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Effect of palm kernel shell and graphene oxide incorporation on the physical, electrical, and wear properties of carbon-copper composite for railway pantograph slides

Koay Mei Hyie [1], Fazira Suriani Mohamed Fadzil [1,2*], Mohd. Asri Selamat [2], Eliasidi Abu Othman [2], Ahmad Aswad Mahaidin [2]

[1] Mechanical Engineering Studies, College of Engineering, Universiti Teknologi MARA Cawangan Pulau Pinang, Permatang Pauh Campus, MALAYSIA.
[2] Advanced Materials Research Centre, SIRIM Industrial Research, SIRIM Berhad, MALAYSIA.
*Corresponding author: fazira@sirim.my

KEYWORDS

Carbon-copper composite
Palm kernel shell
Graphite
Graphene oxide
Pin-on-disc

ABSTRACT

Agricultural waste is of interest for recycling for railway applications. However, the optimal use of agricultural waste is crucial in affecting the properties of the final product. This study investigated the effect of incorporating natural-based carbon, specifically palm kernel shell (PKS), and graphene oxide into graphite-based carbon-copper composites using the warm compaction method as potential pantograph slides, on the properties of the composite. A factorial design was employed to evaluate the influence of different PKS to graphite ratios (20/80, 30/70, 50/50, 70/30, and 80/20) with and without the addition of graphene oxide (GO) on the density, hardness, resistivity, and strength of the composites. The friction and wear behaviour of the composites were also analysed. The variation in the data may be attributed to inconsistencies in the size and shape of the PKS. The GO addition did not yield significant benefits due to poor dispersion stability of GO. Composite with lower PKS content and without addition of GO showed better dispersion and gave similar properties to the commercial carbon pantograph slide. The composites' friction coefficient and wear rate were significantly lower than the reference pantograph slide. These findings offer valuable insights into optimising the natural composite composition contributing to the reliability and efficiency of railway systems.

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1.0 INTRODUCTION

A composite comprises two or more different materials with diverse chemical, physical, and mechanical qualities. When these components are combined, a new material is formed. It differs from the constituent materials in terms of its attributes (Budati et al., 2024). Due to advantageous mechanical characteristics and lightweight, composites are continually evolving towards the most efficient and cheapest products (Elfaleh et al., 2023). Copper-based composites have gained significant attention in electrical and electronic applications due to their excellent electrical and thermal conductivity, good mechanical properties, and wear resistance (S. Fu et al., 2020). Carbon-copper composites have attracted significant attention as they offer a unique balance of electrical and mechanical properties (H. Zuo et al., 2021). They can be key components in many areas for their excellent electro-mechanical properties, heat conduction, and solid lubrication, such as electrical contacts, bearing materials, and thermal management systems (Liao et al., 2021). A good sliding electrical contact material should have excellent mechanical and electrical properties for power transmission and impact resistance (Kubo & Kato, 1998). Therefore, it is beneficial to investigate their properties to develop practical and efficient carbon-copper composites.

In the railway industry, the performance of pantograph is critical, especially in achieving high speed (Wu et al., 2022b). Positioned on the roof of the train cars, the pantograph interacts with the catenary, a network of cables above the tracks. The pantograph slide transmits electric energy from the traction substations to the moving trains (Huang et al., 2020). Contact strips require specific properties such as wear resistance, good lubricating characteristics, high mechanical strength, and adequate electrical conductivity (Kubota et al., 2013). These qualities enhance energy transmission during the interaction between the pantograph carbon strip and the overhead catenary while minimizing energy loss. The material's wear resistance is crucial as it affects the parts' lifespan and the replacement frequency. Additionally, the critical feature of pantograph carbon strips is their ability to self-lubricate (M. Wang et al., 2021).

Traditionally, graphite has been the primary carbon source in carbon-copper composites. Graphite is a crystalline form of carbon, a natural allotrope of carbon, or a distinct molecular form of the same element. It is a soft, grey-black variation with a hallowed spherical and ellipsoid tube structure. Carbon atoms in graphite are exclusively chemically bound to three other carbon atoms, resulting in two-dimensional solid layers that are exceedingly stable. Composites impregnated with copper-graphite are in applications requiring high conductivity (Shivanada et al., 2023). However, the increasing demand for sustainable and cost-effective materials has led to exploring alternative carbon sources. The concept of eco-materials covers many materials, including traditional and innovative options and their diverse uses. Developing and employing eco-materials is essential to achieve sustainable development and reduce the impact of human activities on the environment (Elfaleh et al., 2023).

