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Physical and Mechanical Properties of Local Carbon Materials and Warm Compaction Method on the Production of Current Collectors for Light Rail Transit (LRT) Applications

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ABSTRACT

The purpose of this study is to investigate the physical and mechanical properties of local carbon materials and the warm compaction method in the production of current collectors for light rail transit (LRT) applications. The problem here is that the current collectors used by the railway industry in Malaysia for the LRT are still imported from foreign countries which is very costly. Furthermore, the production method of commercial current collectors, namely C-Cu composites, is compact and sintered, which also results in relatively high costs. Therefore, this study focuses on replacing the old materials and methods of commercial current collector production with new materials and methods. This study used a local carbon, which is the kernel shell of oil palm as the main carbon for the production of current collectors. The compact and sintered production methods are then replaced by warm compaction and post-heating methods. The current collectors that had been produced are then cut into several samples to allow them to be tested in a

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number of physical and mechanical tests. Based on the test results, when using these new materials and methods, the density and hardness were observed to be slightly lower at 1.81 g/cm^3 and 122.6 HRR compared to the commercial current collectors, which have a density of 2.2 g/cm^3 and 126.9 HRR. Meanwhile, in the transverse rupture strength (TRS) and resistivity tests, the warm compaction method based on oil palm kernel shell demonstrated higher values of 175.1 MPa and 1631 Ω-cm, respectively, compared to the commercial current collectors which showed values of 58.71 MPa and 598.77 Ω-cm. In conclusion, there are various advantages and disadvantages between the new current collectors and the commercial current collectors in terms of mechanical as well as physical characteristics. Therefore, various improvements and suggestions need to be made in order to produce physically and mechanically better current collectors to be used in LRT applications.

Keywords: *Current Collector; C-Cu Composites; Local Carbon; Physical and Mechanical Test*

Introduction

Electric trains are currently used in all developed countries, including Malaysia. Among the important components to generate electricity for electric train use is the current collector. Furthermore, the existing collectors used by Malaysia's railway industry are still imported from foreign countries such as France and Canada, at a very high cost of up to RM 2 million a year. Carbon-copper (C-Cu) composites are used to produce current collectors [1]. This is due to the widespread usage of carbon-copper composites in electrical and electronic applications [2]. Among them are carbon brushes for engines and generators or current collectors for railway power collection systems [3].

In addition, this (C-Cu) composite also has a high electrical conductivity, making it suitable to be used as the main composite in the production of current collectors [4]. The (C-Cu) composites combine the good thermal and electrical conductivity properties of Cu as well as the high wear resistance and low thermal expansion of carbon or graphite [5].

In this era of globalization, people are becoming increasingly concerned about the use of renewable energy. Therefore, this study focuses on the replacement of conventional carbon with carbon derived from palm kernel shell waste. Specifically, the carbon used in this case is produced by the Malaysian Palm Oil Board (MPOB) from the shells of oil palm kernels. MPOB is a government agency entrusted with serving the country's palm oil industry [6]. The Malaysian palm oil industry has witnessed significant growth since the crop was first introduced to the country from West Africa in the late 1870s [7]. Initially, oil palm species like "*Elaeis Guineensis*" were cultivated as ornamental plants [8].

Since its introduction as an ornamental plant in Malaysia, palm oil has proven to be one of Malaysia's biggest economic success stories. Thus, based on the value of palm oil crops and exports, it shows that there is a significant amount of kernel shell residue that can be obtained from the palm oil manufacturing process [9]. Oil palm kernel shell has 77.7% holocellulose, which consists of 44.2% α-cellulose and 33.5% hemicellulose. Due to these components, the palm kernel shell has a carbon content of 42% - 43%, making it suitable for replacing conventional carbon [10].

Therefore, this study aims to identify the physical and mechanical properties of local carbon materials for the production of current collectors in Light Rail Transit (LRT) applications. The research focuses on both price and quality factors by utilizing waste materials and replacing them with local carbon sourced from MPOB, instead of using conventional carbon. Warm compaction and post-heating methods will also be employed in this study to replace the sintering process, which typically requires extremely high temperatures for compacting the composite (C-Cu). As the sintering process involves high temperatures, the cost tends to be higher as well. To ensure that this alternative process does not impact the physical and mechanical properties of the produced samples, comprehensive physical and mechanical tests will be conducted and compared with commercial current collectors provided by the railway industry.

