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Performance and evaluation of eco-friendly brake friction materials

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ABSTRACT

Eco-friendly brake friction materials were formulated without copper, lead, tin, antimony trisulfide, and whisker materials, to minimize their potential negative environmental impacts. A combination of scanning electron microscopy with energy dispersive microanalysis, profilometry, and thermogravimetry allows successful analysis of friction surface and thermal stability of friction materials. Extension evaluation method was applied to rank the friction materials using multi-parameter criteria, including friction, wear, thermal stability, cost of raw materials, and parameters from the brake effectiveness evaluation procedure (BEEP) assessment. The eco-pad (sample E) exhibited the best overall quality, expressed as the weighted average dependent degree in extension evaluation.

1. Introduction

Commercially available automotive brake pads are roughly categorized as semi-metallic (SM), low-metallic (LM), or non-asbestos organic (NAO) materials. They are all considered to be organic friction materials since the matrix of these complex composites is formed by one or more polymers [1]. The friction materials usually contain four classes of ingredients: binders, reinforcements, friction modifiers, and fillers. Developing a successful friction material is to find the best balance among many factors yielding acceptable performance, costs, and environmental friendliness. According to the regulations against hazardous ingredients in Europe and the United States, several raw materials usually used in commercial friction materials could have a potential negative environmental impact. Components such as antimony trisulfide, copper, lead, tin, potassium titanate whisker, silicon carbide whisker, and others are often discussed [2–6]. Considering the high cost of aramid fibers and environmental concerns related to the use of copper and asbestos, natural fibers become increasingly attractive material candidates due to their high specific mechanical properties, low cost, and low environmental impact [7–10].

Friction materials were generally developed through *trial and error*, coupled with prior experience of manufacturers. Recently, some mathematical methods were suggested for evaluation and optimization of new brake materials, such as the grey relational analysis [11], fuzzy comprehensive evaluation, the combinational friction materials research method [12], and the single-criterion extension evaluation method [10]. They are not being extensively used by manufacturers, however, and remain more or less academic tools.

In this study, three eco-friendly brake samples were prepared by replacing a portion or all of the metals, aramid pulp, and antimony trisulfide with a natural fiber and a flaky titanate in a model brake lining formulation. The OEM brake pad was used as a reference to rank the newly developed eco-friendly brake pads (eco-pads). The full-scale automotive brake dynamometer and the SAE recommended J2430 procedure were used to characterize the performance of the brake samples. To understand the microstructure, topography, and chemistry of the friction layers on brake surfaces after dynamometer tests, a combination of several analytical methods was applied, including scanning electron microscopy (SEM), energy dispersive X-ray microanalysis (EDX), and profilometry. Thermogravimetric analysis (TGA) was used to determine thermal stability of the brake samples. Moreover, the extension evaluation method was applied for overall ranking of all brake pads, considering brake effectiveness, wear, cost of raw materials, and output from the brake effectiveness evaluation procedure (BEEP) assessment.

2. Experimental

2.1. Sample preparation and dynamometer tests

A list of raw materials used for formulation of brake pads and their costs are presented in Table 1. The cost of raw materials used for brake friction materials serves as a rough orientation based on information from the internet, aftermarket, and manufacturers

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Table 1
List of raw materials and their estimated costs.

