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Materials Testing and Sustainability in Composites
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Contents

Introduction.....	1
Task 1: Composite Materials in Motorsport.....	2
Task 1.1: Overview	2
Task 1.1.1: Carbon Fibre	3
Task 1.1.2: Bio-Fibres	3
Task 1.1.3: Kevlar Fibre	4
Task 1.2: Lifecycle Evaluation.....	5
Task 1.2.1: Synthetic Fibre Composites.....	5
Task 1.2.2: Natural Fibre Composites	5
Task 1.2.3: Feasibility Study.....	5
Task 1.3: Composite Materials in Future Regulations.....	7
Task 1.4: Potential Improvements	7
Task 2: Experimental Testing.....	8
Task 2.1: Methodology	8
Task 2.1.1: Health and Safety Precautions.....	8
Task 2.1.2: Testing Process	8
Task 2.1.3: Analysis Process	9
Task 2.2: Results Analysis.....	10
Task 2.2.1: Aluminium Baseline.....	12
Task 2.2.1: Carbon Fibre	12
Task 2.2.2: Flax	14
Task 2.2.3: Hemp	14
Task 2.2.3: Kevlar	16
Task 3: Recommendations and Future Directions.....	17
Task 3.1: Recommendations for Composite Material Use in Motorsport.....	17
Task 3.2: Future Research and Development.....	17
Conclusion.....	18
References	19

Table of Figures

Figure 1: The main types of composite materials (The Royal Society of Chemistry, n.d).....	2
Figure 2: From left to right: Denison Tensile/Compression Test machine with Aluminium Test Peice Loaded, Test Software on controlling PC Show Baseline Aluminium Results.	9
Figure 3: All Materials Results Time vs Load	10
Figure 4: All Materials Results Time vs Stress	11
Figure 5: All Materials Results Load vs Stress	11
Figure 6: Aluminium Baseline Material Break Point Showing Necking.....	12
Figure 7: Carbon Fibre Variants Time vs Load Graph	13
Figure 8: Carbon Fibre Non-Woven 1 x 300 Bio Resin Break Point.....	13
Figure 9: Flax Non-Woven and Woven Time vs Load Graph.....	14
Figure 10: Natural Fibre Composites Time vs Load Graph.....	15
Figure 11: Hemp Non-Woven 3 x 100 Bio Resin Break Point.....	15
Figure 12: Kevlar Woven 2 x 300 Bio Resin Break Point.....	16
 Table 1: Composite Materials Feasibility Study	 6
 Equation 1: Tensile Stress of a Bar under Axial Tension	 10

Introduction

In this report, an understanding of the properties and performance of composite materials, including both synthetic and natural fibres, will be gained. An evaluation of the sustainability of the tested materials, for use in the motorsport industry will be carried out. Experimental testing and analysis will be carried out on five different composite materials, using aluminium as a baseline for comparison. Recommendations based on the experimental results and sustainability evaluation will be presented. Finally, concluding comments will be made, stating the main findings from the test results analysis, the sustainability evaluation and literature review.

Task 1: Composite Materials in Motorsport

Task 1.1: Overview

Composites consist of two or more distinct materials, each with unique properties, that when combined form a new material with enhanced overall performance. (The Royal Society of Chemistry, n.d) Known for being both strong and lightweight, composites are widely used across various industries that demand high-strength structural materials. (The Royal Society of Chemistry, n.d) Composite materials provide greater specific strength, stiffness, and energy absorption compared to metals, which is encouraging their adoption across various industries. Their ability to reduce weight makes them especially valuable in motorsport. (Meredith, et al., 2011) Figure 1 below shows the main types of composite materials.

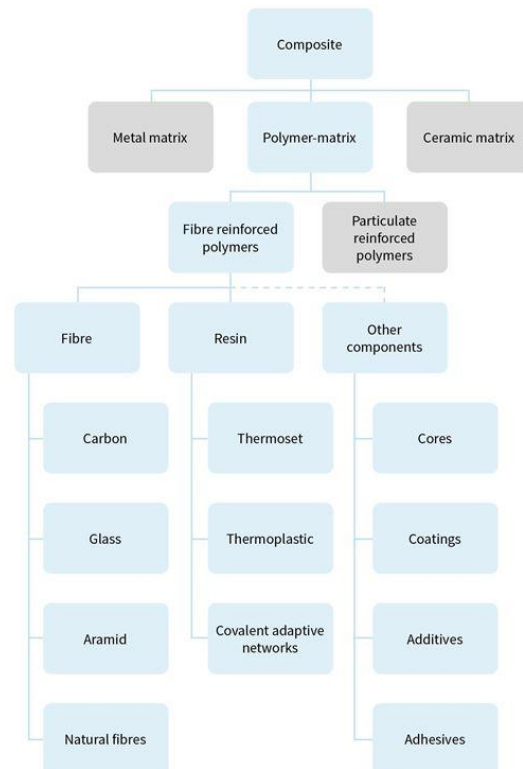


FIGURE 1: THE MAIN TYPES OF COMPOSITE MATERIALS (THE ROYAL SOCIETY OF CHEMISTRY, N.D)

