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Materials Selection of Hybrid Bio-Composites Thermoset Matrix for Automotive Bumper Beam Applicationusing Topsis Method

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ABSTRACT

Materials selection is among the fundamental process involved in automotive product development. Yet, the decision making task is very challenging considering the involvement of multiple conflicting criteria which need to be analyzed simultaneously and selected from list of candidate materials with varying attributes between them, thus multi criteria decision making (MCDM) method is often employed in solving the issue. In this paper, the TOPSIS multi criteria decision making method was applied in the materials selection process of determining the best thermoset matrix for hybrid bio-composites towards the application in automotive bumper beam. Three (3) candidate thermoset materials namely polyester, vinyl ester and epoxy matrics were analysed based on eight (8) performance criteria extracted from the pre-defined product design specification of the bumper beam component. Results from the selection exercise showed that polyester resin is the best thermoset matrix for the hybrid bio-composites construction based on the highest relative closeness to the idea solution score compared to other candidate materials. The use of TOPSIS method was also found able to provide systematic and justified decision making process in gaining the best solution when multi criteria requirement are present and need to be satisfied concurrently.

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INTRODUCTION

A bumper system is a set of components in the front and rear parts of the vehicle designed for damping the kinetic energy without any damage to the vehicle in low-speed impact and for energy dissipation in high-speed impact conditions besides serving aesthetic and aerodynamic purposes [2]. A bumper system mainly comprises three components: fascia, energy absorber, and beam. Dissipation of energy by the bumper beam can be determined both by material and structural energy absorption. The effective parameters in energy absorption of composite materials depend on type of fibre, matrix, fibre orientation, fabricating conditions, inter-laminar bond quality, and toughness.In other hand, looking at another perspective, limited petroleum resources will increase petroleum-based products' prices in the near future. It is estimated that a 25% reduction in car weight would be equivalent to saving 250 million barrels of crude oil. Thus, the utilization of low-density natural fibers towards the formulation of composite materials could lead to a weight reduction of 10–30%; therefore it is possible that manufacturers will consider expanding the use of natural fiber in their new products [3]. Moreover, the recycling concerns being driven by EU regulations (ELV) are forcing manufacturers to consider the environmental impacts of their production and possibly shift from petroleum-based to agro-based materials [4]. Henceforth, natural fiber composite offers significant opportunities for renewable, biodegradable and recyclable materials and from sustainable sources at the same time especially in automotive applications such as bumper components, interior cabin components and under-the-hoodcomponents[11].

Various studies have been conducted in implementing composites materials for automotive bumper beam design.Suddin *et al*. used the weight analysis method to select fascia for a desired vehicle [13]. Elsewhere, Sapuan *et al*. studied the conceptual design and material selection for development of a polymeric-based composite automotive bumper system[12].Apart from that, a study by Hambali *et al*. also employed the Analytical Hierarchy Process (AHP) method in concept selection of bumper beam during the conceptual design

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stage of product development [5]. In the other hand, Davoodi *et al*. are among the first to implement hybrid biocomposites (kenaf/glass fiber reinforced epoxy composites) for bumper beam component [3].

Despite the available literature reviews on bumper beam design using composite materials, it was also found that so far there is limited discussion on the selection of matrix in bumper beam design using hybrid natural fiber/glass fiber composites especially for thermoset matrix. Thus, this study was conducted to fill in the gap by systematically identifying the best thermoset matrix to be used in the hybrid composites formulation for the development of bumper beam component based on product design specifications. Acknowledging the nature of the problem which involved multiple requirements and alternatives simultaneously, multi criteria decision making (MCDM) method is often employed in solving the issue [8]. Among the available MCDM tools applied for the decision making process are VIse Kriterijumska Optimizacija Kompromisno Resenje (VIKOR), Analytic Hierarchy Process (AHP) and Technique for Order Preference by Similarity to Ideal Solution (TOPIS) methods[7,10,5,14]. In this paper, the TOPSIS MCDM method was applied in the thermoset matrix materials selection process for hybrid bio-composites towards the application in automotive bumper beam. TOPSIS is a method to identify solutions from a finite set of alternatives based on the hypothesis that the best solution is close to the positive ideal solution and far from the negative ideal solution (Khorshidi, Hassani, Rauof, & Emamy, 2013). The hybrid biocomposites consists of glass fiber and kenaf fiber as the reinforcement materials. Three (3) candidate thermoset materials namely polyester, vinyl ester and epoxy matrices were analysed based on eight (8) performance criteria extracted from the pre-defined product design specification of the bumper beam component.

Methodology:

The overall flow chart on the application of TOPSIS method in the thermoset matrix materials selection is shown in Figure 1.

