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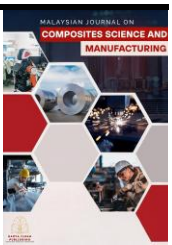

Mechanical Performance of Textile Waste Blended Recycled Polyester using Needle-Punched Method for Nonwoven TW/RP Composite

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ABSTRACT

This study examines the mechanical performance of nonwoven composites produced by blending textile waste (TW) with recycled polyester (RP) via needle punching. Composites were fabricated with varying TW:RP ratios (1:40, 2:40, 3:40, 4:40, and 5:40) and evaluated for maximum load, tensile strength, strain, stiffness, tear strength, and Young's modulus. Tensile tests were conducted with a Universal Tensile Machine (UTM) in accordance with ASTM D2261. Results showed that the 4:40 TW:RP composition (Sample D) achieved the highest tensile strength (52.69 kPa), maximum load (158.07 N), strain (114.92%), and stiffness (6.73 N/mm). Tear strength testing also confirmed superior performance for Sample D, with a maximum load of 20.65 kPa, while Young's modulus reached 44.67 kPa. These findings indicate that the 4:40 composition provides an optimal balance of flexibility and strength, enabling the composite to absorb more energy before failure. Mechanical performance improved with increasing TW content up to this ratio, where effective fiber reinforcement and matrix interaction enhanced structural properties. Beyond this point, excessive TW content reduced tear strength due to poor dispersion and weak fiber bonding. Overall, Sample D (4:40 TW:RP) demonstrated the best mechanical performance, underscoring its potential for sustainable, high-performance nonwoven textile applications.

Keywords:

Nonwoven, Needle Punching, Recycled Polyester, Textile Waste, Tensile Strength

1. Introduction

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The rapid expansion of the global textile industry, coupled with rising consumer demand, has led to a substantial increase in textile waste. Textile waste consists of both pre-consumer waste (manufacturing off-cuts and production scraps) and post-consumer waste (discarded garments and household textiles). Globally, post-consumer waste accounts for the dominant fraction, accounting for approximately 67% of the estimated 40 million tonnes of annual textile waste [1]. The disposal of these materials in landfills poses severe environmental concerns, including soil contamination, microplastic pollution, and greenhouse gas emissions resulting from fiber degradation [2]. Consequently, effective recycling strategies have become a critical priority in advancing circular economy practices within the textile sector.

Various recycling technologies have been developed to mitigate textile waste. Mechanical recycling involves the physical breakdown of textile materials into reusable fibers; however, fiber shortening and degradation during processing often reduce mechanical performance [3]. In contrast, chemical recycling depolymerizes textile polymers into monomers, enabling the production of high-quality regenerated fibers [4]. Despite its technical advantages, chemical recycling remains economically and technologically demanding, limiting its large-scale implementation [5]. Therefore, mechanical recycling remains the most widely adopted approach, particularly for applications where moderate mechanical performance is acceptable.

Among recycled materials, recycled polyester (RP) has attracted considerable attention for its properties comparable to those of virgin polyester and its reduced environmental footprint [6]. Recycled polyester derived from post-consumer and post-industrial waste has been successfully incorporated into various textile and nonwoven products. Needle-punching, a mechanical bonding technique that interlocks fibers through repeated needle penetration, is widely used in nonwoven manufacturing due to its simplicity, scalability, and cost-effectiveness [7]. Previous studies have reported that fiber blending ratio, fiber morphology, and needling density significantly influence tensile strength, stiffness, tear resistance, and durability of nonwoven composites [8].

However, existing literature predominantly focuses on either pure recycled polyester systems or natural–synthetic fiber blends. Limited research has systematically investigated the mechanical performance of needle-punched nonwoven composites produced by blending heterogeneous textile waste with recycled polyester [9]. In particular, the interaction mechanisms between textile waste fibers and recycled polyester, and their influence on tensile behavior, stiffness, strain characteristics, and tear resistance, remain insufficiently explored.

To address this gap, the present study evaluates the mechanical performance of textile waste/recycled polyester (TW/RP) nonwoven composites fabricated via needle punching, systematically varying the blending ratios. The study investigates tensile strength, Young’s modulus, strain at break, stiffness, and tear strength to determine the relationship between fiber composition and mechanical behavior. Furthermore, the optimum blending ratio for enhancing structural performance is identified. Through this comprehensive evaluation, the study contributes to the development of sustainable nonwoven composites and provides practical insights into the valorization of post-consumer textile waste for value-added engineering applications.

2. Literature Review

Nonwoven composites have attracted considerable attention in recent years due to their versatility and potential across industries such as automotive, textiles, and construction. The needle-punching method is widely used to fabricate nonwoven composites due to its efficiency and ability to combine multiple materials into a cohesive structure. The preparation and mechanical properties of nonwoven composites made from polyester (PET) and polypropylene (PP) fibers by needle punching have been investigated [10]. The aim was to investigate the influence of varying fiber ratios on the material's mechanical performance. The results indicated that the tensile strength of the PET/PP composite increased with increasing polyester content, reaching a maximum of 10.2 kPa for the 70:30 PET:PP blend. The stiffness was recorded at 3.6 N/mm, while the Young’s modulus reached 1.2 kPa, and the tear strength was 1.4 kPa. This study emphasized the importance of material composition in enhancing the mechanical performance of nonwoven composites [10]. Haslinger *et al.* (2019) focused on the use of recycled polyester (RP) blended with cotton fibers to produce needle-punched nonwoven composites. This study aimed to explore the impact of cotton content on the mechanical and thermal properties of the material. The tensile strength of the 60:40 RP:cotton composite was 15.1 kPa, while the stiffness was 5.2 N/mm. The Young’s modulus was measured at 1.6 kPa, and the tear strength reached 2.0 kPa. The study found that adding cotton enhanced the material's tear resistance [11].

