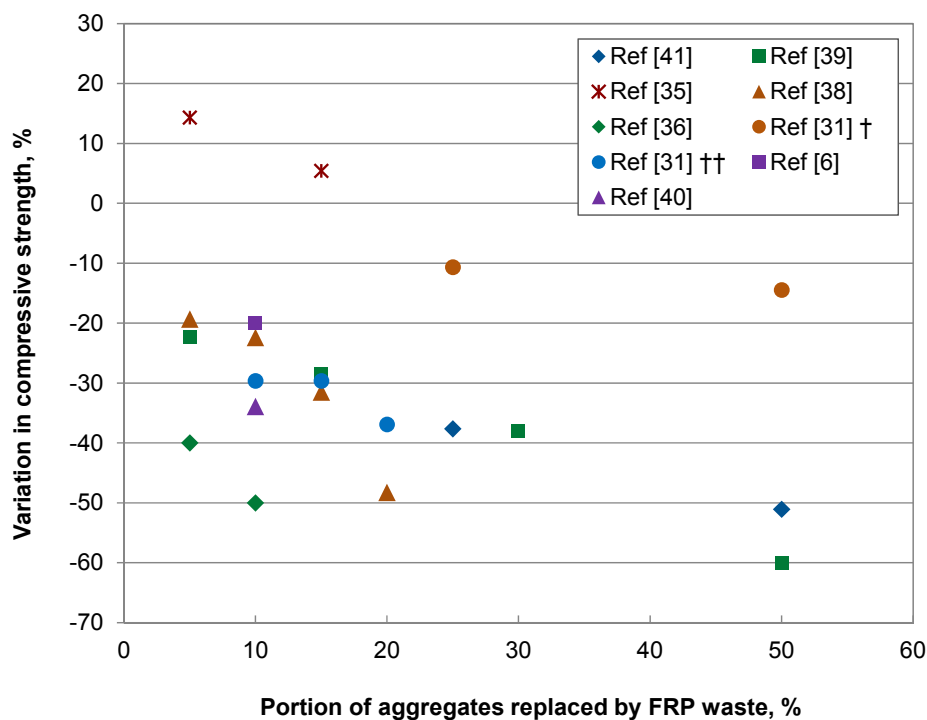
While from these limited studies it appears that finely ground FRP filler does not affect the durability of cementitious materials, in order to obtain conclusive results, further durability tests must be performed on different types and sizes of recycled FRP waste as well as on the mortars and concretes which incorporate them. In addition, rheology investigations should be performed to determine the size range of ground FRP that has the most significant effect on the workability of fresh cement paste (the matrix material of mortar and concrete).

### 3.2. Mechanical Properties

The main problem caused by using recycled FRP in cementitious materials appears to be associated with the mechanical performance. Figure 1 presents results from the key prior investigations that have studied the effect of replacing aggregates (fillers) with mechanically recycled FRP on the compressive strength of cementitious materials. In this figure, the reduction or increase in the compressive strength of the concrete or mortar is plotted against the portion of aggregate in the cementitious material, which has been replaced with recycled FRP waste. It is important to point out that in every one of these prior investigations some of the materials, characteristics, specifications, and ratios (weight or volume) used were different so that the data plotted in Figure 1 is intended to show trends in the behavior. Variables in the prior studies included the type of cementitious material (concrete *vs.* mortar), water to cement ratio and mix constituents/proportions of the cementitious material, the type of FRP waste (GFRP *vs.* CFRP, with different fiber contents and resin types), and finally the size of recycled FRP and the aggregate that were replaced (fine *vs.* coarse). A clear trend can be seen in the results from the majority of the prior investigations; replacement of aggregates with FRP waste resulted in a significant drop in the

strength of the cementitious material. The details of the prior work shown in Figure 1 are discussed in what follows.

