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Effects of Carbon Type and Composition on the Properties of Carbon-Copper Composite as Pantograph Slide in Railway Application

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ABSTRACT

Carbon-copper composites have wide application prospects as high-speed railway pantograph slides due to the self-lubricating ability of carbon and good conductivity of copper. However, carbon-copper composites produced through powder metallurgy may still encounter challenges, such as poor wettability and lower conductivity. The experimental approach in this work involved the fabrication of carbon-copper composites using the warm compaction method, with different types and proportions of carbon materials, namely local carbon from palm kernel shells (PKS) and graphite. Characterisation and testing of hardness, density, resistivity, transverse rupture strength (TRS), and microstructure of the composites have been conducted. An increase in graphite content was found to improve the electrical conductivity of the carbon-copper composite, while the addition of local carbon has enhanced its hardness. Furthermore, the addition of graphene oxide (GO) as filler has significantly improved the mechanical strength of this composite by up to 61.34%. This research has highlighted the potential of locally sourced carbon for developing advanced pantograph slide materials for railway applications. The findings provided valuable insights into the optimisation of composite compositions to achieve the desired balance

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between electrical conductivity and mechanical performance. These carbon-copper composites hold the promise of more efficient and durable pantograph slides, which can contribute to the overall reliability and sustainability of railway systems.

Keywords: *Pantograph Slide; Carbon-Copper Composite; Warm Compaction*

Introduction

In the development of electrified railways, the performance of the pantograph is crucial, especially for obtaining high-speeds [1]. The pantograph is positioned on the roof of the train cars, while the catenary, which is a configuration of cables, is positioned above the tracks. The pantograph slide serves as a device for transmitting electric energy from traction substations to moving trains [2]. The contact strips require particular characteristics, including resistance to wear, good lubricating properties, high mechanical strength, and sufficient electrical conductivity [3]. These attributes not only can enhance energy transmission during contact between the pantograph carbon strip and the current-carrying overhead catenary, but also minimise energy loss. The wear resistance of the materials, which is also important for a pantograph slide, determines the lifespan of the parts and the frequency of the need to change them. Another key characteristic of pantograph carbon strip is their ability to self-lubricate.

Carbon-copper composites can be applied as high-speed railway pantograph slides due to the self-lubricating carbon and the good conductivity of copper [4]. Carbon composites have become widely used because they offer excellent electrical conductivity, high strength, and good wear resistance [5]-[6]. In addition to carbon composites, copper-based composites have also been investigated as potential materials for pantograph slides. These composites have exhibited good electrical conductivity, thermal conductivity, and corrosion resistance. Copper-matrix composite materials can be added with graphite to improve their anti-friction properties and to meet the requirements for pantograph slide usage [2]. Graphite is a naturally occurring form of carbon with excellent lubricating properties. In addition, graphene oxide (GO) has attracted more attraction because of its remarkable properties [7]. Incorporating GO into pantograph slide materials could enhance their mechanical strength, reduce wear and tear, and improve the sliding contact between the pantograph slides and the overhead wires [8].

The demand for improved pantograph slide materials has led to the development of novel carbon-copper composites. It was implied that the utilisation of locally available materials might eventually replace conventional carbon powder in carbon-copper composite applications for current collectors

[9]. Prior studies have explored substituting conventional carbon with palm kernel shells (PKS)-derived carbon for current collectors, but faced challenges due to porosity and insolubility [10]. To address these issues, they have also optimised the material ratios but did not consider adding GO, which recent research proposed could enhance the performance of pantograph slides as current collectors [11]. However, other issues like poor wettability and weak interfacial bonding between carbon and GO with the metal matrix are yet to be resolved.

