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CASE STUDY ON SUITABILITY OF RAIL GREASE PERFORMANCE FOR LIGHT RAIL TRANSIT (LRT) KELANA JAYA, MALAYSIA

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Abstract: *This study evaluates the performance characteristics of three commercial rail curve greases that could potentially be used for Light Rail Transit (LRT) Kelana Jaya. The greases were tested for their tribological, physical, and chemical properties, including elemental composition, rheological behaviour, thermal stability, wear resistance (WP), and extreme pressure (EP) performance. Elemental analysis confirmed the presence of significant elements such aluminium, calcium, phosphorus, and molybdenum, which contribute to the greases' anti-wear and load-carrying capacities. Rheological testing demonstrated that the greases exhibited viscoelastic behaviour with shear-thinning characteristics, and notable differences in yield stress and viscosity were observed at various temperatures. Thermal stability tests showed that Grease A maintained high stability up to 190°C, while Grease B demonstrated the highest thermal resistance, withstanding temperatures up to 250°C. Four-ball testing revealed that Grease B exhibited superior friction-reducing properties and wear resistance, while Grease A showed excellent load-carrying capacity and high EP performance. These findings suggest that grease possesses the necessary attributes to ensure reliable lubrication in rail systems, particularly under extreme operational conditions such as high friction and shock loads. The study highlights the importance of selecting appropriate grease formulations to enhance the performance and longevity of rail lubrication systems, offering valuable insights for future research and optimization of rail lubrication technologies.*

Keywords: *Thermal stability, coefficient of friction, extreme pressure, viscoelastic behaviour*

1. INTRODUCTION

Lubrication involves applying a lubricant between two moving surfaces to reduce friction, wear, and heat. This technique lessens direct contact between the surfaces, promoting smoother motion and minimizing potential damage. Lubricants may be in the form of oils, greases, or solids, depending on their intended use. As stated by [1], the process of lubrication is undoubtedly a complex topic. The friction coefficient between two surfaces in contact is affected by numerous factors, and it is often challenging to isolate the influence of each variable. A thorough evaluation of these factors is essential to grasp how varying conditions influence the effectiveness of a lubricant.

Rail lubrication involves applying lubricants to railway tracks, wheels, or other components to minimize friction, wear, and noise at the contact points between train wheels and rails. This is especially crucial in areas with tight curves, heavy traffic, or large loads, as these conditions intensify the strain on both the wheels and rails. This will help guarantee the safety and economic viability, which rely on the reliability and service life of train wheel pairs and rail tracks operating at speeds of up to 350 km/h and beyond as mentioned by [2].

The term "grease" originates from the Latin word "crassus," which translates to "fat" [3]. Lubricating greases are a type of lubricant that do not flow freely like liquids but release oil (bleed) when subjected to pressure between contact surfaces. With a gel-like consistency, they behave as solid or semi-fluid materials. Due to their non-Newtonian rheological properties, greases offer excellent resistance to dripping, making them suitable for use in vertical or overhead applications [4]. Additionally, their thick structure helps form a protective barrier, reducing wear and corrosion, especially under heavy loads or in equipment exposed to harsh operating conditions. In these situations, grease creates thicker films on surfaces, while oil films can be too thin and easily break.

Grease is composed of three main components: base oil, thickener, and additives. Typically, it contains 75–90% base oil, 5–20% thickening agent, and 0–10% additives [5]. The base oil acts as the main lubricating component, facilitating smooth movement between surfaces, while the thickener imparts a semi-solid consistency to the grease, enabling it to remain in position during use. Additives are incorporated to improve various characteristics, including resistance to oxidation, corrosion, and wear, as well as to offer protection under extreme pressure. The proportion of these components influences the grease's effectiveness in varying operating conditions, such as temperature, load, and speed. Consequently, choosing the appropriate formulation is crucial for specific applications, including lubrication systems for rail wheels.

The LRT Kelana Jaya line currently utilizes a type of grease in its rail and maintenance systems. However, this grease tends to harden over time due to prolonged exposure to operational conditions, such as friction and environmental factors. As the grease hardens, it reduces its effectiveness in lubricating the system, which in turn increases the wear and tear on the tracks and other components. This results in higher maintenance costs, longer repair times, and, ultimately, a decrease in the overall efficiency of the system. Moreover, the hardened grease may cause long-term damage to the rail infrastructure, leading to potential safety risks and operational disruptions

In the current study, the objective is to evaluate the suitable rail grease lubrication for the Light Rail Transit (LRT) Kelana Jaya line, it is crucial to examine the tribological, physical, and chemical properties of various grease lubricants. This analysis aims to identify the grease that best aligns with the operational requirements and environmental conditions of the rail system. By gaining a detailed understanding of these properties, the study seeks to enhance the performance and reliability of the Wheel Lubrication System (WLS), ultimately improving the safety and efficiency of the LRT Kelana Jaya line.

