Journal of Renewable Materials

Tech Science Press

Material Selection of a Natural Fibre Reinforced Polymer Composites using an Analytical Approach

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Abstract: Material selection has become a critical part of design for engineers, due to availability of diverse choice of materials that have similar properties and meet the product design specification. Implementation of statistical analysis alone makes it difficult to identify the ideal composition of the final composite. An integrated approach between statistical model and micromechanical model is desired. In this paper, resultant natural fibre and polymer matrix from previous study is used to estimate the mechanical properties such as density, Young's modulus and tensile strength. Four levels of fibre loading are used to compare the optimum natural fibre reinforced polymer composite (NFRPC). The result from this analytical approach revealed that kenaf/polystyrene (PS) with 40% fibre loading is the ideal composite in automotive component application. It was found that the ideal composite score is 1.156 g/cm^3, 24.2 GPa and 413.4 MPa for density, Young's modulus and tensile strength, respectively. A suggestion to increase the properties on Young's modulus are also presented. This work proves that the statistical model is well incorporated with the analytical approach to choose the correct composite to use in automotive application.

Keywords: Material selection; natural fibre reinforced polymer composites; rule of mixtures

1 Introduction

In recent years, several studies have focused on the use of 'green' material in the automotive industry. A lot of researchers have reviewed the potential of green materials to replace the synthetic materials in the automotive industry [1-3]. Koronis et al. [4] mentioned that, by using green composites, the usage of petroleum resources be reduced. It can benefit manufacturing companies, consumers and the environment [5,6]. Numerous researchers have discussed the advantages of renewable and biodegradable materials [7-9]. Asim et al. [10] highlight the availability and cost effectiveness of natural fibres which have resulted in these materials being preferred as reinforcements or filler in polymer composites. Sapuan et al. [11] confirm that a good system for sustaining natural resources can reduce the social impacts such as human rights, child growth, economic growth and community development. Kenaf, jute, hemp, sugar palm, coir, cotton,

DOI: 10.32604/jrm.2019.07691

bamboo, oil palm, pineapple leaf and banana stem are examples of natural fibres that can cooperate with polymer composite. The production of natural fibre is also increasing due to high demand from the industry [12-14]. Apart from the automotive industry, the textile, food packaging and construction industries are also the main clients that are applying the natural fibre reinforced polymer composite (NFRPC) in their products [15-17]. A good combination between natural fibre and polymer matrix can achieve a great material performance [18]. The unique characteristics of NFRPC would indicate different performances in relation to physical, mechanical, environmental and chemical properties [19-21].

Micromechanics of materials can be measured by using micromechanical properties such as mechanical and physical properties. An integrated method with a micromechanical model is used to perform the life cycle assessment [22]. In addition, micromechanical model is used to classify heterogeneous materials like composite [23,24]. Generally, many parameters influence the micromechanical properties of the composite such as fibre and matrix properties, fibre and matrix loading, size of the composite, fibre and matrix sources, interfacial adhesion between the fibre and matrix and orientation of the composite [25-31]. The most frequently used micromechanical models are rule of mixtures (ROM), rule of hybrid mixtures (ROHM), Halpin-Tsai equation and Tsai-Pagano equation. In this study, ROM is used to estimate the physical and mechanical properties. AL-Oqla et al. [9] mentioned that this model is a good approximation to predict the properties of composites. This model also can predict the unidirectional continuous fibre, random discontinuous and particulate fibre [32,33].

Therefore, to identify the suitable NFRPC is an important task for design engineers in the manufacturing process. Ashby et al. [34] mentioned that more than one material can satisfy a product design specification (PDS) because of the vast variability of the materials in the world. Design engineers should use powerful and practical material selection tools in multiple-criteria decision-making (MCDM) that can reduce the time and cost. Most of the review on MDCM tools point out the advantages and disadvantages of each method [35-37]. Each MCDM has its own strengths and limitations. For example, Jahan et al. [38] mentioned that the knowledge base system, questionnaire and computer-aided materials selection systems are the advanced screening tools used to select the final materials that can replace the traditional chart screening method. Some of the constraints of the conventional MCDM tools are: irregularities and inconsistencies in ranking of analytical hierarchy process; they do not support uncertainty in the analytic network process; they ignore the correlation between the criteria in the technique for order preferences by similarity to ideal solution; and they provide irrational results in simple additive weighting.