Palm kernel shell (PKS), a by-product of the palm oil industry, is a readily available and renewable carbon source that has the potential to replace graphite in various applications. Incorporating PKS into carbon-copper composites can offer several advantages, including reduced material cost, improved sustainability, and potentially enhanced mechanical properties such as hardness and wear resistance. Its fibrous characteristic may aid in improving the structural integrity and helping to maintain the friction level followed by a reduction in wear of the materials under several operating conditions (Raja & Ramkumar, 2023). Moreover, the addition of graphene oxide (GO), a nanomaterial known for its exceptional mechanical and electrical properties, can further improve the performance of these composites. Incorporating GO into the pantograph slide materials can enhance their mechanical strength, reduce wear and tear, and improve the sliding contact between the pantograph slides and the overhead wires (Zhang et al., 2023). Various studies have used PKS as a replacement for graphite in current collector for third rail application (Budin et al., 2016; Ibrahim et al., 2016; Nurul Hadi et al., 2016; Selamat et al., 2016).

Carbon-copper composites are valued for their unique combination of properties inherited from both constituents. Copper provides excellent thermal and electrical conductivity, while carbon contributes to low thermal expansion, good lubrication, and wear resistance. However, many have reported on copper and carbon's poor wettability and suggested ways to overcome it. In a previous study, H. Zuo et al. (2022) used iron reaction products to overcome the poor wettability of copper prepared by gas infiltration technique. Another study suggested modified mechanical doping method to control the interface and improve the wettability of copper and carbon (T. Zuo et al., 2020). Warm compaction, a subset of powder metallurgy, involves compacting powder mixtures at elevated temperatures, typically below the sintering temperature of the main constituents. This technique offers several advantages for fabricating carbon-copper composites, including enhanced densification, reduced sintering temperature, and improved homogeneity. It is also cost-effective for large-scale production due to the reduction of waste material and minimal need for secondary machining operations (Simchi & Nojoomi, 2013). Phenolic resin, which acts as a binder, may also assist in reducing copper and carbon wettability issues.

In this paper, we investigated the significant effects of adding various ratios of PKS and GO into the carbon-copper composites on mechanical, physical, and tribological properties. These results were compared with the behaviour of pure carbon pantograph slide material as reference. This study also investigated the feasibility of incorporating PKS into graphite-based copper composites for pantograph slide applications. Understanding the relationship between composition and properties is crucial for tailoring the composites to meet the specific requirements of pantograph slides. It is also essential to study the tribological properties of carbon-copper composites, which is a fundamental step in their development and application. Knowledge gained from such studies directly impacts material selection, design, performance, lifespan, cost-effectiveness, energy efficiency, environmental sustainability, and safety.

Although this study served as a preliminary investigation, it shall provide valuable insights into the potential of PKS and GO as alternative materials to enhance the performance and sustainability of carbon-copper composites in railway applications. The findings of this study will pave the way for future research in optimizing the composition and processing of these composites to achieve superior pantograph slide properties for other demanding electrical applications.

2.0 MATERIALS AND METHOD

2.1 Material Preparation

Carbon-copper composite materials were produced by combining different amounts of carbon (from natural carbon material and graphite), copper, phenolic resin, and graphene oxide (GO). The natural carbon material used was PKS powder (200 mesh) supplied by Tan Meng Keong Sdn. Bhd. under the TMKCARBON brand. Conventional graphite and phenolic resin were supplied by AFI Brakes Manufacturing Sdn. Bhd. The phenolic resin was used as a binder. Copper powder was obtained from Sigma Aldrich with a particle size range of 10 to 25 µm. GO was supplied by UM Innovations Sdn. Bhd. In this study, GO was added to the matrix at a low amount to provide reinforcement. The material composition is shown in Table 1.

Table 1: Composition of carbon-copper composites with different ratios of PKS to graphite consolidated by warm compaction method.

Sample	PKS/Graphite Ratio (Total 65 g)	Graphene oxide (g)	Copper (g)	Resin (g)
1	20/80	0	20	15
2	20/80	1	20	15
3	30/70	0	20	15
4	30/70	1	20	15
5	50/50	0	20	15
6	50/50	1	20	15
7	70/30	0	20	15
8	70/30	1	20	15
9	80/20	0	20	15
10	80/20	1	20	15