2. EXPERIMENTAL METHODS

2.1 Materials

Commercial rail curve greases currently utilized in the local railway industry for wheel and rail flange lubrication were identified. These greases are sprayable fluid types designed to operate with spray lubrication systems. In practical applications, the grease is stored in a tank mounted on a designated train axle, where it is heated and pumped to two nozzles (positioned on the left and right sides) using compressed air. As the train approaches curved sections of the rail, small amounts of grease are electronically dispensed in pulses and sprayed onto the inner railhead. This grease is then distributed along the rail and onto subsequent wheels. Figure 1 illustrates the three types of commercial rail greases selected for this study.

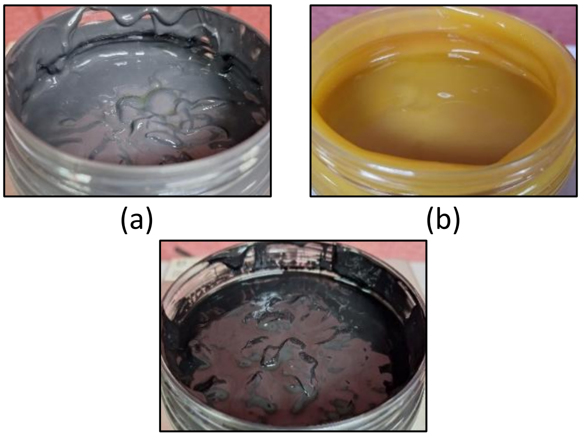


Figure 1. Type of commercial rail grease (a) Grease A (b) Grease B (c) Grease C

Based on the figure, each grease has different colour indicate different element that contain in the grease. These greases are applied to the wheel flange and rail gauge to minimize wear, reduce squealing, and mitigate noise during curves. They are also marketed as biodegradable and are commonly referred to as bio-greases.

2.2 Elemental Analysis

Elemental analysis of the commercial reference greases was performed using the Spectroil Q100 atomic emission spectrometer, following the ASTM D6595 standard for detecting up to 33 elements in the parts per million (ppm) range. A small grease sample was applied to the spectrometer, where it was burned at high temperatures to excite the atoms, causing them to emit characteristic wavelengths of light. These wavelengths were measured to identify and quantify the elements present with high sensitivity and precision. To ensure reliable results, each sample was tested five times, minimizing errors and ensuring consistency.

2.3 Rheological Properties

The rheological characterization of the grease samples was performed using the HAAKE RheoStress 6000 Rheometer, a precise instrument designed for advanced material testing. In this experiment, the rheometer was set up with a parallel-plate configuration, where the plates had a 50 mm diameter and were separated by a gap of 0.5 mm. The flow characteristics under rotational shear were evaluated by analysing the steady-state viscous flow and the relationship between shear stress and shear rate. This analysis was conducted within a shear rate range of 0.1 to 100 s^{-1} and a temperature range of 25°C to 100°C.

2.4 Thermal Stability

Thermogravimetric Analysis (TGA) was conducted using the TGA/DSC 1 Mettler Toledo to assess the thermal stability and composition of grease samples. Approximately 10 mg of each sample was heated from 25°C to 950°C at a controlled rate of 10°C/min under a nitrogen atmosphere (100 ml/min) to prevent oxidation. The samples were placed in platinum crucibles to ensure accuracy and minimize contamination. Weight loss at various temperature stages was monitored, revealing information about volatile evaporation, decomposition, and thermal transitions. This analysis provided valuable insights into the thermal stability, degradation behaviour, and composition of the greases, enabling comparisons between different commercial greases.

2.5 Four Ball Testing

The wear preventive (WP) properties of grease samples were evaluated using the ASTM D2266-01 standard and the four-ball test method. The setup included four AISI 52100 steel balls (61–63 HRC, 14.7 mm diameter), with three stationary balls clamped in a pot and a rotating ball positioned above them. Approximately 10 ml of grease was applied, and the sample was heated to 75°C to replicate operational conditions. A load of 40 kg was applied, and the top ball was rotated at 1200 rpm for 60 minutes. Frictional forces and the coefficient of friction were recorded in real-time. After the test, wear scar diameters on the stationary balls were measured to assess the grease's anti-wear performance. This provided valuable insights into the wear protection capabilities of the grease and allowed comparisons between different formulations.

