Research on the automotive braking performance

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Abstract. Due to the rise in vehicle usage, the number of car accidents and the population of injured users have been increasing by years. In order to reduce these problems, this paper has deeply investigated the current development of the optimization of vehicle braking performance. There are two main focuses in this paper - brake type and material selection. Firstly, in terms of brake type, the comparison of two different types, disc brake and drum brake, it is found that disc brakes are the better one regarding properties of wear rate, braking stability and performance at high temperatures. Moreover, the study on different materials shows ceramic composite materials show better performances than copper fiber materials, which are illustrated in the analysis of braking stability, abrasion resistance, and the impact on the environment. Overall, this study provides the deep understanding of the current automobile brake system, contributing to the future development of new generation of brake system.

Keywords: Braking performance; disc brake; drum brake; friction material.

1. Introduction

Since Karl Benz invented the first car in the world in 1886, more and more people have their own automobiles, and the automobile has become one of the main modes of transportation these years. Based on the statistics from the International Organization of Motor Vehicle Manufacturers (OICA), the inventory of global automobiles, which equals to previous year's inventory-depreciation in the current year+car sales in the current year, increases year by year from 2016 to 2021 as shown in Fig. 1 [1], showing that the highly demand of automobiles in temporary society. Therefore, the performance of automobiles gradually becomes the hot research topic in the automobile manufactory.

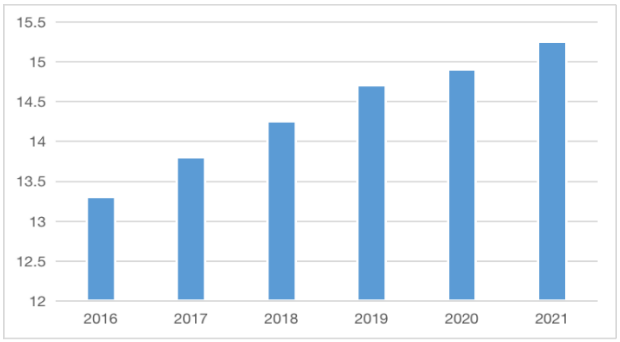


Fig 1. Global inventory of automobiles during 2016-2021 [1].

In the past few years, significant efforts have been made by researchers to develop and optimize the design of automobiles. For example, the power system is an essential part of automobiles that directly affects the driving performance, fuel economy, energy consumption, and emissions. To improve the power system, Hsiao et al. developed a thermoelectric module, consisting of a cooling system and thermoelectric generators, which shows the better performance than the radiator [2]. Besides, Taylor analyzed the effect of friction between bearings, valve trains, and pistons, providing the overall understanding of the engine tribology [3]. Another example could be seen on the design of the car body, which influences the stability, security, aesthetics, etc. To enhance the stability, Mohanty and Fatima used numerical modeling techniques to tweak and modify the design, achieving low noise and vibration levels [4]. Furthermore, to increase security, Li et al. used thinned high-strength steel sheets to make the automobile body, which decreases the weight with the same crashworthiness [5].

However, as the use of cars increased, so has the number of car accidents? Accordingly, the number of injuries and deaths increases with the high usage of automobiles. As shown in Fig. 2, the global data of deaths caused by driving increased from 1.1 million to 1.3 million during 2007-2019 [1], showing an increasing trend. Correspondingly, as shown in Fig. 3, the global number of injuries from traffic accidents also increased between 2007 and 2019 [1].

