Carbon fibers recovery from CFRP recycling process and their usage: A review

Heru Sukanto*, Wijang Wisnu Raharjo, Dody Ariawan, Joko Triyono
Mechanical Engineering Department, Universitas Sebelas Maret
Ir. Sutami 36 A Kentingan Jebres Surakarta, Indonesia
*Email: herusukanto@staff.uns.ac.id

Abstract. Carbon fiber is a popular polymer reinforcing material for forming carbon fiber reinforced polymer composites (CFRP) as a construction material under high loading. The use of this composite has spread in various fields of technology with a quite large production volume annually. Consequently, when the life span of the composite has run out it will leave composite waste and brought up CFRP recycling cases as a dare for scientists and engineers. Research on carbon fiber reclamation from CFRP materials has been carried out with the main purpose of taking and reusing carbon fiber. Several CFRP recycling methods have been investigated in laboratories and applied successfully to business but the capacity of production is not comparable with the addition of CFRP composite waste each year. High recycling energy is one of the main reasons constrained this waste recycling business. Recycled carbon fiber (r-CF) also shows a decrease in performance compared to virgin carbon fiber (v-CF) with a varied distribution of degradation according to the recycling method applied. However, reuse of r-CF in the form of short fibers in a composite materials under medium and low loads has been thoroughly tested and applied with promising results as a reinforcement for new composites.

Keywords: CFRP composite, r-CF, v-CF, pyrolysis, solvolysis

1. Introduction
Carbon fiber usage as a reinforcing in a composite material tend to significantly increase after Boeing has been applied it successfully for about 40% of their airplane components in 2009. The excellent properties and very light weight become a technologically very strong carbon fiber attraction in automotive and aerospace applications. It was predicted that in the future construction engineers will reduce the use of metal and its alloys and switch to using carbon fiber materials so that it will increase its consumption by an average of 12% annually [1]. Indonesia in 2019, it was estimated to require a supply of carbon fiber for industry as much as 230 thousand tons of which among 70 percent were imported from various countries [2].

Carbon fiber is generally used as a reinforcement material for polymer thermosetting or thermoplastic and a small portion is used for reinforcing of metals. The mixture of polymers and carbon fiber matrix forms a new material called carbon fiber reinforced plastic (CFRP) composites that have high strength, lightweight, easily formed, corrosion and wear resistances and fatigue resistant characteristics [3]. Generally, carbon fiber fabricated forms are fabric, woven, yarn (continuous) or chopped (short fiber) [4], while the thermosets polymers are dominantly used as
matrix in CFRP composites involving diglycidyl ether of bisphenol A (DGEBA), tetragnolylidene diamino-
diphenyl methane (TGDDDM) or unsaturated polyester [5]. The application of CFRP composites are
often found in aircraft components, ship construction, automotive, civil buildings, sports
equipment and several types of household appliances [6].

Growing up of CFRP composite usage volume has an adverse effect related to the increase in
composite waste. Traditionally, CFRP composite waste is only become landfilled or burned. In
some developed countries, the traditional way is no longer allowed with consideration of
pollution, economic losses and legal standards imposed by countries around the world [7]. So that
recycling of CFRP composite waste becomes a very important issue or problem to be resolved
immediately. The development of the carbon fiber composite recycling process always raises one
question that must be answered, namely: how good is the performance of the recycled carbon
fiber and its composite? Recycling of CFRP composites is in fact very complicated to do because (a)
the composition is very complex that is the material involves fibers, matrices and fillers of various
types, (b) cross-linked properties in thermoset resins, (c) combinations with other materials for the
purposes of metal fixing, honeycomb, hybrid composites and others [8].

In this article is reviewed CFRP composite recycling which has been carried out on a research or
business scale. Some recycling methods are still limited in laboratory tables due to cost and
technology constraints in their applications for industry. For example, recycling using sub or super
critical fluids encounters device technology constraints to create the state fluids on a large scale.
On the other hand, the quality of the recycled carbon fiber and its re-application as a
reinforcement are discussed to illustrate the prospects for developing recycled technology.
Surface quality, bonding strength to matrix and fiber tensile strength are generally the properties
tested for r-CF.

2. CFRP recycling methods and technologies

Several CFRP composite recycling technologies have been developed up to an industrial scale.
Mechanical, chemistry, thermal and electrical methods have been successfully applied to recycle
CFRP composite waste come from manufacturing waste, unused mold or end of life parts. Each
recycling method has advantages and weaknesses as measured by its effectiveness in breaking
down or decompose composite matrices and reclaim carbon fibers.

2.1. Conventional Incineration

Burning of CFRP wastes is able to recycle of a part of the attached energy for useful purpose. A
complete facility of burning or incineration stations may be developed to produce a heat and
electricity for supplying their local thermal energy and electricity and their networks as well.
Previous investigations have introduced that CFRP garbage can be mixed at 10% loading in
municipal solid waste (MSW) and processed to become an energy resource [9]. Energy generated
of CFRP waste is dependent on its energy contents that are reinforcement and matrix fraction and
the calorific value is predicted in the range of 30 MJ/kg [10] to 32 MJ/kg based on the CFRP
composition weight of 60% fibers and 40% matrix. However, the efficiency of CFRP waste
incineration for energy recovery or heat and electricity sources is not good enough that is not
exceed of 38% [9]. The investigation of CO₂ emissions produced from incineration process are
calculated based on stoichiometric equilibrium reaction by assuming that all of CFRP carbon
content is oxidized and emitted as CO₂. Non-CO₂ emissions from combustion are negligible. Net
greenhouse gas emissions are reported by taking into account both the direct emissions from CFRP
waste combustion and avoided emissions associated with displacing grid electricity and heat
power from natural gas. Residual materials following combustion, such as ash, account for 8% of
CFRP waste and is disposed of in landfill [11].