The extreme pressure (EP) test, conducted per ASTM D2596, evaluated the load-carrying capacity and wear prevention capabilities of the grease under high-pressure conditions. Using four thoroughly cleaned AISI 52100 steel balls, the test simulated extreme mechanical pressures by rotating the top ball at 1760 rpm for 10-second cycles at 27°C. The load was initially set high and incrementally decreased until the balls no longer seized or welded together, indicating the grease's maximum load-bearing capacity. Fresh balls were used for each cycle to ensure accuracy. The recorded seizure load represented the grease's ability to maintain a protective film under extreme pressure, with higher values indicating superior performance in preventing wear and failure in demanding conditions. The summary of the tests parameters for WP and EP are listed in Table 1.

Table 1. Test parameters of WP and EP testing

Parameters	WP (ASTM D 2266)	EP (ASTM D 2596)
Speed (rpm)	1200 ± 60	1760 ± 40
Load (kg)	40	At decreasing load until unseizure occur
Duration	60 ± 1 min	Series of 10 seconds
Temperature (^{o}c)	75 ± 2	27 ± 8

3. RESULTS AND DISCUSSIONS

3.1 Elemental Analysis

Elemental analysis was performed to identify the elements present in three different rail curve greases using a Spectroil Q100. The detected elements provide valuable insights into the composition of the base oil, thickener, and additives, which in turn helps predict the grease characteristics. Table 3 summarizes the major elements identified in the greases, reflecting the types of thickeners and additives used. The analysis revealed that the greases contained several common elements, including aluminium (Al), calcium (Ca), iron (Fe), potassium (K), magnesium (Mg), sodium (Na), phosphorus (P), silicon (Si), strontium (Sr). Notably, Grease A exhibited a high concentration of Ca 427 ppm on average, while Grease B had an average P concentration of 324 ppm. Grease C, on the other hand, showed a concentration of 683 ppm for molybdenum (Mo).

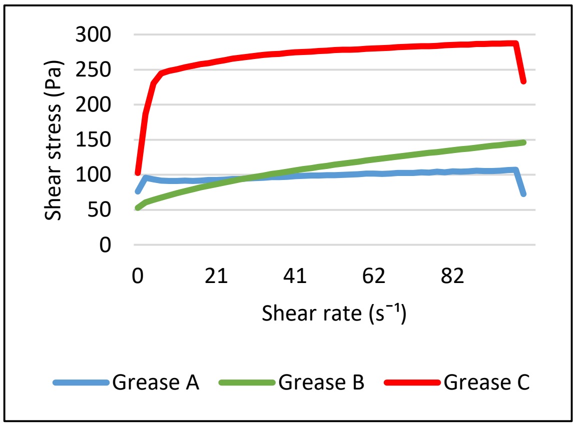
According to [6], various elements in greases can be attributed to specific sources. Silicon (Si) may originate from contaminants in clay thickeners, zinc (Zn) is typically derived from additives, and calcium (Ca) can come from both the thickener and extreme pressure additives. Aluminium (Al) and magnesium (Mg) are primarily sourced from clay thickeners, while elements such as molybdenum (Mo), phosphorus (P), bismuth (Bi), and zirconium (Zr) are associated with anti-wear and extreme pressure additives. Additionally, barium (Ba) found in Grease C is likely to be from an inhibitor additive. These findings are consistent with the work of [7], who outlined the essential properties for rail curve greases, which include excellent extreme pressure and anti-wear performance, along with strong adhesion.

Table 2. Element analysis of the grease

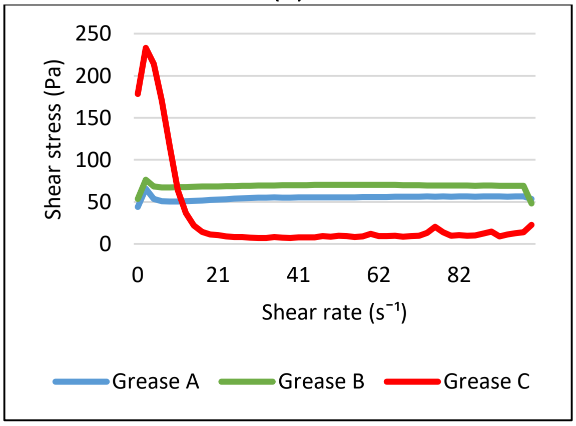
Grease A	Grease B	Grease C
Al	Al	Al
Ca	Ca	Ca
Fe	Fe	Fe
K	K	K
Mg	Mg	Mg
Na	Na	Na
P	P	P
Si	Si	Si
Sr	Sr	Sr
V	Li	Ba
Zn	Ti	Mo