Raw material	Cost ($/kg)	Trademark	Supplier
Phenolic resin	1.243	HRJ-1797	Schenectady International
Nitrile rubber powder (NBR)	1.757	BAYMOD 34.52	Lanxess
Baryte ($BaSO_4$)	0.088	325	Cimbar
Vermiculite	0.095	Multi-use Vermiculite	Schundler
Synthetic graphite	0.366	FX5014R	Superior Graphite
Resilient graphite carbon (RGC)	0.366	FXRGC14A	Superior Grpahite
Coke	0.410	4571	Asbury Carbons
Molybdenum disulfide (MoS_2)	8.195	Bem-molySF-1	Rose Mill
Antimony trisulfide (Sb_2S_3)	3.073	S.P. Grade	Anzon, Inc.
Magnesium oxide (MgO)	0.366	MG-603	Atlantic Equipment Engineers (AEE)
Potassium titanate	1.303	Fricon-P	Xinyi New-type Material Co., Ltd.
Alumina (Al_2O_3)	0.864	33,200	Alfa Aesar
Zirconium silicate ($ZrSiO_4$)	1.199	30,477	Alfa Aesar
Aramid pulp	15.000	Kevlar 29	DuPont
Natural fiber	0.586	JMM	Interfibe
Steel fiber	0.805	2106	Global Material Technologies, Inc.
Copper fiber	5.121	GCU-540	Dazheng Metal Fiber Co., Ltd.
Iron powder	0.732	P-100	Toho Zinc Co., Ltd.
Tin powder	3.657	00941	Alfa Aesar

Table 2
Formulations of investigated friction materials (content in vol%).

Function	Raw materials	Sample B	Sample C	Sample D	Sample E
Binder	Phenolic resin	36.5	36.5	36.5	36.5
	Nitrile rubber powder (NBR)	8.5	8.5	8.5	8.5
Fillers	Baryte ($BaSO_4$)	6.6	6.6	6.6	6.6
	Vermiculite	3.5	3.5	3.5	3.5
Friction modifiers	Synthetic graphite	4.8	4.8	4.8	4.8
	Resilient graphite carbon (RGC)	5.3	5.3	5.3	5.3
	Coke	16.8	16.8	16.8	14.2
	Molybdenum disulfide (MoS_2)	0.4	0.4	0.4	0.4
	Antimony trisulfide (Sb_2S_3)	1	0	0	0
	Magnesium oxide (MgO)	3.3	3.3	3.3	3.3
	Potassium titanate	0	6	6	6
	Alumina (Al_2O_3)	1.4	1.4	1.4	4
	Zirconium silicate ($ZrSiO_4$)	0.9	0.9	0.9	0.9
Reinforcement	Aramid pulp	3	3	0	0
	Natural fiber (JMM)	0	3	6	6
	Metals (steel and copper fiber, iron and tin powder)	8	0	0	0
Total		100	100	100	100
Cost ($/kg)		1.381	1.149	0.826	0.839

from all over the world. Table 2 shows formulations of individual friction materials examined in this study. In addition to sample A, which is a commercial low-metallic brake pad used as a reference with the cost of raw materials approximately 1.5$/kg, four types of brake pads were developed in four phases: (I) sample B was a model low-metallic brake pad; (II) sample C was a NAO brake pad, using a natural fiber and potassium titanate to replace the metals and antimony trisulfide in sample B; (III) sample D was prepared using 3 vol% of natural fiber to further replace the same amount of aramid pulp in sample C; and (IV) sample E was modified form of sample D, in which coke was partly replaced by alumina to improve thermal fade resistance. The brake pads were prepared by mixing (10 min, in a Littleford W-10 vertical batch mixer), molding (mold type D-748, Ford Crown Victoria), hot pressing (170 °C, 70 MPa, 20 min), post-curing (180 °C, 4 h), and machining (grinding, chamfering, and slotting). During the hot pressing, the mold was released several times to eliminate gas entrapment during curing of phenolic resin. The brake pads were tested in a full-scale single-ended inertia brake dynamometer (Model 2584, Link Engineering, Troy, MI) using the SAE recommended J2430 procedure for performance evaluation [13]. A schematic diagram of the tester is shown in Fig. 1. Commercially available original equipment cast iron discs and brake calipers were used. Furthermore, the brake effectiveness evaluation procedure (BEEP) criteria were used to assess overall performance of brake pads during the J2430 procedure test. Brake effectiveness (μ), speed, pressure, torque, and temperature were recorded during the entire test using a computer based data acquisition system. Wear was calculated from mass and thickness losses obtained from measurements before and after the J2430 test.