Investigation of the Usability of Agricultural and Biomass Wastes in Brake Pad Composites

İlker Sugözü
Mersin University
Elçin Sayar
Tarsus University
Uğur Eşme
Tarsus University
Banu Sugözü
banusugozu@mersin.edu.tr

Mersin University

Research Article

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Abstract

Brake pads are critical friction components in automotive braking systems. Recently, the focus has shifted toward sustainable, non-toxic, and cost-effective alternatives to conventional brake pad materials. Agricultural and biomass waste fillers offer promising reinforcement potential due to their abundance, biodegradability, and low cost.

This study explores the tribological and physical performance of brake pads reinforced with five natural fillers: corn husk, flax, hemp, coconut shell, and bamboo powder. Each was incorporated at 5, 10, and 15 wt.% using the powder metallurgy method. Tribological tests were performed against a gray cast iron disc to evaluate specific wear rate and coefficient of friction. Physical properties such as hardness, density were also assessed. SEM and EDS analyses were conducted to examine the worn surfaces and elemental composition.

Results showed that filler type and content significantly influenced composite performance. Composites with 10 wt.% coconut shell and bamboo powder exhibited the most stable friction behavior and highest average coefficient of friction, outperforming the reference. SEM images revealed that samples with 15 wt.% filler had better surface morphology, denser tribo-layers, and stronger matrix–filler bonding. However, 10 wt.% was optimal for balancing mechanical integrity and tribological performance.

This study demonstrates the potential of coconut shell, bamboo powder, flax, and hemp as sustainable reinforcements in eco-friendly brake pad composites, offering a viable pathway toward greener automotive materials.

1. Introduction

Brake pads are essential components of braking systems, directly influencing the vehicle's braking efficiency, reliability, and safety. These components are typically composed of composite friction materials that must exhibit a balance of mechanical strength, thermal stability, and consistent tribological behavior under varying operating conditions. To meet such requirements, brake pad formulations usually include a wide range of constituents such as binders, friction modifiers, fillers, abrasives, and reinforcements.

In recent years, growing environmental concerns and the increasing demand for sustainable and cost-effective materials have encouraged researchers to explore alternative raw materials in brake pad production. Conventional fillers and reinforcements, some of which may be hazardous or non-renewable—are being progressively replaced by natural, biodegradable, and renewable alternatives [1–3]. Among these, agricultural and biomass wastes have gained particular attention due to their abundance, low cost, biodegradability, and relatively low environmental impact.

Agricultural residues such as corn husk, flax, hemp, coconut shell, and bamboo powder contain lignocellulosic structures that can offer beneficial properties when used as reinforcement materials in composite structures [4–13]. Their integration into brake pad composites may not only reduce material costs and environmental footprint but also improve or maintain key frictional and wear performance parameters.

This study aims to investigate the usability of selected agricultural and biomass waste materials as reinforcement additives in composite brake pads. A total of sixteen brake pad formulations were developed using five types of bio-based fillers (corn husk, flax, hemp, coconut shell, and bamboo powder) at three different weight percentages (5%, 10%, and 15%). The brake pads were produced using the powder metallurgy method. The effects of filler type and content on the tribological performance and physical properties of the composites were evaluated through friction and wear testing, microstructural analysis, and physical property measurements.

2. Materials and Method

In this study, a total of 16 different brake pad samples were produced using five types of organic waste materials: corn husk, flax, hemp, coconut shell, and bamboo powder. Each of these materials was added to the composite formulation in three different weight ratios (5 wt.%, 10 wt.%, and 15 wt.%), along with a reference sample without any organic additive.

The brake pad composites were formulated using various materials, each serving a specific purpose to enhance performance. Phenolic resin acted as the binder, providing structural integrity and thermal stability. Steel wool was used as a reinforcement fiber to improve the mechanical strength of the pad, while cashew nut shell powder served as a friction modifier to maintain consistent friction and reduce surface glazing. Alumina, an abrasive material, was included to enhance wear resistance, and graphite acted as a solid lubricant to reduce friction and prevent overheating. Copper and brass chips were used as additional friction modifiers to regulate heat dissipation and improve thermal stability. Lastly, barite was used as a filler to improve density, vibration damping, and thermal management of the brake pads.

The samples were labeled based on the type and weight percentage of the organic waste material used. Corn husk (M), flax (KT), hemp (KN), coconut shell (H), and bamboo (B) were coded according to their content levels—for example, a sample containing 5 wt.% corn husk was labeled as M5. The reference sample, which did not contain any organic waste material, was labeled as R. The contents of the composites are presented in Table 1.

Table 1
Functional composition of brake pad samples with varying organic additives

Sample	Binder	Reinforcement	Solid lubricant	Abrasive	Friction modifiers	Organic Additive	Filler
R	20	10	5	10	20	0	35
M5	20	10	5	10	20	5	30
M10	20	10	5	10	20	10	25
M15	20	10	5	10	20	15	20
KT5	20	10	5	10	20	5	30
KT10	20	10	5	10	20	10	25
KT15	20	10	5	10	20	15	20
KN5	20	10	5	10	20	5	30
KN10	20	10	5	10	20	10	25
KN15	20	10	5	10	20	15	20
H5	20	10	5	10	20	5	30
H10	20	10	5	10	20	10	25
H15	20	10	5	10	20	15	20
B5	20	10	5	10	20	5	30
B10	20	10	5	10	20	10	25
B15	20	10	5	10	20	15	20

Brake pad composites were produced using a powder metallurgy process, starting with the careful selection of raw materials. The materials included five types of organic waste additives—corn husk, flax, hemp, coconut shell, and bamboo powder—along with traditional components such as phenolic resin, steel wool, graphite, alumina, cashew nut shell powder, brass chips, and barite. These components were chosen based on their specific functions, such as enhancing friction, improving mechanical properties, and promoting lubrication. The organic waste materials were used at varying percentages (5%, 10%, and 15%), depending on the desired properties of the final brake pad.