3.2 Rheological Properties

The rheological behaviour of lubricating grease is closely related to its flow and deformation under applied stress or strain. From a rheological perspective, greases are considered viscoelastic substances, with their flow characteristics influenced by the type and concentration of the thickener used [8]. The elasticity plays a crucial role in preventing grease leakage from lubricated joints, while the fluidity is important for both the effectiveness of lubrication and the ease of grease pumping. Figure 2 shows the shear stress versus shear rate for different types of grease.



(a)



(b)

Figure 2. Shear stress for different type grease (a) at 25°C and (b) at 100°C

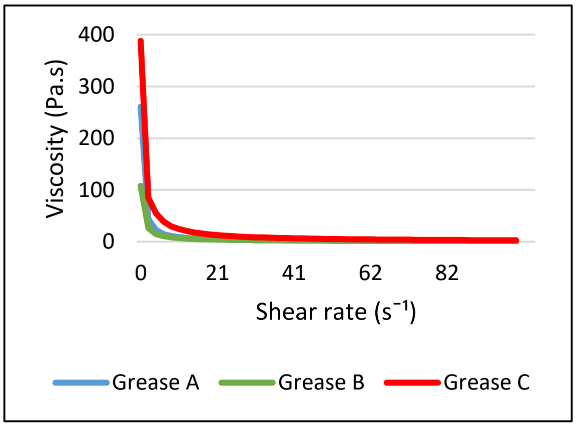
Figure 2(a) illustrates the shear stresses of the three greases samples at room temperature (25°C), showing pseudoplastic behaviour with a yield stress occurred at similar range of shear rate. The results indicate that a shear rate range of approximately 0.4 to 6.2 s^{-1} is needed to initiate flow in the palm greases tested. In its resting state, the grease forms an intermolecular network structure that gives it solid-like properties, predominantly exhibiting elasticity [9]. When external stress is applied through rotational shear, the intermolecular network structure is altered. Once the yield stress is surpassed, the grease undergoes elastic deformation and begins to flow. As the shear rate increases, the shear stress continues to rise, demonstrating the typical shear-thinning behaviour of lubricating grease systems [10].

Furthermore, moderate fluctuations in the yield point values of the greases were observed. For example, the grease B, which exhibited the lowest yield point, indicated instability in the suspension, likely due to external factors during the formulation process. In contrast, the grease C showed inadequate thickener content, which led to poor binding and resulted in low shear stress at low shear rates. Figure 2(b) illustrates the stress behaviour of the grease samples at an elevated working temperature of 100°C. The grease A and B maintained their pseudoplastic behaviour, although with a lower yield point compared to grease C. Figures 3 show the apparent viscous flow curves for the three greases respectively, at a room temperature of 25°C and 100°C.

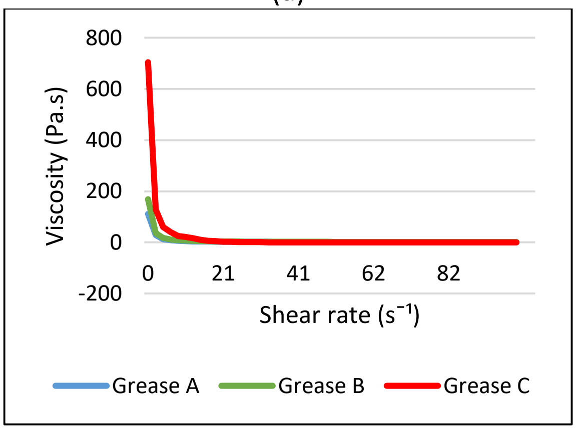
A viscosity peak was observed for three greases, indicating that the greases underwent elastic deformation or stretching. This peak corresponds to the yield point, where the elastic structure of the grease breaks down, and the grease starts to flow. In general, viscosity decreased steadily as the shear rate increased, exhibiting shear-thinning behaviour or pseudoplastic flow, with a limiting viscosity observed in the high shear rate region. Shear thinning occurs due to microstructural rearrangements within the grease under applied shear.

