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Material Selection of Natural Fibre Composite Webbing Sling Using Rule of Mixture

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ABSTRACT

Natural fibre composites have grown in popularity as environmental concerns and knowledge about using eco-friendly materials versus synthetic materials. Furthermore, due to their low density and high strength, natural fibres are suitable for use as lightweight composite and reinforcing materials. Webbing slings are commonly used in many industries to lift loads and are typically made of synthetic fibres such as nylon and polyester. This study analysed the physical and mechanical properties, such as density, tensile strength, and Young's modulus of natural fibre composites. Bananas, pineapple, and jute with polymer matrices such as polypropylene (PP) and epoxy (EP) were used as alternative natural fibre composites for webbing sling application. Furthermore, descriptive statistical analysis was done to summarise the secondary data from the previous study of the physical and mechanical properties of natural fibre and polymer matrix. The rule of mixture (ROM) is used to identify the optimum fibre loading for manufacturing the webbing sling. This study's volume fractions of fibre were 10%, 30%, and 50%. Using the ROM equation, the results revealed that the higher fibre loading of up to 50% could increase the mechanical properties such as tensile strength and Young's modulus. Based on the results, pineapple/epoxy composite was the best material to manufacture the webbing

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sling and complied with the requirements of Product Design Specifications of polyester webbing sling compared to banana and jute composites.

Keywords: Material selection, natural fibre composite, webbing sling, ROM

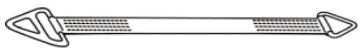
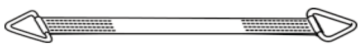
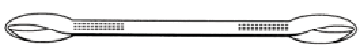
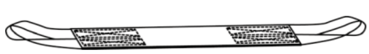
INTRODUCTION

Many industries are struggling to reduce plastic consumption and dispose of bio-waste generated by various plants and trees. Waste management is also an important issue that needs to be overcome to optimise the cost and space in the long term. Many studies published natural fibres and bio-waste utilisation in the current year. Wood, sisal, hemp, coconut, cotton, kenaf, flax, jute, banana, and pineapple are natural fibres. The demand for these materials is increasing due to recent researchers who proved the potential of natural fibre composite (NFC) to replace synthetic or traditional materials (Ilyas et al., 2022). The advantages of these materials are lightweight, low cost, low energy generation, eco-friendly, and biodegradable (Todkar & Patil, 2019).

Moreover, a huge number of researchers reported NFC achieving most of the properties, such as physical, mechanical, thermal, and rheological, of synthetic material based on the applications (Milosevic et al., 2017; Prabhu et al., 2020). Different NFCs have different properties, and many factors influence the characteristics of NFC, such as the type of fibre, reinforcement agent, fibre loading, chemical treatments, and the manufacturing process (Delgado-Aguilar et al., 2017). Aircraft, automotive, construction, food packaging, and textile industries use NFC as their alternative materials to support green technology (Jumaidin et al., 2017). Webbing sling is one of the components used in various industries to lift and secure heavy loads. A webbing sling is a flexible and durable lifting accessory used in ports to transfer cargo or containers. Different webbing slings provide different security and are reliable for lifting and transporting heavy loads, such as cargo containers, onto ships, trucks and other vehicles.

Most webbing slings are currently manufactured from polyester, nylon, and polypropylene, especially in the construction industry (Neto et al., 2018). Multiple factors should be considered to manufacture the webbing sling, such as load capacity, environmental conditions, and chemical resistance. There are many types of webbing slings with different widths and lengths in the market to accommodate different loads and lifting configurations. Table 1 shows six types of webbing slings, describing the market nowadays. The size has to fulfil the applications with adequate support and stability. Choosing the best material to comply with all industry requirements is crucial, particularly safety. Another factor is stitching and reinforcement, in which the webbing sling should have reinforced stitching along its length to ensure durability and strength. It is a good credit to replace this material with the best NFC based on its product design specification to fulfil the physical and mechanical properties of the webbing sling. Moreover, NFC has reinforcement features that can withstand high wear resistance and non-corrosive nature to enhance longevity (Chang et al., 2014; Dalbehera & Acharya, 2015).

