Jurnal Tribologi 46 (2025) 13-31

MYTRIBOS Malaysian Tribology Society

Jurnal Tribologi

Website : jurnaltribologi.mytribos.org e-issn: 2289-7232

Sustainable greases from waste cooking oil: A multi-aspect study of formulation, physical properties, and tribological performance

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KEYWORDS

Coefficient of friction
Sodium soap thickener
Tribology properties
Waste cooking oil
Wear scar diameter

ABSTRACT

The diminishing supply of mineral oil is increasing environmental concerns. This study explores the potential of waste cooking oil (WCO) as a viable alternative. WCO, sourced from improperly discarded, used vegetable oil (VO), offers a sustainable, long-term solution to oil scarcity issues. This study aims to create semi-solid lubricants known as greases made from WCO by mixing them with different amounts of sodium soap thickener (SST) for evaluating their performance characteristics. The first step involves treating WCO via heating and filtering to remove undesired impurities. The treated WCO is defined as TWCO. Then, the greases were formulated with specific amounts of SST and additives to achieve the desired quality. Hence, the greases produced were tested for performance. The consistency, oil bleeding, oil separation, dropping point, and tribology properties like the coefficient of friction (COF) and wear scar diameter (WSD) are the most important properties that are looked for. Therefore, this study shows that all WCO-based greases met performance standards, with $SG_{58}M$ being the best due to its low COF and WSD values. However, this study reveals that TWCO is a suitable base oil for producing long-lasting grease, offering a sustainable alternative to mineral oil-based greases.

Received 30 September 2024; received in revised form 25 January 2025; accepted 1 March 2025.
To cite this article: Hairunnaja et al. (2025). Sustainable greases from waste cooking oil: A multi-aspect study of formulation, physical properties, and tribological performance. Jurnal Tribologi 46, pp.13-31.

1.0 INTRODUCTION

In the pursuit of sustainable environmental practices, the importance of recycling waste cooking oil (WCO) cannot be overstated. By reusing WCO for alternative applications such as lubricants or even as base oil in the production of grease, we contribute significantly to the reduction of environmental pollution. This innovative recycling strategy aligns with global efforts to mitigate the impact of waste on our natural ecosystems and reduce the strain on limited natural resources (Abd Aziz et al., 2017; Abd Aziz et al., 2018; Alias et al., 2018; Muhammad Auni Hairunnaja et al., 2023). Research in this area continues to expand our understanding of how WCO can be repurposed effectively, underscoring the necessity of such efforts in our collective commitment to environmental conservation. The term vegetable oil (VO) describes a class of lipids that come from a variety of plant-based sources, such as fruits (e.g. avocados or olives), grains (e.g. corn or wheat), nuts (e.g. almonds or walnuts), and seeds (e.g. sunflower or sesame). One of the most important steps in the production process is the extraction of these raw materials, which frequently involves techniques like solvent extraction, pressing, or a combination of both to optimize oil yield. Vegetable oil has numerous applications, despite being mostly utilized for human consumption in cooking, frying, and as an ingredient in processed foods. These include its application in technological fields such as lubricants, cosmetics, and biofuels; its use as a base or excipient in pharmaceutical preparations; and its inclusion in animal feed formulation.

According to Zambelli et al. (2015), the major components of vegetable oils are triacylglycerols, making up around 92% to 98% of their composition. Other components include monocylglycerols, diacylglycerols, polar lipids (phospholipids and galactolipids), and minor elements such as poly-isoprenoids and free fatty acids are commonly found (Angelo, 1996; Zambelli et al., 2015). WCO is known as the used VO which refers to the leftover oil after consumption. The amount of WCO increases because people use more edible oils like vegetable and animal oils. These oils come from restaurants and homes, and authorities collect them to prevent environmental pollution. If WCO is improperly disposed of, it may lead to water contamination problems (Isa et al., 2017; Sia Yiik Swan et al., 2024).

Due to the chemical composition of WCO which comprises unsaturated fatty acids (USFAs), and saturated fatty acids (SFAs), WCO is commonly sustainable and effective as base oil for grease product (Mannu et al., 2019). These USFAs including oleic and linoleic acids provide low-temperature performance and non-gel structure in lubricant which provide the required fluidity and flexibility (Abdullah et al., 2016; Swathi et al., 2017). Unfortunately, they are prone to oxidation and undergo a reduction in the thermal stability and sometimes may disintegrate when used for a long time or in severe conditions (Zhang et al., 2013).

While on the other hand due to their high melting point and non-susceptibility to chemical degradation, SFAs including palmitic, stearic, arachidic are very necessary for enhancing the oxidative and thermal stability of WCO (Anand et al., 2021; Hammoud et al., 2021; Verma & Banerjee, 2019). For example, stearic acid has the COF under boundary lubrication conditions and hinders direct metal-to-metal contact by forming a stable anti-wear film on the rubbing surface (Kumar et al., 2019). Grease's base oil also consists of palmitic acid, which determines the grease's viscosity and thickening characteristics and is highly important for maintaining high-load lubrication (Verma & Banerjee, 2019).

Another long-chain SFA which is responsible for the increased lubricity of vegetable oil is Arachidic acid. Due to the increase in the length of the hydrocarbon chain, this fatty acid gives better film strength on steel surfaces as well as adhesion, and enhances the ability of the oil to reduce wear and friction between contact surfaces at high temperature & pressure (Su et al., 2023). This fatty acid also intensifies the functionality of stearic and palmitic acids and is more appropriate for the applications that demand stability under strong shear force in the long-run.