At a working temperature of 25°C, the grease C exhibited the highest viscosity, with values of 241.78 Pa.s, respectively, at a shear rate of 0.42 s^{-1}. As the shear rate increased to 49 s^{-1}, the viscosity of these samples decreased to 5.65

Pa.s, representing reductions of approximately 97%, respectively. In comparison, the grease A and grease B experienced a 1% higher of viscosity reduction which is around 98%, dropping from 147.02 Pa.s to 2.06 Pa.s and for grease B dropping from 106.78 Pa.s to 2.26 Pa.s across the same shear rate range. This demonstrated that the flow behaviour of the three greases was comparable to each other. In contrast, the grease B, exhibited lower viscosity compared to the others, showing only minimal shear thinning. This was due to the semi-solid structure of the grease, which behaved more like a Newtonian fluid and resulted in a low yield point (Figure 3). Figure 4 illustrates the impact of temperature on the viscosity for different greases.



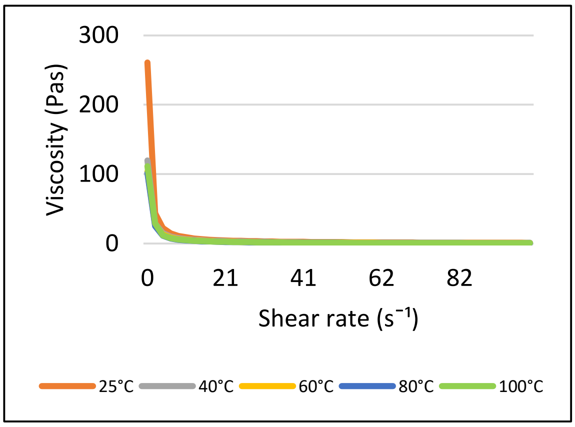
(a)



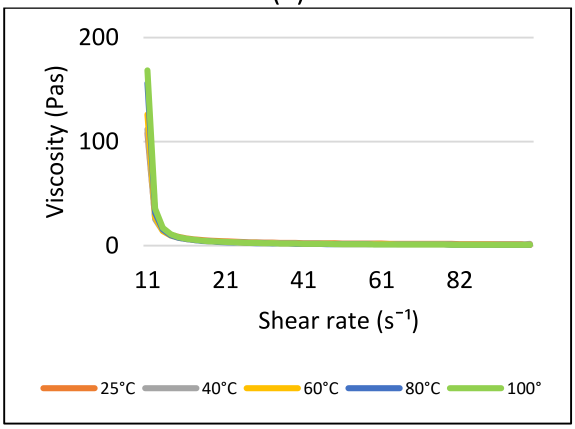
(b)

Figure 3. Viscous flow curves of the grease samples at (a) 25°C and (b) 100°C operating temperature

As shown in Figure 4(a) and 4(b), the viscosity of the greases gradually decreased when the temperature increased from 25°C to 100°C. However, the grease C exhibited a more abrupt viscosity drop between 25°C and 40°C. At higher temperatures, its viscosity became comparable to that of the 25°C since it could be due to the grease characteristic that hardens at high temperature thus increase the viscosity. In practical applications, the reference grease is typically heated to 75°C before being applied via a spraying method.



(a)



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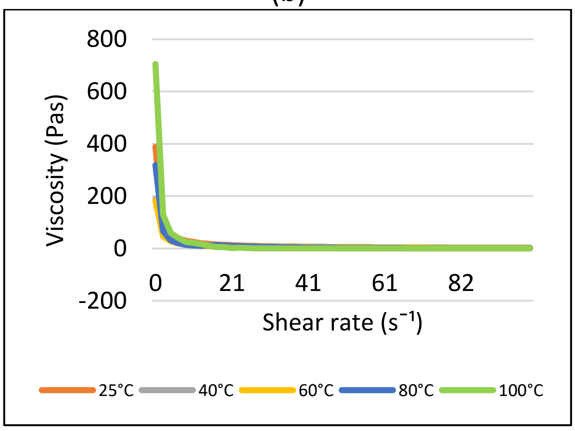


(c)

Figure 4. The impact of temperature on the viscosity for different greases (a) Grease A (b) Grease B and (c) Grease C

The higher viscosity at room temperature is primarily for storage purposes, facilitating handling, particularly for export. Notably, the grease B demonstrated the greatest temperature stability, showing the least variation in viscosity at higher working temperatures and somehow would not harden at high temperatures.

3.3 Thermal Stability

Figure 5 presents the thermal stability of the three commercial greases, emphasizing the differences in performance among commercial greases.