The raw materials were thoroughly mixed to ensure a homogenous distribution of all components. This step is crucial for ensuring that the properties of the final product are consistent throughout. Once mixed, the material was pre-shaped into an initial form using a hydraulic press. This stage was important for compacting the material and achieving a stable form before the hot-pressing process.

Next, the pre-shaped brake pad samples underwent hot pressing at a temperature of 150°C and a pressure of 13 MPa. The hot-pressing process is critical for fusing the materials together, ensuring that the brake pads have the necessary density and strength to perform effectively under braking conditions. The heat and pressure also help in achieving the desired structural integrity and uniformity across all samples.

Once the hot pressing was complete, the brake pads were allowed to cool to room temperature, which facilitated the hardening of the material. The samples were then carefully demolded from the press molds, and any excess material or imperfections were removed. The brake pads were subjected to post-processing, including surface polishing, to achieve the required finish. The surface finish is particularly important as it affects the brake pad's interaction with the brake disc during operation, influencing both performance and wear rates.

This comprehensive production process, which combines organic waste materials with traditional friction components, resulted in brake pad composites that were both functional and potentially more sustainable. The finished brake pad samples were then prepared for further testing to evaluate their tribological properties and overall performance under typical braking conditions.

The custom-designed brake testing device was employed to assess the tribological properties of the composites. The composites were subjected to frictional testing for a duration of 10 minutes, during which the coefficient of friction was recorded on a per-second basis, alongside the monitoring of the disc-composite contact temperature.

The hardness of the composites was measured using the Rockwell HRL scale, with a preload of 10 kgf and a total load of 60 kgf. Measurements were taken from three different surfaces of each composite, and the average value was calculated for each sample.

The density of the composites was calculated using the Archimedes principle.

After the friction tests, the worn surfaces of the composites were analyzed using Scanning Electron Microscopy (SEM) to examine the wear patterns and surface morphology.

3. Results and Discussion

The coefficient of friction (COF) is a fundamental tribological parameter that indicates the resistance to sliding between two contact surfaces. In composite materials, especially those used in braking applications, maintaining a stable and adequate coefficient of friction is essential for safety, performance, and durability [14–20].

In organic waste-reinforced composites, the COF is influenced by both the thermal behavior and the tribological interaction between the matrix and the natural reinforcement. Organic fillers generally contribute to the formation of stable friction films during sliding, which can enhance the consistency of the COF. However, due to their lower thermal conductivity and tendency to degrade at elevated temperatures, maintaining a stable COF under severe braking conditions can be challenging. To address this, such organic materials are often combined with ceramic reinforcements or metallic oxides to improve thermal resistance and wear stability. An ideal friction material exhibits a moderate and thermally stable coefficient of friction with minimal fading during prolonged or high-temperature use [21–30].

During the 10-minute friction test, the coefficient of friction and temperature data were recorded every second. For ease of comparison, each waste group was presented in the same graph along with the reference sample. Figure 1 shows the COF values recorded during the friction testing of the composites. The x-axis of a coefficient of friction (COF) graph represents time. The y-axis represents the coefficient of friction (μ), indicating the frictional resistance between two surfaces.

The graph typically goes through several general phases. In the initial phase, the coefficient of friction may be low because the material surface has not fully adapted or optimized its contact. In brake pads, this corresponds to the initial contact and surface adaptation phase, where the graph may show a gradual increase in friction as the surfaces interact. The steady-state phase follows, during which the coefficient of friction stabilizes as the material surfaces fully adapt, maintaining a consistent interaction. For brake pads, this steady-state usually results in a friction coefficient ranging between 0.35 and 0.45, and the graph shows a flat or stable section where friction remains constant during regular use. The fade and recovery phase occurs with prolonged usage or increased temperatures, causing a decrease in the friction coefficient due to the fade effect, where the material loses its ability to maintain high friction at elevated temperatures. On the graph, this is visible as a drop in the friction coefficient, indicating that the material has overheated or experienced wear. The recovery phase happens when the friction coefficient begins to rise again after the temperature decreases or the material cools. Lastly, in cases of excessive friction or load, a sharp increase in the coefficient of friction can be observed. The graph shows a sudden spike in friction, suggesting that the material is undergoing excessive wear or harsh operating conditions.

Upon examination of the graphs, it was observed that the composites containing corn husk exhibited lower friction coefficient values compared to the reference sample without organic waste. A similar trend was partially observed in the composites containing hemp fibers. The composites with corn husk showed more pronounced fluctuations in friction behavior, which is considered undesirable in brake pad applications as it leads to inconsistent braking performance. In the composite containing 5% flax, distinct peaks were observed during friction, which are indicative of brake fade. Brake fade refers to a temporary reduction in braking efficiency under high temperature or prolonged braking conditions. A similar behavior was also observed in the samples labeled H15 and KN15. In terms of braking performance, it is essential to evaluate the average coefficient of friction, temperature response, and frictional stability together.