Table 1
Six different types of webbing slings

Types	Description
 Type I	A web sling with a slotted triangle choker fitting on one end and a triangle fitting on the other. Often used in vertical, basket, or choker hitches.
 Type II	Triangle fittings on both ends of a web sling. It is only used with vertical or basket hitches.
 Type III	Each end of the web sling has a flat loop eye, which opens in the same plane as the sling body. A flat eye and eye, or double eye sling, is another name for this sort of sling.
 Type IV	Web Sling with both loop eyes is constructed as in Type III, except that the loop eyes are rotated to produce a loop eye perpendicular to the sling body's plane. A twisted eye sling is the usual name for this sort of sling.
Type V	An endless web sling, often known as a grommet. A load-bearing splice joins the ends of the webbing together to form a continuous loop.
 Type VI	Multiple thicknesses of webbings are held edge to edge to make a return eye (reversed eye) web sling. A worn pad is connected to one or both sides of the web sling body and one or both sides of the loop eyes to produce a loop eye at each end at a right angle to the plane of the web sling body.

Various interesting results indicate the potential of NFC to achieve the performance of traditional or common materials in many industries. There are many tools for multi-criteria decision-making nowadays; the rule of mixture (ROM) is one of the easy and common tools in engineering materials that can provide solutions with minimum time and cost compared to other tools (Tham et al., 2019). ROM is also flexible in multiple applications, such as finance and engineering design (Hine et al., 2014). The properties of individual components in the composite are very important for this method. It provides a way to predict the overall behaviour of the composite by knowing the relative proportions and its constituents. The basic assumption is that the composite material is made up of two materials. Another method is named the rule of hybrid mixture for more than two combinations of materials. Muhammad et al. (2022) validated that the final ROM result was consistent with the experimental data. A previous study also worked on improving the final result by considering the Kelly-Tyson model to estimate the tensile properties of the composite (Summerscales et al., 2019). Monte Carlo simulation was also used with ROM to increase the precision of the final result (Yerbolat et al., 2018).

However, most of the studies in the open literature did not simultaneously examine the analytical analysis of the final material that can replace the synthetic material for webbing slings. Based on the literature, very limited studies are available for webbing sling applications. This present study focuses on estimating physical and mechanical properties using an analytical analysis named ROM to select the best NFC for webbing sling applications. The current study contributes to the industry by addressing three important properties of manufacturing webbing slings in construction and transportation: density, tensile strength, and Young's modulus.

Literature Review

There are three types of natural fibre sources: (1) plant, (2) animal, and (3) mineral. These materials are composed of protein and cellulose, and a current study on plants reported an annual increment of plant fibres compared to animal and mineral natural fibres. The industry trend and forecast for the year 2022 to 2029 based on data year 2021 expected the natural fibre value to reach up to USD 68 447 Million by 2029 (https://www.databridgemarketresearch.com/reports/global-natural-fibers-market). Specifically, the forecast is for the automotive, textile, insulation, and medical applications. Pineapple, banana, flax, hemp, bamboo, kenaf, sisal, and jute are natural fibres of plants. Many applications utilise NFC to replace synthetic materials. For example, in the automotive industry, NFC has proved its ability to replace synthetic materials for interior door panels, dashboards, seat backs, and trunk linings (Ishak et al., 2016; Muhammad et al., 2022; Shaharuzaman et al., 2018).

The mechanical properties of this material are reported worldwide to be equivalent to those of metal-based materials. Having lightweight and excellent cost-effectiveness are the other reasons this material is preferable in the automotive industry. NFC is also utilised to produce building materials in the construction industry, such as roofing tiles, window frames, and wall cladding (Das, 2017). They provide thermal and acoustic insulations and are also environmentally friendly for long-term usage (Saba et al., 2016). Its other applications include consumer goods and packaging, where NFC promises an eco-friendly alternative to conventional materials. Examples of these applications are trays, containers, boxes, toys, furniture, sports, and household items. Aerospace and marine industries are the top industries that support plant-based sources that can offer weight reduction benefits, especially in manufacturing the interior components, non-structural parts, boat hulls, and decks (Asim et al., 2018; Pellicer et al., 2017). NFC provides good resistance to water and also reduces environmental impacts, especially in marine vessels (Hawary et al., 2023).

