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Sustainable Concrete with Beneficial Byproducts

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Editor:
Moncef L. Nehdi

American Concrete Institute
Always advancing

Sustainable Concrete with Beneficial Byproducts

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PREFACE

Sustainable Concrete with Beneficial Byproducts

To improve the eco-efficiency and sustainability of concrete, the cement and concrete industry can exploit many byproducts in applications that could, in some cases, outperform conventional materials made with traditional ingredients. This Special Publication of the American Concrete Institute Committee 555 (Concrete with Recycled Materials) is a contribution towards improving the sustainability of concrete via using recycled materials, such as scrap tire rubber and tire steel wire fiber, GFRP waste, fluff, reclaimed asphalt pavements, recycled latex paint, and recycled concrete aggregate. Advancing knowledge in this area should introduce the use of recycled materials in concrete for applications never considered before, while achieving desirable performance criteria economically, without compromising the quality and long-term performance of the concrete civil infrastructure.

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Mechanical Performance of Concrete Incorporating Slender Elements from Recycling GFRP Waste

Yuan Tian and Ardavan Yazdanbakhsh

Synopsis: Due to their unique mechanical characteristics, glass fiber reinforced polymer (GFRP) composite materials are difficult to recycle at the end of their service lives. In the present work, a specific approach of recycling GFRP waste for use in concrete is investigated. Scrap from GFRP rebar and waste from a GFRP wind turbine blade shell were processed into slender elements, referred to as "needles," with a length of 100 mm and used in concrete to replace 5% and 10% of natural coarse aggregate. The results of testing various concrete specimens revealed that the incorporation of needles with longitudinally aligned glass fibers increased the splitting tensile strength of concrete significantly. Both types of recycled needles, regardless of the source of waste and orientation of glass fibers, increased the tensile toughness of concrete significantly. In addition, it was observed that incorporating needles did not reduce concrete's slump, due to the relatively high specific surface area of the needles. The findings suggest that recycling GFRP waste into needles as concrete reinforcement may be a viable GFRP waste management strategy and deserves further research.

Keywords: Concrete, Discrete reinforcement, GFRP waste, Mechanical performance, Recycled composites

ACI student member **Yuan Tian** is a Ph.D. candidate of Civil Engineering at the City College of New York (CCNY). She received her Bachelor's and Master's degrees in civil engineering from Hohai University, China, in 2011 and 2014, respectively. Her research focuses on recycling the waste from composite materials for use in new construction.

ACI member **Ardavan Yazdanbakhsh** is an associate Professor of Civil Engineering at the City College of New York (CCNY). The scope of his research includes recycling solid waste for use in construction, life cycle assessment of alternative waste management strategies, and properties of concrete incorporating nanomaterials.

INTRODUCTION

Concrete is one of the most widely used construction materials. However, it has several shortcomings, one of which is the labor-intensive and time-consuming preparation and placement of continuous steel reinforcement. Discrete reinforcing elements, which can be added during mixing concrete, can partially eliminate this shortcoming. Currently, fibers are the only widely researched and commercialized type of discrete reinforcing elements. Fibers increase the post-failure toughness of hardened concrete, but significantly reduce the workability of fresh concrete due to their high specific surface area. Chemical admixtures that cause additional cost and environmental impacts are required to improve the workability of fresh fiber-incorporated concrete. Moreover, when used beyond limited dosages, fibers tend to agglomerate, resulting in poor reinforcement and formation of weak zones in concrete. For this reason, the dosages of fibers used in concrete are typically limited to about 0.5% of concrete volume.

The present work discusses a different type of discrete reinforcing element with low specific surface area. These elements, hereafter referred to as "needles," are rod-shape, slender and stiff. The needles studied in the present work are produced by cutting the end-of-life waste of glass fiber reinforced polymer (GFRP) composite materials. The mechanism by which needles function in concrete as reinforcement is fundamentally different from that of commercially used fibers [1-2]. Needles have relatively low aspect ratios, large diameters and, as mentioned earlier, low specific surface areas. Therefore, they do not tend to agglomerate or reduce the workability of concrete. In addition, because needles can be produced from GFRP waste, their use can be environmentally beneficial. Despite the rapid growth in the use of GFRP materials, landfilling and incineration are the primary methods for managing GFRP [3]. Processing the GFRP waste into discrete reinforcing elements for use in concrete is a potential approach to mitigate the environmental burdens of managing GFRP waste.