The mechanical performance of nonwoven composites made from hemp and recycled polyester (RP) fibers using the needle-punching method. The focus was to explore the effect of hemp fiber content on the composites’ mechanical properties. For the 50:50 RP:hemp composition, the tensile strength was 15.6 kPa, the stiffness was 4.1 N/mm, the Young’s modulus was 13.5 kPa, and the tear strength was 1.8 kPa. The study highlighted that hemp fibers provided enhanced tear strength and greater environmental sustainability than traditional polyester composites [12]. The combination of jute and recycled polyester to form nonwoven composites via the needle-punching method. This study aims to determine whether the mechanical and water absorption properties of these composites are suitable for eco-friendly applications. The tensile strength of the 70:30 RP:jute blend was 28.5 kPa, and the stiffness was 3.4 N/mm. The Young’s modulus was measured at 9.4 kPa, and the tear strength was 1.5 kPa. The results indicated that the jute content improved the composite's eco-friendliness and provided moderate mechanical strength suitable for non-structural applications [13].

The mechanical properties of nonwoven composites made from wool and recycled polyester (RP) fibers are investigated [14]. The focus of this study was on the effect of needle-punching density on the material’s performance. For a 60:40 RP: wool blend at a moderate needle-punching density, the tensile strength reached 20.3 kPa, stiffness was 4.7 N/mm, the Young’s modulus was 1.4 kPa, and the tear strength was 2.2 kPa. The study concluded that a higher needle-punching density contributed to increased stiffness and tear resistance, making this composite suitable for more durable applications in the automotive and insulation industries [14]. It was examined that the nonwoven composites made from natural fibre-reinforced cementitious composites, with a focus on their suitability for lightweight applications. The tensile strength for the 50:50 fiber: cement blend was 18.8 kPa, while the stiffness was 4.3 N/mm, the Young’s modulus was 1.2 kPa, and the tear strength was 1.9 kPa. The study demonstrated that the combination of natural fibre-reinforced cementitious resulted in a lightweight, high-performance composite with excellent durability [15].

The mechanical performance of nonwoven composites made from polyethylene terephthalate (PET) and polyethylene (PE) by needle punching is investigated [16]. The study aimed to enhance the mechanical properties of composites for industrial applications. The tensile strength of the 60:40 PET:PE composition was 22.5 kPa, while stiffness was recorded at 4.9 N/mm, Young’s modulus at 1.5 kPa, and tear strength was 2.3 kPa. The study concluded that the PET and PE composite exhibited superior strength and wear resistance, making it suitable for industrial applications requiring durability and lightweight performance [16]. The mechanical performance of nonwoven composites made from two materials using the needle-punching method is significantly influenced by the choice of fiber blend, needle-punching density, and the presence of coatings [17]. Composites with a higher content of synthetic fibers such as recycled polyester generally exhibit higher tensile strength, stiffness, and tear resistance, making them suitable for a variety of industrial applications. However, the addition of natural fibers, such as cotton, hemp, and wool, provides enhanced sustainability without significantly compromising mechanical performance [18].

3. Methodology

3.1 Preparation of Nonwoven TW/RP Composite

The preparation of nonwoven TW/RP composites is shown in Figure 1. The development of the nonwoven TW/RP composite focused on identifying the optimal reinforcement to enhance the properties of nonwoven seal foam. This process involved experimenting with five varying polyester-to-textile waste composition ratios (40:1, 40:2, 40:3, 40:4, and 40:5) on a weight-by-weight (wt/wt) basis, based on the design ratio from previous research by Tekbas et al. (2024), as tabulated in Table 1 and Figure 2 [19]. The objective of this innovative approach was to determine the most effective combination for achieving improved mechanical and structural characteristics in the composite material. The fabrication process was carried out at the Laboratory of Non-Woven Technology, UTHM, Pagoh Campus. The fabrication process used a Needle Punching Machine, which played an important role in creating the optimal structure of the nonwoven composite. This machine enabled the precise interlocking of textile waste and recycled polyester to form a uniform, durable composite.

