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**Materials Testing and Sustainability in Composites for Motorsport
& Automotive Industries**

Automotive Materials and Sustainability | ACHA6012

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1 Introduction

The automotive, motorsport, and motorcycle industries, driven by the demand for lightweight, high-performance materials, increasingly rely on composites for their excellent strength-to-weight ratios, fatigue resistance, and design flexibility, enhancing vehicle performance, efficiency, and safety. However, with rising global sustainability goals and stricter environmental regulations, there is a pressing need to evaluate and enhance the sustainability of these materials.



Figure 1 - Audi A2 Aluminium Space Frame (Leitermann and Christlem, 2000)

This report presents a comprehensive study into the properties, performance, and sustainability of selected composite materials. The report aims to provide a detailed evaluation of various composites' suitability for continued and expanded use in motorsport and automotive applications, with particular attention to their lifecycle considerations, such as manufacturing processes, recyclability, and end-of-life disposal options.

2 Materials Walkthrough

Before experimental testing, a selection of composite material samples were provided. The materials chosen for testing are detailed below:

2.1 Aluminium

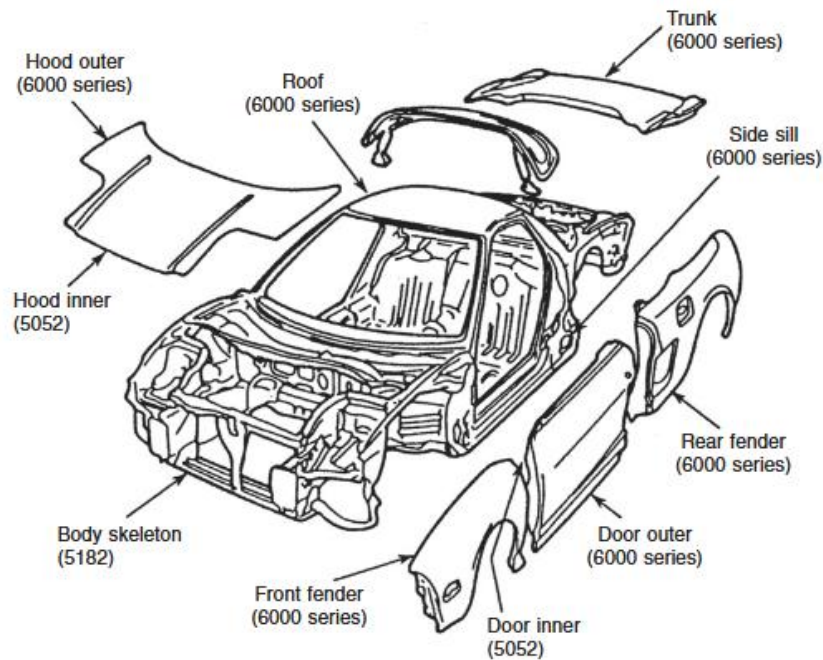


Figure 2 - Aluminium Alloys Used in the Honda NSX (Davies, 2012)

Aluminium has been used in vehicle manufacturing since the early 20th century, notably during World War II due to steel shortages and cost, initially for specialist and military applications. Its widespread adoption by automotive manufacturers began in the late 1980s and early 1990s to reduce weight and boost efficiency, exemplified by the original Honda NSX, which utilized aluminium for enhanced rigidity and reduced mass.

Steel has long been the dominant material in Body-in-White (BIW) manufacturing due to its strength, availability, and cost-effectiveness. However, the push for lighter vehicles to improve fuel economy and meet stringent emission targets has driven manufacturers to explore alternatives like aluminium. As shown in Figure 3, using different grades of steel and aluminium can achieve significant weight savings, with aluminium offering a clear advantage in mass reduction over mild steel, making it a favoured choice for structural and exterior components.

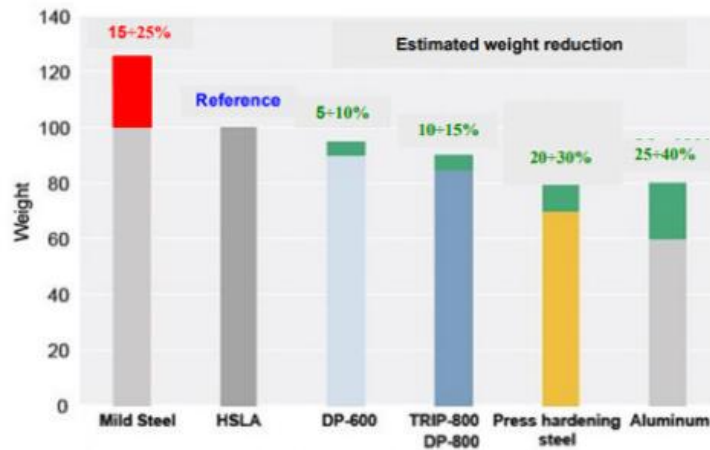


Figure 3 - Weight Reduction Potential of Various Materials in Car Body Manufacturing (Pană, 2020)

Advantages:

- Low density (roughly 1/3 of steel), good corrosion resistance, high strength-to-weight ratio, excellent conductivity, and strong crash energy absorption.
- Can be alloyed with magnesium/silicon for better strength and durability (Pană, 2020).
- Potential to be used in body panels, frames, chassis, wheels, engine blocks, drivetrains.
- Audi A2 (1999): 40% lighter than steel, achieved 3L/100km (94 MPG UK) (Leitermann & Christlem, 2000).
- Reduces weight, improves fuel economy, lowering emissions.
- Advances in alloys, joining, and recycling enhance viability, balancing strength, weight, sustainability.

