Resources, Conservation & Recycling 128 (2018) 11–21

Contents lists available at ScienceDirect

Resources, Conservation & Recycling

journal homepage: www.elsevier.com/locate/resconrec

Full length article

Concrete with discrete slender elements from mechanically recycled wind turbine blades

Ardavan Yazdanbakhsh[a,*], Lawrence C. Bank[b], Klaus-Alexander Rieder[c], Yuan Tian[d], Chen Chen[d]

[a] Department of Civil Engineering, City College of New York, Steinman Hall 110, 160 Convent Avn., New York, NY 10031, USA
[b] Department of Civil Engineering, City College of New York, Steinman Hall 103, 160 Convent Avn., New York, NY 10031, USA
[c] GCP Applied Technologies, 62 Whittemore Ave, Cambridge, MA 02140, USA
[d] Department of Civil Engineering, City College of New York, Steinman Hall 194, 160 Convent Avn., New York, NY 10031, USA

ARTICLE INFO

Keywords:
Concrete
GFRP
Needles
Recycled
Wind turbine blade

ABSTRACT

A wind turbine blade shell made of glass fiber reinforced polymer (GFRP) composite materials was mechanically processed into slender elements referred to as "Needles". The Needles were used to replace 5% and 10% of the coarse aggregate, by volume, in concrete mixtures that were tested to investigate a number of important properties of fresh and hardened concrete. It was found that the Needles did not affect the stability and workability of fresh concrete negatively. Although the incorporation of the Needles did not have a notable effect on compressive, tensile, and flexural strength of concrete, it resulted in a significant increase in energy absorption capacity (toughness) from 1.2 J in control specimens up to 33.3 J in those with 10% Needle replacement. A polymer burn-off test revealed that, due to the directions in which the shell was cut, in most of the Needles glass fibers were perpendicular to the Needle axis, and therefore to the tensile stress carried by the Needles. Although the Needles with transversely-aligned fibers improve the mechanical performance of concrete, if the cutting directions of wind blades can be optimized so that in the majority of the Needles the fibers are primarily aligned longitudinally, improvements are expected to be more significant.

1. Introduction

1.1. Motivation

The use of wind energy has been increasing globally with an accelerating rate. Since 1999 the production of wind power has grown 30 times and the annual installation of new wind turbines has grown 10 times greater in the United States, which is currently the 2nd largest producer of wind power after China (Hunt et al., 2016). The rapid growth of the wind energy industry in the last 15 years has led to a commensurate rapid growth in the amount of wind blade waste that will need to be disposed of in the near future.

The components of modern wind turbine blades are mostly made of glass fiber reinforced polymer (GFRP) composite materials. GFRP materials consist of continuous or discrete glass fibers encased in a matrix of resins that have fiber concentrations typically in the range of 12%–60% by volume (Reynolds and Pharaoh, 2010) and inorganic fillers typically in the range of zero to 20% by volume. GFRP materials used in load-bearing members such as wind blades have a high content of continuous fibers (approximately 50%) and contain very low dosages of fillers, if any. The life span of some of the most widely used load-bearing GFRP products are relatively short. Wind blades are typically designed for a service life of 20 years (Beauson et al., 2014; Hardee, 2012).

Currently, the vast majority of GFRP waste in the US is landfilled. GFRP materials are non-biodegradable and landfill disposal of GFRP is already severely restricted in a number of countries, including Germany and the Netherlands. It is possible that when the currently produced GFRP materials reach the end-of-life stage landfilling regulation in the rest of the world will be stricter. The recently inaugurated U.S. Department of Energy's Institute for Advanced Composite Manufacturing Innovation (IACMI) has a mandate to increase the ability to recycle composite materials with a goal of 80 percent recyclability within the next decade (IACMI, 2016). The analyses of the data provided by the American Wind Energy Association (AWEA) on the annual number of in-service wind turbines, up to 2015 shows that by 2035 wind blade GFRP waste will amount to over 700,000 tonnes (Arias, 2016). Based on the existing growth in wind energy use it was also estimated that by year 2055 the amount of wind blade waste will be over 2.7 million tonnes.

Recycling GFRP is challenging since approximately 75% of GFRP products (including all of those used in wind blades) are made with

---

[*] Corresponding author.
E-mail address: ayazdanbakhsh@ccny.cuny.edu (A. Yazdanbakhsh).

http://dx.doi.org/10.1016/j.resconrec.2017.08.005
Received 1 June 2017; Received in revised form 28 July 2017; Accepted 3 August 2017

thermoset polymers, which do not melt in high temperature. A number of methods for recycling FRP waste have been developed involving chemical and/or thermal processes for reclaiming the fibers, or mechanical processes such as grinding or shredding GFRP into powder or small fragments for use as fillers in the production of new materials (Yazdanbakhsh and Bank, 2014). In addition, GFRP waste can be incinerated (burnt at high temperature) for producing energy or reducing the waste volume. Among the above-mentioned processes mechanical recycling of GFRP is an attractive option as it has the lowest energy demand and does not incorporate chemical processes. The energy required for mechanical recycling is between 0.5% and 5% of that required for chemical recycling and between 0.4% and 16% of the energy used for thermal recycling (pyrolysis) (Job et al., 2016).