Methods and Materials

Sample preparation

The process starts to produce current collectors using local carbon for light rail transit (LRT) applications. As illustrated in Figure 1, the process begins with the crushing process of the oil palm kernel shell. The kernel shell received from MPOB was crushed using a Turbula shaker mixer machine. This process was carried out by mixing the oil palm kernel shell and a stainless-steel ball used as the blending medium.

Figure 1: Oil palm kernel shell

To ensure that the particle size of the oil palm kernel shell is properly crushed and fine, the crushing process is carried out for 60 minutes. The shell of the oil palm kernel is then sifted to obtain finer particles. The purpose of the sifting process is to acquire a good size of carbon in order to make the mixing and compaction process easier. This process is carried out by using a vibrating sieve machine. Only oil palm kernel shell powder with a size of (<150 µm) will be used for the current collector production process while the rest will be used as waste material. The preparation for the production of this current collector is continued by preparing raw materials consisting of carbon, copper, and 67.5 g of epoxy resin as the main materials as shown in Figure 2. The main materials consist of 65% (292.5 g) carbon, 20% (90 g) copper and 15% (67.5 g) epoxy resin. These main materials are then mixed using a Turbula shaker mixer machine for 30 minutes at a speed of 50 rpm. The prepared raw materials are then compacted in a cold compaction process using a mold to create a current collector sample. This cold compaction process is carried out using an Automatic hydraulic press machine with a pressure of 18 tons for 1 minute.

Figure 2: Carbon powder, copper, and epoxy resin

Upon compaction, the compacted sample called a green body with a density of 70% of the theoretical density is removed from the mold using a Carver 12 tons hydraulic hand press machine. The material is then compacted once again for 5 minutes using a warm compaction technique at a predetermined temperature of 150 °C and a pressure of 70 tonnes. After this process, the sample density is expected to be higher than after the cold compaction process.

Then, the sample would undergo a post-heating process at a predetermined temperature of 200 °C. This post-heating process is carried out using a forced air-drying oven machine. In this process, the epoxy resin in the warm compaction composition would turn out to be more even and uniform as well. The purpose of this post-heating process is to produce a better surface final finish. Finally, the sample is then cut into required sizes to be made into a specimen to proceed with physical and mechanical testing. The sample is cut to size 25.4 x 25.4 x 8 mm for the density and hardness test, while for the transverse rupture strength (TRS) test the sample had to be cut to a size of 25 x 8 x 8 mm. Figure 3 shows a flow process for the sample preparation process.

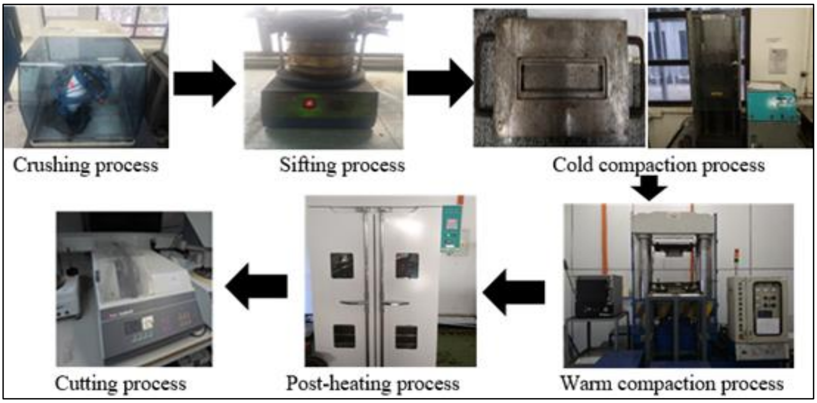


Figure 3: Sample preparation of processes flow

Experiment set-up

Among the mechanical tests that were carried out was a hardness test to determine the hardness of the sample by means of a Rockwell hardness tester machine using a load of 60 kgf (588.399 N) and a 0.5-inch ball point as shown in Figure 4(a). Next, a transverse rupture strength test or a three-point bending test using a Universal testing machine as shown in Figure 4(b). A cross speed of 2.5 mm/min with a span of 20.5 mm between the supported rollers and samples with dimensions of around 25 x 8 x 8 mm were used for this test. While the physical test consisted of an X-ray diffraction (XRD) test using an X-ray diffraction machine as shown in Figure 5(a). XRD analysis is a non-destructive versatile analysis technique for the identification and quantitative determination of crystalline compounds. This was followed by a density test to determine the density of the sample using an electronic density meter machine as shown in Figure 5(b).