Several studies have been conducted on the use of GFRP waste in concrete, to extend the use phase of GFRP composite materials. The scope of those studies can be divided into two categories; using pulverized or shredded GFRP waste to partially replace fine aggregate, and using the cut pieces of the waste to partially replace coarse aggregate in concrete. Tittarelli and Correia explored the possibility of replacing fine aggregate in mortar and concrete with powdered GFRP [4-5]. The test results revealed that using GFRP powder has negative impacts on the mechanical properties of both concrete and mortar. Shahria Alam reported reduction in compressive strength and flexural strength of concrete when flat square pieces of GFRP scraps from waterslides were used as a partial replacement of coarse aggregate [6]. Yazdanbakhsh et al. found that the full and partial replacement of coarse aggregate with aggregate-shape cut pieces of GFRP rebar scrap has a negative impact on the compressive strength, and more so, on the splitting tensile strength of concrete [7-9].

The mechanisms by which needles and fibers resist the growth of the cracks in concrete are fundamentally different [2]. When fiber reinforced concrete (FRC) is subjected to 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. The fiber may break before or during pullout. Efficient needles have high flexural stiffness values and have high strength in both tension and shear. Therefore, the only way for a concrete crack bridged by an inclined needle to grow in width is that the concrete encasing the needles crumbles and/or spalls in at least one side of the crack. Additionally, because of the larger size and high stiffness of GFRP-needles, they can function as both discrete reinforcement and coarse aggregate in concrete.

This work presents studies on GFRP Needles recycled from two different waste sources, which were used as partial replacement of coarse aggregate in concrete. The studies investigate the effect of the needles on a number of important mechanical properties of concrete. Details on the production of the two types of needles and testing concrete incorporating them are presented separately in two articles by the authors [1-2].The present work summarizes and compares the results of those studies, and discusses the parameters that affect the effectiveness of recycled GFRP needles as concrete reinforcing elements.

EXPERIMENTAL PROGRAM

Materials

The two types of GFRP waste used in the experiments are (i) scrap from the production of GFRP reinforcing bars (rebars), and (ii) a piece of GFRP shell from a dismantled wind turbine blade. The GFRP scrap constituted high quality but short GFRP rebars which were cut off during production in a pultrusion plant due to occasional production problems. The rebars have a diameter of 6mm and are sand-coated and helically wrapped by an additional strand of fiber to enhance the bond to concrete. The mechanical properties of the GFRP rebar provided by the manufacturer are presented in Table 1. The GFRP rebar needles were produced by cutting the scrap rebars with a diamond saw into small sections with a length of 100 mm (4 in) (Figure 1), resulting in an aspect ratio of 17. The length is the upper limit beyond which even distribution and orientation of needles in the mold used in the present study would be impacted. And the resulting aspect ratio distinct the needles from fibers.

The 25 mm (1 in) thick waste wind blade shell plate used for producing needles was provided by the Wind Technology Testing Center (WTTC) of National Renewable Energy Lab. A table saw was used to cut the shell into 100 mm long elements with a square cross-section and a side length of 6 mm (0.24 in) (aspect ratio of 15). Compared with the sand coated and helically wrapped GFRP rebar needles, the surface of wind blade needles are smoother. To promote the bond between concrete and embedded needles, half of the produced wind blade needles were grooved with shallow notches perpendicular to the long axis of the needles (Figure 1). The effects of the plain and grooved needles on the performance of concrete were investigated separately. The specific gravity of the wind blade needles is 1.95. and their tensile strength was estimated to be within a wide range from 35 MPa (5000 psi) to 1,150 MPa (167 ksi), depending on the alignment of glass fibers relative to needle axis [2].

Crushed granite with a nominal maximum size of 19 mm (3/4 in) and a specific gravity of 2.7 was used as coarse aggregate. The particle size distribution of the coarse aggregate was graded to comply with the limits specified by ASTM C33 for No.56 aggregate. An ASTM graded manufactured sand with a specific gravity of 2.58 was used. The finesses modulus of the fine aggregate is 3.1. Type I/II Portland cement with specific gravity of 3.15 was used in all concrete mixtures. Tap water was used for both concrete production and curing the concrete specimens in an environmental chamber.

Concrete mixtures

The proportions of constituents of all the concrete mixtures are presented in Table 2. Control concrete mixtures were proportioned to achieve the compressive strength values typically prescribed by the designers of reinforced concrete structures. Needle-incorporated mixture proportions are the same as those of control mixtures with the exception that predetermined portions (5% and 10% by volume) of coarse aggregate were replaced with needles. Since the water absorption capacities of the GFRP needles are very low, the magnitudes of mixing water were not adjusted to account for the negligible amounts of water absorbed by the needles.

Test specimens and procedures

For each of the three batches in the first phase of the study investigating GFRP rebar needles (1st Series) 6 cylinders with a diameter of 150 mm and a height of 300 mm were cast, three of which were tested to measure compressive strength, and the other three were tested to measure splitting tensile strength. Similarly, 8 cylinders of the same size were produced for each of the five batches in the second phase of the study investigating GFRP wind blade needles (2nd Series). Four of the cylinders were used to measure compressive strength and the remaining four were used to measure splitting tensile strength.

