Pre-Materials Selection for Eco-Aware Lightweight Friction Material

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Abstract. In the automotive industry, non-asbestos based components, such as brake pads, have been in high demand due to environmental and human health concerns. Therefore, the purpose of this study is to design and select an alternative friction material, which is desired to eco-aware lightweight, cost effective, and non-toxic. This will be accomplished using Cambridge Engineering Selector (CES) Edupack software, embedded within an Eco-Audit Tool. The results show that Kenaf, which is a commodity plant in Malaysia, is the most suitable alternative friction material that passes all of the design stages and consumes less energy, compared to asbestos and other potential materials.

Keywords: Eco-Lightweight; Friction Materials; CES Edupack

1.0 INTRODUCTION

In order to reduce weight, there are two important methods. One of these methods is to redesign the selected parts to optimize their structure. The other method is to replace traditional materials with lightweight materials, such as aluminium alloy, polymer, or composites [1, 2]. Of these two methods, material replacement is generally more effective in achieving a lightweight than structural modification.

An automotive brake functions by converting the vehicle's kinetic energy into heat energy. The two currently used types of automotive brake friction material are semi-metallic and non-asbestos organic (NAO) [3,4]. Automotive brake friction material (i.e., for brake shoes and brake pads) is combination of several materials with unique complex compositions, that are known as binder, reinforcing fiber, filler, and friction modifier [5]. Desirable performance requirements for automotive brake friction materials include stability and a high friction coefficient (μ) (according to SAE J899a), reduced vibration (judder) and noise, environmentally friendly, resistance to heat, wear, water, and oil, does not damage the brake disc, and has the capability of being manufactured with consistency and a reasonable cost [2,4,6-7].

Although asbestos is used as a friction material, it has been proven to be a human carcinogenic. Therefore, asbestos has been banned by the Environmental Protection Agency (EPA) since 1992 [8]. Since then, the development of potential NAO materials has increased to identify a safer alternative [3, 9-15]. A major challenge for this paper is to design and select potential alternative materials that are capable of high performance, lightweight, at an acceptable price, with a low impact to the environment.

The CES Edupack^{TM} (developed by M. Ashby and co-workers at Cambridge University, UK [16]), is a software that provides a database of >3000 materials and process information that help in selecting materials and processes to meet the desired complex design requirements. The optimal potential materials can be ranked using the desirable criteria or properties that meet the design's requirement. This software is also provided with Eco-audit, which is able to calculate the embodied energy used and the CO_2 produced during five key life phases of a product (i.e., material, manufacture, transport, use, and end of life) [17]. The results produced can be used for targeted environmental impact minimizing parameters.

Thus, the aim of this paper is to select an alternative friction material, which is eco-aware lightweight, cost effective, and non-toxic using a systematic approach. This paper is structured following the basics of the CES Edupack selection material approach, with a short overview of the material's selection; design requirement; results of the preliminary material's selection; comparison of the ranked materials series, obtained via eco audit tools; and selection of the best alternative material.

2.0 MATERIAL SELECTION STEPS

Automotive brake friction materials are considered to be a key safety element of vehicles through their various roles for brake performance, such as stopping distance, pedal feel, disc wear, and brake induced vibrations [16]. Automotive friction materials are required to be strong and able to withstand the braking torque produced during high temperatures and wet or dry environmental conditions [19]. High resistance to wear is a

desirable requirement for all automotive friction material, because during the braking process, the friction material is pressed against a rotating brake disc or drum and subjected to wear [20]. If the friction material has a high wear rate, it must be changed more frequently, thus increasing the cost to maintain the performance of the vehicle. Due to kinetics and pressure, heat is produced during braking. Normal operating temperatures recorded usually range from 200-250^{0}C, and 370^{0}C was registered for the front wheel disc pads [21] of passenger cars. For a normal passenger car, typical pressure applied during braking ranged from 0 to 4MPa [22,23]. For safety, a modern brake system is designed for an exerted pressure on the pads of approximately 0-10MPa.

Developing a successful friction material requires the best balance of factors that yield acceptable performance, cost, and environmental friendliness. Friction materials were generally developed through trial and error, coupled with previous experience of the manufacturer. However, mathematical methods were suggested for evaluation and optimization, such as grey relational analysis [9] and single-criterion extension evaluation method [24]. The correct combination and composition of materials and particle sizes can enhance the tribological performance of the braking interface [25,26].