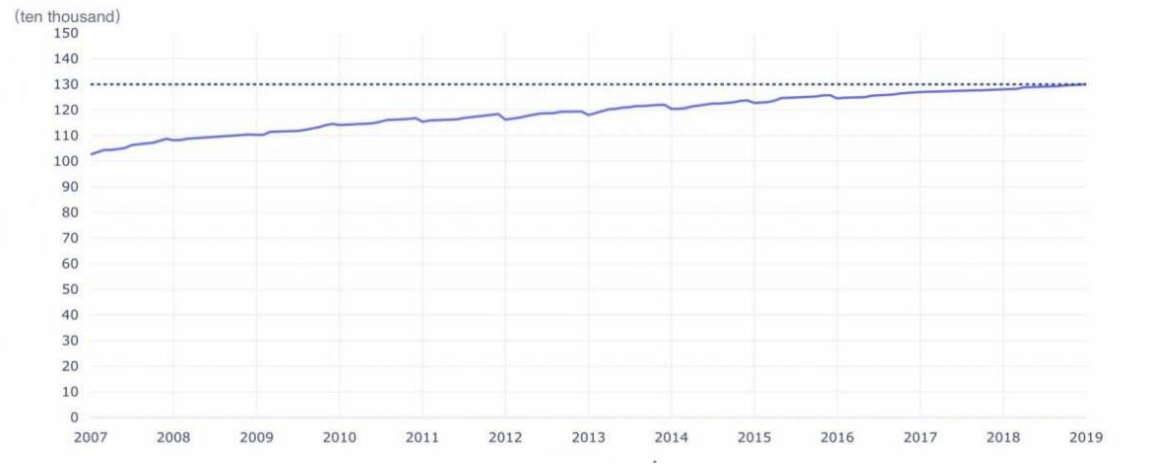


Fig 2. The annual number of deaths from traffic accidents worldwide from 2007 to 2019 [1].

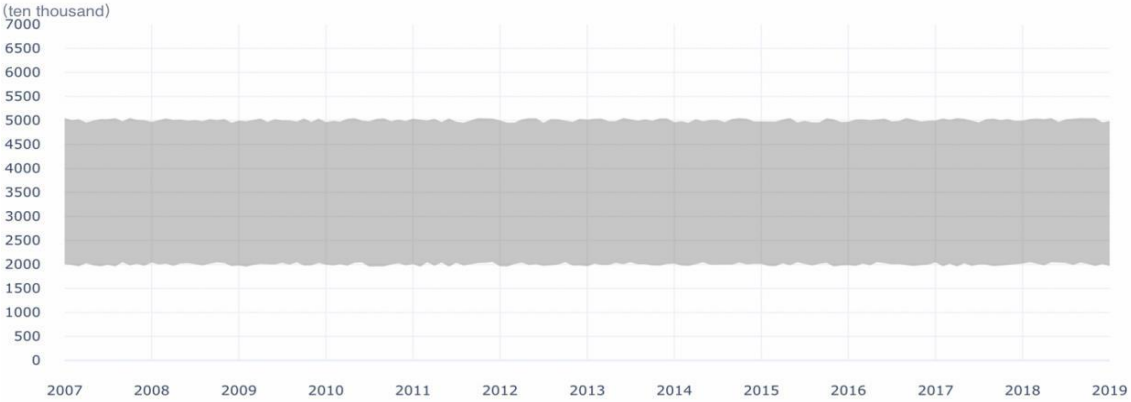


Fig 3. The annual number of injuries from traffic accidents worldwide from 2007 to 2019 [1].

The main causes of traffic accidents are speeding, distraction, bad weather, and others. However, these accidents could be efficiently avoided if a better braking system would be developed in the car. Braking performance controls the braking torque to provide a sufficient value on individual wheels to decelerate and meanwhile prevent wheels from being completely locked. A good braking performance allows automobiles to stop as quickly as possible, at same time maintaining the stability and controllability of the direction [6].

The brake system has developed over years, and the development can be divided into the following periods: mechanical braking, hydraulic braking, electromechanical and hydraulic fusion braking, and line control braking. At the beginning, when cars were lighter and traveling at low speeds, mechanical braking was used, where the driver applied force to the brakes directly through a mechanical device. However, with the development of automobiles, mechanical brakes could not meet the realistic requirements. So, hydraulic brakes were invented. As the top speed of cars continued to increase, more emphasis was placed on safety. By the 1970s, the development of digital electronic computer technology brought about a breakthrough in braking systems, with the emergence of anti-lock braking systems incorporating electromechanical and hydraulic controls. In recent years, the development of purely electric vehicles has brought about the popularity of drive-by-wire control, which converts the driver's maneuvering commands directly into electrical signals for a precise and rapid response [7].
Therefore, this research uses the method of literature collection to find a solution to optimize automotive braking performance. The research analyzes the main factors that affect braking and

determines aspects that will be further discussed and compared to get a better program. Finally, the final optimization will be determined. The aim of this research is to improve braking performance, which can effectively reduce the number of traffic accidents, contributing to a decrease in the number of deaths and injuries from traffic accidents.