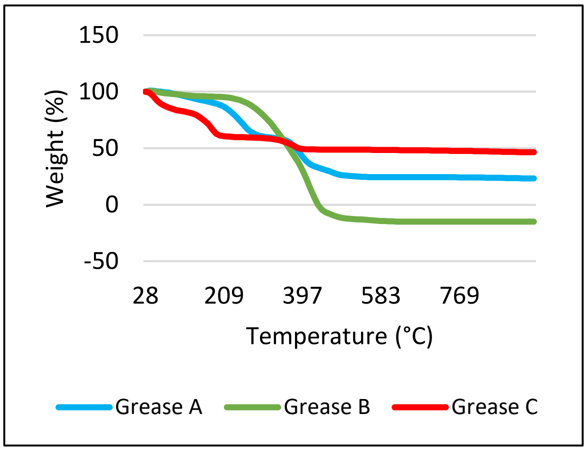


Figure 5. Thermal stability for different grease

Grease A demonstrated considerable thermal stability, maintaining more than 90% of its original properties up to 190°C, with no significant degradation observed. Grease B exhibited the highest stability, withstanding temperatures up to 250°C without notable deterioration. The possibility of having high phosphorus (P) in Grease C improved its thermal resistance, enabling it to maintain stability and perform effectively at temperatures of 150°C and above, thus meeting the temperature requirements for rail lubrication applications. In contrast, Grease C exhibited the lowest thermal stability among the tested formulations, with degradation occurring at temperatures exceeding 60°C.

3.4 Four Ball Testing

The friction and wear behaviour of commercial rail curve greases were assessed through tribological testing using the four-ball test method. The results of the wear preventive (WP) test are presented in Table 3, while the friction coefficient measurements over time for the three types of greases are shown in Figure 6.

Table 3. WP properties for different type of grease

Rail Curve Greases	Average Friction Coefficient	Average Wear Scar Diameter (mm)
Grease A	0.062	0.64
Grease B	0.051	0.59
Grease C	0.062	0.93

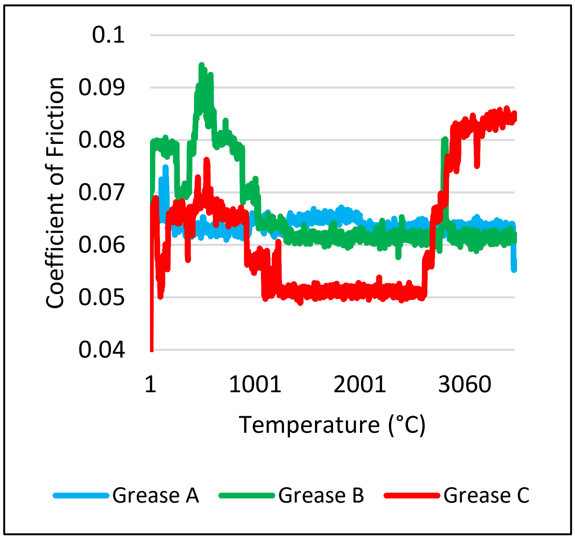
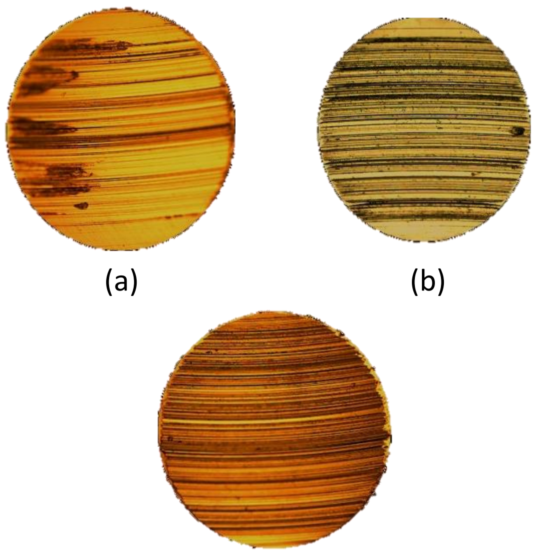


Figure 6. Coefficient of friction reading for different grease

The average friction coefficients ranged from 0.040 to 0.090, indicating good friction-reducing properties. Grease B demonstrated the lowest friction coefficient, being approximately 17% lower than Greases A and C, respectively. This reduction is likely attributed to the presence of higher phosphorus (P) element in the grease. P provides rolling effects and forms protective films on the contact surfaces, which reduces friction. This observation aligns with [11], who noted that phosphorus-based additives are generally highly effective in situations involving low sliding speeds and rough surface conditions. Therefore, this is particularly relevant to wheel and rail applications involving sliding contacts. Additionally, other metal elements such as Si, Al, Fe, Ca, and Zr in the greases are believed to contribute significantly to their low friction and anti-wear properties. These metals have been widely studied in previous research as nanoparticle additives in lubricating oils and greases, where they have been shown to effectively reduce friction and wear ([12], [13], [14]). Table 4 and Figure 7 shows the WP properties of wear scar diameter for different type greases.