The temperature generated during friction plays a critical role in evaluating the thermal resistance and tribological performance of composite brake materials. Excessive heat can compromise the structural integrity of the composite by inducing thermal degradation, particularly at the matrix–filler interface, which may lead to a decline in the coefficient of friction. This is especially evident in composites containing organic fillers, where high temperatures can trigger thermal decomposition, resulting in brake fade — a temporary loss of braking efficiency. Conversely, lower frictional temperatures are indicative of good thermal stability and may reflect higher wear resistance. Sudden spikes in temperature during braking can disrupt frictional stability, leading to inconsistent performance and potential safety concerns. Additionally, the accumulation of heat may create thermal mismatches within the composite structure, causing internal stresses and the formation of microcracks, which further deteriorate the material's durability. Figure 2 shows the temperature generated during the friction process.

The specific wear rate (SWR) is a critical parameter in evaluating the wear resistance of brake pad materials under frictional loading. A lower SWR indicates superior wear performance, as it reflects a reduced volumetric material loss per unit load and sliding distance. In the context of braking systems, a low specific wear rate is essential to ensure consistent braking efficiency, extended component lifespan, and minimized generation of wear debris. Figure 3 presents the specific wear rates of all the composite samples investigated in this study. It can be observed that the specific wear rates vary depending on the type and content of the reinforcement materials. The composite samples reinforced with corn husk exhibited relatively high specific wear rates compared to those containing other fillers. This indicates that the wear resistance of corn husk-based composites is lower under identical test conditions. The increased wear rate may be attributed to the lower interfacial bonding strength between the corn husk fibers and the polymer matrix, as well as the lower hardness and thermal stability of the organic filler. These characteristics likely contribute to the accelerated material loss during sliding, reducing the composite's overall tribological performance.

The hardness and density of composite materials are key physical properties that directly influence their mechanical performance and wear behavior. Hardness reflects the material's resistance to localized plastic deformation and is often correlated with improved wear resistance. Higher hardness values typically indicate a more robust microstructure, which can better withstand frictional forces during service. Density, on the other hand, provides insight into the material’s mass per unit volume and is affected by the type and amount of fillers or reinforcements used. Variations in density can influence the composite’s overall weight, which is particularly important in automotive applications where weight reduction is desired without compromising mechanical integrity. Figure 4 presents the hardness and density values of the composites studied.

The mean coefficient of friction and frictional stability of the composites are presented in Fig. 5. The mean coefficient of friction and frictional stability of the composites are critical parameters for evaluating their tribological performance. The mean coefficient of friction provides a measure of the resistance to sliding between the composite surface and the counterface, while frictional stability reflects the consistency of this resistance over time and under varying operating conditions. The frictional stability of the composites was quantified by calculating the standard deviation of the coefficient of friction values measured during the sliding tests. A lower standard deviation indicates more stable frictional behavior. Additionally, a stability index, defined as the ratio of the average coefficient of friction to its standard deviation, was used to compare the samples. Composites exhibiting higher stability indices demonstrate more consistent frictional performance over the testing period. The composite samples reinforced with 10% coconut shell and bamboo powder demonstrated promising frictional performance in comparison to the reference sample. This improvement suggests that the incorporation of natural fillers can effectively enhance the tribological behavior of the material, making them viable alternatives for eco-friendly friction applications.

The SEM micrographs in Fig. 6 revealed important details about the surface morphology and wear mechanisms of the composite samples. The worn surfaces of the composites exhibited features such as microcracks, fiber pull-out, and matrix fragmentation, which are typical indicators of abrasive and adhesive wear. The SEM analysis revealed that all samples containing corn husk, as well as those with 5% flax, hemp, bamboo, and coconut shell content, exhibited poor surface morphology. The worn surfaces showed signs of weak interfacial bonding, fiber pull-out, and increased porosity, indicating inadequate structural integrity under frictional loading. These observations suggest that a 5% filler content is insufficient to ensure effective reinforcement and stable tribological behavior for these types of natural fillers.

During sliding, the formation of friction layers—commonly referred to as third-body or tribo-layers—was observed on the worn surfaces of the composites. These layers are composed of compacted wear debris, transferred material, and fragmented reinforcement particles. The presence of stable and uniform friction layers plays a critical role in reducing direct asperity contact, minimizing material removal, and stabilizing the coefficient of friction. In some samples, particularly those containing bamboo, coconut shell and flax reinforcements, a more continuous and adherent friction layer was evident, indicating enhanced surface protection and improved wear resistance. In contrast, samples with low filler content or weak filler–matrix bonding showed discontinuous or poorly developed friction layers, which correlated with higher wear rates and more unstable frictional behavior.

The combined use of SEM and EDS analyses provides comprehensive insight into the surface morphology and elemental composition of the worn composite samples. SEM images reveal detailed microstructural features such as fiber pull-out, matrix cracking, and wear patterns, which are indicative of the underlying wear mechanisms. Complementarily, EDS analysis identifies the elemental constituents present on the worn surfaces, confirming the presence of organic fillers, metallic reinforcements, and ceramic additives. This correlation between the morphological observations from SEM and the elemental data from EDS allows for a deeper understanding of how the composite composition influences wear behavior and friction layer formation. Together, these techniques validate the structural integrity and tribological performance of the composites by linking surface damage characteristics with material composition.