2. Effects of Different Brakes

The principle of friction braking is that the kinetic energy of the vehicle is converted into heat energy by brake, thereby slowing it down. Different brakes give different results. There are two types of brakes, disc brakes and drum brakes.

2.1. Disc brake

Disc brakes have been developed since the 1890s. Disc brake is also divided into a variety of categories, such as spot-type and caliper-type [8]. Spot-type disc brakes are widely used in automobiles due to their high heat dissipation capacity and good thermal stability [9].

The spot-type disc brake consists of a rotor, caliper, brake pads, and a hydraulic system [9], as shown in Fig. 4. As for the rotor, it is rigidly mounted on the axle hub and connects the wheel to the braking system. As for the caliper, the hydraulically controlled piston is right on the caliper, which have several types, such as sliding, fixed, and floating, as shown in Fig. 4 and 5. The most obvious difference between fixed and sliding or floating calipers is that fixed calipers are rigidly mounted to the vehicle, whereas sliding calipers have mounting brackets that allow them to move laterally toward the disc. In addition, fixed calipers usually have a set of pistons that are connected to a hydraulic system to balance the driving forces, whereas sliding calipers have only one piston and need to interact with each other to balance the forces on both sides of the disc. As for the brake pad assemblies, they consist of friction material and are usually divided into inboard and outboard sections. In addition, between the padded backing plate and the piston, squeal-prevention measures, such as damping substances, are usually used. As for the hydraulic system, the device that converts the driver's version of stepping on the brake into a hydraulic signal is called the master cylinder, which is usually connected to the caliper by brake lines and hoses.

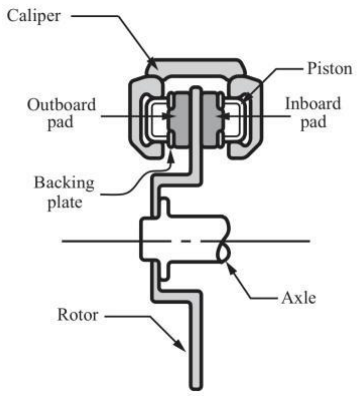


Fig 4. The cross-section part of a simplified disc brake, containing the fixed caliper [9].

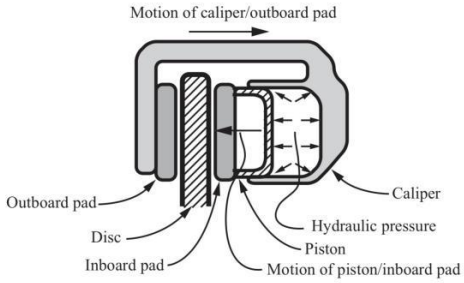


Fig 5. The cross-section part of a simplified disc brake, containing a floating caliper [9].

As discussed above, when the driver steps on the brake pedal, the hydraulic pressure in the piston increases and causes the brake pads to press against the rotor, slowing it down by friction. When the driver leaves the brake pedal free, the hydraulic pressure returns to its normal value, the brake pads move away from the rotor again, and the rotor continues to turn.

2.2. Drum Brake

In 1900, Wilhelm Maybach invented the first drum brake for automobiles [10], after which drum brakes gained more attention and been greatly developed. Depending on the mounting and operation of the brake shoes, there are five main types of drum brakes – simplex brake, duplex brake, duo duplex brake, uni-servo brake, and duo servo brake [11], which are shown in Fig. 6. All these brakes have two brake shoes. The simplex brake has the simplest construction with only one wheel cylinder. Whereas the duplex brake has 2 wheel cylinders, the duo duplex brake has a similar construction to the duplex brake but it has 2 double wheel cylinders. Also, uni-servo brakes and double-servo brakes have a similar construction in that they both have only one wheel cylinder but also have a support bearing. All these brakes make noise when turning. Of these, the simplex brake is the most used one [11].