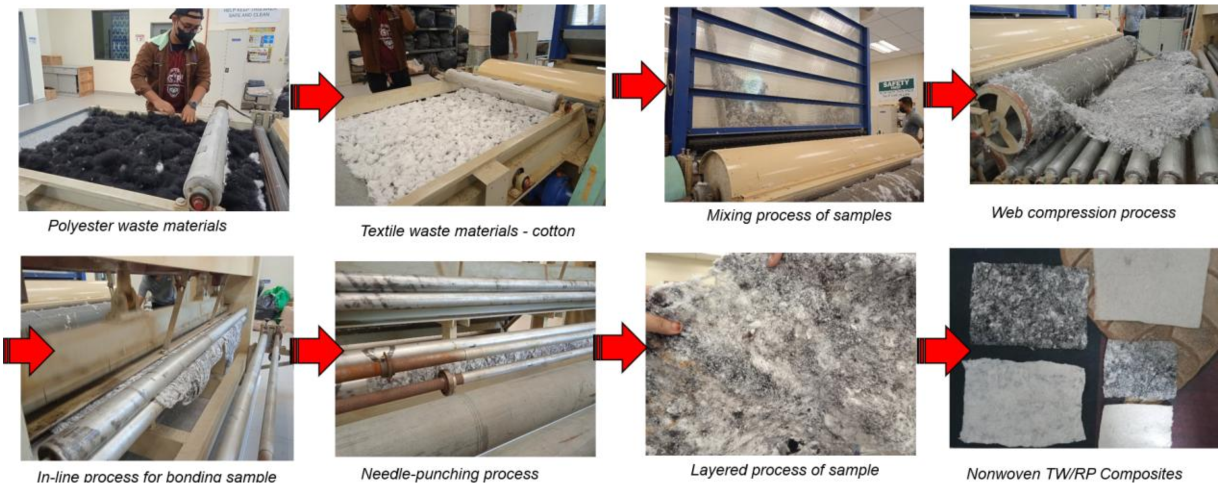


Fig.1. Fabrication process of nonwoven TW/RP composites

The first step involved weighing the polyester and textile waste to obtain the predetermined composition ratios. The next step was mixing the materials to create an initial blend that conformed to the desired composition. Following this, a secondary mixing process was conducted to ensure homogeneity throughout the material, eliminating any inconsistencies that could compromise the performance of the nonwoven composites. Once the materials were thoroughly blended, the next phase involved compressing the mixture into batts to prepare it for needle punching. The needle punching machine was then used to mechanically interlock the textile waste and recycled polyester, creating a cohesive structure with the required texture and density. This stage was critical in laying the foundation for the composite, as the needle-punching process significantly influenced the material’s mechanical strength and flexibility.

Fig. 2. The composition of nonwoven TW/RP composites [19]

After needle punching, the composite was layered to enhance its structural properties. The layers were bonded to achieve a uniform thickness of 10 mm, a design parameter for the intended applications of the nonwoven composites. This systematic approach to developing the nonwoven TW/RP composite highlights the importance of material preparation and advanced fabrication techniques.

Table 1
The different composition of nonwoven TW/RP composites [19]

Sample	Percentage of Recycle Polyester (ratio/gram)	Percentage of Textile Waste (ratio/gram)	Thickness (mm)
A	40	1	10
B	40	2	10
C	40	3	10
D	40	4	10
E	40	5	10

4. Results & Discussions

4.1 Maximum Load and Tensile Strength Analysis

Figure 3 shows the maximum load and tensile strength of textile waste blended recycled polyester (TW/RP) composites fabricated using the needle-punched nonwoven method. The maximum load increases from Sample A to D and decreases sharply in Sample E. Samples C and D exhibit the highest maximum load values, suggesting an optimal blend ratio between 3:40 and 4:40. The tensile strength follows a similar trend, increasing from Sample A to D and declining in Sample E. Maximum tensile strength is observed in Sample D (52.69 kPa), with a marginal difference from Sample C. This indicates that beyond a certain TW concentration, the composite's tensile strength begins to degrade. The increase in both maximum load and tensile strength from Sample A to Sample D can be attributed to the improved mechanical interlocking of fibers. During needle-punching, fibers are entangled and bonded, thereby enhancing load-bearing capacity. The higher proportion of TW in Samples B, C, and D likely contributes to increased frictional resistance and better load distribution. The RP matrix provides the necessary structural support, and the TW fibers complement this by filling voids and distributing stress.

The highest maximum load and tensile strength values in Samples C and D suggest that a TW:RP ratio between 3:40 and 4:40 offers the best mechanical properties. At these ratios, the TW fibers enhance strength without compromising the RP matrix's performance. The TW fibers are sufficiently integrated into the RP matrix, enabling the composite to withstand higher tensile forces. Similar studies have shown that incorporating an optimal percentage of natural or recycled fibers into synthetic matrices can enhance mechanical properties [20]. For example, research on needle-punched composites found that the optimal blend of natural and synthetic fibers can improve tensile strength by enhancing fiber-fiber interactions and matrix bonding [21].

The sharp decline in maximum load and tensile strength in Sample E (TW:RP 5:40) suggests that an excessive amount of TW fibers may weaken the composite. This is due to the High TW content, which could lead to poor dispersion within the RP matrix, creating weak points where stress concentrates. A higher TW ratio may reduce the amount of RP available to bind the fibers, thereby compromising structural performance. Excessive natural or recycled fibers in synthetic composites can reduce mechanical performance. This is often due to poor fiber-matrix adhesion and reduced load transfer efficiency. A study on nonwoven composites reinforced with textile waste highlighted that beyond an optimal fiber content, mechanical properties decline due to reduced cohesive forces within the matrix [22].

