**Wear Testing**

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# Tribological and thermal characteristics of copper-free brake friction composites

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**Abstract:** The effects of zinc, steel, aluminum, and brass materials that can be used instead of copper in brake friction composites on braking performance were investigated in this study. The specimens containing three different ratios of metallic shavings were produced by the dry mixing method. In terms of comparison, a total of 16 specimens were examined by producing the specimen containing copper at the same rates and the specimen containing no metallic chip. The weight loss, specific wear rate, and friction coefficient of the specimens were determined by the brake test results. The hardness and density tests were carried out. Thermal conductivity tests of the specimens were carried out to determine the thermal characteristic of copper. Among the metallic chips used, aluminum and steel wool were found to be good alternatives to copper.

**Keywords:** friction; wear; brake; copper-free; composite

## 1 Introduction

Vehicle brake pads are composites consisting of many functional materials and are called brake friction composites in the literature. These components include binders (phenolic resin, NBR, etc.), fibers (aramid, rockwool, carbon, etc.), fillers (barite, calcium carbonate, vermiculite, etc.), and frictional modifiers (cashew, graphite, copper, metal sulfides, etc.) [1]. The reason why there are many materials in the content is to obtain the multifunctionality expected from brake pads. These functions are low wear rate, steady friction, environmental friendliness, low noise, and good thermal stability [2]. The materials in the brake friction composites must be eco-friendly while providing the expected functions. For example, while asbestos improves the tribological properties of brake pads, it is prohibited because it is toxic and lung damaging. A similar situation has emerged for copper in recent decades. Since copper has a high melting point, it creates a film that increases thermal conductivity at the friction interface and provides good heat transfer. Thus, the friction coefficient of the brake pads becomes stable even at high temperatures, and tribological improvement is achieved. However, there is a risk for aquatic life of copper particles separated from the brake pad during braking. For this reason, a regulation was established in North America, limiting the copper content in the brake pads to wt.5 % or less by 2021 and to wt.0.5 % or less by 2025 [3]. The use of copper in the brake friction composites will be reduced and eventually prohibited in the next years [4]. Thus, researchers focused on studies on the material or materials that can be used instead of copper [5–23].

This study aims to investigate the effect of using four different metallic chips instead of copper in the content of brake friction composites and to investigate the thermal and tribological characteristics of the composites. The metallic chips used in the study were added to the content at three different rates and compared with those containing the same amount of copper chips.

## 2 Experimental

### 2.1 Formulation of brake friction composites

In this study, five different metallic material chips, including steel, copper, zinc, brass, and aluminum were used in three varying ratios. Brake friction composites containing eight ingredients were formed by keeping wt.55 % fixed (comprising a binder, fibers, solid lubricant, abrasive, and friction dust) as a parent composition. The balance is wt.45 % was adjusted by varying the metallic material as wt.0 %, wt.10 %, wt.15 %, and wt.20 % and compensated with barite (filler material). Sixteen different versions of brake friction composite specimens in the present work, as described in Table 1.

The parental basic materials used for the manufacturing of brake friction composites includes phenolic resin as the

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**Table 1:** Designation of brake friction composite specimens.

| | |
|---|---|
| M0 | Specimen without metallic material |
| S10 | Specimen containing wt.10 % of steel |
| S15 | Specimen containing wt.15 % of steel |
| S20 | Specimen containing wt.20 % of steel |
| C10 | Specimen containing wt.10 % of copper |
| C15 | Specimen containing wt.15 % of copper |
| C20 | Specimen containing wt.20 % of copper |
| Z10 | Specimen containing wt.10 % of zinc |
| Z15 | Specimen containing wt.15 % of zinc |
| Z20 | Specimen containing wt.20 % of zinc |
| B10 | Specimen containing wt.10 % of brass |
| B15 | Specimen containing wt.15 % of brass |
| B20 | Specimen containing wt.20 % of brass |
| A10 | Specimen containing wt.10 % of aluminum |
| A15 | Specimen containing wt.15 % of aluminum |
| A20 | Specimen containing wt.20 % of aluminum |

