DESIGN AND FABRICATION OF SUSTAINABLE FLAT WASHERS USING TEXTILE FABRIC WASTE

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***Abstract*— Sri Lanka's vibrant textile and apparel industry generates a substantial amount of textile waste, particularly discarded denim, from its manufacturing processes. Both large-scale production facilities and small garment workshops contribute to this accumulation, making denim waste an abundant, yet largely untapped, resource and a significant pollutant. Currently, most discarded denim ends up in landfills, where synthetic dyes and chemical finishes contaminate ecosystems. To mitigate this environmental impact, this research investigates the feasibility of designing and fabricating sustainable flat washers using a denim fabric waste composite. The composite material was prepared by embedding denim fabric waste into an epoxy resin matrix, which was then cross-linked using a methyl ethyl ketone peroxide catalyst. Different denim fiber-to-resin ratios (1:15, 1:20, 1:25, and 1:30) were prepared according to ASTM standards to investigate their mechanical properties, including compressive strength, tensile strength, flexural strength, and hardness. The 1:20 denim fiber-to-resin ratio composite consistently exhibited superior mechanical properties compared to the other composites. The 1:20 denim to resin ratio composite showed the flexural strength of 356.67 MPa which suggests the material's capability to withstand bending loads effectively. The tensile strength of 5.33 MPa was achieved by 1:20 fiber to resin composite indicating sufficient durability for tension-based applications and also exhibited compressive strength of 29.47 GPa highlights the material's ability to resist high compressive forces, making it suitable for heavy-load applications. Although their hardness is lower compared to conventional washers made from aluminum and mild steel, they still provide adequate hardness for many applications. The findings underscore the potential of using recycled textile waste as a viable alternative to traditional materials, offering environmental benefits without significantly compromising mechanical performance. This makes the 1:20 ratio composite flat washers a promising option for applications where sustainability is a key consideration, such as induction motor holder, fan head screw, automobile engine holding place and bicycle rear wheel axle washers. This work contributes to Sustainable Development Goals (SDGs) 9 and 12 in Sri Lanka.**

I. INTRODUCTION

The global textile industry has become one of the most environmentally damaging sectors, generating over 92 million tons of waste annually [1]. Among textile products, denim stands out as both a staple and a significant pollutant. Approximately 1.3 billion pairs of jeans are sold yearly, with 85% ultimately discarded into landfills, where synthetic dyes and chemical finishes contaminate ecosystems [2]. Moreover, denim production is resource-intensive, requiring 3,781 liters of water and emitting 33.4 kg of CO_2 per pair, contributing to climate change [3]. Post-consumer denim waste exceeds 2.16 million metric tons annually, yet only 12% of all textiles are recycled, and less than 1% are upcycled into new products [1]. The rise of fast fashion exacerbates this crisis, with brands continuously introducing short-lived designs that accelerate disposability and landfill accumulation [4]. The traditional linear "take-make-dispose" model of production is unsustainable in the face of climate urgency, necessitating a shift toward circular economy principles. Shirvanimoghaddam et al. [5] emphasize the importance of transitioning to a circular economy by integrating innovative waste-repurposing strategies, advancements in material science, and changes in consumer behavior. Radukic [6] underscores the role of upcycling and recycling in transforming textile waste into valuable resources, reducing landfill dependency, and conserving raw materials.

One promising approach to addressing textile wastes is its incorporation into composite materials. Harsanto et al. [7] and Mishra et al.[8] demonstrates that textile waste can be effectively utilized in green and thermoset composites, offering both environmental and performance benefits. These studies explore the mechanical properties, thermal degradation behavior, and water absorption characteristics of such composites, suggesting their viability for sustainable product development. Spasenović et al. [9] highlight how composite gears and structures integrating metallic hubs achieve enhanced mechanical performance with lower environmental impact.

This study explores the feasibility of utilizing denim fabric waste in the design and fabrication of sustainable flat washers. The research aims to investigate the mechanical performance of denim-based composite washers, assessing key properties such as tensile strength, compressive strength, and hardness. The study aligns with global sustainability efforts, particularly the United Nations' Sustainable Development Goals (SDGs), including SDG 12 (Responsible Consumption and Production) and SDG 9 (Industry, Innovation, and Infrastructure) [2].

II. METHODOLOGY

A. Materials

In this study, denim waste was sourced from local textile production facilities and neighborhood collection points, ensuring a sustainable and readily available raw material supply. Epoxy resin (1,3-bis(2,3-epoxypropoxy)-benzene) was selected as the matrix due to its excellent mechanical properties and strong fiber adhesion properties. Methyl ethyl ketone peroxide (MEKP) was employed as a curing agent due to its ability to initiate the cross-linking process effectively, ensuring structural integrity of the composite [10].