Results and Discussion

X-ray Diffraction (XRD) test

Figure 6 shows a graph resulting from X-ray diffraction between atomic planes in a composite (C-Cu) current collector using an oil palm kernel shell as the main carbon and compacted using the warm compaction method. There were several peaks generated consisting of the main materials of carbon and copper. This indicates that there was more than one phase, namely amorphous and crystalline. In addition, the peak was formed also because this current collector used 65% carbon and 20% copper as the main material to produce this current collector.

(a) (b)

Figure 4: (a) Rockwell hardness tester machine and (b) Universal testing machine

(a) (b)

Figure 5: (a) X-ray diffraction (XRD) machine and (b) Electronic density meter machine

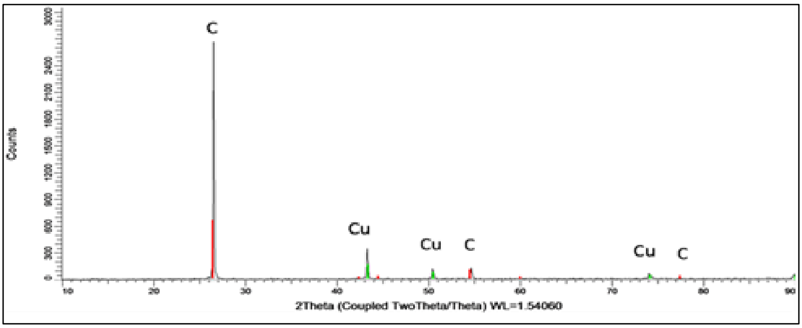


Figure 6: X-ray diffraction of a C-Cu composite current collector using local carbon and compacted using the warm compaction method

Density test

The density of the current collector is significantly influenced by the raw material used. Characteristics such as powder particle size selection, method, and compaction temperature are very important to obtain a good density and are suitable for the use of LRT current collectors. Table 1 shows that the density of the current collector with local carbon as well as the warm compaction method and post-heating is around 1.81 g/cm^3. Whereas the density of a commercial current collector is 2.20 g/cm^3. The production method of the commercial current collector, i.e. carbon-copper composite, is done by compaction and sintering process. Therefore, based on these findings, using these new materials and methods, the density of the current collectors is slightly lower than that of the commercial current collectors. This is likely due to the lack of pressure and temperature applied during the compaction process. Therefore, another way to increase the density of the current collector is by adding another element such as Titanium [11]. Because the density of this current collector test sample is slightly low, it implies that the porosity of this current collector sample is high, thereby reducing its lifespan [12].

Table 1: Density of current collectors with local carbon as well as warm compaction and post-heating methods

Sample	**Density (g/cm$^{3)}$**
A	1.75
B	1.82
C	1.88
D	1.77
E	1.85
Average (A, B, C, D, and E)	1.81
Commercial current collector (*Carbone Lorraine* brand)	2.20

Hardness test

The hardness of a sample is dependent on the temperature applied to it during the compaction process. In general, the high temperature applied during the compaction process will result in the hardness of the sample produced also increasing [13]. Commercial current collectors with C-Cu composite materials are produced using a compaction and sintering process at temperatures of up to 2500 °C [10]. Table 2 shows that the hardness of the current collector made with this oil palm kernel shell using the warm compaction method is around 122.6 HRR. While the hardness of commercial current collectors is at 126.9 HRR. Therefore, replacing the compaction and sintering process with a 150 °C warm compaction process as well as a 200 °C post-heating process causes the sample hardness to be slightly reduced compared to commercial current collector samples. However, by using a warm compaction process as well as post-heating, the production cost of the current collector can be reduced as a lower temperature is applied during the compaction process.