Safer alternative materials are investigated using CES Edupack software that considers the objectives of this study. The selection method summary is shown in Figure 1. Ashby and Cebon [16] described a solution to materials selection approach using the following five CES steps:

1. *Problem definition* – product characteristics
    a. Function – purpose of the product
    b. Objective of the selection – eco-aware lightweight friction materials
    c. The constraints – stage limit properties for material requirements (criteria) must be met.
2. *Objective function* – by example, to minimize weight and cost of current components, with the capability to be normally functional, with less environmental impact.
3. *Constraints* – stage limit for material selection must be met. This is normally achieved by 'performance indices' and 'attributes limit'. Performance indices for this study were derived from an equation that affects performance material properties, while attribute limits, where maximum and minimum values or properties, were filled for the overall assessment of the new design's characteristics, such as durability for water and toxicity.
4. *Implementation* – of the stage constraints requirement for material selection using CES Edupack material's selection charts. In this study, several material charts were plotted using material properties (or combinations) against each other on logarithmic axes. Performance indices and attributes were used in these charts to identify potential material candidates. Potential materials that met all of the design constraints (stage limits) were evaluated again by Eco-audit to calculate embodied energy and CO_2 footprint produced.
5. *Interpretation of the results* – Summarize materials that meet the requirements. Potential materials are ranked following the objectives, in order to select the best material.

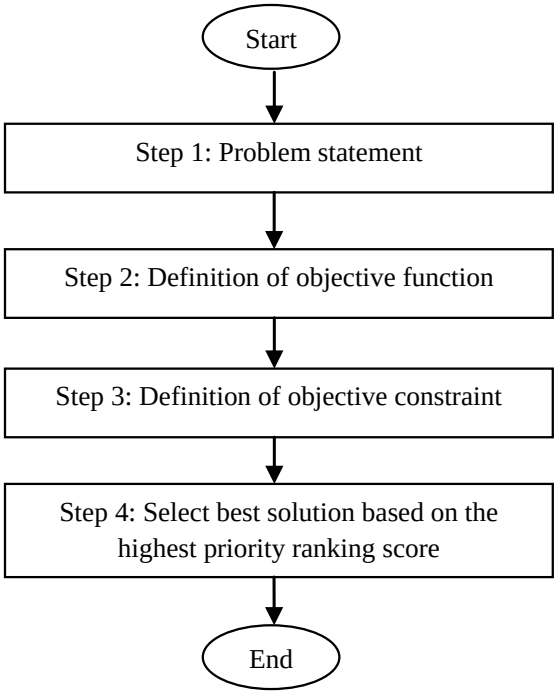


FIGURE 1. CES Methodology for material selection

3.0 MATERIAL SELECTION FOR ECO-AWARE LIGHTWEIGHT FRICTION MATERIALS

In order to illustrate the material selection approach, straight forward examples were considered. The overall selection process of new eco-aware friction materials is described as follows:

Step 1 - Problem definition.

Asbestos, proven as a human carcinogenic, production for raw materials was banned. Asbestos is a compulsory material added to automotive friction materials. In order

for a safer alternative, developing a NAO is the best solution for replacing asbestos in automotive friction materials.

Step 2 - Definition of objective function.

The objective of this project is to define eco-aware lightweight potential materials, with a capable functional performance, easily available, and at a reasonable cost, using asbestos as a datum. The alternative materials selected must be on a par or have better properties than asbestos, in order to be proven as valid alternatives.

Objective function can be described as the requirements that selected materials must meet, added to the new requirements of an eco-aware lightweight friction material for this study. For example, function stages for new eco-aware lightweight friction materials selected for this study are performance; which is identified through a review of material specifications including, weight, and standard operation performance based on SAE edge code on tribological performance, disposal, environment, and cost. Objective function and specifications for the designed eco-aware lightweight friction material are shown in Figure 2 and elaborated upon further in Table 1.

Step 3 - Definition of objective constraint.

Objective constraint is a sub-function that is considered to meet the objective (or requirements) for the product. For example, to select a material that is strong, stiff, and lightweight, several literatures suggested graphical engineering selections, such as Young's Modulus (E) against density (ρ), Yield Strength (σ) against density (ρ) plotted,

and performance indices slope (M) are included, aligned with datum by considering Equations (1) and (2);

$$\log E = 3\log \rho + \log C \quad (1)$$

$$\log \sigma = 2\log \rho + \log C \quad (2)$$

Where, E is Young's Modulus, ρ is density, and σ is yield strength. Materials that lie on the line of constant E/ρ perform equally as light and stiff; those above the line perform better, and those below, less well [16]. Figures 3 and 4 show graphical charts plotted for lightweight selection materials. In order to identify materials that are capability functional, even at high temperatures, and materials with higher maximum service, were considered. Therefore, for dry or wet conditions, excellent and acceptable durability properties against water were selected. When considering the environment, materials with toxicity properties were filtered. Considering cost, materials with lower prices were highlighted for further consideration.

