Sustainable Engineering Materials
ISSN: 3105-1960 (Print); ISSN: 3105-1979 (Online)
http://www.sustain-dpl.com/picnews.asp?id=177
DOI: 10.54113/j.suem.2026.000015

ORIGINAL ARTICLE

Recycling carbon-glass fiber composites via thermal process: mechanical property evaluation

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Abstract: Polymer composites are not readily biodegradable in nature, resulting in significant material waste. The growing use of polymer composites has led to increased material waste due to their limited recyclability. This research recycles a carbon-glass fiber-reinforced hybrid composite (CGFRC) and investigates the mechanical properties of the recycled specimen, comparing them with those of the new specimen. The work focuses on recovering carbon and glass fiber from the epoxy matrix through a thermal recycling method and remanufacturing the composite with recycled fibers. New and recycled composite specimens underwent tensile and flexural strength tests to assess their mechanical properties. The findings showed that the recycled specimens had reduced physical and mechanical properties compared to the new ones. The new specimen demonstrates a tensile strength of 36.85 MPa and a flexural strength of 37.19 MPa. In contrast, the recycled specimens exhibit a tensile strength of only 11.15 MPa and a flexural strength of 29.82 MPa. This indicates a notable reduction in mechanical properties for the recycled material, which retains approximately 80% of its initial flexural strength but only 30% of its tensile strength. SEM analysis revealed the presence of voids, poor distribution of fibers, and epoxy residue in the recycled specimen.

Keywords: recycled polymer composites, thermal recycling, hybrid composites, sustainability, Polymer Matrix Composite

1 Introduction

Fiber-reinforced composites are widely employed owing to their exceptional properties. The fibers, which constitute the primary elements of these composite materials, are broadly categorized as natural or synthetic [1, 2]. Synthetic fibers generally demonstrate superior resistance to moisture, chemicals, and heat, outperforming Natural Fibers in these aspects [3–6]. Their high strength and resistance to inertia make synthetic fibers especially valuable in the fabrication of advanced composites for sectors such as aerospace and automotive engineering [3, 7]. There's a steady rise in demand for synthetic fibers, mainly because they play a crucial role in fiber-reinforced composites applications. These composites are created by combining two or more distinct components to achieve properties that are different and often superior to those of the individual constituents [8].

Composite materials are characterized by their adaptable properties and ease of fabrication into various shapes [9]. Rising demand for high-performance, lightweight materials consistently fuels innovations in composite technology and supports advancements in modern engineering systems [10]. In the context of lightweight materials, fiber-reinforced composites exhibit outstanding characteristics,

Received: 13 October 2025; Received in revised form: 24 March 2026; Accepted: 8 May 2026

including being lightweight, possessing high strength, and resisting corrosion and fatigue. Additionally, it offers excellent moldability and design flexibility [11, 12]. As a result, both the aerospace and automotive industries have been particularly focused on developing lightweight composite materials and enhancing designs [13, 14]. The advancement of fiber-reinforced composites has empowered engineers and designers to create solutions that support a sustainable, emission-free future [13, 15]. According to Katunin et al.[16], about half of the bodies of Boeing 787 Dreamliner and Airbus A350 airplanes are constructed using carbon fibers. Composite materials are highly appealing in various applications due to their excellent strength characteristics. They provide a better strength-to-weight ratio compared to traditional metallic alloys [8]. Although metal structures are inherently prone to corrosion, this issue can be mitigated through the application of composite materials [17–19]. The major issue with these materials is their high initial cost and repair difficulty. Moreover, UV radiation and temperature changes can weaken the composite structure [20].

As carbon and glass fiber-reinforced composites (CFRC and GFRC) continue to gain prominence in the aerospace, automotive, and renewable energy sectors, a significant waste management issue has arisen [21, 22]. According to Wei et al. [23], these composites are expected to make up the majority of global waste streams by 2030. It's estimated that the aircraft and wind turbine industries will generate around 8,40,300 metric tons of waste by 2050. Pickering et al. [24] observed that waste prevention aims to minimize waste generation during production processes. If prevention is not possible, the best option is recycling, where materials are recovered and processed for reuse. Recycling processes follow circular economy principles, aiming to cut waste and keep materials useful for as long as possible [25].