Disadvantages:

- Energy-intensive production, high environmental impact if fossil fuel-powered.
- Complex, costly repairs compared to steel, may shorten vehicle lifecycle.

2.2 Hemp Composites

Hemp composites, bio-based materials made by reinforcing polymer matrices with natural fibres, are sustainable alternatives to synthetic fibres like glass and carbon, ideal for non-structural automotive parts like interior panels and trim due to their low density, reduced environmental impact, and moderate strength. However, their hydrophilic nature can cause moisture absorption and property degradation over time unless treated or coated for water resistance (Dhakal et al., 2007).

Hemp fibre composites gained traction in the automotive industry since the early 2000s for interior parts like door panels and dashboards. Major manufacturers use them to reduce vehicle weight and boost sustainability. As life cycle impact and circular material use gain focus, hemp composites are expected to see wider automotive integration.

2.2.1 Woven

Woven hemp composites are made by aligning fibres into patterns like plain, twill, or satin weaves, then impregnating them with resins to form rigid composites with improved directional properties (Yan et al., 2014).

Advantages:

- **Enhanced mechanical performance:** Woven hemp fabrics offer better tensile strength and stiffness than non-woven forms, ideal for load-bearing applications (Yan et al., 2014).
- **Predictable failure:** Organised fibre layout ensures consistent mechanical behaviour, aiding engineering analysis.

Disadvantages:

- **Higher production costs:** Weaving natural fibres raises processing time and complexity.
- **Limited formability:** Woven mats are less adaptable to contoured surfaces than non-woven types.

2.2.2 Non-woven

Non-woven hemp composites are made by bonding random fibres into mats via mechanical, thermal, or chemical agents, then infusing resin or compression moulding, ideal for formability, impact resistance, and acoustic damping (Yan et al., 2014).

Advantages:

- **Excellent formability:** Non-woven mats mould into complex 3D shapes.
- **Good impact absorption:** Random fibre orientation improves energy dissipation.
- **Cost-effective manufacturing:** Simpler fabrication and lower material costs reduce expenses.
- **Sound insulation:** Loose fibres enhance acoustic absorption.

Disadvantages:

- **Lower structural strength:** Random fibre orientation reduces tensile and flexural performance versus woven forms.
- **Inconsistent properties:** Uneven fibre distribution causes variable stress responses.

- **Moisture vulnerability:** Susceptible to degradation unless treated (Dhakal et al., 2007).

2.3 Carbon Fibre

Carbon fibre composites, made of carbon fibres in a polymer matrix, are known for their high strength-to-weight ratio, stiffness, and fatigue resistance, making them ideal for high-performance use in automotive, aerospace, and sporting goods industries. Their properties can be customized by varying fibre architecture and resin systems (Chung, 1994).

2.3.1 Woven

Woven carbon fibre composites are made from interlaced carbon fibres in patterns like plain, twill, or satin weaves, offering balanced mechanical properties across multiple directions (Mallick, 2007).

Advantages:

- **High strength and stiffness:** Interlaced structure provides strong tensile and stiffness in both directions.
- **Improved damage tolerance:** Distributes loads well, enhancing impact and delamination resistance.

Disadvantages:

- **Lower formability:** The interlaced fibres can limit drapability over complex geometries.
- **Potential for crimp-induced weaknesses:** Fibre waviness (crimp) can reduce the effective modulus and strength.

2.3.2 Non-woven

Non-woven composites with randomly oriented chopped fibres offer improved in-plane property uniformity and easier moulding (Mallick, 2007).

Advantages:

- **High formability:** Fits complex shapes; ideal for high-volume moulding.
- **Cost-effective:** Lower labour and faster cycles than lay-up methods.

Disadvantages:

- **Lower performance:** Random fibre orientation reduces strength and stiffness.
- **Property variability:** Uneven fibre distribution causes inconsistent behaviour.

2.3.3 Bio Resin

Bio-based resins from renewable sources offer a sustainable alternative to petroleum-based resins, reducing the environmental impact of carbon fibre composites (Mohanty et al., 2005).

Advantages:

- **Sustainable:** Lower carbon footprint and less fossil fuel use.
- **Biodegradable potential:** Some bio-resins break down under certain conditions.

Disadvantages:

- **Mechanical limits:** Lower strength and heat resistance than synthetics.
- **Processing issues:** May need special curing or additives.

2.3.4 Synthetic Resins

Traditional resins like epoxy, polyester, and vinyl ester are widely used in carbon fibre composites for their reliable performance (Mallick, 2007).

Advantages:

- **High performance:** Epoxy resins provide excellent adhesion, strength, and chemical resistance.
- **Versatile:** Compatible with various applications and processing methods, from hand lay-up to resin transfer moulding.

Disadvantages:

- **Environmental impact:** Petroleum-based resins release volatile organic compounds during processing, raising health and environmental concerns.
- **Recycling issues:** Thermosetting resins' cross-linked structure complicates recycling, contributing to waste.