2.2. Mechanical recycling

Mechanical recycling for CFRP waste is performed by mechanism of attrition, compression,
shearing and impact [12]. Mechanical method allows to recycle carbon fibers and matrices at once
process and do not use or produce hazardous chemicals ingredient. Mechanical processing
involves crushing and shredding followed by further grinding and milling down CFRP waste to
become 10–50 mm of fine particles [13]. However, carbon fiber produced is generally coarse and inconsistent in size, decreases in strength, not suitable for long carbon fibers and not recommended for high load structural applications [8]. Because of significant degradation in mechanical properties and poor bonding between the fibrous fraction and matrices, mechanical recycled materials are still being used in small capacity only [14].

CFRP composite waste has been performed mechanically on an industrial scale composite recycling machine manufactured by Wittmann. The machine consists essentially a large milling cutter in a size limited drum diameter. The hammer heads are inserted by high speed steel cutting tools which is run at a fixed set of speed. Small cut composite panels are fed into the machine through a channel and gradually reduced by milling until short fibers and resin powder can be passed through the screen with certain mesh size. The matrices powder and short fibers can then be used as fillers or reinforcement in re-manufacturing a product. The internal structure scheme of machine is shown in Figure 1 (left). For several machines, CFRP waste plates of 3 mm thickness and a total of 1 kg can be processed over a period of 6 min, which equates to a capacity rate of 10 kg each hour [15]. The Wittmann MAS1, as illustrated in Figure 2 (right), with a fixed drum speed of 200 rpm, exit screen diameter size of 5 mm results in capacity of 30 kg each hour of both powder and fibrous recyclates collected in a bin [16]. In addition, hammer mills are generally as a main choice for reducing composite waste. They do not have blade that need for sharpening regularly, unlike cutting mills in which the blades are sometime severely worn and blunt by abrasion from the fibers within composite waste. The ensuing injured to the processing equipment always increases the operational cost of mechanical recycling, thus decreasing the economic value of the recyclates and often making this a questionable choice in terms of viability and continuity [17]. Hammer mills are also safe from impact of other materials, such as metals, that may often present inside composite scraps of sheet or bulk molding compound [18].

![Figure 1](image1.png)

**Figure 1.** Cross section of Wittmann machine [15] and the rotor blades image of MAS1 [16].

Generally, outputs from recycling are designated into three categories namely short fiber, fine powder, and coarse recyclates. Figure 2 shows the distribution of mass balances through the mechanical recycling process. Short fibers, fine powder and coarse recycle fractions represent 24 wt%, 19 wt% and 57 wt% of outputs respectively [19]. Short fiber, termed as recycled carbon fibers (r-CF) can be reclaimed and reused as reinforcement material in new composites by substituting a certain proportion of virgin fiber material. However, there are constrains of part of r-CF that able to be applied without resulting in a crucial degradation of composite properties [8]. Experimental investigations for r-CF application to replace the same volume of virgin glass fiber (vGF) have shown that mechanical properties are not significant different with composites using 100% vGF. When produced with r-CF, the flexural modulus of the composite has slightly increased by 15% but flexural strength decreased by 14%. Some literature depicts r-CF might be used to replace virgin carbon fiber (v-CF) via direct injection molding process with nearly no decreasing of mechanical properties [20]. However, the other researchers reports evaluating v-CF replacement with r-CF have delivered to significant degradation of the composite mechanical properties [21].
2.3. **Fluidized bed thermolysis recycling**

The thermal method can be done by decomposition of matrices in fluidized bed or pyrolysis [22]. Thermal methods generally produce fibers that are clean of contaminants and at the same time convert the resin matrices into fuel. The disadvantages of the thermal method include (i) required a high energy supply, (ii) degradation of carbon fiber strength and (iii) producing gas from resin which endangers humans and the environment [23]. Fluidized bed process (FBP) is a thermolysis process using silica sand bed which is heated by hot air so that the condition is to become oxidant.

This condition allows the rapid heating of CFRP composite waste material to obtain fibers by crushing resin matrices. The FBP process at 550°C can produce carbon fibers which is degraded their strength up to 25% [24] and the oxygen content on the fibers surface is decreased slightly so that it still has the potential for binding the polymer matrix [8].