Task 1.1.1: Carbon Fibre

Carbon fibres were among the first materials used for reinforcing composites. (Khurshid, 2019) These fibres, typically around 5 μm in diameter and composed mostly of carbon atoms, offer several key benefits over other fibre types. They are known for their exceptional mechanical strength, high stiffness, low weight, minimal thermal expansion, and excellent resistance to chemicals. Thanks to these outstanding properties, carbon fibres are widely used in sectors such as aerospace, defence, automotive, motorsport, civil engineering, and related fields. (Joseph, 2020) In motorsport specifically, carbon fibre is used for many applications such as bodywork, monocoque chassis, survival cells and trim pieces. Compared to alternatives like plastic or glass fibres, carbon fibre is very expensive. (Joseph, 2020)

To create composites, carbon fibres are often combined with polymer-based matrices. When these fibres are impregnated with a suitable resin and moulded, they form advanced carbon fibre-reinforced polymer composites. These materials exhibit high specific strength and stiffness, although they can be somewhat brittle. (Joseph, 2020) Being derived from petrochemicals, carbon fibre is non-biodegradable and difficult to recycle. However, it is considered to be highly durable, reducing the time before replacement, compared to other materials.

Task 1.1.2: Bio-Fibres

The need to find a sustainable alternative to the man-made fibres used in reinforcing composites has led the automotive manufacturers and parts suppliers to shift to natural fibre reinforcements. (Elseify, et al., 2021) In recent years, the utilization of natural fibres has increased substantially, primarily due to their widespread availability, low density, and cost advantages over synthetic fibres. (Sair, et al., 2018) In comparison Carvalho explains that although natural fibres offer clear advantages as a renewable alternative to carbon fibre or fibre glass, recently their widespread commercial adoption in composite applications has progressed at a relatively slow pace. (Carvalho, et al., 2024)

Natural fibres made from materials like flax and hemp offer an environmentally sustainable alternative to traditional glass and carbon fibre composites. As renewable resources, they possess significantly less embodied energy than synthetic fibres. Additionally, natural fibres are cost-effective, lightweight, exhibit high specific mechanical properties, are non-abrasive, and pose minimal health risks during handling. (Meredith, et al., 2011) Currently, the long-term performance and moisture sensitivity of bio-fibres are under researched.

Task 1.1.3: Kevlar Fibre

Kevlar is a type of aramid fibre known for its exceptional strength and light weight. It is woven into textile materials and exhibits excellent resistance to heat and corrosion. Kevlar is widely used in various applications, including aerospace structures (such as aircraft bodies), body armour, bulletproof vests, automotive brake systems, and marine vessels. It is typically incorporated into composite materials and can also be combined with other fibres to create hybrid composites for enhanced performance. (Jawaid, et al., 2019) In motorsport, Kevlar is used for high performance applications such as fuel bladders in F1 cars and prototypes. Kevlar, while a durable and valuable material, has sustainability challenges due to its non-biodegradability and the environmental impact of its production using sulphuric acid.

Task 1.2: Lifecycle Evaluation

A Life Cycle Assessment (LCA) is a method used to analyse the environmental impacts of a product throughout its entire lifespan, with the aim of improving resource efficiency and minimizing environmental burdens. (European Environmental Agency, n.d)

Task 1.2.1: Synthetic Fibre Composites

Synthetic composites life cycles involve high energy consumption and significant carbon emissions especially if production is large scale and using autoclaves. They also have challenges in end-of-life disposal due to poor recyclability and long-term persistence in landfills. Moreover, unlike natural fibre composites they are not renewable. For example, Ramachandran found that “carbon composites indicated a global warming potential (GWP) of 54 kgCO₂Eq. whereas bio composites showcased 12 kgCO₂Eq. This implies that GWP of bio composites were approximately four times less than carbon composites and if pesticides and fibre spinning are controlled, emission could be further reduced along with the overall energy consumption along with other emissions. Although bio composites showcased lower environmental impact in mostly every scenario, the transition towards bio composites still requires research to fulfil gaps with regards to the enhancement of mechanical properties compared to carbon fibre composites.” (Ramachandran, et al., 2023)

Task 1.2.2: Natural Fibre Composites

Natural fibre composites are made from renewable sources like flax or hemp and have a low environmental impact during collection and manufacturing due to minimal energy use and biodegradability. While they offer reduced mechanical performance and durability compared to synthetics, their end-of-life advantages, such as composability and lower emissions, make them a sustainable option for low to moderate performance applications.

Task 1.2.3: Feasibility Study

A feasibility study was carried out for the four composite materials focused on in this report, as well as aluminium as a baseline for comparison. For the purposes of conciseness, the criteria ratings are focused on only the reinforcement fibre within the composite.

