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# Recycling of carbon fibers from carbon fiber reinforced polymer using electrochemical method

Hongfang Sun [a], Guanping Guo [a], Shazim Ali Memon [b], Weiting Xu [a], Qiwu Zhang [c], Ji-Hua Zhu [a,*], Feng Xing [a,*]

[a] Guangdong Province Key Laboratory of Durability for Marine Civil Engineering, School of Civil Engineering, Shenzhen University, Shenzhen 518060, Guangdong, PR China
[b] Department of Civil Engineering, COMSATS Institute of Information Technology, Abbottabad 22010, Pakistan
[c] Department of Civil Engineering, Chongqing University, Chongqing 400044, PR China

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ABSTRACT

In this research, we proposed an electrochemical method for the recycling of carbon fibers from carbon fiber reinforced polymer (CFRP). Experiments were designed with different solution concentrations (3%, 10%, and 20% NaCl) and various levels of applied current (4 mA, 10 mA, 20 mA, and 25 mA) so as to identify the significant parameters that affect carbon fiber recycling efficiency. The recycled carbon fibers were characterized by using the single fiber tensile strength test, SEM, XRD, and XPS techniques. Test results showed that the maximum tensile strength of the reclaimed carbon fibers was 80% of the virgin carbon fibers (VCF). The increase in electrolyte concentration did not improve the recycling efficiency but resulted in severe oxidation and chlorination on the surface of recycled carbon fibers. From the experimental results, it can be concluded that the recycling of carbon fibers with electrochemical method is simple, effective, and economical.



## 1. Introduction

Carbon fiber reinforced polymer has been widely used in architecture, aerospace, automotive, medical sectors, etc. [1–4] due to improved mechanical, fatigue and corrosion resistance properties, and high strength-to-weight ratio offered by these composites [2]. However, the increasing use of CFRP also generates an increasing amount of CFRP waste [5]. For example, the first aircraft with structural CFRP components will soon be decommissioned [6]. The same thing is going to happen to the next generation composite aircraft (8500 commercial planes service life will end by 2025 [5,7]), with each aircraft representing more than 20 tons of CFRP waste [8]. The construction waste is also a serious concern due to wide application of CFRP for structural strengthening [9]. Besides, the world-wide demand for carbon fibers is growing rapidly. According to the statistics, the world-wide demand for carbon fibers reached approximately 35,000 tons in 2008 and this number is expected to double in 2014, indicating a growth rate of over 12% per year [5]. The increasing requirement of carbon fiber has raised an environmental and economic awareness among researchers for the need to recycle the CFRP waste material in a suitable way [10].

A variety of technologies have so far been investigated for recycling high value carbon fiber from carbon fiber reinforced composites. The main recycling approach is to decompose the polymeric matrix by different methods leaving clean carbon fiber [11]. Currently, the technologies used for the recycling of CFRP can be classified into three types [5]. The first one is based on mechanical recycling process. The process of recycling involves breaking-down the CFRP by shredding, crushing, or other similar mechanical process. The resulting scrap can then be segregated by sieving into rich in resin powdered products and rich in fibrous products [5]. During processing, no hazardous gas is produced. However, the recycled carbon fibers extracted by this process show significant degradation in mechanical properties and fiber length [12]. The second type is a thermal process (pyrolysis or oxidation), which is one of the most wide spread recycling processes for CFRP [13,14]. In this process, heat is used to decompose organic molecules in an inert atmosphere. The polymeric matrix is degraded into smaller molecules and relatively clean carbon fibers can be recovered [1,11]. The tensile strength of recycled carbon fibers obtained through this process is approximately 70–80% of virgin carbon fiber [15,16]. However, this process possibly deposits char on fiber surface and produces multiple hazardous gases [3,4,15,17]. The third type of recycling is based on the chemical process, where reactive medium (catalytic solutions, benzyl alcohol, and supercritical fluids, etc.) are used under the condition of

* Corresponding authors. Tel.: +86 755 26534021.
*E-mail addresses:* zhujh@szu.edu.cn (J.-H. Zhu), xingf@szu.edu.cn (F. Xing).

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low temperature. The polymeric resin is decomposed into relatively large oligomers and the carbon fibers, which remain inert, can be collected [1,2]. The mechanical properties of recycled carbon fibers obtained through chemical process can be approximately 90% of VCF [1,2]. However, increased cost of reagent and production of massive hazardous gases [1,2,5] are the biggest challenge for the recycling of carbon fibers through chemical process.

In this research, we proposed an electrochemical method for the recycling of carbon fibers from CFRP. Experiments were designed with different solution concentrations and various levels of applied current so as to identify the significant parameters that affect carbon fibers recycling efficiency. The proposed method is simple in operation and efficient in nature. Moreover, all the materials required for the electrochemical process are readily and commercially available. Thus, the suggested electrochemical recycling process would be cost effective and this aspect is important for mass recycling. Finally, the whole electrochemical recycling process produces minor hazardous gases. However, these gases are easy to control and can be recycled. Therefore, the suggested process is relatively environmental friendly.