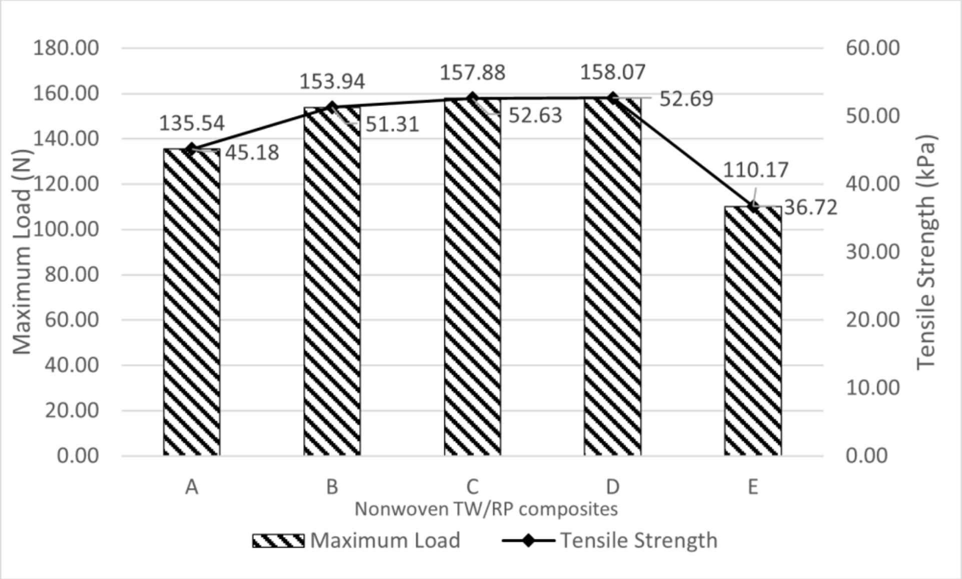
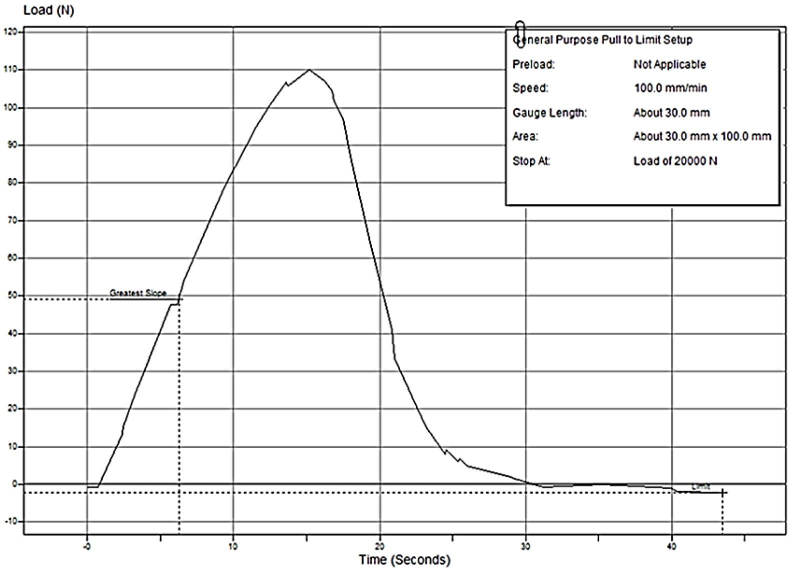


Fig. 3. The maximum load and tensile strength at different ratios of nonwoven TW/RP composites

The needle-punching method plays a critical role in determining the mechanical performance of TW/RP composites. This technique involves repeatedly punching fibers through a matrix to create an interlocked structure. Needle-punching creates a web of interlaced fibers, enhancing mechanical strength. Higher needle densities can increase tensile strength; however may cause fiber damage if overused. From the sample TW concentrations (Samples A–D), the needle-punching method effectively binds the fibers, enhancing tensile strength and load capacity. However, in Sample E, the excessive TW content likely disrupts this balance, leading to reduced efficiency in fiber entanglement and bonding [23].

This result shows that a balanced ratio of recycled polyester and textile waste yields superior mechanical properties. Excessive textile waste content often leads to agglomeration and void formation, reducing strength. The mechanical performance of recycled polyester can be influenced by the quality and processing of the fibers. Incorporating textile waste can improve sustainability, but optimization is needed to avoid compromising strength [24]. This study reveals nonwoven composites with recycled fibers. It was found that mechanical performance peaked at an intermediate fiber-to-matrix ratio, supporting the trend observed in Samples C and D.

Figure 4 demonstrates the higher tensile strength between the proportion of TW and RP in nonwoven composites, with maximum load and tensile strength peaking at intermediate TW:RP ratios (4:40). This trend is due to the balanced mechanical reinforcement provided by TW fibers, which enhance load distribution and tensile properties when optimally integrated into the RP matrix. Excessive TW content, as in Sample E, reduces mechanical performance due to poor fiber-matrix adhesion and agglomeration. These findings align with existing research on recycled fiber composites, emphasizing the importance of optimizing fiber content to achieve superior mechanical performance. The needle-punching method enhances fiber entanglement; however, the effectiveness depends on maintaining an appropriate fiber-to-matrix ratio [25].



