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Investigation of Flexural Properties of Cement Reinforced with Recycled Carbon Fiber-Reinforced Polymer Composite Additives

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Abstract: The use of fiber-reinforced polymer (FRP) composites has significantly increased across various industries, due to their exceptional physical and mechanical characteristics. However, the sustainability of composite parts remains a considerable challenge. Typically, end-of-life (EOL) composite parts are disposed of in landfills due to the high costs of recycling and the limited application of recycled composites. This article introduces a preliminary study that investigates the application of mechanically recycled composite materials for construction purposes. Carbon fiber-reinforced composite laminates, with an average thickness of 3.175 mm, were pelletized to create additives. The size of these mechanically recycled composite additives was standardized at 25.4 mm x 25.4 mm. These pelletized additives were then blended with cement to produce cement beam test specimens, which were evaluated for their flexural properties. The study considered two key variables: the surface condition of the additives and the additive content. To assess the impact of the surface condition on enhancement, one group of additives underwent surface treatment through sandblasting, while another group remained untreated. Additionally, different additive concentrations, specifically 2% and 5%, were used to fabricate cement flexural test specimens, with the aim of investigating the effect of additive content on structural performance. The test results showed that the inclusion of recycled composite additives led to a significant improvement in the maximum load and modulus of rupture (between 21% and 39% increase) as well as bending stiffness (between 12% and 27% increase) of the cement beams, in comparison to non-reinforced cement beams.

Keywords: Recycled Composites, Additive Reinforcement, Cement, Flexural Properties

1. Introduction

Fiber-reinforced polymer (FRP) composites have been receiving more attention due to their superior mechanical and physical properties, including high strength-to-weight ratio, durability, and corrosion resistance [1]. FRP composites have been used in various applications, including aerospace, automotive, marine, civil engineering, and sports equipment. Despite the numerous advantages of FRP composites, their sustainable disposal and the management of their end-of-life (EOL) have remained significant challenges [2, 3]. The disposal of EOL FRP composite parts in landfills is the most common practice due to the lack of cost-effective and viable recycling methods [2]. The accumulation of FRP composite waste in landfills raises environmental concerns. Most composites are non-biodegradable and do not naturally decompose over time [3]. While the composite materials may fragment into smaller pieces, they do not entirely dissipate, thereby becoming a potential source of microplastic pollution, which can have adverse effects on the environment and wildlife [2, 3]. To address these issues, many countries have implemented regulations and policies to promote the recycling of composite materials to reduce waste and environmental impact. These regulations are intended to encourage the development of new recycling technologies that can be used to recycle composite materials [4, 5].

Three primary methods for recycling FRP composites are commonly used in industries: thermal, chemical, and mechanical. Thermal and chemical methods can extract continuous fibers, but the process is often complicated and expensive, making it uneconomical for widespread use [2]. The mechanical recycling method is a process of shredding the composite material and cutting continuous fibers into short fiber. For thermoplastic composites, the shredded composite can be melted and reformed through a process to create short fiber-reinforced composite parts. For thermoset composites, which do not melt when heated, the shredded parts need to be bonded back together using a binder or incorporated into another material as an additive to enhance its structure [6]. The short fibers cannot provide as high structural performance as continuous fibers, the mechanical recycling process of FRP composite significantly devalued in terms of its properties and value. The application range of recycled composites is significantly constrained by the reduced mechanical properties of shredded composite materials [7]. Despite the devaluation of composite materials during the mechanical recycling process, it remains a widely used recycling method due to its cost-effectiveness and simplicity. Mechanically recycled shredded composites hold significant potential for the construction materials [8, 9]. The recycled composites can be used in various construction components and structures, such as beams, columns, panels, facades, and reinforcement elements. The incorporation of recycled composites into construction materials offers numerous benefits, including the potential for stronger and more durable structures [8, 9]. This integration can enhance safety and extend the service life of constructed assets. Among numerous construction materials, one intriguing application of recycled composites is cement/concrete materials [8, 9].

