



# Development and characterization of structural composites using waste plastic core, rough cellular leather, and glass fiber-reinforced plastic additives: concept of waste recycling

V. Jayaseelan<sup>1</sup> · D. Jayabalakrishnan<sup>2</sup> · S. Sambath<sup>3</sup> · VijayAnanth Suyamburajan<sup>4</sup> · M. Seeman<sup>5</sup>

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## Abstract

This study investigates the mechanical, wear, water absorption, and flammability properties of vinyl ester composites reinforced with recycled PET core, industrial tanned leather, and silane-treated GFRP filler, offering a novel approach for sustainable material production. The composites were prepared by combining vinyl ester resin with varying amounts of GFRP filler (1 vol.%, 3 vol.%, and 5 vol.%) and 40 vol.% industrial waste leather. A PET core was integrated to enhance structural performance. The prepared composites were characterized for tensile, flexural, hardness, impact strength, wear resistance, water absorption, and flammability properties. The results demonstrated significant improvements in the performance of the composites. Specimen VLG2, containing 3 vol.% GFRP filler, exhibited superior mechanical properties, including a tensile strength of 135 MPa, flexural strength of 155 MPa, Shore-D hardness of 83, and Izod impact strength of 6.4 J. These improvements were ascribed to the filler particles' ideal distribution, which enhanced the matrix's ability to support loads and distribute stress. At a particular wear rate of 0.012 mm<sup>3</sup>/Nm, water absorption of 0.47%, and flame propagation speed of 8.14 mm/min, specimen VLG3, which contained 5 vol.% GFRP filler, demonstrated exceptional wear resistance and flammability performance while retaining a UL-94 V-0 certification. The improved wear resistance was due to the higher GFRP filler content, which strengthened the composite against abrasion. The slower flame propagation and absence of flaming drips were attributed to the flame-retardant properties of GFRP filler and the char-forming ability of tanned leather. SEM analysis revealed that the uniform dispersion of fillers in VLG2 contributed to its superior mechanical properties, while the agglomeration of fillers in VLG3 did not significantly affect its wear resistance, water absorption, or flame performance. These findings highlight the importance of optimized material selection and microstructural

Extended author information available on the last page of the article

design in developing durable, high-performance composites suitable for applications in industries such as automotive, aerospace, marine, and construction.

**Keywords** Composites · Recycle · Polymers · Fiber · Additives · Mechanical properties

## Introduction

Reducing waste and promoting sustainable production have become crucial due to growing environmental concerns. As the need for sustainability and efficient waste reduction grows, eco-friendly materials that can convert debris into useful products are being developed. One promising approach toward this idea is the development and utilization of composite materials in which one or more distinctive components combined together to form an innovative material with good mechanical properties and performance [1]. These composite materials are light weight, strong, durable, less toxic, and low cost and offer better mechanical properties. Further, one of the most common pollutants in the environment is the plastic. Further, around 3.3 million tons of plastic waste is generated in India per year [2]. In order to mitigate the waste, research scholars, scientist and academicians utilized this plastic waste as a foam or core in the composite material which provides the essential structural integrity. Further, the strength-to-weight ratio of the composite is improved by a plastic core, which offers lightweight structure and strong impact resistance [3]. Additionally, it resists corrosion, which qualifies it for long-lasting uses. Due to these features, the plastic cores are utilized in the composite material. For example, Sariman et al. [4] demonstrated the effect of incorporating a hollow plastic core, reporting a concrete compressive strength of 25 MPa and a yield strength of 475 MPa, respectively. Similarly, Yang et al. [5] studied the situ microfiber reinforced with high filled wood-plastic composite and their mechanical properties. The highest tensile strength of 97% and the maximum flexural strength of 114% were noted; the study concludes.

Along with the plastic core, tanned leather is reinforced in the matrix to improve the flexibility, toughness, durability, and impact strength and abrasion resistance. In addition to this, the tanned leather acts as a sustainable, biodegradable compound to enhance the eco-friendliness of the composite [6]. Owing to these characteristics, tanned leather has been widely utilized by numerous research scholars. For instance, tanned leather/areca fiber and chitosan carbohydrate polymer reinforced with hybrid epoxy composite were studied by Surianarayanan et al. [7]. Izod impact toughness of 7.0 J, maximum tensile strength of 172 Mpa, maximum flexural strength of 4.98 GPa, maximum flexural modulus of 208 Mpa, and hardness value of 87 Shore-D were all determined by this investigation. Similarly, natural fibers derived from wet blue leather reinforced with polymer composites were investigated by Naani et al. [8]. The author resulted that adding wet blue leather and PLA-based composites enhanced the tensile strength of +1.5%, Young's modulus of +18%, impact strength of +10%, creep resistance of +5%. Furthermore, the blend of tanned leather and

plastic core improves the material's overall structural integrity and durability, making it strong and lightweight for a variety of uses.