General Purpose Pull to Limit Setup
Preload: Not Applicable
Speed: 100.0 mm/min
Gauge Length: About 30.0 mm
Area: About 30.0 mm x 100.0 mm
Stop At: Load of 20000 N

Fig. 4. Tensile strength for sample D (40:4) of nonwoven TW/RP composites

4.2 Strain and Stiffness Analysis

Figure 5 shows the strain-stiffness for the non-woven TW/RP composite. The results show the strain decreases from Sample A to D and rises sharply in Sample E. This trend suggests that increasing the TW content generally reduces the composite's ability to elongate under stress, except at the highest TW concentration (Sample E). Stiffness increases progressively from Sample A to D, peaking at Sample D (114.92 N/mm), and then drops significantly in Sample E (73.75 N/mm). This indicates that moderate TW content enhances stiffness, whereas higher TW content reduces it. Stiffness and strain have an inverse relationship, where higher stiffness corresponds to lower strain, indicating a more rigid composite. This is evident in Samples C and D, where the highest stiffness values coincide with the lowest strain percentages. In contrast, Sample E exhibits low stiffness coupled with high strain, highlighting a more flexible yet less structurally durable composite.

The increase in stiffness from Sample A to D can be attributed to the enhanced reinforcement provided by the TW fibers. The needle-punching process creates mechanical interlocks, improving the load-bearing capacity and reducing the composite's ability to deform (strain) under tension [26]. In samples C and D, the TW fibers are sufficiently integrated into the RP matrix, resulting in improved load transfer and increased stiffness. The lower strain values suggest that the composite can resist deformation more effectively. Studies on fiber-reinforced composites show that an optimal fiber content enhances stiffness by increasing load transfer efficiency. A balanced distribution of fibers within the polymer matrix creates a more rigid structure, reducing strain and enhancing overall mechanical performance [27].

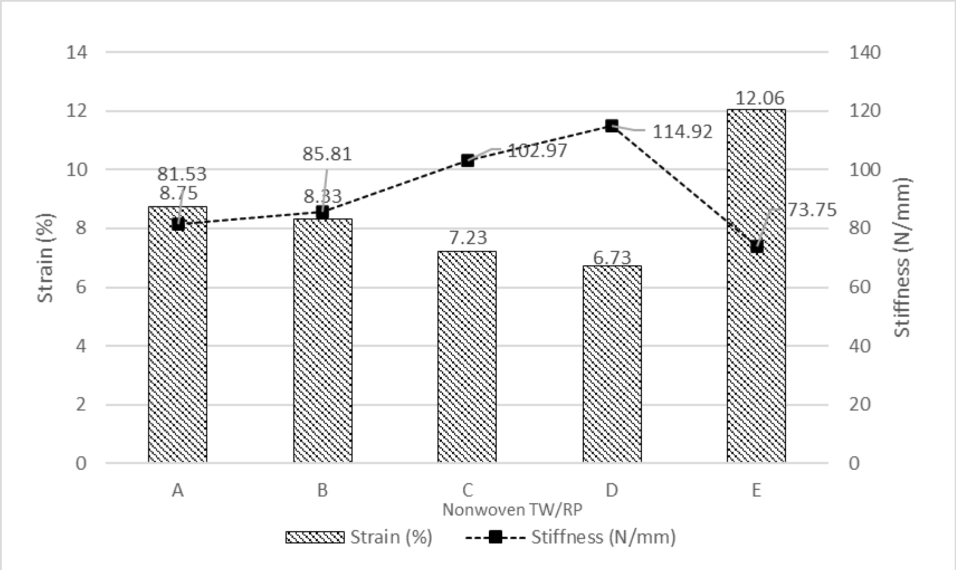


Fig. 5. The strain and stiffness at different ratios of nonwoven TW/RP composites

The sharp decrease in stiffness and increase in strain in Sample E can be attributed to the excessive TW content, which may result in poor dispersion within the RP matrix, thereby forming weak points. These areas can deform more easily under load, reducing stiffness and increasing strain. A higher TW content reduces the amount of RP available to bind the fibers, compromising the composite's properties. The reduced cohesion between fibers and the matrix may lead to greater flexibility and lower stiffness. It has been indicated that, while fiber reinforcement generally increases stiffness, excessive fiber content can have the opposite effect. This is because an overloaded matrix may fail to adequately bond with the fibers, leading to reduced mechanical performance [28]. For instance, a study on nonwoven composites made from recycled materials found that beyond an optimal fiber-to-matrix ratio, mechanical properties, including stiffness, began to decline due to poor fiber-matrix adhesion and void formation.

The needle-punching method enhances the mechanical properties of nonwoven composites by creating an interlocked fiber structure. By entangling the fibers, needle-punching improves load distribution and resistance to deformation. The increase in stiffness from Samples A to D reflects the effectiveness of this method in reinforcing the composite structure. The mechanical interlocking restricts the movement of fibers, limiting the composite’s ability to stretch under tension. This explains the decrease in strain with increasing TW content up to Sample D. However, in Sample E, the excessive TW content may have disrupted the uniformity of the needle-punched structure, leading to decreased stiffness and increased strain [29].