A considerable number of composites are used daily, and they create waste, which is then expelled after reaching their shelf life. A composite with an unusual shape and complicated structure is hard to recycle [26]. It's more efficient and convenient to recycle long, continuous, and aligned fibers [27]. Additionally, this orientation provides an opportunity to recycle the composites multiple times. Pizzi et al. [13] noted that although fiber recycling can considerably cut manufacturing costs and reduce environmental impact, its adoption in the composites industry remains limited. This is mainly due to the discontinuous form of recycled fiber. Such characteristics make them more challenging to process using conventional manufacturing methods. These recycled fibers also show less mechanical strength than the virgin fibers [13].

There are two common methods used to recycle fiber-reinforced composites: mechanical recycling and fiber reclamation. By reviewing composite recycling techniques, Oliveux et al. [28] mentioned that mechanical recycling seems to be appropriate for Glass fiber reinforced composite (GRFC) and lower-grade Carbon fiber reinforced composite (CFRC). However, the fiber reclamation method is considered more effective and sustainable for recycling [29]. Similarly, an investigation on the recycling of glass fiber and carbon fiber epoxy composites shows that reclaimed fibers retained lower but functional tensile strength. These fibers were reclaimed using pyrolysis and a mechanical recycling technique [8]. Additionally, Pimenta et al. [29] also explored various methods for recycling carbon fiber from composite waste, including mechanical, thermal, and chemical processes, and the reclaimed fibers retain much of their mechanical performance. A study conducted by Gopalraj et al. [27] recycled pre-consumed CFRP and GFRP waste using a novel thermal process and successfully recovered 95–98% of carbon fibers and 80–82% of glass fibers. The recycled fibers were aligned to create new unidirectional, non-woven composites. The results showed that this closed-loop recycling method improved the mechanical properties of the materials. Recycling study findings suggest that the recycling approach offers a cost-effective and eco-friendly solution [13].

While substantial research has focused on recycling either carbon or glass-fiber composites, limited attention has been given to carbon–glass hybrid composites, despite their growing use. Moreover, few studies have systematically evaluated the mechanical performance of recycled hybrid composites. However, a notable gap exists in the analysis of the synergetic effect of recycled carbon and glass fiber composites. Understanding this synergetic behavior is crucial for optimizing performance and durability. Furthermore, there is a lack of focused study on assessing the performance of recycled synthetic hybrid composites. To address this gap, the present research investigates the recycling and mechanical property evaluation of a carbon–glass fiber reinforced hybrid composite

(CGFRC) using a conventional thermal recycling method. The study aims to advance sustainable materials engineering by exploring an environmentally friendly pathway for managing composite waste.

2 Materials and Methods

2.1 Materials

The materials used in the research are glass fiber, carbon fiber, and epoxy resin. The fiber and epoxy resins were sourced from the local market in Bangladesh. Lapox B-11 grade epoxy resin with hardener (Lapox B-6) was used as the matrix. The glass fiber and the carbon fiber were both woven bidirectionally in fiber orientation. The carbon fiber is specified as bi-directional 3K Plain Weave Woven Fabric. The average density of carbon fibers was specified as 200 grams per square meter (GSM). For the glass fiber, the average density was 660 grams per square meter (GSM).

2.2 Preparation of composites

The overall process, illustrated in **Fig.1**, involves four key steps: manufacturing, recycling, remanufacturing, and testing. The first step involves composite manufacturing, where glass and carbon fiber are combined to create a hybrid composite using epoxy resin. The second step proceeds towards thermal recycling and fiber reclamation. The third step involves remanufacturing the hybrid composite using recovered fibers. The final step is to analyze the mechanical properties of the samples.

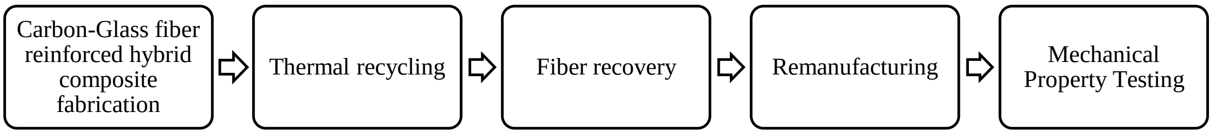


Fig.1. Schematic overview of the work process

This research employed the hand layup technique for fabrication, as it is quite straightforward and involves fewer components, making it the easiest [30]. The initial fabrication process was conducted in a silicone mold, as the silicone mold doesn’t stick to the epoxy resin easily. The fibers were cut according to the internal dimensions of the silicone mold.