NFC's physical and mechanical properties are very important to be published in research findings. The facts and figures of this material's performance can increase the end users' trustworthiness (Wahab et al., 2015). For example, the user must consider several factors to increase the ability to rely on new cars with parts manufactured from NFC. Strength, stiffness, impact resistance, fatigue resistance, weight reduction, and thermal expansion are among the vital factors influencing the performance of new cars (Hagnell et al., 2020). Moreover, to ensure the interior components in the car can withstand normal usage and reflect the potential impact forces, it also provides durability and safety in maximum years of usage. Besides that, in the construction industry, the contractor can use NFC to substitute traditional materials based on structural requirements, costs, sustainability, safety, design, and environmental factors (Tezara et al., 2016). It is a crucial task to meet all the requirements. Hence, a current study reported that the strength of kenaf composite is similar to that of synthetic materials (Tholibon et al., 2019). Chemical treatment also increased the performance of the jute-tea leaf fibre-reinforced hybrid composite. The tensile, flexural, and inter-laminar shear strengths were increased, and the morphological properties were improved (Prabhu et al., 2019).

Webbing sling is one of the important tools used in the material handling and lifting industries. Every industry has different requirements for using webbing slings based on the applications that include construction, manufacturing and warehouse facilities, shipping and logistics, utilities and power generation, rigging and offshore operations, and entertainment and events. Tables 2 and 3 show the different sizes and loads based on the types of webbing slings. The minimum width sling is 25mm, and the maximum width is 152mm. Table 3 shows the maximum load of 12 000 kg for 152mm width by vertical basket hitch type. It is important to know the maximum load for every type of webbing sling to prevent accidents or injuries during the lifting process (Nathan et al., 2019). Based on a previous work studying 60 case studies for over 25 years, 87% of sling accident investigations involved synthetic slings (Chi & Lin, 2022). Identifying the best material that fulfils all the factors in multiple applications is difficult. ROM is one of the simplest tools in material selection that minimises cost and time (Noryani et al., 2019). The prediction of the physical and mechanical properties of the webbing sling can reduce the number of failures during the inspection.

Table 2
Different types and sizes of webbing slings (single and two legs)

Sling width (mm)	SINGLE LEG			2 LEGS OR SINGLE BASKET			
	Hitch Types			Horizontal Angles			
	Vertical	Choker	Vertical Basket	Vertical	60^{o}	45^{o}	30^{o}
25	500 kg	400 kg	1 000 kg	1 000 kg	866 kg	707 kg	500 kg
38	725 kg	580 kg	1 450 kg	1 450 kg	1 256 kg	1 025 kg	725 kg
44	850 kg	680 kg	1 700 kg	1 700 kg	1 472 kg	1 202 kg	850 kg
51	1 000 kg	800 kg	2 000 kg	2 000 kg	1 732 kg	1 414 kg	1 000 kg
76	1 500 kg	1 200 kg	3 000 kg	3 000 kg	2 598 kg	2 121 kg	1 500 kg
102	2 000 kg	1 600 kg	4 000 kg	4 000 kg	3 464 kg	2 828 kg	2 000 kg
127	2 500 kg	2 000 kg	5 000 kg	5 000 kg	4 330 kg	3 535 kg	2 500 kg
152	3 000 kg	2 400 kg	6 000 kg	6 000 kg	5 196 kg	4 242 kg	3 000 kg

Source: https://www.scribd.com

Table 3
Different types and sizes of webbing slings (hitch and horizontal)

Sling width (mm)	Hitch Types			Horizontal Angles		
	Endless Vertical	Choker	Vertical Basket	60°	45°	30°
25	1 000 kg	800 kg	2 000 kg	1 732 kg	1 414 kg	1 000 kg
38	1 450 kg	1 160 kg	2 900 kg	2 511 kg	2 050 kg	1 450 kg
44	1 700 kg	1 360 kg	3 400 kg	2 944 kg	2 404 kg	1 700 kg
51	2 000 kg	1 600 kg	4 000 kg	3 464 kg	2 828 kg	2 000 kg
76	3 000 kg	2 400 kg	6 000 kg	5 196 kg	4 242 kg	3 000 kg
102	4 000 kg	3 200 kg	8 000 kg	6 928 kg	5 656 kg	4 000 kg
127	5 000 kg	4 000 kg	10 000 kg	8 660 kg	7 070 kg	5 000 kg
152	6 000 kg	4 800 kg	12 000 kg	10 392 kg	8 484 kg	6 000 kg

Source: https://www.scribd.com

MATERIALS AND METHODS

Data collection of secondary sources on natural fibre and polymer matrix were identified. Based on the literature review from 2004 to 2022, banana, pineapple and jute are the common natural fibres used for composite applications. Many studies have reported that the properties of this material can achieve the tensile strength of synthetic material for webbing slings. Polypropylene (PP) and epoxy (EP) are considered as the alternatives to select the best material for the webbing sling industry because the properties of PP and EP are almost equal to nylon and polyester, which are the command materials used for webbing slings. Descriptive statistical analysis was used to summarise the properties of the materials. The physical and mechanical properties prediction using the Rule of Mixture (ROM) was compared with the product design specification (PDS) to finalise the composite and identify the best composites for manufacturing the webbing sling. Figure 1 shows the methodology to select the best NFC for webbing slings applications using ROM.