2.4 Flax Composite Bio Resin

Flax composite bio-resins, made by combining flax fibres with bio-based resins, are sustainable materials offering lightweight construction, good stiffness, and excellent vibration damping, typically manufactured through vacuum-assisted resin transfer moulding.

2.4.1 Woven

Woven flax composite bio-resins are made by aligning flax fibres in patterns like plain or twill weaves and impregnating them with bio-based resins, offering enhanced directional properties for semi-structural applications.

Advantages:

- **Superior strength:** Woven structure offers better tensile strength and stiffness, outperforming non-woven composites in load-bearing applications (Yan et al., 2014).
- **Predictable failure:** Organized fibre layout ensures consistent and reliable mechanical responses for design and safety.
- **Sustainability:** Bio-resins reduce carbon footprint and reliance on petroleum-based materials.
- **Aesthetic appeal:** Woven texture provides a natural finish, ideal for visible components in automotive interiors or furniture.

Disadvantages:

- **Higher costs:** Weaving process increases labour and processing time, raising expenses compared to non-woven alternatives.
- **Limited formability:** Interlaced fibres restrict adaptability to complex or contoured shapes.
- **Moisture sensitivity:** Flax fibres absorb water, compromising durability unless treated.
- **Crimp weaknesses:** Fibre waviness in the weave reduces modulus and strength, causing potential stress concentrations.

2.4.2 Non-woven

Non-woven flax composites are made by bonding randomly oriented flax fibres into mats and impregnating them with bio-based resins, offering versatile, formable, and impact-resistant applications.

Advantages:

- **Excellent formability:** Random fibre arrangement enables moulding into complex shapes.
- **Superior impact absorption:** Random orientation improves energy dissipation.
- **Cost-effective:** Simpler fabrication and lower material costs.

Disadvantages:

- **Lower strength:** Random fibre orientation reduces tensile and flexural performance.
- **Inconsistent properties:** Variability in fibre distribution causes uneven stress responses.

- **Moisture and degradation:** Flax fibres absorb moisture and degrade biologically, compromising durability.

2.5 Kevlar Woven

Woven Kevlar composite bio-resins are made by interlacing kevlar fibres in patterns like plain or twill weaves, then impregnating with bio-based resins such as epoxidized soybean oil, resulting in composites known for exceptional toughness and impact resistance (Chung, 1994).

Advantages:

- **Impact resistance:** Woven Kevlar fibres provide outstanding energy absorption and toughness.
- **Improved damage tolerance:** The woven layout distributes loads, enhancing delamination resistance and structural integrity under dynamic stress.

Disadvantages:

- **Higher production costs:** Weaving and premium Kevlar fibres increase manufacturing costs.
- **Limited formability:** Interlaced fibres restrict drapability, making moulding over complex surfaces challenging.
- **Moisture sensitivity:** Kevlar can absorb moisture, degrading performance over time.
- **UV degradation:** Prolonged UV exposure weakens Kevlar fibres, requiring protective coatings or limiting outdoor use (Chen et al., 2011).

3 Methodology

Tensile tests were performed using the Denison Tensile/Compression testing machine in Science Lab IQ007 to assess the tensile performance of various composite materials, including synthetic fibres, natural fibres, and a base metal (aluminium) for comparison.



Figure 4 - Gripping Configuration for Tensile Testing

Test specimens were produced using a resin infusion process, incorporating an embedded mesh layer for improved grip during testing. The composite materials were assumed to have a 50/50 fibre-to-resin volume fraction for both carbon and Kevlar samples. All materials were provided by Easy Composites, with mechanical property data sourced from the respective material data sheets.



Figure 5 - Test Samples

Table 1 - Test Specimen Summary

Test No.	Material	Fiber Orientation	Resin Type	Cross-Sectional Area (mm ²)	Fibre Tensile Strength (MPa)	Fibre Youngs Modulus (GPa)	Fibre/Resin %	Resin Tensile Strength (MPa)	Resin Youngs Modulus (GPa)
Test 1	Aluminium	N/A	N/A	30	N/A	N/A	N/A	N/A	N/A
Test 2	Aluminium	N/A	N/A	30	N/A	N/A	N/A	N/A	N/A
Test 3	Hemp Composite	Non-Woven	Bio-Resin	24	46	6	40	68.0	3.04
Test 4	Hemp Composite	Non-Woven	Bio-Resin	17.55	46	6	40	68.0	3.04
Test 5	Carbon Composite	Non-Woven	Bio-Resin	29.4	290	25	50	68.0	3.04
Test 6	Carbon Composite	Non-Woven	Bio-Resin	29.4	290	25	50	68.0	3.04
Test 7	Carbon Composite	Woven	Bio-Resin	14.96	4120	234	50	68.0	3.04
Test 8	Carbon Composite	Woven	Bio-Resin	15.36	4120	234	50	68.0	3.04
Test 9	Carbon Composite	Woven	Epoxy Resin	15.6	4120	234	50	76.0	3.5
Test 10	Carbon Composite	Woven	Epoxy Resin	13.65	4120	234	50	76.0	3.5
Test 11	Flax Composite	Non-Woven	Bio-Resin	23.64	44	5	18	68.0	3.04
Test 12	Flax Composite	Non-Woven	Bio-Resin	21.78	44	5	18	68.0	3.04
Test 13	Flax Composite	Woven	Bio-Resin	33.49	61	7	29	68.0	3.04
Test 14	Flax Composite	Woven	Bio-Resin	31.52	61	7	29	68.0	3.04
Test 15	Kevlar	Woven	Bio-Resin	17.55	3000	112.4	50	68.0	3.04
Test 16	Kevlar	Woven	Bio-Resin	17.55	3000	112.4	50	68.0	3.04

4 Results & Analysis

Since the samples do not adhere to standard testing dimensions, despite their shape resembling the ISO 6892-1 standard, they will be treated as a modified version of this standard. A length of 133 mm will be used for strain calculations, as specified.