However, the composite may exhibit weak interfacial bonding and thermal instability, leading to diminished mechanical performance. Thus, to improve the strength, thermal stability, durability, and interfacial bonding, additives are added to the composites [9]. Particularly, glass fiber-reinforced polymer (GFRP) additives are added in the composite since these improve the overall mechanical performance. Additionally, GFRP additives offer superior stiffness, increased fatigue resistance, and high tensile strength [10]. Additionally, they provide dimensional stability, improved durability under challenging climatic conditions, and good impact resistance, all of which contribute to the composite's strength and longevity. Typically, Alshahrani et al. [11] investigated the GFRP-reinforced sandwich composites using liquid thermoplastic resin and resulted that the flexural and flatwise strength improved by 53% and 75%, respectively. Similarly, Aryaswara et al. [12] studied the hybrid glass fiber and glass powder as a filler reinforced with polymer composite. The author concluded that the addition of 2.5 wt.% of glass powder increased the flexural strength and interlaminar shear strength up to 18.86% and 19.54%, respectively. Likewise, Lin et al. [13] analyzed the GFRP fillers in the asphalt mastics and resulted that the low density of the GFRP fillers improved aging and moisture resistance, respectively.

The aforementioned literature reviews, however, make it clear that the composite has good mechanical performance and characteristics. The main focus of the study is to investigate the mechanical, wear, flammability, and water absorption properties of the recycled plastic core, tanned leather, and GFRP additives-reinforced vinyl ester composites for a safer and sustainable environmental production. Further, no such combination of study has been established yet bringing a novel approach to the present research. The novelty of this research lies in the integration of multiple waste-derived constituents—post-consumer plastic as a hollow structural core and rough cellular leather from industrial scrap—synergistically enhanced with targeted GFRP additives to overcome common limitations of recycled-material composites, such as poor interfacial bonding and thermal instability. This unique material combination not only addresses waste management challenges by valorizing non-biodegradable materials but also introduces a sustainable, lightweight, and durable structural composite concept that has not been extensively reported in existing literature. Since these composites offer good mechanical properties and performance, these are employed in various industries including marine, automotive, aerospace, biomedical, packaging, building, and infrastructure, etc.

## Experimental procedure

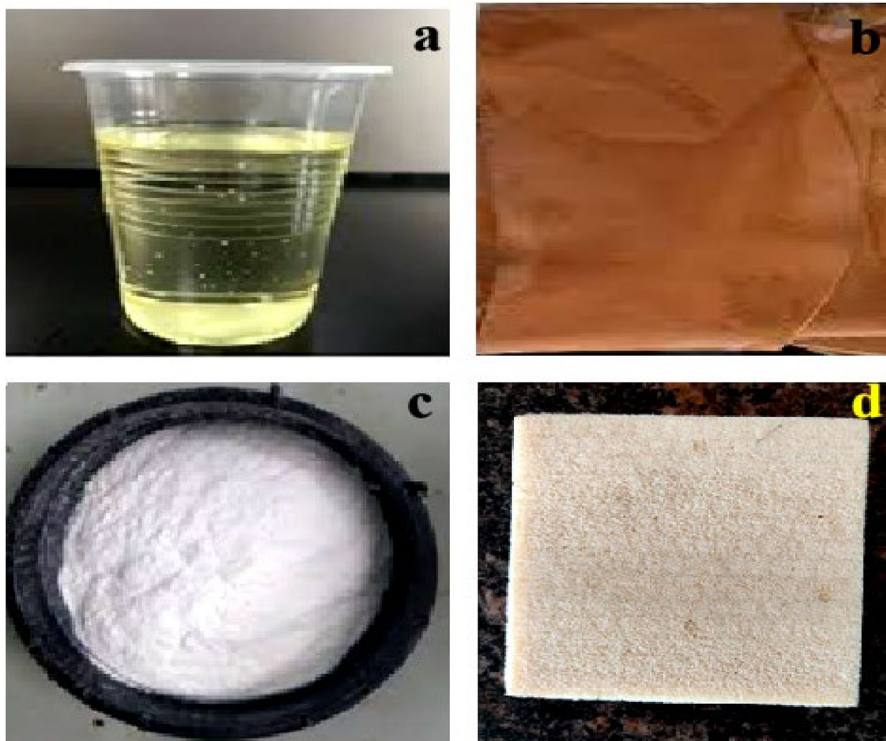
### Raw material

Vinyl resin is a polymer that is frequently used in composite manufacturing, especially in the transportation and maritime industries. It is frequently combined with glass fiber to produce a rigid, durable composite with a high strength-to-weight ratio

and stiffness comparable to lightweight metals such as aluminum alloys. Vinyl ester has a flash point of 95°F and a density of 1.95 g/cm<sup>3</sup>. All gel coatings need methyl ethyl ketone peroxide (MEKP), a hardener that aids vinyl ester resin in curing at room temperature. Pon Pure Chemical, located in Chennai, India, provided both the resin and the hardener. Tanned leather from industrial waste was gathered from ANS Leathers, Chennai, India. GFRP used as a filler particle in composite fabrication projects alongside PET core; both GFRP and PET core was provided by Metro Composite in Chennai, India. Figure 1 shows the photographic views of base materials used (a) vinyl ester resin, (b) leather scarp, (c) GFRP powder, and (d) PET core. Similarly, Fig. 2 shows the FESEM image of (a) waste leather and (b) GFRP powders used. The fiber is cellular in nature, and the fillers are in spherical shape.