**Table 2:** Formulation of brake friction composite specimens (wt. %).

| Classification | Ingredient | M0 | S10<br>C10<br>Z10<br>B10<br>A10 | S15<br>C15<br>Z15<br>B15<br>A15 | S20<br>C20<br>Z20<br>B20<br>A20 |
|---|---|---|---|---|---|
| Binder | Phenolic resin | 20 | 20 | 20 | 20 |
| Fibers | Rockwool | 15 | 15 | 15 | 15 |
| | Glass fibers | | | | |
| Friction modifiers | Graphite | 20 | 20 | 20 | 20 |
| | Cashew | | | | |
| | Zircon | | | | |
| | Metallic material[a] | 0 | 10 | 15 | 20 |
| Filler material | Barite | 45 | 35 | 30 | 25 |

[a]Varying ingredient.

binder (wt.20 %), rockwool and glass fiber as fibers (wt.15 %), graphite, zircon, cashew as friction modifiers (wt.20 %). Subgroups called solid lubricant, abrasive, and friction dust belongs to the main group of friction modifiers. The formulated brake friction composites compositions are listed in Table 2. The five ingredients (metallic materials) subjected to research were varied and the rest of the others were kept constant. All ingredients were obtained from local raw material suppliers.

## 2.2 Development of brake friction composites

Conventional routes have been taken to make brake friction composites including dry mixing, pre-forming, and hot pressing. To ensure macroscopic homogeneity, mixing was done by shaking for 10 min in a chamber. Optimum production parameters such as mixing chamber, mixing time, and shaking shape were determined based on the authors' previous studies [24–28]. Then, the mixture was placed in a four-column hydraulic machine. The mold cavity was filled with the mixture and pre-forming in a compression molding machine under a pressure of 8 MPa for 2 min. After pre-forming the hot-pressing was done at 150 °C for 10 min at 13 MPa. Two intermittent breathings were provided to allow the volatiles to be expelled during hot-pressing initiation. Finally, the surface of the brake friction composites was smoothed with sandpaper.

## 2.3 Characterization of brake friction composites

The density of brake friction composites was measured according to the Archimedes principle using a computerized density measuring device with a 0.01 g cm$^{-3}$ precision.

The hardness of brake friction composites was calculated using a Rockwell hardness machine the L scale intender having 6.35 mm diameter. Gradual load of 600 N was applied. The procedure was done at five points and the average result was reported.

The thermal conductivity of brake friction composites was measured using a C-Therm TCi thermal conductivity analyzer. Each case was measured five times, after which the results were averaged.

The brake friction composites employed in this study were produced into a cylindrical shape with diameter of 2.54 mm to be used as specimens in the laboratory-scale brake friction tester. Figure 1 shows a photograph and a

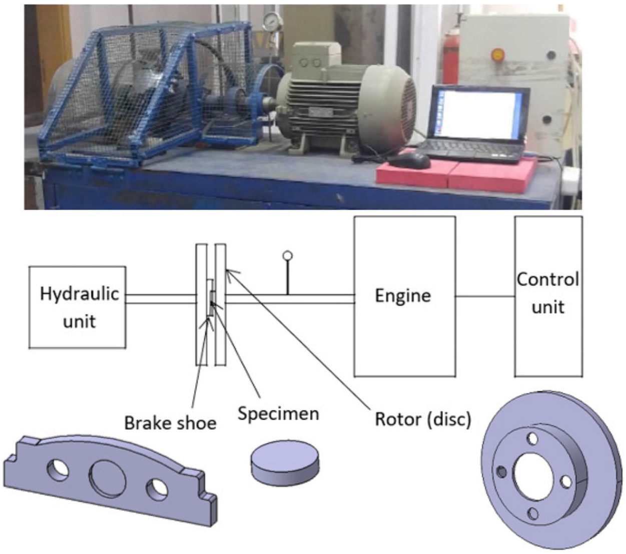

**Figure 1:** Laboratory-scale brake friction tester.

scheme of the laboratory-scale brake friction tester, the geometry of the disc made of gray cast iron, and the specimens used in this study. The laboratory-scale brake friction tester allows the recording of normal force, braking torque, rotor speed, temperature of the disc, and friction coefficient recorded every second. The technical specifications and more details about the functions of the brake friction tester are found in [24, 25].

