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Thermoplastic Matrix Material Selection using Multi Criteria Decision Making Method for Hybrid Polymer Composites

M.R. Mansor[1,2,a], S.M. Sapuan[1,4,b], E.S. Zainudin[1,4,c] , A.A. Nuraini[1,d] , and A. Hambali[3,e]

[1]Department of Mechanical and Manufacturing Engineering, Faculty of Engineering, Universiti Putra Malaysia, 43400 UPM Serdang, Selangor, Malaysia
[2]Faculty of Mechanical Engineering, Universiti Teknikal Malaysia Melaka, Hang Tuah Jaya, 76100 Durian Tunggal, Melaka, Malaysia
[3]Faculty of Manufacturing Engineering, Universiti Teknikal Malaysia Melaka, Hang Tuah Jaya, 76100 Durian Tunggal, Melaka, Malaysia
[4]Institute of Tropical Forestry & Forest Products, University Putra Malaysia, 43400 Serdang, Selangor, Malaysia
[a]muhd.ridzuan@utem.edu.my, [b]sapuan@upm.edu.my, [c]edisyam@upm.edu.my, [d]nuraini@upm.edu.my, [e]hambali@utem.edu.my

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Abstract. Multi criteria decision making (MDCM) methods are amongst the approaches available in aiding composite designers to make the final decision especially during the material selection process where multiple solutions are present and various requirements are required to be satisfied simultaneously. Thus, in this paper, material selection process of thermoplastic matrix using MDCM methods for hybrid natural fiber/glass fiber polymer composites is presented. The aim is to identify the most suitable type of thermoplastic matrix to be used in the hybrid polymer composites formulation. The Weighted Sum Method (WSM) is applied in the selection process of seven candidate thermoplastic matrix materials based on the product design specifications. The overall analysis highlights that low density polyethylene (LDPE) is the preferred matrix for the intended application based on the highest scores obtained compared to other candidate materials. A signal-to-noise (S/N) ratio analysis was further performed to validate the initial selection results where LDPE once again outperformed other candidate materials with highest S/N ratio score in the non-compensatory approach.

Introduction

Increasing awareness on sustainability nowadays has generated greater effort in incorporating environmental friendly raw materials in especially in product design applications. One of the initiatives is by utilizing natural based fiber as the reinforcement element for the construction of polymer composites and its hybrids construction [1, 2]. However, the latter type of polymer composites involving the combination of natural fiber and synthetic fiber such as glass provides more attractive cost-performance-sustainability solution especially involving semi-structural and structural applications where higher load bearing capacity is demanded [3]. One of the challenges faced in designing hybrid composites is to select the most appropriate matrix or resin to be bind together with the selected fibers hence enabling stiff and workable products to be made for the intended application. The composites matrix material selection task, despite being straightforward in term of the final goal, is actually quite overwhelming in practice for composite designers where multiple product requirements such as cost, performance and environmental conditions need to be satisfied simultaneously by the potential candidate material chosen from a wide range of matrix types with varying attributes between themselves [4].

Thus, in this project, a multi criteria decision making (MCDM) solution using Weighted Sum Method (WSM) and signal-to-noise (S/N) approach were implemented in the polymer composites design problem. The aim is to determine the best candidate material between six (6) most common synthetic thermoplastic matrix materials towards the construction of hybrid natural fiber/glass fiber polymer composites. Thermoplastic matrix provides more sustainable solution in term of recycling capability despite possessing lower mechanical strength compared to thermoset matrix counterparts, thus its potential as the matrix material for hybrid polymer composites construction is greater in condition where environmental effect is the main concern in the product design. Four (4) main criteria and seven (7) sub-criteria were involved in the decision process while the individual material properties analyzed were obtained through literature review. WSM method is implemented to determine the preferred solution from the given candidate thermoplastic materials and finally the recommended decision was validated using the S/N ratio analysis.