TABLE 1: COMPOSITE MATERIALS FEASIBILITY STUDY

Feasibility Criteria	Details	Aluminium	Carbon Fibre	Flax Fibre	Hemp Fibre	Kevlar (Aramid Fibre)
Score						
1. Strength-to-Weight	Mechanical strength relative to it's weight?	3	5	2	1	5
Score						
2. Recyclability	Is it recyclable?	5	2	3	3	2
Score						
3. Renewability	Is it renewable material?	1	1	5	5	1
Score						
4. Environmental Impact	Amount of impact on the Environment during its life cycle?	1	2	4	4	2
Score						
5. Manufacturing Difficulty	How difficult is the manufacturing process?	4	2	3	3	2
Score						
6. Manufacturing Energy	How much Energy does production require?	1	2	4	4	2
Score						
7. Biodegradability	Is it Biodegradable?	1	1	4	4	1
Score						
8. Cost	How much does it cost to produce, use and dispose/recycle?	4	2	3	3	1
Score						
9. Safety	How safe is it throughout all stages?	4	2	3	3	2
Score						
10. Motorsport Suitability	How suitable is it for Motorsport use?	4	5	3	2	5
Total points	Out of 50	28	24	34	32	23
Ranking	1 to 5	3	4	1	2	5

Task 1.3: Composite Materials in Future Regulations

As well as the FIA running a dedicated Environmental Accreditation Programme, in 2019, Formula 1 announced a target for “Net Zero by 2030” (Formula 1, 2019), with teams being encouraged to explore sustainable materials. Moreover, the World Endurance championship stated that it is considering life cycle analysis and sustainability scores in future homologation. These current and future sustainability plans could very likely include requirements for a minimum number of composites on cars of equipment to be made from natural fibres or a mixture of natural and synthetic fibres.

Task 1.4: Potential Improvements

Lowering the amount of energy required during the manufacturing process of composite materials such as introducing natural fibres and bio resins in place of carbon fibre and epoxy resins could reduce the carbon footprint of the industry and improve motorsport sustainability. For example, BMW found that “employing renewable raw materials and natural fibres such as hemp, kenaf or flax minimises material usage while also achieving a weight reduction of up to 50 per cent over conventional materials. This in turn helps to lower the energy consumption of the vehicles in which they are used. What is more, the natural materials bring down the calculated CO₂ figure, as their original plants have absorbed CO₂ while growing and released oxygen.” (BMW, 2022)

Task 2: Experimental Testing

Tensile testing was conducted on a variety of fibre composites with different weaves and resins to assess their mechanical performance and support informed material selection within the motorsport industry. These composites included non-woven and woven Carbon Fibre with bio and Epoxy resin. Natural fibres Flux and Hemp were tested, with non-woven and woven versions tested for Flux. Furthermore, woven Kevlar was also tested. Aluminium metal was used as a baseline to compare the composites to.

Task 2.1: Methodology

Task 2.1.1: Health and Safety Precautions

Before testing began, the equipment was inspected for any damage which could be hazardous and effect the test results. The grips to hold the material test samples were checked for correct alignment and positioning. Appropriate Personal Protective Equipment (PPE) such as safety goggles for eye protection were worn, in case any material is ejected from the machine during operation. Furthermore, workshop clothing, with short sleeves, was worn to reduce the chance of entanglement during machine operation.

When loading the test material samples, the clamps were securely tightened and checked to avoid asymmetric loading or ejection. Additionally, the machine's emergency stop button location was identified and tested to ensure it was functioning correctly. During operation, all personal remained a safe distance away from the machine to avoid entanglement and minimise the chance of ejected material hitting a user. Following testing, the material fragments were handled with care to avoid injury from sharp edges.

Task 2.1.2: Testing Process

The testing process consisted of first measuring the width and length of the tested section of the first sample (Aluminium) to calculate its cross-sectional area (CSA) this would allow for the tensile stress to be calculated following testing. Next, the test sample was placed into the upper and lower clamps of the material tensile test machine. These clamps were then tightened. The machine clamps were zeroed and the test started. The material sample was then subjected to linear tensile loading until the material failed. Following the material failing, the test was stopped and the recorded load and time data saved. The material sample halves were inspected on the machine then removed or retrieved and placed on an organised table for further inspection, while

the test machine clamps were returned to zero and the next sample was measured and loaded. This process was repeated for each sample, with the clamps and grips inspected for damage or a change in position in between tests.