Then, the proportion of the USFAs to the SFAs can be altered and optimized by blending or through chemical conversion to meet the specific formulation needs of the WCO for grease formulation process (Karmakar et al., 2017). This is due to the fact that the oxidative stability of the oil also increases when hydrogenation raises the concentration of SFA, thereby making the oil to be more suited for extreme temperatures (Daniels et al., 2006). In Addition to this, the utilization of WCO that contain higher amounts of SFAs acts as a way to enhance the WCO functionality. This balance is important to ensure that the grease has enough mobility for lubrication, yet it has the right rheological properties, tribology characteristics, and mechanical shear and heat stability.

Even though fresh VO contains antioxidant agents such as vitamin E (tocopherols), polyphenols, and carotenoids, which help enhance the oil's stability during heating (Taghvaei & Jafari, 2015). Studied research shows antioxidant content in VO tends to decrease with extended use (Reda, 2011). People usually agree that fresh VO contains more USFA oils than SFAs. VO transforms into WCO, making the amount of USFAs decrease over repeated utilizations. Therefore, the WCO still retains its role as a grease’s base oil due to the amount of SFAs presence which maintains its functionalities. The SFAs single bond makes them more heat-resistant and stronger compared to other fatty acids (Anand et al., 2021). Meanwhile, the USFAs bonds tend to be stronger but weaker and more prone to break under thermal stress (Petersen et al., 2024).

Then, beyond the previously listed elements, WCO's efficacy as a lubricant depends on specific compounds that enhance its stability in various scenarios, particularly by offering emulsification, microbiological resistance, environmental friendliness, friction reduction, and water resistance. Herman et al. (2021) have emphasized the importance of these capabilities in guaranteeing the overall reliability of WCO in lubricant applications. The source of many of these compounds is coming from SFAs, which are generated when VO is repeatedly consumed. WCO is not recommended for human consumption due to the SFAs formation that occurs when vegetable oil is often used.

Apart from that, the incorporation of WCO in grease production has the additional advantage of being an environmental win-win solution that replaces petroleum-based oils by offering a sustainable and eco-friendly choice. It has been discovered that WCO greases can further enhance the durability and performance of numerous industrial applications by controlling the composition of USFAs to SFAs and incorporating antioxidants into the grease’s mixture. The SFAs therefore work in synergistic action to support the WCO, reduce the USFA oxidation rates, and enhance the general performance of the oil. This mixing ideal not only improves the performance of the WCO greases but also shows its potential for the versatility sector of the lubrication industry with low environmental impact.

In addition, researchers are concerned about the ongoing decrease in mineral oil, which is crucial for making products like grease. Previous studies by Abdulbari et al. (2011) showed that using WCO instead of mineral oil in grease production is possible. Grease is a mix of solid and semi-solid substances from base oil, thickener, and additives. In this study, WCO is the base oil, and sodium soap is the thickener. Although it is true that the thickening makes the base oil in grease more viscous, it also plays a crucial role in determining other important aspects of the grease. The type and concentration of thickener used have a big impact on things like mechanical stability (consistency), tribology and lubricity, temperature resistance, and overall performance. Thus, it is oversimplified to say that the thickener just thickens without changing other characteristics. In order to guarantee an accurate portrayal, a thorough investigation into these effects is required.

Grease is also included with additional components like various additives to enhance performance and minimize the bad perception towards its necessity and functionalities, especially in the industrial sector (Indah Thuraya Herman et al., 2024; Rohazriny Rohim et al., 2024). In around 2400 B.C., grease was also known as the traditional lubricant when it was involved in formulation using VO as base oil (Muhammad Auni. Hairunnaja et al., 2023). The good thing is, that the formulated grease was made from environmentally friendly components that may undergo biodegradation process naturally without any concerns due to its lower potential pollution ability. According to Sofi et al., (2019), well-made grease can perform better in various industries, depending on the production process and equipment involved. Then, the grease's properties are strongly influenced by factors like the thickener used, oil viscosity, and additives. Grease also can reduce friction between two moving parts and minimize the wear and heat effects (Muhammad Auni. Hairunnaja et al., 2023; Nur Amira Fatihah Bashari et al., 2024).

However, this study aims to turn waste cooking oil into a practical grease product by using soap thickener. The research is motivated by soap's ability to thicken and concerns about the environmental impact of waste oil utilization. Different combinations of waste cooking oil and soap thickener, including additives like Molybdenum disulfide (MoS_2) and graphite were implemented, to understand their effects on properties like consistency, oil bleeding, oil separation, corrosive ability, tribology analysis (e.g. coefficient of friction (COF) and wear scar diameter (WSD)) (M. A. Hairunnaja et al., 2023). Additionally, MoS_2 and graphite are known as friction modifier agents (Shahira Liza Kamis et al., 2024), but graphite is also known as a thermal resistor agent (Abd Aziz et al., 2024). Hence, this study aims to create an environmentally friendly soap-based grease, establish a production method, and analyze the result product's characteristics. Therefore, this study aims to determine the best grease formulation based on established standards.

2.0 MATERIALS AND METHODS

2.1 Materials

This research followed a method described in a previous study by Abdulbari et al. (2011) to create greases. WCO and sodium stearate were employed for base oil and thickening agent. In contrast, this study used fixed amount (2wt%) of additives—molybdenum disulphide (MoS_2) and graphite—to enhance the grease's thermal stability and friction-modifying properties. The WCO came from the university cafeteria, and sodium stearate was purchased from R&M Chemicals (Malaysia). MoS2 and graphite were bought from Sigma-Aldrich and R&M Chemicals. To ensure a well-blended grease, a rotor-stator homogenizer was employed to thoroughly mix all the components.