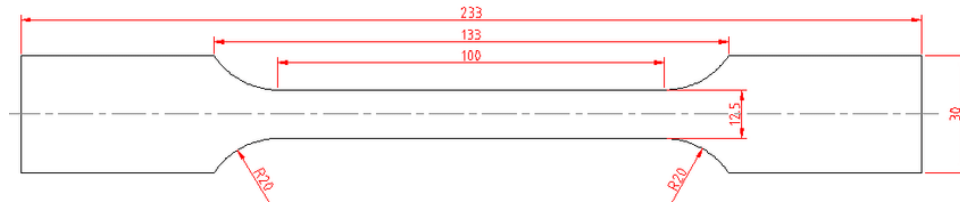


Figure 6 - Tensile Test Specimen According to ISO 6892-1 (Guzmán, 2016)

4.1 Aluminium (Test 1 and 2)

The tensile tests on two aluminium specimens (Test 1 and Test 2) showed consistent mechanical properties, with a cross-sectional area (CSA) of 30 mm². Test 1 yielded an ultimate tensile strength (UTS) of 116.33 MPa and Young's modulus of 4357.05 MPa, which are consistent with typical values for aluminium alloys.

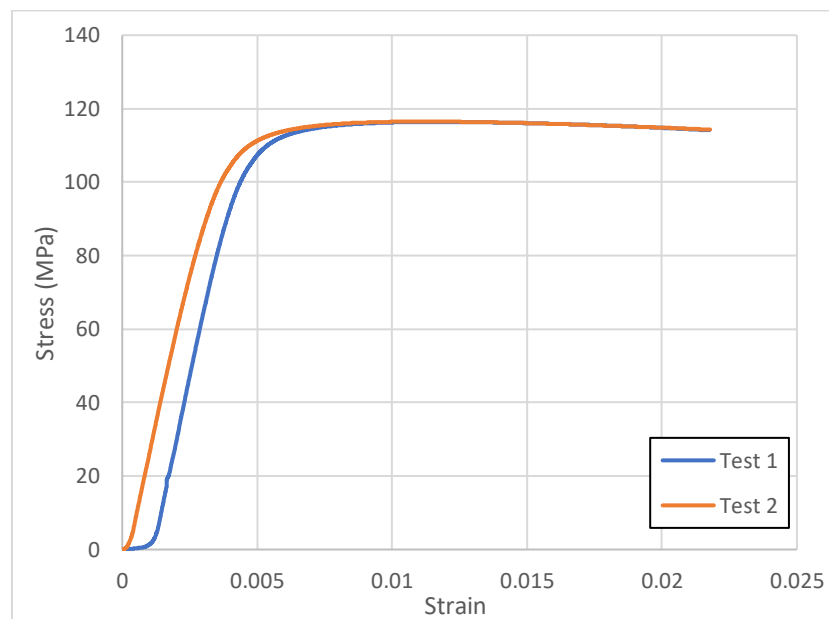


Figure 7 - Stress-Strain Curves for Test 1 and 2

The observed offset between the two lines in the graph in **Error! Reference source not found.** is likely due to minor slack in the tensile tester system before force was applied to the test sample.

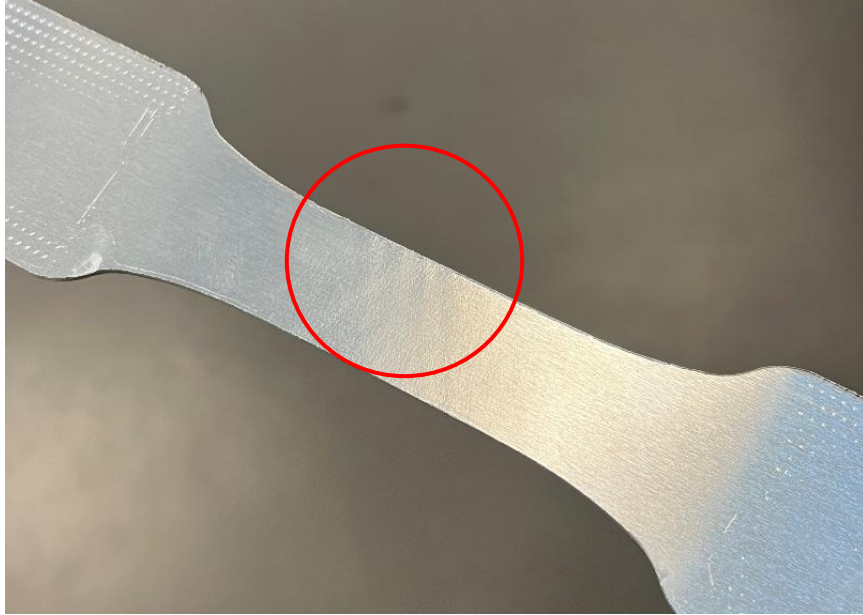


Figure 8 - Aluminium Test Sample Necking Region

Figure 8 shows the necking region of the test sample, highlighting the stretching and localized deformation during the tensile test. The absence of complete rupture explains the plateau at the end of the stress-strain graph, indicating the sample reached maximum strain without fracturing.