For composite fabrication, the epoxy resin was mixed with liquid hardener in a 3:1 ratio as per the manufacturer's guidelines. The mixture was poured into the silicon mold uniformly. Then, a glass fiber layer was placed over the resin layer. The layer was pressed evenly with the help of a roller brush to minimize air voids. Subsequently, another layer of resin was poured, and a 0.2 mm bidirectional carbon fiber was placed over that. Later, a layer of resin was applied over the carbon fiber, and a second layer of glass fiber was then added. Finally, the resin was poured over the second layer of glass fiber. Extra attention was given to prevent air voids and uneven resin distribution. A plastic Sheet was placed over the mold. A specifically cut-glass plate was used to press the composite with the help of a 50N weight block. It acted as a downward weight and employed compression molding. The composite was left to cure for 24 hours at room temperature. Later, from the fabricated sample, three samples were cut according to a specific ASTM standard for each mechanical property testing, and the rest was kept for thermal recycling.

2.3 Recycling

Fig. 2(c) shows the custom-made 240 mm by 140 mm cast-iron material holder prepared for use in the recycling process. The holder was designed specifically to collect the fibers after the resin evaporates in the furnace.

From previous literature, it is known that cured epoxy evaporates at a temperature range of 450-600°C [27,31,34]. Batista et al. [35] processed carbon fibers at 550 °C for 45 min and achieved clean fiber recovery with only 12% tensile strength loss relative to virgin fibers. Similarly, Nistratov et al. [36] reported that glass fibers recycled at 500 °C for 1 h yielded approximately 32% yield, while carbon fibers treated at 700 °C retained sufficient strength for reuse. Naqvi et al. [37] reviewed the temperature range for glass fiber recycling (500–600 °C) and reported minimal fiber degradation in this range. Based on these findings, a recycling temperature of 500 °C for 15 min was selected in the present study as a practical compromise. This temperature is sufficiently high to degrade the polymer matrix while minimizing thermal damage to both glass and carbon fibers. Then, the sample was adjusted in the material holder and placed carefully in the furnace. Initially, smoke was observed after introducing the material holder into the furnace, as shown in **Fig. 2(a)**, and it eventually disappeared. The temperature was maintained at 500 °C for 15 minutes. After 15 minutes, the material holder was carefully removed from the apparatus. Subsequently, the resin completely evaporates and leaves only the fibers in the holder, shown in **Fig. 2(b)**. Next, the fibers were collected carefully from the holder. Each layer of fiber was separated and cleaned of resin debris. The remanufacturing of the composite using recycled fibers followed the same resin-hand lay-up methodology as the virgin composite, with slight process modifications to accommodate the different physical conditions of the reclaimed fibers. After thermal recovery, the recycled carbon–glass fibers were obtained in entirely woven form; however, excessive resin residue remained on the fiber surface. Before lay-up, the fibers were manually cleaned to maximize spread ability. Although the fiber surface remained slightly uneven in some places. Epoxy resin was applied gradually during layering, ensuring full wet-out and minimizing dry spots. Moderate hand compression was applied intermittently to expel trapped air and encourage resin infiltration into the loosely packed regions. After curing, three samples were cut from the recycled specimen according to a specific ASTM standard for each mechanical property testing.