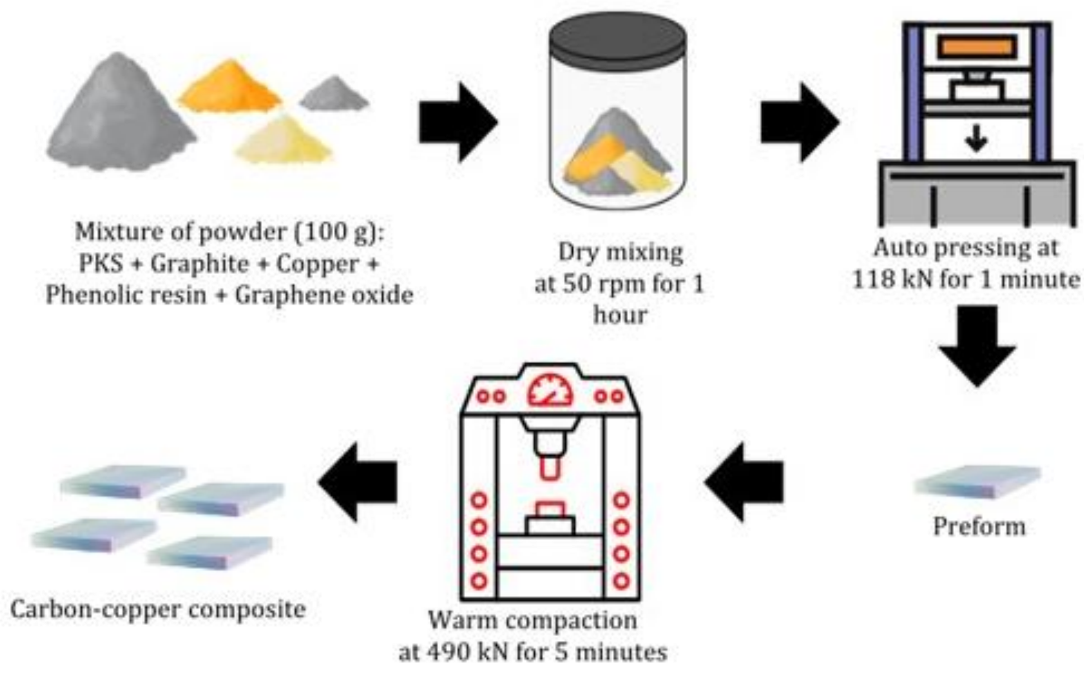

Figure 1: Carbon-copper composite fabrication process flow using warm compaction method.

The first step in the consolidation process was to mix a total of 100 g powder, consisting of 65% carbon (a mixture of PKS and graphite at different ratios), 20% of copper, 15% of resin, and addition of GO in the tubular mixer at 50 rpm for 1 hour. The composition of the materials was selected based on the optimum composition reported by previous work (Selamat et al., 2016)(Ibrahim et al., 2016). This was the optimised composition used to produce a carbon-copper composite for current collector in third rail application, which is similar to the function of pantograph slide (Wu et al., 2022a). Each powder was weighed according to the selected composition before mixing. Using automatic hydraulic press machine, 118 kN (12 tonne) of cold compaction was applied to the mixture to produce the green body or preform. Subsequently, the preform was inserted into the four-cavity mould with 1 inch x 1 inch dimensions. The preform was subjected to hydraulic compression moulding press machine at 490 kN (50 tonne) and warm compaction process at temperature of 200°C and soaking period of 5 minutes. Figure 1 illustrates the carbon-copper composite fabrication process. The composites were evaluated for density and hardness. Prior to the resistivity and TRS tests, the sample was cut into three equal sections using Struers Secotom precision cutter equipped with an alumina blade.

2.2 Characterization of Carbon-Copper Composite

The composite's density was determined using density balance (MD-300S) based on Archimedes' principle, as shown in Eq. (1).

$$d = m/v \qquad (1)$$

where, d is density, m is mass, and v is volume. Density is expressed in units of grams per cubic centimetre (Patel et al., 2022). The average value was taken from three measurements for each sample.

Hardness test was performed using Rockwell hardness tester (Mitutoyo model HR-430MR), with 60 kg load and ½ inch ball-type indenter. Three readings were recorded at three different spots for each sample, and the average value was determined. The electrical resistivity was obtained by measuring the electrical resistance using Fluke Digital Multimeter (Model 88V). Electrical resistivity was calculated using Eq. (2).

$$\rho = \frac{RA}{l} \qquad (2)$$

where, ρ refers to electrical resistivity, R refers to electrical resistance, A refers to the area of the sample, and l refers to the length of the sample. The average value of three measurements was determined for each sample. The three-point bend test was performed to obtain the transverse rupture strength (TRS) using Instron Universal Tensile Machine, model 3369. This test was performed according to ASTM D790. The crosshead speed was set at 3 mm/min. The TRS was calculated using Eq. (3).

$$TRS = \frac{3Pl}{2wt^2} \qquad (3)$$

where, P denotes the maximum yield strength, l refers to sample length, w is the sample width, and t is the sample thickness.

The tribological properties of the composite were examined using pin-on-disc CSEM tribometer (CSEM, Switzerland) with 10-mm diameter copper ball at sliding speed of 0.1 m/s and sliding distance of 1,000 m under 10 N load. A copper ball was used in this test to simulate the contact between the pantograph slide and the overhead line, where the overhead railway line is typically made of copper. The ball's hardness ranged from 9 to 10 on the Rockwell scale. The carbon-copper composite was set as the disc. The test was performed according to ASTM G99-23. Figure 2 depicts the schematic diagram of the pin-on-disc wear test system.