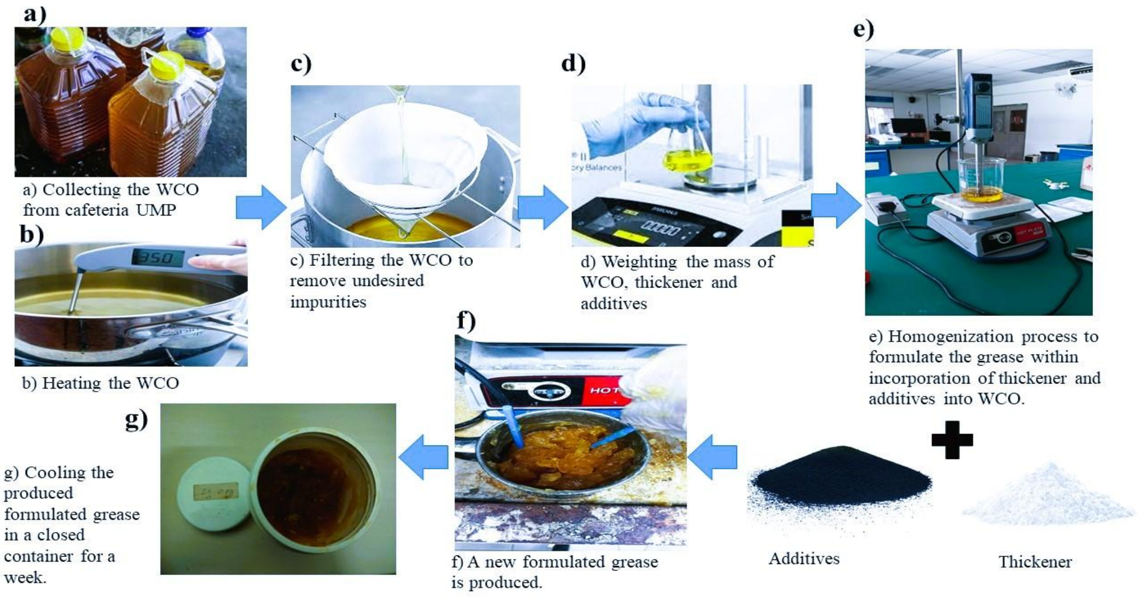
2.2 Grease Formulation

2.2.1 Pre-treatment of WCO

The Waste Cooking Oil (WCO) goes through a pre-treatment to get rid of impurities and water in the oil, known as moisture content. There are two steps in this process: filtering and heating. In the beginning, the oil is passed through filter paper with tiny pores (1.2 μm) to remove small impurities. Next, the oil is heated to over 100˚C to eliminate water, which evaporates quickly beyond its boiling point of 100˚C. This heating process takes 1 to 2 hours at temperatures exceeding 150˚C to remove moisture content completely (Abdu Rahman et al., 2019; Chandraseagar et al., 2019). The current WCO which is now called treated waste cooking oil (TWCO), is ready and will be used in the sodium grease formulation.

2.2.2 The Process of Sodium Grease Formulation Within Additives Addition

This study created three types of sodium greases, both with and without additives. The process began by heating TWCO to 180°C for an hour. During this time, a small amount of Sodium stearate was slowly added to the heated TWCO. After that, it took another three hours to thoroughly mix the components using a stator-rotor homogenizer (Daihan Model HG-15A) at a minimum speed of 5000 rpm. This process continued until a smooth sample was achieved. This step was specifically to produce sodium grease with additives. Therefore, when making sodium grease with additives, the additives were added after a smooth paste was formed by stirring for an hour without heating. This ensures a thorough mixing of additives in the mixture. The process includes cooling the formulated grease in a sealed container for 2-5 days. This to ensure the grease was completely cooled down and removed the heat effectively. Heat can disrupt the molecular structure cohesion between base oil, thickener, and additives. It's important to note that all sodium greases follow the compositions outlined in Table 1. Figure 1 depicts the steps in the formulation of grease.



a) Collecting the WCO from cafeteria UMP

b) Heating the WCO

c) Filtering the WCO to remove undesired impurities

d) Weighting the mass of WCO, thickener and additives

e) Homogenization process to formulate the grease within incorporation of thickener and additives into WCO.

f) A new formulated grease is produced.

g) Cooling the produced formulated grease in a closed container for a week.

Figure 1: Steps in grease formulation process.

Table 1: Composition stated for formulation of sodium greases.

Sample	Abbreviation	TWCO (wt %)	Thickener (wt %)	Additives
Sodium Grease	SG_{60}	60 %	40 %	-
	$SG_{58}G$	58 %	40 %	2 % Graphite
	$SG_{58}M$	58 %	40 %	2% MoS_2

SG_{60} is sodium grease with 60% TWCO. $SG_{58}G$ and $SG_{58}M$ are sodium greases with 2% graphite and 2% MoS_2, respectively. These abbreviations will be used in the following discussion.

2.3 Grease Analysis

To determine the properties of the grease itself, the formed grease will be subjected to several physical tests, including tribology, oil bleeding and separation, dropping point, and consistency tests.

2.4 Consistency Test

The Consistency test helps determine the hardness of grease. It's crucial to use this method to identify grease consistency when choosing the right type for a specific use. According to Sofi et al., (2019), the best grease for industrial applications usually has a consistency value in the NLGI range of 2-3. This grease tends to stay solid due to internal binding forces but can turn from semisolid to liquid if subjected to excessive force. In this study, the SKF's grease test kit was used to measure grease consistency. The test involved placing a set amount of grease between a glass plate and a 500-gram weight. The plate was positioned on the NLGI scale, and the weight was applied for 15 seconds to record the NLGI values of the greases. Figure 2 shows the way of using the SKF grease test kit and NLGI scale of the grease sample.