Research Methodology

The Weighted Sum Method is amongst the most common approaches adopted for MCDM problem sespecially in the engineering field where it create a single objective based on a group of objectives through pre-multiplying each objective with a specific weight defined by the user[5]. Gjorgiev and Cepin (2013) implemented the WSM in their new proposed selection model to find the best solution on the combined economic-environmental power dispatch problem for thermal and hydrothermal power systems [6].Zhou et al. (2013) also demonstrated the application of the WSM in the optimal design of hydrogen network for petroleum refineries. In their report, the method was applied in the selections of purification technologies as well as fuel types which satisfy both the economic efficiency demand and the environmental requirement [7].

In general, the overall score of the analyzed solutions using the WSMis determined using Eq. (1)[8]

$$Score_i = \Sigma\omega_{(performance)}.NP_{j(performance)} + \Sigma\omega_{(weight)}.NP_{j(weight)} + \Sigma\omega_{(service\ condition)}.NP_{j(service\ condition)} + \Sigma\omega_{(cost)}.NP_{j(cost)} \quad (1)$$

Where i= number of evaluated solutions, ω= weight of each criteria, and NP_j= normalized values for each properties used for the comparison. The best solution to the problem is selected based on the lowest score obtained between the compared thermoplastic matrices at the end of the analysis.

In this project, based on literature review, six (6) thermoplastic matrix commonly used in natural fiber polymer composites fabrication are selected to be analyzed which are polypropylene, low density polyethylene, high density polyethylene, and polystyrene as well as two (2) variants of polyamides namely nylon 6 and nylon 6,6.The specific properties with respect to the main criteria (performance, weight, service condition and cost) and sub-criteria (such as tensile strength, density and raw material cost) of the thermoplastic matrix applied to the material selection process in this project are listed in Table 1. On the other hand, Table 2 summarized the weight or importance for all the main criteria used in the analysis which was derived based on the designer-defined preferences.

In the material selection analysis, normalization technique is required for comparison purposes due to varying properties with varying units are presented and evaluated simultaneously. Apart from that, in the case of criteria and sub-criteria such as raw material cost, density and water absorption, the values are multiplied by '-1' after the normalization process to indicate that lower material property value are preferred for the thermoplastic matrix.

Table 1. Properties of typical thermoplastic polymers used in natural fiber polymer composites fabrication[9,10]

Matrix	Performance			Weight	Service Condition	Cost	
	Tensile strength [Mpa]	Young Modulus [Gpa]	Impact Strength [J/m]	Density [g/cm^3]	Water absorption – 24 hours [%]	Melting temperature [^{o}C]	Raw material cost [USD/lb]
PP	26-41.4	0.95-1.77	21.4-267	0.899-0.920	0.01-0.02	160-176	0.95-0.98
LDPE	40-78	0.055-0.38	>854	0.910-0.925	<0.015	105-116	1.05-1.07
HDPE	14.5-38	0.4-1.5	26.7-1068	0.94-0.96	0.01-0.2	120-140	0.89-0.91
PS	25-69	4-5	1.1	1.04-1.06	0.03-0.10	110-135	1.18-1.22
Nylon 6	43-79	2.9	42.7-160	1.12-1.14	1.3-1.8	215	2.08-2.12
Nylon 6,6	12.4-94	2.5-3.9	16-654	1.13-1.15	1.0-1.6	250-269	1.98-2.09

Note:
PP= Polypropylene, LDPE = Low Density Polyethylene, HDPE = High Density Polyethylene, PS = Polystyrene, Nylon = Polyamide

Table 2. Initial weights of different criteria categories based on the designer/decision maker's viewpoint

	Selection Main Criteria			
	Performance (PR)	Weight (WE)	Service Condition (SC)	Cost (CS)
Weight	0.25	0.25	0.25	0.25

Results and Discussion

Table 3. summarized the overall scores based on the WSMfor each thermoplastic matrix analyzed in the material selection process. Based on the analysis, low density polyethylene (LDPE) thermoplastic matrix scored the lowest overall value of 0.0506, followed by polystyrene, polypropylene, high density polyethylene, nylon 6 and nylon 6,6. The results suggest that LDPE as the best thermoplastic matrix solution which satisfied the identified set of requirements for the hybrid natural fiber/glass fiber polymer composites construction.