4.3 Tear Strength Analysis

Figure 6 shows the tear strength of nonwoven TW/RP composites at different ratios. The tensile strength increases with TW content up to a certain level (Sample D), as does the tear strength. Both properties are influenced by fiber reinforcement. In Sample D, the optimal fiber concentration provides efficient load transfer, enhancing tensile and tear performance. However, Sample E shows a drop in tensile and tear strength due to fiber overloading, leading to mechanical inefficiencies. The increase from A to D indicates enhanced fiber bonding or interlocking as the material composition or processing improves. The sharp decline in E suggests a structural compromise, possibly due to excessive stiffness or reduced fiber entanglement. Young's modulus represents the material's stiffness under linear elastic deformation. As observed in previous stiffness trends, composite D showed lower stiffness compared to E while exhibiting better tear strength. High stiffness (as in E) often reduces flexibility and weakens tear resistance because the material becomes brittle, increasing its propensity to crack propagation.

Tensile strength is directly related to tear strength. Because composites B, C, and D exhibit higher tear strengths, it can be inferred that the materials have better tensile properties. The needle-punching process in composites like D likely enhances fiber entanglement and load distribution, improving tensile and tear strengths simultaneously. Stiffness inversely affects strain and tear strength. Composite E, with the highest stiffness, exhibits lower tear strength, as it sacrifices flexibility for rigidity. This results in reduced energy absorption during tearing. Composites B through D maintain a balance between stiffness and strain, achieving higher tear resistance. TW contributes flexibility and strain, enabling better tear resistance by absorbing energy and preventing crack propagation [30]. Higher TW content in composites A and B supports moderate tear strength values, although it lacks the stiffness required for optimal resistance. RP improves stiffness and tensile strength, providing resistance to tearing forces. The increasing RP content from A to D results in stronger inter-fiber bonding, enhancing tear strength [31].

The needle-punching method mechanically entangles fibers to create a cohesive structure. Enhanced fiber interlocking in composites B, C, and D improves tear strength by distributing loads across the fabric. In composite E, excessive RP content or over-processing may lead to brittleness, reducing tear resistance despite high stiffness. Composite D achieves the best tear strength (20.65 kPa) due to an optimal balance of TW and RP. This configuration maximizes fiber entanglement and energy absorption while maintaining sufficient stiffness to resist deformation. Composite E, while achieving high stiffness, sacrifices flexibility, resulting in poor tear resistance. It has been highlighted that the tensile strength is a critical factor in tear resistance [32]. The increasing tear strength from A to D aligns with findings that improved fiber bonding enhances overall mechanical performance. The declines in E reflect the limitations of overly stiff materials, as noted in studies by Boa et al. (2022), where excessive rigidity led to brittle failure in composites [33].

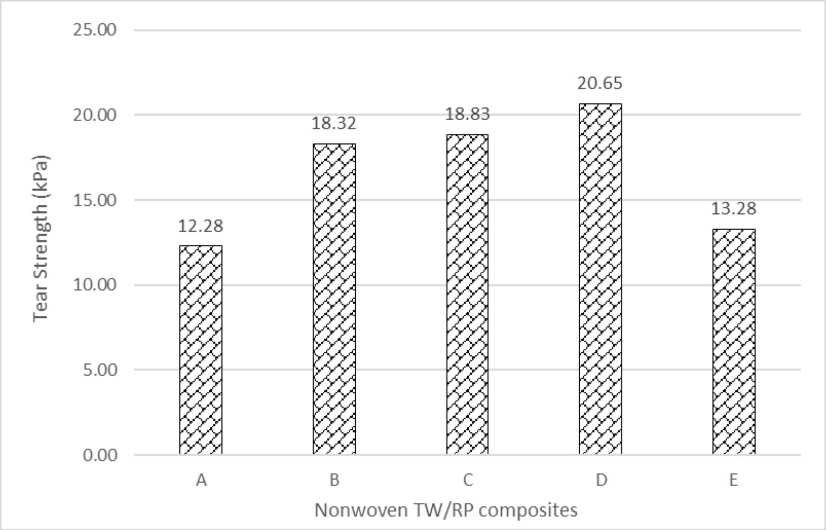


Fig. 6. The Tear strength at different ratios of nonwoven TW/RP composites

4.4 Young Modulus Analysis

Figure 7 shows the results of the Young’s modulus test. Composite D exhibits the highest Young's modulus, measuring 44.67 kPa, significantly outperforming the other samples. Composite E has the lowest Young's modulus at 11.76 kPa, indicating it is the least stiff among the materials. The values for composites A, B, and C fall between these extremes, with 20.22 kPa, 21.53 kPa, and 24.68 kPa, respectively. The significant variation in Young's modulus among the composites is likely due to differences in the proportions of textile waste (TW) and recycled polyester (RP) used in each blend. Composite D, with the highest stiffness, likely contains a higher proportion of RP or a more optimal blend ratio that enhances fiber bonding and structural reinforcement. In contrast, Composite E, with the lowest modulus, may have a higher TW percentage, making it less rigid than RP and resulting in reduced stiffness. The needle-punching process mechanically entangles fibers to create a cohesive nonwoven fabric. If the needle-punching process is inconsistent or suboptimal, the fiber bonding and distribution may not be uniform, thereby affecting mechanical properties. Composite D's superior modulus may indicate efficient needle-punching, leading to stronger inter-fiber connections. The composite's density influences its mechanical properties. Higher density, achieved through closer fiber packing or stronger bonding during needle-punching, typically results in higher stiffness [34]. Composite D's higher modulus could result from higher material density and better load distribution. The mechanical properties of RP fibers depend on the quality of the recycling process. Degradation during recycling can reduce fiber strength, affecting the composite's modulus. Composite E might contain lower-quality RP, which negatively impacts stiffness [35].