The wear of the brake friction composites was measured through mass loss, by subtracting the mass of each specimen before and after the braking tests. For this purpose, an electronic balance with precision of ± 0.001 mg was used for weighing the brake friction composites. Thus, the specific wear rate of brake friction composites was determined by Equation (1) [29]:

$$V = \frac{1}{2 \cdot \pi \cdot R} \cdot \frac{1}{n} \cdot \frac{W_1 - W_2}{f_\mathrm{m} \cdot \rho} \tag{1}$$

with $V$: specific wear rate ($\mathrm{cm^3\,Nm^{-1}}$), $W_1$: mass of the specimen before the (g), $W_2$: mass of the specimen after the test (g), $R$: distance between the center of the specimen and the axis of rotation of the disc (m), $n$: total number of rotations of

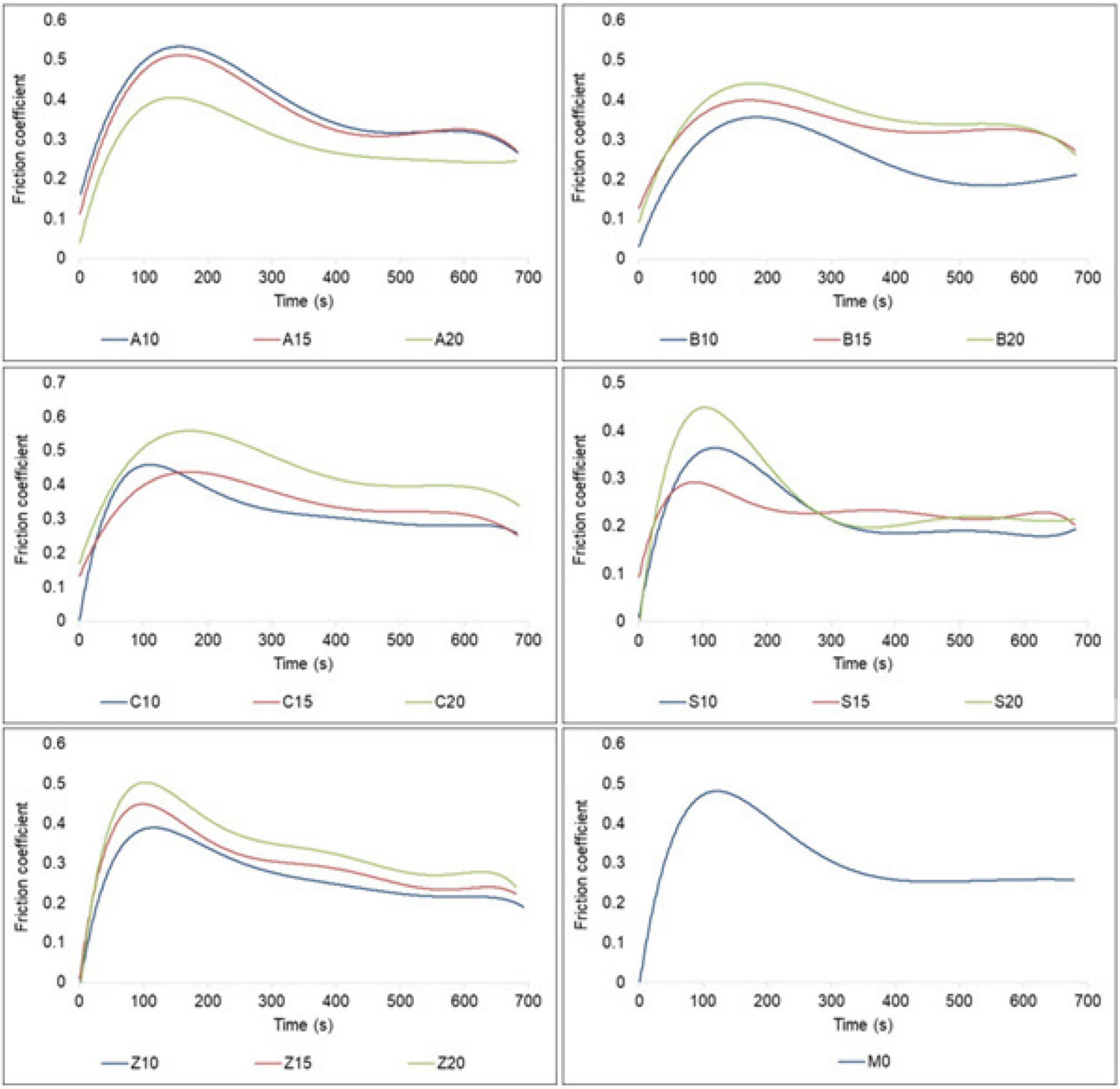

**Figure 2:** Braking time versus the friction coefficient graph for brake friction composites.

the disc during the braking test, $f_m$: total average friction force over the test period (average friction force over total friction distance) ($N$) and $\rho$: density of specimen (g cm$^{-3}$).

Furthermore, the worn surface properties of the brake friction composites were investigated using a ZEISS EVO LS10 scanning electron microscope. All specimens were coated with a thin layer of gold using a sputtering coater.

# 3 Results and discussion

## 3.1 Friction and wear properties of brake friction composites

The variation in the friction coefficient recorded every second with the braking time of the brake friction composites is shown in Figure 2. Since the first 150 s of the braking time is a run-in process for the disc and the specimen, the sudden increase in the friction coefficient is normal. Tribological performance was evaluated by considering the variation in friction coefficient after 150 s. As the braking continues, the temperature at the disc and pad interface increases, and friction efficiency is affected. This phenomenon is known as fade in the literature.

Tribological properties of the specimens including the mean friction coefficient, specific wear rate, and wear amount are given in Figure 3. Accordingly, the mean friction coefficient of Specimen C20 containing 20 % copper by mass is higher than the other specimen, and the specific wear rate is also high. In terms of wear performance, the specific wear rate of Specimen S10 containing 10 % steel wool by mass is low. A low specific wear rate is among the desired properties of brake friction composites, but the mean friction coefficient of Specimen S10 is not high enough. In terms of the performance of brake friction composites, it is known that the friction coefficient is more important when it is necessary to compare the wear and friction coefficient. This theory agrees with the literature [6, 7]. It was observed that the mean friction coefficient of aluminum-containing brake friction composites was close to copper-containing brake friction composites. When the metallic chip ratios in the content were examined, it was seen that the friction coefficient increased as the ratio of metallic chips, excluding aluminum, in the content increased. This situation also shows the importance of using metallic chips in brake friction composite contents. In addition, the high wear amount, and the high specific wear rate of Specimen M0, which does not contain metallic chips, is proof that metallic chips improve wear. The positive effect of metallic chips on tribological properties has been shown in studies [11, 14].