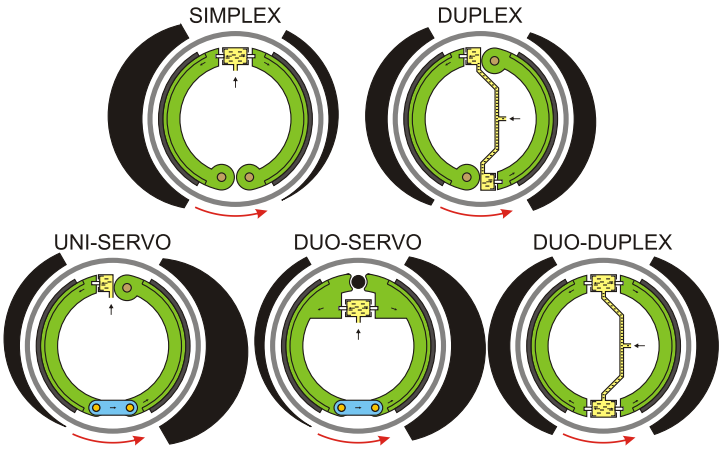


Fig 6. 5 types of drum brakes [12].

The working principle is shown in Fig. 7. The brake is attached to the wheel and rotates with it. When the driver presses on the pedal, the hydraulic pressure in the drum brake increases, the piston pushes the brake shoe outward, and the friction material on the brake lining is pressed against the brake drum and creates friction to slow down the vehicle. When keeping the brake pad free, the brake shoe returns to its original position and the wheel rotates normally.

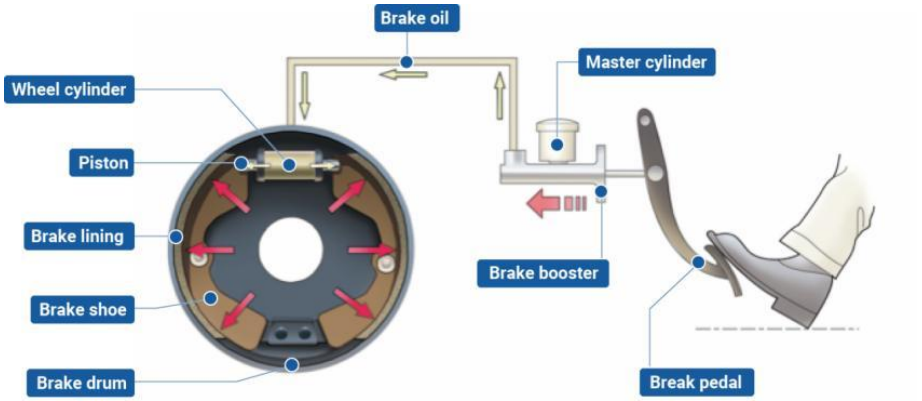


Fig 7. Working principle of drum brake [10].

2.3. Comparison of the disc brake and drum brake

To select a brake with better performances, this study will consider three aspects – braking stability, wear level, and performance at high temperatures.

Firstly, the braking coefficients of the drum brake and the disc brake made from two materials A and B, respectively, are measured under different loads, which is shown in Fig. 8. It can be concluded that the stability of both brakes made from material A is good, but the discs are still a little bit better. The stability of the disc brake made from material B is still good, but that of drum brake is not very satisfied [13].

	Material A				Material B			
	Disc Brake		Drum Brake		Disc Brake		Drum Brake	
Part of Schedule	Cold Test	Medium Duty Test	Cold Test	Medium Duty Test	Cold Test	Medium Duty Test	Cold Test	Medium Duty Test
After Bedding	0.076	0.068	0.089	0.054	0.063	0.058	0.055	0.061
After Light Duty	0.073	0.067	0.072	0.062	0.061	0.059	0.075	0.061
After Medium Duty	0.075	0.068	0.068	0.058	0.064	0.064	0.087	0.069
After Heavy Duty	0.074	0.052	0.069	0.065	0.061	0.058	0.083	0.093
After Overload Test	--	--	0.116	0.186	0.066	0.056	--	0.073

Fig 8. Brake factors of disc brake and drum brake [13].