B. Preparation of Composites and Testing

The collected denim waste underwent pre-processing to remove contaminants such as synthetic dyes, residual chemicals, and physical debris. This ensured the uniformity and integrity of the fibers. Once cleaned, the denim fabric was shredded into fine strips and further broken down into small fiber fragments. The shredding process increased the surface area of the fibers, promoting better adhesion between the reinforcement (denim fibers) and the epoxy resin matrix during composite casting. The optimized fiber size distribution was crucial in enhancing the mechanical performance of the final composite material.

The composite material was fabricated by combining denim fabric waste (as the reinforcement) with epoxy resin (as the matrix). The denim fibers were embedded into the epoxy resin matrix, which was then cross-linked using the methyl ethyl ketone peroxide catalyst. This process formed a durable composite material capable of withstanding mechanical loads. The research focused on different denim to resin ratios (100% resin, 1:15, 1:20, 1:25, 1:30) were experimented to identify the optimal compressive strength and flexibility.

Denim fabric strips were cut into various sizes to study how fiber size affects the composite's mechanical performance. Curing temperature and stripe orientation were varied during composite fabrication to determine their influence on the material's properties. After the casting process, the washers were subjected to post-curing and finishing treatments to enhance their mechanical properties. The washers were left to cure under controlled conditions, allowing the epoxy resin to fully harden and bond with the denim fibers (Figure 1). This process was critical in achieving the desired mechanical properties.

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Figure 1. Fabricated flat washers

The testing was conducted according to ASTM standards for fiber-reinforced composite materials. These tests provided quantitative data on the tensile, compressive, and flexural strengths of the washers. The specimen prepared is shaped into the required dimension. The dimensions, gauge length, and cross-head speeds are chosen according to the ASTM D3039 standard. The tensile test is performed on the Universal Testing Machine (UTM). The process involves placing the test sample in the UTM and applying tension to it until the fracture of the material. The specimen is prepared according to the ASTM D6041 standard for compressive test. This provides insight into the material's ability to withstand compressive loads without deforming or failing. The flexural specimens are prepared as per the ASTM D7264 standards and the test is carried out. The 3-point flexural test is the most common flexural test and is used in this experiment for checking the bending strength of the composite materials. The testing process involves placing the test specimen in the UTM and applying force to it until it fractures and breaks. Three molds were designed and fabricated to create standard-sized specimens for each mechanical test. This ensured consistency and compliance with the ASTM standards, allowing for accurate comparison of the results across different samples and resin-to-fiber ratios. The hardness of the composites was measured using a Shore A durometer.

III. RESULTS AND DISCUSSION

The mechanical properties of the denim-based composites were analyzed and compared with conventional materials. Key findings are summarized below.

A. Compressive Strength Analysis

Compressive tests were conducted on various sample compositions, including 100% resin, 1:15, 1:20, 1:25, and 1:30 denim-to-resin ratios. Compressive strength tests showed that the 1:20 ratio composite achieved an average of 306.13 MPa, outperforming other compositions. The samples with higher resin content (C0 – 100% resin) exhibited significantly lower compressive strength (37.0 MPa), highlighting the importance of fiber reinforcement in enhancing load-bearing capacity. Interestingly, while the 1:15, 1:20, and 1:25 ratios performed similarly in compression, the 1:20 composite slightly outperformed the others, suggesting an optimal balance between fiber reinforcement and resin distribution. The high fiber content in the 1:15 composite (305.91 MPa) did not significantly improve compressive strength (Table 1). This may be due to presence of internal voids and stress concentrations. Conversely, the 1:25 and 1:30 composites (305.30 MPa and 305.61 MPa, respectively) showed a minor decline in strength, likely due to an excess of resin, which may have led to brittleness and reduced structural integrity under compression.

TABLE 1. Compressive strength of composites

Sample Identification	Fiber-resin ratio	Average Compressive Strength in MPa
C0	0:1	37.0
C1	1:15	305.91
C2	1:20	306.13
C3	1:25	305.30
C4	1:30	305.61

B. Flexural Strength Analysis

The flexural tests, conducted according to ASTM D7264, evaluated the bending strength of the samples. Flexural testing revealed that the 1:20 composite had an average flexural strength of 356.67 MPa, significantly exceeding that of previously studied textile composites. The high flexural strength suggests that denim fibers effectively resist bending forces, likely due to their high modulus of elasticity and ability to distribute stress along their length.