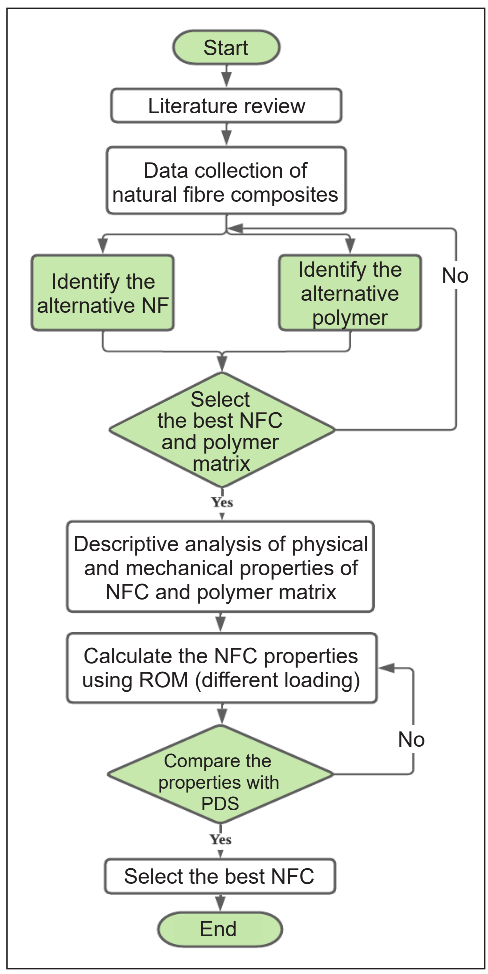


Figure 1. The methodology to identify the best NFC

Descriptive Statistical Analysis of Physical and Mechanical Properties of NFC

The secondary data on the physical and mechanical properties of the material are summarised using descriptive statistical analysis such as minimum, maximum, mean, and standard deviation. These informative values are very important for further estimation analysis using ROM. Equations 1 and 2 were used to calculate the sample mean ($\bar{x}$) and standard deviation (s), where x_i is the physical and mechanical properties and n is the number of observations.

$$\bar{x} = \frac{\sum x_i}{n} \quad (1)$$

$$s = \left[\frac{1}{n-1}\left(\sum x^2 - \frac{\left(\sum x_i\right)^2}{n}\right)\right]^{1/2} \quad (2)$$

Rule of Mixture (ROM) of NFC

Analytical analysis using the ROM method was used to estimate the physical and mechanical properties of the composite, such as density (ρ), tensile strength (σ), and Young's modulus (E). Equations 3 to 5 were used to calculate the properties of the composite, where V is the volume for the subscript, f, m, and c are the fibre, matrix, and composite, respectively.

$$\rho_c = \rho_f V_f + \rho_m \left(1 - V_f\right) \quad (3)$$

$$E_c = E_f V_f + E_m \left(1 - V_f\right) \quad (4)$$

$$\sigma_c = \sigma_f V_f + \sigma_m \left(1 - V_f\right) \quad (5)$$

Three types of fibre loading are used based on previous studies, which are 10%, 30% and 50% for the composite materials using ROM (Noryani et al., 2019). The predicted density, tensile strength, and Young's modulus of the composite were compared with the PDS of commercial materials such as polyester and nylon. The density of polyester is 1.39 g/cm^3, the tensile strength is 784 MPa, and the Young's modulus is 13.2 GPa (Nathan et al., 2019).