Next, wear experiments were conducted with brakes made of material A and B, where wear represents the percentage loss of total usable thickness. It was found that the drum brakes had greater wear than the disc ones at light, medium, and heavy duties, and that the drum brakes made of material B also had greater wear than the disc brakes in the overload test. However, under the overload test, the wear of the disc brakes made of material A is much greater than that of the drum brakes, as the results shown in Fig. 9 [13].

	Material A		Material B	
Part of Schedule	Disc Brake	Drum Brake	Disc Brake	Drum Brake
Light, Medium, and Heavy Duties	3	12	3	7
Overload Test	100+	12	3	10

Fig 9. Wear of disc brake and drum brake [13].

Combined all results discussed, in terms of performance at high temperatures, drum brakes not only affect the contact between the drum and the lining and have an adverse effect, but they may also heat up causing distance from the brake shoes and increasing pedal travel. On the contrary, disc brakes are easier to dissipate heat, and high temperatures do not affect them that much [13].

Overall, the comparison of these three aspects shows that disc brakes are a better choice. They have a relatively good stability, lighter wear, and higher performance at high temperatures.

3. Effect of Different Friction Materials

Aside from the brake, the friction material is one of the main factors in determining braking effectiveness. In the past, asbestos was a popular friction material. However, studies found that the wear particles of asbestos brake pads were highly carcinogenic, and asbestos was banned by the Environmental Protection Agency in 1986[14]. Currently, there are four main types of friction materials on the market – metallic or semi-metallic, non-asbestos organic, metal matrix composite, and ceramic or carbon-carbon materials [14]. This part will mainly focus on copper fiber materials and ceramic materials and compare them in detail.

3.1. Copper fiber materials

Copper is regarded as a good friction material because of its good frictional and mechanical properties. Firstly, the experiment of Barros et al. investigates the effect of different copper contents (no copper, 10%, 30%) on braking under 100, 200, 300 °C, respectively. According to Fig. 10, it can be summarized that an increase in copper content leads to a decrease in the coefficient of friction. Fig. 11 shows that the absence or excess of copper increases the brake friction material (BFM) wear and an increase in copper content reduces the wear of the disc. These experimental results show that adding the suitable amount of copper to the friction material helps to reduce the wear of the brake [14].

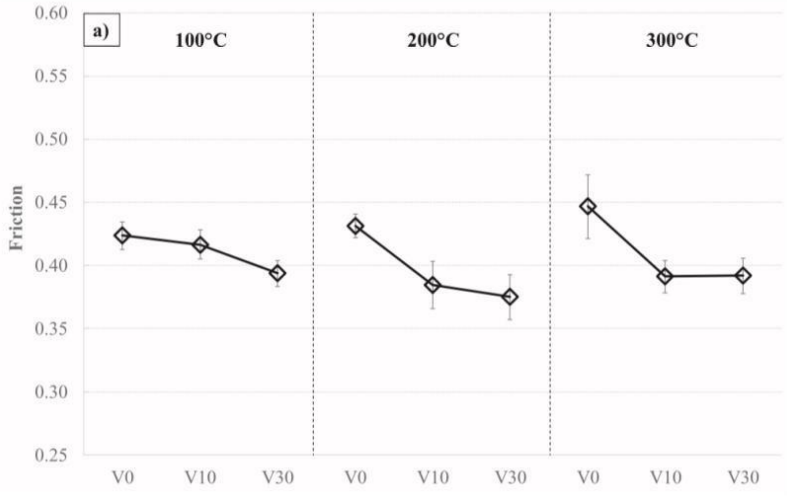


Fig 10. Mean friction coefficient [15].