**Figure 1.** The effect of replacing aggregates in cementitious materials with fiber reinforced polymer (FRP) waste on the compressive strength of concrete as reported by different investigators. (†: glass fiber reinforced polymer (GFRP) waste used in self-compacting concrete; ††: GFRP waste used in mortar) [6,31,35,36,38–41].



### 3.2.1. Replacement of Fine Aggregates

Asokan *et al.* [39] used ground GFRP waste powder that passed 2 mm sieve as a substitute to fine aggregate in concrete. Fifty percent of the GFRP waste powder particles was below 18  $\mu\text{m}$  and almost 90% of the GFRP waste powder particles was below 63  $\mu\text{m}$ . They produced concrete batches with fine aggregate replacements of 5%, 15%, 30%, and 50%. They observed a reduction of 60% in compressive strength when replacing 50% of the fine aggregate by GFRP. However, the values of  $w/c$  ratio for control and 50% GFRP batches were 0.5 and 0.71 (for the purpose of maintaining a constant concrete workability). Such a reduction in  $w/c$  ratio causes an approximately 40% decrease in compressive strength [42]. Asokan *et al.* [35] performed another study in which superplasticizer (2.0% by the weight of cement) was used in concrete batches with 5% and 15% replacement of fine aggregates with ground GFRP. Although the concrete batches containing GFRP had slightly higher  $w/c$  ratios (0.37 and 0.38 in GFRP-incorporated concrete and 0.34 in the control concrete), they had higher compressive strength values compared to control concrete.

Tittarelli *et al.* [36] used a GFRP powder obtained from a shipyard as an industrial by-product to partially replace the natural silica sand in mortars. The GFRP powder composition was about 20% by volume of glass fibers and 80% by volume of polyester resin. SEM observation showed that the powder comprised polymeric granules surrounding the fibers of a low alkali glass. Replacing 5% and

10% of natural silica sand in mortars with a  $w/c$  ratio of 0.5 caused significant reductions of approximately 40% and 50% in compressive strength, respectively (based on the graphs presented in their article). The reductions in flexural strength were approximately 17% and 20%. In another study, Tittarelli and Shah [6] observed that replacing 10% of natural silica sand with the GFRP powder in mortars with a  $w/c$  ratio of 0.50, resulted in a decrease of 50% in compressive strength when wet curing was adopted. They observed that when the concrete specimens were dry-cured (as in the open air or in the oven), the mechanical penalization due to GFRP dust addition was partially recovered. A similar observation was made by Asokan *et al.* [39]. Tittarelli and Moriconi [31] used the GFRP powder as a partial replacement of natural calcareous sand in mortars of higher  $w/c$  ratio (0.62). Their results show that replacing 20% of sand with the GFRP powder resulted in an approximately 35% decrease in the compressive strength (based on the graphs presented in their article). They also used the GFRP powder to replace 25% and 50% of sand in self-compacting concrete with a  $w/c$  ratio of 0.62 and observed relatively low values (10% and 15%, respectively) of decrease in compressive strength.

Correia *et al.* [38] used the fine particles generated during the production of GFRP products by the cutting of pultruded profiles. Ninety-six percent of the GFRP particles were smaller than 63  $\mu\text{m}$ . These particles were used as the partial replacement of fine aggregates in concrete. They investigated the volume replacement ratios of 5%, 10%, 15%, and 20%, and they used the same amount of superplasticizer in control and GFRP batches. Like Asokan *et al.* [39], they used higher  $w/c$  ratios for higher GFRP waste content to maintain a constant workability ( $w/c$  ratios for the control and 20% GFRP were 0.40 and 0.46, respectively). They observed reductions of 48% in compressive strength and 47% in splitting tensile strength due to replacing 20% of fine aggregates with GFRP particles. These reductions are in part due to the higher  $w/c$  ratio in the GFRP mix.