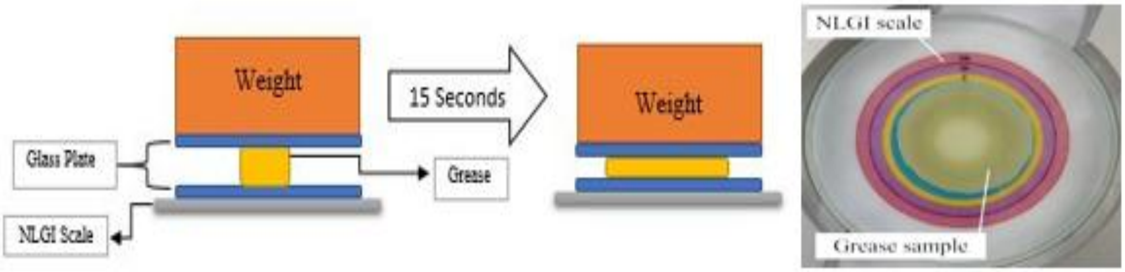


Figure 2: Method of applying the NLGI grease sample scale and SKF grease test kit.

2.5 Oil Separation Test

This test checks how well waste cooking oil (WCO) separates from a specific grease over time during storage. It follows the ASTM D-1742 standard for oil separation in stored grease. The test involves leaving 100g of grease undisturbed in a closed container for a month. After that, the oil that separates from the grease is collected and measured as a percentage of weight. Equation 1 was used to calculate this percentage based on the mass of the separated oil and the original grease sample. Figure 3 depicts the systematic diagram for oil separation process on grease.

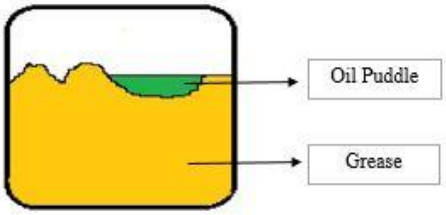
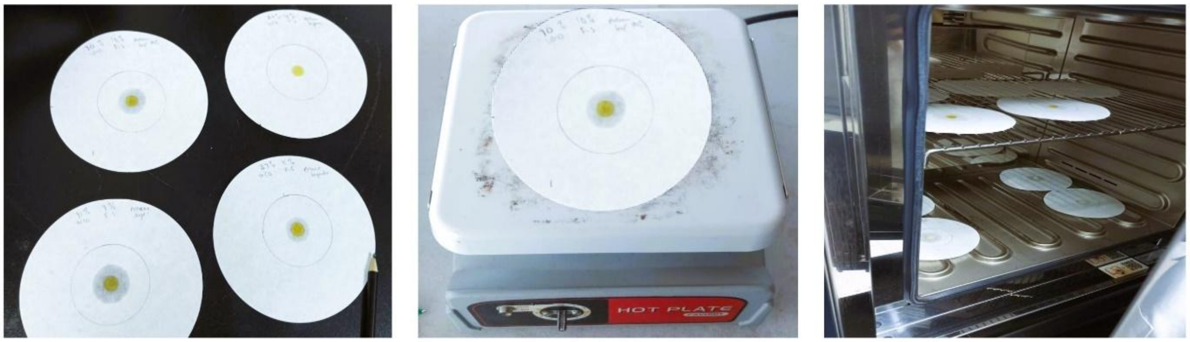


Figure 3: Systematic diagram showing the grease oil separation process.

$$\%\,Oil\ separation = 100 \times \frac{Mass_{Oil\ Separated}}{Mass_{grease\ sample}} \quad (1)$$

2.6 Oil Bleeding Test

This study used SKF's grease test kit to measure the precise amount of grease consistently while heating. The oil bleeding values were measured using blotter paper, with a hot plate as the heating medium. The test started by placing a small amount of grease on blotter paper using SKF's test kit to ensure a consistent amount for each sample at 5g, ensuring accurate bleeding area results. The test was repeated three times for each sample to calculate the average bleeding area diameter. Afterwards, the blotter paper with grease was heated for two hours at 60°C on the hot plate (A. Japar et al., 2019; Suhaila et al., 2018), which is considered to generate the oil bleed on fresh grease. This heating process caused the base oil to come out of the grease through the thickener matrix and be absorbed by the blotter paper. This study created two types of greases: fresh grease (heated at 60°C), which is newly formulated, and aged grease, which is subjected to force for a specific time. The aged grease falls into two categories: one left in an oven at 70 °C for 10 days and another at ambient temperature (Japar, Aziz, & Abdu Rahman, 2020; Rahman & Aziz, 2022). Figure 4 and figure 5 depict the different types of oil bleeding analysis conditions and the schematic diagram of grease's oil bleeding process. Meanwhile, equations 2 and 3 show the percentage difference in bleed area between fresh and aged grease. Aged grease, considered used, had its oil bleeding measured after completing the heating process.



a) Oil bleeding of greases at room temperature after being left for ten days at room or ambient temperature

b) Oil bleeding of greases above hot plate at 60°C for two hours

c) Oil bleeding of greases in oven for extreme temperature category at 70 °C for ten days

Figure 4: The analysis of oil bleeding processes under three distinct scenarios.