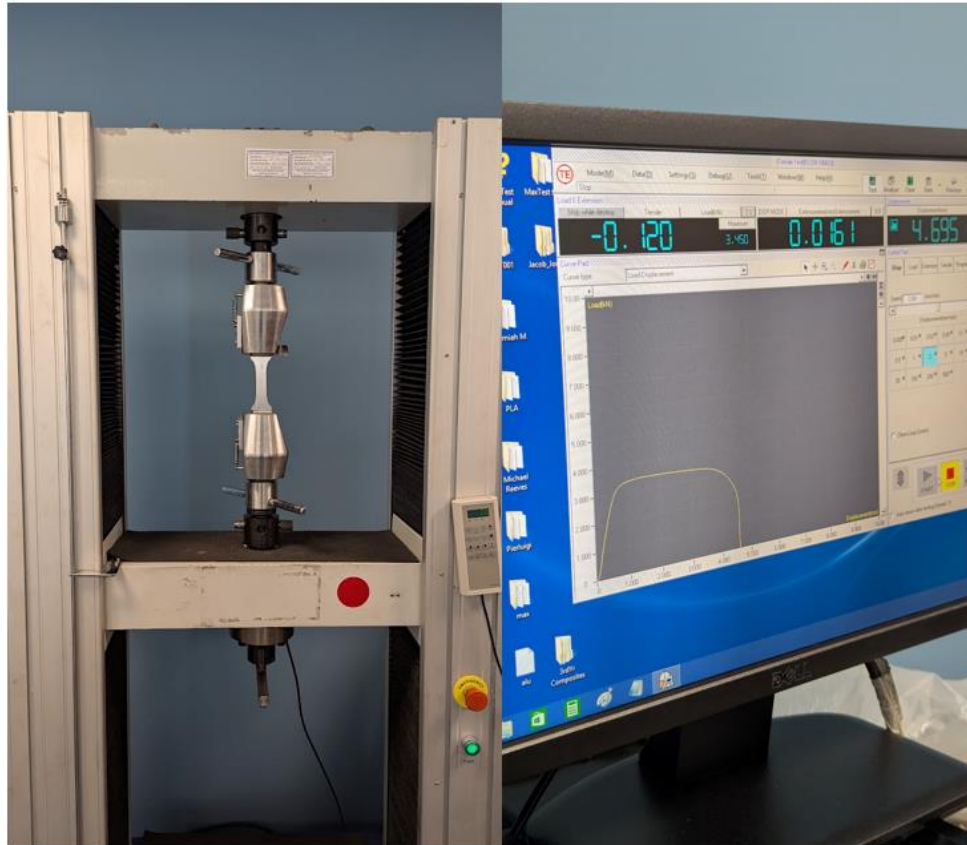


FIGURE 2: FROM LEFT TO RIGHT: DENISON TENSILE/COMPRESSION TEST MACHINE WITH ALUMINIUM TEST PEICE LOADED, TEST SOFTWARE ON CONTROLLING PC SHOW BASELINE ALUMINIUM RESULTS.

Task 2.1.3: Analysis Process

Following export of the data from the testing software, the data files were converted into excel documents and the time, load, CSA and young's modulus data from all tests were extracted into one excel document for analysis. Using the load and CSA data, the tensile stress was then calculated for each test sample, using Equation 1 below for a bar under axial tension. Time vs Load, Time vs Stress and Load vs Stress graphs were then created from plotting the gathered data. This would allow the materials mechanical performance to be directly compared and analysed.

EQUATION 1: TENSILE STRESS OF A BAR UNDER AXIAL TENSION

$$\sigma = \frac{P}{A}$$

σ = tensile stress (Pa or N/m²)

P = applied load (N)

A = cross – sectional area (before loading)(m²)

(YOUNG & BUDYNAS, 2002)

Task 2.2: Results Analysis

Figure 3 below presents the mechanical performance of the tested composites and the baseline aluminium under the applied loading conditions. The aluminium has a peak load of around 3.5 kN with a failure time of near to 130 seconds. This shows the high ductility of aluminium compared to the composites tested, which results in necking, explaining the long duration of failure.

