SELECTION OF MATERIALS FOR NATURAL FIBRE METAL LAMINATES USING INTEGRATED CAMBRIDGE ENGINEERING SELECTOR AND PUGH METHOD

D. Sivakumar[1], N.M. Ishak[1], N.L. Feng[1], R. Nadlene[1], A.F. Ab. Ghani[2], and I. Siva[3]

[1]Faculty of Mechanical Engineering,
Universiti Teknikal Malaysia Melaka, Hang Tuah Jaya, 76100 Durian Tunggal, Melaka, Malaysia.

[2]Faculty of Mechanical and Manufacturing Engineering Technology,
Universiti Teknikal Malaysia Melaka, Hang Tuah Jaya, 76100 Durian Tunggal, Melaka, Malaysia.

[3]Faculty of Mechanical Engineering,
Kalasalingam University, Anand Nagar, Krishnankoil-626126
Tamil Nadu, India.

Corresponding Author's Email: [1]sivakumard@utem.edu.my

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ABSTRACT: Nowadays, most scientists and manufacturers are looking for lightweight materials to reduce fuel consumption and gas emissions from vehicles to the surroundings. Alternative lightweight materials are highly valued by scientists and manufacturers to reduce gas emission problems. Fibre metal laminates are a new range of lightweight hybrid materials with high levels of fatigue resistance, toughness, strength and energy-absorbing capacity. Natural fibre-reinforced composites have been attracting the attention of scientists and manufacturers as they are biodegradable, environmentally friendly, lightweight and inexpensive. Therefore, the fascinating physical and mechanical properties exhibited by a combination of natural fibre and metal laminates deserve further investigation. This research presents the selection of natural fibre and matrix for natural fibre metal laminates for use in automotive body panels. The material selection was carried out using the Cambridge Engineering Selector software and the Pugh method of analysis. Based on the analysis, kenaf fibre and polypropylene (darified/nudeated) were determined to be the materials that fulfilled the objective constraints of this study, namely, lightweight materials at a minimal cost with maximum performance.

KEYWORDS: *Fibre Metal Laminate; Material Selection; Natural Fibre; Cambridge Engineering Selector*

1.0 INTRODUCTION

As the number of vehicles on roads increases, CO2 gas emissions from fuel combustion have also been on the rise continuously. Remarkably, according to the statistics in a 2016 report on the trend in global CO2 emissions [1], fuel consumption has decreased considerably over the last few years. This occurrence is due to the increasing awareness of the environmental impact on the requirement to reduce CO2 emissions for new cars. Thus, this change is driving new trends in automotive product designs and the entire product development process to meet performance, safety, and sustainability requirements. Many efforts have been made to comply with the legislation and at the same time, to improve the performance of vehicles. Automotive manufacturers have used a number of methods to achieve the objectives of the legislation, and one of the most relevant methods of reducing CO2 emissions is to reduce the weight of vehicles The fuel consumption of vehicles can be improved by up to 6-8% if a weight reduction of 10% is achieved. The development of lightweight materials must also take into account aspects of safety, affordability and environmental friendliness as a key approach priority. Emulating the material development pattern, a new range of lightweight hybrid materials, known as fibre metal laminates (FMLs) showed in Figure 1, was developed over the last few decades at the Delft University of Technology. Sharing the advantages of metal and fibre-reinforced composites FMLs have high levels of fatigue resistance, toughness, strength and energy-absorbing capacity.

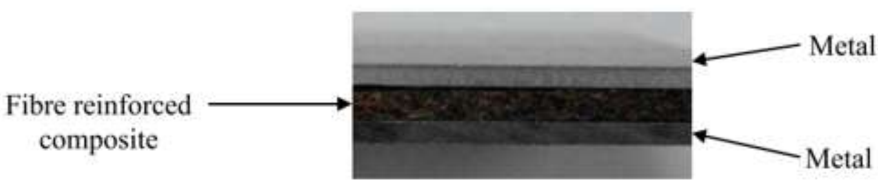

Figure 1: Fabrication of natural fibre metal laminate [2]

According to Alkbir et al. [3], natural fibre-reinforced composites are drawing the attention of scientists and manufacturers because they are biodegradable, environmentally friendly, lightweight, inexpensive, and exhibit interesting physical and mechanical properties (high specific stiffness, low density, relative flexibility, and good strength).