A small number of investigators have studied the use of mechanically processed GFRP as a filler in concrete (Asokan et al., 2009; Tittarelli et al., 2010; Tittarelli and Shah, 2013; Yazdanbakhsh and Bank, 2014) and concrete-polymer composite materials (Ribeiro et al., 2015). The problem with traditional mechanical processing (pulverizing or shredding) is that the recycled products are no longer composite materials; they are mostly separate pieces of damaged fibers and resin particles. When used in concrete, the glass fibers become further damaged by the high alkalinity of concrete, and the resin particles that are low in strength and stiffness, reduce the compressive strength of concrete significantly. Cutting GFRP waste into relatively large pieces that are useable in concrete is an attractive potential recycling option for two reasons: (1) cutting a piece of solid material into large pieces rather than grinding or shredding it into powder or small fragments results in generating a smaller surface area and therefore requires less energy, and (2) cut pieces of GFRP are composite materials (fibers embedded in resin), rather than damaged fiber fragments and resin particles, with mechanical properties the same as those of the GFRP before being processed.

Limited research has been conducted on the properties of concrete incorporating slender elements from cut GFRP waste. In a recent study by Yazdanbakhsh et al. (2016), scrap from production of GFRP reinforcing bars (rebars) with different diameters were cut into short cylindrical pieces with aspect ratio of one (Fig. 1), titled FRP-RA, and used in concrete as full and partial (40% by volume) replacement of coarse aggregate. The study found that the full replacement of coarse aggregate with FRP-RA resulted in approximately 20% reduction in compressive strength and splitting tensile strength of concrete, due to the weak bond between FRP-RA particles (particularly the smooth saw-cut base surfaces of the cylindrical pieces) and concrete matrix. In an effort to produce recycled elements that can enhance, rather than decrease, the mechanical performance of concrete, GFRP rebar scrap was cut into short rods to be used as discrete slender reinforcing elements in concrete (Yazdanbakhsh et al., 2017). These elements, referred to as FRP-Needles, had a diameter of 6 mm and a length of 100 mm (Fig. 2). Incorporating FRP-Needles in concrete mixtures to replace volumetrically 5% and 10% of coarse aggregate (1.76% and 3.52% of concrete) led to 22% and 33% increase in the tensile strength of concrete, respectively. In addition, the use of FRP-Needles in concrete resulted in a significant increase in the post-peak toughness (energy absorption capacity) of concrete. Concrete specimens with 5% and 10% Needle replacement were, respectively 5% and 9% weaker in compression than the control specimens.

Fig. 1. FRP-RA used as a replacement of coarse aggregate in concrete.

Fig. 2. FRP-Needles with a diameter of 6 mm and length of 100 mm.

1.2. Needles and their fundamental difference from fibers

Fibers, particularly those made from steel and polymers, have been primarily used to control shrinkage cracking in concrete, and also to reduce or even replace rebars in various types of applications such as fiber reinforce concrete (FRC) panels for architectural uses (Bentur and Mindess, 2007), flat structural members such as airport taxiways (Murrell, 1993), slabs-on-ground (Roesler et al., 2006) and elevated slabs (Soranakom et al., 2007). The use of fibers in concrete is attractive since they can be added during mixing to reduce time and labor cost for preparing (bending, cutting and connecting) and placing traditional steel rebars. Rigid FRP fibers have also been studied by (Patnaik et al., 2013, 2014) and (Branston et al., 2016). However, these elements are similar to the fibers used in concrete and do not have the proposed properties and characteristics of Needles.

Fibers have three main shortcomings: (1) They tend to agglomerate and form clumps in fresh concrete. Therefore, the maximum dosage of fiber used in concrete industry is typically limited to 1.0% of the total volume of concrete; (2) Fibers reduce the workability of concrete significantly due to their high specific surface area resulting from their small cross-section dimensions and high aspect ratios. (3) Although fibers can enhance the post-failure toughness of concrete significantly, because only a limited dosage of fibers can be used, their effect on the tensile strength of concrete – an important parameter in the design of structures such as rigid pavements – is typically low (Choi and Yuan, 2005; Nanni, 1988; Wafa and Ashour, 1992), although a number of studies have shown that properly designed FRC can have a higher tensile strength compared to plain concrete (Mobasher 2012). It is expected that Needles, if properly designed, eliminate the aforementioned shortcomings.

When FRC carries increasing external load and a propagating crack intersects a fiber, high tensile strain develops in the fiber in the zone between the crack surfaces, resulting in a high shear stress in the interface between the fiber and cementitious matrix in the zone close to the crack. This shear stress may result in debonding which progresses toward the end of the fiber, after which the fiber will start to move out of its groove at one side of the crack. As shown in Fig. 3a, in order for an inclined fiber (i.e., a fiber that lie at an angle to the crack surface) to slip out, it must bend over crack surfaces. Even fibers made with high-elasticity-modulus materials, such as steel fibers, bend in plastic mode at crack surface during crack opening.