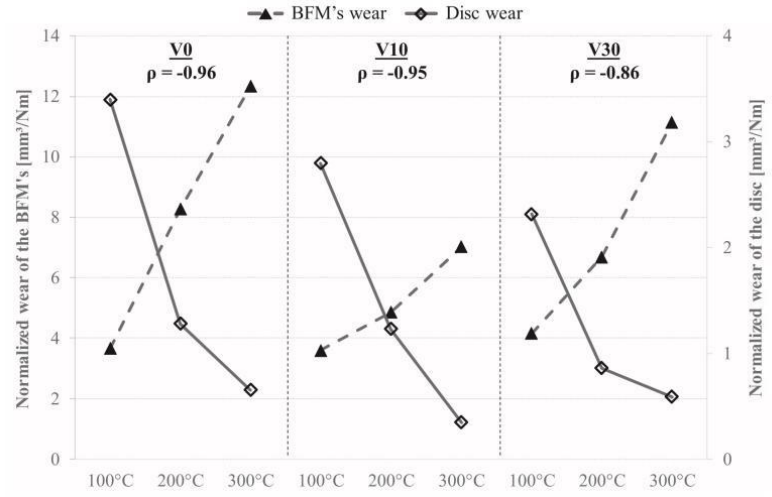


Fig 11. Mean wear of BFM and disc [15].

In addition, the experiments conducted by Osterle et al. illustrated that the addition of copper fulfils the most important characteristics of good braking performance, i.e., frictional stability and smooth sliding conditions. As shown in Fig. 12, although large particles of copper are much softer than steel fibers, copper can be strengthened due to severe plasticity changes and form nanocrystalline microstructures. Also, according to Fig. 13, copper can form soft inclusions that provide a solid lubricant effect similar to graphite, stabilizing smooth sliding [16].

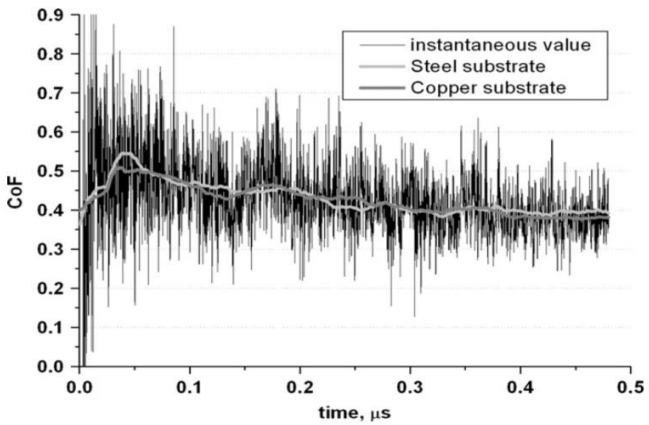


Fig. 12 Mean friction coefficients (CoF-values) of steel and copper substrate [16].

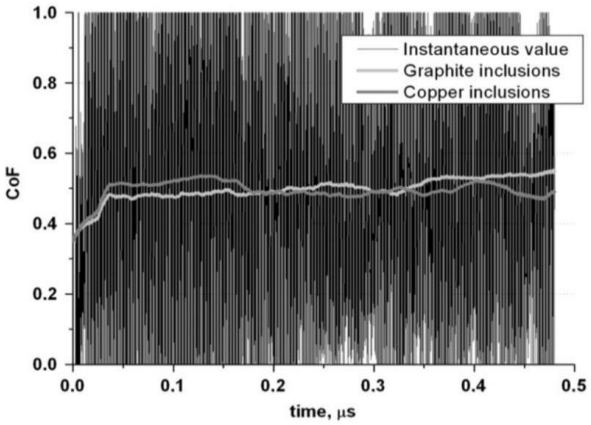


Fig 13. Mean friction coefficients (CoF-valus) of graphite and copper inclusions [16].

3.2. Ceramic composites

Ceramics are also regarded as a good friction material because of their chemical stability and high melting point. In particular of oxide ceramics, they have good hardness, wear resistance and corrosion resistance, which endow them the capacity to replace metal-based materials.

However, its biggest drawback is its brittleness. For example, it tends to fracture under mechanical and thermal shocks. So, this study will focus on ceramic composites [17]. In order to enhance the fracture toughness of the ceramics, $FeSi_2$ can be used as the addition in the material. As shown in Fig. 14, the average flexural strength and average fracture toughness of C/C-SiC increased after the addition of $FeSi_2$ [16]. Besides, in order to improve the thermal shock properties, CeO_2 can also be added. When Al_2O_3 is used as a base, it has the best thermal shock properties when the CeO_2 percentage is 2%, as shown in the Fig. 15 [17].