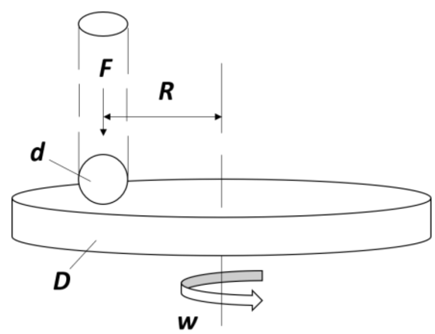

Figure 2: Schematic diagram of pin-on-disc wear test system.

where, F is the normal force on the ball, d is the ball diameter, D is the sample diameter, R is the wear track radius, and w is the rotation velocity of the disc. From the pin-on-disc test using the CSEM tribometer, the friction coefficient, μ, was obtained from the TriboX software. The friction coefficient was calculated using Eq. (4).

$$\mu = \frac{F}{P} \quad (4)$$

where, F is the frictional force in Newton, and P is the applied load in Newton.

The mass of the sample was weighed before and after the test. The wear rate was calculated using Eq. (5).

$$Wr = \frac{\Delta w}{Sd} \quad (5)$$

where, Wr is the wear rate, Δw is the weight loss of the test sample (g), and Sd is the sliding distance (m).

3.0 RESULTS AND DISCUSSION

Table 2 summarises the average density, hardness, electrical resistivity, and TRS values for all composite samples. The following subsections present a detailed explanation of each property.

Table 2: Average value of density, hardness, electrical resistivity, and TRS of carbon-copper composite at different PKS to graphite ratios

Sample Name	Density g/cm^3	Hardness HRR	Resistivity $\mu\Omega.m$	TRS MPa	Friction Coefficient μ	Wear rates mg/m
1	1.874	90	45	41	0.088	0.0042
2	1.820	96	224	36	0.052	0.0039
3	1.852	87	156	38	0.035	0.0031
4	1.653	88	298	29	0.042	0.0117
5	1.671	104	719	39	0.093	0.0051
6	1.643	105	701	35	0.054	0.0081
7	1.468	102	1164	31	0.037	0.0265
8	1.372	66	1212	31	0.062	0.0269
9	1.572	118	1382	31	0.014	0.0301
10	1.292	56	1868	30	0.043	0.0238

3.1 Density

Figure 3 shows the density values of carbon-copper composites at different PKS to graphite ratios with and without the addition of GO. Overall, the density of carbon-copper composites is slightly higher without the addition of GO, which may be due to the poor dispersion stability of GO (Zhang et al., 2023). The graphene oxide appears as thin, wrinkled platelets, exhibiting a layered structure. The large surface area of plate-structure has a high tendency to form aggregation, making them difficult to uniformly disperse in composites.

The highest density value was obtained at the 20/80 PKS to graphite ratio. PKS has a more porous and less dense structure compared to graphite. Higher PKS ratios may lead to more voids within the composite, resulting in lower density. Conversely, lower PKS ratios (20/80) resulted in a denser structure due to the predominance of graphite. This was evidenced in the scanning electron microscope (SEM) micrographs in Figure 4(a) for Sample 1 with density value of 1.874 g/cm^3 and Figure 4(b) for Sample 10 with density value of 1.292 g/cm^3. Larger sizes of voids were found in Sample 10, hence giving lower density value. In addition, the difference in particle size between the PKS and graphite could also lead to non-uniform particle distribution within the composite, especially at higher PKS ratios, that could create voids and decrease density (Ulusoy, 2023). Smaller particles of PKS have higher surface areas relative to their volume. PKS might be agglomerated when mixed with larger particles of graphite. The difference in surface energy and surface area between the two different particle sizes can impact the physical and mechanical properties of the composite. Besides, the bonding between PKS and the copper matrix may be weaker than that between graphite and copper (Yuan et al., 2020). Higher PKS ratios could lead to weaker inter-particle bonding within the composite, inducing less dense structure. Comparing to the commercial pure carbon pantograph slide from the literature (Kuznar et al., 2021) (Wu et al., 2022b) (Li et al., 2022) (P. Wang et al., 2021), composites developed in this study have densities exceeded the required range (1.65 – 1.70), especially at lower PKS content.

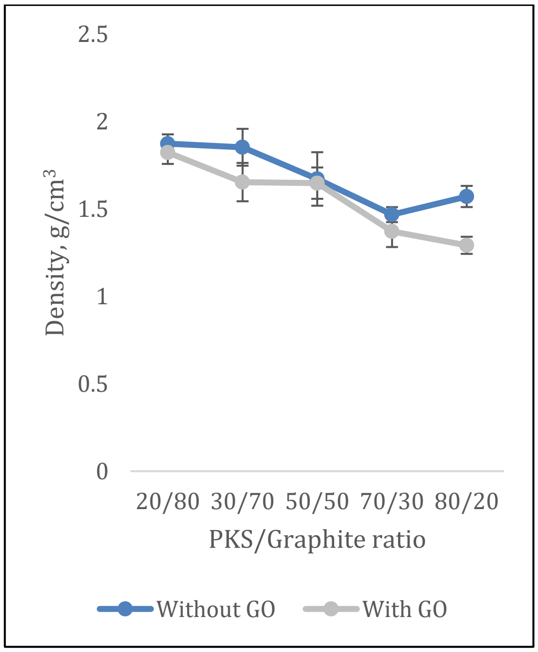

Figure 3: Density values of carbon-copper composites at different PKS to graphite ratios with and without GO.