Thus, natural fibre-reinforced composites are considered to be excellent materials for automotive industries. Several types of natural fibre, such as jute, flax, hemp, sisal, ramie, and kenaf, are commonly used in the automotive industry. The natural fibre is commonly used in the automotive industry as an alternative material to provide the same structural performance as conventional materials but with less weight. Composite materials have been widely used for the interior and exterior body parts of cars like the dashboard, door panels, parcel shelves, seat cushions, backrests and cabin linings. Materials experts from various automakers have estimated that an advanced composite autobody could be 50% - 60% lighter than the current similarly sized steel autobody, 40% - 55% lighter than an autobody in aluminium and 25% - 30% for an autobody in aluminium steel [4].

As there is an increasing variety of materials, each material has its own mechanical and physical properties, advantages, and disadvantages. Therefore, the material selection process in the engineering design is essential to meet the design requirements in particular products to prevent failure during fabrication. Properties of the materials like density, cost, Young modulus and yield strength are the essential criteria that need to be considered in the material selection of the automotive body panel. Material's density directly related to the component weight, the cost is the variables that determine whether any new material has an opportunity to be selected for a vehicle component, while the Young modulus and yield strength of the materials are the critical parameters for the performance of the material which could influence the automotive body panels performance [5].

Among the many methods in material selection, the Cambridge Engineering Selector (CES) software is one of the methods that is usually employed in industries. Some researchers utilized this approach to determine the suitable material; Mustafa et al. [5] determined the material selection for eco-aware lightweight friction materials, Adetuji and Abioye [6] determined the material for jaw crusher equipment, while Akinluwade et al. [7] determined the material for heat sinks in high-powered computing microchips using the CES software.

The CES software contains a database of over 3000 materials and process properties, including the science-related fundamentals and selection of design requirements that enable it to propose several candidate materials. Therefore, the approach will be integrated with the Pugh method to select the best candidate. The integration of two approaches enables decision-makers to break a master problem into smaller sub-problems to be solved [8] and the decision results are more reliable and accurate [9]. The CES software has proven to be an incredibly successful resource in the support and enhancement of the teaching on the engineering, science, processing, and design of materials. The aim of this paper was therefore to determine the best natural fibre and matrix that would be suitable for manufacturing FMLs for car body panels using the CES approach, followed by the Pugh method of analysis.

2.0 METHODOLOGY

2.1 Cambridge Engineering Selector (CES)

The natural fibre and matrix were selected using the CES and Pugh method. As described by Ashby and Cebon [10], there are five steps for the selection of materials using the CES. Mustafa et al. [11] summarised these steps to four steps, as shown in Figure 2. It starts with the determination of the problem statement for the product involved, the purpose of the product, the objective function of the product like lightweight, stiff, and strength. The next stage is the identification of the limitations of the material since the objective function must be achieved subject to the product limitations or constraints followed by the implementation of the product constraints and requirements. CES will provide the outcomes of the possible materials that fulfil the requirements and limitations of the product.

2.2 Pugh Method for Verification of Best Material Selection

Several candidate materials will be proposed by the CES software. By using the database from the software, the materials are compared with the current material as a datum in the Pugh method. The Pugh method needs two tables to set up the datum, namely, a table for the data and another table for the analysis. A few symbols are used to indicate the comparison with the datum, namely, the equal sign (=) for equalities, the positive sign (+) for better, and the negative sign (-) for less. The end of the row in the table shows the total number of positive signs (+) for each material. The candidate with the most number of positive signs (+) will be selected as the best material.