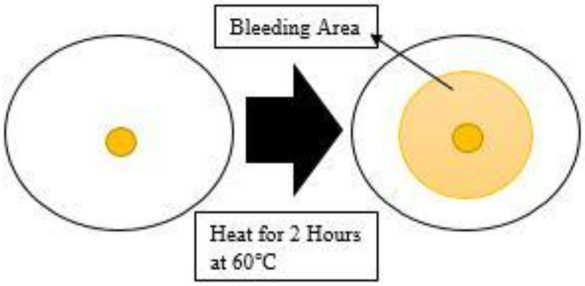


Figure 5: Schematic diagram of oil bleeding process.

$$S_i = 0.785 \times (D_{AV}^2 - 100) \tag{2}$$

$$\% \, Diff = 100 \times \frac{S_{Used} - S_{Fresh}}{S_{Fresh}} \tag{3}$$

S denotes as the bled area from a fresh and used sample, DAV defines the average diameter of the bled area, and %Diff known as the bleed area difference between fresh and used sample.

2.7 Dropping Point Test

The dropping point was tested following the ASTM D2265 standard (A. Japar et al., 2019). This point indicates the temperature at which grease turns from a semi-solid to a liquid. Sodium-based grease commonly undergoes this change. Testing the dropping point is crucial for identifying grease types and ensuring quality (A. Japar et al., 2019). This test also defines the maximum temperature of the grease either can withstand without fully melting or with melting, as shown in Equation 4 for the calculation on dropping point value of grease. However, figure 6 depicts the equipment used for this test and the result values were subsequently calculated using Equation 4.

Figure 6: HK-3498 high temperature dropping point equipment (ASTM D2265).

$$DP(°C) = ODP + \left[\frac{BT - ODP}{3}\right] \tag{4}$$

DP is the temperature when grease starts to drop, BT is the temperature when the first grease drop appears on a block, and ODP is the temperature when the first grease drop reaches the bottom of a test tube.

2.8 Tribology Test

The purpose of this test is to gather important information about the performance of grease against the mechanical components. This analysis helps to determine the effectiveness of grease in reducing friction and wear on interacting surfaces (Izatul Hamimi Abdul Razak et al., 2024). The analysis also falls under ASTM D2266 which utilizes four-ball tester equipment to determine the frictional behavior: coefficient of friction (COF) of the grease (Abhinav Manoj et al., 2024). Table 2 provides specifications for the four-ball testing equipment used in the study. Meanwhile, figure 7 below is the picture of four ball tester FBT3 equipment. However, grease with COF below 0.1 is considered to have high oily properties (Zhang, 2014). Plus, wear scar diameter (WSD) values also would be obtained from this test analysis.

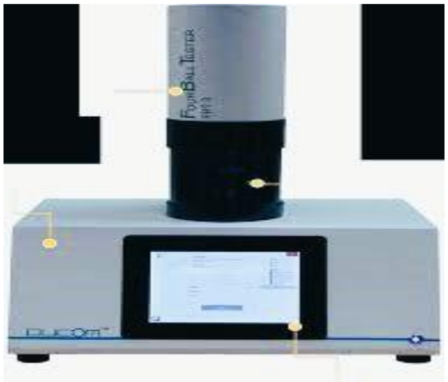


Figure 7: Four ball tester FBT3 for ASTM D2266.

Table 2: Summarization of Parameters in For Anti-Wear Test Parameter.

Sample	ASTM D Standard Method	Parameters
Sodium Grease (SG) 1) SG without additives (SG_{60}) 2) SG within the addition of MoS2 ($SG_{58}M$) 3) SG within the addition of graphite ($SG_{58}G$)	ASTM D2266	Anti-wear properties **1. COF vs Time** Time: 60 min Load: 398N Temperature: 75°C Speed: 1400 rpm

3.0 RESULTS AND DISCUSSION

The study's findings were discussed in this section. The results of the consistency, oil bleeding, dropping point, oil separation, and corrosion tests that were part of the grease properties analysis are displayed in Table 3 below.

Table 3: Overall results for the formulated greases after testing.

Code Greases	NLGI Consistency Values	Oil Bleeding Values		Oil Separation Values	Dropping Point Values	COF Values
		At ambient (%)	At 70^{o}C (%)			
SG$_{60}$	2	12.1934	5.8672	0.7576	225.33	0.0437
SG$_{58}$G	2-3	11.8376	7.0375	0	234.00	0.0343
SG$_{58}$M	2-3	11.9372	6.9463	0	222.33	0.0253

3.1 Consistency of Sodium Greases

Consistency in grease refers to its stiffness and resistance to deformation when force is applied. The hardness of grease is determined by its consistency, a property influenced by the amount of thickener. The results of consistency test in Table 3, reveals the greases made with sodium stearate exhibit similar trends either with or without additives. Greases with higher TWCO are softer, as seen at SG$_{60}$ with an NLGI value of 2. Meanwhile, SG$_{58}$G and SG$_{58}$M have NLGI values of 2-3. These findings are aligned with A. Japar et al. (2019), who stated that grease consistency depends on the availability of base oil and thickener in its composition.

Table 3 shows a slight change in the NLGI value of sodium grease when additives were added. While there haven't been previous studies on how additives affect grease NLGI values, in this case, the NLGI value of sodium grease tended to increase by 2-3 when additives were added. This is due to human error or mistakes in measuring the mass of thickener, base oil, or additive during the reformulation process. Fortunately, this small change in NLGI value doesn't impact the grease structure or adhesion properties. It's worth that all the greases still meet the acceptable NLGI value range of 2-3, as indicated by A. Japar et al., (2019). Figure 8 below shows the bar chart which defines the trend of NLGI value for similar greases with and without different incorporation of additives.