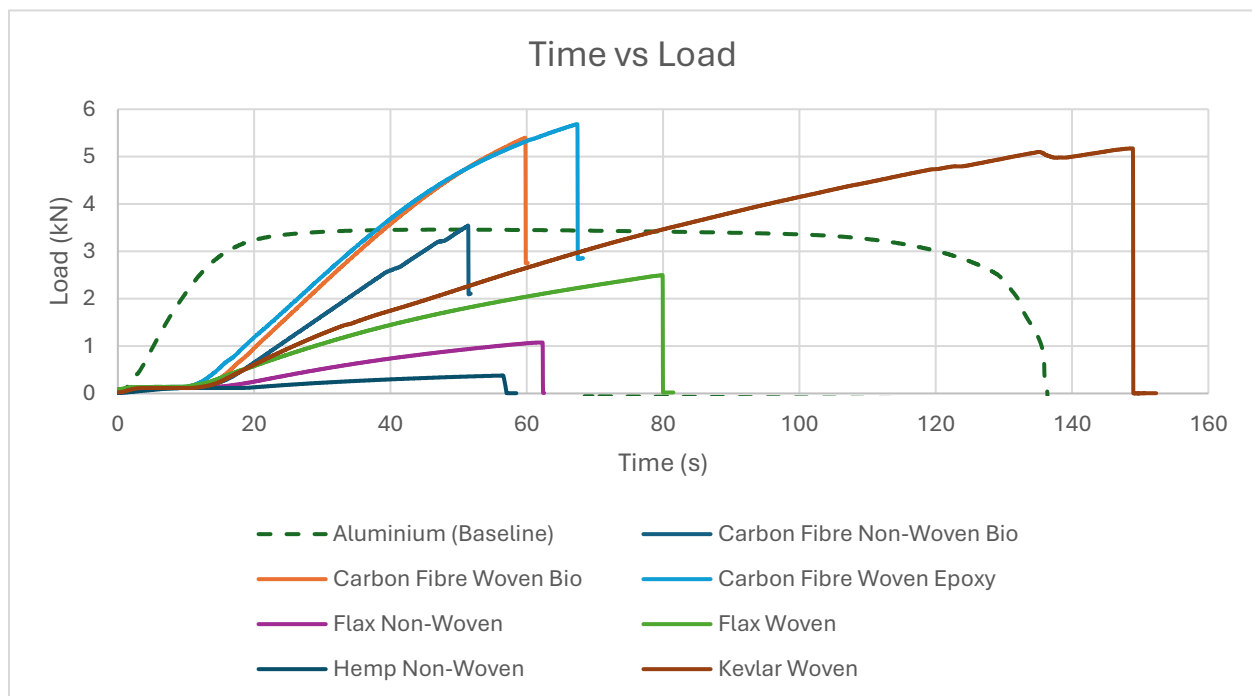


FIGURE 3: ALL MATERIALS RESULTS TIME VS LOAD

Figure 4 presents the calculated stress values vs time for each sample tested. The data follows a near identical shape and position for each sample compared to figure 3. This shows that the tensile stress increases with tensile loading.