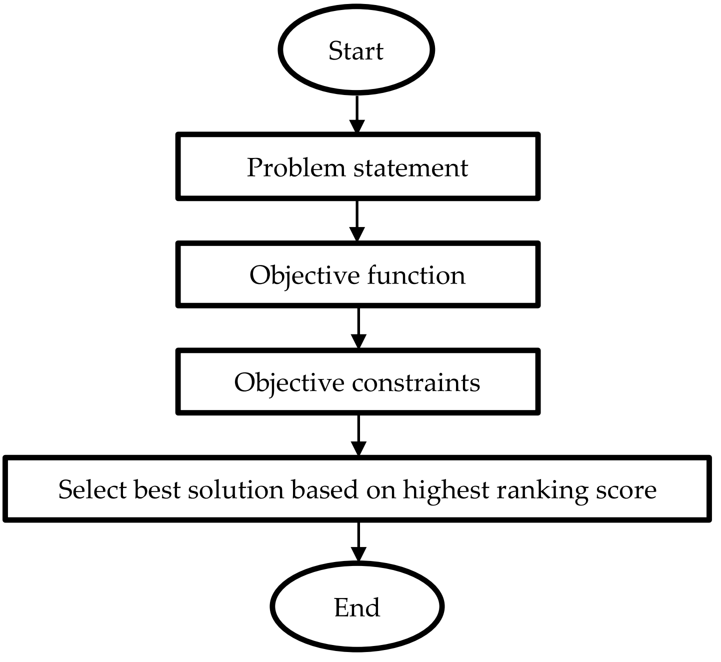

Figure 2: Material selection using CES [11]

2.3 Selection of Materials for Natural Fibre Metal Laminate

The objectives of this study is to define appropriate natural fibre and matrix for the fabrication of FMLs' fibre reinforced composite as automotive body panels with a capable, functional performance like strength and stiff, readily available and reasonable cost. In this material selection, material processing like forming or bending is not in consideration as this selection is focusing on the FML's core layering. The environmental conditions were taken into account in the determination of the suitable material for the manufacture of FML reinforced fibre composites as automotive body panels. The objective constraint involved is biodegradable. Table 1 shows the function and criteria desired for the automotive body panel.

Table 1: Design requirements for a natural FML for automotive body panels

Model	Design requirements
Function	Automotive body panel
Objective	Better performance: high strength, stiffness Lightweight, Lower price,
Constraints	Toxicity rate: Nontoxic Durability (freshwater): acceptable, excellent Biodegradable Easily available
Free variables	Shape and size of the component, choice of materials, and orientation of natural fibre reinforcement

Step 1: Problem Statement

As the number of vehicles on the roads increases, the CO2 gas emissions from fuel combustion have also steadily increased. One of the ways that has attracted the most attention towards reducing CO2 emissions is to reduce the weight of vehicles. As an alternative material, the use of natural FMLs for car body panels is expected to contribute to the weight reduction of vehicles.

Step 2: Objective Functions

The objective functions for the design of natural FMLs as automotive body panels are strength, stiffness and lightweight material at a reasonable price. Equations (1) and (2) were considered in the selection of the material [10]. Where E is Young's modulus, ρ is density, C is constant and σ is yield strength.

$$\log E = 3\log\rho + \log C \tag{1}$$

$$\log\sigma = 2\log\rho + \log C \tag{2}$$

Step 3: Objective Constraints

In determining the strength, stiffness and weight of the material, the environmental conditions also had to be taken into consideration. Therefore, the objective constraints which needed to be observed were that the material should be readily available, non-toxic, biodegradable, and have excellent durability in water.

Step 4: Implementation

The material selection requirements and constraints were applied to the CES software, and the explanations are given in the sections that follow. The process involved the selection of the natural fibre and matrix that would be used as the fibre-reinforced composite layering to fabricate the natural FML. Since the fabrication of the FMLs involved natural fibre, therefore, the maximum service temperature of the natural fibre also had to be taken into consideration. The maximum service temperature was limited to below 200°C to avoid degradation of the natural fibre and the maximum melting point of the matrix not more than 200°C.

2.3.1 Selection of Natural Fibre

The natural fibre was selected from the material universe (all materials) based on the database in the software to avoid a biased selection. As the candidates comprised all materials, the materials were limited to those that are non-toxic and biodegradable, which are the characteristics of natural fibre. With regard to dry and wet conditions, the materials needed to have acceptable and excellent durability towards the water. The type of water that was considered in the limitation stage was freshwater.

The next step was the ranking of the materials with regard to the objective functions, where the materials were ranked according to Young's modulus (E) against the density (ϱ), and the yield strength against density, respectively. The reason for charting these graphs was to find the material with the highest stiffness and strength. The material with the highest value of stiffness will be an advantage to the product design because it will not deform easily if specific forces are applied, as opposed to the yield strength.

In the next stage, the materials were sorted using the performance indices line known as the slope constraints. The materials above the line were selected as the candidate materials, while the materials below the line were those that turned grey. The logarithmic forms of the slope were expressed as straight lines, which were for Young's modulus against the density, E/ϱ, and yield strength against the density, σ/ϱ, as in Equations (1) and (2). The materials that lay above the slope line had a better performance compared to the materials below the line. The plotted graphs are shown in Figures 3 and 4.