### 3.2.2 Replacement of Coarse Aggregates

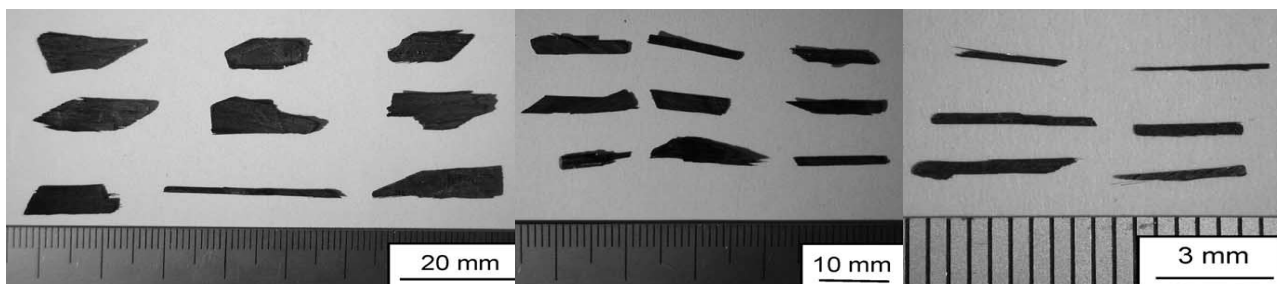
Alam *et al.* [42] used GFRP scrap that was excess from the composite manufacturing process for casting waterslides. The GFRP was coated with a thin layer of gel to make it smooth. The long strips of the scrap were recycled by simply cutting them into small squares using an abrasive wet tile saw. The recycled GFRP was used to replace portions of (25% and 50% by volume) coarse aggregate in concrete with a water to cement ratio ( $w/c$ ) of 0.4. The GFRP particles and coarse aggregate had similar maximum particle sizes. However, the GFRP particles had similar sizes while the coarse aggregates were well-graded. Replacement of aggregates with recycled GFRP resulted in up to more than 50% and 40% decreases in the compressive strength and flexural strength of concrete, respectively. The very smooth surface of the GFRP pieces resulted in a poor bond with mortar and was an important reason for the significant loss of strength in the concrete. The flat shape and poor gradation of the GFRP particles are among other possible reasons for the poor mechanical performance of concrete.

Ogi *et al.* [43] used recycled CFRP waste as an additional filler in concrete batches with  $w/c$  ratio of 0.45. They crushed CFRP to relatively flat pieces of three different size categories with average length by width values of 3.4 mm  $\times$  0.4 mm, 9.9 mm  $\times$  2.2 mm, and 21 mm  $\times$  7.7 mm. The thickness of CFRP pieces was in the range of 0.05–0.2 mm. They produced concrete batches with CFRP to coarse aggregate weight ratios ranging from 0% to 22% (volume ratios are not reported). The compressive



and flexural strength test results showed that the incorporation of CFRP did not affect the mechanical properties of concrete significantly. However, it was observed that smaller CFRP particles tended to slightly increase the strength of concrete while the larger CFRP particles tended to slightly reduce the strength of concrete. One possible reason is that the smaller particles had fibrous shapes (higher aspect ratio) (Figure 2); since carbon fibers are very stiff and strong, they can postpone the initiation and opening of cracks, and thereby enhance the strength of concrete.

**Figure 2.** Recycled CFRF used in concrete by Ogi *et al.* [43]. Reprinted with permission from [43], copyright 2014, Elsevier.