Numerous studies have already demonstrated the high potential of fiber-reinforced concrete/cement. The incorporation of the fiber into these materials offers a compelling opportunity to enhance their strength and durability, resulting in the construction of more resilient structures with extended service life and reduced maintenance requirements [10, 11]. Simões et al. [10] studied mechanical behavior of fiber-reinforced concrete using different fiber reinforcements such as polypropylene, glass, and steel fiber. They reported that each fiber type showed distinct characteristics, with higher percentages generally showing superior mechanical performance. Similarly, Li et al. [11] investigated the effects of different fiber types, including polypropylene, steel, and basalt fibers, when added to concrete. They reported significant increases in the mechanical properties of concrete, such as direct shear strength, shear toughness, and residual shear load. Indeed, there have been several studies focusing on recycled fiber reinforcements for cement/concrete materials. Fraternali et al. [12, 13] conducted research on recycled PET fiber-reinforced concrete (RPETFRC) and observed improved thermal resistance, mechanical strength, and ductility compared to plain concrete. Kim et al. [14] also investigated the reinforced concrete with recycled PET fibers and reported a significant increase in structural performance. Al-Tulaian et al. [15] studied the use of recycled plastic waste fibers to reinforce concrete. They found a substantial increase in flexural toughness and flexural strength. Additionally, the incorporation of these fibers helped reduce the total area of plastic shrinkage cracks in the concrete slabs compared to those without fibers [15]. Rotin et al. [16] explored the use of shredded end-of-life (EOL) glass fiber-reinforced polymer composite parts in mortar, replacing traditional aggregates. The results showed a significant increase in modulus of rupture (maximum 35% increase) compared to plain mortar mixes. Cement and concrete play a vital role in the construction industry. The amount of cement and concrete use in the construction industry is enormous. Using recycled composite materials as additives for cement/concrete structures presents an excellent opportunity to reduce composite waste in landfills, promoting a more sustainable approach. Beyond their mechanical advantages, utilizing recycled composites in cement or concrete aligns with sustainability goals, promoting the circular economy and reducing waste generation.

This study aimed to investigate the enhancement of the structural performance of cement through the incorporation of recycled carbon fiber-reinforced composite additives. Unlike other studies that primarily used recycled fiber (without matrix) to reinforce the construction material, this study used fragmented EOL composite parts instead. This method eliminated the need for complex pyrolysis processes and simplifies the incorporation of recycled additives. Several factors influence the mechanical properties of fiber/composite-reinforced cement/concrete, including the type and content of fibers, the length and aspect ratio of fibers, and the surface treatment of additives and fibers. This study examined how different additive contents and additive surface treatments influenced the resulting flexural properties of the cement. The additives used in this study were fabricated from a carbon fiber-reinforced epoxy composite laminate. To control the fiber length in the additives, they were cut into dimensions of 25.4 mm x 25.4 mm using an abrasive waterjet. Afterward, the additives were blended with cement and molded, incorporating various amounts of additives and different surface treated additives. The test specimens were subjected to a four-point loading flexural test, and various flexural properties such as maximum load, modulus of rupture, and bending stiffness were investigated. This study contributes to the understanding of the flexural performance of cement reinforced with recycled composite additives. By exploring the effects of different additive contents and surface treatments, it aimed to provide insights into optimal strategies for enhancing the structural performance of cement and promoting sustainable practice of composite material recycling in construction industry.

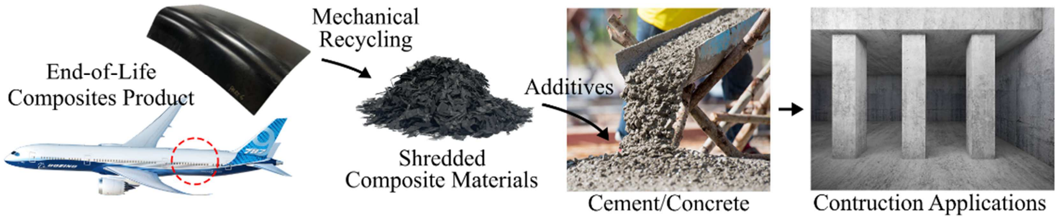

Figure 1. *Schematic drawing illustrating the process of using mechanically recycled composite material additives for cement/concrete construction applications.*

2. Methodology

2.1. Flexural Test Specimen Fabrication

To investigate the influence of recycled composite additives on the flexural properties of cement, cement flexural test specimen was fabricated according to ASTM C78; Standard Test Method for Flexural Strength of Concrete. Cement casing molds with dimensions of 355.6 mm × 101.6 mm × 101.6 mm were created. Portland cement type 1 was used for the fabrication of test specimens. The recycled composite additives were obtained by cutting EOL composite laminate using an abrasive waterjet. This method was used to ensure that the additives had the same fiber length for each test specimen. The dimensions of each additive were 25.4 mm × 25.4 mm, with a thickness of about 3.175 mm. Two different additive contents were used in this study: 5% and 2% by volume.