Table 2: Hardness of current collectors using oil palm kernel shell based warm compaction method

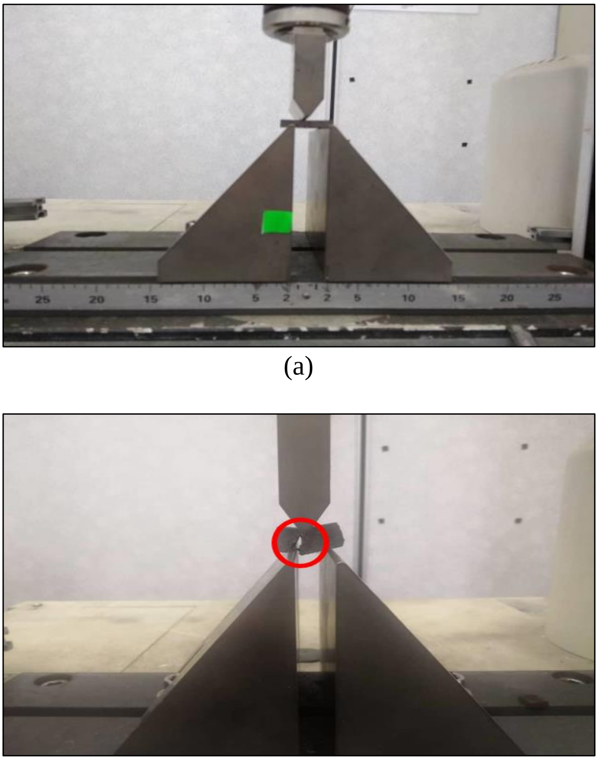
Sample	Hardness (HRR)
A	125.3
B	123.5
C	118.9
D	124.0
E	121.2
Average (A, B, C, D, and E)	122.6
Commercial current collector (*Carbone Lorraine* brand)	126.9

Transverse Rupture Strength (TRS) test

In theory, the flexural strength is determined by the stress applied during the compaction process. Thus, the high stress used during the compaction process will cause an increase in the flexural strength of a sample. This is due to the large contact area between copper particles [14]. Therefore, the contact rate of copper generally has the greatest impact on the overall flexural strength. Table 3 shows that the average transverse rupture strength stress for this sample is 175.1 MPa. While the transverse rupture strength stress for commercial samples was measured at 58.71 MPa. This indicates that employing local carbon as well as warm compaction and post-heating methods will cause an increase in the value of the transverse acceleration strength stress. This is especially good because higher stresses are important for current collector applications. However, these results are regarded as less consistent and too high. The observed discrepancies can be attributed to various factors, such as imprecise cut sizes and uneven thickness. Meanwhile, Figures 7 show the condition of the samples before and after the test.

Table 3: Transverse rupture strength (TRS) test

Sample	Displacement (mm)	Load (kN)	Stress (MPa)	Strain (mm/mm)
A	0.9165	0.4147	155.5	0.0012
B	0.9851	0.6565	246.2	0.0013
C	1.2600	0.3299	123.7	0.0017
Average (A, B, and C)	1.0539	0.4670	175.1	0.0014
Commercial current collector (*Carbone Lorraine* brand)	-	-	58.71	-



(a)

(b)

Figure 7: The condition of the sample; (a) before and (b) after the TRS test

Resistivity test

Resistivity or electrical resistivity test is a test conducted to measure a material's resistance ability to withstand the flow of electric current. Therefore, low resistivity allows electrical charge to travel more easily, and this is very important for electrical applications, especially current collectors. For the resistivity test of this study, a critical review was conducted for unavoidable reasons. Hadi et al. [15] conducted a study of the physical and mechanical properties of carbon-copper composites compacted with different powder formulations. The samples that were produced were then labelled as samples X, Y, and Z according to the material formulation used as shown in Table 4. The oil palm kernel shell was also used as the main carbon source in the study. The study's findings include the resistivity and transverse rupture strength (TRS) of carbon-copper composite samples. The results of the study, namely the resistivity and TRS of the samples, were then plotted on a graph according to samples X, Y, and Z as shown in Figure 8 [15]. Based on the results, the resistivity of samples X, Y, and Z were 1788 Ω-cm, 1691 Ω-cm and 1414 Ω-cm. Meanwhile, the resistivity of the commercial current collector, Carbone Lorraine was 598.77 Ω-cm.