**Figure 3. Fluidized bed process [9].**

Figure 3 shows the illustration process of fluidized bed thermolysis. The waste of composite material is shredded for reducing in size so that the maximum is typically not exceed than 25 mm. This will constrain the longest fibers length in the feed. These waste segments are then fed into a bed in which silica sand with a particle size of about 0.85 mm is fluidized by a hot air stream. The temperature adjustment of fluidized bed should be controlled to become properly sufficient for decomposing the matrix rapidly but not lead to damage the fibers quality. For processing a CFRP composite with epoxy thermoset as a matrix, the temperature has to be set at the level of 550°C for optimum result. A chamber with higher temperature commonly is needed for further combustion in order to get a complete oxidation stage when the fibers are finished separated from gases flow in the cyclone zone. Rotating screen separator is more suitable for separating fillers and additive agents and has been developed [25] in which the fibers are screened by the sieve mesh whereas the gasses products and fillers flow away for the next separation stage in a cyclone chamber. CFRP epoxy resin is able to be successfully recovered at temperature of 550°C in air atmosphere but there is an residual oxidation lay on the surface fiber when the dwell time at this temperature is over than 20 minutes [26].
The advantage of FBP is able to recycle CFRP composites with various materials additives, such as layers of paint or additional fillers or metal inserts. It is seemingly to be very difficult for separating these other materials away from the composite before recovering process of fibers has been finished. In the FBP, any polymer materials are decomposed and fully oxidized whereas any others materials inserted within composite remain in the hot bed so that they can be easily taken from the silica sand. Almost all of epoxy resin comprises the elements of carbon, hydrogen, and oxygen but other than carbon will going to fully oxidize and flow out as a nontoxic pollutant. However, sometime halogenated elements in the polymer exist in the thermoset composite as an additive of fire retardant. These potentially produce an emission of acid gas and as consequence some gas cleanup system should be required after recovering energy stage. Unfortunately, when compared to the pyrolysis process, FBP is unable to process the oil content inside the polymer matrix as an added value of recyclates. Carbon fiber also has the potential to experience damage due to crushing by fluidized sand and it is a constrain of developing this recycling method [27].

2.4. Pyrolysis recycling

Pyrolysis process for CFRP recycling has been studied with recovering carbon fiber in a high-quality as a principal aim which further can be used to rival with v-CF. Firstly pyrolysis was conducted in Japan [28] in which CFRP composites within matrices of epoxy and phenolic were exposed under high temperature. The r-CF obtained from pyrolysis process at temperature of 500°C is exhibited reduction in tensile strength of 15% [29]. Compared to v-CF heated in air at the same condition, r-CF was found to loss of about 25% in tensile strength. In a holistically of CFRP pyrolysis research, it was established for optimum process conditions. Pyrolysing CFRP within a conventional furnace with no presence of air or oxygen yields the decomposition of the matrix into components of gasses and solid in the form of residual char which sticks to the carbon fiber surface with weight quantity of about 19% [30]. This char or pyrolytic carbon has an effect to decrease a bonding quality between fiber and matrix [31]. It is the most difficult problem in pyrolysis for getting back a reinforcement fiber. Fortunately, there is an opportunity to fully eliminate this char from fibers surface by oxidation within air atmosphere to obtain qualified fibers at the end of process. It is known that this oxidation has to take place between 500 and 600°C for 60 minutes. The technique is potentially able to reduce char in a significant volume but the process needs a precisely control of parameters [32]. Oxidation below 500°C, the char is oxidized slowly and the clean carbon fibers will be obtained in unreasonable of time whereas oxidation at temperature over of 600°C, the carbon fibers are going to burn fast causing fibers damage.

Elevating temperature by microwave has been reported [33] which it was able to keep away the creation of char on the fiber surface. Microwave requires less energy consumption for increasing the rate of thermal transfer without interfering the principle of pyrolysis. Mechanical properties of fibers can be maintained at high level after finishing the pyrolysis process [27]. It was achieved a 100% resin elimination ratio after 300 seconds using a microwave with power of 700 W, 2.45 GHz, argon atmosphere with flow rate of 2.5 l/min [34]. The r-CF had just 0.7% decrease in tensile strength compared to v-CF. Similarly, CFRP recycle has also been conducted at 500 °C for 30 min with a 0.70 m³ min⁻¹ nitrogen flow rate. The r-CF shows a clear fiber surface with mechanical properties very close to virgin fibers [35].

Pyrolysis processes for recovering strengthener fiber from CFRP composite waste have accepted commercial world with the flow process is on Figure 4. Although the energy required in the pyrolysis process is the highest compared to other methods, the ease with which the process can be made continuously and automatically causes the pyrolysis process to be most widely applied on an industrial scale. The predicted production capacity of recycled carbon fiber (r-CF) reaches 500 to 2000 tons annually [27]. Several companies have been known to commercialize the pyrolysis processes for carbon fibers reclamation from composite materials which the most of them operate in Europe and America [9]. On a business basis, the important target is to produce
the carbon fiber which meet the mechanical requirements as reinforcement within short time and less cost. It is not clear that there are any efforts for getting another material recovery rather than carbon fibers from the pyrolysis products. However, Recycled Carbon Fibre Ltd has declared that it is impractical for composite constituents recovering but that energy generated from the CFRP scrap is more attractive [33].

Figure 4. Pyrolysis process (with little modification from [36])

2.5. Chemical Recycling

In a chemical recycling process, the thermoset polymeric matrix present in the waste composite is decomposed by dissolving it into certain chemical solution, such as acids, bases or solvents. Normally, the right chemicals and solvents are chosen based on the natural properties of the polymer substrate [37], while the solid composites are mechanically crushed before chemical recycling to increase the surface area. Once the thermoset polymer is dissolved, the recycled fibers are washed to remove a surface residue [38]. Fibers reclaimed using chemical recycling have retained long fibers with minor decreasing of mechanical properties. This process has a higher resin decomposition ratio as well.