Figure 7 shows the EDS analysis of the composites, indicating that oxygen (O), iron (Fe), carbon (C), and zirconium (Zr) are the predominant elements on the worn surfaces. The presence of these elements highlights the composite’s composition, with O and C primarily originating from the organic fillers and matrix, Fe from the metallic components or wear debris, and Zr likely from the ceramic additives, contributing to the material’s tribological performance and wear resistance. Additionally, in the composites containing coconut shell and bamboo powder, aluminum (Al) and copper (Cu) were notably detected. These elements are associated with the ceramic and metallic additives incorporated to enhance thermal stability and frictional properties, which likely contribute to the improved wear resistance observed in these samples.

4. Conclusions

- A total of sixteen composite brake pad samples were developed using five types of natural fillers—corn husk, flax, hemp, coconut shell, and bamboo powder—at varying contents (5%, 10%, and 15% by weight), and their tribological and physical properties were systematically evaluated.
- The incorporation of natural fillers significantly influenced the tribological behavior of the composites. Among them, 10 wt.% coconut shell and bamboo powder exhibited the most promising performance in terms of friction stability and average coefficient of friction, even surpassing the reference material.
- Composites containing corn husk generally demonstrated lower coefficients of friction and higher wear rates compared to other samples. This is attributed to poor filler–matrix bonding and lower thermal stability, which resulted in more severe surface damage and frictional instability.
- SEM analysis revealed that composites with 15 wt.% organic filler content consistently exhibited better surface morphology across all filler types, characterized by more uniform structure, denser tribo-layers, reduced porosity, and stronger interfacial adhesion. In contrast, the 5 wt.% filler composites showed weak bonding and poor morphological integrity.
- The hardness and density values of the composites were affected by both the type and amount of filler used. Increasing filler content generally led to reduced density, while the hardness varied depending on the compatibility and dispersion of the fillers within the matrix.
- The results suggest that optimal performance is achieved at moderate filler content (around 10 wt.%), balancing reinforcement effects with thermal and mechanical stability.
- The study highlights the potential of specific biomass waste materials, particularly coconut shell, bamboo powder hemp and flax, as sustainable and effective reinforcements in eco-friendly brake pad formulations.

Declarations

Author contribution Elçin Sayar: conceptualization, investigation, methodology, writing original draft, visualization, and data curation. İlker Sugözü: conceptualization, investigation, methodology, visualization, and support for data interpretation. Uğur Eşme: conceptualization, validation, visualization, and data curation. Banu Sugözü: conceptualization, investigation, methodology, supervision, writing original draft, visualization and data curation, writing—review & editing.

Data Availability The data supporting this study’s findings are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

Ethical approval: Not applicable.

Competing interests: The authors declare no competing interests.