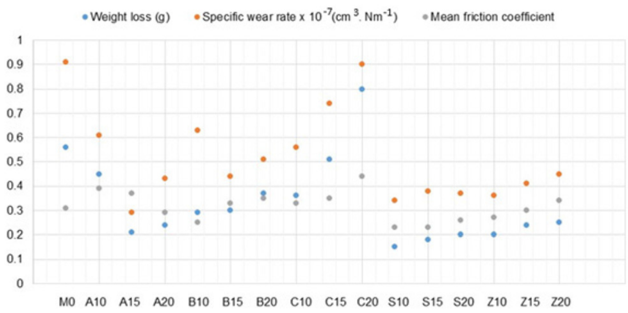

**Figure 3:** Tribological characteristics of brake friction composites.

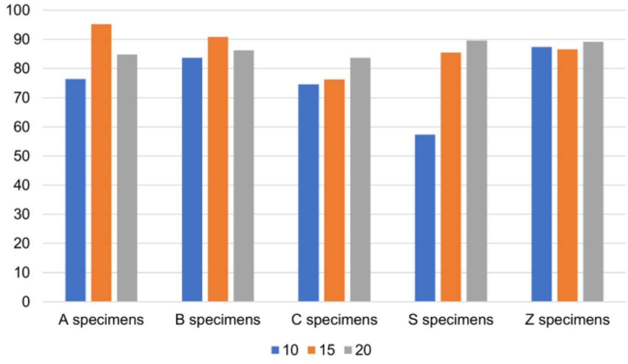

**Figure 4:** Hardness of brake friction composites (HRL).

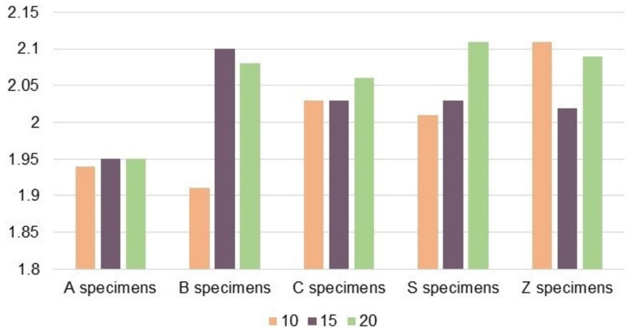

**Figure 5:** Density of brake friction composites (g cm$^{-3}$).

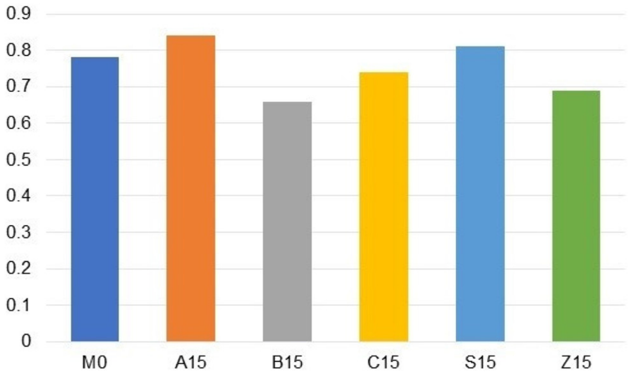

**Figure 6:** Thermal conductivity of brake friction composites (W mK$^{-1}$).

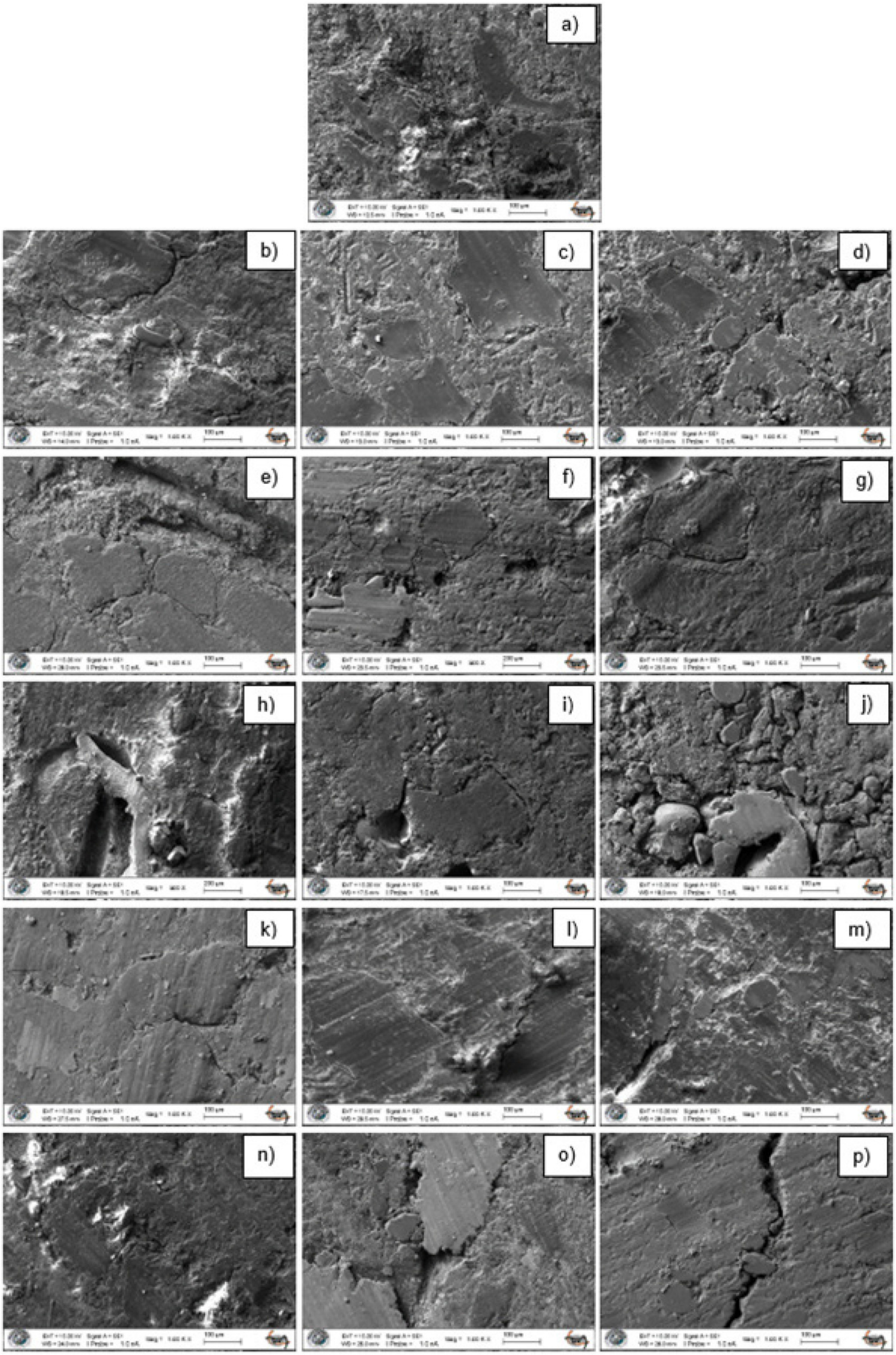

**Figure 7:** Worn surface images of brake friction composites, a) M0, b) A10, c) A15, d) A20, e) B10, f) B15, g) B20, h) C10, i) C15, j) C20, k) S10, l) S15, m) S20, n) Z10, o) Z15, p) Z20.

The hardness test results of brake friction composites are given in Figure 4. Accordingly, among the specimens containing metallic chips, the highest hardness value belongs to Specimen A15 containing 15 % aluminum by mass. However, the metal chipless Specimen M0, which is not included in the figure, has a higher hardness value. The high hardness increased the fragility of the Specimen M0 and thus the amount of wear increased. When all specimens were examined, no direct correlation was found between hardness and copper. In addition, the metallic swarf ratio in the content did not directly affect the hardness.

Archimedean densities of the specimens are shown in Figure 5. It is expected that the density of the specimens containing aluminum is lower compared to its values because aluminum is a light material. The metallic swarf ratio in the content did not directly affect the density. The density of Specimen M0 without metallic chips is the same as Specimen C15 containing 15 % copper by mass. Density may be related to the content of the material and the amount of barite used as a space filler.