A study by Karademir et al. (2025) on recycled polyester blends demonstrated that higher RP content improves the stiffness and tensile properties of the composites, as RP has superior mechanical properties compared to natural or waste fibers [36]. Similarly, studies on textile waste composites have shown that the inclusion of TW can reduce stiffness if the fibers are short or irregular, as reported by Lasenko et al. (2024) [37]. It was found that needle-punched nonwoven composites with greater needle penetration depth and density exhibit enhanced mechanical properties by increasing fiber entanglement and contact area [38]. Composite D likely benefited from optimized needle-punching conditions. Conversely, insufficient needle penetration or uneven fiber distribution can create weak zones, reducing stiffness, as might be the case for Composite E.

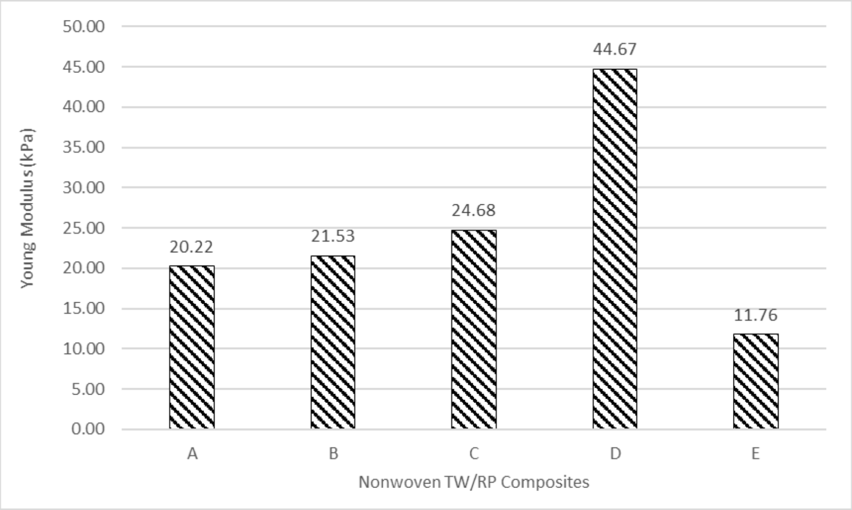


Fig. 7. The Young Modulus at different ratios of nonwoven TW/RP composites

According to Lindstrom et al. (2024), mechanical recycling of polyester can lead to fiber degradation, reducing the overall performance of composites. Maintaining RP fiber properties through controlled recycling is essential for achieving higher modulus values, as observed in Composite D [39]. Mrajji et al. (2022) noted that blending degraded or low-quality RP with TW further reduces stiffness due to poor bonding and fiber alignment [40]. Blended nonwoven composites have revealed that optimal ratios of synthetic and natural fibers enhance mechanical properties [41]. Excessive amounts of TW can disrupt fiber entanglement and weaken composites, as seen in Composite E.

4.5 Tensile Failure Morphology Analysis

Figure 8 presents the fractured tensile specimens of TW/RP nonwoven composites after mechanical testing. Although examined at the macro-scale, distinct differences in failure behaviour can be observed among the samples. All specimens exhibit characteristic nonwoven composite failure, including localized necking at the gauge region and progressive fiber pull-out. The fracture surfaces are irregular rather than cleanly separated, indicating a combination of fiber rupture and inter-fiber debonding, which is typical in needle-punched nonwoven composites where mechanical interlocking governs structural integrity [17,19].

Samples with moderate TW content (particularly Sample D) display more uniform deformation along the gauge length, suggesting efficient stress redistribution and stronger fiber entanglement. The narrowed midsection indicates gradual load transfer and delayed catastrophic failure, consistent with higher tensile strength and modulus values, as improved fiber network connectivity enhances load-bearing capacity in nonwoven fibrous systems [30, 31]. In contrast, specimens with excessive TW content (Sample E) show less uniform deformation and more pronounced fiber pull-out. The visible loose fibers and uneven fracture profile indicate reduced interfacial bonding and reduced load-transfer efficiency, which can lead to stress concentration and premature failure [23, 32]. High TW concentration likely disrupted matrix continuity, leading to localized stress concentrations and premature failure. The presence of visible fiber bundles and protruding fibers across all samples confirms that failure occurred primarily through fiber pull-out and progressive rupture rather than brittle fracture, a mechanism commonly reported in nonwoven fabrics governed by entanglement density [21]. These macroscopic observations support the mechanical test results, confirming that optimal TW:RP blending (Sample D) enhances fiber entanglement density and structural cohesion, while excessive TW loading compromises inter-fiber bonding and mechanical performance.