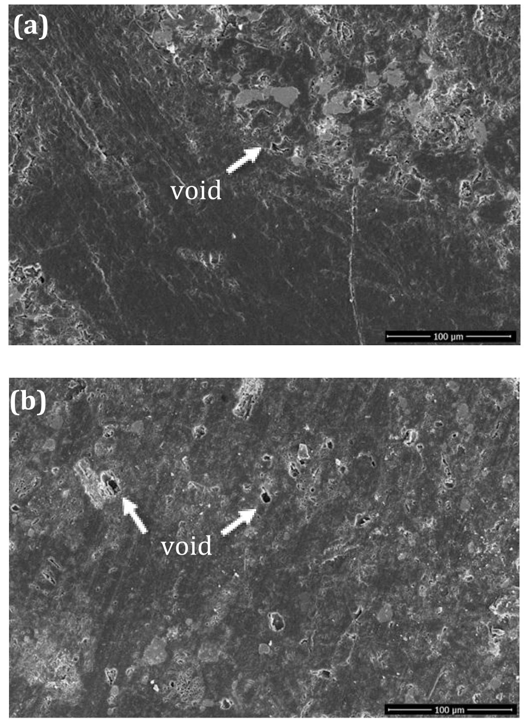

Figure 4: SEM micrographs at 100X magnification of (a) Sample 1 and (b) Sample 10.

3.2 Hardness

Hardness values of the carbon-copper composites at different PKS to graphite ratios with and without GO are shown in Figure 5. Overall, the hardness is slightly higher at the composite without addition of GO. The highest hardness value of 118 HRR was obtained at the PKS/graphite ratio of 80/20 without GO. PKS is a natural material with a relatively high intrinsic hardness due to its lignocellulosic composition and structure (Baffour-Awuah et al., 2021; Uchegbulam et al., 2022). A higher proportion of PKS in the composite, such as the 80/20 ratio, could contribute to an increase in overall hardness for composite without the addition of GO. However, the hardness dropped when the PKS ratio is higher than graphite in the composite with the addition of GO. This may be due to several factors such as inconsistency of the natural PKS (Saw et al., 2012), non-uniformity dispersion, and interfacial bonding between the materials (Issakah et al., 2024). It is reported that the GO could potentially increase hardness due to its high mechanical strength (Shuai et al., 2023). However, the decrease in hardness with the addition of GO at higher PKS ratios suggested poor interaction between GO, PKS, and graphite, which may not be beneficial for all cases. The poor dispersion issue was also reported by Ramezani et al. (2024), highlighting the challenges in attaining a uniform dispersion of graphene and its derivatives within matrices. Comparing to the commercial pure carbon pantograph slide from the literature (Kuznar et al., 2021) (Wu et al., 2022b) (Li et al., 2022) (P. Wang et al., 2021), almost all of the hardness value obtained, are still within the required range (65 - 92 MPa).

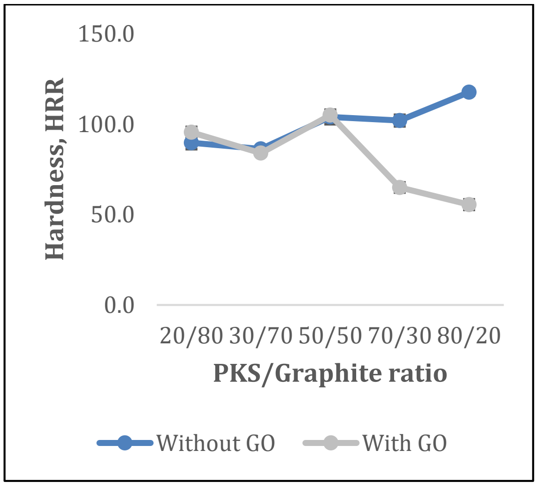

Figure 5: Hardness values of carbon-copper composites at different PKS to graphite ratios with and without GO.