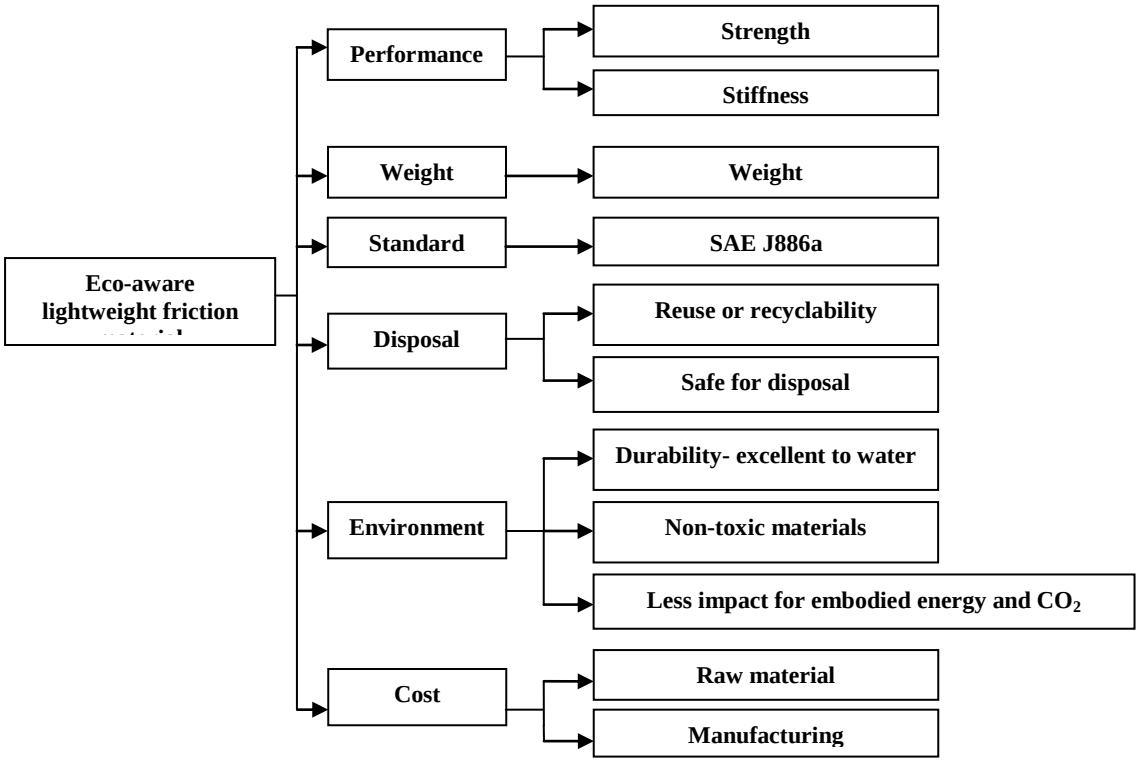


FIGURE 2. New automotive eco-aware lightweight FMs design specifications

TABLE 1. Function and criteria desired for the eco-aware lightweight friction material

Function	Criteria	Definition
Performance	i.Strength ii.Stiffness ii.Maximum working temperature v.Durability to water	Manage to tolerate or against deflect impact during braking, are important requirements for automotive brake friction material to enhance braking performance. Young's Modulus, Yield Strength, high specific heat, capability to work, even at high temperatures, wet or dry conditions, are all key performance parameters.

Lightweight	i.Density	To minimize the weight of components and maintain the required structural strength, and be safe for functional operation. Capability to reduce weight for fuel efficiency.
Product cost	i.Raw material cost	Minimize product cost and be easily available
Environmentally friendly	i.Non-toxic ii.Less energy and CO_2	For the environment and be potentially safe

Step 4 - Selection material on CES Edupack.

Selection materials constraints and requirements were applied to CES Edupack material software. During material selection, design constraints of acceptable and excellent water durability, toxicity properties, followed by raw material cost strong were selected. Then, several graphical charts were plotted with performance indices applied, in order to meet the complex multi-criteria design for the new eco-aware friction material (as shown in Figures 3 and 4). Materials that meet these specifications are shown by colour, while failed materials are either hidden or transparent. Materials that meet the requirements for strength, stiffness, and being lightweight are lie and upper on the slope and selected for further consideration.