### Composite preparation

The curing process was started during the composite preparation by mixing 10% vinyl ester resin with 1% hardener. The resin–hardener combination was then mixed with predetermined amounts of GFRP, as indicated in Table 1. The resin and GFRP are thoroughly mixed to ensure uniform distribution of the GRFP throughout the



**Fig. 1** Photographic views of base materials used **a** vinyl ester resin, **b** leather scarp, **c** GFRP powder, and **d** PET core

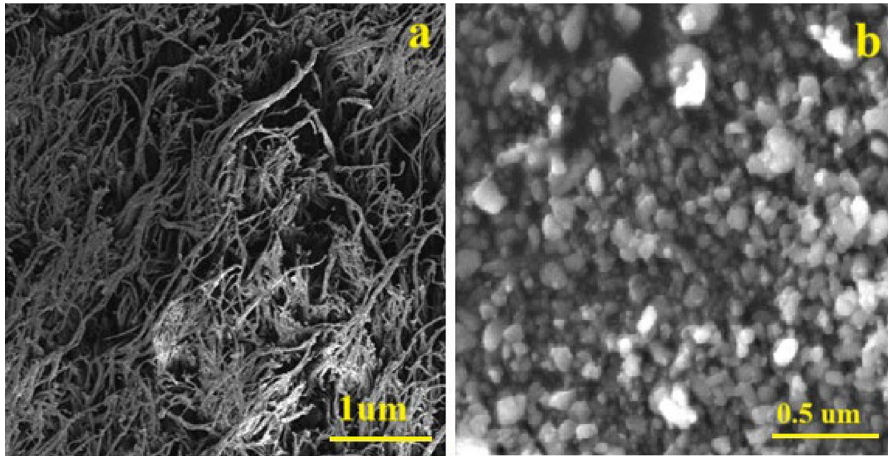


Fig. 2 FESEM image of a waste leather and b GFRP powders used

Table 1 Various composite designation of vinyl ester rein composite

Composite designation	Vinyl ester (vol. %)	GFRP filler (vol. %)	Industrial waste leather (vol. %)
V	100	–	–
VL	60	–	40
VLG1	59	1	40
VLG2	57	3	40
VLG3	55	5	40

resin. A recycled plastic core was placed on top of the resin-coated tanned leather layer. This layer is again coated with the resin mixture to ensure uniform saturation of the leather and the underlying plastic core. The resulting composite material was post-cured in a drying oven in a laboratory that is set at 120 °C after all the layers had been stacked and the resin saturated. It was then left to cure at room temperature [14]. Figure 3 shows the schematic representation of composite preparation process.

### Characterization

To assess the performance of cured vinyl ester composites and their potential for usage in engineering applications, characterization is essential. To access and maximize the performance of vinyl ester composites under various loading circumstances, one must comprehend its behavior. Numerous techniques, including tensile, flexural, Izod impact, hardness, wear, water absorption, and flammability, are used to evaluate the mechanical properties of composites. Furthermore, non-destructive evaluation methods such as SEM analysis have been created to evaluate the internal