C. Tensile Strength Analysis

Tensile testing revealed that the 1:20 ratio exhibited a tensile strength, ranging from 5 to 6 MPa. Unlike the high compressive and flexural results, tensile testing revealed a significant weakness, with the 1:20 composite recording only 5.33 MPa in tensile strength. This value is significantly lower than previous studies. The most probable reason for this low tensile strength is fiber pull-out and poor stress transfer between the fibers and the resin. Since tensile stress primarily relies on fiber reinforcement, the randomly oriented denim fibers in the composite may not have provided adequate load-bearing capacity, leading to premature failure.

D. Hardness test

Shore A durometer testing revealed that the composite reached a hardness of 95.6, comparable to aluminum and mild steel washers. This suggests that the material can be used in applications requiring high surface durability and resistance to wear. The high hardness values further reinforce the compressive strength findings, indicating that the epoxy matrix has effectively solidified around the denim fibers, creating a dense, well-compacted structure. However, while high hardness is beneficial for abrasion resistance and load-bearing applications, it may also contribute to brittleness, which could partly explain the low tensile strength observed in this study.

E. Comparison with other textile waste composites

The compressive strength in this study was significantly higher than those reported in previous literature, suggesting enhanced load-bearing capabilities. The denim-epoxy composite of fiber: resin ratio 1:20 bonds well. Haque & Naebe [11] and Temmink et al. [12] reported compressive strengths of 62.3 MPa and 58.5 MPa, respectively, which are five times lower than this study. The significant improvement is likely due to better fiber orientation and resin bonding, as well as the higher fiber density at the optimized 1:20 ratio, which enables better stress distribution under compression. Yalcin-Enis [13], who used a denim-E glass hybrid composite, recorded a much lower compressive strength (30.0 MPa), indicating that while hybrid reinforcements improve tensile properties, they may not necessarily enhance compressive performance if the fiber-matrix adhesion is insufficient.

This study's flexural strength (356.67 MPa) is the highest recorded among textile-based composites. Haque & Naebe [11] reported 102.5 MPa, while Temmink et al. [12] and Yalcin-Enis [13] recorded 115.2 MPa and 120.0 MPa, respectively (Table 2).

However, the tensile strength was lower than other studies, indicating potential limitations for applications requiring high tensile resistance. Haque & Naebe [11] recorded a tensile strength of 81.4 MPa, nearly 16 times higher than this study. Temmink et al. [12] and Petrucci et al. [14] also achieved tensile strengths exceeding 70 MPa, highlighting a clear disparity. The reason for the low tensile strength in this study could be the lack of fiber alignment and weak interfacial bonding. Future studies should explore fiber treatments (e.g., alkali or silane modification) or introduce woven denim reinforcements to improve load transfer under tensile stress.

TABLE 2. Comparison study of composites

Study	Material	Tensile Strength	Flexural Strength	Compressive Strength
Current Study	Denim-epoxy (1:20)	5.33	356.67	306.13
Haque & Naebe [11] (2022)	Denim-Epoxy	81.4	102.5	62.3
Temmink et al. [12] (2018)	Denim Waste & Bio-Resin	72.0	115.2	58.5
Yalcin-Enis [13] (2023)	Denim & E-glass hybrid composite	75.0	120.0	30.0
Mandal et al. [15] (2024)	Recycled Denim & Jute Fiber Bio composite	62.5	98.0	46.8
Petrucci et al. [14] (2015)	Cotton Textile Waste/Polypropylene	90.5	85.4	-
Belgacem et al. (2021)	Date Palm Waste Reinforced Polymer	72.0	128.0	-
Mishra et al. [8] (2014)	Recycled Cotton Composite	60.8	90.1	55.7

IV. DISCUSSION & CONCLUSION

The study confirmed that 1:20 fiber-to-resin ratio optimally balanced tensile, flexural, and compressive properties, making denim waste composites suitable for mechanical applications. The 1:20 denim-to-resin ratio exhibited superior mechanical properties, balancing tensile, flexural, and compressive strength. Tensile tests demonstrated a tensile strength of 5.33 MPa for the 1:20 ratio, indicating sufficient durability for tension-based applications. The flexural strength of 356.67 MPa for the same ratio suggests the material's capability to withstand bending loads effectively. The compressive strength of 29.46 GPa highlights the material's ability to resist high compressive forces, making it suitable for heavy-load applications. This work contributes to Sustainable Development Goals (SDGs) 9 and 12 in Sri Lanka.

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