## 2. Experimental investigation

### 2.1. Materials

The CFRP for recycling were obtained from CA.BEN Composite Co Ltd (Hong Kong). The CFRP strips are made from multi-layer carbon fibers (Toray T700) with a volume fraction of 60% and bounded by LAM-125/-226 epoxy (Pro-Set Inc., Bay city, MI, USA). The chemical composition of epoxy used in CFRP is shown in Table 1. The epoxy cured CFRP strips were machined from $500 * 500\ mm^2$ into rectangle strips of $30 * 150\ mm^2$ and having a total thickness of approximately 2 mm (Fig. 1). The total length of CFRP is divided into three regions. The first region (50 mm length) was used for recycling (only one side exposed with surface area of $1500\ mm^2$); the second region was protected by Kafuter K-5704RTV sealant while the third region was used as electrical connection. The detailed dimensions of CFRP are shown in Fig. 1. In order to evaluate the properties of recycled fibers, the virgin fibers were also purchased from the same company (CA.BEN Composite Co Ltd). We would like to mention here that the virgin fibers and the fibers used CFRP strips were exactly the same.

### 2.2. Details of experimental matrix and specimen designation

The details of experimental matrix are shown in Table 2. For this research, we used different NaCl solution concentration (3%, 10%, and 20%) and various levels of applied current (4 mA, 10 mA, 20 mA, and 25 mA). Each specimen was labeled according to the applied current and solution concentration. For example, in I4S3, the first part 'I4' defines the nominal applied current of 4 mA while the second part S3 indicates the concentration of NaCl solution (3%). Moreover, each applied current group (I4, I10, I20, and I25) was tested at solution concentration of 3%, 10%, and 20%, respectively. The virgin carbon fiber was labeled as VCF and was used for comparison with the recycled carbon fibers.

**Table 1**
Chemical composition of epoxy in CFRP.

| Ingredients | Concentration |
|---|---|
| Bisphenol-A type epoxy resin | 37–38% |
| Novolac epoxy resin | 19–20% |
| Dicyandiamide | 5–6% |
| Methyl ethyl ketone (MEK) | 36–37% |

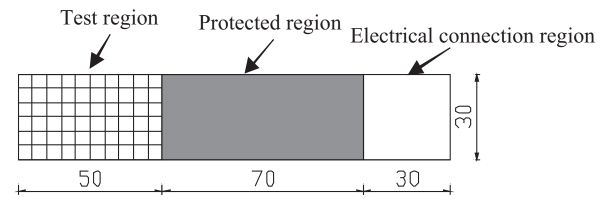


**Fig. 1.** Geometric dimensions of CFRP specimen used for testing (unit: mm).

**Table 2**
Details of experimental matrix.

| Group | Specimen | Current ($I$) (mA) | Current density ($i$) ($mA/m^2$) | NaCl solution (S) concentration (%) |
|---|---|---|---|---|
| I4 | I4S3 | 4 | 2.67 | 3 |
| | I4S10 | 4 | 2.67 | 10 |
| | I4S20 | 4 | 2.67 | 20 |
| I10 | I10S3 | 10 | 6.67 | 3 |
| | I10S10 | 10 | 6.67 | 10 |
| | I10S20 | 10 | 6.67 | 20 |
| I20 | I20S3 | 20 | 13.33 | 3 |
| | I20S10 | 20 | 13.33 | 10 |
| | I20S20 | 20 | 13.33 | 20 |
| I25 | I25S3 | 25 | 16.67 | 3 |
| | I25S10 | 25 | 16.67 | 10 |
| | I25S20 | 25 | 16.67 | 20 |

### 2.3. Recycling process of carbon fibers

The electrochemical recycling system is shown in Fig. 2. The system consists of the following parts: a direct current (DC) power source so as to provide energy for the entire system, a stainless steel cathode connected to the negative terminal of the power supply, and a CFRP anode connected to the positive terminal of a power source. NaCl solution with concentration of 3%, 10%, and 20% was used as electrolyte. During the recycling process, the DC power provided a constant current of 4, 10, 20, and 25 mA to the system (for a tested region of $1500\ mm^2$, Fig. 1), and the corresponding current densities were 2.67, 6.77, 13.33, and $16.67\ A/m^2$, respectively. After the recycling duration of 21 days, the softened part of CFRP was collected and ultrasonically cleaned with water and ethyl alcohol so as to obtain the recycled carbon fiber. Thereafter, the carbon fibers were dried at 50 °C for 3 days before testing. It needs to be pointed out here that all the electrodes and electrolyte materials are readily and commercially available. Moreover, it can be seen that the electrochemical recycling system is simple in operation.

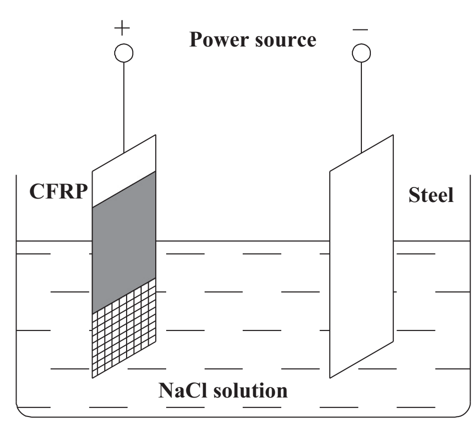


**Fig. 2.** Schematic view of electrochemical recycling system for CFRP.