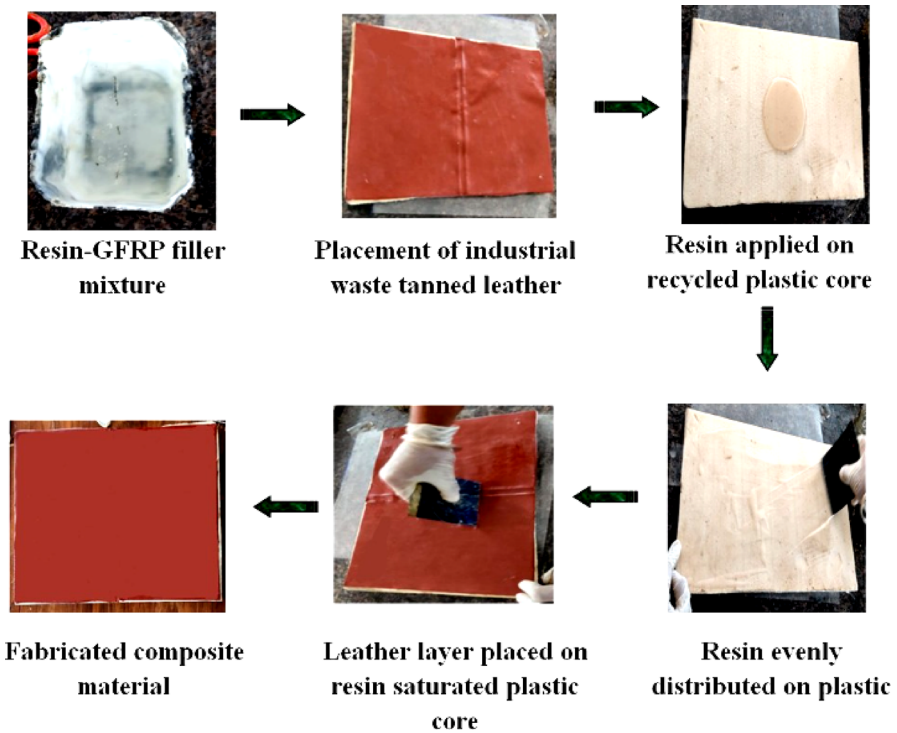


Fig. 3 Schematic representation of composite preparation process

structure and flaws of composites. The test and machine specifications are shown in Table 2, and the test specimens are photographed in Fig. 4.

### Sample preparation

Following composite fabrication, test specimens were cut from the cured laminates to the required dimensions for each characterization test in accordance with the relevant ASTM standards. For tensile testing (ASTM D3039), specimens measuring 250 mm × 25 mm were prepared, tabbed, and bonded using a high-shear strength adhesive to ensure proper load transfer. Flexural specimens (ASTM D790) were cut to 125 mm × 12.7 mm, while Izod impact specimens (ASTM D256) measured 63.5 mm × 12.7 mm and were notched as per the standard. Hardness specimens (ASTM D2240) were prepared with dimensions of 35 mm × 35 mm, and wear test specimens (ASTM G99) were machined to 40 mm × 12 mm with a 3-mm tip for the pin-on-disk setup. For water absorption testing (ASTM D570), samples were cut to 60 mm × 60 mm, while flammability specimens (ASTM D635) were prepared to 125 mm × 25 mm. All specimens were finished to ensure smooth edges, conditioned at  $23 \pm 2$  °C and  $50 \pm 5\%$  relative humidity for 48 h prior to testing, and stored in a desiccator to prevent premature moisture uptake.

**Table 2** Test and the machine specification

Test	ASTM standard with dimension	Machine specification
Tensile Flexural	D3039 (Length—250 mm Width—25 mm) D790 (Length—125 mm Width—12.7 mm)	When testing a tabbed tensile specimen, shear at the gripped tab surfaces was used to introduce the load. In order to transfer the load into the composite and cause failure, the tabbing material and the adhesive bond must possess sufficient shear strength. In accordance with ASTM regulations, the strength properties of 10 average composite testing specimens were analyzed using the INSTRON 4855 UK universal testing equipment
Izod impact	D256 (Length—63.5 mm Width—12.7 mm)	One popular test for determining notch sensitivity in plastics was Izod impact testing, often known as Notched Izod. The result was shown as the specimen's thickness-related energy absorption after the flexural impact stress was applied edgewise to a notched specimen that is grasped on one end. The strength characteristics of ten average composite testing specimens were investigated
Hardness	D2240 (Length—35 mm Width—35 mm)	By measuring how deeply the indenter point penetrates the test specimen's surface when applying a preset force, a Shore-D (Durometer) is used to determine the hardness. The depth of the indentation was then used to calculate the composites' hardness value in accordance with ASTM standard
Wear	G99 (Length—40 mm Width—12 mm Tip-3 mm)	The wear test was performed using pin-on-disk equipment in accordance with ASTM standards. As part of the wear test, a test specimen was put on the sliding track and a pin was permitted to move 1000 m along the track. A 10N force was applied during the test to move the pin around the specimen at the speed of 500 rpm. To assess the wear behavior of composites, a ten test samples were used
Water absorption	D570 (Length—60 mm Width—60 mm)	This study examined how composites absorbed water in compliance with ASTM standard. Ten test specimens that had been previously weighed were submerged in distilled water at room temperature in order to evaluate the composite materials' ability to absorb water. The samples were then taken out of the water and weighed using a 4-degit balance
Flammability	D635 (Length—125 mm Width—25 mm)	The UL-92 Laboratory Vertical Test was used to evaluate the burning characteristics of composite materials. In this test sample was positioned vertically above the Bunsen burner, the flame was applied to the bottom of the sample, and the dripping behavior and propagation rate of the substance were observed. Average propagation speed of the ten test samples was calculated using applicable ASTM standard

**Table 2** (continued)

Test	ASTM standard with dimension	Machine specification
SEM	-	The surface morphology of the composite materials was examined using scanning electron microscopy (HITACHI S-1500 SEM-Japan). The test sample surfaces were coated with a thin layer of gold to prevent sample charring. The morphological properties of the composites are evident in the ensuing SEM pictures



Fig. 4 Photographic view of testing specimens

## Results and discussion

### Mechanical properties:

The mechanical properties of the composite are illustrated in Fig. 5. The mechanical characteristics of the composites, including tensile strength, flexural strength, Shore-D hardness, and Izod impact, demonstrate notable improvements when comparing the baseline specimen (V), consisting of 100 vol.% vinyl ester, to the modified composites VL, VLG1, VLG2, and VLG3. These modified composites incorporate