(a) (b) (c)

Fig. 2. (a) Thermal recycling of CGFRC fibers in the furnace, (b) Recycled fibers after heat exposure, (c) Custom-made material holder for recycling

2.4 Material Characterization

2.4.1 Tensile Test

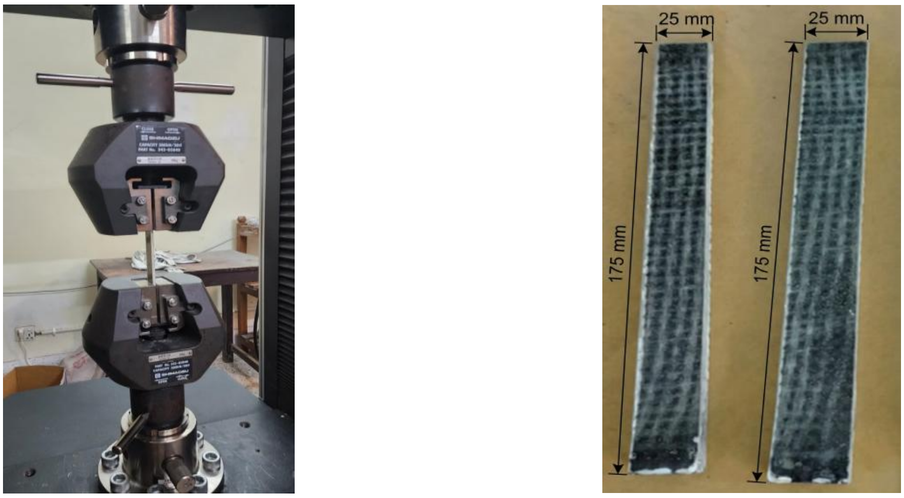
In this study, tensile testing was performed on composite specimens, with three samples tested for each type, following the ASTM D3039 standard [38]. The specimens were subjected to axial loading using a Universal Testing Machine (Shimadzu AGX-V 300 kN) with a gauge length fixed at 100 mm as specified by the ASTM standard. The test was conducted at a loading rate of 5 mm/min until the specimen fractured at its ultimate load. According to ASTM D3039 standards, rectangular samples measuring 175 mm × 25 mm were cut from the composite sheet shown in **Fig. 3(b).** For testing, three samples from each specimen were used. To evaluate the mechanical behavior during tensile testing, several key equations [32,33] were applied, as described in Equations (1)-(4). **Fig. 3(a)** shows the specimen setup in the UTM before testing, while **Fig. 3(b)** shows the specimen itself. After reaching the maximum applied load, the specimen failed, and the corresponding data were collected.

$$\sigma_{\mathrm{t}} = \frac{F}{A} \tag{1}$$

$$\varepsilon_{\mathrm{t}} = \frac{L - L_0}{L_0} \tag{2}$$

$$E_{\mathrm{t}} = \frac{\sigma_t}{\varepsilon_t} \tag{3}$$

$$UTS = \frac{F_{max}}{\sigma} \tag{4}$$

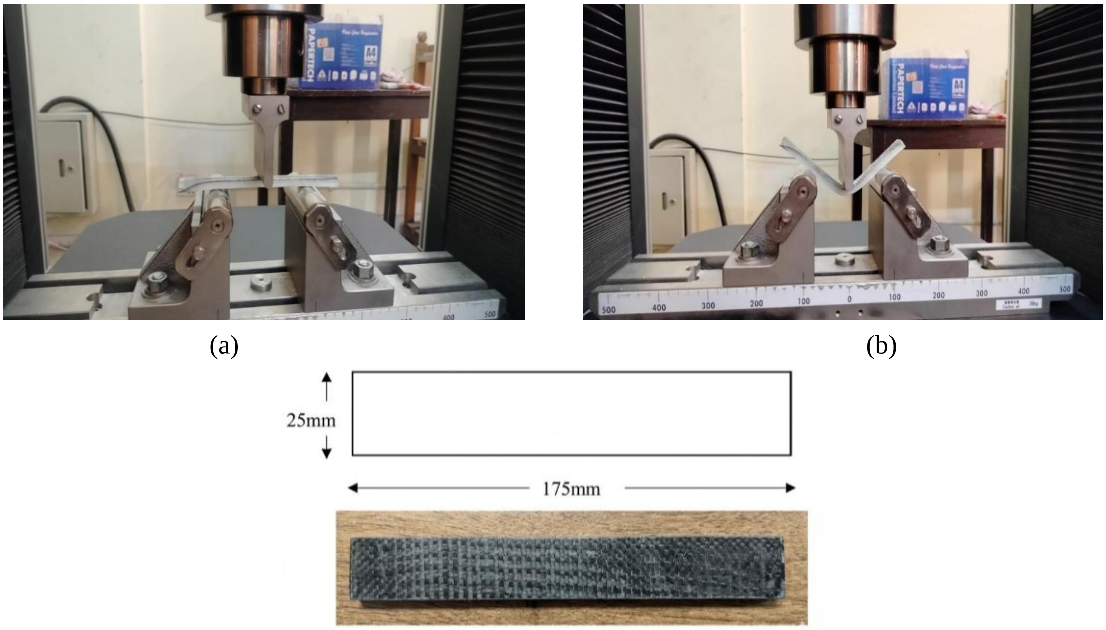


(a) (b)