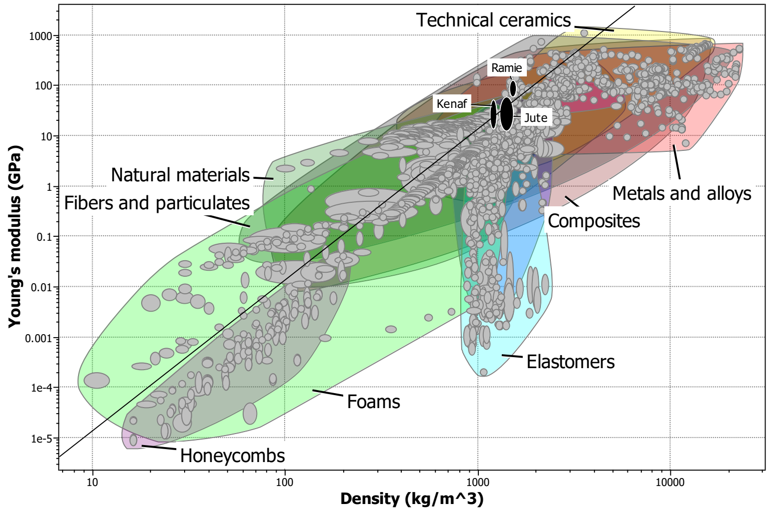

Figure 3: Young's modulus against density

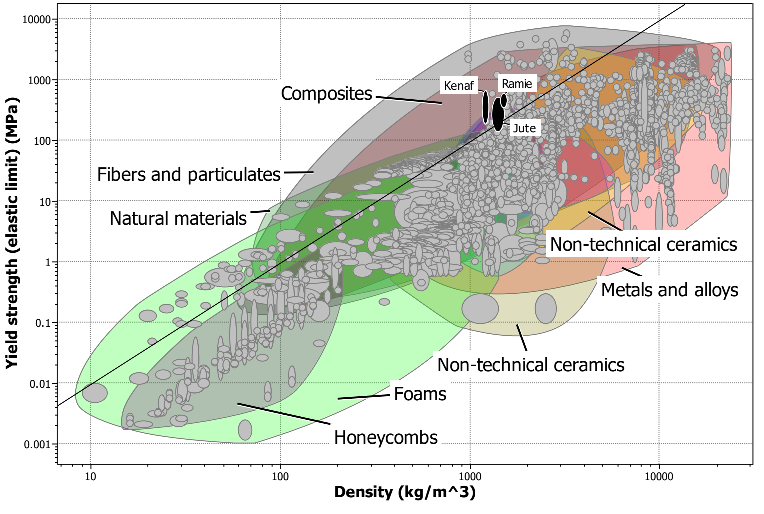

Figure 4: Yield strength against density

In order to fulfil the objective functions of a lower price but better performance, charts were plotted of the specific strength against the price, as shown in Figures 5. Based on the results, kenaf, jute, and ramie were nominated as suitable natural fibres for the fabrication of natural FMLs for automotive body panels.

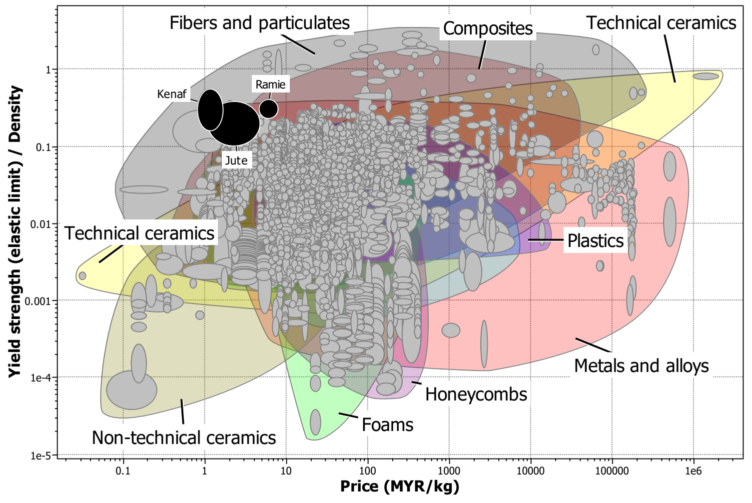

Figure 5: Specific strength against price

2.3.2 Selection of Matrix

The polymer material for the matrix was selected from the material universe in the CES database and five final candidates had passed all the screenings for an alternative matrix material. Figures 6, 7and 8 show the plotted graphs for the selection of a suitable matrix. Five candidates that passed the constraints are Polypropylene (PP) (darified/nudeated), PP (high flow), PP (low flow), Polystyrene (PS) (heat resistant), and Polylactide (PLA) (unfilled).