Modern chemical recycling depicts that resin degradation is either achieved using solvents (solvolysis) or water (hydrolysis). Solvolysis is used a solvent or heated solvent to disperse or break the polymeric portion of a composite. Solvolysis offers many ways of decomposing because of the availability of a wide range of solvents combined with different processing parameters such as temperature, pressure, stir, and often in conjunction with a catalyst. In hydrolysis, resin degradation takes place because of water. Water is broadly used over other solvents because of its environmentally friendly nature. Other solvents such as ethanol, acetone, methanol and their mixture with water at low critical temperature and pressure have also been applied for CFRP waste recycling [39].

Thermal-chemical recycling of CFRP composites (solvolysis) produces two products at once, namely carbon fiber which is very clean and at the same time the resin matrix is also decomposed. The quality of the carbon fiber produced depends on the type of chemical solution used for soaking, the temperature and time of immersion and stir energy if available. CFRP resin epoxy composites were decomposed in a supercritical solution of n-butanol and n-propanol at 360°C for 60 minutes to produce clean carbon fibers with tensile strength reaching 3.04 GPa or equivalent to 98% v-CF strength [40]. The use of tetralin and dihydroanthracene to immerse the CRFP-epoxy composite for 2 hours at 340°C resulted in a carbon fiber that showed no microstructure defects and the tensile strength was close to the tensile strength of v-CF [41]. The solvolysis method could also involve ZnCl$_2$ liquid catalyst on epoxy CFRP composite waste. Immersion at 360°C for 80 minutes results in complete degradation of epoxy resin and carbon fiber which is very clean and flawless. The surface character and mechanical properties of carbon fiber are better than conventional pyrolysis recycled products [42].
As a note, the drawback of improper fiber alignment in discontinuous r-CF with a length of more than 5 mm can be suppressed using a centrifugal alignment rig concept [43] or by applying calendaring through rollers with 0.10 - 0.15 mm gap at temperature of 110°C [44]. Furthermore, the chemical reaction that occurs in the carbon fiber causes the fiber to matrix resin binding strength for the production of CFRP composites to be weak. In addition, this chemical method is also very susceptible to causing pollutants that are very dangerous to human health and safety and have the potential to cause environmental pollution [45].

3. r-CFRP application

r-CF is usually in the form of short fibers (but not always short fibers) as a consequence of (1) size reduction of CFRP composites waste before they are subjected to the recycling process, (2) fibers break down during recycling, (3) cutting fibers after recycling. The entire recycling process, except mechanical method, removes the sizing or coating material on the carbon fiber surface so that the r-CF results are generally random and low in density packing. Thus, the r-CF engineering reuse must also be adapted to the obtained r-CF characteristics [46].

Several manufacturing processes have been involved in making products using r-CF. The injection molding process is conducted by mixing a thermoplastic resin matrix, short r-CF or chopped and filler or additive into a pellet form. Next, the pellets are injected into the mold with a pressure of up to 100 MPa. The composite with r-CF reinforcement made by injection molding produces 25% and 12% lower in stiffness and tensile strength respectively compared to v-CF [47]. Remanufacturing of r-CF has also been carried out by making a matrix mixture of resin, r-CF, filler and curing agent into a large solid form (bulky) followed by compression in the mold. This process is called bulky molding compound compression (BMC) which it uses compression pressures between 3.5 MPa and 35 MPa [48]. The main factors influencing on the mechanical strength of the r-CF composite are the filler fraction and carbon fiber. The mechanical properties of r-CF composites show significantly higher than the strength of glass fiber composites which are similarly made by the BMC [22]. However, it still requires in-depth review before r-CF being used to replace v-CF, both technologically and economically [49].

3.1. r-CF for reinforcing thermoplastics materials

Carbon fibers with length of tenths of a millimeter are amalgamated with plastics polymer to produce a fiber reinforced polymer composite as a raw material for molding injection manufacturing. Moreover, very short carbon fiber can improve an electrically conducting properties of thermoplastic. Carbon fibers with length of a few millimeters until their critical length provides better mechanical properties. When milled r-CF were used for reinforcing polyethylene, it was mixed within the polyethylene pellets and blended by screw extruder. Then, the extruder outputs were molded by injection molding to obtain a final product. It has been known that by adding r-CF of up to 30 wt%, the tensile modulus and strength of the polyethylene were improved by 180% and 28% respectively [50].

Similar to polyethylene, r-CF has been selected to reinforce polymeric of polypropylene. Toray T600 carbon fiber resulted from fluidized bed process of with a volume content of 30% was combined with the polypropylene within a twin screws mixer to provide pellets for injection molding. Polypropylene has nonpolar nature properties so that it cannot bind carbon fibers well. Thus, it desperately needs a coupling agent such as maleic anhydride-grafted polypropylene which is compounded with the polypropylene before adding the r-CF. For maintaining the fiber length, it was first transformed to become a nonwoven mat and then this mat was cut in 5 mm of length and finally fed directly into compounder. Increasing r-CF content up to 30 wt% has improved both the polypropylene tensile modulus dramatically from 1.7 to 14.7 GPa and the tensile strength from 29 to 51 MPa. Meanwhile, further addition of 5 wt% of the coupling agent has increased the modulus and strength tensile up to 17 GPa and 125 MPa respectively. The benefit of the coupling agent application on improving interfacial shear strength between the fiber and polypropylene was evidenced clearly by increasing of 250% in its tensile strength.