Fig. 3. (a) Tensile test setup using Universal Testing Machine (UTM), (b) Specimen before the testing.

2.4.2 Flexural test

For the flexural test, specimens were prepared following ASTM D790 [41] Standards, with three samples evaluated for each type. This study employed the 3-point bending test, the most common method for assessing flexural properties, on the prepared composite samples. The test was conducted using a Universal Testing Machine (Shimadzu AGX-V 300 kN). As per ASTM D790 standards, the specimens were cut into a rectangular shape for the test. The sample size was kept at 175 mm × 25 mm, as shown in **Fig. 4(c)**. Three samples were taken from each of the new and recycled specimens for testing. The test was conducted on all specimens at a crosshead speed of 5 mm/min and a span length of 100 mm, following the ASTM D790 standard. Tests were performed on both the new specimen and the recycled specimen.



(a) (b)

(c)

Fig. 4. (a) Flexural test setup using Universal Testing Machine (UTM), (b) Specimen after testing, (c) fabricated sample and dimensions

The key equations [39,40] used to calculate flexural strength (σ_f), flexural modulus (E_f), and surface strain (ε_f) In a three-point bending test conducted on the specimen using a Universal Testing Machine (UTM) provided in equations (5)-(7), respectively.

$$\sigma_f = \frac{3FL}{2bd^2} \tag{5}$$

$$\sigma_f = \frac{3FL}{2bd^2} \tag{6}$$

$$\varepsilon_f = \frac{6Dd}{L^2} \tag{7}$$

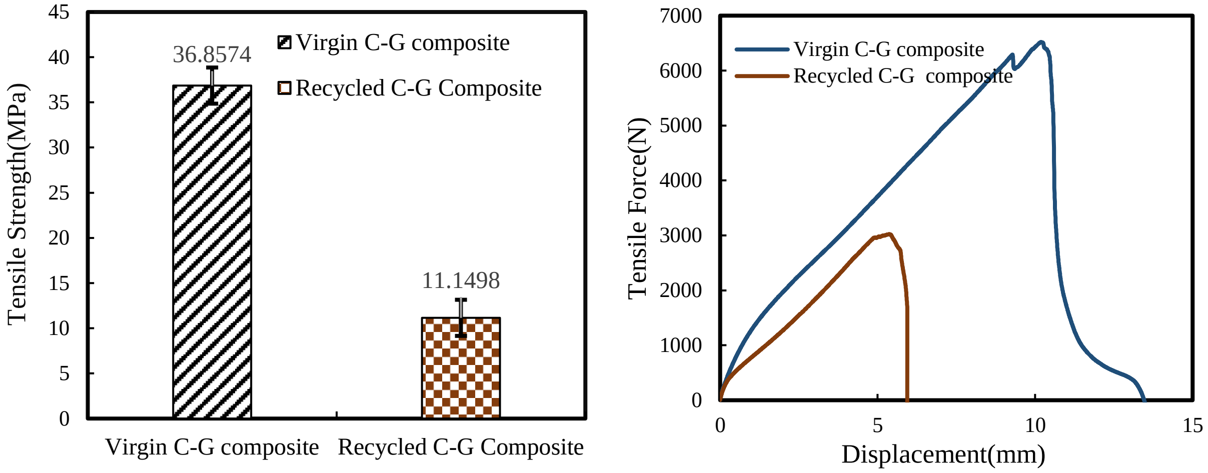
Fig. 4(a) illustrates the specimen prior to testing, while **Fig. 4(b)** shows the specimen following the test. The corresponding test results are detailed in Section 3.2.