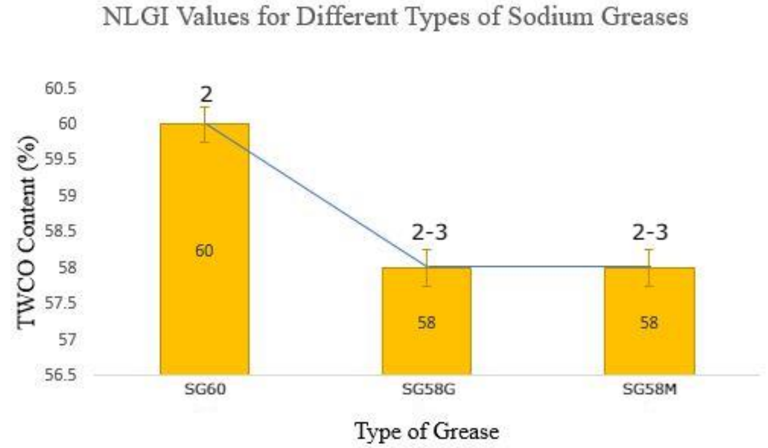


Figure 8: The trend of NLGI value for similar greases with and without different incorporation of additives.

3.2 Oil Bleeding and Oil Separation Values of Sodium Greases

When oils are released due to mechanical and thermal stress in a controlled way, it's called oil bleeding or dynamic oil bleeding. This process is crucial in grease to ensure effective lubrication. Greases need to bleed because the thickener in them is not a lubricant. The right amount of oil bleeding is necessary to provide sufficient lubrication, reduce friction, and prevent wear between surfaces in various temperatures. The oil bleeding values at different temperatures, like ambient or extreme (70°C), are determined by the grease's oil bleeding rate. The study results in Table 3 explore the relationship between TWCO content and oil bleeding values for SG_{60}, $SG_{58}G$, and $SG_{58}M$ at ambient and 70°C. The oil bleeding values for these greases at ambient and 70°C are as follows: SG_{60} (12.1934%, 5.8672%), $SG_{58}G$ (11.8376%, 7.0375%), and $SG_{58}M$ (11.9372%, 6.9463%).

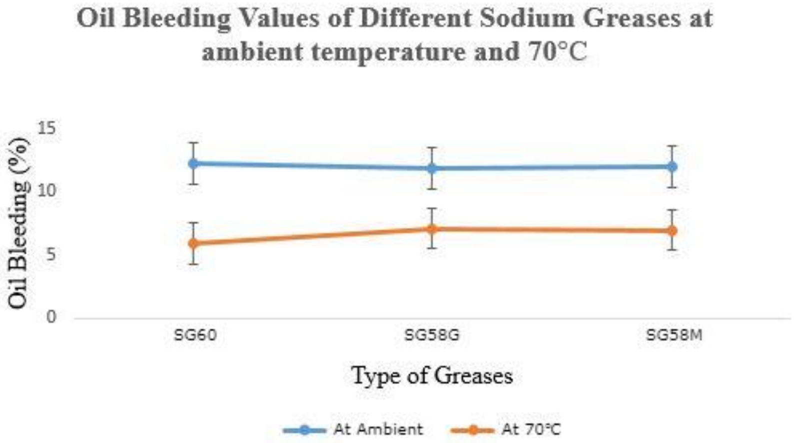


Figure 9: Oil bleeding values for different type of sodium greases at different temperature.

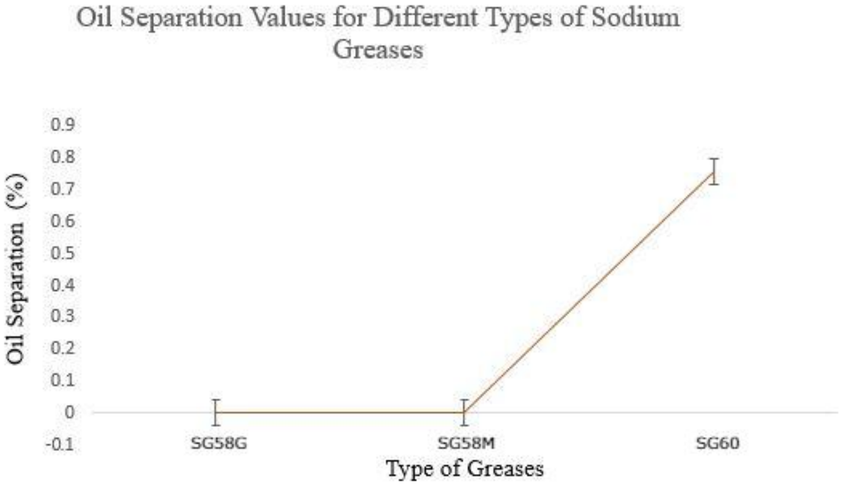


Figure 10: Trend of oil separation values for different type of greases.

Meanwhile, the oil separation values of SG_{60}, $SG_{58}G$, and $SG_{58}M$ are 0.7576, 0, and 0 respectively, indicating that all the greases are acceptable due to having oil separation values below 4% (Japar, Aziz, & Hamid, 2020). Figure 9 depicts the trend of oil bleeding values for different type of sodium greases at different temperatures. Meanwhile, figure 10 defines the trend of oil separation values for different type of greases.