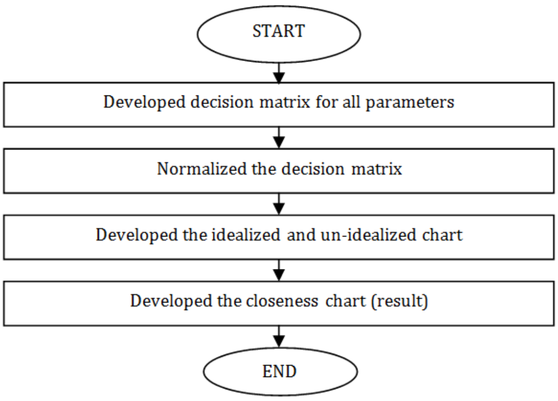

Fig. 1: Thermoset matrix materials selection flow chart [1].

Davoodi *et al*. proposed a new product design specification (PDS) for automotive bumper beam design using hybrid bio-composites which is divided into three main criteria namely design, material and manufacturing [2]. Based on their report, eight (8) sub-criteria was later defined and selected for the thermoset matrix materials selection which are tensile strength, Young modulus, elongation, compressive strength, impact strength, density, water absorption and material cost. The mechanical properties selected were to comply with the design performance main criteria, while density and water absorption properties are related to the material's weight and environment main criteria respectively. Finally, cost property is selected to represent the manufacturing cost criteria as listed in the PDS.

Apart from that, in this paper, three type of thermoset matrices typically applied for natural fiber composites was chosen as the candidate materials for the hybrid bio-composites formulation which are polyester, vinyl ester and epoxy resins [6]. Details of the individual properties for each matrix are shown in Table 1.

Finally, details of the TOPSIS method applied in performing the ranking process for the identified candidate thermoset matrices are listed below.

Step 1: The overall TOPSIS decision matrix was first formulated based on Equation (5)

$$D = \begin{matrix} & C_1 & C_2 & \cdots & C_n \\ A_1 & X_{11} & X_{12} & \cdots & X_{1n} \\ A_2 & X_{21} & X_{22} & \cdots & X_{2n} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ A_m & X_{m1} & X_{m2} & \cdots & X_{mn} \end{matrix} \qquad \text{Equation (5)}$$

where A_1, A_2, …, A_n are potential alternatives that decision makers need to select and C_1, C_2, …, C_n are criterion, which evaluated the alternative performance and was calculated, X_{ij} is the rating of alternative Ai with respect to criterion C_j when w_j is the weight of criterion C [1].

Table 1: Properties of thermoset matrices for hybrid bio-composites materials selection (Holbery & Houston, 2006)

	Polyester Resin	Vinyl Ester Resin	Epoxy Resin
Tensile strength (MPa)	40-90	69-83	35-100
Young's modulus (GPa)	2-4.5	3.1-3.8	3-6
Elongation (%)	2	4-7	1-6
Compressive strength (MPa)	90-250	100	100-200
Impact strength (J/cm)	0.15-3.2	2.5	0.3
Density (g/cm^3)	1.2-1.5	1.2-1.4	1.1-1.4
Water absorption (24h @ 20°C)	0.1-0.3	0.1	0.1-0.4
Cost	Low	Medium	High

Step 2: The normalized decision matrix was calculated using Equation (1)

$$n_{ij} = \frac{X_{ij}}{\sqrt{\sum_{j=1}^{m} X^2{}_{ij}}} \text{ where } i = 1,\ldots, m, \text{ and } j = 1,\ldots, \qquad \text{Equation (1)}$$

Step 3: The weighted normalized decision matrix was determined using Equation (2)

$$V = N_D . W_{n\times n} = \begin{vmatrix} V_{1i} & \cdots & V_{1j} & \cdots & V_{1n} \\ \vdots & & \vdots & & \vdots \\ V_{m1} & \cdots & V_{mj} & \cdots & V_{mn} \end{vmatrix} \qquad \text{Equation (2)}$$

where w_j is the weight of the ith attribute or criterion, and $\sum_{j=1}^{n} w_j = 1$

Step 4: The positive ideal and negative ideal solutions were calculated using Equation (3) and Equation (4):

$$A^+ = \left\{ \left({}^{max}_{j} v_{ij} \,;\, i \in I \right) \left({}^{min}_{j} v_{ij} \,;\, i \in J \right); i = 1, 2, \ldots, n \right\} \qquad \text{Equation (3)}$$

$$A^- = \left\{ \left({}^{min}_{j} v_{ij} \,;\, i \in I \right) \left({}^{max}_{j} v_{ij} \,;\, i \in J \right); i = 1, 2, \ldots, n \right\} \qquad \text{Equation (4)}$$

where I is associated with a benefit criterion, and J is associated with cost criterion.

Step 5: The separation measures were later calculated using the n-dimensional Euclidean distance. The separation of each alternative from the ideal solution is given as Equation (5):

$$d_{i^+} = \left\{ \sum_{j=1}^{n} \left(v_{ij} - v_{j^+} \right)^{1/2} ; i = 1, 2, \ldots, m \right\} \qquad \text{Equation (5)}$$

Similarly, the separation from the negative ideal solution is given as Equation (6)

$$d_{i^-} = \left\{ \sum_{j=1}^{n} \left(v_{ij} - v_{j^-} \right)^{1/2} ; i = 1, 2, \ldots, m \right\} \qquad \text{Equation (6)}$$

Step 6: Finally, the relative closeness to the ideal solution values for every alternatives were determined where the relative closeness of the alternative A_i with respect to A^+ is determined using Equation (7). The ranking of alternatives is finally made by ranking the preference in decreasing order based on the indices

$$cl_{i^+} = \frac{d_{i^-}}{(d_{i^+} - d_{i^-})}, 0 \le cl_{i^+} \le 1; i = 1, 2, \ldots, m \qquad \text{Equation (7)}$$

RESULTS AND DISCUSSION

The average values for all the material properties was calculated and implemented in the TOPSIS analysis. Results of the analysis performed are shown in Table 2 to Table 5 while Table 6 summarized the final rank of the candidate thermoset matrices.