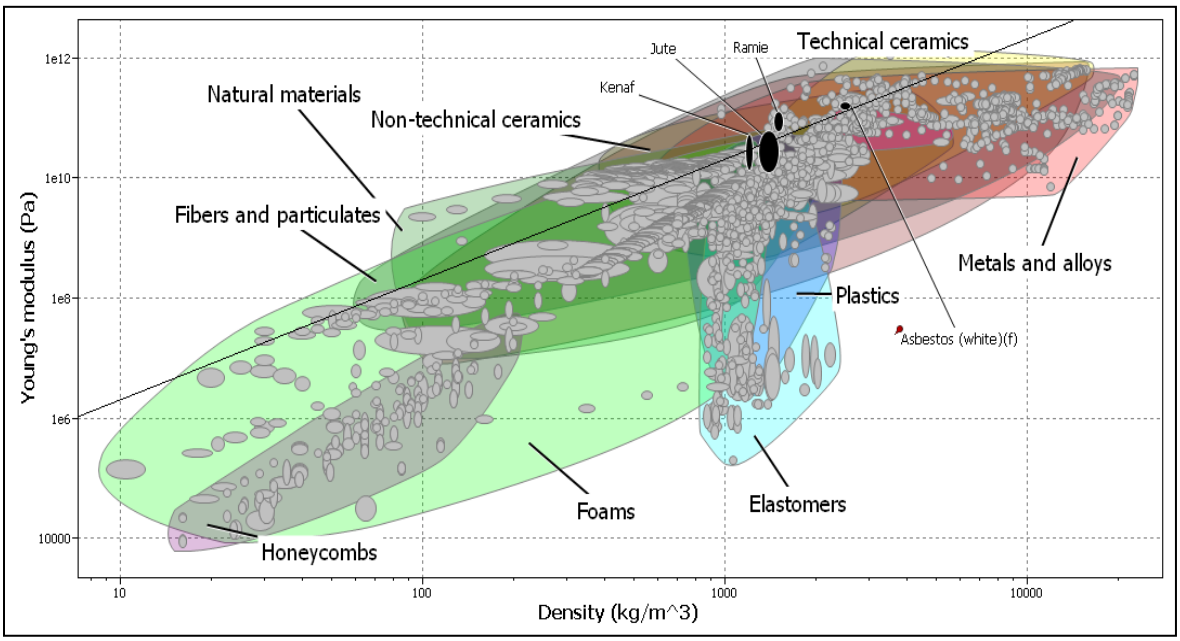


FIGURE 3. Plotted graphical material for Young's Modulus (Pa) against Density (kg/m^3)

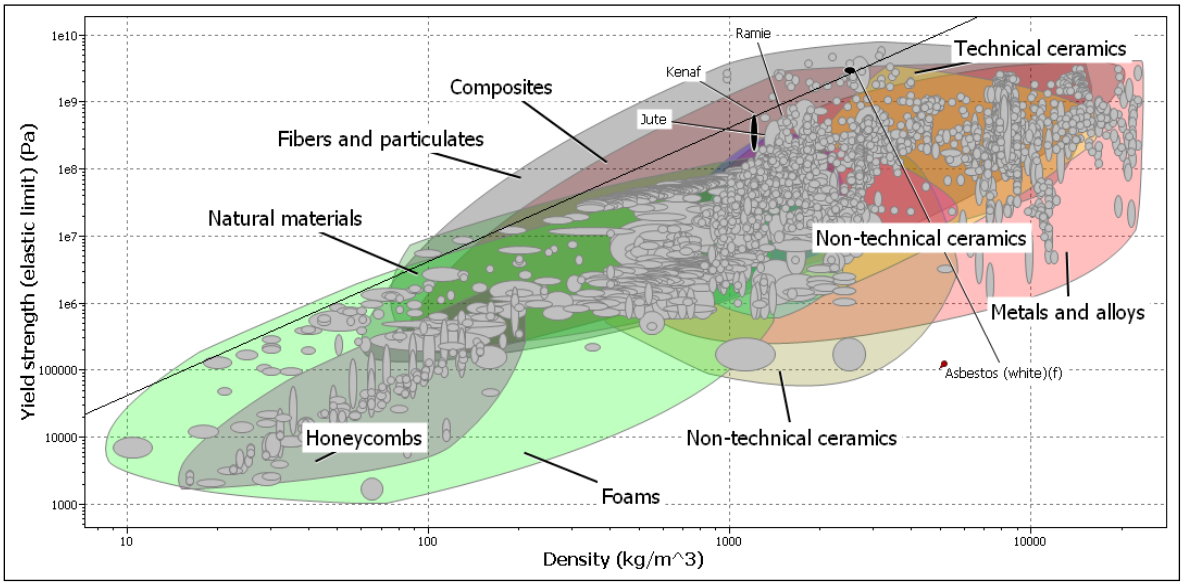


FIGURE 4. Plotted graphical material for Yield strength (Pa) against Density (kg/m^3)