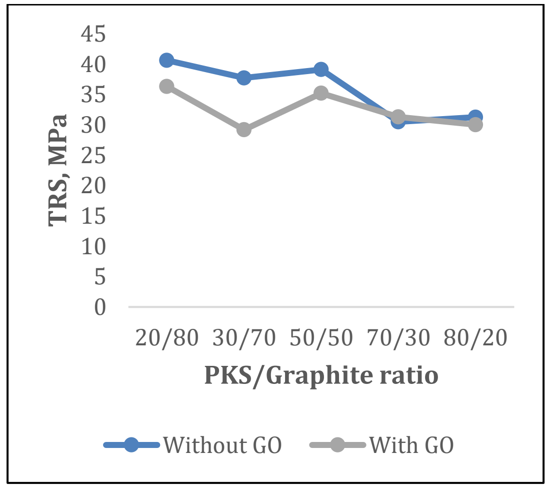

Figure 6: TRS of carbon-copper composites at different PKS to graphite ratios with and without GO.

3.3 Transverse Rupture Strength

The transverse rupture strength (TRS) values of the carbon-copper composites at different PKS to graphite ratios with and without GO are depicted in Figure 6**.** Overall, the composite without GO showed higher TRS value. Despite the fluctuating data, higher TRS is observed at the lowest PKS content for both with and without the addition of GO. The TRS results showed a decreasing trend as amount of PKS is increased. Comparing to the commercial pure carbon pantograph slide from the literature (Kuznar et al., 2021) (Wu et al., 2022b) (Li et al., 2022) (P. Wang et al., 2021), the TRS value obtained for most of the developed composite, especially without GO, are still within the required range (35 – 50 MPa). With its layered structure and strong in-plane bonding, graphite could act as a reinforcing agent within the composite. Higher graphite content could improve load transfer and stress distribution, enhancing the overall strength of the material, particularly TRS. While PKS could contribute to strength, its interfacial bonding with the copper matrix may not be as strong as that of graphite. Higher proportion of PKS could introduce weaker interfaces due to its inconsistency of grain size and shape, as shown in Figure 7 (a). This may potentially lead to crack initiation and propagation under stress, as reported by Fu et al. (2008). They found that effect of particle size is significant on the fracture toughness. Higher fracture toughness often leads to higher TRS. Dispersion among PKS, graphite, GO and copper was poor as shown in Figure 7 (b). Dark region are likely carbon-based particles, including graphite, PKS, and GO. Brighter areas represent the copper matrix. The image revealed porosity region around dark area, that may be the PKS particles. This indicated poor particle packing and weak interfacial bonding both of which can reduce TRS. Besides, porosity also found between carbon and copper area due to poor wetting. This finding was supported by Ibrahim et al. (2016) and Selamat et al. (2016).

The addition of GO could potentially improve TRS due to its high mechanical strength, which could increase the original strength of a material up to five times (Smith et al., 2019) and ability to bridge microcracks (Mowlaei et al., 2021). However, the decrease in TRS values with the addition of GO at specific ratios suggested no synergistic interaction between GO, PKS, and graphite in some cases. This could be due to poor dispersion or adverse chemical interactions. High TRS is essential for pantograph slides to withstand the mechanical stresses encountered during operation, such as bending and friction (Liu et al., 2023). The PKS to graphite ratio of 20/80 without GO exhibited the highest TRS value of 118MPa, suggesting a potential composition for further investigation and optimisation.

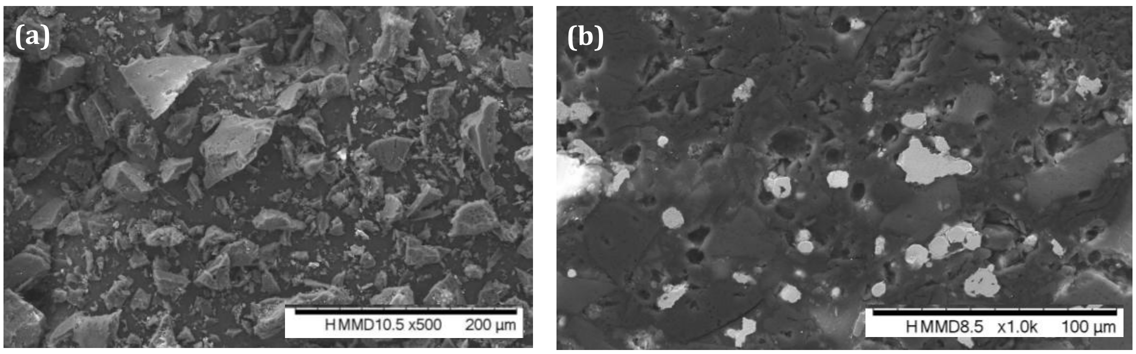

Figure 7: SEM micrographs of (a) PKS powders and (b) cross-section of developed composite.

3.4 Resistivity

Figure 8 presents the electrical resistivity values of carbon-copper composites at different PKS to graphite ratios with and without GO. Lower electrical resistivity value is desired for the pantograph slide application, which was obtained at lower PKS to graphite ratio.