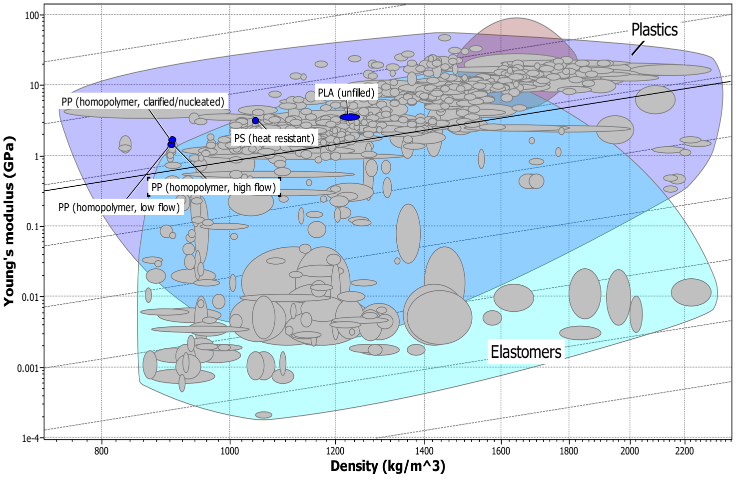

Figure 6: Young's modulus against density

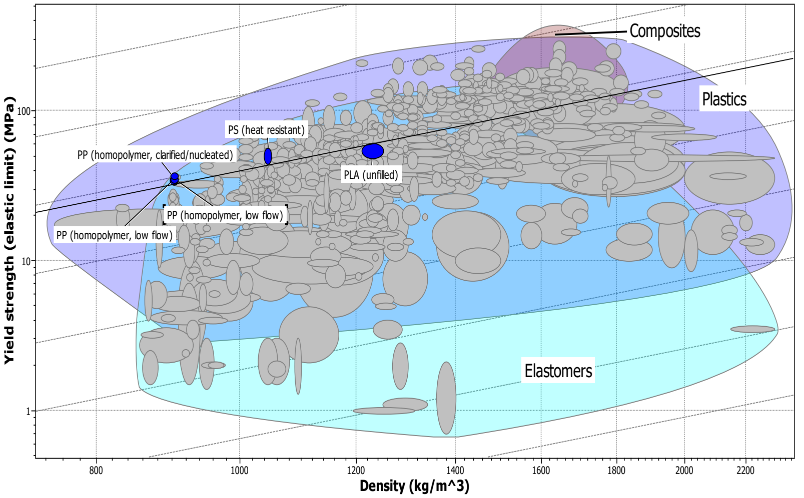

Figure 7: Yield strength against density

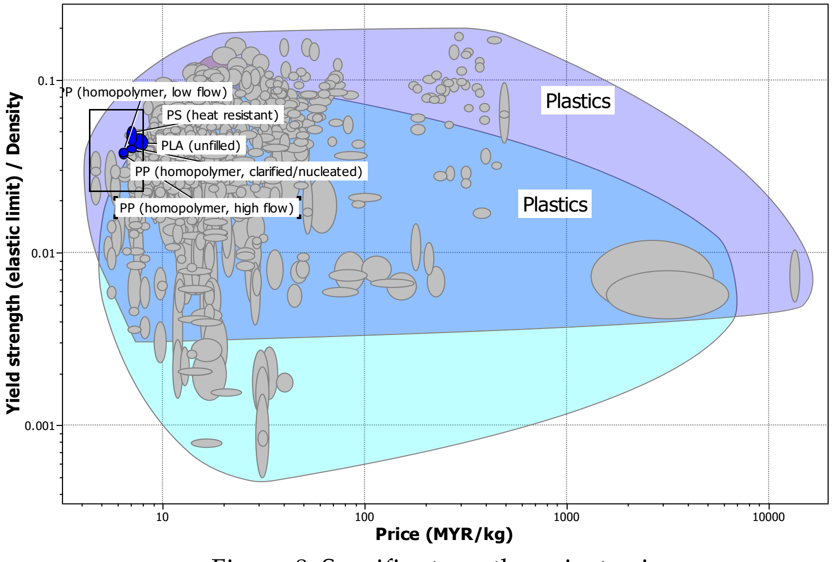

Figure 8: Specific strength against price

2.4 Comparative Approach Using Pugh Method

2.4.1 Comparison for Natural Fibre

In order to select the best material for natural FMLs, the result from the CES was used to compare it with steel using the Pugh method. The selection of materials was based on the objective functions of the natural FMLs in this study to avoid bias or randomisation. Kenaf fibre was selected as the material with the least weight, followed by jute and ramie fibre. Therefore, a positive (+) symbol was used for all the natural fibres with regard to their density. Since the stiffness and strength of natural fibres are lower than those of steel, the negative symbol was used for Young's modulus and yield strength of the natural fibres. The dry and wet conditions and environment-friendly requirement had to be taken into consideration. The candidate materials had to have acceptable and excellent durability against water and non-toxic materials. Therefore, the equal symbol was issued to all the natural fibres based on their durability and toxicity. Another important property that was taken into account in the overall selection was the price of the lightweight material that would be able to improve the performance of the FMLs. Based on the results, kenaf fibre was the cheapest material, followed by jute, steel, and ramie. Thus, a comparison using the Pugh method showed that kenaf fibre and jute fibre were suitable replacement materials, as shown in Table 2 from the data generated from the CES results.

Table 2: General properties of natural fibres for material selection

General properties	Steel	Kenaf	Jute	Ramie
Density (kg/m^3)	7800-7900	1190-1200	1300-1500	1450-1550
Price (MYR/kg)	3.8-4.18	0.811-1.61	1.09-4.68	4.68-7.79
Young's modulus (MPa)	200-221	14-53	13-60	61.4-128