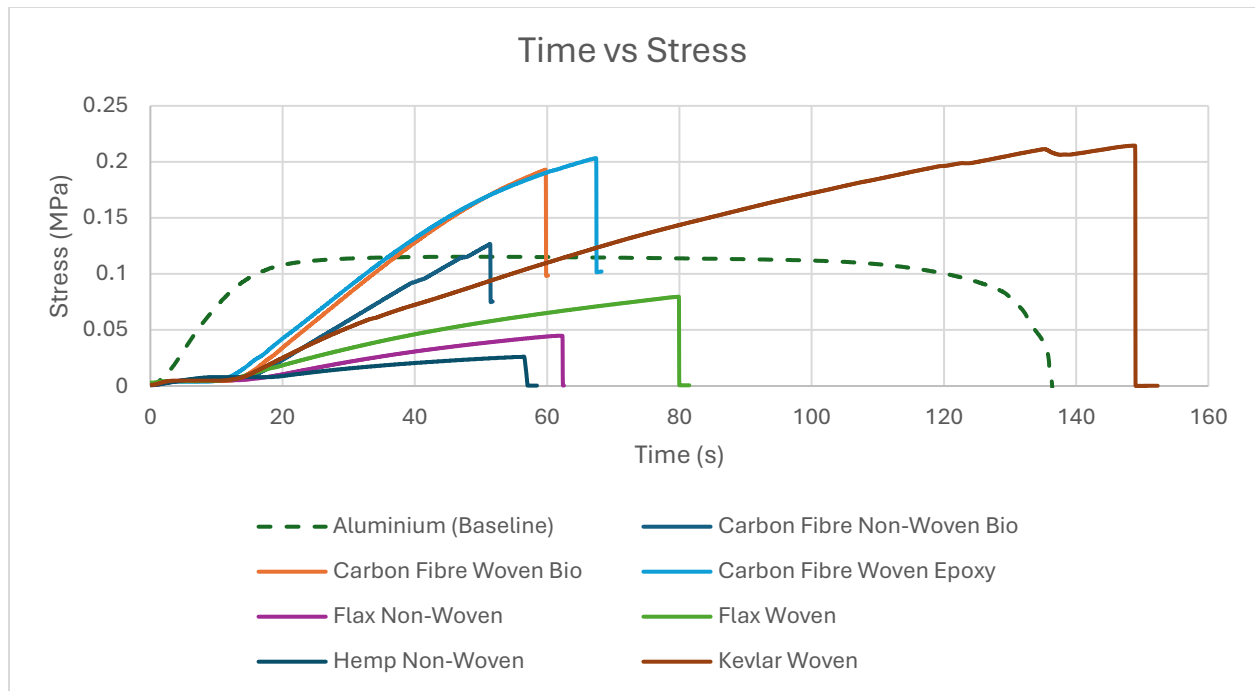


FIGURE 4: ALL MATERIALS RESULTS TIME VS STRESS

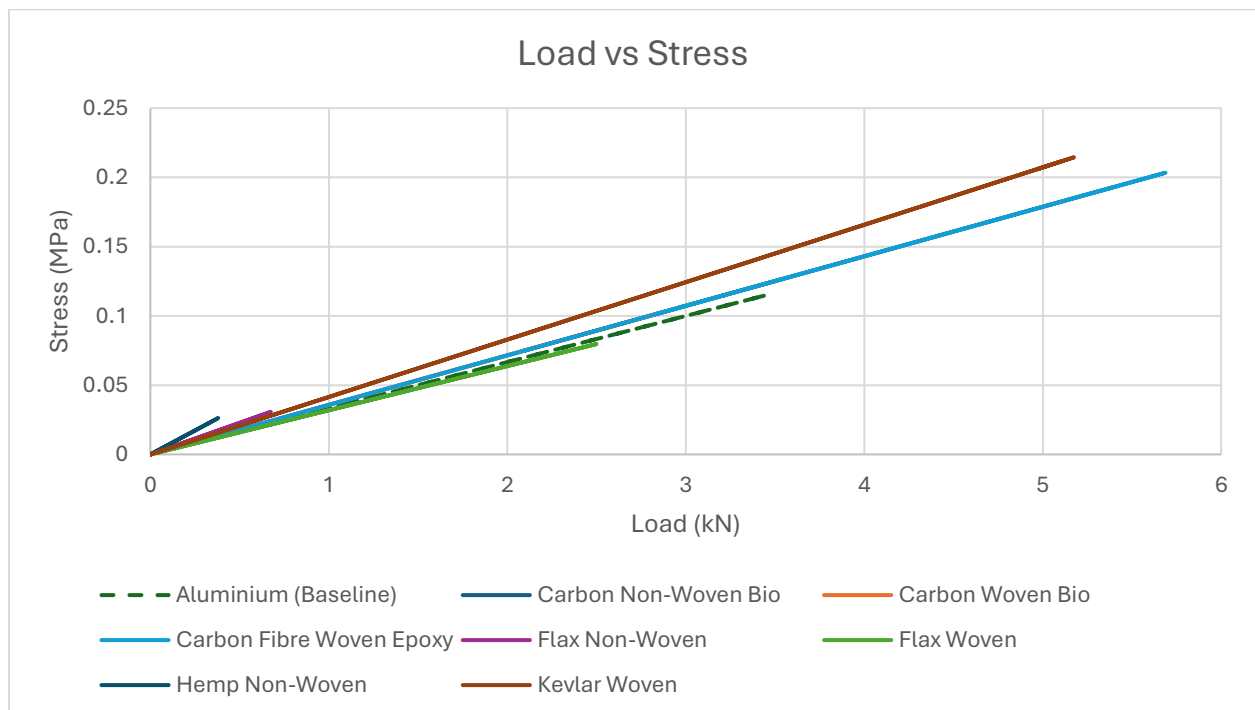


FIGURE 5: ALL MATERIALS RESULTS LOAD VS STRESS

Task 2.2.1: Aluminium Baseline

As can be seen in Figure 6 below, the aluminium baseline samples produced the expected failure shape of straight, non-fragmentating necking in the immediate area of failure. This is due to aluminium's high ductility compared to the other composites tested.

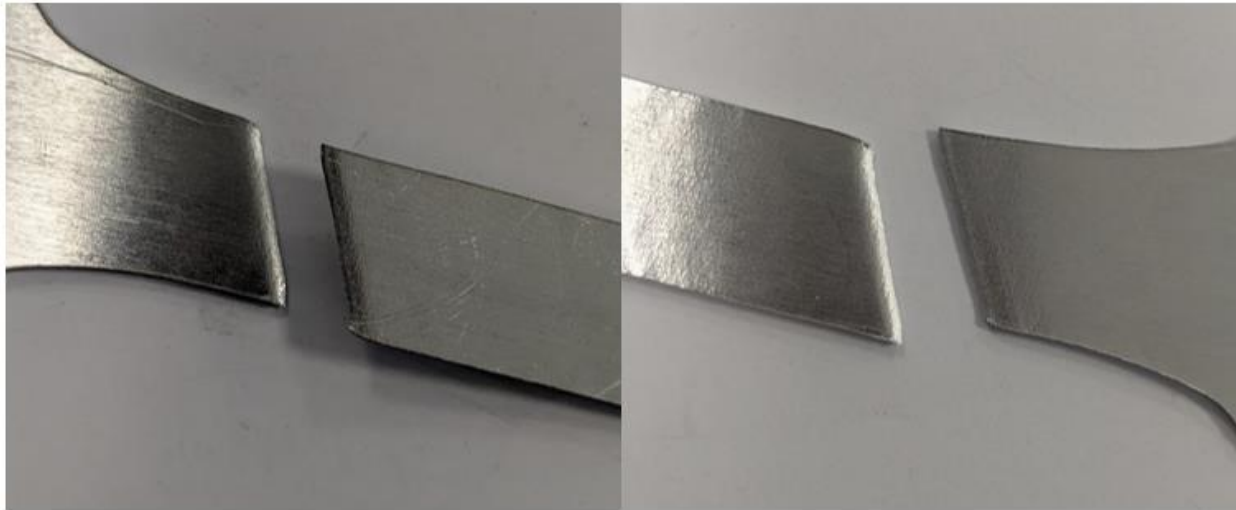


FIGURE 6: ALUMINIUM BASELINE MATERIAL BREAK POINT SHOWING NECKING

Task 2.2.1: Carbon Fibre

Figure 7 below shows the time vs load results from the three carbon fibre variants tested. The non-woven bio resin samples failed at the lowest load compared to the woven bio and woven epoxy resin samples. An increase of the maximum load can be seen with the woven bio sample; however, the woven epoxy resin withheld the highest amount of load before failing. This shows the importance of using woven fibre for tensile uses. It also shows the difference in performance between bio and epoxy resin with carbon fibre.