Bonding between the additives and cement is known to be a key factor in reinforcing the structural performance of the concrete. To investigate the effect of additional surface treatment on the enhancement of the bonding, one test specimen group was fabricated with non-treated additives, and another test specimen group was fabricated with additives with sandblasted surface. The cement was mixed with water and the additives were added during the mixing process. The mixed cement was then poured into the mold and cured under water for 7 days. The cured cement test specimens were demolded and dried at a room temperature. Figure 2 shows the recycled composite additives-reinforced concrete test specimen fabrication process.

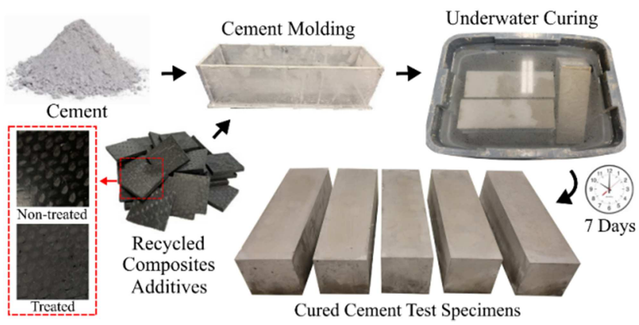

Figure 2. *The recycled composites additives-reinforced cement test specimen fabrication process.*

2.2. Flexural Test Setup

To test the flexural strength of the concrete test specimens, a four-point loading flexural test was conducted in accordance with ASTM C78. The test was conducted using a support span length of 308 mm and a loading span length of 102 mm, as set on a four-point loading test fixture. A load-controlled test rate of 3000 N/min was applied to the specimens. Figure 3 shows the four-point loading flexural test setup. The collected load and deflection data were used to analyze the effect of additive content and additive surface treatment on the flexural strength of the cement reinforced with recycled carbon fiber composite additives. The results of the test were compared to the test specimen without additives to evaluate the structural performance of the recycled carbon fiber composite additive-reinforced cement. The comparison was done by analyzing the load-deflection curves, ultimate load, modulus at rupture, and bending stiffness of the specimens.

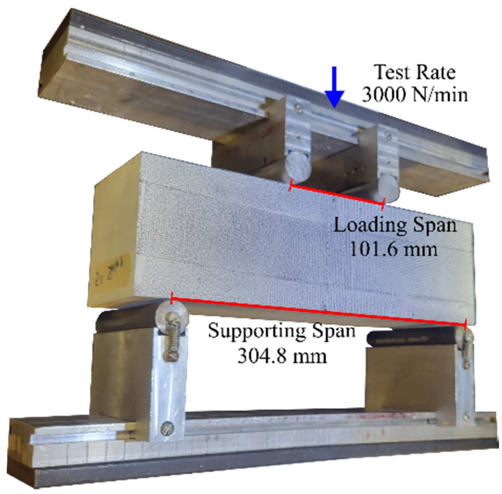

Figure 3. *The four-point loading flexural test setup.*

3. Results and Discussion

3.1. Flexural Test Results

A total of five cement flexural test specimens were tested. Load and displacement data were collected, and the maximum load and modulus of rupture were calculated to compare the flexural properties. Figure 4 (a) displays the load displacement curves for each test specimen. The control test specimen experienced some data lagging and missing data points at the beginning of the test, however, the collected data was enough to calculate the flexural properties used for comparison in this study. The maximum load refers to the highest load attained before the test specimen failed. In this test, the test specimens showed brittleness, gradually increasing without multiple load drops until reaching the maximum load just before failure. The modulus of rupture was calculated using the maximum load. The modulus of rupture is a measure of the maximum stress a structure can withstand before fracturing under flexural loading conditions. The modulus of rupture for each test specimen was calculated using following equation;

$$R = \frac{PL}{bd^2} \tag{1}$$

Where R represents modulus of rupture, P is maximum load, L is span length, and b and d are width and depth of the test specimen. The test result showed that all the recycled composite-reinforced concrete had higher maximum load and modulus of rupture than the control test specimen. The results showed a 21% to 39% improvement in the modulus of rupture with the additives. For the test specimens with non-treated additives, the test specimen with 5% additive content had higher performance than those with 2% additive content. However, there was no difference in performance between the two additive contents for the surface treated additives. In terms of surface treatment of the additives, 2% treated additives had higher performance than 2% non-treated additives. On the other hand, there was no difference in performance between non-treated and treated additives for 5% additives. Figure 4 (b)-(c) shows bar graphs of the maximum load and modulus of rupture for each test specimen. Table 1 shows the maximum load and modulus of rupture of each test specimen.