The fabrication of carbon-copper composite may be difficult due to the low solubility of carbon-copper. Hence, the use of an external binder to facilitate the interactions between particles is a strategy frequently used in carbon granular technology [12]. Epoxy resin and phenolic resin are examples of good binders because of their low cost, good wettability to carbons, and capacity for generating matrices with a different microstructure on carbon-copper composites [13]. The phenolic resin was used as the binder because of its high adhesive strength and compatibility with carbon and graphite [14]. These characteristics were expected to effectively mitigate the inadequate wetting between carbon, graphite, GO, and copper. The warm compaction technique was used to heat the carbon-copper composite to 200 °C, which was sufficient for the resin to liquefy and to bond the carbon and copper components together [15].

As a current collector, the pantograph slide must exhibit good anti-friction, corrosion resistance, wear resistance, and self-lubrication properties, in addition to good density, resistivity or electrical conductivity, thermal stability, and impact resistance [16]-[17]. While there has been extensive research on the materials and processes for developing pantograph slides or carbon strips, only a few studies have investigated the impact of using locally sourced carbon materials in their formation. It is beneficial to understand the effect of each material on the density, hardness, resistivity, and strength of the formed materials. This understanding will enhance our knowledge of the materials, thus, facilitating the utilisation of abundant and cost-effective local resources in Malaysia [18]-[19]. Hence, the focus of this study was to investigate the processing and properties of carbon-copper composites with different types and compositions of carbon, namely, carbon from palm kernel shells (PKS) and conventional graphite. Furthermore, the effect of GO addition on the physical, mechanical, and electrical properties of the developed materials was also investigated.

Materials and Methods

Materials

Carbon-copper composite materials were produced by incorporating different amounts of carbon (from local carbon material and conventional graphite), copper, phenolic resin, and graphene oxide (GO). The local carbon material used was PKS powder (200 mesh), supplied by Tan Meng Keong Sdn. Bhd. under the brand TMKCARBON. Conventional graphite and phenolic resin were supplied by AFI Brakes Manufacturing Sdn. Bhd. Graphite was the second type of carbon studied in this work, while phenolic resin was used as the binder. Copper powders with sizes ranging from 10 to 25 µm were sourced from Sigma Aldrich, as supplied by a local provider, PLT Scientific Sdn. Bhd. GO was supplied by UM Innovations Sdn. Bhd. In this study, GO was added at a low percentage into the matrix to provide reinforcement. Details of the materials' compositions are shown in Table 1.

Table 1: Composition of raw materials from different types of carbon for producing carbon-copper composites: (A) PKS and (B) graphite

Sample name	**Carbon (g)**	**Copper (g)**	**Resin (g)**	**Graphene oxide (g)**
A1	65	20	15	0
A2	65	20	15	1
A3	70	10	20	0
A4	70	10	20	1
B1	65	20	15	0
B2	65	20	15	1
B3	70	10	20	0
B4	70	10	20	1

Process methodology

The consolidation process began with the mixing of carbon, copper, and resin in a tubular mixer. The main material was carbon at 65% and 70%. Two types of carbon were studied in this work, i.e., local carbon (palm kernel shells, PKS) and graphite. Before undergoing mixing, each powder was weighed according to the selected composition. Table 1 displays the material compositions used in separate eight trial runs. Sample A is indicative of a carbon-copper composite made from PKS, whereas sample B is representative of the composite made from graphite. The mixing time was set for 1 hr at 50 rpm.

Subsequently, the mixed raw materials were subjected to 12 tonnes of cold compaction to create a green body or preform using an automatic hydraulic press machine. The preforms were then fixed into a four-cavity mould measuring at 1 × 1 inch. These preforms underwent further development through the warm compaction method using the hydraulic compression moulding press machine. The pressure was set at 50 tonnes, with a temperature of 200 °C and a soaking time of 5 min. Next, a post-baking process was executed at a temperature of 200 °C and a soaking time of four hours. Figure 1 depicts the process flow for fabricating the carbon-copper composites. Finally, the cured carbon-copper composite was tested for its density and hardness. For resistivity and TRS test, the sample was first sliced into three equal pieces using a Struers Secotom precision cutter with an alumina blade. Scanning electron microscope (SEM) images of the composite cross-sections were captured and discussed.