A recent study has proven that statistical analysis can be one of the methodologies for the MCDM technique [39]. This methodology is flexible enough to be implemented in various applications, especially in automotive component selection. Noryani et al. [36] mentioned that this numerical solution can overcome the MCDM user's judgement preference. Another issue such as biasness in final decision is formed from this subjective personal preference. Although there have been many studies on material selection of the NFRPC of automotive components such as selection of anti-roll bar, buggy bonnet, body in white, bumper beam and hand-brake parking lever parking [40-44], most of them ignore the effect of fibre loading of the materials. Therefore, it is necessary to conduct an in-depth study on ideal fibre loading of the selected final NFRPC.

The above literature review inspires the incorporation of a numerical and analytical solution using statistical analysis and a micromechanical model to identify the ideal fibre loading in automotive application. In this study, the resultant natural fibre and polymer matrix from previous study is used to verify the integration of two approaches according to PDS. Lastly, the ideal fibre loading is finalized by comparing the estimated score from ROM with different levels of fibre loading. This new combine approach can produce better results in material selection.

2 Methodology

Based on the previous study, natural fibre and polymer matrix is selected using statistical analysis. A novel statistical framework was introduced by Noryani et al. [39]. This approach proven to be one of the MCDM tool for materials selection [45,46], specifically, to identify the best composite in automotive application. Focus in this study, rule of mixtures is used to optimize the physical and mechanical properties for manufacturing purpose. The overall methodology is shown in Fig. 1.

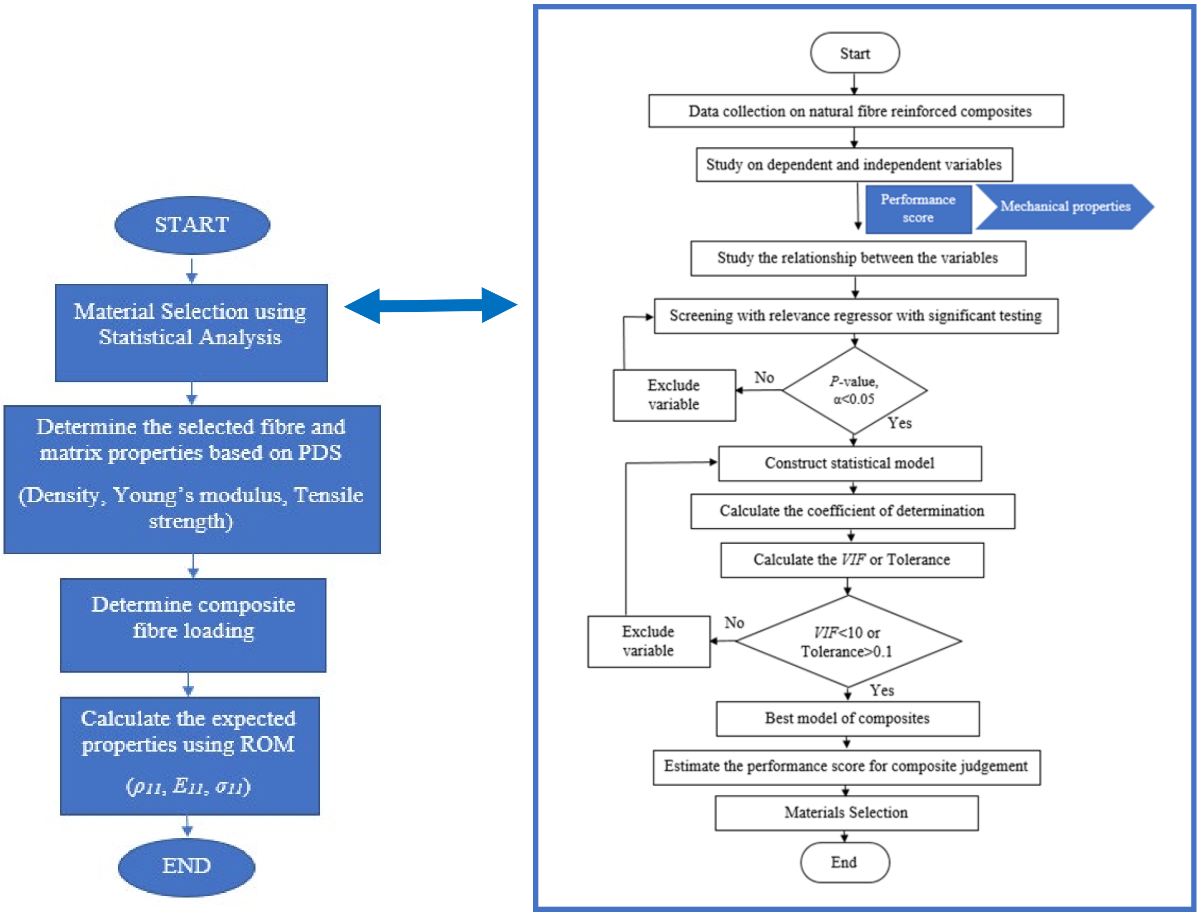

Figure 1: Overall methodology to determine final natural fibre reinforced polymer composite