Commonly, the additives might not cover the entire performance to increase quality of the grease itself. As can be seen in table 3 shows the fluctuations trends in oil bleeding values within and without the additives' presence. These additives might enhance the grease lubrication by increasing the oil bleeding rate values. Unfortunately, grease without additives exhibits the highest oil bleeding at ambient temperature compared to grease with additives. Meanwhile, greases with additives exhibit the highest oil bleeding values at extreme temperatures (70°C), indicating its endurance via pleasant high oil bleeding value due to the additives' presence. Therefore, even though there's a slight decrease in oil bleeding values, this doesn't significantly affect grease performance. The oil bleeding rate is crucial and highly affects the tribology system. Without it, greases will lack lubrication and may reduce the lifespan of machines due to increased friction between surfaces (Ibrahim Ali Audu et al., 2023). However, the oil bleeding values of sodium greases, ranging from -15% to +15% are considered acceptable, while the positive oil bleeding values indicate the higher grease lubricity compared to negative oil bleeding values (Muhammad Auni. Hairunnaja et al., 2023; Japar et al., 2018).

3.3 Dropping Point Value of Sodium Greases

The dropping point in grease formulation refers to the temperature at which the grease changes from a semi-solid to a liquid state. It defines the grease's thermal stability based on the thickener type and base oil used. The interaction between the base oil and thickener is tested, considering the van der Waals attraction during formulation. The dropping point values for sodium greases SG_{60}, $SG_{58}G$, $SG_{58}M$ are 225.333°C, 234°C, and 222.33°C respectively, as shown in Table 2. A soap thickener is thought to prevent the grease dropping point from exceeding 350°C compared to a non-soap thickener. Additionally, the choice of base oil is essential for maintaining its interaction with the thickener structure, depending on its viscosity index (VI) value. A higher VI value helps resist oxidation, and the VI value of TWCO is approximately 195-210 according to Veluri (2022). Figure 11 depicts the dropping point values between different sodium greases either with or without additives.

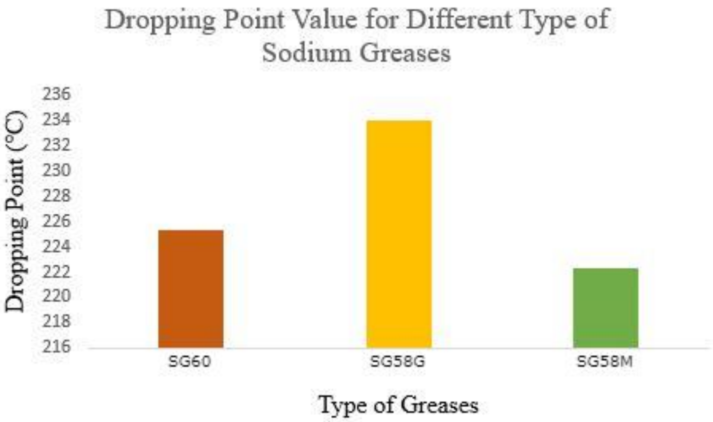


Figure 11: Comparative study for dropping point values between different sodium greases with and without additives.

In this scenario, the TWCO grease exhibited a remarkably elevated dropping point, reaching nearly 300°C, due to its high viscosity index (VI) when combined with a sodium thickener. The elevated VI of TWCO enhances its ability to withstand thermal disturbances and reduces oxidation during heating (Veluri, 2022). As a result, the dropping point surpassed the typical value of 175°C for sodium grease, attributed to the beneficial interaction between TWCO and sodium stearate, along with its high VI. Moreover, incorporating graphite into sodium grease can raise the dropping point by approximately 8.667°C compared to sodium grease without any additives, while MoS_2 did not significantly influence the dropping point. Thus, graphite serves as a thermal-resistant additive, enabling the grease to perform effectively across a broader temperature range (A. Japar et al., 2019).

3.4 Coefficient of Friction (COF) Values of Sodium Greases

This analysis measured the coefficient of friction (COF) for an hour on these greases within and without the additive's presence. Figure 12 illustrates the performance differences in COF among the greases. The fluctuating trend with peaks indicates the grease initially lubricates by releasing a specific amount of oil between two surfaces before stabilizing. Even if greases share the same thickener and are classified as similar, the presence of additives in their composition leads to variations in COF values, making it unpredictable.

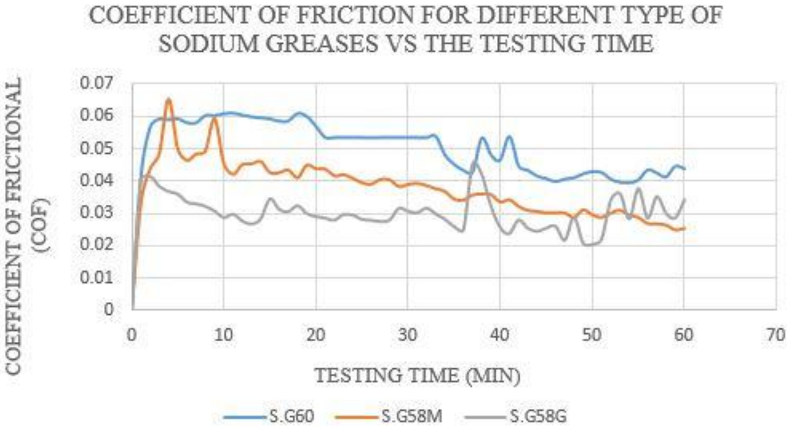


Figure 12: COF trends for sodium greases.