In addition, the bending stiffness of the test specimens was examined. Bending stiffness indicates how much a material resists deformation when subjected to bending forces. Bending stiffness was determined by calculating the slope of the linear section of the load-displacement plot. Similar to the modulus of rupture, the test results showed that all recycled composite reinforced cement test specimens had higher bending stiffness than the test specimen without the additives. The bending stiffness increased by approximately 12% to 27%. The test specimens with a 2% additive content showed lower bending stiffness compared to the test specimens with a 5% additive content. When comparing the non-treated additive and treated additive specimens, both the 2% and 5% additive content test specimens showed higher bending stiffness in the non-treated additives. Figure 4 (d) shows a bar graph of the bending stiffness for each test specimen. Table 1 shows the bending stiffness of each test specimen.

Table 1. *Maximum load, modulus of rupture, and bending stiffness of each test specimen.*

Additive Condition	Control	Non-treated		Treated	
Additive Content		**2% Content**	**5% Content**	**2% Content**	**5% Content**
Maximum Load	2529 N	3073 N	3418 N	3509 N	3419 N
Modulus of Rupture	75 MPa	91 MPa	101 MPa	104 MPa	101 MPa
Bending Stiffness	7261 N/mm	8568 N/mm	9248 N/mm	8106 N/mm	9034 N/mm

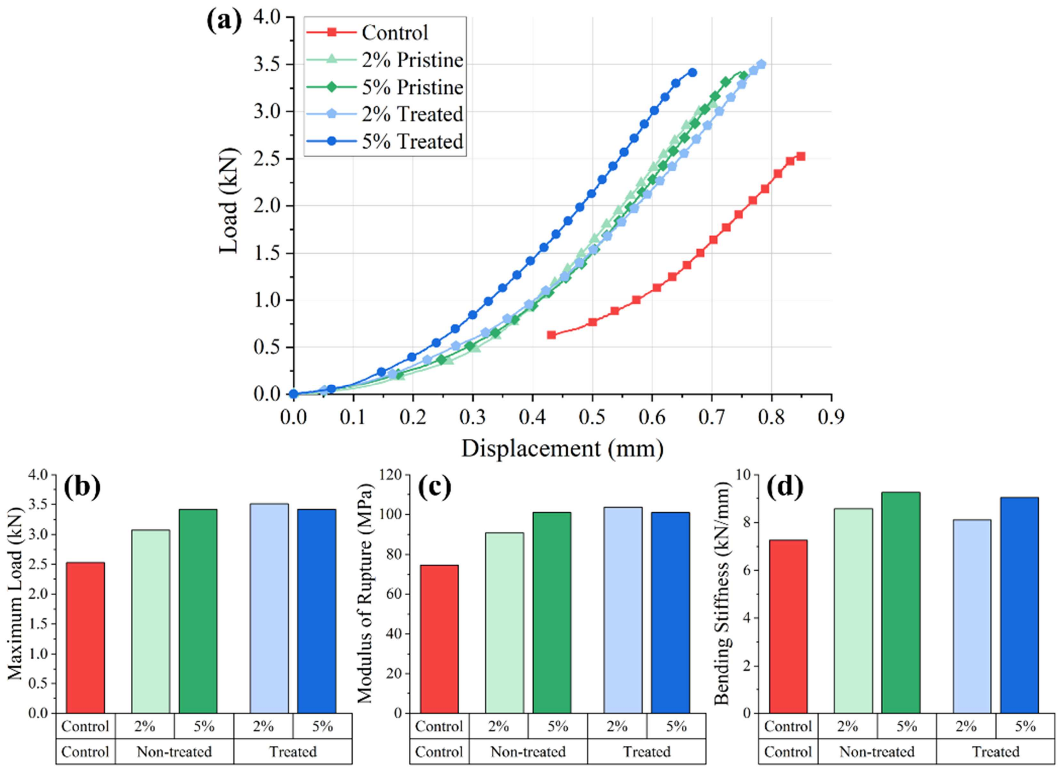

Figure 4. *Flexural test results. (a) Load-displacement plot for each test specimen. Bar graphs showing the (a) maximum load, (b) modulus of rupture, and (c) bending stiffness.*