4.2 Hemp Composites

4.2.1 Non-woven (Test 3 and 4)

Due to the random fibre orientation in non-woven hemp composites, there is uncertainty in their alignment relative to the applied load, as fibres may be positioned longitudinally, transversely, or at varying angles. This lack of controlled directionality results in isotropic in-plane properties but complicates the prediction of load-bearing capacity, as only a portion of the fibres are optimally aligned to resist tensile forces. The random orientation is quantified by an efficiency factor of $3/8$ in the modified rule of mixtures for 2D randomness (Papageorgiou et al., 2016).

Consequently, the modulus of this laminate can be determined using the following method:

$$E_c = \frac{3}{8} V_f E_f + V_m E_m$$

From this, the value obtained for non-woven hemp is 3.86 GPa.

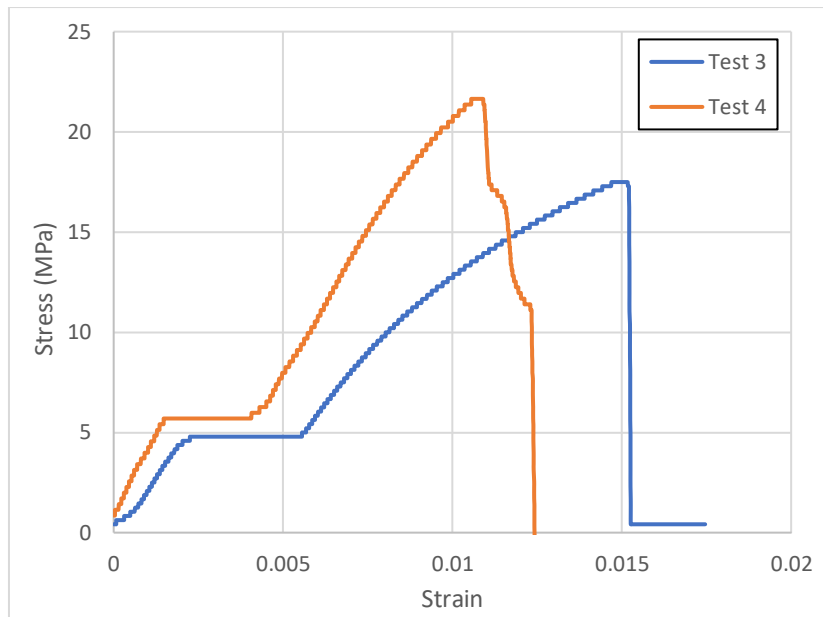


Figure 9- Stress-Strain Curves for Test 3 and 4



Figure 10 - Hemp (Bio Resin) Sample Failure Point

The composite shows a two-stage failure mechanism, as shown in Figure 9. The initial plateau in both tests indicates resin failure, followed by a second stage where the randomly oriented fibres reach their maximum load-bearing capacity and fracture. The random fibre orientation results in a reduced ultimate tensile strength (UTS) and a more gradual failure compared to aligned fibre composites, as only some fibres are optimally aligned to withstand the tensile load. Additionally, the non-woven structure leads to inconsistent stress distribution, which may be further affected by defects such as voids or weak fibre-matrix interfaces.

4.3 Carbon Fibre

4.3.1 Non-woven Bio Resin

Using the given values, the composite modulus for this sample is calculated to be **6.21 GPa**.