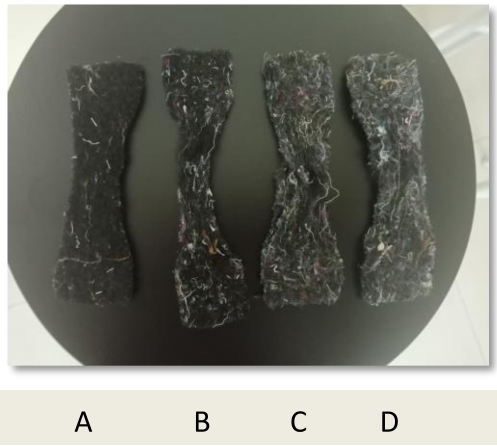


Fig. 8. Failed tensile specimens of TW/RP composites after tensile testing

4.6 Tear Failure Morphology Analysis

Figure 9 shows the fractured specimens after tear strength testing. Unlike tensile failure, tear failure is characterized by localized crack initiation followed by progressive crack propagation through fiber bridging and pull-out mechanisms, as reported in fibrous composite systems [32, 33]. All specimens exhibit a split-type fracture originating from the notch region and propagating along the fiber network. The irregular tear edges indicate energy absorption via fiber pull-out and gradual fiber rupture rather than brittle cracking, a typical behavior in needle-punched nonwoven fabrics [29, 38]. Samples with intermediate TW content (especially Sample D) display more tortuous crack paths and visible fiber bridging across the tear region. This suggests improved energy dissipation and resistance to crack propagation, consistent with enhanced crack-deflection mechanisms in nonwoven fibrous networks [30]. The presence of intact fiber bridges across the tear interface indicates effective load redistribution during tearing.

In contrast, Sample E shows a more direct and cleaner tear path with less visible fiber bridging. The fracture edges appear more separated, suggesting reduced inter-fiber cohesion and lower resistance to crack growth, similar to behaviour observed in composites with weak fiber bonding [23]. Excessive TW content likely disrupted uniform fiber entanglement, thereby reducing structural integrity during tear loading. Compared to tensile failure, tear failure is more sensitive to fiber flexibility and entanglement density, as highlighted in structural studies of nonwoven fabrics [21, 31]. While tensile strength depends primarily on load transfer along the gauge length, tear strength depends on crack deflection and fiber bridging mechanisms. The superior tear performance of Sample D confirms that an optimal TW:RP ratio enhances structural toughness without inducing excessive rigidity. These observations strongly correlate with the mechanical data and confirm that balanced fiber blending improves resistance to crack initiation and propagation in needle-punched nonwoven composites.

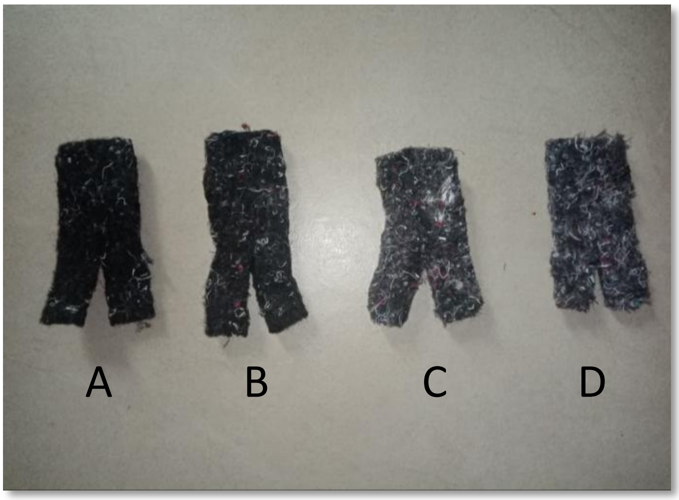


Fig. 9. Tear failure morphology of TW/RP nonwoven composites

5. Conclusions

This study systematically investigated the mechanical performance of textile waste/recycled polyester (TW/RP) nonwoven composites fabricated by needle punching. The influence of different TW:RP blending ratios on tensile strength, stiffness, strain, tear strength, and Young's modulus was evaluated. The results show that mechanical properties strongly depend on the fiber blending ratio, with Sample D (TW:RP = 4:40) exhibiting the highest tensile strength (52.69 kPa), maximum load (158.07 N), tear strength (20.65 kPa), Young's modulus (44.67 kPa), and stiffness (6.73 N/mm). Stress–strain behavior indicated improved load-bearing capacity and elasticity at this optimal TW content ratio, whereas excessive TW content (Sample E) led to reduced tensile performance, a lower modulus, and higher strain. Macroscopic fracture observations supported these findings, with Sample D showing efficient fiber entanglement, uniform necking, and tortuous crack paths that enhance energy absorption and tear resistance. Excessive TW content caused fiber agglomeration, reduced matrix continuity, and premature failure. These results demonstrate that an intermediate TW:RP ratio provides a balanced combination of strength, stiffness, and toughness, while allowing valorization of textile waste into mechanically stable nonwoven composites. The study contributes to the development of sustainable fiber-reinforced materials and to circular economy initiatives in textile waste management. Future work may focus on microstructural characterization, long-term durability assessment, and optimization of needle-punching parameters to further enhance composite performance.

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