Table 2: Decision matrix for selecting the best thermoset matrix.

	Tensile Strength	Modulus Young	Elongation	Compressive Strength	Impact Strength	Density	Water Absorption	Cost
WEIGHT	0.0625	0.0625	0.03125	0.03125	0.0625	0.25	0.25	0.25
Polyester	65.000	3.250	2.000	170.000	1.6750	1.350	0.200	1.000
Vinyl Ester	76.000	3.450	5.500	100.000	2.5000	1.300	0.100	2.000
Epoxy	67.500	4.500	3.500	150.000	0.3000	1.250	0.250	3.000

Table 3: Normalized matrix.

	Tensile Strength	Modulus Young	Elongation	Compressive Strength	Impact Strength	Density	Water Absorption	Cost
Polyester	0.539	0.497	0.293	0.686	0.554	0.599	0.596	0.267
Vinyl Ester	0.630	0.528	0.807	0.404	0.827	0.577	0.298	0.535
Epoxy	0.559	0.689	0.513	0.605	0.099	0.555	0.745	0.802

Table 4: Weighted normalized matrix.

	Tensile Strength	Modulus Young	Elongation	Compressive Strength	Impact Strength	Density	Water Absorption	Cost
Polyester	0.0337	0.0311	0.0092	0.0214	0.0346	0.1498	0.1491	0.0668
Vinyl Ester	0.0394	0.0330	0.0252	0.0126	0.0517	0.1443	0.0745	0.1336
Epoxy	0.0350	0.0430	0.0160	0.0189	0.0062	0.1387	0.1863	0.2004

Table 5: The positive and negative ideal solution matrix.

	Tensile Strength	Modulus Young	Elongation	Compressive Strength	Impact Strength	Density	Water Absorption	Cost
Positive ideal solution	0.0394	0.043	0.0252	0.0214	0.0517	0.1387	0.0745	0.0668
Negative ideal solution	0.0337	0.0311	0.0092	0.0126	0.0062	0.1498	0.1863	0.2004

Table 6: Overall rank of TOPSIS thermoset material selection

Matrix	Positivie ideal solution, Si*	Negative ideal solution, Si-	Relative closeness to the ideal solution, Ci*	Rank
Polyester	0.0801	0.1418	0.6392	2
Vinyl Ester	0.0684	0.1391	0.6704	1
Epoxy	0.1804	0.0188	0.0944	3
Note: Ci = (Si-)/(Si*+ Si-)*				

Based on TOPSIS results as shown in Table 6, it was observed that vinyl ester resin scored the highest relative closeness to the ideal solution value (0.6704), followed by polyester resin (0.6392) and finally epoxy (0.0944). Thus, final rank revealed that vinyl ester resin is the best thermoset resin which fulfills all the required product requirements to be used for the hybrid bio-composites towards the development of automotive bumper beam component compared to polyester and epoxy resins. The predicted preference of vinyl ester as the best candidate material can be validated based on the available data of materials properties applied in the analysis as shown in Table 2. It can be observed that vinyl ester performed better than other candidate thermoset matrices in the majority of the material specifications namely tensile strength, elongation, impact strength and water absorption despite having fair performance in term of stiffness (Young modulus), density and cost. Thus, it is expected that vinyl ester will possessed the highest overall performance compared to the other thermoset matrices. Nevertheless, similar data can also be analyzed using other MCDM method as listed previously in order to determine the consistency of the decision obtained using the TOPSIS method, thus may further increase the level of confidence gained from the exercise.

Apart from that, it should also be noted that the final rank obtained using the TOPSIS method may also be reversed if new product requirements are added in to decision criteria or the initial decision on the weight of the criteria are altered. In spite of that, the probable change in the final rank proposed due to the stated reasons also showed the advantage in term of flexibility of the TOPSIS method in adapting to changes in design which often occurs in the initial stage of product design.

Conclusions:

In conclusion, implementation of TOPSIS method in the multi criteria decision making process showed that vinyl ester resin is the best thermoset matrix to be used in the development hybrid bio-composites automotive bumper beam component. Vinyl ester scored the nearest value to the targeted ideal solution based on TOPSIS method compared to the other material candidate based on the given sets of bumper beam product design specification. The use of TOPSIS method was also found able to provide systematic and justified decision making process in gaining the best solution when multi criteria requirement are present and need to be satisfied concurrently, thus help designers to perform and complete the materials selection process towards the development of bumper beam component.

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