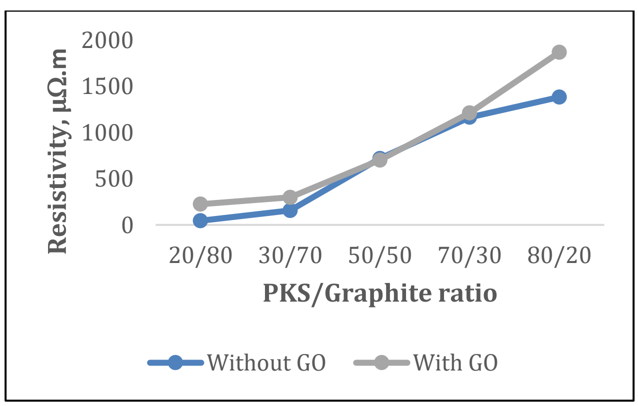

Figure 8: Electrical resistivity values of carbon-copper composites at different PKS to graphite ratios with and without GO.

Graphite is naturally an excellent electrical conductor due to its delocalised electrons (Ayyappadas et al., 2019). PKS, as a natural material, is primarily composed of carbon in a non-graphitic form, which is less conductive than graphite (Baffour-Awuah et al., 2021). Higher PKS ratios introduced more insulating material into the composite, increasing the resistivity. Although GO is conductive in its reduced form, the oxidised form of GO used in this study contained oxygen functional groups that disrupted the electron delocalisation, making it less conductive. Disruption of sp^2 bonding orbitals of graphene inhibits its electrical conductivity, making it electrically resistant (Smith et al., 2019). However, Senis et al. (2019) contended that a small amount of GO added to the composite may not significantly affect conductivity. Comparing to the commercial pure carbon pantograph slide, the best resistivity value is slightly higher (45 μΩ.m) than the range of 23.8 – 34.5 μΩ.m given in the references (Kuznar et al., 2021) (Wu et al., 2022b) (Li et al., 2022) (P. Wang et al., 2021). The addition of conductive fillers like graphene or carbon nanotubes may be considered in future study to further enhance the overall performance of the composite, .

3.5 Friction Coefficient and Wear Rate

Figure 9 shows the variation in the friction coefficient of carbon-copper composites with different ratios of PKS/graphite. It can be seen that the friction coefficient fluctuated with increasing PKS/graphite ratio. However, the overall friction coefficient for all carbon-copper composites was lower (less than 0.1) than the reference sample (0.5) (Li et al., 2022) (P. Wang et al., 2021).

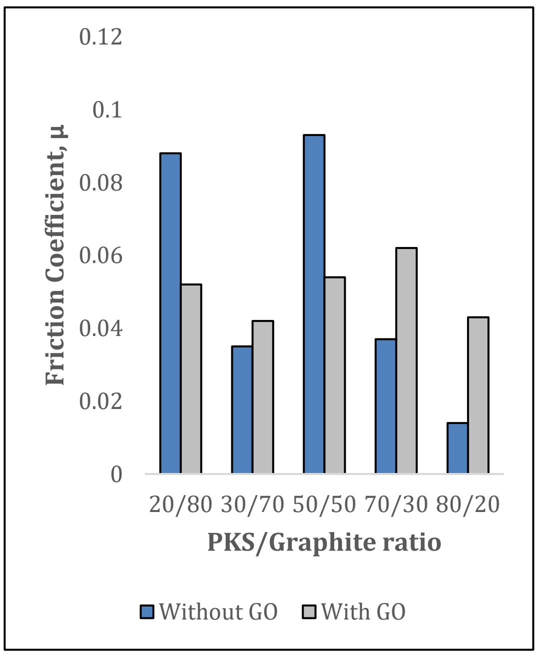

Figure 9: Friction coefficient of carbon-copper composites at different PKS to graphite ratios, with and without GO.

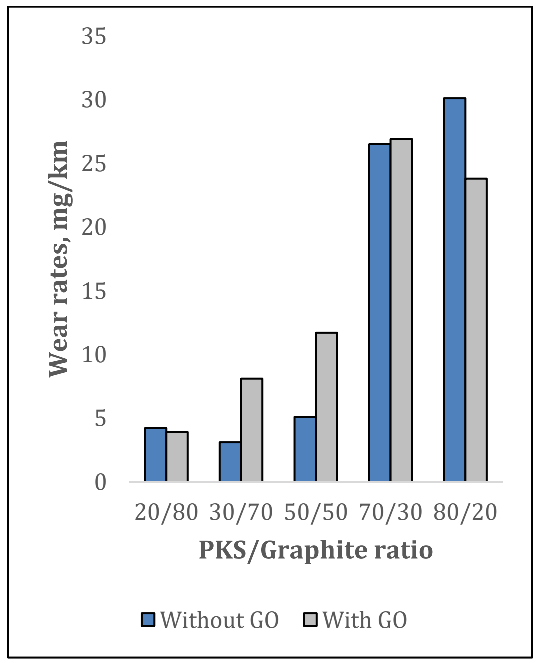

Figure 10: Wear rates of carbon-copper composites at different PKS to graphite ratios, with and without GO.