RESULTS AND DISCUSSIONS

Physical and Mechanical Properties of NFC Using Descriptive Analysis

Table 4 shows the minimum, maximum, mean, and standard deviation of the properties of banana, pineapple, jute, PP, and EP: density, tensile strength, and Young's modulus. These statistical values are used to measure the distribution of the physical and mechanical properties. The larger the range and standard deviation, the more properties were dispersed, and the distribution was wider from the mean. The standard deviation value for tensile strength was large for all materials compared to density and Young's modulus. For example, the tensile strength of the banana was 135.69 compared to the density of 0.026 and Young's modulus of 23.46 GPa. This pattern was consistent with other materials: pineapple, jute, PP, and EP. PP is a lighter material than other materials. It is widely used in different applications, such as automotive, aircraft, food industry, and construction, due to its lightweight and ease of manufacturing (Altay et al., 2017; Ghasemi et al., 2016; Serrano et al., 2014). Ali et al. (2015) found PP to be the best material used in the material selection, and it complied with the requirements of automotive component manufacturers, compared to polystyrene and polyethene. Based on tensile strength, pineapple was the highest with 1522.05 MPa, compared to banana and jute with 718.44 MPa and 542.91 MPa, respectively. Asim et al. (2015) reviewed the properties and strength of pineapple leaf fibre (PALF), and its composite revealed that the maximum range of PALF was 1627 MPa. Moreover, the demand and production of this fibre are increasing yearly. Further investigation on the improvement of tensile strength of pineapple by chemical treatment was performed and compared to kenaf fibre (Asim et al., 2016). The average Young's modulus of pineapple also had a higher score of 67.17 GPa, compared to banana with 19.69 GPa and jute with 33.33 GPa. This result is consistent with the ones reported by Shiju et al. (2015), with Young's modulus of pineapple reaching up to 82.5 GPa for 20 to 80 mm fibre diameter.

Table 4
The physical and mechanical properties of natural fibre and polymer

Material	Properties	Mean ($\bar{x}$)	Standard deviation (s)	Maximum	Minimum
Banana	ρ	1.33	0.026	1.37	1.30
	σ	718.44	135.69	914	493
	E	19.69	23.46	32	3.5
Pineapple	ρ	1.44	0.087	1.54	1.32
	σ	1522.05	212.86	1627	898.5
	E	67.17	14.47	82	41
Jute	ρ	1.43	0.167	1.8	1.23
	σ	542.91	214.70	900	190
	E	33.33	15.44	60	15
PP	ρ	0.91	0.0129	0.92	0.89
	σ	34.2	5.89	41.4	26
	E	1.53	0.282	1.8	0.95
EP	ρ	1.15	0.030	1.18	1.096
	σ	64.47	24.02	85	13.7
	E	3.32	0.614	4.4	2.9

Prediction of Physical and Mechanical Properties Using ROM

The expected density, tensile strength, and Young's modulus of NFC are shown in Table 5 for fibre loading of 10%, 30%, and 50% using ROM. All expected properties were increasing with the increase in fibre loading. A previous study reported a positive linear significance of the properties of NFC for hand-brake parking lever application (Noryani et al., 2019). Both pineapple-reinforced polymer composites with 50% fibre loading scored the highest tensile strengths, which are 778.13 MPa and 793.26 MPa, compared to banana/PP, banana/EP, jute/PP, and jute/EP. The tensile strength of single pineapple fibre is highest on average 1522 MPa compared to banana fibre with 718.44 MPa and jute fibre with 542.91 MPa, as shown in Table 4.

The cellulose percentage of pineapple fibre is also high, with 71.6 wt.% compared to banana fibre at 61.5 wt.% and jute fibre at 63.24 wt.% (Venkatachalam et al., 2016). Pineapple leaf is also an interesting material to study nowadays, as this material is a more sustainable, eco-friendly, and alternative fabric-reinforced composite (Mahmud et al., 2022). Moreover, waste management in the agriculture industry will improve and be more cost-efficient in the long term. Based on the calculated density in Table 3, PP with three types of fibre loading is lighter than EP. PP is a common polymer produced in large quantities and has versatile applications in different industries (Altay et al., 2017).

