Construction and Building Materials 187 (2018) 738–751

Contents lists available at ScienceDirect

Construction and Building Materials

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

Recycled glass fiber reinforced polymer composites incorporated in mortar for improved mechanical performance

Harry Rodin III [a], Somayeh Nassiri [b,*], Karl Englund [c], Osama Fakron [a], Hui Li [a]

[a] Washington State University, 2001 East Grimes Way, PACCAR, Pullman, WA 99164-5815, United States
[b] Washington State University, 2001 East Grimes Way 248, PACCAR, Pullman, WA 99164-5815, United States
[c] Washington State University, 2001 East Grimes Way 152, PACCAR, Pullman, WA 99164-5815, United States

HIGHLIGHTS

- Recycled glass fiber reinforced polymer (GFRP) was used as reinforcement in the mortar.
- Fiber-like GFRP shapes replaced fine aggregate in mortar.
- Aspect ratios were compared in terms of toughness and strength.
- Volumetric percentages of 1 and 3 showed the most successful results.

ARTICLE INFO

Article history:
Received 27 November 2017
Received in revised form 18 July 2018
Accepted 22 July 2018

Keywords:
Mortar
Glass fiber reinforced polymer (GFRP)
Compressive strength
Flexural strength
Toughness
Alkali-silicate reaction (ASR)

ABSTRACT

Glass fiber reinforced polymer (GFRP) panels from retired wind turbines were recycled into discrete structural elements in mortar. Based on 7-day testing, out of Powder, Small, Medium, and Large fiber size groups, the Large group was identified as the optimum size due to the highest modulus of rupture (*MR*) and toughness index (*TI*) while maintaining comparable compressive strength (f'_c) relative to control. Implementing the Large group at 1, 3, and 5% replacement of sand resulted in 5, 25 and 35% increases in 90-day *MR* with significant increases in *TI* and minimal reductions in f'_c and no expansion due to alkali-silica reaction.

1. Introduction

1.1. Overview

Glass fiber reinforced polymer (GFRP) composites are being used in many different sectors such as aeronautics, transportation, electrical and electronics, pipes and tanks manufacturing, and the wind energy [1]. Among others, the wind energy sector is a growing industry with total 539 GW global wind power (84.944 GW in the United States) which is forecasted to resume rapid annual growth after 2018 [2,3]. With increased usage, mounds of retired wind turbine blades made of GFRP composites buildup that need recycling and reusing. The blades are decommissioned when they need to be replaced by newer models, reach their end-of-life, or are permanently damaged [4]. The retired wind turbines comprise of GFRP composites made of a thermoset polymer matrix and glass fibers. Thermosets (as opposed to thermoplastics) are cured and difficult to remold into other shapes; therefore, recycling these GFRP composites present a challenging issue now and in near future [4]. In this study, GFRP composites from end-of-life wind turbine blades were resized into various size elements and were used as discrete reinforcement in mortar. The following section is a review of literature on the use of GFRP in cementitious materials and the subsequent impact on various properties of concrete.

1.2. Literature review on use of GFRP in concrete

Lightweight concrete is favored in many structural applications because of the reduction in dead loads. GFRP is relatively light compared to the raw materials used to manufacture concrete, which can reduce fresh and hardened density when implemented

* Corresponding author.
E-mail addresses: harry.rodin@wsu.edu (H. Rodin III), snassiri@wsu.edu (S. Nassiri), englund@wsu.edu (K. Englund), osama_fakron@wsu.edu (O. Fakron), lihui@wsu.edu (H. Li).

https://doi.org/10.1016/j.conbuildmat.2018.07.169
0950-0618/

as a replacement fine or coarse aggregate. Asokan et al. (2009) showed that the use of powdered GFRP waste contents ranging from 5 to 50% replacement of fine aggregate lowered hardened density from 1 to 11 percent [5]. Dehghan et al. (2017) reported that the use of GFRP powder and small fiber combinations reduced fresh unit weight by less than 0.5%, while using GFRP fibers resulted in fresh unit weight reductions up to 2 percent [6]. Correia et al. (2011) obtained 1.7–5.8% reductions in fresh density when incorporating 5, 10, 15 and 20% replacement of fine aggregate with fine powder waste generated from GFRP production. According to their study, the used GFRP was 30% lighter than the substituted fine aggregate [7].