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Figures

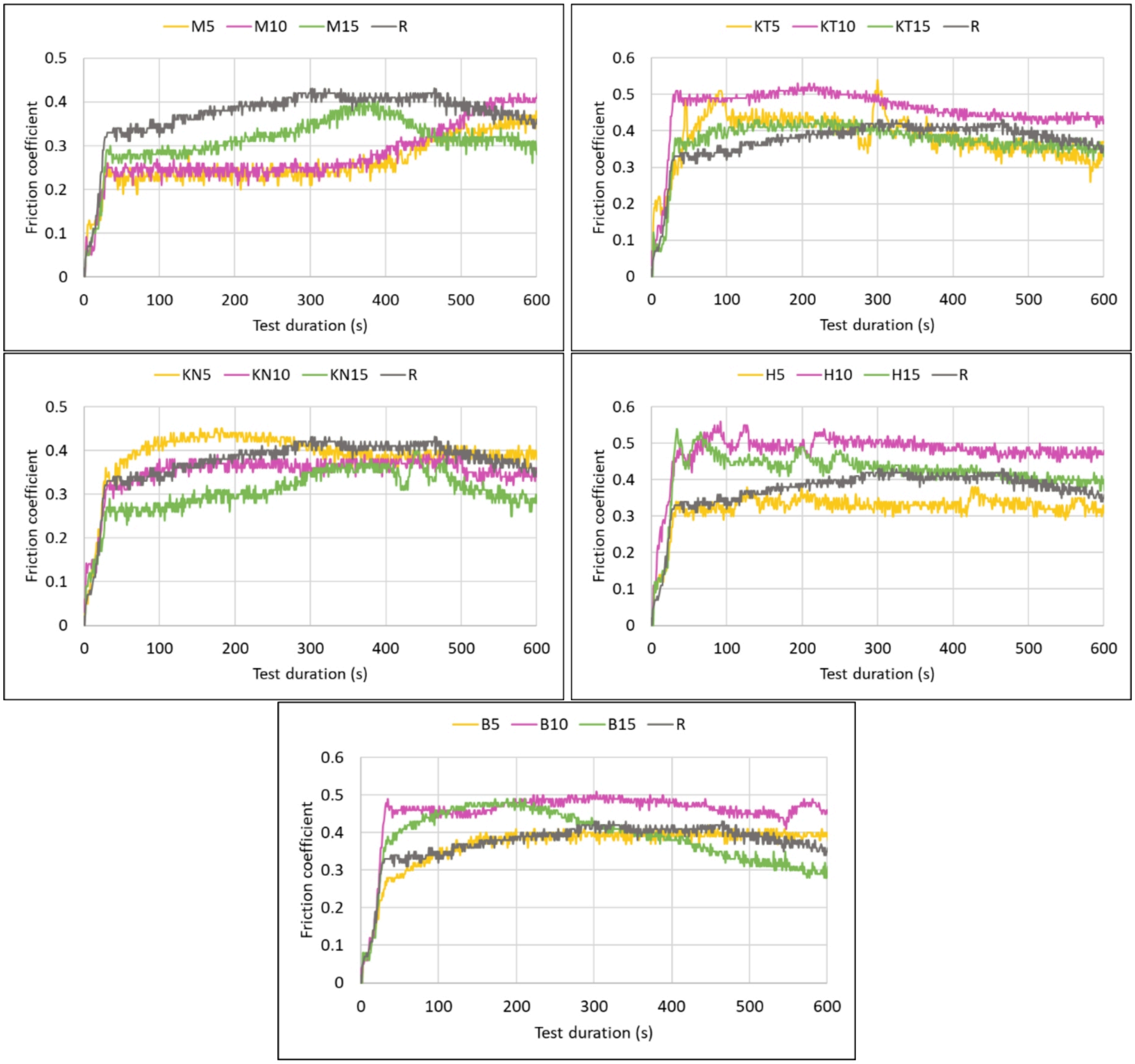

Figure 1

Graph of the coefficient of friction values measured during the friction experiment