2.1 Materials

A previous study found that coir, kenaf and cotton were the top three materials to manufacture a hand-brake parking lever based on the assessment toward the performance score using stepwise regression and error analysis [47]. In this study, three types of polymer matrix are used, which are polypropylene (PP), polystyrene (PS) and high-density polyethylene (HDPE), to find the suitable final composite that can optimize the PDS to manufacture a hand-brake parking lever. Eq. (1) to Eq. (3) are used to determine the performance score of this polymer.

$$y = -.879 + 1.009IS + .965E + 1.116TS \tag{1}$$

$$y = 4.945 + 1.097TS + .822E \tag{2}$$

$$y = .072 + 1.09TS + E + .999IS \tag{3}$$

where, y is the performance score, IS is impact strengths, TS is tensile strength and E is the elongation at brake.

2.2 Requirement to Manufacture a Hand-Brake Parking Lever

As shown in Fig. 2, the automotive industry should fulfil the PDS to manufacture hand-brake parking lever. Density, Young's modulus and tensile strength are the properties of the materials that involved in product design testing for hand-brake parking lever in the manufacturing process [48]. To avoid component failure during the testing, the design engineer should select the suitable materials that satisfy the requirements.

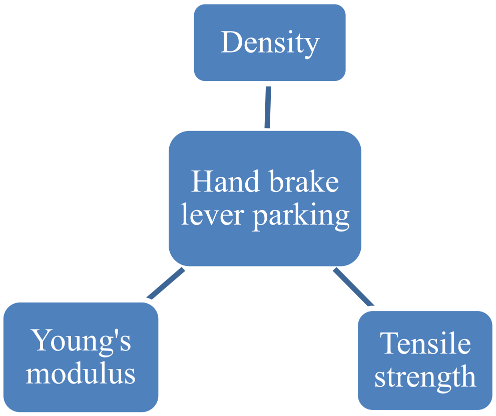

Figure 2: Product design requirement for hand-brake parking lever

2.3 Analytical Approach Using Rule of Mixtures (ROM)

The concept of Poisson's ratio applied in the ROM equation has become a common model to estimate the mechanical properties of the polymer composite micromechanical model for unidirectional continuous long fibre, random discontinuous fibre and particular fibre. This model is used to verify the final composite in this study.

Below are the assumptions when using ROM [28,32]:

1. Fibre size and properties are similar for all fibres.
2. Fibre distribution is uniform and homogenous over the whole matrix.
3. There is a good interface between the fibres and matrix.
4. Deformation of the constituents is within the elastic region.
5. No literal deformations occur.
6. Maximum tensile stress at the middle and zero at both ends of the fibre.
7. Fibre and matrix are free of voids.

To estimate the density, Young's modulus and tensile strength of a composite, Eq. (4) to Eq. (6) are used respectively:

$$\rho_c = \rho_f V_f + \rho_m \left(1 - V_f\right) \tag{4}$$

$$E_c = E_f V_f + E_m \left(1 - V_f\right) \tag{5}$$

$$\sigma_c = \sigma_f V_f + \sigma_m \left(1 - V_f\right) \tag{6}$$

where:

ρ_c = density of composite (g/cm^3)

ρ_f = density of fibre (g/cm^3)

ρ_m = density of matrix (g/cm^3)

E_c = Young's modulus of composite (GPa)

E_f = Young's modulus of fibre (GPa)

E_m = Young's modulus of matrix (GPa)

σ_c = tensile strength of composite (MPa)

σ_f = tensile strength of fibre (MPa)

σ_m = tensile strength of matrix (MPa)

V_f = fibre loading (%)

ROM is the simplest micromechanical models to estimate the mechanical properties for natural fibre reinforced polymer composite. Later, this model is used to confirm the final composite from the resultant natural fibre and polymer matrix in the previous study.