Yield strength (MPa)	476-525	195-666	145-530	360-612
Durability: water (fresh)	Acceptable	Acceptable	Acceptable	Excellent
Toxicity	Non toxic	Non toxic	Non toxic	Non toxic

Table 3: Selection of natural fibre material using Pugh method

General properties	Steel	Kenaf	Jute	Ramie
Density (kg/m^3)	DATUM	+	+	+
Price (MYR/kg)		+	+	-
Young's modulus (MPa)		-	-	-
Yield strength (MPa)		-	-	-
Durability: water (fresh)		=	=	=
Toxicity		=	=	=
Total		+2	+2	+1

Indicator: = equally, + better, - lower

2.4.2 Comparison for Matrix

Based on the results from the CES software, PP (darified/nudeated), PP (high flow), PP (low flow), PS (heat resistant), and PLA (unfilled) were selected as materials for the matrix. For the lightweight material, the group of PP materials had the least weight, followed by PS and PLA. Therefore, a positive (+) symbol was used for the density of all the materials for the matrix in comparison with the datum. The stiffness and strength of the matrix against the density showed that the group of PP materials was better than the PS and PLA. However, all the candidate materials for the matrix had a lower stiffness and strength compared to the datum. Thus, the negative symbol was used for Young's modulus and yield strength, as presented in Table 5. Based on the results, the PP materials were the cheapest, followed by PS and PLA. Thus, the comparison using the Pugh method showed that all the materials could be used as a replacement for epoxy which is the current practice in FML. Hence, the utilisation of thermoplastic is beneficial in recyclability and environmental friendly.

However, according to the general properties generated from the CES results summarised in Table 4, the PLA matrix was out of the range in terms of being lightweight and with regard to the price, although it had the highest stiffness and strength, followed by PS, for the matrix. Therefore, PP matrix was more suitable due to its lightweight and lower price, which compromised its stiffness and strength as an epoxy replacement.