Table 4. Wear scar diameter for different grease

Type of grease	Wear scar diameter (mm)
Grease A	0.32
Grease B	0.29
Grease C	0.51



(a) (b)

(c)

Figure 7. Wear scar diameter for different grease

The surface analysis revealed that the steel balls tested with grease C exhibited a larger wear scar diameter, measuring 0.51 mm as shown in Figure 7. The scar was more pronounced, though not perfectly circular, in comparison to those from the other greases. Grease B exhibits a notable wear scar diameter that correlates with its coefficient of friction, resulting in a smaller wear scar. This behaviour, especially when compared to grease A and C, is likely attributed to the presence of solid additives in grease B as stated before.

The solid additive particles help reduce friction at the sliding surfaces by providing rolling effects. However, a high concentration of such particles in the lubricant can create stress concentrations on the contact surface, potentially leading to abrasive wear and rubbing between the surfaces. This observation aligns with the findings of [15] cited by [7], who reported that a 0.5 mass % concentration of hexagonal boron nitride (hBN) nanoparticles in a lubricant resulted in a larger wear scar diameter compared to a 0.05% mass concentration of hBN. In contrast, Grease B exhibited both a low friction coefficient and a smaller wear scar diameter, approximately half the size of Grease C's and 8% smaller than Grease A's. This can be attributed to the high presence of silicone (Si) and phosphorus (P) elements in Grease B. Previous studies have demonstrated the effectiveness of these elements as lubricant additives for reducing friction and wear ([16], [17]).

The extreme pressure (EP) properties of the tested greases revealed that all the rail curve greases exhibited excellent load-carrying capacity as shown in Table 5.

Table 5. Extreme pressure properties for different grease

Grease	Range maximum load (kg)
Grease A	220 – 225
Grease B	135 – 140
Grease C	145 - 150

Grease A shows that with weld loads exceeding 200 kg. This is particularly suitable for applications involving steel wheel-to-steel rail contact, where the surfaces are subjected to very high loads and extreme contact pressures. As a result, the grease must be capable of protecting the surfaces and preventing welding under conditions of intense friction. As shown in Table 5, grease B and grease C had smaller range of maximum load at 135kg - 150 kg. In contrast, Grease A demonstrated superior load-carrying capacity, able to withstand up to 220 kg and resist welding at 225 kg. Despite its relatively softer properties compared to grease C and lesser thermal stability compared to grease B, Grease A maintained its lubricating film effectively under high loads without degradation. This performance is primarily attributed to the extreme pressure additives in the form of solid particles, as discussed earlier.

4. CONCLUSIONS

The present study examined the fundamental characteristics of three commercial greases potentially used in the LRT Kelana Jaya Line, specifically at the wheel flange and rail gauge contact points. These characteristics were assessed in terms of elemental composition, rheological behaviour, thermal stability, wear resistance, and extreme pressure performance. The test results revealed that all three greases contained a range of elements, including aluminium (Al), calcium (Ca), iron (Fe), potassium (K), magnesium (Mg), sodium (Na), phosphorus (P), silicon (Si), and strontium (Sr), which contribute to their anti-friction, anti-wear, and load-carrying properties.

The three greases exhibited viscoelastic behaviour, with viscosity decreasing progressively as shear strain increased, demonstrating shear-thinning or pseudoplastic characteristics that were comparable across the samples. Notably, Grease A exhibited the highest thermal stability, showing minimal viscosity variation at elevated temperatures and retaining its performance without hardening at high temperatures.

The inclusion of molybdenum, aluminium, and phosphorus-based compounds enhanced both the friction-reducing properties and the thermal stability of the greases, allowing them to withstand temperatures exceeding 250°C and maintain extreme pressure capabilities up to 220 kg of non-seizure load. These properties enable the grease to reduce wear by ensuring effective lubrication under high friction and shock-loading conditions.