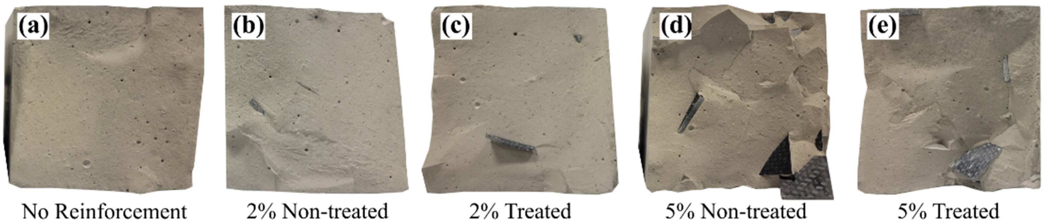

Figure 5. *The fractured surface of the test specimens (a) without reinforcement, (b) with 2% non-treated additives, (c) with 2% treated additives, (d) with 5% non-treated additives, and (e) with 5% treated additives.*

3.2. Fractured Surface Analysis

After conducting the flexural test, the fractured surface of the test specimens was analyzed. The results showed a different fractured surface between the control test specimen and the reinforced test specimen. The control test specimen showed a clean and perpendicular cut fractured surface, while the reinforced test specimen showed a fragmented pattern characterized by the protruded additives within the fractured surface. Upon examining the fractured surface of the test specimens, it was evident that the bond between the concrete and additive was not substantial. The surface of the additive was completely detached from the concrete, regardless of whether the additive was surface treated or not. It was observed that the additives did not crack with the concrete. Rather, the cement cracked while avoiding the additives.

3.3. Discussion

The test results showed the recycled composite additives improved flexural properties of the cement test specimens. Both the modulus of rupture and bending stiffness were higher in the specimens with the additives. It was difficult to provide solid statement how the additive content and additive condition affect to the test result. In the case of additive content, both the non-treated and treated samples showed higher bending stiffness values with 5% content compared to 2% content. For maximum load and modulus of rupture, the non-treated samples showed higher values with 5% content, whereas the treated specimens showed higher values with 2% content. In the case of additive condition, the test specimen with the treated additives showed higher modulus of rupture than the non-treated test specimen in the 2% content group. However, the 5% content non-treated and treated test specimen had the same modulus of rupture. For the bending stiffness, the non-treated additive specimen had a higher value than the treated additive specimen for both 2% content and 5% content group. Overall, the test results indicated the possibility that higher additive content contributed to improved flexural properties in the test specimen. However, it showed that the additive surface treatment used in this study, sandblasting, did not show a significant impact on the flexural properties. It is also important to note that the location and orientation of the recycled composite additives within the test specimens varied, resulting in variations and potential volatility in the mechanical properties of the reinforced cement. Therefore, further investigation into the consistency of the recycled composite additives in reinforced cement is necessary to ensure the safety of the structure. This study is a preliminary study that does not have enough test data to perform a statistical analysis due to the low number of test specimen. Future studies will include a larger number of test specimens to investigate the impact of various variables on the flexural properties of cement beams using more in-depth statistical analysis.

One of the major challenges identified in this study for the recycled composite additives-reinforced cement was the bonding between the cement and additives. Despite surface treatment through sandblasting, the examination of the fractured surface showed not optimal bonding between the additives and cement. In this study, the recycled composite additives were fabricated using an abrasive waterjet instead of traditional mechanical composite recycling shredder to control the fiber length in the additive. The surface of the additives remained smooth with the fibers enclosed within the matrix, thereby minimizing fiber exposure. Further study is needed to enhance the bonding between the cement and additives. Overall, the findings of this study support the effective utilization of recycled carbon fiber composites for cement reinforcement in construction applications, offering a sustainable solution for EOL composite materials.

4. Conclusion

This study investigated the incorporation of mechanically recycled composite additives into cement to enhance its flexural properties. The results showed that the addition of recycled composite additives significantly improved the modulus of rupture and bending stiffness of the cement specimens compared to non-reinforced cement. The modulus of rupture increased by 21% ~ 31%, and the bending stiffness increased by 12% ~ 27% depends on the different additive content and additive condition. Higher additive content generally showed enhanced flexural properties, while the impact of additive condition seemed to be less significant in this study. The bonding between the cement and additives remained an issue, highlighting the need for further research to improve the interfacial adhesion between the materials.

Further investigation with a larger number of test specimens and in-depth statistical analysis are recommended to deepen the understanding of the influence of various factors on the flexural properties of the recycled composite reinforced cement. Additionally, exploring alternative methods for fabricating the additives and investigating different surface treatment methods to optimize the bonding between the additives and cement are important for future research. The findings of this study support the effective utilization of recycled composites, offering a sustainable solution for EOL composite materials and contributing to the reduction of environmental impact.

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