Table 5
The expected density, tensile strength, and Young's modulus of NFC using ROM

Composites	**Volume fraction**		**Expected Properties**		
	V_f	Vm	$\rho 11$ (g/cm^3)	σ11 (MPa)	E11(GPa)
Banana+ PP	0.1	0.9	0.95	102.62	3.35
	0.3	0.7	1.04	239.47	6.98
	0.5	0.5	1.12	376.32	10.61
Pineapple+ PP	0.1	0.9	0.96	182.99	8.09
	0.3	0.7	1.07	480.56	21.22
	0.5	0.5	1.18	778.13	34.35
Jute + PP	0.1	0.9	0.962	85.07	4.71
	0.3	0.7	1.07	186.81	11.07
	0.5	0.5	1.17	288.55	17.43
Banana + EP	0.1	0.9	1.17	129.87	4.96
	0.3	0.7	1.20	260.66	8.23
	0.5	0.5	1.24	391.46	11.51
Pineapple + EP	0.1	0.9	1.18	210.23	9.71
	0.3	0.7	1.24	501.74	22.48
	0.5	0.5	1.30	793.26	35.25
Jute + EP	0.1	0.9	1.18	112.31	6.32
	0.3	0.7	1.23	208	12.32
	0.5	0.5	1.29	303.69	18.33

Physical and Mechanical Properties Compared to PDS of Webbing Slings

Calculated density, tensile strength, and Young's modulus for six NFCs with the PDS of polyester webbing sling were plotted in Figures 2 to 4. The dashed blue line in Figures 2 to 4 is the PDS of the polyester as the commercial material for webbing sling. Based on the physical properties of density, all composites produced lighter webbing slings based on 1.4g/cm^3 as the PDS to manufacture webbing slings. 784 MPa are needed to produce a webbing sling in industry, and Figure 3 shows pineapple/EP composite with 50% fibre loading complied with the requirement of 793.26 MPa. Another important feature is Young's modulus, with 13.2 GPa, which is the PDS to manufacture a webbing sling. Six different compositions of composites exceeded the PDS, which were 30% and 50% pineapple/PP. EP composite scored more than 13.2 GPa, while only 50% fibre loading of jute/PP and EP scored 17.43 and 18.33 GPa. Based on three PDS for webbing sling, pineapple/ EP is the best material using ROM prediction with the highest strength, low density and good achievement on Young's modulus.

Another study suggested improving the final result using the hybrid mixture (ROHM) rule, which is believed to generate more alternative materials in different applications (Muhammad et al., 2022). Besides fibre loading, the type of natural fibre is also an important factor in identifying the best material to manufacture webbing slings. Recent studies have shown that potential natural sources for composite materials such as pineapple leaves can optimise the abundance of agriculture. In addition, coconut waste and banana peels in the food industry can be used as recycled material for other end products. In the textile industry, pineapple leaf fibre is the most explored reinforcement component in producing sustainable fabrics that can improve strength, durability, and breathability compared to conventional textiles.