Together, these characteristics indicate that the greases are well-suited for the demanding conditions of rail curve lubrication in the LRT Kelana Jaya Line. Future studies are recommended to explore the tribological properties of these greases further, employing methods such as the pin-on-disc test to gain additional insights into their performance.

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REFERENCES

[1] R. E. Wilson and D. P. Barnard, "The Mechanism of Lubricant," vol. 17, pp. 282–320, 1922.

[2] V. Alisin, B. Pokidko, M. Roshchin, and G. Simakova, "Lubricants to reduce wear of wheels and rails high-speed rail transport," *IOP Conf. Ser. Mater. Sci. Eng.*, vol. 919, no. 2, 2020, doi: 10.1088/1757-899X/919/2/022032.

[3] E. Becker, *Automotive Tribology*, vol. 80, no. 10. 2024. doi: 10.1007/978-981-15-0434-1.

[4] D. Puhan, "Lubricant and Lubricant Additives," *Intech*, vol. 11, no. tourism, p. 13, 2016, [Online]. Available: https://www.intechopen.com/books/advanced-biometric-technologies/liveness-detection-in-biometrics

[5] U. Chandra Sharma and N. Singh, "Biogreases for Environment Friendly Lubrication," *Environ. Sci Eng*, vol. 1, no. March, pp. 1–13, 2019, [Online]. Available: https://www.researchgate.net/publication/331904328

[6] C. Marume, "Elemental Determination of Lubricating Grease Using Icp-Oes," 2014.

[7] I. H. A. Razak, M. A. Ahmad, and S. W. Puasa, "Tribological and physiochemical properties of

greases for rail lubrication," *Tribol. Online*, vol. 14, no. 5, pp. 293–300, 2019, doi: 10.2474/trol.14.293.
[8] L. Salomonsson, G. Stang, and B. Zhmud, "Oil/thickener interactions and rheology of lubricating greases," *Tribol. Trans.*, vol. 50, no. 3, pp. 302–309, 2007, doi: 10.1080/10402000701413471.
[9] I. H. A. Razak, M. A. Ahmad, S. H. Abdullah, and M. H. F. M. Hazani, "Rheological and tribological behaviors of bio-grease based on palm ester thickened with calcium complex thickener," *J. Tribol.*, vol. 38, no. May, pp. 100–117, 2023.
[10] A. Saxena, D. Kumar, and N. Tandon, "Development of eco-friendly nano-greases based on vegetable oil: An exploration of the character via structure," *Ind. Crops Prod.*, vol. 172, no. July, p. 114033, 2021, doi: 10.1016/j.indcrop.2021.114033.
[11] L. R. Rudnick, "Lubricant additives: Chemistry and applications, third edition," *Lubr. Addit. Chem. Appl. Third Ed.*, pp. 1–694, 2018, doi: 10.1201/9781315120621.
[12] A. Nabhan, A. Rashed, N. M. Ghazaly, J. Abdo, and M. Danish Haneef, "Tribological properties of al2o3 nanoparticles as lithium grease additives," *Lubricants*, vol. 9, no. 1, pp. 1–12, 2021, doi: 10.3390/lubricants9010009.
[13] A. Rylski and K. Siczek, "The effect of addition of nanoparticles, especially ZrO2-based, on tribological behavior of lubricants," *Lubricants*, vol. 8, no. 3, pp. 1–25, 2020, doi: 10.3390/lubricants8030023.
[14] S. Shahnazar, S. Bagheri, and S. B. Abd Hamid, "Enhancing lubricant properties by nanoparticle additives," *Int. J. Hydrogen Energy*, vol. 41, no. 4, pp. 3153–3170, 2016, doi: 10.1016/j.ijhydene.2015.12.040.
[15] N. Talib, R. M. Nasir, and E. A. Rahim, "Tribological behaviour of modified jatropha oil by mixing hexagonal boron nitride nanoparticles as a bio-based lubricant for machining processes," *J. Clean. Prod.*, vol. 147, no. 2017, pp. 360–378, 2017, doi: 10.1016/j.jclepro.2017.01.086.
[16] D. W. Johnson, "The Tribology and Chemistry of Phosphorus-Containing Lubricant Additives," *Adv. Tribol.*, no. October, 2016, doi: 10.5772/63654.
[17] J. F. Luiz and H. Spikes, "Tribofilm Formation, Friction and Wear-Reducing Properties of Some Phosphorus-Containing Antiwear Additives," *Tribol. Lett.*, vol. 68, no. 3, 2020, doi: 10.1007/s11249-020-01315-8.