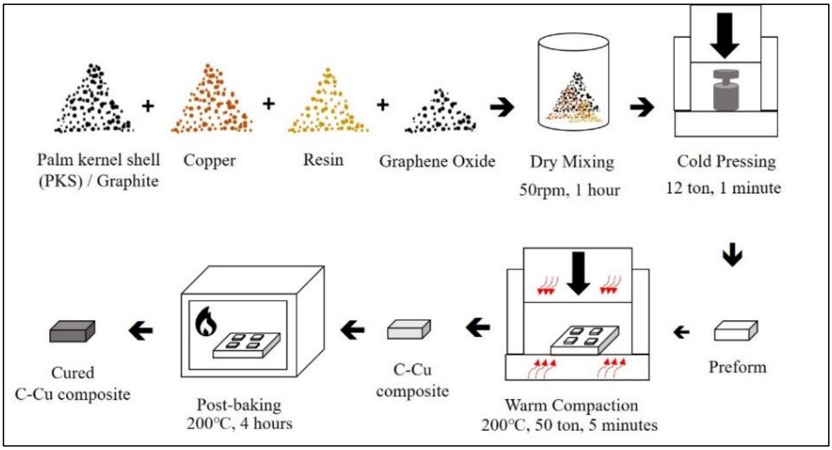


Figure 1: Process flow for fabricating carbon-copper composites

Density test

Density was determined using a density balance (MD-300S) based on Archimedes' principle. The average value was taken from three measures for each sample.

Hardness test

A hardness test was performed using the Rockwell hardness tester (Mitutoyo model HR-430MR), with 60 kgf load and ½ inch ball. Three readings were recorded at three different spots for each sample and an average value was then determined.

Resistivity test

Electrical resistivity was obtained by measuring the resistance using an electrical safety tester from Extech Electronics Co., model EEC. Electrical resistivity was calculated using the following Equation (1):

$$\rho = \frac{RA}{l} \tag{1}$$

where ρ refers to resistivity, *R* refers to 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.

Transverse Rupture Strength (TRS)

The three-point bend test was performed to obtain the TRS using an Instron Universal Tensile Machine, model 3369. This test was performed according to ASTM B528 and ASTM D790. The crosshead speed was set at 3 mm/min. The TRS was measured using the following Equation (2):