3 Results and Discussion

3.1 Tensile Test

Fig. 5(a) presents the tensile strength data, where the new specimen tensile strength reaches approximately 36.85 MPa. In contrast, the recycled specimen exhibits a significant drop in strength to approximately 11.15 MPa, retaining only about 30% of its original strength. Fiber deterioration and structural irregularities introduced during recycling are responsible for this significant loss.

Similar results were found by Sales-Contini et al. [42], where using only recycled carbon fibers reduced the tensile strength by about 36.02%. Williams et al. [43] recycled glass fibers at 450°C and reported a 45% reduction in tensile strength in the recycled composite. Criado et al. [44] also recycled glass fiber at 550°C, and these recycled fibers showed 82% of tensile strength reduction compared to virgin fibers. Iglésias et al. [45] got a 51.14% reduction in tensile strength after recycling at 400°C for 180 min.



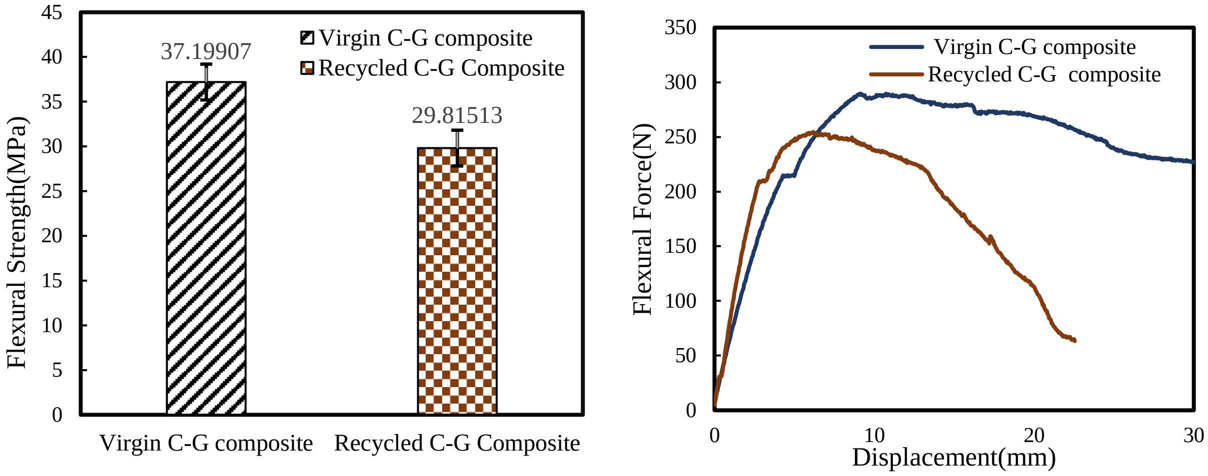
(a) (b)

Fig. 5. (a) Tensile strength comparison (b) Tensile force versus displacement curve

In **Fig. 5(b)**, the tensile force–displacement responses of the virgin and recycled C–G composites show distinct behavioral differences. The virgin specimen exhibited a higher peak tensile force of approximately 6511 N and sustained an elongation of about 13 mm before failure, indicating a greater ability to carry load and deform plastically. In contrast, the recycled specimen reached a lower peak force of roughly 3000 N and failed at a shorter displacement of around 8 mm. This reduction in force capacity and deformation suggests that the recycling process led to a decrease in the load-bearing capability and ductility of the material. Similar observations were reported by Boulanghien et al. [46], where the recycled fibers exhibited earlier failure due to reduced strain at break. The tensile test results show an apparent reduction in the strength of the recycled composite compared to the virgin specimen. This decrease can be attributed to fiber damage during recycling and the less uniform fiber distribution in the remanufactured laminate, both of which weakened the fiber–matrix interaction and caused premature failure.

3.2 Flexural test

From **Fig. 6(a)**, it is evident that after flexural testing, the virgin C-G composite had higher strength than the recycled C-G composite. The new composite specimen had a flexural strength of 37.19 MPa, while the recycled specimen had 29.81 MPa, representing a 19% decrease. Sales-Contini et al. [42] observed a similar trend, where flexural strength decreased by 13.2% after using recycled carbon fibers into the composite. Also, Iglésias et al. [45] had observed a 33.98% reduction in flexural strength after recycling glass fiber composites.