In another investigation, r-CF which is littered by 5% of residual char on the surface with length from 1 to 20 mm has been adopted for reinforcing a recycled polypropylene. The r-CF were
formed into a random nonwoven and then stacked in between polypropylene films. The amount of fibers fraction used were 30% and then molded into composite using hot compression process [51]. This composite was reported to has mechanical properties such as tensile modulus and tensile strength varying from 8.1 to 9.6 GPa and 23 to 27.9 MPa respectively. The description above illustrates the success of using r-CF as a reinforcement for thermoplastic materials.

3.2. R-CF for reinforcing thermosets materials

Resins epoxy thermoset were broadly applied as a matrix for producing a composite with r-CF as a strengthener. This composite is widely investigated and developed for automotive applications [46]. There are three products found in automotive components established by primary materials of r-CF with length of 12 mm and epoxy resins, they are (i) bulk molded compound (BMC) with 10 vol% of fiber and filler in the form of epoxy resin and calcium carbonate mixture with a ratio of 1:3, (ii) a sheet molded compound (SMC) with 23 vol% of fiber and ratio filler/epoxy resin of 3:2, and (iii) prepg with volume fractions of r-CF varying between 17% and 44%. The BMC was produced in the manual way by entering very short of r-CF into a mixer with Z-blade model. The both SMC and prepreg were produced using r-CF in the form of nonwoven mat resulting from a wet lay process. BMC, SMC and prepregs depict that these composites can be made successfully with r-CF and even has better mechanical properties when compared to glass fiber reinforced composites. Availability and competitive prices are the requirements for this composite to be accepted and applied on an industrial scale.

In another investigations, thermoset epoxy resin was selected for matrix and final composites was made by hot compression molding of epoxy resin film and r-CF which has been prepared in form of nonwoven mat. From the composite test with the content of the carbon fiber fraction varied from 20% to 40%, it shows the fact that the maximum mechanical properties of the composite were obtained at the r-CF volume fraction of 30% with stiffness and strength comparable with aluminum. The mechanical properties decrease at fiber volume fraction of 40% due to the high pressure required during the production of composites with high volume fraction of fiber which results in excessive deformation of the carbon fiber. Mechanical properties investigations and analysis of a composite made with 27% fiber volume fraction revealed that 60% of the fibers were below its critical length and this would get more when fiber volume fractions are ascended [52].

3.3. r-CF for Reinforcing Cementitious Mortars

An r-CF recovered via mechanical recycling of thermoset CFRP is potentially able to be reinforced for cementitious mortars. The low bond between fiber and mortar interfaces due to residual char on the fiber surface is a major engineering problem. Modification of the fibers surface by treating the acid or alkaline solutions often results in the strengthening of their interfacial bonds. The effect of r-CF chemical treatment before being used in mixture with cementitious mortar has been researched broadly. Some researchers used a mixture of water and cement with a volume ratio of 0.5 as a binder to make mortar composites with reinforcement of r-CF, filler of concrete pore and other additive materials such as tri-isopropanol-amine and montmorillonite nano-clay. The results prove that the use of r-CF not only improves the mechanical bonding of cementite mortar but the tests carried out also show that the chemical bonds in the composites are improved through a very complicated reaction. Another investigation employed recycled carbon fiber from wind turbine blades which was treated with NaOH solution to strengthen the cement mortar composite. The presence of r-CF infiltrated into the mortar composite plays a significant role in maintaining dimensional and volume stability and contributes to enhancing mechanical strength. Fiber immersion in solution of mild NaOH with maximum concentration of 1 mol/liter give a better effect on the interfacial bonding of fiber and mortar than higher concentrations. The maximum advantage of using r-CF in mortar composites is obtained in ultra-high loading concrete applications because the costs required are much lower than utilizing of other reinforcing additive materials. Mixing mortar composites under wet conditions resulted in uniform r-CF distribution and generally better workability. The addition of r-CF inclusions with a volume portion of 0.2% to 0.8% results in the electrical resistance value of the mortar composites in the range of 3 to 0.6 Ω.
m. It means that the r-CF content in the mortar may be modified to obtain a cementite material that functions as a load or damage sensing in commercial applications [53]. Often times r-CF is also used as a mixture in Portland cement, geo-polymerized fly ash and metakaolin without prior treatment or as received and it has been shown to increase flexural strength and impact toughness without decreasing compressive strength or creation additional porosity. This result was obtained in the mixing of the prepreg scrap volume of 5%. Workability and moisture absorption of these composite admixtures were going to low with increasing r-CF fraction even if without changing in the porosity. In additional, improvements of the interfacial bond between fiber and cement and efficiency of the recycling process can be obtained by adding nitric acid to the composite mortar. Therefore, the cemented composite mortar incorporated by r-CF can improve mechanical strength, stability and sensing functionality, thus providing opportunities for industrial applications as multifunctional construction materials [52].