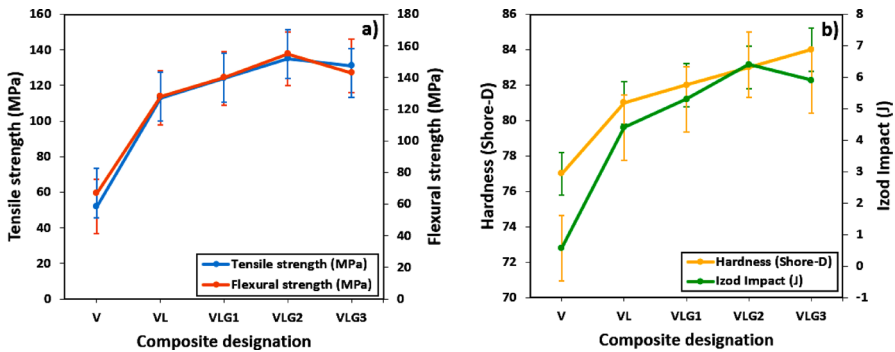


Fig. 5 Mechanical properties of various composite specimens

varying proportions of industrial waste leather and GFRP filler. Starting with tensile strength, specimen V achieves a value of 52 MPa, which is relatively low due to the absence of reinforcing materials, making the composite brittle and less ductile [15]. In contrast, specimen VL, which includes 40 vol.% industrial waste leather, achieves a tensile strength of 113 MPa, marking a significant 117% enhancement over specimen V. The rise in strength is due to the strengthening impact of industrial leather, which reinforces the matrix and offers structural assistance, thereby increasing the composite's entire mechanical characteristics [16]. The inclusion of GFRP filler in specimens VLG1, VLG2, and VLG3 further enhances tensile strength, with VLG1 reaching 124 MPa (a 138% increase), VLG2 achieving 135 MPa (a 160% increase), and VLG3 recorded 131 MPa (a 152% increase) above specimen V. These gains are primarily attributed to the improved stress distribution and load-bearing capacity provided by the GFRP filler.

A similar trend is observed for flexural strength. Specimen V records a flexural strength of 67 MPa, which improves significantly to 128 MPa (a 91% increase) in specimen VL due to the incorporation of 40 vol.% industrial leather. This addition enhances both the flexibility and toughness of the material. Specimens VLG1, VLG2, and VLG3 achieve flexural strengths of 140 MPa (109% increase), 155 MPa (131% increase), and 143 MPa (113% increase), respectively, compared to specimen V. The improved performance is attributed to the combined effect of leather and GFRP filler in enhancing the composite's resistance to bending. However, a slight decline in flexural strength from VLG2 to VLG3 is noted, possibly due to reaching an optimal filler content where further additions no longer proportionally enhance performance and may even slightly compromise it.

Regarding hardness, specimen V records a Shore-D hardness of 77. The inclusion of 40 vol.% industrial leather in specimen VL increases this value to 81, reflecting a 5% improvement and highlighting the leather's contribution to rigidity. With the addition of GFRP filler, hardness increases further, reaching 82 in VLG1 (a 6.5% increase), 83 in VLG2 (an 8% increase), and 84 in VLG3 (a 9% increase). The hardening effect of GFRP filler, which raises resistance to surface deformation, is responsible for this improvement. The samples' Izod impact resistance considerably increases. Sample V exhibits the least amount of impact resistance, with an Izod impact strength of 0.57 J. When 40 vol.% industrial waste leather is added, specimen VL shows a significant increase to 4.4 J, which is 672% better than specimen V. This enhancement is attributed to the energy-absorbing nature of the industrial leather. Further enhancements are observed in specimens VLG1, VLG2, and VLG3, which achieve impact strengths of 5.3 J (an 830% increase), 6.4 J (a 1022% increase), and 5.9 J (a 936% increase) compared to specimen V. The combination of 1 vol.%, 3 vol.%, and 5 vol.% GFRP filler along with 40 vol.% industrial waste leather contributes to these improvements by reinforcing the composite matrix. This reinforcement not only enhances the matrix's ability to absorb and dissipate impact energy but also improves the material's toughness and resistance to sudden impacts. The addition of filler particles further boosts these properties by strengthening the matrix through improved adhesion, thereby enhancing load-bearing capacity [17].

Overall, the tensile and flexural strength values of the prepared composites display a consistent enhancement with the addition of leather and glass fibers. Tensile

strength increases from 52 MPa in V to 135 MPa in VLG2, while flexural strength rises from 67 to 155 MPa over the same range. Both properties follow a similar trend, peaking at VLG2 and maintaining relatively high values in VLG3, indicating that the reinforcement effectively boosts overall load-bearing capability.

The difference between tensile and flexural strengths becomes more balanced as reinforcement content increases, with the percentage gap narrowing from 28.85% in V to just 9.16% in VLG3. This demonstrates that the composite design improves mechanical performance in a more uniform manner, ensuring that bending and stretching capacities are enhanced together rather than at the expense of one another.