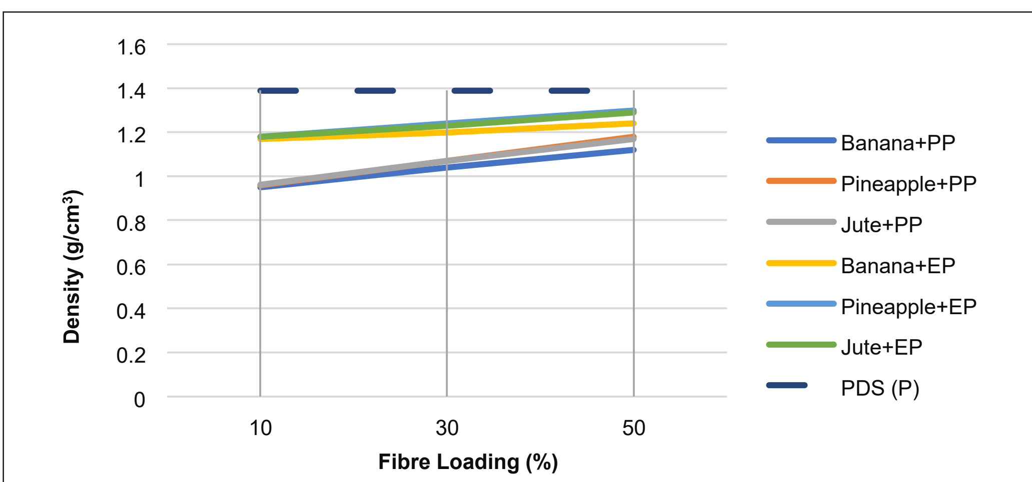


Figure 2. The density of NFC compared with PDS polyester webbing sling

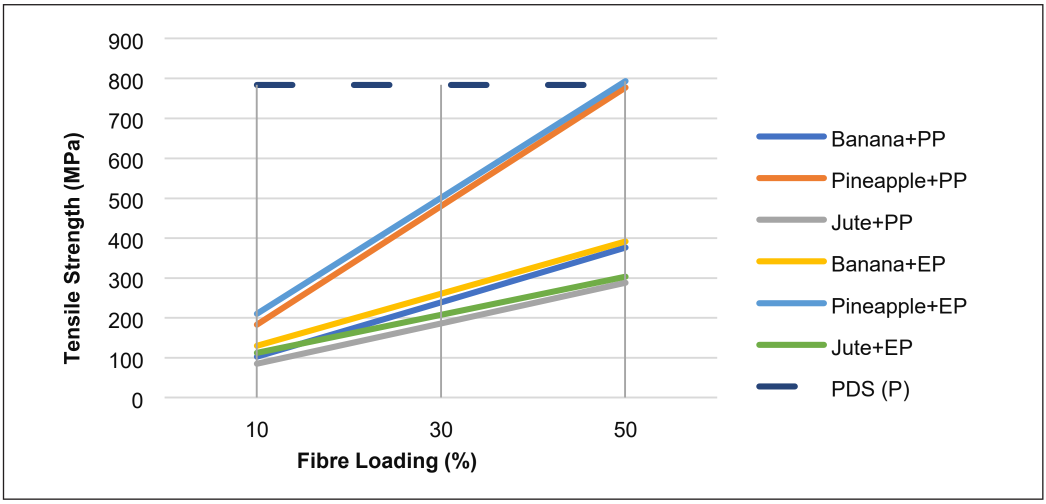


Figure 3. The tensile strength of NFC compared with PDS polyester webbing sling

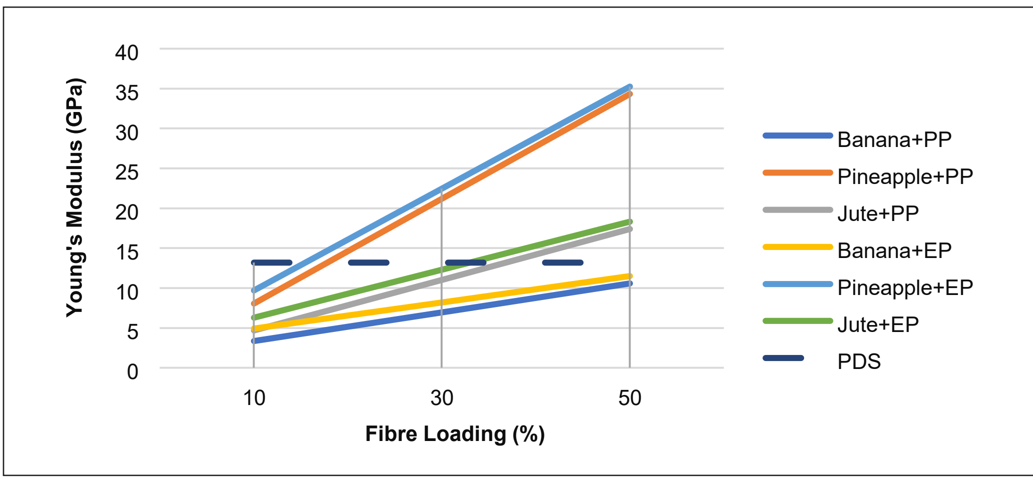


Figure 4. The Young's modulus of NFC compared with PDS polyester webbing sling

CONCLUSION

The analysis and comparison of NFC properties using ROM were performed, and it was found that the combination of pineapple with epoxy was the best material and had the best performance in manufacturing webbing slings at an optimum fibre loading of 50%. The value of tensile strength and Young's modulus were 793.26 MPa and 35.25 GPa, the highest compared to banana and jute composites. The mechanical properties of pineapple/epoxy have achieved comparable PDS as synthetic polyester for the manufacturing of webbing slings. However, the density of pineapple/epoxy did not fulfil the PDS of the polyester webbing sling of 1.30 g/cm^3 at 50% of fibre loading, lacking 0.09 g/cm^3. From all the results, it has been proved that pineapple epoxy is the most suitable material compared to other composites for manufacturing webbing slings. As a result, the mechanical and physical properties of pineapple fibre with epoxy, as well as the optimum fibre loading, have been determined and finalised. These findings are based on the approximate prediction by ROM, experimental characterisation, and testing necessary to validate and refine the predicted properties in this study. Further study on the engineering design of the detailed webbing sling structure, including holes, tears, cuts, snags, and burns, could be conducted in the future.

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