Composites	σ_f(MPa)	K_{IC}(MPa·m$^{0.5}$)
C/C-SiC	165 ± 30	7.9 ± 0.3
C/C-SiC-$FeSi_2$	200 ± 20	10.0 ± 2.0

Fig 14. Parameters of composites [C/C-SiC and C/C-SiC-$FeSi_2$] for flexural strength and fracture toughness, respectively [17].

CeO_2 content/%	Thermal shock times	Macroscopic changes of coating surface during thermal shock
0	45	42 times, there are small protuberances on the edge of the sample. 45 times, the protuberances are broken.
1	43	39 times, protuberances appear in the center of the sample. 40 times, the protuberances are broken. 43 times, the detachment area increases.
2	above 50	The sample is intact and a small part of the edges fall off.
5	42	40 times, the protuberances are broken. 42 times, the edges fall off.

Fig 15. The capacity of thermal shock resistance datum of different CeO_2 content-coating Al_2O_3-based ceramic [17].

Overall, composite ceramic materials are very good friction materials. By adding different ceramic substances in different proportions, it is possible to achieve a wide range of different effects to meet braking requirements.

3.3. Comparison of copper fiber materials and ceramic composites

In order to select a better friction material, this study will consider three aspects, braking stability, abrasion resistance, and the impact on the environment.

As for the braking stability, Fig. 16 shows the friction coefficients of three different friction materials with different copper contents at different temperatures. Fig. 17 shows the friction

coefficients of four different composite ceramic materials at different temperatures. We can find that the ceramic friction materials, except for F0, have a smaller change in friction coefficient with the thermal variation, which indicates that the composite ceramic material will have better braking stability than the copper fiber material.

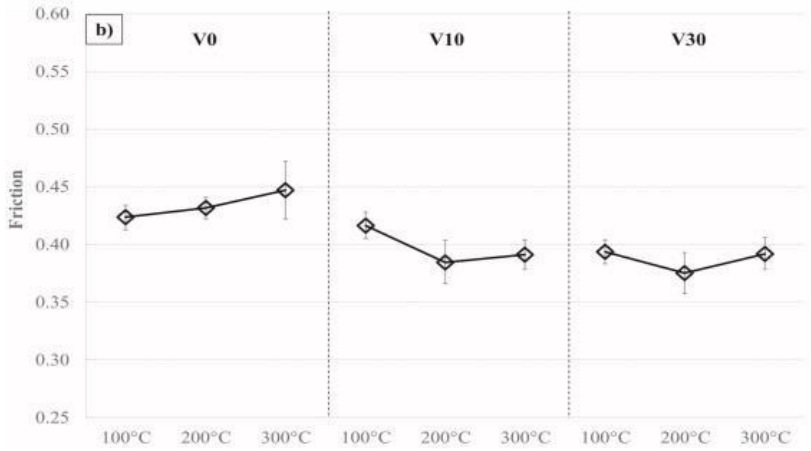


Fig 16. Mean friction of 3 copper fiber materials under different temperatures [15].

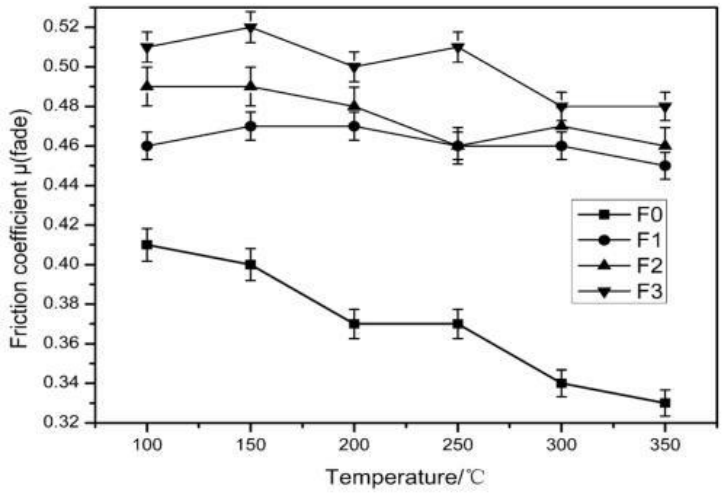


Fig 17. Mean friction of 4 ceramic composites under different temperatures [18].