The average value and associated standard deviation of copper fibre and carbon fibre reinforced carbon-based composite were reported to be in the range of 0.135 ± 0.038–0.144 ± 0.043 (P. Wang et al., 2024). On the other hand, copper-carbon composite made from flake graphite, carbon black, pitch coke and needle coke had friction coefficient value of 0.27± 0.002 (Ren et al., 2023). This demonstrated that the developed carbon-copper composite with PKS and graphite has significantly reduced friction, which is less than 0.1, with smoother sliding and movement. This also generally leads to reduced surface wear and tear, thereby increasing lifespan. Low friction could also reflect improved energy efficiency and less energy lost to overcome friction.

Furthermore, all the composite samples showed very low wear rates of less than 4.0 mg/km, as shown in Figure 10. Copper-carbon composite made from flake graphite, carbon black, pitch coke and needle coke had wear rates value of 2.1 – 4.7 mg/km (Ren et al., 2023). This indicated that the carbon-copper composite has acceptable value of wear resistance against the copper ball counterface under the test condition. However, the wear rate was increased with increasing PKS content and decreasing graphite content, indicating that the graphite had good self-lubricating properties.

Figure 11 shows a SEM micrograph of a wear track on a carbon-copper composite surface after the wear test. During the pin-on-disc test, a wear track was created where a copper ball slid against the composite disc. The wear track exhibits a combination of adhesive wear and abrasive wear. Adhesive wear was formed when the material from the pin adhered to the composite surface and is subsequently removed, leaving behind a transferred layer. Abrasive wear occurred when the hard particles, such as debris or loose particles from the composite itself, scratched and removed material from the surface. This is likely contributing to the roughened surface and the formation of grooves within the wear track (Singh & Gautam, 2018).

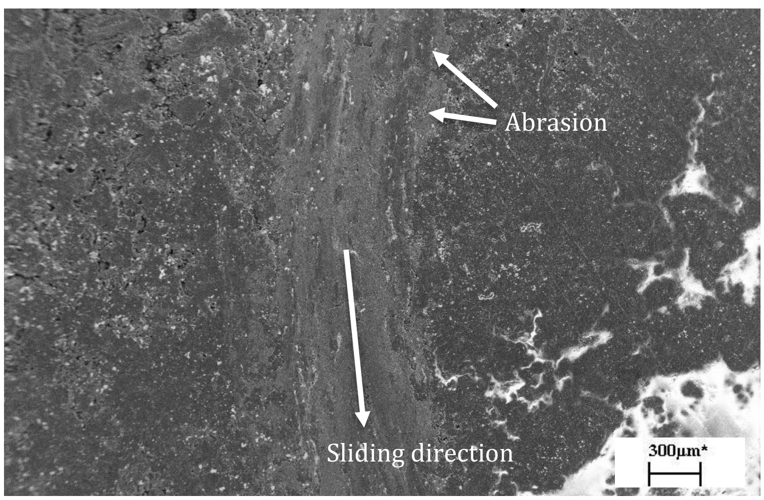

Figure 11: SEM micrograph of the worn surface of Sample 2.

CONCLUSIONS

In conclusion, this preliminary study suggested that incorporating PKS as a natural-based carbon source in copper-based composites has potentials for railway pantograph slide applications. Varying the PKS to graphite ratios and incorporating GO significantly influenced the composites' density, hardness, resistivity, TRS, friction coefficient, and wear rates. All properties showed inconsistent and variation of data upon increment of PKS in the composite. The fluctuation was likely due to the inconsistency of particle size and shape of PKS that may lead to non-uniformity dispersion and weak interfacial bonding between the materials. The composite with lowest PKS to graphite ratio without GO yielded the highest density value of 1.874 g/cm^3, the lowest resistivity (45 μΩ.m) and the highest TRS (41 MPa) values. The results highlighting its potential to enhance electrical conductivity. On the other hand, the highest PKS to graphite ratio without GO resulted in the highest hardness value of 118 HRR. Wear rate and friction coefficient were obtained from the tribometer and compared with the reference pantograph slide. The carbon-copper composites showed significantly reduced friction and low wear rates. The friction coefficient value was less than 0.1 and the wear rate was less than 4 mg/km. This indicated a good tribological compatibility between the copper ball and carbon-copper composite. The composite with lower PKS content and without addition of GO showed a better dispersion and gave similar properties to the commercial carbon pantograph slide. Nevertheless, these findings were based on average data and required further validation through comprehensive statistical analysis with replication. Future research should focus on optimising the PKS to graphite ratio and other conductive filler, including graphene and multi-walled carbon nanotube (MWCNT). Development of copper-based composites with tailored properties has promising potentials for improvement of performance and durability in railway pantograph slides.

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