3 Case Study on Material Selection for a Hand-Brake Parking Lever

In this section, using an analytical approach, the final NFRPC is selected for hand-brake parking lever.

3.1 Problem Definition

Recently, the demand to use natural fibre in automotive applications is increasing, the annual fibre market in United State report the annual growth rate is increasing more than 20% [49,50]. The highest annual growth rate was in Europe, where it increased by 48% [51]. This demand is expected to continuously increase year by year. The replacement of conventional materials such as metal and steel by natural-based materials has a positive impact on the environment and the end-user of the product [52-54]. Thus, natural fibre reinforced polymer composite (NFRPC) has become attractive to researchers and scientists all over the world. Due to the major limitations of this material, a good composition between the fibre and matrix is the main concern in this study. The properties of NFRPC are unique because it is a combination of two materials. The properties of natural fibre itself are influenced by the origin, plant's location, plant's age, quality of the soil and parts of the plant (seed, bast, fruit, stem, wood, leaf). The geographical factors also contribute to the performance of the mechanical properties [55]. Many of the studies on material selection in automotive application ignore the composition of the materials. Their considerations are only the design criteria, environmental issues and customer requirements [40,41,56,57]. A recent study on material selection using statistical analysis used a single model to examine natural fibre and the polymer matrix [45,46]. The objective in this study is to find the ideal composition to manufacture hand-brake parking lever based on the PDS propose by the industry. It could be challenging for design engineers to select the best NFRPC with perfect composition. Therefore, both statistical model and micromechanical model are important approaches to be considered in order to produce a good automotive component for the industry.

3.2 Product Design Specification of Hand-Brake Parking Lever

In order to manufacture hand-brake parking lever, there are PDS that the automakers must fulfil. According to Petal and Sarawade [58], there are three criteria on which the manufacturer need to focus. Density, Young's modulus and tensile strength are the mechanical properties involved in this study to produce a good hand-brake parking lever. The design requirement of this component is shown in Tab. 1. This specification is from structural steel grade (S235), which is a conventional material used to manufacture the Suzuki Maruti's hand-brake parking lever. However, the properties from secondary data on previous study[45, 46] of natural fibres and polymer matrices are shown in Tab. 2.

Table 1: Material specification of the hand-brake parking lever [58]

Product Design Specification	Requirement
Tensile strength	460 MPa
Young's Modulus	200 GPa
Density	7.85 g/cm^3

Table 2: Mechanical properties of natural fibres and polymer matrices[45,46]

Natural Fibre and Polymer Matrix	Mechanical Properties		
	Density (g/cm^3)	Young's Modulus (GPa)	Tensile Strength (MPa)
Coir	1.20	9	175
Kenaf	1.20	53	930
Cotton	1.60	28	597
PP	0.92	1.80	41.4
PS	1.06	5	69
HDPE	0.97	1.5	38

3.3 Material Selection from Statistical Analysis

According to the authors' previous work [45,46], the top three potential natural fibres and polymer matrices are selected using a statistical approach. The final result is used to identify the most suitable material to manufacture a hand-brake parking lever in this study. By using a statistical framework [39], the relationship between the criteria is identify using a coefficient of correlation. The issue of multicollinearity between the criteria is eliminated at this stage. Stepwise regression provides a powerful statistical model with significant criteria to be used for estimation of the performance score of each candidate material. In summary, after considering the error on the estimation modelling, coir (1), kenaf (2) and cotton (3) are the top three natural fibres in the application. Another consideration relating to the theory of thermoplastics and thermosetting is used to select the polymer matrix. Statistical inferences such as hypothesis testing and confidence interval are implemented to sort the top polymer matrix. Therefore, polypropylene (512.48), polystyrene (509.56) and high-density polyethylene (501.47) are the optimum performance scores of the polymer matrices according to tensile strength value. Here, the previous numerical solution is compared with the analytical solution using ROM to identify the detailed volume fraction of the composite. The final NFRPC that optimizes all the PDS to manufacture the hand-brake parking lever is then selected.