3.4. r-CF for Non-Structural Application
The growing rate of batteries utilization as a storage medium for direct current electrical energy creates new opportunities for the application of r-CF as an electrode material. These materials have to has endurance in mechanical flexibility as well as to gravimetric energy density, rate charge capability, and cyclic life requirements [54]. Reclaimed oxidized polycrylonitrile fibers are used to construct a three-dimensional pore network of carbon-spun fabric structures. This porous is considered suitable to function as a material with high activity loading on the current collector of rechargeable batteries. According to analysis of structural, electrical, mechanical, and thermal it is known that these spun fabrics have enormous potential for use as heat insulation or heat sink components. In addition, the porous structure results in an increase in surface area which provides significant benefits in terms of stability and retention rate capability for LiFePO4 electric charging. Hence, r-CFs have become a strong candidate material to be used as un-stiffness lithium batteries [55].

4. Conclusion
The effort to recover carbon fiber from CFRP waste is a crucial activity for the present and the future. Development and innovation of methods and technology is still needed to build a CFRP waste recycling company that is profitable in business. The existing mechanical, thermal and chemical methods will be difficult to develop without support from various parties. There are still a lot of researches that need to be done and the technologies that need to be modernized for handling CFRP waste. All stakeholders need to be involved in taking CFRP waste management policies and reusing them in construction and non-construction integrally, including regulation maker.

5. Acknowledgment
This article has been funded by PNBP UNS 2020 according to the scheme of Penelitian Unggulan with contract number of 452/UN27.21/PN/2020.

6. References
[1] A. Roberts. "The Carbon Fibre Industry Worldwide 2008-2014". Innov Text, Vol. 4, 2009.
[2] I. Wibowo. "Black carbon industry was ready for reducing Indonesia’s import". Medcom Media, pp. 1–3, 2019.
[3] W. Frohs, H. Jaeger. "Carbon fiber & composite material - Landscape Germany-". SGL Carbon, Vol. 249, pp. 174–8, 2011.
[4] R. Gibson. "Principles of Composite Material Mechanics", Fourth Edition. CRC Press Taylor & Francis, 2016. https://doi.org/10.1201/b19626.
[5] P.K M. Fiber-reinforced composites. 3rd ed. Boca Raton, FL: 2007.
[6] J. Sloan. "Carbon Fiber 2007 looks forward with optimism". Carbon Fibers, Vol. 16, pp. 1–4, 2018.
[7] P. Xu, J. Li, J. Ding. "Chemical recycling of carbon fibre/epoxy composites in a mixed solution of peroxide hydrogen and N,N-dimethylformamide". Compos Sci Technol, Vol. 82, pp. 54–9,
Recycling technologies for thermoset composite materials-current status. Compos Part A Appl Sci Manuf, Vol. 37, pp. 1206–15, 2006. https://doi.org/10.1016/j.compositesa.2005.05.030.

S.J. Pickering, "Recycling Thermoset Composite Materials". Wiley Encyl Compos, pp. 1–17, 2012. https://doi.org/10.1002/9781118097298.weoc214.

A. Hedlund. "Model for End of Life Treatment of Polymer Composite Materials". Royal Institute of Technology, 2005.

X. Li, R. Bai, J. Mckechnie. "Environmental and financial performance of mechanical recycling of carbon fibre reinforced polymers and comparison with conventional disposal routes". J Clean Prod, Vol. 127, pp. 451–60, 2016. https://doi.org/10.1016/j.jclepro.2016.03.139.

R.M. German. "Powder Fabrication". Powder Metall. Basic Sci., Vol. 1. 2nd ed., Metal Powder Industries, p. 83–125, 1994.

A. Molnar. "Recycling Advanced Composites". 1995.

H. Li, K. Englund. "Recycling of carbon fiber–reinforced thermoplastic composite wastes from the aerospace industry". J Compos Mater, Vol. 51, pp. 1265–73, 2017. https://doi.org/10.1177/0021998316671796.

J. HOWarth, S.S.R. Maredy, P.T. Mativenga. "Energy intensity and environmental analysis of mechanical recycling of carbon fibre composite". J Clean Prod, Vol. 81, pp. 46–50, 2014. https://doi.org/10.1016/j.jclepro.2014.06.023.

N.A. Shuaib, P.T. Mativenga. "Energy demand in mechanical recycling of glass fibre reinforced thermoset plastic composites". J Clean Prod, Vol. 120, pp. 198–206, 2016. https://doi.org/10.1016/j.jclepro.2016.01.070.

J. Zhang, V.S. Chevali, H. Wang, C.H. Wang. "Current status of carbon fibre and carbon fibre composites recycling". Compos Part B Eng, Vol. 193:108053, 2020. https://doi.org/10.1016/j.compositesb.2020.108053.

R. DeRosa, E. Telfeyan, J.S. Mayes. "Current state of recycling sheet molding compounds and related materials". J Thermoplas Compos Mater, Vol. 18, pp. 219–40, 2005. https://doi.org/10.1177/0892705705045006.

J. Palmer, L. Savage, O.R. Ghita, K.E. Evans. "Sheet moulding compound (SMC) from carbon fibre recycle". Compos Part A Appl Sci Manuf, Vol. 41, pp. 1232–7, 2010. https://doi.org/10.1016/j.compositesa.2010.05.005.