The past work on the properties of FRP waste incorporating cementitious materials is too limited to lead to a conclusion about whether or not using mechanically recycled FRP in concrete or mortars is a viable option. In addition, to assess such an option, the feasibility of use, and the effect of incorporating FRP waste in other composites should be studied in detail. The use of finely ground FRP in materials such as FRP, asphalt, engineered wood and polymer concrete has been researched in the past [10,17,44–46]. Some studies have shown that using ground FRP as a filler in new polymeric composite materials can reduce mechanical performance of the new composite [47], while other studies have reported similar or even enhanced properties of polymeric composite materials as a result of incorporating mechanically recycled FRP waste. For example, it has been observed that substitution of up to 88% of the calcium carbonate filler in sheet molding compounds (SMCs) by fine particulate recycled FRP resulted in materials with comparable strength and stiffness [48]. Inoh *et al.* [49] reported that replacing up to 20% of filler in SMC with finely ground SMC does not affect the mechanical performance of the composite material. Kojima and Furukawa [50] observed 30% improvement in strength when finely ground polymer matrix composite (15–12  $\mu\text{m}$ ) was used in its own production stream as a replacement for calcium carbonate filler.

#### 4. Can the Use of FRP Production and End-of-Life Waste in Concrete be Optimized?

Three filler characteristics affect the mechanical performance of a composite material: (1) strength of the filler, (2) Young's modulus, or in general the stiffness, of the filler, and (3) the filler-matrix interface bond strength. Natural aggregates are the strongest component of normal-strength concrete. Alexander and Mindess [51] have presented a comprehensive list of the mechanical properties of different rocks used as aggregates. The average compressive strength of most rocks is notably above 100 MPa, while that of hydrated cement paste even with low  $w/c$  ratios is below 100 MPa; according to Cong *et al.* [52] the compressive strength of cement paste with  $w/c$  ratios in the range of 0.39 down to 0.30 is from 70 MPa to 100 MPa. The failure of concrete carrying increasing compressive stress

occurs due to the formation and propagation of crack in weakest zones, namely (1) the interfacial transition zone (ITZ), which is the most porous portion of cementitious matrix (hydrated cement) around aggregates, and (2) the cementitious matrix itself.

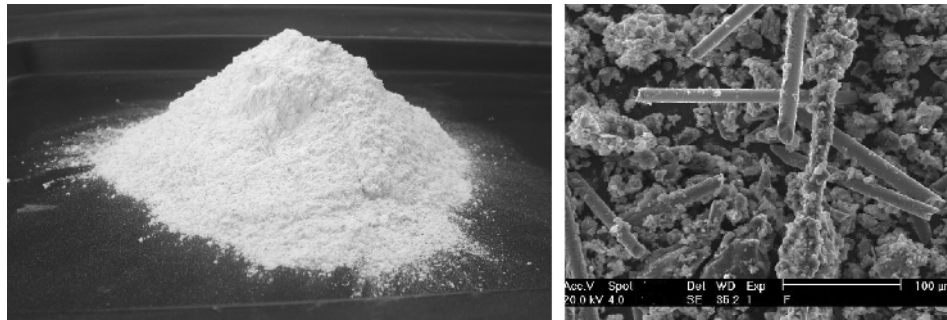
The strength of FRP materials vary widely depending on the type of the composite. For example, the strength of BMCs can be as low as 30 MPa due to the low dosage of fiber and high dosage of filler, while the strength of FRPs obtained by the Vacuum Assisted Resin Transfer Molding (VARTM) method can be higher than 500 MPa when reinforced with glass fibers or 1000 MPa when reinforced with carbon fibers [1]. In addition, FRP composite materials containing continuous fibers are anisotropic and have different strength values in different directions. For example, the longitudinal compressive strength of the commonly used glass-reinforced pultruded vinylester is in the range of 207–359 MPa while their transverse strength is within 110–138 MPa [53,54]. However, a review of the mechanical properties of all types of FRP indicates that the compressive strength values of FRP materials in the weakest direction are mostly higher than the compressive strength of cement paste. As for stiffness, the compressive Young's modulus of pultruded glass fiber reinforced vinylester in the transverse (least stiff) direction can be as low as 7 GPa which is about half of the estimated compressive Young's modulus of hydrated cement paste. However, the longitudinal compressive Young's modulus of the same FRP is approximately the same as that of hydrated cement paste. Therefore, while FRP composite materials are typically weak in shear, it is possible that the mechanical properties of FRP are not the main or only cause of the reported significant drop in the strength of FRP-waste-incorporated concrete.