Although cylinder molds with the largest commonly used dimensions (150 mm (6 in) in diameter and 300 mm (12 in) in height) were used for compressive and splitting tensile strength tests, the length of the needles was two third of the cylinder diameter. This relatively large length was expected to affect the spatial distribution of the needles in the cylinders. Slump tests were conducted on all batches according to ASTM C143/C143M [10] after concrete was removed from the mixer. Visual examination was conducted to monitor the consistency of fresh concrete mixtures and detect signs of segregation and agglomeration of needles. The specimens were demolded 24 hours after casting and transferred to an environmental chamber with a relative humidity of 98%. All the specimens from the same mixture were tested on the same day, 28 days after casting. A few hours before testing, the specimens were removed from the curing chamber, wiped dry with towels, and placed in the testing laboratory. The specimens designated for measuring compressive strength were first tested to measure static modulus of elasticity according to ASTM Standard C469/C469M [11] and then tested to measure compressive strength [12]. Two strain gages were attached at the mid-point along the length of each specimen, on the diametrically opposite sides. The strain gauges have a strain capacity of 0.05, much higher than the strain of the concrete specimens when subject to a load 40% of their bearing capacity. Neoprene pads were also placed at both ends of cylindrical specimens to uniformly distribute the applied axial pressure. ASTM C469 permits measuring modules of elasticity prior to measuring compressive strength if the strain gauges attached to the specimens are flexible or protected.

RESULTS AND DISCUSSION

Fresh concrete properties

The slump test results from both phases of the experiments are presented in Table 3. The differences between the slumps of GFRP needle incorporated concretes and those of the control groups are insignificant. These results show that superplasticizers are not needed for needle incorporated concrete mixtures to keep the slump similar to that of the corresponding control concrete; an advantage that cannot be achieved when producing fiber reinforced concrete (FRC). The insignificant effect of GFRP needles on workability can be contributed to the similar specific surface areas of the needles and the coarse aggregates that they replace in concrete. The slump of GRV-10 concrete was slightly lower than those of other concrete batches, potentially due to the higher surface area of the grooved needles. Visual observations during mixing and casting concrete revealed that the needles did not agglomerate and had a relatively random distribution in concrete. Neither agglomeration of GFRP needles nor segregation of GFRP needles from the concrete mixtures were observed.

Hardened concrete properties

Performance in compression. The results of the compressive strength and modulus of elasticity tests are presented in Table 4. Compared with the corresponding control groups, the average compressive strengths of the specimens with 5% and 10% rebar needle replacement were 5.5% and 8.7% lower, respectively. This reduction of compressive strength is insignificant and within the margin of error. Similarly, the replacement ratios of 5% and 10% for plain wind blade needles, and 5% and 10% for grooved wind blade needles resulted in -1.4%, 0.3%, 7.2%, and -4.4% change in compressive strength, respectively. All of the above-mentioned changes are similarly of low significance despite the differences between the physical and mechanical characteristics of rebar and wind blade needles. The insignificant impact of the needles on compressive strength can be due to the low dosage of the needles in concrete (3.5% or less, by volume); the concrete matrix surrounding the needles is the primary component contributing to compressive strength. The results also show that incorporating needles did not have a significant impact on the modulus of elasticity of concrete, which can be similarly explained by the low content of the needles in concrete.

Splitting tensile strength. The splitting tensile strengths of the concrete specimens are presented in Table 4. The splitting tensile strength of the specimens in which 5% and 10% of coarse aggregates were replaced with GFRP rebar needles were respectively 22% and 33% higher than that of the corresponding control concrete. However, the average splitting tensile strength of none of the wind blade needle incorporated concretes was significantly higher than that of the corresponding control concrete. The average splitting tensile strengths of the specimens with 5% plain wind blade needle, 10% plain wind blade needle, 5% grooved wind blade needle, and 10% grooved wind blade needle are lower than that of control specimens by 13.7%, 0.0%, 13.1%, and 7.8%, respectively.

Visual observation of the specimens after splitting tests showed that the control specimens broke into two separate pieces immediately after the peak load, while all GFRP incorporated specimens remained one-piece despite the formation of multiple cracks (Figure 2 and Figure 3). Figure 4 shows the load-displacement curves from the splitting tests. All GFRP incorporated concretes have much higher post-failure toughness and post-failure strain compared to the control groups. Among the GFRP incorporated concrete groups, both GFRP rebar incorporated specimen groups have higher toughness than any of the wind blade needle incorporated specimen groups. This finding