Table 4: General properties of material selection for matrix

General properties	Epoxy	PP (Clarified/ nudeated)	PP (High flow)	PP (Low flow)	PS (Heat resistance)	PLA (Unfilled)
Density (kg/m³)	1500-1800	900-909	898-908	899-908	1040-1050	1210-1250
Price (MYR/kg)	16.1-20.3	6.67-7.36	6.08-6.67	6.08-6.67	6.67-7.33	6.86-8.26
Young's modulus	13.8-27.6	1.6-1.78	1.37-1.58	1.34-1.59	3.1-3.34	3.45-3.83
Yield strength (MPa)	110-193	35.4-38	31.9-36.4	32.9-36.4	44.4-56.2	48-60

Table 5: Material selection for matrix using Pugh method

General properties	Epoxy	PP (Clarified/ nudeated)	PP (High flow)	PP (Low flow)	PS (Heat resistance)	PLA (Unfilled)
Density (kg/m^3)	DATUM	+	+	+	+	+
Price (MYR/kg)		+	+	+	+	+
Young's modulus (MPa)		-	-	-	-	-
Yield strength (MPa)		-	-	-	-	-
Total		+2	+2	+2	+2	+2

Indicator: = equally, + better, - lower

3.0 RESULTS AND DISCUSSION

3.1 Results for Natural Fibre

According to the summary of the general properties in Table 4, both fibres had an almost similar Young's modulus ranging between 14-53 MPa for kenaf fibre and 13-60 MPa for jute fibre. However, kenaf fibre had a yield strength of 195-666 MPa, which was better than that of jute fibre, which had a yield strength of 145-530 MPa. As the main objective of this study was the application of lightweight material; therefore, the most crucial criterion for measurement was the density. Based on the results, kenaf fibre had a lower density of 1190-1200 kg/m^3. In contrast, the density of jute fibre was 1300-1500 kg/m^3, which means that kenaf fibre fulfilled the lightweight criterion for selection as a natural fibre material for natural FMLs compared to jute fibre. Apart from that, the market price for kenaf fibre at Ringgit Malaysia (RM) 0.811 to 1.61 per kg was also lower than that of jute fibre at RM1.09 to 4.68 per kg.

Dynamic mechanical analysis done by Anuar and Zuraida [12] showed that kenaf fibre has consistent tensile and 3-point bending test and revealed that this fibre is very stiff, hence leading to higher modulus of bio composite. To enhance the properties of composites, it depends on fibre matrix interface, and this contributes to transfer stress from the matrix to the fibre. Therefore, based on the analysis, kenaf fibre was selected as a suitable natural fibre for the fabrication of natural FMLs for automotive panels, having satisfied the objective of this study. Studies have been conducted on the suitability of kenaf as the best natural fibre for an automotive application like car front hood, brake pads and parking brake lever [5, 13-14].

3.2 Results for Matrix

The Pugh method showed that all the selected materials could be used as a replacement for epoxy since the number of better improvements was equal for all the candidate materials, as shown in Table 5. However, according to the summary of the properties in Table 4, the PLA was out of the range of lightweight materials and the price consideration, although it had the highest stiffness and strength, followed by the PS matrix. Although the PS had the same price range as PP (darified/nudeated) which was RM 6.67- 7.33/kg, it was rejected because it had a higher density compared to the PP (darified/nudeated). Since PP had three nominations, therefore, each criterion played a vital part and had to be analysed. Table 4 shows that all the PP candidates had the same density range of 898-909 kg/m^3. According to the results, the PP (darified/nudeated) matrix was more suitable due to its lightweight, lower price, and compromised stiffness and strength for the epoxy replacement. Although PP (darified/nudeated) had a higher price range compared to PP (high flow) and PP (low flow), it had a better Young’s modulus (1.6-1.78 MPa) and higher yield strength (35.4-38 MPa). PP has good toughness, which is suitable for compression moulding compared to epoxy which has low toughness after curing and very prone to poor resistance to mechanical shocks and vibrations [15]. Studies have been conducted on the suitability of PP as the best natural fibre for an automotive application like the instrument panel, floor component and bumper beam [16-18].

4.0 CONCLUSION

In this study, the selection of a suitable natural fibre and matrix was identified using the CES based on the design requirements of natural FMLs for use in automotive body panels. Using the database from the software, the materials were compared with the current material, steel, as a datum in the Pugh method. Through the comparison judgement of the Pugh method, kenaf fibre and PP (darified/nudeated) were selected as suitable materials for the fabrication of natural FMLs for automotive body panels which could contribute to the reduction of vehicle weight and CO2 emissions.

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