The FRP waste used in most of the experimental studies performed on the properties of FRP-incorporated concrete have been in the form of fine powder. An SEM image of such a powder from Tittarelli and Shah [6] is shown in Figure 3. The image shows that the polymer particles and the broken fibers are mostly separated from each other; in other words, a ground FRP particle cannot be regarded as a composite material. When FRP particles are incorporated within the matrix of a new material these particles act independently. Approximately 80% of the content of the FRP powder used in the studies of Tittarelli and coworkers was polyester resin. Polyester resin has an approximate tensile strength of 65 MPa [4] and its compressive strength is roughly twice as high [55], which means that although polyester resin is weaker than commonly used natural aggregates, it is nearly as strong as hydrated cement. Therefore, the strength of the resin is probably not the major reason for the observed significant reduction in the strength of the mortar when the fine aggregate is partially replaced with the ground FRP. However, the modulus of elasticity of polyester resin (approximately 3 GPa), and most other thermosetting resins is on average more than 10 times lower than that of natural aggregate and approximately five times lower than that of cement paste. Therefore, due to the resulting low modular ratio, the amount of stress transferred and resisted by resin particles in the concrete is approximately 10 times lower than that of natural aggregates and five times lower than that of the cementitious matrix.

Based on the above discussion, it seems that a better form of FRP waste that can be used as a partial replacement of natural aggregates in concrete is larger particles/pieces with rough surfaces in which fibers and the polymer matrix are well bonded. Experimental investigations are required to confirm this hypothesis as it seems to contradict some findings about incorporating FRP waste particles in polymeric materials; according to DeRosa *et al.* [48], Dzeskiewicz and Ralston [56] found that when 17.5 wt% BMC recycle with an average size of 0.25 mm was added to another BMC, tensile strength

increased slightly over the base formulation, while when 0.50 mm recycle was added at 17.5 wt%, a 15% reduction in tensile strength in the new BMC was observed. However, it is not known if the particles of waste BMC used by Dzeskiewicz and Ralston were in the form of composite or separated ingredients. If the latter is the case, the waste particles consisted of poorly-bonded agglomerates of smaller particles that create weak zones in the matrix of the new BMC.

**Figure 3.** GFRP powder used by Tittarelli and Shah [6] and relative SEM image. Reprinted with permission from [6], copyright 2014, Elsevier.



To the knowledge of the authors, two studies have been performed on replacing coarse aggregates with similar-size or large pieces of FRP (reported in Section 3). In the investigations of Alam *et al.* [42], the excess from the casting of waterslides were used, which were coated with a layer of polymer (“gel-coat”) to make them smooth. Figure 4 shows that this smooth surface resulted in a poor bond between the pieces of FRP and concrete matrix, and was the main cause of the poor mechanical performance of the FRP-incorporated concrete. Since all FRP closed mold processes (such as pultrusion, resin-transfer molding (RTM), VARTM) use a release agent to prevent the polymer sticking to the mold upon curing, it is likely that this will be a similar issue with recycled FRP from these processes. The other investigation on incorporating coarse pieces of FRP in concrete was performed by Ogi *et al.* [43]. They used crushed CFRP with rough surfaces (Figure 2). As can be seen in Figure 2, (1) the FRP particles have rough surfaces, and (2) each particle can be regarded as a composite material. As mentioned earlier, Ogi *et al.* did not observe any significant reduction in the compressive strength of concrete due to the replacement of natural coarse aggregate with the CFRP waste. This reinforces the hypothesis of the authors of this article that using coarser FRP waste in which fibers and matrix material are bonded can provide better mechanical performance. To further assess this hypothesis, similar investigations must be performed on FRP waste with different sizes, different fiber types, and different fiber contents.