$$TRS = \frac{3Pl}{2wt^2} \tag{2}$$

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

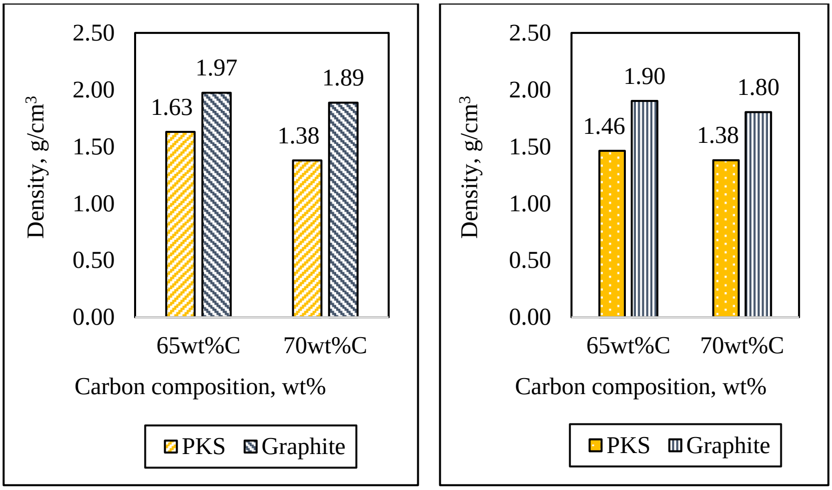
Results and Discussion

Effect of carbon types and compositions on density

Figure 2 illustrates the density of composites composed of PKS and graphite at different compositions, 65 wt%, and 70 wt%, with and without the addition of 1 wt% of GO. In general, the density of the composite composed of graphite was higher than the composite composed of PKS. The highest density of 1.974 gm/cm^3 was obtained with 65 wt.% graphite, 20 wt.% copper, and 15 wt.% resin, without the addition of GO. A similar trend with a higher density was obtained for the graphite-based carbon-copper composite. The density of the composite was decreased when the composition of carbon was increased, and GO was added. Both PKS and graphite showed the same trend. The possible reason for this phenomenon could be due to the increased porosity in the composites when more carbon and GO were added [20].

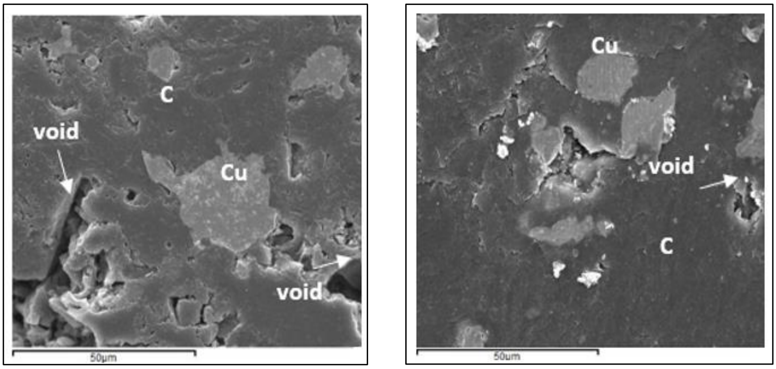
The previous results are supported by the SEM images shown in Figure 3. Regions of the micrographs displaying a smoother and brighter appearance could correspond to the copper matrix. These areas showed a uniform texture due to the conductive nature of copper. The darker regions were indicative of carbon materials.

These SEM images have revealed the distribution and interaction of the constituents of the composites. Homogeneous dispersion of the materials is critical for enhancing mechanical properties and conductivity [21]. The presence of voids affected the effective mass per volume of the sample. Figure 3(b) shows that the sample consisting of graphite has fewer voids. Fewer voids have led to the graphite-copper composite sample with a higher density compared to the sample consisting of PKS [22].



(a) (b)

Figure 2: Density of carbon-copper composites composed of PKS and graphite (a) without GO and (b) with GO



(a) A4 1,000× magnification (b) B4 1,000× magnification

Figure 3: SEM micrographs of the cross-sections of carbon-copper composites (a) PKS and (b) graphite.

Effect of carbon types and compositions on hardness

The hardness of carbon-copper composites with different carbon types at different compositions, without and with GO are shown in Figure 4. The composite composed of PKS showed a higher hardness value compared to the composite composed of graphite. PKS particles could provide a more consistent strengthening effect compared to graphite, which could have a less structured and dispersed presence within the composite matrix [20]. PKS is a natural material that may contain fibrous structures and other components. These properties could enhance the hardness of the composite when PKS is combined with copper [23]. The specific microstructure and composition of PKS could contribute towards the increased resistance of the composite to deformation and increased hardness [24].