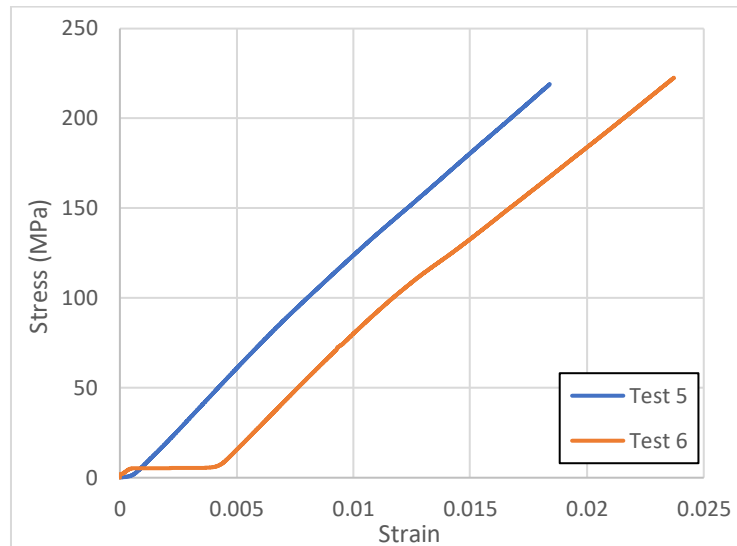


Figure 11 - Stress-Strain Curves for Test 5 and 6

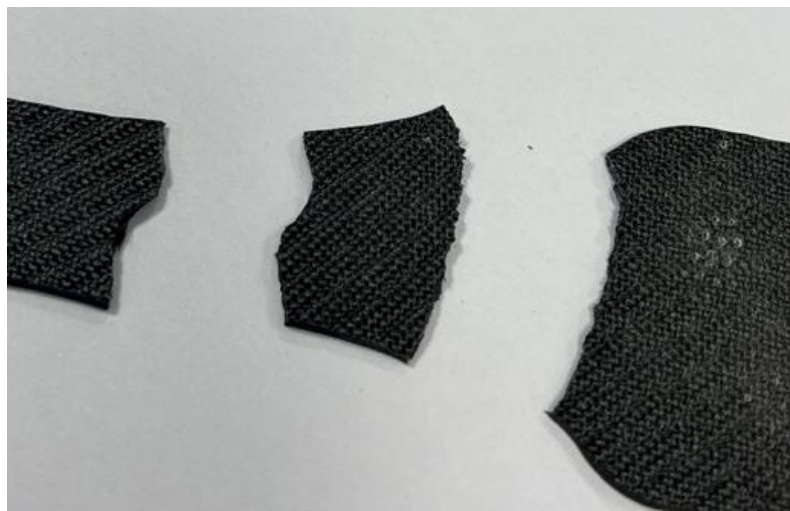


Figure 12 - Non-woven Bio Resin Sample Failure Point

The sample fractured at two distinct locations, with no clear pattern emerging, as expected for a non-woven composite. The lack of fibre alignment in the material led to unpredictable failure points, highlighting the inherent variability in stress distribution typical of non-woven structures.

4.3.2 Woven Bio Resin

The multi-layered woven materials were configured with layers oriented 45° apart, resulting in a three-layer composite: one longitudinal (0°), one at 45°, and one transverse (90°). The fibre orientation distribution factors are 1.0 for the longitudinal layer, 0 for the transverse layer, and 0.2 for the 45°

layer, approximating random orientation (Kopeliovich, 2023). The equation derived is presented below:

$$E_{Total} = \frac{(V_f E_f + V_m E_m) + (0.2 \times V_f E_f + V_m E_m) + (V_m E_m)}{3}$$

The calculated modulus for this composite is of 48.32GPa.

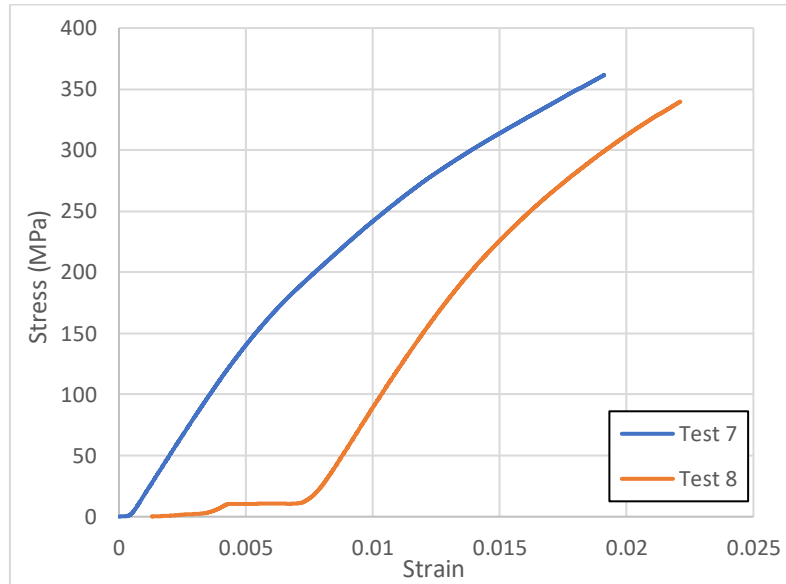


Figure 13 - Stress-Strain Curves for Test 7 and 8

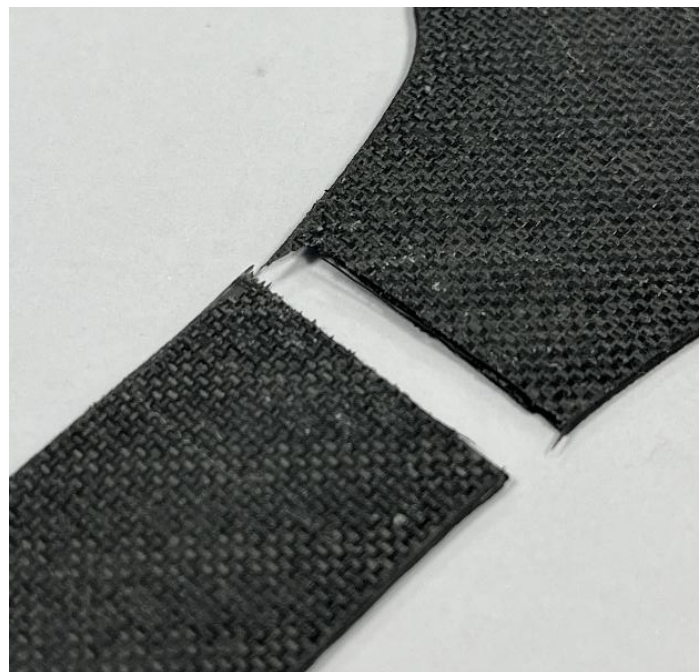


Figure 14 - Woven Bio Resin Sample Failure Point

In the woven sample, the clear failure of the transverse layer is evident, with the longitudinal fibres visibly stretched before failure.