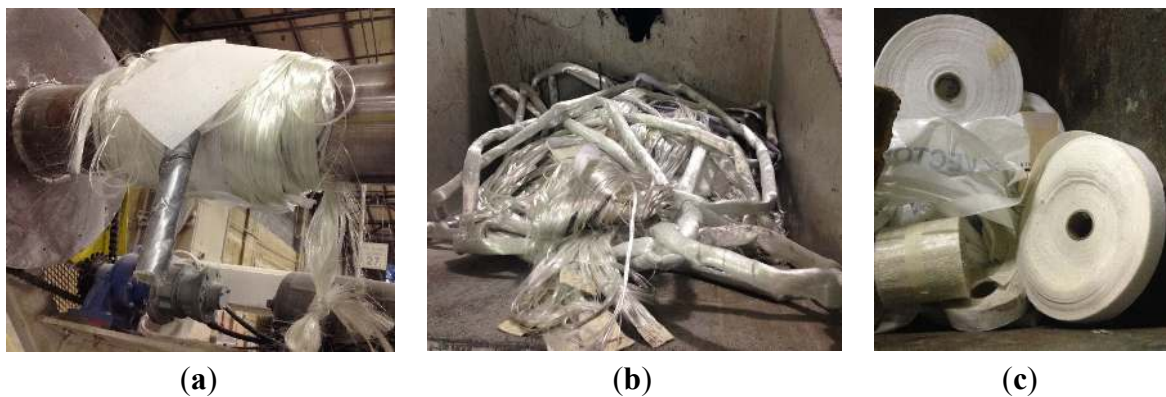
Recycling the fiber portion of FRP production waste and using it as aggregate in cementitious materials is another possible option to manage the waste from the FRP industry. Producing GFRP parts by the pultrusion process results in a significant amount of waste glass rovings and mats (Figure 5). Instead of landfilling, which is the common practice in the U.S., the rovings can be recycled and reused by (1) melting procedures to produce new glass products [57], or (2) cut into discrete fibers, or ground into powder and used in the production of new materials. The use of glass fibers in cementitious materials have been commercialized since the 1970s [58]. Glass fibers have been widely used in mortars to produce thin sheet architectural components such as building facades and in concrete for reducing plastic shrinkage cracking [59]. A main concern with using glass fibers in concrete is that they may lose strength (and therefore the reinforcing capacity) rather quickly due to the

very high alkalinity ( $\text{pH} \geq 12.5$ ) of the cement-based matrix [60]. However, alkali-resistant glass fibers (AR-glass fibers) have been developed that provide improved long-term durability. Therefore, it is important to investigate the resistance of glass rovings currently used (such as Boron-free E-CR glass rovings [61–63]) for producing GFRP, and compare it with that of AR-glass fibers. It should be mentioned that there are different methods for lowering the alkalinity level of the cementitious matrix (e.g., by adding silica fume or metakaolin) to enhance the durability of glass fibers in concrete. Some of those methods are outlined in the ACI report on fiber reinforced concrete [58].

**Figure 4.** Fractured surface of concrete incorporating pieces of FRP scrap used by Alam *et al.* [42] as a partial replacement of coarse aggregate.



**Figure 5.** Unused glass rovings and mats after the production of GFRP parts using the pultrusion method, from two FRP manufacturers: (a) Strongwell, and (b,c) Creative Pultrusions.



Using ground glass fibers/mats in concrete and mortars is another potential FRP waste management option. As mentioned earlier, Tittarelli and Moriconi [31] investigated the alkali–silica reactivity of finely ground GFRP and did not find any potential deleterious reactivity due to the glassy part present in the waste. Rajabipour *et al.* [64] used scanning electron microscopy (SEM) with X-ray energy dispersive spectroscopy (EDS) capability, as well as the ASTM C1260 [65] mortar bar method to investigate the role of glass particle size on their alkali silica reactivity in cementitious matrices. They observed that for particles smaller than 0.6 mm, the ASR is minimal and insignificant. Based on these findings it is expected that the use of ground waste glass rovings and mats will not cause ASR in cementitious materials.