3.4 Properties of Individual Natural Fibre and Polymer Matrix

Light weight material is important requirement, especially in the automotive industry because it can reduce fuel consumption in the long term and can save a lot of energy [59,60]. Cost effectiveness by using recycled and renewable material can benefit the community and industry such as the level of air pollution is decreasing by appropriate fuel consumption used and the public have a health environment. In practice, more than 50% mass saving can be achieved by using composite material compared to structural metallic material such as aluminium alloy, steel and metal [61]. In addition, the good adhesion of composites can help to reduce the mass of automotive components [62]. From Tab. 2, it is observed that coir and kenaf have a smaller value of density compared to cotton. For polymer, PP has become the polymer of preference in the industry because of the ease of handing this material compared to others [63,64]. Young's modulus measures the ability of a material to remain in length when under lengthwise tension. In other words, it is the measurement of the materials' elasticity from stress over the strain. Many studies have reported the significance of this mechanical property [47,49,65]. Young's modulus has been an important property in material selection especially in automotive applications, since 2000 [66,67]. Tab. 2 shows that kenaf and PS have the highest Young's modulus for natural fibre and polymer matrix, whilst, coir and HDPE have the lowest value of Young's modulus. Tensile strength is found to be the consistent significant mechanical property in statistical modelling constructed for 12 types of natural fibres using stepwise regression [45]. This property is frequently used as a measurement to analyze the performance of material, especially in experimental work [68-70]. Kenaf and PS exhibited the highest value of tensile strength in single performance, as shown in Tab. 2. Here, the value lies at 585 MPa and 47 MPa, respectively.

3.5 Analytical Solution of NFRPC using ROM

The density (ρ), Young's modulus (E) and tensile strength (σ) of NFRPC were determined using ROM, micromechanical models as described in the earlier section. Based on the individual properties of the natural fibres and polymer matrices in Tab. 2, the overall density, Young's modulus and tensile strength are shown in Tab. 3 by varying the fibre loadings. The volume fraction of the fibre (V_f) is between 10% to 40% and the volume fraction of the polymer matrix (1-V_f) is between 60% to 90%. Generally, there are positive linear effect on the properties of NFRPC by increasing the fibre loading of the composite.

Table 3: Predicted overall density, Young's modulus and tensile strength for NFRPC using ROM at different fibre loadings

Composite	Volume Fraction		Expected Properties		
	V_f	$1-V_f$	ρ_{11}	E_{11}	σ_{11}
Coir + PP	0.4	0.6	1.032	4.68	94.84
	0.3	0.7	1.004	3.96	81.48
	0.2	0.8	0.976	3.24	68.12
	0.1	0.9	0.948	2.52	54.76
Coir + PS	0.4	0.6	1.116	6.6	111.4
	0.3	0.7	1.102	6.2	100.8
	0.2	0.8	1.088	5.8	90.2
	0.1	0.9	1.074	5.4	79.6
Coir + HDPE	0.4	0.6	1.062	4.5	92.8
	0.3	0.7	1.039	3.75	79.1
	0.2	0.8	1.016	3	65.4
	0.1	0.9	0.993	2.25	51.7
Kenaf + PP	0.4	0.6	1.072	22.28	396.84
	0.3	0.7	1.034	17.16	307.98
	0.2	0.8	0.996	12.04	219.12
	0.1	0.9	0.958	6.92	130.26

Kenaf + PS	0.4	0.6	1.156	24.2	413.4
	0.3	0.7	1.132	19.4	327.3
	0.2	0.8	1.108	14.6	241.2
	0.1	0.9	1.084	9.8	155.1
Kenaf + HDPE	0.4	0.6	1.102	22.1	394.8
	0.3	0.7	1.069	16.95	305.6
	0.2	0.8	1.036	11.8	216.4
	0.1	0.9	1.003	6.65	127.2
Cotton + PP	0.4	0.6	1.192	12.28	263.64
	0.3	0.7	1.124	9.66	208.08
	0.2	0.8	1.056	7.04	152.52
	0.1	0.9	0.988	4.42	96.96
Cotton +PS	0.4	0.6	1.276	14.2	280.2
	0.3	0.7	1.222	11.9	227.4
	0.2	0.8	1.168	9.6	174.6
	0.1	0.9	1.114	7.3	121.8
Cotton + HDPE	0.4	0.6	1.222	12.1	261.6
	0.3	0.7	1.159	9.45	205.7
	0.2	0.8	1.096	6.8	149.8
	0.1	0.9	1.033	4.15	93.9