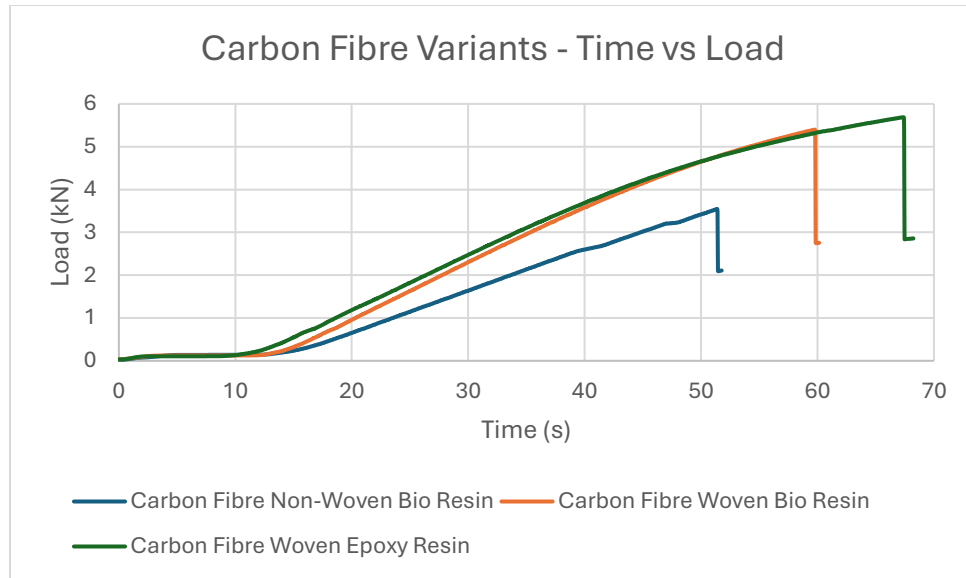


FIGURE 7: CARBON FIBRE VARIANTS TIME VS LOAD GRAPH

Figure 8 displays the carbon fibre non-woven bio resin break points. These samples show brittle, complex fractures, with the left hand sample having a complete fragmentation resulting in the fragments ejection during testing. The right hand side sample shows no fragmentation; however, like the left hand side, it shows a brittle fracture which propagated quickly whilst changing directions.



FIGURE 8: CARBON FIBRE NON-WOVEN 1 x 300 BIO RESIN BREAK POINT

Task 2.2.2: Flax

Figure 9 below presents a direct comparison between the non-woven flax and woven flax in a time vs load graph. As can be seen, changing the flax fibre to woven, increases its mechanical performance. This shows that woven flax is the superior option for higher load applications, whereas flax non-woven is suited to lower load, potentially low cost or design applications.

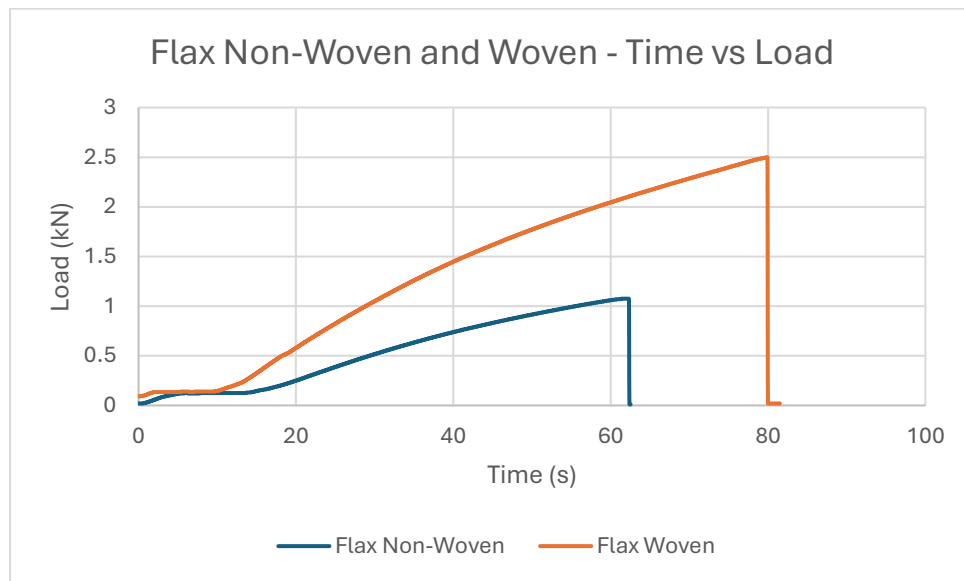


FIGURE 9: FLAX NON-WOVEN AND WOVEN TIME VS LOAD GRAPH

Task 2.2.3: Hemp

Figure 10 displays a comparison between the natural fibres tested, Flax and Hemp. Hemp non-woven fails at the lowest load amount out of the three sample types. This shows that woven flax offers a viable eco-friendly alternative where moderate strength is sufficient, whilst non-woven flax and hemp are better suited for low-load and short-duration applications.