4.3.3 Epoxy Resin

The total composite modulus is calculated to be 6.75 GPa.

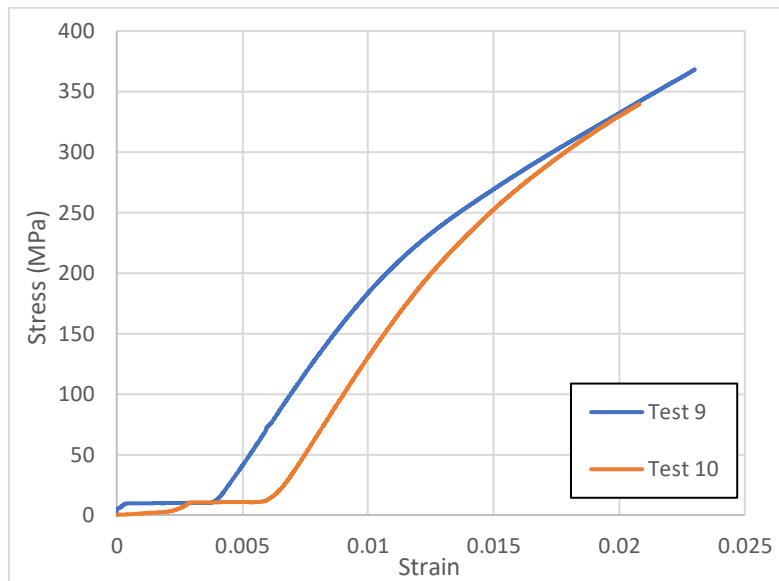


Figure 15 - Stress-Strain Curves for Test 9 and 10

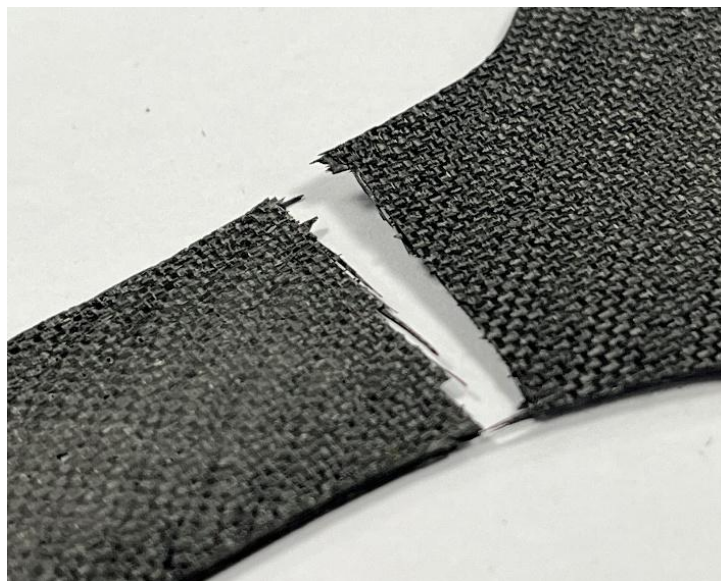


Figure 16 - Woven Epoxy Resin Sample Failure Point

In the woven sample, the stronger epoxy resin is evident, as shown by the enhanced bonding between fibres. This is illustrated by the progressive breakdown of the transverse weaves during the failure process which did not happen with the bio resin sample.

4.4 Flax Composite Bio Resin

4.4.1 Non-woven

Using the provided values, the composite modulus is calculated as 2.83 GPa.

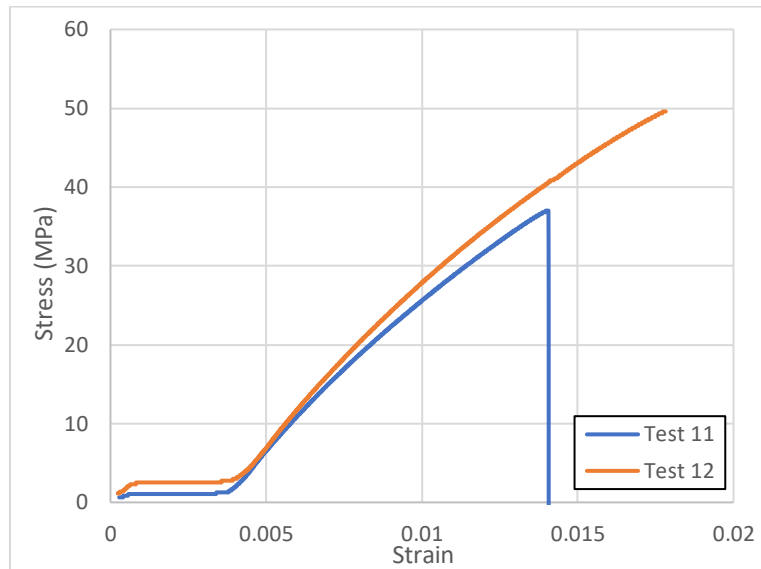


Figure 17 - Stress-Strain Curves for Test 11 and 12



Figure 18 - Flax Non-woven Sample Failure Point

As expected, the non-woven nature of this sample resulted in unpredictable behaviour. The failure point clearly shows the breakdown of the resin matrix, followed by the stretching and eventual failure of the fibres.