Implementing GFRP in concrete influence the mechanical properties of hardened concrete. Compressive strength (f'_c) does not always improve when implementing recycled materials, commonly due to the added weak linkages between the paste and other constituents. The effect of recycled GFRP on f'_c when implemented in cementitious materials is summarized in Table 1 for easy comparison. In most studies, a decline is reported for f'_c but four of the studies reported improvements in compressive strength. Askan et al (2018) found addition of 2% superplasticizer as the key contributor of improvement in strength. Ribeiro et al. (2015) implemented GFRP in polyester-based mortar and found silane as a coupling agent helped improved the strength results. Mastali et al. (2016) also achieved improvements in f'_c by adding GFRP to self-compacting concrete; however, their mixture design does not seem to have followed a volumetric proportioning for a uniform comparison among the evaluated mixtures. Yazdanbakhsh et al. (2018) recycled wind turbine blades into needle-like discrete element that were used as 5 and 10% replacement of coarse aggregate. Only the grooved needles resulted in increased f'_c by 7 percent. Overall, the condenses regarding impact of GFRP addition on f'_c seem to be the replacement of fine aggregate with GFRP materials generally results in some reductions in compressive strength unless certain preventive measures are taken.

Flexural strength or the modulus of rupture (*MR*) is another important mechanical property required for concrete bending members such as slabs and beams. The implementation of GFRP may improve *MR*, especially if GFRP elements are able to bridge microfractures, transfer stresses across small cracks, and mitigate formation of larger cracks. Summary of results in Table 1 shows that implementation of GFRP in all but two cases improved the flexural strength of the cementitious materials.

One concern with using glass-based waste in concrete is the potential to develop an internal expansive gel due to alkali-silicate reaction (ASR) over time, which can cause cracking and damage. One study found that all of the GFRP mixtures, using both powder and fibers resulted in higher ASR expansion than the control mixture, however, all of the mixtures were under the 0.1% expansion threshold specified in ASTM C1260 [6]. Glass waste in concrete can potentially cause durability issues due to ASR so should be investigated based on the reviewed literature.

In the present study, recycled GFRP composites from end-of-life wind turbine blades were implemented as discrete structural elements as a partial replacement for sand in mortar. The GFRP was processed into various graded classes of fiber- and powder-like elements for use in mortar. The purpose of this feasibility study was to gain an initial understanding of the varied influences of the GFRP when implemented in mortar, for various size groups and then replacement contents of the recycled materials. Based on the literature reviewed above the properties of hardened mortar including density, strengths, toughness and volumetric instability were established and are reported and discussed. To test all these aspects the following tasks were conducted:

- Monitor how the GFRP changes the hardened density of the mixture on hardened samples.
- Evaluate strength changes at 7, 28, and 90-day ages in both compression and flexural loading.
- Monitor toughness to evaluate GFRP's influence on post-peak behavior.
- Assess potential development of ASR gel and the resulting expansion in the mortar.

2. Methodology

2.1. Mechanical processing of GFRP

The GFRP materials used in this study to produce the discrete structural elements are rectangular panels from end-of-life wind turbine blades. The mechanical recycling process starts with the panels first cut into small rectangular pieces before being fed into a shredder and hammer mill (Fig. 1-a). Several cut panels before the shredding process can be seen in Fig. 1-a as examples. The result of the shredding and milling processes is a mixture of fines, fiber-like, and plate/flake-like materials. The particle size distribution for the material after grinding can be seen in Fig. 3-a.

This material was then placed in a sieve shake table to process the different GFRP size groups. The larger sieves resulted in fiber-like strands while the smallest sieves resulted in glass powder (Fig. 1-b). Four different size groups were sieved and designated letter names (see table in Fig. 3-a). Each of the group sizes besides the powder were evaluated using image analysis to find their respective aspect ratios. A MATLAB code was developed to establish the aspect ratio of each GFRP size group by analyzing their respective binary images (see example images in Fig. 2). The aspect ratio data was a combination of the results from four different sample images for each group size. Fig. 3-b shows the aspect ratio range for each

Table 1
Summary of the effect of GFRP implementation in cementitious materials.

References	GFRP replacement of aggregate (%)			Effect on f'_c (%)	Effect on MR (%)
	Powder	Fibers	Combo		
Asokan et al. [5]	5 ~ 50	–	–	−22 to −60	up to + 58
Asokan et al. [8]	–	–	5, 15	+14, +6	+30, –
Correia et al. [7]	5, 10, 15, 20	–	–	−19 to −47	–
García et al. [9]	–	5, 10	–	< −50	up to −37
Ribeiro et al. [10]	8	–	–	+12	+8
	–	8	–	+13	+6
Fox [11]	–	–	25 ~ 50	−22 to −45	–
Mastali et al. [12]	–	0.25 ~ 1.25	–	+25 to +48	up to + 58
Dehghan et al. [6]	–	–	5	−4 to −12	up to + 40
Yazdanbakhsh et al. [13]	–	5, 10 plain	–	−3, −9	–
Yazdanbakhsh et al. [14]	–	5, 10 (plain needles)	–	0, −2	−9, −11
	–	5 (grooved needles)	–	+7	−6