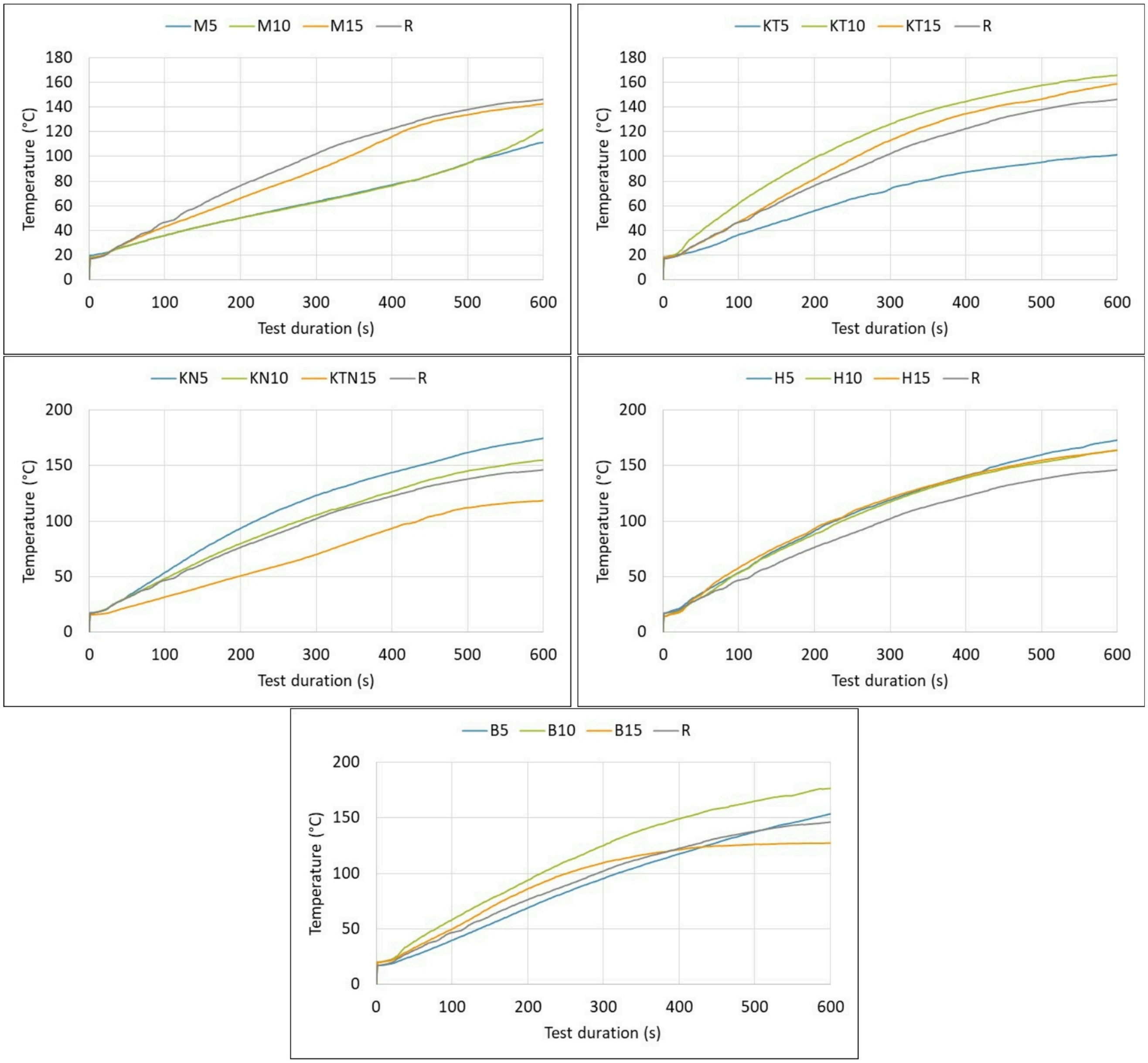

Figure 2

Thermal response of the composite during the frictional interaction

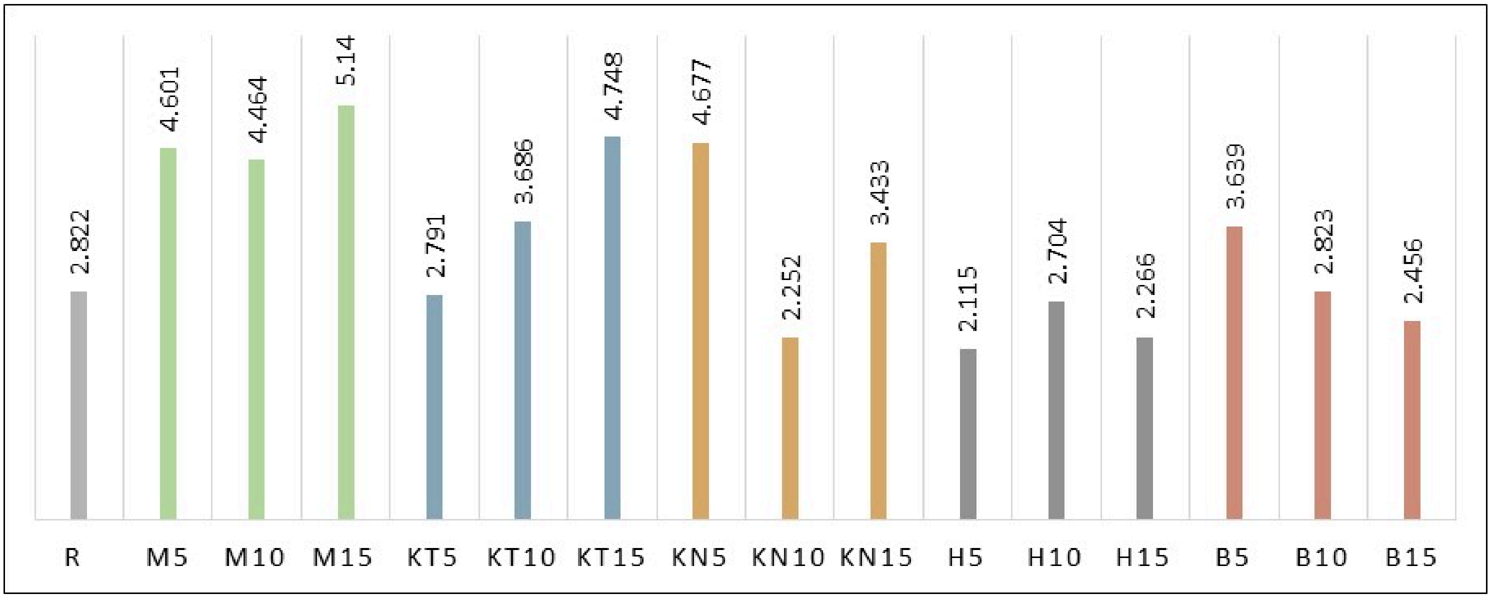

Figure 3

The specific wear rate (×10^{-6} cm^3/Nm) exhibited by the composites

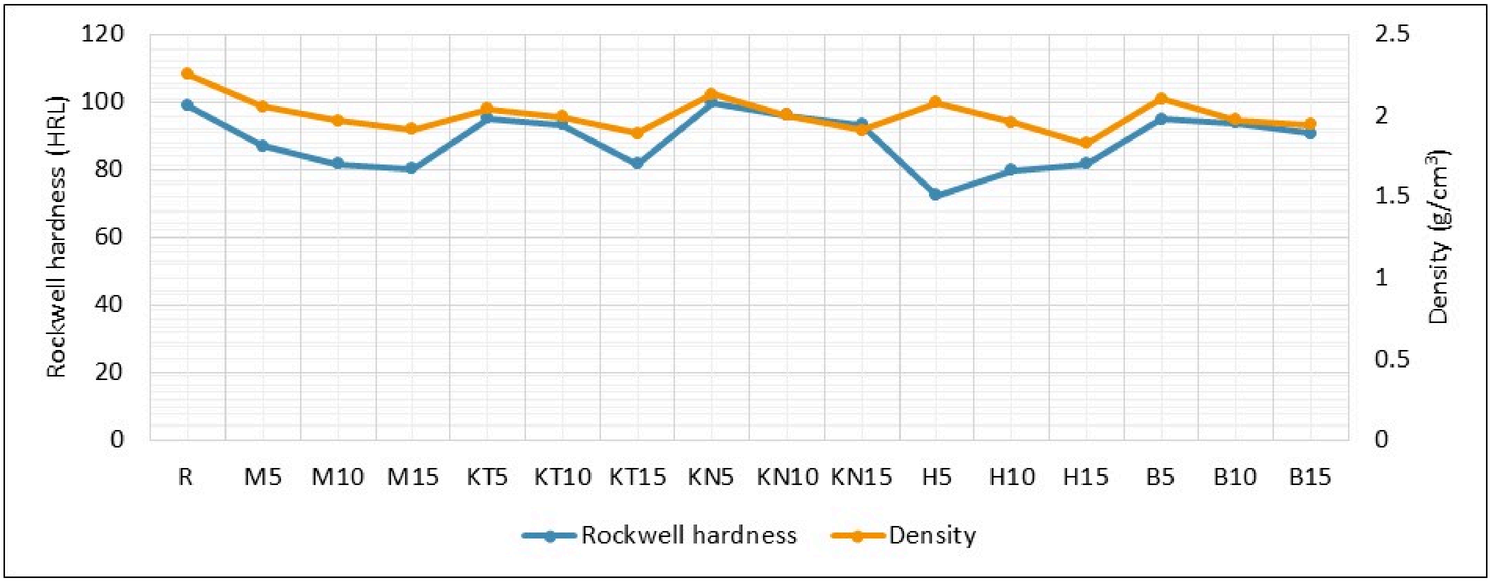

Figure 4

The hardness and density of the composites

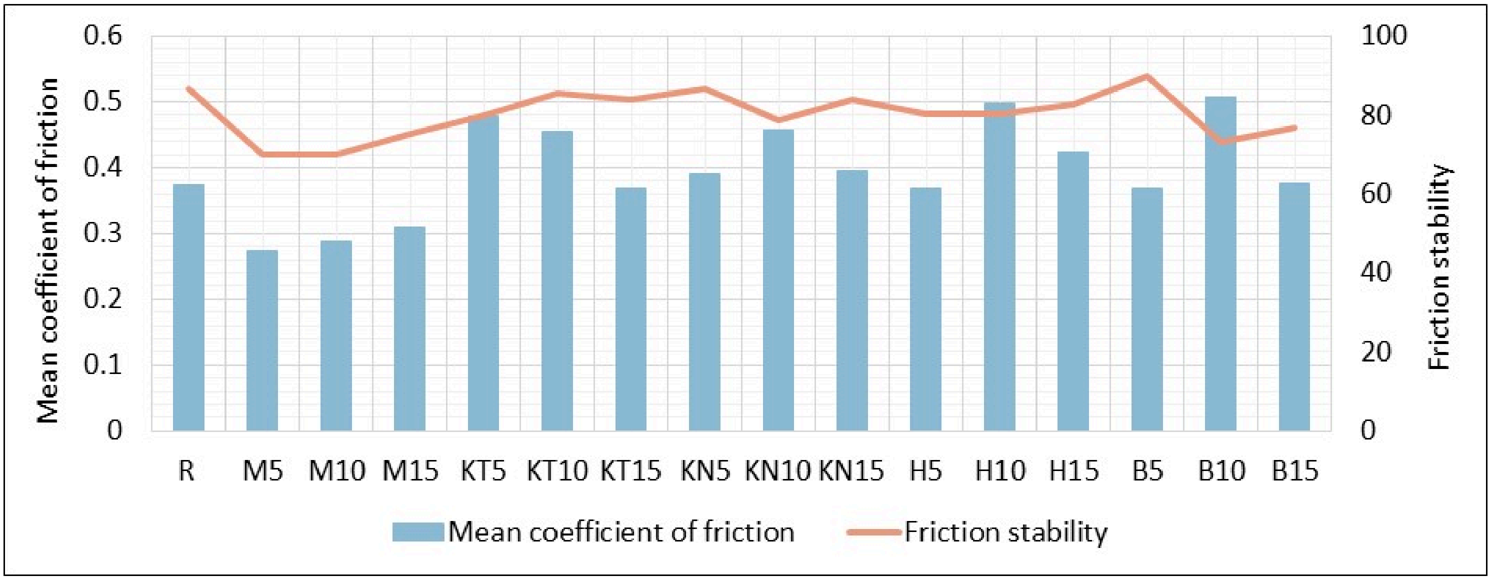

Figure 5

The frictional properties of the composites