In the case of hardness, Shore-D measurements show only minimal numerical variations across the composite series. These small but steady increases confirm that while stiffness and strength improve considerably, the surface hardness remains stable—an advantage for maintaining surface durability and wear resistance.

The SEM images in Figs. 6a through 6d) illustrate the microstructural characteristics of the composites at different stages of reinforcement and filler incorporation. Figure 6a shows the plain resin matrix with a lack of reinforcements, highlighting the homogeneity of the vinyl ester matrix without any added materials. This absence likely contributes to the lower mechanical properties seen in the unreinforced specimen. Figure 6b reveals the presence of brittle fractures due to the inclusion of leather reinforcement. The leather fibers introduce regions susceptible to brittle fracture, which, while enhancing strength, also create potential weak spots under stress. Figure 6c shows that filler particles are evenly distributed throughout the matrix, which is critical for the composite’s increased mechanical characteristics. This even distribution ensures consistent reinforcement throughout the material. Figure 6d shows agglomerated filler particles, which can act as stress concentrators and potentially reduce the overall strength and durability of the composite. This highlights the challenges of achieving perfect filler dispersion and the importance of uniformity in reinforcement. Figure 6e reveals the fiber region, where the reinforcing fibers are

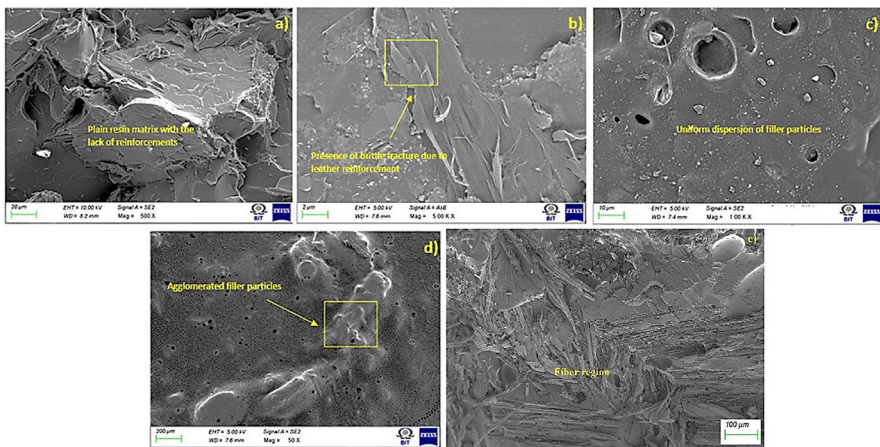


Fig. 6 SEM fractured morphology of tensile tested composites

embedded within the matrix. Uniform fiber dispersion and strong interfacial adhesion are visible, enabling effective stress transfer. Any observed pull-out or gaps at the fiber–matrix interface indicate localized debonding, which can compromise mechanical performance. These images collectively demonstrate how the microstructural variations, influenced by reinforcement and filler distribution, significantly impact the composite's properties.

## Wear proaperties

Wear aspects of composites, particularly specific wear rate and COF, show notable improvements when comparing specimen V, made of 100 vol.% vinyl ester, with the modified composites VL, VLG1, VLG2, and VLG3, which incorporate industrial waste leather and GFRP filler. Specimen V exhibits a wear rate of  $0.034 \text{ mm}^3/\text{Nm}$  attributed to the low resistance of the pure vinyl ester matrix. Plastic deformation during abrasion leads to three-body wear phenomena, resulting in high wear rates [18]. Incorporating 40 vol.% industrial leather in specimen VL significantly reduces the wear rate to  $0.022 \text{ mm}^3/\text{Nm}$  due to leather's toughening effect, which enhances matrix resilience. Further reductions are observed in VLG1 ( $0.017 \text{ mm}^3/\text{Nm}$ ), VLG2 ( $0.014 \text{ mm}^3/\text{Nm}$ ), and VLG3 ( $0.012 \text{ mm}^3/\text{Nm}$ ). The increasing GFRP filler content improves resistance to surface wear by reinforcing the matrix, reducing material loss during friction, and enhancing abrasion resistance. Specimen VLG3 exhibits the best wear performance due to its higher hardness, indicating superior resistance to abrasive forces [19].

The COF also shows a decreasing trend. Specimen V records a COF of 0.35, indicating high frictional resistance. Adding 40 vol.% industrial leather in VL reduces the COF to 0.32, reflecting better lubrication and smoother sliding surfaces. With increasing GFRP filler, the COF further decreases in VLG1 (0.3), VLG2 (0.28), and VLG3 (0.26). The fillers generate a homogeneous surface, reducing friction and heat generation, improving energy efficiency, and making these composites excellent for applications that need low friction and wear resistance. Figure 7 represents the wear properties of the composite specimens.