(a) (b)

Fig. 6. (a) Comparison of flexural strength between new and recycled composite specimens, (b) Flexural force versus displacement curve.

Fig. 6(b) illustrates that the virgin C-G composite can withstand a maximum flexural load of approximately 295 N, maintaining its structural stability over a displacement of nearly 40 mm. In contrast, the recycled specimen sustained a lower peak load of approximately 255 N. It exhibited failure at an earlier displacement of around 22 mm, indicating a decline in flexural performance. Despite the expected reduction in mechanical properties, the recycled composite specimen still demonstrated a reasonably good flexural strength. The recovered fibers retained sufficient stiffness to contribute effectively to bending resistance. This indicates that even with partial fiber damage and alignment variations, the recycled reinforcement can still provide meaningful structural performance.

Based on the above observations, the decrease in tensile and flexural strength of the recycled specimen may be attributed to several factors. Thermal degradation during the recycling process at 500 °C can weaken the fiber-matrix interface. Simultaneously, char formation or resin residue has a bad impact on lowering the properties [27,47]. Another reason is the presence of air voids in the recycled composites, which further weakens the material by reducing the strength of the matrix. Additionally, in the remanufacturing process using recycled fibers, the condition of the fibers may have influenced the compression molding technique, leading to air void formation and lower composite performance.

3.3 Morphological Analysis

Fig. 7 shows SEM micrographs of carbon-glass fiber reinforced composites. SEM analysis reveals changes in the fiber surface topography due to the thermal recycling process. **Fig. 7(a)** and **Fig. 7(b)** display images from a virgin C-G specimen, while **Fig. 7(c)** and **Fig. 7(d)** show images from a recycled specimen. Notably, clear fiber breakage is visible, with fibers embedded in the fractured matrix in **Fig. 7(b)**. It shows a manufacturing defect characterized by fiber clustering and partial matrix cracking. This micrograph does not represent the typical fiber–matrix adhesion of the specimen but rather an isolated flaw resulting from uneven resin impregnation during fabrication.