The resistivity of carbon-copper (C-Cu) composite samples fabricated using the oil palm kernel shell and warm compaction method exhibits a marginally higher value compared to that of commercial current collectors. This outcome is undesirable since current collectors should ideally possess low resistivity to enable the smooth flow of electric current. This high resistivity is possible due to the large amount of porosity within the sample [14]. Therefore, by increasing the compaction pressure and the compaction temperature, the resistivity can be reduced. In addition, the resistivity can also be reduced by adding a percentage of copper to the sample production formulation.

As a result of these findings, the C-Cu carbon-copper composite samples produced using the warm compaction method are suitable for current collector applications. However, several aspects need to be improved, such as increasing the sample compaction pressure. Additionally, by increasing the compaction temperature and adding a copper percentage to the sample production formulation, the resistivity of the sample will be reduced. Therefore, after taking into account these aspects, this method of warm compaction may be seen as suitable to be applied in current collector production, especially for LRT use.

Table 4: Formulation of carbon-copper (C-Cu) composite sample [15]

Sample	**Carbon (%)**	**Copper (%)**	**Epoxy resin (%)**
X	65	20	15
Y	60	25	15
Z	55	30	15

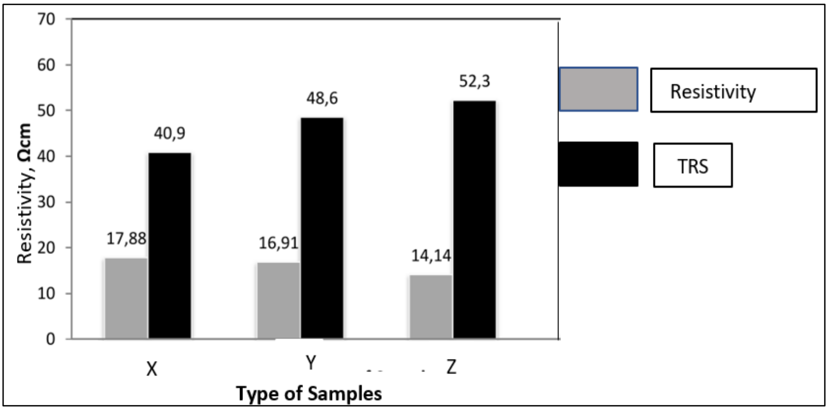


Figure 8: Resistivity and TRS results of samples X, Y, and Z [15]

Conclusion

In conclusion, the use of these materials and advanced technologies has had a positive impact on current collector production. In addition, replacing the compaction and sintering process with a warm compaction and post-heating process has also slightly influenced the hardness but is able to reduce the production cost for current collectors. This is very good because it lowers the operating costs of the railway industry which usually needs to change the current collector every 6 months.

Furthermore, local carbon which is oil palm kernel shell can also be used to replace conventional carbon as it does not adversely affect the production and main characteristics of current collectors. This is great because in addition to being able to reduce the cost of production of current collectors, it also promotes environmental sustainability by replacing conventional resources with waste materials.

Additionally, the selection of the size of local carbon powder, which is the finer oil palm kernel shell (<150 µm) is also good because it has a positive effect on the hardness and transverse rupture strength of the current collector. This is probably due to the use of a finer powder that can reduce the porosity of the sample or collector current produced.

Finally, by conducting this study, a prototype sample of a current collector using oil palm kernel shell as the main carbon and compacted using the warm compaction and post-heating method has been successfully produced. In addition, the physical and mechanical properties of current collectors with these new materials and methods have also been successfully obtained. Finally, this study also compared with a commercial current collector labeled Carbone Lorraine to ensure that the results obtained meet the standard to be used in LRT applications.

Contributions of Authors

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

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Conflict of Interests

All authors declare that they have no conflicts of interest.

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