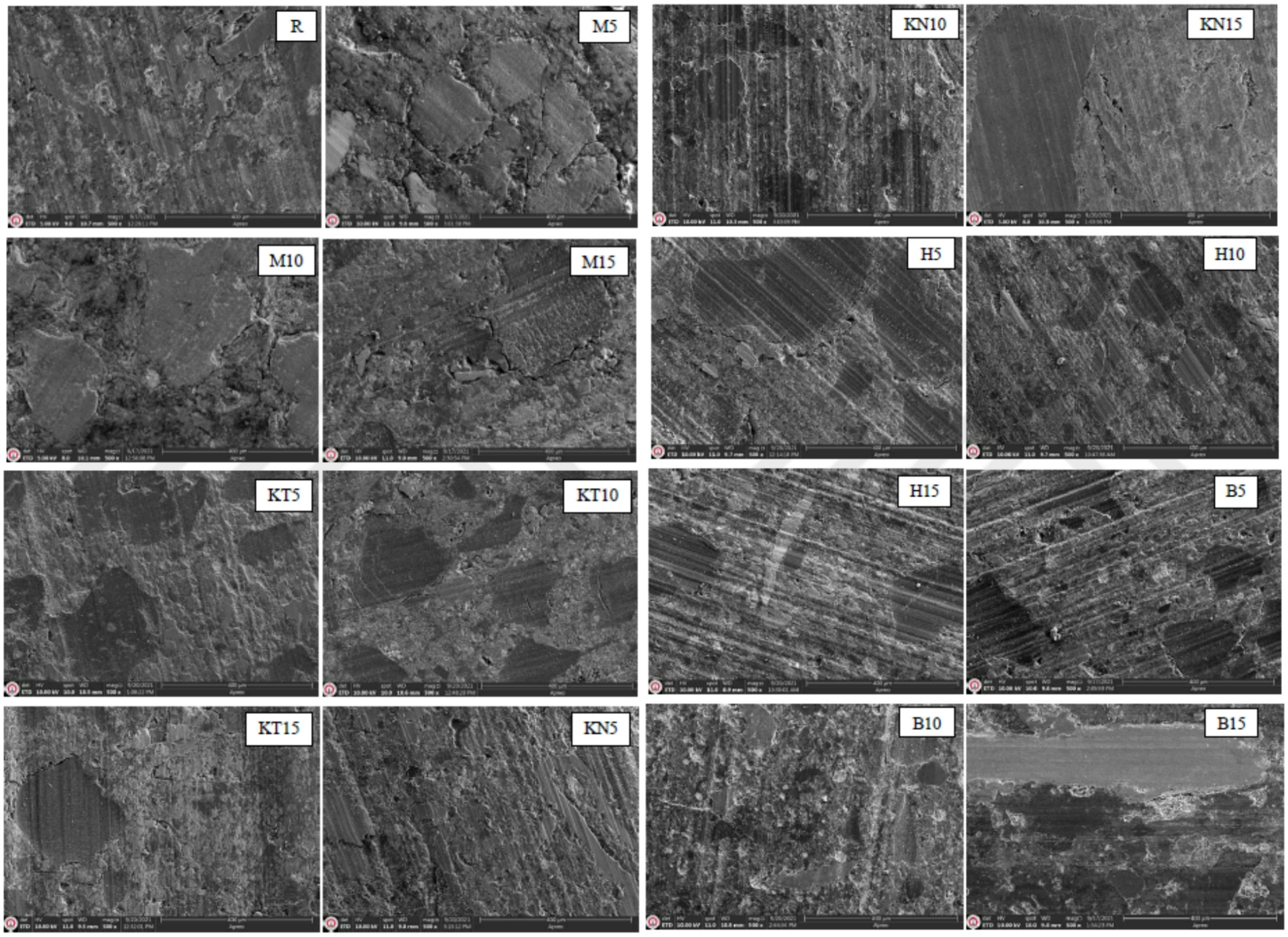

Figure 6

SEM micrographs of the composites (x500 magnification)

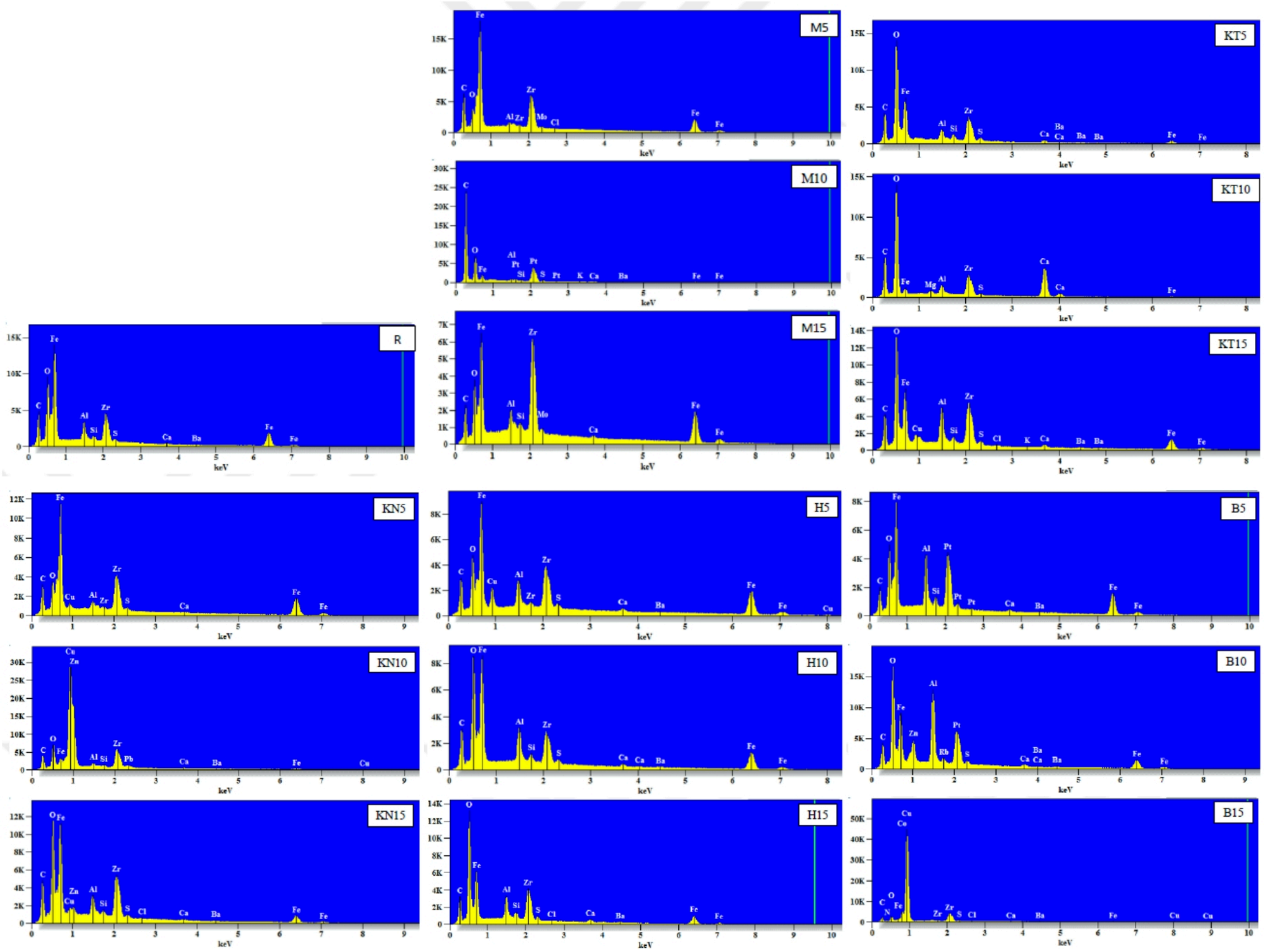

Figure 7

EDS analysis of composites