One of the important roles of copper in brake friction composite content is to reduce the fade caused by the temperature effect during braking and to improve the tribological properties by providing heat conduction. The thermal conductivity results of the specimens are given in Figure 6. For ease of comparison, the results of specimens containing only 15 % metallic shavings and specimen without metallic shavings were evaluated. Accordingly, the thermal conductivity of the aluminum-containing specimen is higher than the others. Thus, it has been seen that the materials chosen as alternatives to copper meet the expectations in terms of thermal conductivity.

The worn surfaces of the specimens after the braking test are shown in Figure 7. The surface properties of the specimens give us information about friction performance. For example, the friction plateaus formed on the surface reduce the fade and increase the adhesion between the disc and the lining. Thus, the friction coefficient increases. Material losses caused by micro-cracks and abrasion on the surface prepare the ground for the fade. When the images are examined, micro-cracks and material losses are seen in copper and zinc-containing specimens. Friction plateaus were formed in the specimens containing aluminum and steel wool.

## 4 Conclusions

This study aims to investigate the effect of metallic chips, which can be used as an alternative to copper in brake friction composites, on braking performance in many ways. The test results of the specimens produced using zinc, steel, aluminum, and brass instead of copper are summarized below:

- The metallic chips used in the content have a positive effect on wear.
- In terms of tribological properties, aluminum, and steel are good alternatives to copper.
- The thermal conductivity of the specimen containing aluminum is very good.
- The friction coefficients of all the produced specimens are in the appropriate range.
- More friction plateaus were formed in specimens containing aluminum.

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