## Water absorption behavior

The ability to absorb water of the composites is given by the percentage of water absorbed and shows an increasing trend when comparing the baseline specimen V, which contains 100 vol.% vinyl ester, with the modified composites VL, VLG1, VLG2, and VLG3, each containing varying vol.% of GFRP filler and industrial waste leather. Starting with specimen V, it exhibits the lowest water absorption at 0.31%. This low absorption is typical for pure vinyl ester, which is known for its hydrophobic nature, making it less prone to water uptake. However, the addition of fillers and other materials into the vinyl ester matrix tends to increase the overall water absorption due to the introduction of more hydrophilic (water-attracting) components and voids within the composite structure. In specimen VL, which contains 40 vol.% industrial waste leather, the water absorption increases to 0.37%. Because

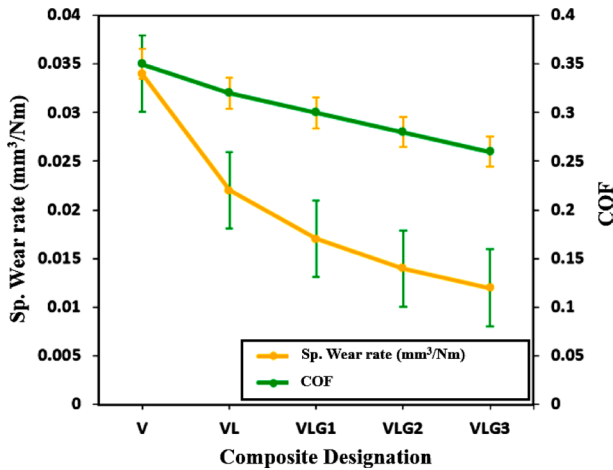
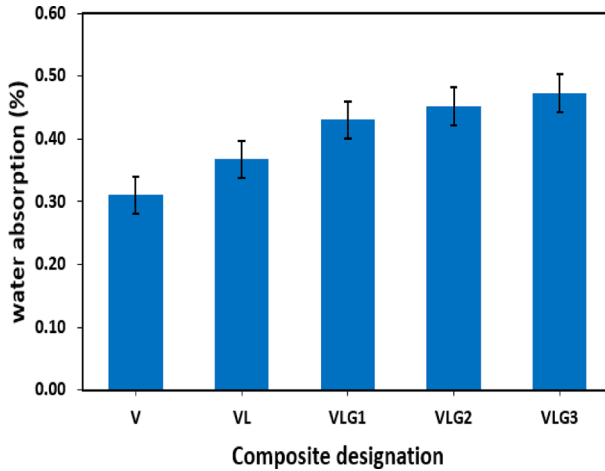


Fig. 7 Wear properties of various composite specimens

industrial waste leather is more hydrophilic than the vinyl ester matrix, it is thought to be the cause of the increase in water absorption. Leather contains natural fibers that have an inherent ability to absorb moisture, which contributes to the overall increase in water uptake. Specimens VLG1, VLG2, and VLG3, which comprise 40 vol.% industrial waste leather and 1 vol.%, 3 vol.%, and 5 vol.% GFRP filler, show further increases in water absorption. In particular, water absorption is 0.43% for VLG1, 0.45% for VLG2, and 0.47% for VLG3, which is the greatest. The combination of the industrial waste leather and the rising GFRP filler content is the main cause of the slow increase in water absorption from VLG1 to VLG3. While GFRP filler itself is generally less hydrophilic, the overall composite structure may develop micro-voids or micro-cracks at the contact among the filler as well as the matrix, which traps water and causes higher absorption. Additionally, the more complex composite structure with multiple phases (vinyl ester, leather, and GFRP filler) might create pathways for water to penetrate, resulting in higher water absorption percentages. In comparison with composites with a smaller volume fraction, those with a higher volume percentage of filler demonstrated faster rates of water absorption [20]. The surface imperfections and holes allow water to accumulate, increasing the composite’s weight [21]. Figure 8 represents the water absorption % of the composite.

**Flammability behavior:**

Table 3 presents the flame behavior of composites. It is noted that when comparing the modified composites VL, VLG1, VLG2, and VLG3—all of which contain varying vol.% of GFRP filler and industrial waste leather—with the baseline specimen V, the flammability values of the composites—as shown in Table 3 by the propagation speed, UL-94 V rating, and the behavior of falling drops—clearly demonstrate improved fire resistance. Starting with specimen V, it exhibits a



**Fig. 8** Water absorption % of various composite specimens

**Table 3** Flammability of various composite specimens

Composite designation	Propagation speed (mm/min)	UL-94 V Rating	Falling drops	Cotton lightens
V	12.05	V-0	N0	N0
VL	10.42	V-0	N0	N0
VLG1	9.78	V-0	N0	N0
VLG2	8.89	V-0	N0	N0
VLG3	8.14	V-0	N0	N0

propagation speed of 12.05 mm/min, with a UL-94 V-0 rating. The V-0 rating indicates that the material stops burning within 10 s without dripping flaming particles that could ignite cotton beneath. This high standard of fire resistance is typical for pure vinyl ester, which has inherent flame-retardant properties. In specimen VL, which contains 40 vol.% industrial waste leather, the propagation speed decreases to 10.42 mm/min, while maintaining the V-0 rating.