Finally, while using recycled waste in any form may reduce the performance of new materials incorporating the waste, this by itself is not necessarily the crux of the issue in the authors' opinion. For example, the strength reduction in concrete caused by the partial replacement of aggregates with recycled FRP can be compensated for by changing concrete mix proportions. In our opinion, the major issues associated with the use of recycled waste in new materials are (1) the unknown properties of the source material that has been recycled, and (2) the potentially high variation in the properties of recycled materials supplied to a concrete production plant. Since a recycling plant receives waste materials from different, and possibly changing, sources, the batch-to-batch compositions of the recycled materials can be different. That results in higher variations in the properties and performance of the materials incorporating waste.

This issue can be resolved or mitigated in three ways: (1) using waste with known properties before combining it with the waste from other sources; and (2) developing criteria and procedures for characterizing the properties of the recycled waste materials.

The first method is implementable mostly on production waste. An example is recycling the waste glass rovings from the production of pultruded FRP (Figure 5). The properties of these fibers are known by the manufacturer and the waste rovings can be recycled (e.g., by grinding to powder), before being stored and mixed with other types of waste, to produce fillers with constant quality. In the second approach, a set of material tests are selected and performed on the recycled waste to (a) measure the physical and geometric properties, (b) determine the types and amounts of impurities, (c) characterize the composition. Then, based on performance tests on the waste-incorporated composite material, a set of limits on the material test results will be established, which if not exceeded the waste is regarded as usable for producing the new composite material. FRP waste can be examined by (a) visual observations to find the amounts of different visible impurities, (b) optical and electron microscopy to determine the portions of fiber, polymeric matrix materials, smaller impurities, and voids, and (c) spectroscopy and diffraction methods, such as XRD, XRF, Raman spectroscopy, *etc.*, to determine the constituents and types of fibers, matrix materials, and impurities.

## 5. Conclusions

The critical review and discussion presented in this article leads to a number of important conclusions:

- Landfilling FRP waste is still the easiest and cheapest method for managing FRP waste in most countries, including the U.S. However, environmental regulations are becoming tighter and it is expected that landfilling FRP will become more restricted, as it already is in several countries, including Germany.
- The most researched application of mechanically recycled FRP waste is its use as a partial replacement of fillers in new FRP composite materials. This usually reduces the mechanical properties of the new composite material.
- Partial replacement of aggregates in concrete and mortars is another potential application of mechanically recycled FRP. The few investigations performed on this topic suggest that recycled FRP fillers do not notably affect the durability of cementitious materials, but significantly reduce their mechanical properties.

- In most of the experimental studies on the mechanical properties of FRP-waste-incorporated concrete and mortars, finely ground FRP particles have been used as a partial replacement of aggregates. Finely ground FRP waste particles consist of poorly bonded pieces of polymer resin and fibers. Since polymer resin particles have a low stiffness, if the FRP waste has a high resin content, it can significantly reduce the strength of concrete or mortars.
- It was hypothesized that using larger FRP aggregates with rough surface will have a much smaller adverse effect on the mechanical properties of cementitious materials. In some types of FRP waste, this will require removing the gel coat or release agents from the material surface in order to improve the bond between the FRP pieces and the cement matrix. However, this option might not be feasible.
- To determine if using FRP waste in concrete is a viable option, further investigations must be performed on both durability and mechanical properties. In addition, for use in structural concrete, the fire resistance and mechanical performance of the FRP-waste-incorporated concrete at high temperatures should be investigated.

### Acknowledgments

The authors wish to thank Dustin Troutman and Ronald Allison from Creative Pultrusions and Glenn Barefoot from Strongwell, for providing technical information and support.

### Conflicts of Interest

The authors declare no conflict of interest

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