4.4.2 Woven

Using the provided values, the composite modulus is calculated as 2.97 GPa.

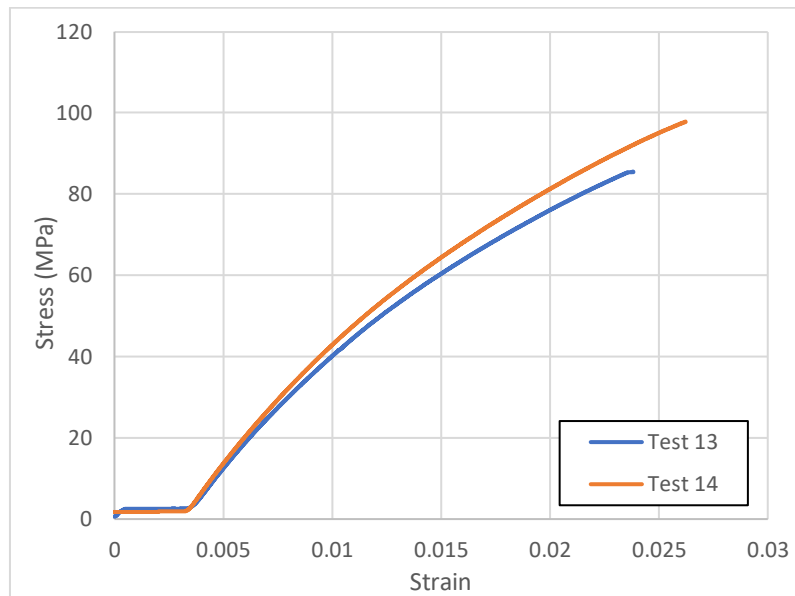


Figure 19 - Stress-Strain Curves for Test 13 and 14



Figure 20 - Flax Woven Sample Failure Point

The flax-woven fibre failed as expected, demonstrating very predictable behaviour.

4.5 Kevlar Woven

The calculated modulus for the woven Kevlar composite is 15.19 GPa.

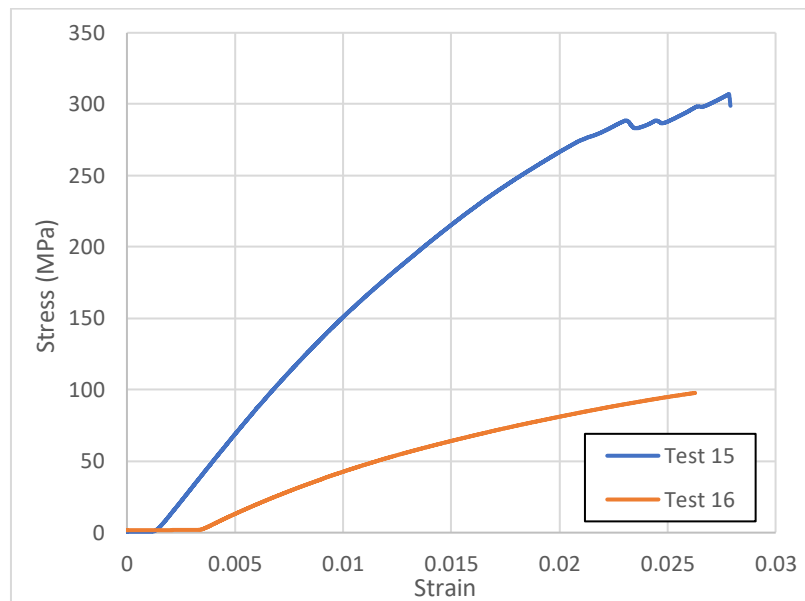


Figure 21 - Stress-Strain Curves for Test 15 and 16



Figure 22 - Kevlar Sample Failure Point

Test 16 was classified as a failure. In contrast, Test 15 displayed a unique failure mode—the fibres broke down progressively and individually without fully separating. This indicates that Kevlar is significantly more compliant than the comparable carbon fibre sample, which fractured abruptly and shattered.

5 Conclusions

In conclusion, the mechanical testing of various composite materials revealed how fibre type, orientation, and resin choice critically influence performance. Woven composites consistently outperformed non-woven ones in terms of tensile strength and structural predictability, with their aligned fibre architecture providing more reliable load distribution and failure behaviour. Non-woven samples, while offering greater formability and manufacturing flexibility, demonstrated lower stiffness and more inconsistent mechanical responses due to random fibre orientation.

Kevlar-woven composites stood out for their superior toughness and damage tolerance, exhibiting gradual fibre failure rather than abrupt fracture, in contrast to the brittle behaviour observed in carbon fibre samples. Natural fibre composites, such as flax and hemp, showed potential for sustainable applications, though their performance was limited by moisture sensitivity and lower mechanical properties. Overall, the results emphasize that composite selection must balance mechanical performance, environmental impact, and manufacturing requirements based on the intended application.

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