Table 3. Summary of Weighted Sum Method overall scores for thermoplastic matrix material selection

Matrix	Performance (PR)	Weight (WE)	Service Conditions (SC)	Cost (CS)	Total Score	Rank
	Score ($\Sigma\omega_{PR}.NP_{PR}$)	Score ($\Sigma\omega_{WE}.NP_{WE}$)	Score ($\Sigma\omega_{SC}.NP_{SC}$)	Score ($\Sigma\omega_{CS}.NP_{CS}$)		
PP	0.2168	-0.1989	-0.0019	-0.2742	-0.2582	3
LDPE	0.4860	-0.2013	-0.0029	-0.2312	0.0506	1
HDPE	0.1171	-0.2080	-0.0019	-0.2270	-0.3197	4
PS	0.3957	-0.2301	-0.0058	-0.2518	-0.0920	2
Nylon 6	0.4438	-0.2478	-0.2500	-0.4650	-0.5190	5
Nylon 6,6	0.2330	-0.2500	-0.1923	-0.4880	-0.6973	6

Note:
i) PP= Polypropylene, LDPE = Low Density Polyethylene, HDPE = High Density Polyethylene, PS = Polystyrene, Nylon = Polyamide
ii) Sample calculation: For PP matrix Performance criteria, the WSM score = ($\Sigma\omega_{PR}.NP_{PR}$) = ($\Sigma\omega_{PR}.NP_{PR\_Tensile\ Strength}$) + ($\Sigma\omega_{PR}.NP_{PR\_Young\ Modulus}$) + ($\Sigma\omega_{PR}.NP_{PR\_Impact\ Strength}$) = 0.25x(26/43) + 0.25x (0.95/4.00) + 0.25x(21.4/854)=0.2168.
Thus, the total WSM score for PP matrix is = 0.2168 + (-0.1989) + (-0.0019) + (-0.2742) = -0.2582

To further validate the suggested solution obtained from the analysis, a signal-to-noise (S/N) concept as proposed by Milani et al. is later applied [8].The S/N concept is a non-compensatory ranking preferences approach where the direct compensation as applied in the WSM can be limited among the selection criteria based on the variability, thus providing other insight of the optimal solution in the decision making process to the designers. In general, the S/N may be defined based on the inverse of coefficient of variation (CV), also known as unitized risk, where it is a normalized measure of dispersion which is found by dividing the mean value (μ) to its standard deviation value [8]. For example, for PP matrix, the S/N ratio is calculated using Eq. (2)

$$S/N_{(PP)} = \frac{\text{Average}(0.2168, -0.1989, -0.0019, -0.2742)}{\text{STD}(0.2168, -0.1989, -0.0019, -0.2742)} = -0.2935 \tag{2}$$

The overall results of the S/N ratio analysis are summarized in Table 4 where in general the largestvalue is preferred. It can be observed that LDPE again emerged with the highest S/N ratio value compared to the other thermoplastic matrix candidates. This shows that LDPE performed well in all criteria while at the same time has acceptable low variation among different categories of criteria which makes the material as the preferred thermoplastic matrix for the hybrid natural fiber/glass fiber polymer composites construction.

Table 4. Summary of signal-to-noise (S/N) ratio values for thermoplastic matrix material selection

Resin	Average, μ	Standard Deviation (STD), σ	Signal to Noise (S/N) ratio
PP	-0.0645	0.2199	-0.2935
LDPE	0.0126	0.3314	0.0382
HDPE	-0.0799	0.1663	-0.4808
PS	-0.0230	0.3005	-0.0766
Nylon 6	-0.1298	0.3957	-0.3279
Nylon 6,6	-0.1743	0.3002	-0.5807

Summary

In conclusion, material selection process using WSM revealed that low density polyethylene (LDPE) is the best thermoplastic matrix solution to be used as the matrix component for the hybrid natural fiber/glass fiber polymer composites construction in this project based on the overall score compared to other five (5) thermoplastic candidates. Further analysis using S/N approach also shows that LDPE has the largest S/N ratio value which validated the result as suggested using WSM. The WSM as well as S/N concept also proved very suitable to be applied in similar polymer composites material selection process involving multiple criteria and solution decision making scenario where both method complements each other successfully as well as providing a systematic comparison and selection method to polymer composites designers.

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