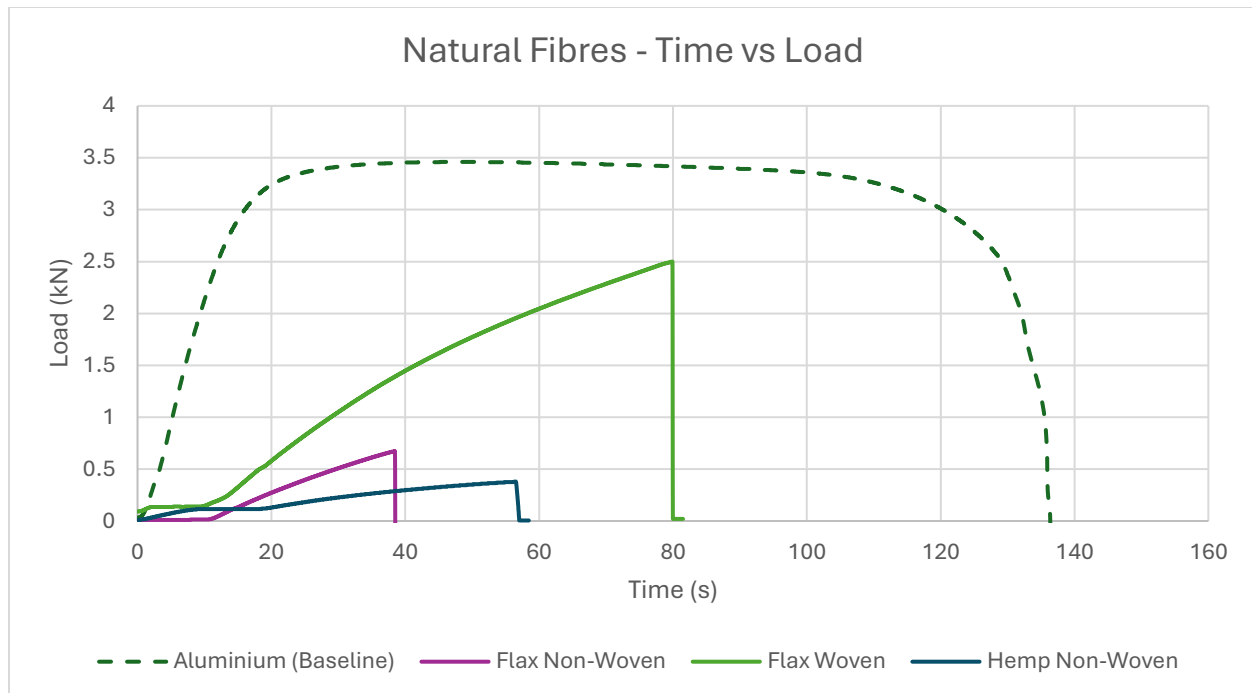


FIGURE 10: NATURAL FIBRE COMPOSITES TIME VS LOAD GRAPH

Figure 11 shows a close view of the break areas of the hemp non-woven bio resin samples. As can be seen, fibre strands are left following failure, suggesting that the failure was a fibre pull-out failure.



FIGURE 11: HEMP NON-WOVEN 3 x 100 BIO RESIN BREAK POINT

Task 2.2.3: Kevlar

Figure 12 below presents images of the break point for the two Kevlar samples. The samples show a fibre dominated response, evident in the significant fraying. A notable characteristic of these samples is that both maintained connection following failure, with the left sample fully breaking only when handling after.



FIGURE 12: KEVLAR WOVEN 2 x 300 BIO RESIN BREAK POINT

Task 3: Recommendations and Future Directions

Task 3.1: Recommendations for Composite Material Use in Motorsport

Following the experimental testing and analysis, recommendations for the use of composite materials in motorsport would include increasing the use of natural fibre composites such as woven and non-woven flax, and hemp, in areas which don't require exceptional mechanical performance, such as non-aerodynamic device bodywork as well as interior and visual parts.

Task 3.2: Future Research and Development

Future research and development to enhance sustainability of composite materials should focus on improving the process of recycling of carbon fibre, improving the manufacturing of Kevlar to reduce the use of or replace sulphuric acid, and improve the performance of bio resin to eventually replace epoxy resin.

Conclusion

To conclude, a variety of composite materials were researched, with carbon fibre being found to be the most used currently, whilst natural fibres such as hemp and flax are increasing in popularity due to changes in rules and regulations from governing bodies in motorsport to improve material waste, sustainability and motorsport's environmental impact. The rate of which natural fibres are increasing in popularity is debated. Further detail and accuracy could be added to the feasibility study by including a specific resin with each composite rating.

The tensile testing results proved that carbon fibre and Kevlar are used for high-performance applications in motorsport due to their superior mechanical properties under tensile loading. However, natural fibres with bio resin have mechanical properties suitable to replace synthetic fibres for less critical applications such as bodywork. Testing could be expanded to include a wider number of samples and fibre-resin combinations. As well as that, the carbon fibre non-woven 1x300 bio resin contained horizontal ridges within material testing zone which could have affected the gathered result. Composites were hand laid up so resin to material ratio could vary.

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