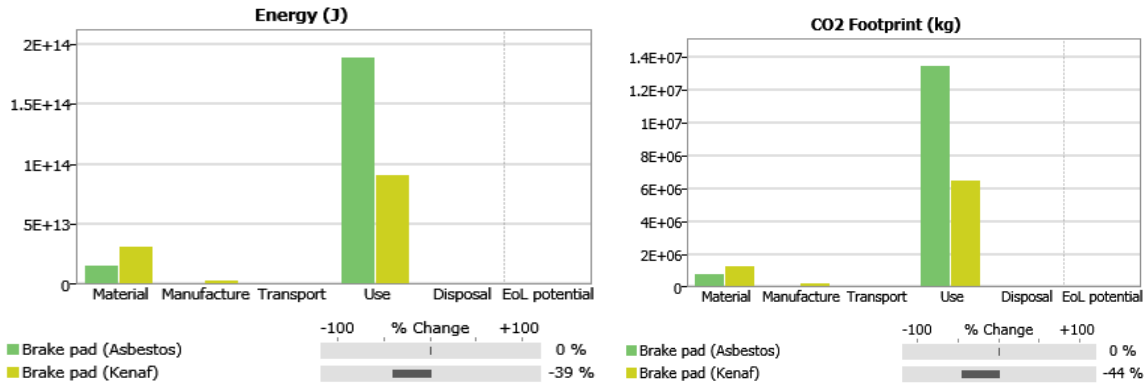
Maximum service temperature materials followed the universal properties database provided by CES Edupack, because the remaining materials were asbestos and Kenaf fibers. Summary results for all design stages are shown in Table 2.

TABLE 2. Summary results for all design stages using CES Edupack.

Stage	Attribute	Constraint	Pass
1	Toxicity rating	Non-toxic	2154
	Water (fresh)	Acceptable, Excellent	
2	Price (MYR/kg)	0.0301 to 6.57	1007
3	Young's modulus (Pa)		
	Density(kg/m^3)	≥ 3	733
	Performance index		
4	Yield strength (elastic limit) (Pa)		
	Density (kg/m^3)	≥ 2	30
	Performance index		
5	Records passing: All Stages		2

The environmental impact caused by the selected materials was assessed using environmental Life Cycle Assessment (LCA). The assessments were carried out using the Eco audit tools embedded within the CES Edupack software. Two types of input data were used. The first came from a user-entered bill of materials, process choice, transport requirements, and duty cycle. The results were used as a reference source for environmental

impacts and other information about the given material's process. Figures 5a and 5b show the comparisons for potential material's embodied energy and CO_2 footprint, which could be used to identify materials producing less impact to the environment. Materials that met these requirements were ranked for being lightweight, eco-aware constraint for the selection of new eco-aware lightweight materials to replace asbestos in automotive brake friction materials.



(a) (b)

FIGURE 5. Eco-audit results between materials for (a) energy and (b) CO_2 footprint

Based on Figures 5a and 5b, total reduction energy and CO_2 for Kenaf fibers to the environment were 39% and 44%, respectively. This proves that Kenaf fiber is a potential material, with less impact to the environment. There are four material comparison phases, namely (extraction from raw material), manufacturer (joint and process), transport (nearest supplier), use, and % changes that contain overall fractions for both materials. According to O' Hare et al. [17], the most dominant changes of energy and CO_2 can be selected; if the

gap already contains a big difference. Therefore, Kenaf was chosen as the material that had less impact to the environment.

4.0 CONCLUSION

Pre-selection for an alternative material to asbestos, to be included as an automotive friction material, was performed using CES Edupack software, based on a formulated design and its requirements. Through all of the criteria and the constraints, Kenaf fibers were identified as being the best material of all, which pass all the design requirements. This was proved using Pugh's method, where the results show a promising potential for Kenaf fibers by capability on eco-aware with reduction impact to the environment, lightest, and the cheapest.

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