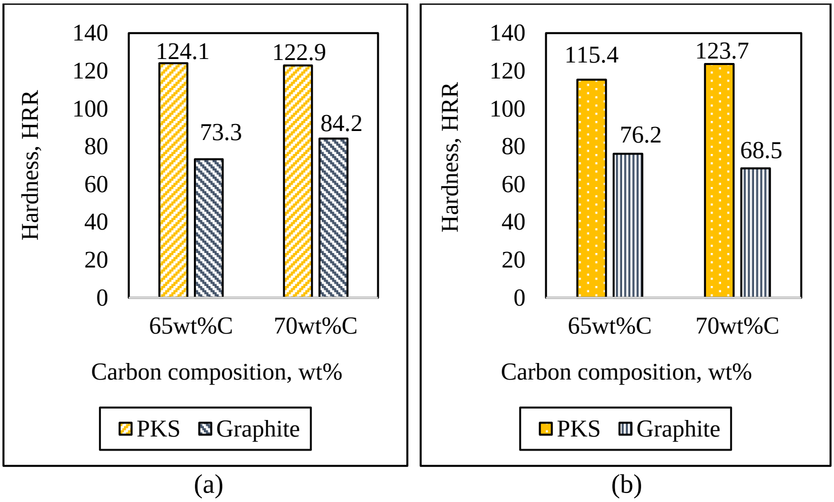
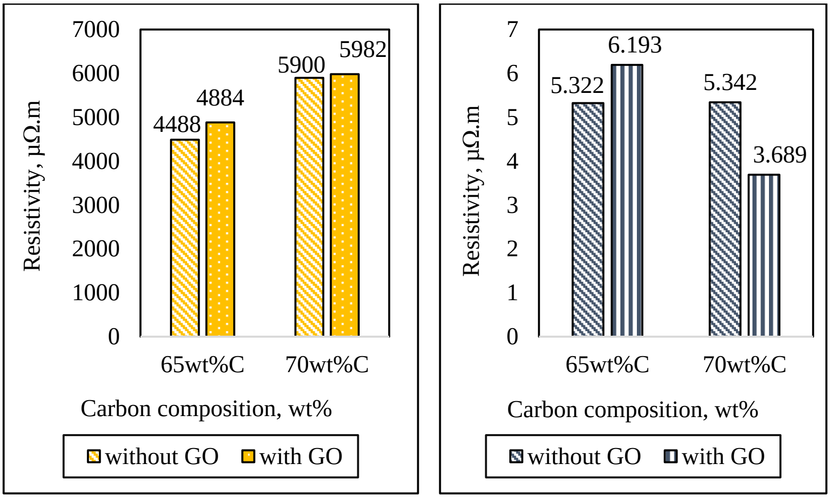


Figure 4: Hardness of carbon-copper composites composed of PKS and graphite (a) without GO and (b) with GO

Graphite is known for its lubricating and slippery nature due to its layered structure [25]. The layers in graphite can slide over each other easily, which may result in a lower hardness compared to a composite that consists of PKS. The lubricating nature of graphite might reduce the ability of the composite to resist deformation. This study has found that the effect of GO on the hardness of the composite was varied. Hence, it did not significantly influence the hardness.

Effect of carbon types and compositions on resistivity

Figure 5 reveals the resistivity of carbon-copper composites composed of PKS and graphite, respectively. The composite with graphite content showed better electrical resistivity compared to the composite with PKS. A low resistivity signifies a high conductivity, indicating the materials' increased ease in permitting the flow of electric charge [10]. Graphite is known for its relatively high electrical conductivity due to its unique hexagonal lattice structure, which allows electrons to move easily between layers [26]. Graphite particles, due to their inherent conductivity, may provide more efficient conductive pathways within the composite [27]. The interfacial contact between graphite and copper may result in better electrical conductivity, thus, leading to a lower resistivity in the composite [28]-[29].



(a) (b)

Figure 5: Resistivity of carbon-copper composites composed of (a) PKS and (b) graphite