As for the abrasion resistance, again using three copper-containing materials and four composite ceramic materials, as shown in the Fig. 18 and Fig. 19, we can see that the wear of both at the same temperature depends on the copper content as well as on the different ceramic materials, but is close overall.

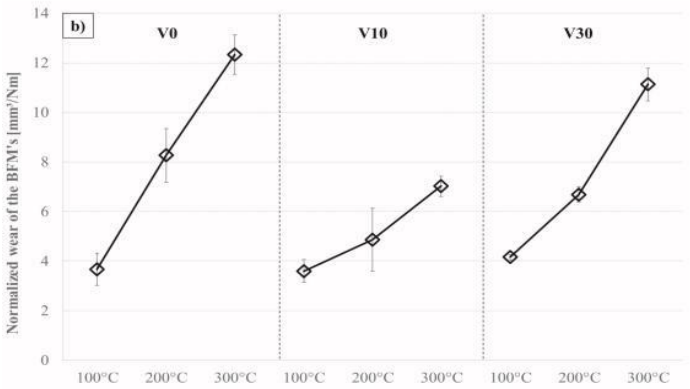


Fig 18. Wear of 3 copper fiber materials under different temperature [15].

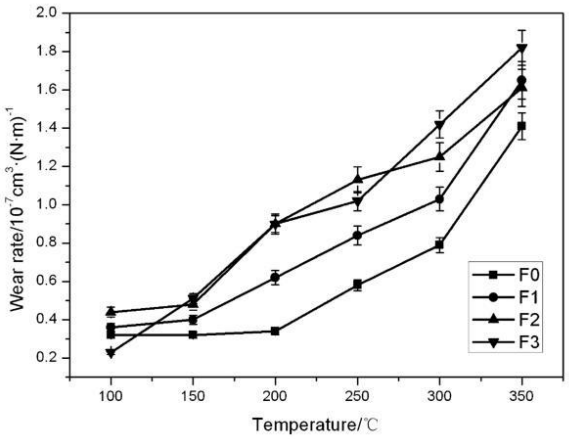


Fig 19. Wear of 4 ceramic composites under different temperature [18].

As for the impact on the environment, ceramic composites would be a better choice. The reason can be seen that ceramic materials are relatively stable and less harmful to both humans and the environment. However, copper particles are released from brake wear, which fall to the ground and are carried by rainwater into rivers, where they are eventually deposited on the bottom and posting more hazards to aquatic animals [16].

Taking all into consideration, ceramic composites are a better friction material. It has good thermal stability, wear resistance and has little impact on the environment.

4. Summary

Due to the increasing number of people using automobiles, the number of car accidents is increased. Therefore, in order to reduce the likelihood of car accidents as well as the number of casualties, this study focuses on the options to optimize the braking properties of automobiles.

Starting with the types of brakes, this paper focuses on disc brakes and drum brakes. Then, a comparison is made in terms of brake stability, wear rate, and performance at high temperatures. It is revealed that the disc brake is a better choice. Secondly, this paper investigates the effect of copper fiber materials and ceramic composites on braking performance separately. Then, they are compared from the point of view of braking stability, abrasion resistance, and the impact on the environment, and it is finally decided that ceramic composite is a better choice as a friction material.

However, this study also has some limitations. Firstly, this study did not integrate the materials and brake types to do the experiment and analyze them, so these conclusions are all relatively independent and do not exclude that there will be other influences when they are used together. In addition, because there are many different materials that can be experimented with, only two were selected for this paper to focus on and compare, so other possibilities were not considered.

Hence, in the future, each material could be tested on disc brakes and drum brakes separately and then the best combination could be developed alternatively, there could be more research focused on other brake materials.

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