J. Takahashi, N. Matsutsuka, T. Okazumi, K. Uzawa, I. Ohsawa, K. Yamaguchi, et al. "Mechanical properties of recycled CFRP by injection molding method. ICCM Int. Conf. Compos. Mater., pp. 1–6, 2007.

C.E. Kouparitas, C.N. Kartalis, P.C. Varelidis, C.J. Tsengoglou, C.D. Papaspyrides. "Recycling of the fibrous fraction of reinforced thermoset composites". Polym Compos, Vol. 23, pp. 682–9, 2002. https://doi.org/10.1002/pc.10468.

S. Pimenta, S.T. Pinho. "Recycling carbon fibre reinforced polymers for structural applications: Technology review and market outlook". Waste Manag, Vol. 31, pp. 378–92, 2011. https://doi.org/10.1016/j.wasman.2010.09.019.

K. Wood. "Carbon fiber reclamation: Going commercial". Compos World, Vol. 18, pp. 1–9, 2010.

J.R. Hyde, E. Lester, S. Kingman, S. Pickering, K.H. Wong. "Supercritical propanol, a possible route to composite carbon fibre recovery: A viability study". Compos Part A Appl Sci Manuf, Vol. 37, pp. 2171–5, 2006. https://doi.org/10.1016/j.compositesa.2005.12.006.

S.J. Pickering, R.M. Kelly, J.R. Kennerley, C.D. Rudd, N.J. Fenwick. "A fluidized-bed process for the recovery of glass fibres from scrap thermoset composites". Compos Sci Technol, Vol. 60, pp. 509–23, 2000. https://doi.org/10.1016/S0266-3538(99)00154-2.

Y. Yin, J. Binner, T. Cross. "The oxidation behaviour of carbon fibres". J Mater Sci, Vol. 29, No. 2250–4, 1994. https://doi.org/10.1023/A:1018612214572.

G. Oliveux, L.O. Dandy, G.A. Leeke. "Current status of recycling of fibre reinforced polymers: Review of technologies, reuse and resulting properties". Prog Mater Sci, Vol. 72, pp. 61–99, 2015. https://doi.org/10.1016/j.pmatsci.2015.01.004.
[28] U. Kenji, K. Nobuyuki, S. Morihiko. "Recycling of CFRP by Pyrolysis". J Soc Mat Sci Japan, Vol. 44, pp. 428–31, 1995. https://doi.org/10.2472/jsms.44.428.

[29] M.H. Akonda, C.A. Lawrence, B.M. Weager. "Recycled carbon fibre-reinforced polypropylene thermoplastic composites". Compos Part A Appl Sci Manuf, Vol. 43, pp. 79–86, 2012. https://doi.org/10.1016/j.compositesa.2011.09.014.

[30] L.O. Meyer, K. Schulte, E. Grove-Nielsen. "CFRP-recycling following a pyrolysis route: Process optimization and potentials". J Compos Mater, Vol. 43, pp. 1121–32, 2009. https://doi.org/10.1177/0021998308097737.

[31] F.A. López, O. Rodríguez, F.J. Alguacil, I. García-Díaz, T.A. Centeno, J.L. García-Fierro, et al. "Recovery of carbon fibres by the thermolysis and gasification of waste prepreg". J Anal Appl Pyrolysis, Vol. 104, pp. 675–83, 2013. https://doi.org/10.1016/j.jaap.2013.04.012.

[32] L. Mazzucchelli, T. Benelli, E. D’Angelo, C. Leonardi, G. Zattini, L. Giorgini. "Validation of carbon fibers recycling by pyro-gasification: The influence of oxidation conditions to obtain clean fibers and promote fiber/matrix adhesion in epoxy composites". Compos Part A Appl Sci Manuf, Vol. 112, pp. 504–14, 2018. https://doi.org/10.1016/j.compositesa.2018.07.007.

[33] E. Lester, S. Kingman, K.H. Wong, C. Rudd, S. Pickering, N. Hilal. "Microwave heating as a means for carbon fibre recovery from polymer composites: A technical feasibility study". Mater Res Bull, Vol. 39, pp. 1549–56, 2004. https://doi.org/10.1016/j.materresbull.2004.04.031.

[34] K. Obunai, T. Fukuta, K. Ozaki. "Carbon fiber extraction from waste CFRP by microwave irradiation". Compos Part A Appl Sci Manuf, Vol. 78, pp. 160–5, 2015. https://doi.org/10.1016/j.compositesa.2015.08.012.

[35] L. Jiang, C.A. Ulven, D. Gutschmidt, M. Anderson, S. Balo, M. Lee, et al. "Recycling carbon fiber composites using microwave irradiation: Reinforcement study of the recycled fiber in new composites". J Appl Polym Sci 2015;132. https://doi.org/10.1002/app.42658.

[36] S. Karuppannan Gopalraj, T. Kärki. "A review on the recycling of waste carbon fibre/glass fibre-reinforced composites: fibre recovery, properties and life-cycle analysis". SN Appl Sci, Vol 2, 2022. https://doi.org/10.1007/s42452-020-2195-4.

[37] S. Pimenta, S.T. Pinho. "Recycling carbon fibre reinforced polymers for structural applications: Technology review and market outlook". Waste Manag, Vol. 31, pp. 378–92, 2011. https://doi.org/10.1016/j.wasman.2010.09.019.