3.6 Final Natural Fibre Reinforced Polymer Composite for Hand-Brake Parking Lever

The predicted density, Young's modulus and tensile strength of NFRPC using ROM at different fibre loadings in the previous section are plotted in Fig. 3 to Fig. 5. Based on Fig. 3, all the combinations of the composites are below the requirement to manufacture the hand-brake parking lever, which is 7.85 g/cm^3. The highest density was cotton/PS at 40% fibre loading with 1.28 g/cm^3. In contrast, Wirawan et al. [71] reported the density of the sugarcane bagasse reinforced poly (vinyl chloride) is decrease by increasing the fibre loading. The low density of NFRPC has resulted in this material being preferred across the world, especially in the automotive and building industries [72,73]. Recent studies mentioned that the density of NFRPC is between 1.1 and 1.6 g/cm^3 [74,75]. By using NFRPC, the automotive industry can support the government regulation towards vehicle standards that was implemented in 2011 in the United States [76-78]. This Corporate Average Fuel Economy is applied for car models by year 2017 until 2025 that approved for 13 large automakers such as Ford, GM, BMW, Honda, Mazda, Toyota and Volvo. Young's modulus is an important property that can measure the strength of the materials. In order to prepare the hand-brake parking lever, 200GPa is required on the material performance. Fig. 4 shows the highest Young's modulus was kenaf/PS with 40% fibre loading. Overall, kenaf has a good performance compared to coir and cotton respectively. This is because the individual property of kenaf is higher, which is 53 GPa compared to 9 GPa and 28 GPa for coir and cotton respectively. Mansor et al. [79] also found kenaf is a suitable natural fibre that fulfils the design objectives and performance requirements to manufacturer hand-brake parking lever. However, the expected score of Young's modulus in this study is too far from the industry's requirement. Some studies have suggested to hybridizing the NFRPC with glass or carbon to increase the mechanical properties [80,81]. Most of the hybridization material can positively increase the performance of the materials [82,83]. Mansor et al. [79] verified that the hybridized material can provide a good design structure for a vehicle hand-brake parking lever. A new automatic design for hand-brake parking lever was reported by Maske et al. [84]. In addition, many treatments have been proven to increase the properties of NFRPC. Chemical treatment such as alkaline, silane, benzoylation and maleated are the common treatment used in research [85]. Sodium hydroxide and maleic anhydride grafted polypropylene are the frequent coupling agents used to improve the properties [86-88]. Moreover, fibre orientation is one of the factors that influence the properties of NFRPC [89,90]. All the treatments can not only increase the properties, and bonding between the fibre and matrix, and reduce water absorption, but can also improve the surface of the final materials for a better product finishing for marketing purposes.