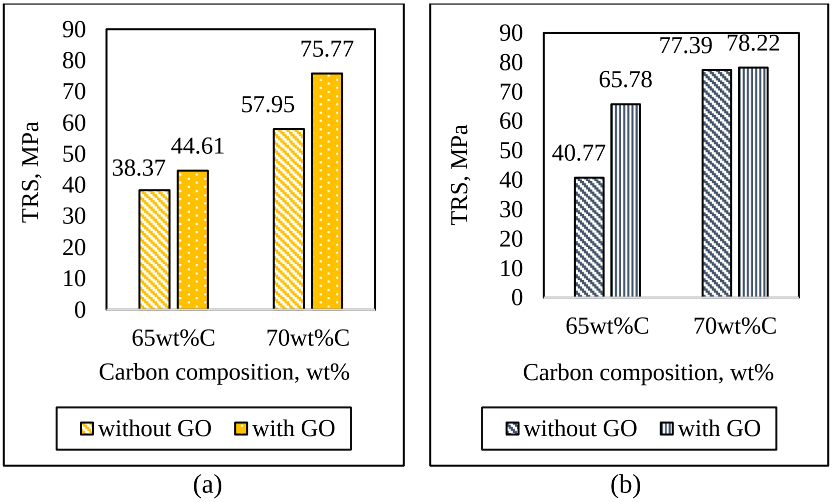
Composites composed of PKS, however, showed a higher electric resistance, thus, implying a low conductivity. The resistivity of the composite could be influenced by the fibrous structure and organic nature of PKS [23]. The specific chemical composition, the presence of impurities, and the arrangement of carbon in the PKS structure could all affect its electrical conductivity [30].

The addition of GO showed insignificant improvement in the resistivity value for both PKS and graphite. Generally, GO would elevate the value of resistivity, which was not favoured for this application.

Effect of carbon types and compositions on TRS

According to Figure 6, the TRS of the PKS composite is lower than the TRS of graphite composite. This phenomenon could be due to the organic and potentially fibrous nature of PKS [23]. The fibrous structure of PKS may not provide as much resistance to transverse rupture as the crystalline structure of graphite. Graphite composite, being a crystalline material with strong interlayer bonding [26], has exhibited a higher TRS compared to PKS composite. The inclusion of GO acted as a reinforcement in both composites, which could enhance their mechanical properties. The addition of GO to the

PKS composite could strengthen the material and improve its resistance to transverse rupture [31].



(a) (b)

Figure 6: TRS of carbon-copper composites composed of (a) PKS and (b) graphite

The addition of GO showed significant enhancement to the strength of the composites. GO, with its high strength and stiffness, could reinforce the potentially weaker PKS composite [32]. While graphite is inherently mechanically strong, the addition of GO as a strengthening agent [6] can further enhance its mechanical strength (TRS) by reinforcing the structure of the composite [31]. The interaction between these components during consolidation and the resulting microstructure could also have an impact on the mechanical properties of the composites [33].

Conclusion

This study has demonstrated that the utilisation of different carbon types and compositions in the consolidation of carbon-copper composites using the warm compaction method could significantly impact their properties. The findings showed the potential of using locally sourced carbon for developing advanced pantograph slide materials in railway applications. Different carbon types and weight ratios have been successfully used to characterise their effects on the properties of carbon-copper composite materials. PKS has shown a more consistent strengthening effect compared to graphite, which could reduce the wettability and interfacial bonding issues. On the other hand, graphite showed a lower resistivity value, between 3.689 μΩ.m to 6.193 μΩ.m, indicating a higher conductivity compared to the PKS-based carbon-copper composite. This would be better for the pantograph slides to transfer current from the traction substation to the moving trains. Blending both types of carbon could potentially enhance the efficiency of the resulting carbon-copper composite and warrants further investigation in the upcoming phase. Carbon-copper composites, with the addition of GO, showed a significant improvement in mechanical strength (TRS) for PKS from 44.61 MPa to 75.77 MPa and from 65.78 MPa to 78.22 MPa for graphite. These carbon-copper composites are promising as efficient and durable pantograph slides, which could contribute to the overall reliability and sustainability of railway systems. These findings could provide valuable insights into optimising the composition of the composite to achieve the desired balance between electrical conductivity and mechanical performance.

Contributions of Authors

The authors have confirmed equal contribution in each part of this work. All authors have reviewed and approved the final version of this work.

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Conflict of Interests

The author, Fazira Suriani Mohamed Fadzil, has received a research grant from SIRIM Berhad and executed this project both at SIRIM Berhad and Universiti Teknologi MARA Cawangan Pulau Pinang. The remaining authors have no conflict of interest to declare.

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