[38] E. Asmatulu, J. Twomey, M. Overcash. "Recycling of fiber-reinforced composites and direct structural composite recycling concept". J Compos Mater, Vol. 48, pp. 593–608, 2014. https://doi.org/10.1177/0021998313476325.

[39] S. Job, G. Leeke, P.T. Mativena, G. Oliveux, S. Pickering, N.A. Shuaib. "Composites recycling : Where are we now ?". Compos UK, Vol. 11, 2016.

[40] H. Cheng, H. Huang, J. Zhang, D. Jing. "Degradation of carbon fiber-reinforced polymer using supercritical fluids". Fibers Polym, Vol. 18, pp. 795–805, 2017. https://doi.org/10.1007/s12221-017-1151-4.

[41] D. Braun, W. Von Gentzkow, A.P. Rudolf. "Hydrogenolytic degradation of thermosets". Polym Degrad Stab, Vol. 74, pp. 25–32, 2001. https://doi.org/10.1016/S0141-3910(01)00035-0.

[42] T. Wu, W. Zhang, X. Jin, X. Liang, G. Sui, X. Yang. "Efficient reclamation of carbon fibers from epoxy composite waste through catalytic pyrolysis in molten ZnCl 2". RSC Adv, Vol. 9, pp. 377–88, 2019. https://doi.org/10.1039/c8ra08958b.

[43] N. van de Werken, M.S. Reese, M.R. Taha, M. Tehrani. "Investigating the effects of fiber surface treatment and alignment on mechanical properties of recycled carbon fiber composites". Compos Part A Appl Sci Manuf, Vol. 119, pp. 38–47, 2019. https://doi.org/10.1016/j.compositesa.2019.01.012.

[44] B. Xiao, T. Zaima, K. Shindo, T. Kohira, J. Morisawa, Y. Wan, et al. "Characterization and elastic property modeling of discontinuous carbon fiber reinforced thermoplastics prepared by a carding and stretching system using treated carbon fibers". Compos Part A Appl Sci Manuf, Vol 126:105598, 2019. https://doi.org/10.1016/j.compositesa.2019.105598.

[45] G. Jiang, S.J. Pickering, E.H. Lester, T.A Turner, K.H. Wong, N.A. Warrior. "Characterisation of carbon fibres recycled from carbon fibre/epoxy resin composites using supercritical n-
propanol”. Compos Sci Technol, Vol. 69, pp. 192–8, 2009. https://doi.org/10.1016/j.compscitech.2008.10.007.

[46] T.A. Turner, N.A. Warrior, S.J. Pickering. "Development of high value moulding compounds from recycled carbon fibres". Plast Rubber Compos, Vol 39, pp. 151–6, 2010. https://doi.org/10.1179/174328910X12647080902295.

[47] M. Connor. "Characterization of Recycled Carbon Fibers and Their Formation of Composites Using Injection Moulding". North Carolina State University, 2008.

[48] B. Allen. "Characterization of Reclaimed Carbon Fibers and Their Integration into New Thermoset Polymer Matrices via Existing Composite Fabrication Techniques". North California State University, 2008.

[49] S. Pickering, Z. Liu, T. Turner, K. Wong. "Applications for carbon fibre recovered from composites". 37th Riso Int. Symp. Mater. Sci., IOP Conf. Series, pp. 1–19, 2016. https://doi.org/10.1088/1757-899X/139/1/012005.

[50] T. McNally, P. Boyd, C. McClory, D. Bien, I. Moore, B. Millar, et al. "Recycled Carbon Fiber Filled Polyethylene Composites”. J Appl Polym Sci 2008;107:2015–21. https://doi.org/10.1002/app.27253.

[51] M. Szpieg, M. Wysocki, L.E. Asp. "Mechanical performance and modelling of a fully recycled modified CF/PP composite". J Compos Mater, Vol. 46, pp. 1503–17, 2012. https://doi.org/10.1177/0021998311423860.

[52] S. Pimenta, S.T. Pinho, P. Robinson, K.H. Wong, S.J. Pickering. "Mechanical analysis and toughening mechanisms of a multiphase recycled CFRP. Compos Sci Technol, Vol. 70, pp. 1713–25, 2010. https://doi.org/10.1016/j.compscitech.2010.06.017.

[53] Y. Wang, S. Zhang, D. Luo, X. Shi. "Effect of chemically modified recycled carbon fiber composite on the mechanical properties of cementitious mortar". Compos Part B Eng, Vol. 173, 2019. https://doi.org/10.1016/j.compositesb.2019.05.064.

[54] S. Wu, Y. Han, K. Wen, Z. Wei, D. Chen, W. Lv, et al. "Composite nanofibers through in-situ reduction with abundant active sites as flexible and stable anode for lithium ion batteries". Compos Part B Eng, Vol. 161, pp. 369–75, 2019. https://doi.org/10.1016/j.compositesb.2018.12.039.

[55] H. Cho, Y. Kim, Y.J. Yun, K.S. Lee, J. Shim, C.H. Lee, et al. "Versatile 3D porous recycled carbon garments with fully-loaded active materials in the current collector for advanced lithium-ion batteries". Compos Part B Eng, Vol. 179: 107519, 2019. https://doi.org/10.1016/j.compositesb.2019.107519.