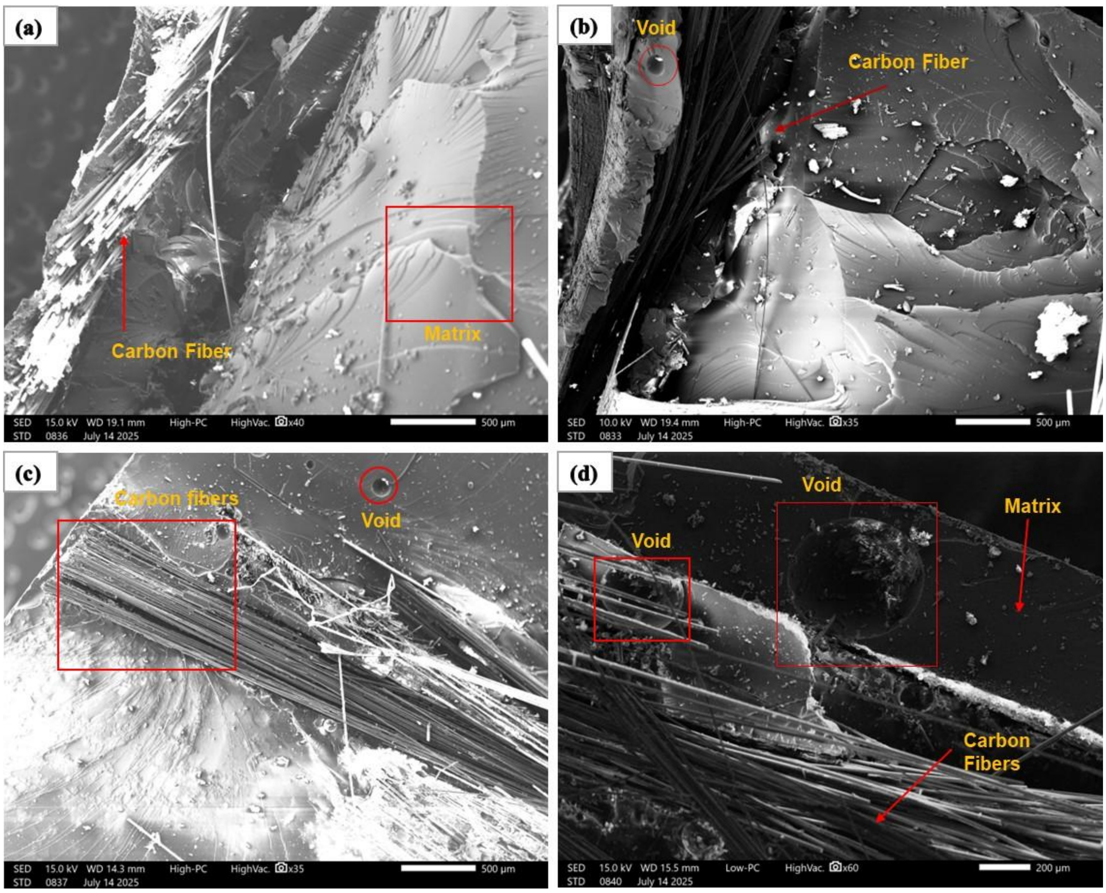


Fig. 7. SEM micrographs showing the morphological features of: (a, b) new specimen (×40 and ×35, respectively), and (c, d) recycled specimen (×35 and ×60, respectively)

In **Fig. 7(c)**, the recycled specimen exhibits clustered fibers and irregular dispersion that can weaken the overall microstructural integrity of the composite. These clustered regions interfere with the uniform stress distribution by forming localized weak points, and these weak points hinder the load transfer between the fibers and the matrix. In the clustered regions, some fibers are effectively shielded and bear minimal load, while nearby areas experience increased stress concentrations. This uneven distribution of stress may have promoted premature microcracking and fiber pull-out. Consequently, only a fraction of the reinforcement actively participates in load sharing, resulting in a decrease in the tensile strength of the recycled specimen. Numerous voids and air bubbles are present in the matrix, likely formed during the thermal recycling process, as shown in **Fig. 7(d)**. These defects degrade the fiber–matrix interface and act as crack initiation sites, further weakening the mechanical performance.

4 Conclusion

The study presents important findings on the thermal recycling of carbon-glass fiber-reinforced hybrid composites. It examines changes in tensile and flexural strength of both new specimens and recycled specimens. It also highlights the potential of thermal recycling as a practical, scalable, and cost-effective approach for managing composite waste, supporting sustainable materials engineering and the circular economy.

The results showed that while flexural strength was mainly preserved, retaining about 80% of the initial flexural strength. Tensile strength experienced a considerable reduction, retaining only 30% of its initial strength, which may be attributed to fiber fragmentation and weakened interfacial bonding during recycling. This contrast suggests that flexural properties are more resilient to degradation induced by recycling than tensile properties. SEM analysis indicates the presence of fiber dispersion and air voids.

The recyclability of these composites enables their reuse in applications where bending strength is more important than tensile strength, such as panels, casings, and other non-structural parts. From a sustainability perspective, thermal recycling decreases reliance on new raw materials, reduces landfill waste, and prolongs the life of advanced composites. This benefit of recyclability and sustainability supports the principles of the circular economy and makes recycled composites a practical choice for secondary applications. Future research could focus on refining recycling techniques to minimize fiber damage and applying surface treatments to enhance fiber-matrix adhesion. Additionally, future research could explore combined mechanical and chemical recycling methods and develop a residue-free process to enhance the performance of recycled hybrid composites further.

Acknowledgement

This research work was technically supported by Khulna University of Engineering & Technology (KUET), Khulna, Bangladesh.

Funding Statement

No funding was received for this research.

CRediT authorship contribution statement

Rayat Hasan: Conceptualization, Methodology, Resources, Writing - review & editing. **Muhammad Omar Faruk:** Investigation, Data curation, Visualization, Writing - original draft. **Ehsanul Islam Fahim:** Conceptualization, Methodology, Writing - review & editing. **Arup Kumar Debnath**: Supervision, Conceptualization, Investigation, Visualization, Writing - review & editing. **Md. Abdul Hasib:** Investigation, Visualization, Data Curation, Writing - review & editing. **Jasim Ahmed Chowdhury**: Resources, Formal analysis, Writing - review & editing.

Conflicts of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

Data Availability Statement

Data will be made available on request.

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