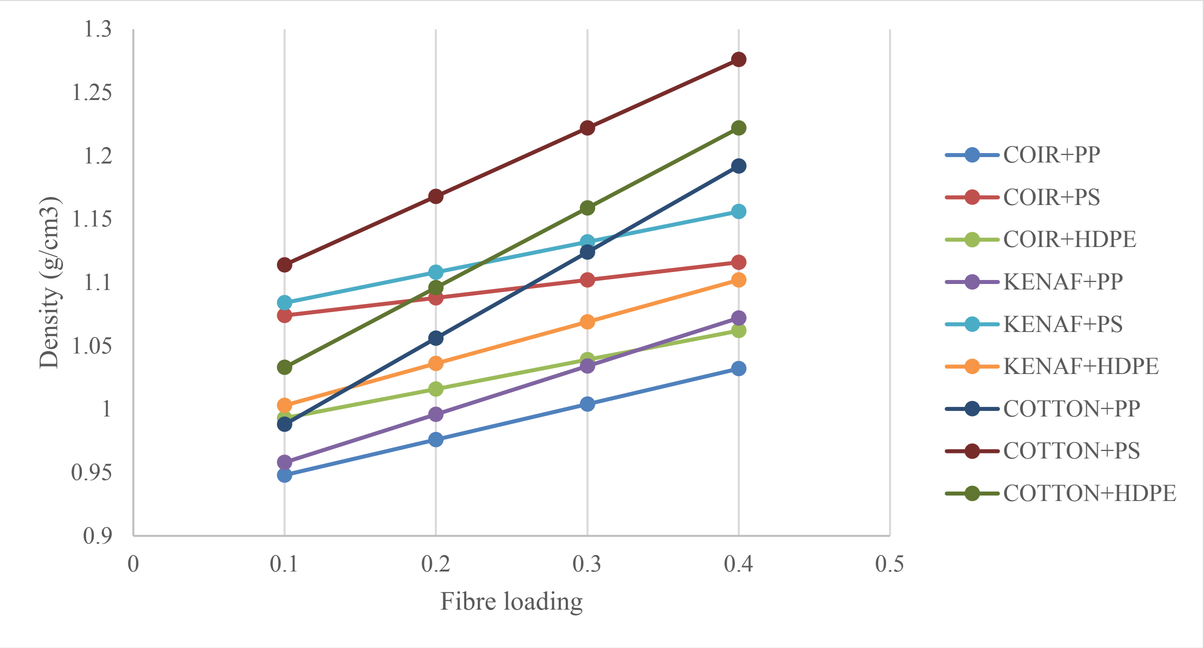

Figure 3: Prediction of density for NFRPC

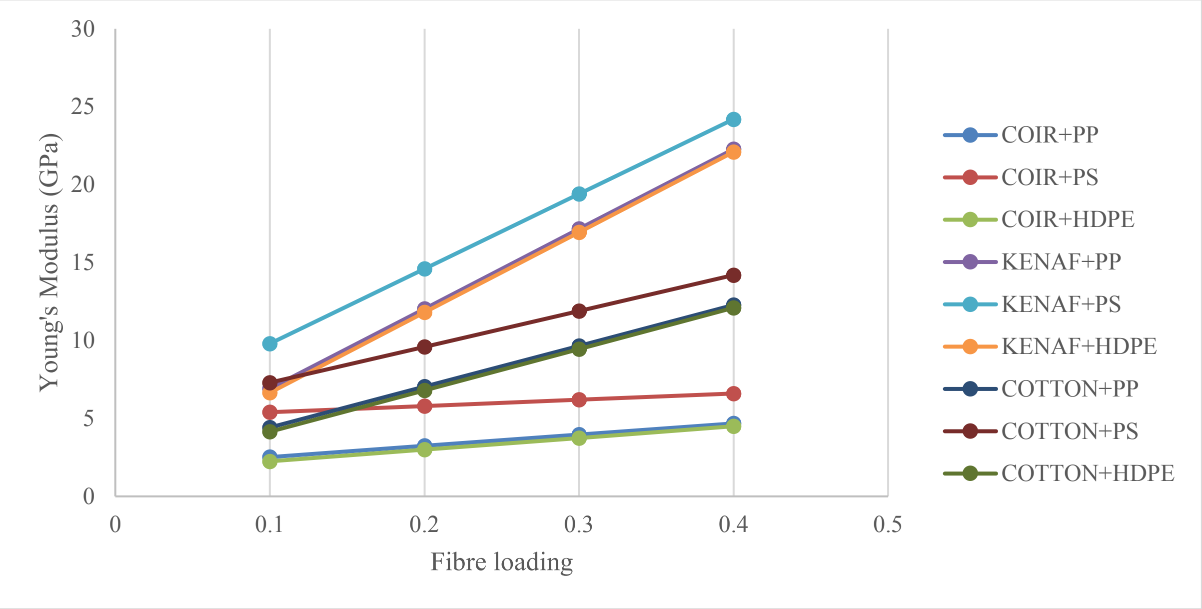

Figure 4: Prediction of Young's modulus for NFRPC

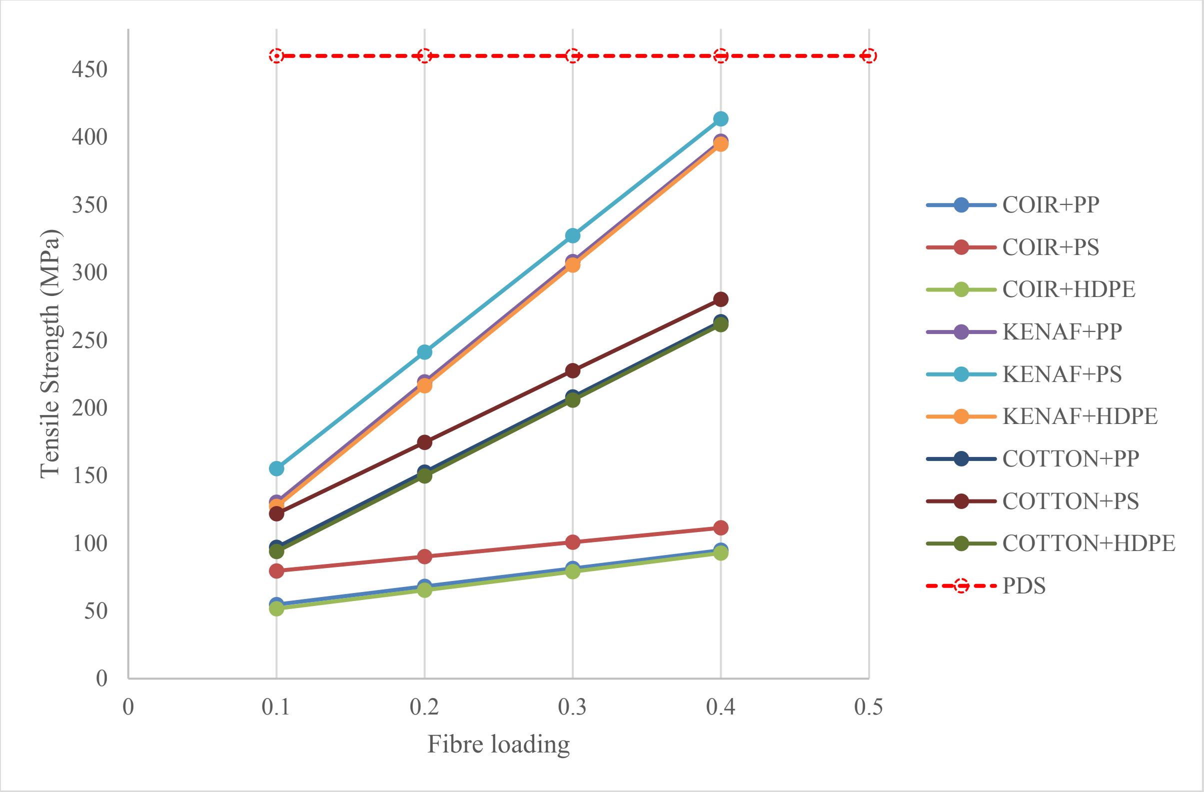

Figure 5: Prediction of tensile strength for NFRPC

In Fig. 5, the kenaf/ PS with 40% fibre loading shows a good tensile strength value, where it is close to the PDS to manufacturer hand-brake parking lever, which is 460 MPa. This composite score of 413.4 MPa of tensile strength from the estimation using ROM. Another study on hand-brake parking lever found kenaf and LDPE are the best natural fibre and polymer matrix in individual selection using an analytical hierarchy process [42,79]. Many studies have reported the increment of mechanical properties due to the addition of fibre loading to the composite. Fairuz et al. [91] studied the effect of fibre loading on the tensile, flexural and compressive properties of kenaf fibre reinforced vinyl ester. They also concluded that, at the stage of fibre loading 30-50%, the tensile, flexural and compressive properties are optimized. Another study on the impact strength of abaca fibre reinforced epoxy composites also agreed with the finding of 40% fibre loading to achieve the optimal impact strength on the composites [87,92]. Some researchers have used a constant fibre loading with different types of fibre for selection; for example, a case study of Pugh selection used 40% fibre loading of sisal, kenaf, flax, hemp, jute, coir and oil palm empty fruit [81]. It is clear that there is a good agreement on the performance of the composite at this stage of fibre loading, as many researchers have chosen the 40% fibre fraction in their experimental work [93-95]. A comprehensive review by Faruk et al. [96] on bio-composites reinforced with natural fibres for years 2000 until 2010 also showed a good interaction between the fibre and polymer at 40% fibre loading.

4 Conclusion

The predicted physical and mechanical properties of the PDS to manufacture hand-brake parking lever were successfully estimated using micromechanical modelling which is rule of mixtures. Various fibre loadings were used from the resultant natural fibre and polymer matrix value based on previous work. There are nine possible combination of the natural fibre and polymer composite with four types of fibre loading. A combination of statistical model and micromechanical model can produce the final composite with suitable fibre loading that satisfies the industry's demand. From the analysis and comparison of density, Young's modulus and tensile strength, the final composite with appropriate fibre loading that optimized the performance was selected. The kenaf/ PS with 40% fibre loading was selected as the suitable composite to manufacture hand-brake parking lever with a score of 1.156 g/cm^3, 24.2 GPa and 413.4 MPa of density, Young's modulus and tensile strength, respectively. Overall, the analytical solution can be used together with the statistical solution to select the final composite.

Acknowledgement: The authors would like to thank Universiti Putra Malaysia for the opportunity to conduct this study as well as Universiti Teknikal Malaysia Melaka and the Ministry of Education of Malaysia for providing the scholarship award and grant scheme Hi-COE (6369107) to the principal author in this project.

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