The reduction in propagation speed is a positive indication that the composite is less prone to fire spread. The inclusion of industrial waste leather likely contributes to this improvement, as the leather components may char upon exposure to flames, forming a protective barrier that slows down further combustion. Additionally, the char layer helps insulate the underlying material, preventing the flame from propagating quickly. In specimens VLG1, VLG2, and VLG3, which include 40 vol.% industrial waste leather and 1 vol.%, 3 vol.%, and 5 vol.% GFRP filler, further decreases in propagation speed are noted. In particular, the propagation speed of VLG1 is 9.78 mm/min, that of VLG2 is 8.89 mm/min, and that of VLG3 is the lowest at 8.14 mm/min. This gradual decrease in propagation speed from VLG1 to VLG3 is indicative of the enhanced fire resistance provided

by the increasing GFRP filler content. In order to emphasize the resin's flame-retardant qualities, filler was added, which slowed the resin's flame propagation speed [22]. Glass fibers do not burn and can serve as a heat barrier to inhibit the spread of flames, making GFRP (glass fiber-reinforced polymer) renowned for its exceptional flame-retardant qualities. All specimens, including VLG1, VLG2, and VLG3, maintain the V-0 UL-94 rating, indicating consistent high-level flame retardancy across the different composite formulations. Additionally, none of the specimen's exhibit falling drops that ignite cotton, further confirming the effectiveness of the composite design in preventing secondary ignition hazards. Filler provides heat insulation via two different ways. The fire's spread is slowed by keeping heat from penetrating the epoxy matrix [23]. In conclusion, the incorporation of industrial waste leather and GFRP filler into the vinyl ester matrix significantly enhances the flammability resistance of the composites. The decreasing propagation speed and the consistent V-0 rating demonstrate the effectiveness of these materials in improving fire safety. The combination of materials not only slows down flame spread but also prevents flaming drips, making these composites suitable for applications where high fire resistance is critical.

## Conclusions

This study shows that adding mixed GFRP filler made from industrial scrap leather to the vinyl ester matrix significantly improves composite performance. VLG2 has remarkable mechanical qualities among the examined specimens, such as an Izod impact strength of 6.4 J, a Shore-D hardness of 83, a flexural strength of 155 MPa, and a tensile strength of 135 MPa. The best mix of 40 percent industrial waste leather and 3 percent GFRP filler is responsible for these improvements, which increase load-bearing capacity and better disperse stress, leading to better mechanical performance. In contrast, VLG3 exhibits exceptional performance in tests related to flammability, water absorption, and wear resistance. It maintains a UL-94 V-0 flammability rating while achieving a specific wear rate of 0.012 mm<sup>3</sup>/Nm, water absorption of 0.47 percent, and a flame propagation speed of 8.14 mm/min. Because of its greater GFRP filler content of 5%, which fortifies the composite against abrasion and surface wear, VLG3 has improved wear resistance. The hydrophilic nature of leather and the micro-voids created by the fillers are responsible for the minor increase in water absorption; nonetheless, this has no negative impact on the composite's overall performance. Furthermore, the char-forming capacity of leather and the flame-retardant qualities of GFRP filler led to the slowest flame propagation and the absence of blazing drips. Crucial details regarding the microscopic structure of these composites are revealed by SEM analysis. While the agglomeration of fillers in VLG3 does not substantially impair its wear resistance, water absorption, or flammability performance, the uniform dispersion of fillers in VLG2 accounts for its superior mechanical qualities. These results highlight how crucial the best material choice and microstructural design are to creating high-performance composite materials.

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**Author contributions** All authors equally contributed.

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**Data availability** No datasets were generated or analysed during the current study.

## Declarations

**Competing interests** The authors declare no competing interests.

**Ethical approval** Not available.

**Consent to participate** Yes.

**Consent for publication** Yes.

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## Authors and Affiliations

V. Jayaseelan<sup>1</sup> · D. Jayabalakrishnan<sup>2</sup> · S. Sambath<sup>3</sup> ·  
Vijayananth Suyamburajan<sup>4</sup> · M. Seeman<sup>5</sup>

✉ M. Seeman  
mseeman2025@outlook.com

Vijayananth Suyamburajan  
ssvijayananth@gmail.com

- <sup>1</sup> Department of Mechanical Engineering, Saveetha Engineering College, Chennai 602105, India
- <sup>2</sup> Department of Mechanical Engineering, Chennai Institute of Technology, Kundrathur, Chennai 600069, India
- <sup>3</sup> Department of Mechanical Engineering, SRM Madurai College for Engineering and Technology, Pottapalayam, Sivaganga District, Tamil Nadu 630612, India
- <sup>4</sup> Department of Mechanical Engineering, VELS Institute of science, Technology & Advanced Studies, Chennai, Tamilnadu 600117, India
- <sup>5</sup> Department of Manufacturing Engineering, Annamalai University, Chidambaram 608001, India