The differences in trends in COF values are the evidences obtained from Figure 12 for these greases. With MoS_2 presence, there is an initial fluctuation in COF for the first 10 minutes, followed by stabilization and a slight decrease until reaching the minimum COF after an hour. On the other hand, $SG_{58}G$ shows a slight decrease in COF for ten minutes, followed by a brief increase of 5 minutes and stabilization for 21 minutes. Afterward, fluctuation occurs until the end of the analysis period. In contrast, SG_{60} has a consistent highest COF value within an hour. It stabilizes for 18 minutes, decreases slightly for 3 minutes, stabilizes again for 12 minutes, and experiences fluctuation for 9 minutes before stabilizing until the end of the analysis. Overall, the additives significantly impact the tribological system, providing effective anti-wear and anti-frictional properties for operating machines. However, by reviewing Table 3, SG_{60} showed the highest average COF values of 0.0437 for sodium grease. The highest COF value indicates a significant amount of frictional force between different contact surfaces during the analysis, suggesting lower anti-wear and anti-frictional properties. $SG_{58}M$ had the lowest average COF value of 0.0253, making it more lubricant than $SG_{58}G$ with a final average COF value of 0.0343. However, the presence of additives in sodium grease improved its anti-frictional properties. $SG_{58}M$ has the lowest friction compared to other greases when looked at their COF values. The study showed that greases with TWCO as a base oil rely on additives to improve their lubrication performance. This indicates that adding additives to grease is a good choice for better lubrication.

3.5 Wear Scar Diameter (WSD) Values of Sodium Greases

The surface structure degradation brought by the frictional force generated between two contact surfaces due to the result of the grease's low lubricity is referred to as WSD values. The WSD's contact surfaces have some scratches, which could lead to a reduction in the quality of the equipment after use. This is how the anti-wear and anti-frictional properties of different grease additives work. The WSD values may also explain the lubricating film's stability under pressure in the direction of the minimization effects (Izatul Hamimi Abdul Razak et al., 2023). According to Sivebaek et al. (2003), grease used for lubrication is anticipated to lower the WSD by lowering friction between the equipment's surface. Figure 13 shows studies comparing the WSD of the sodium greases with different additives. Meanwhile, figure 14 shows the WSD image for each grease presence.

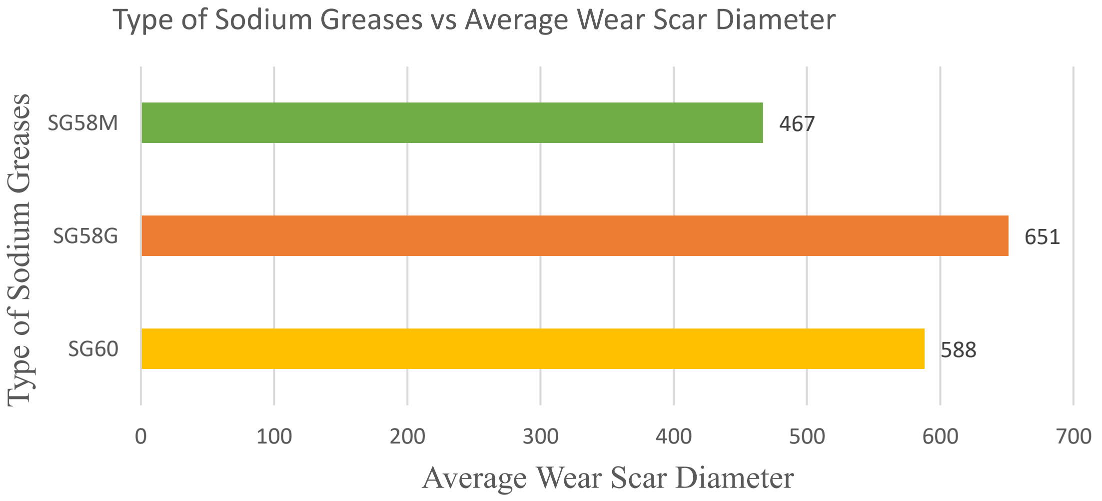


Figure 13: Comparison of WSD values with different type of greases.

WSD values for SG_{60} and $SG_{58}G$, were 588μm and 651μm, respectively. The WSD of $SG_{58}G$ is considered greater than $SG_{60,}$ according to the analysis results. In the meantime, $SG_{58}M$ had the lowest WSD value (467 μm) among the other sodium grease samples. While it is understandable that $SG_{58}M$ would have the lower WSD values compared to the SG_{60} and $SG_{58}G$, the highest WSD value of $SG_{58}G$ is unreasonable due to have lower minimum COF value than SG_{60}. As result, this data is contradicted with the data that is really available, which indicates that based on their COF values, SG_{60} should theoretically has higher WSD value than $SG_{58}G$.

Figure 14: WSD images for each grease presence after the COF analysis.

Apart from that, the correlation between WSD value of SG_{58}G and SG_{60} may be associated with an abrasion issue. According to John (2022), abrasion is the surface degradation (wearing out) of a material as a result of direct frictional contact with another material. According to Farias et al. (2014), there are two types of abrasion: two-body abrasive wear, which happens when a softer surface rubs against a hard, rough surface, and three-body abrasive wear, which happens when tough particles accumulate between two moving surfaces. However, for this instance, three-body abrasive wear is the abrasive type that produces WSD values. Thus, the nanoparticles that are defined as small and unwanted contaminants were not completely removed after WCO treatment but were still present in the grease compositions. These particles are thought to be the cause of the abrasion problem. If the number of nanoparticles is excessive, they will eventually form a large cluster and cause surface damage to the equipment rapidly. In contrast to commercial sodium grease with MoS2 as an ingredient additive, which has a value of 500 μm or less, this value posed no harm to the grease's qualities.

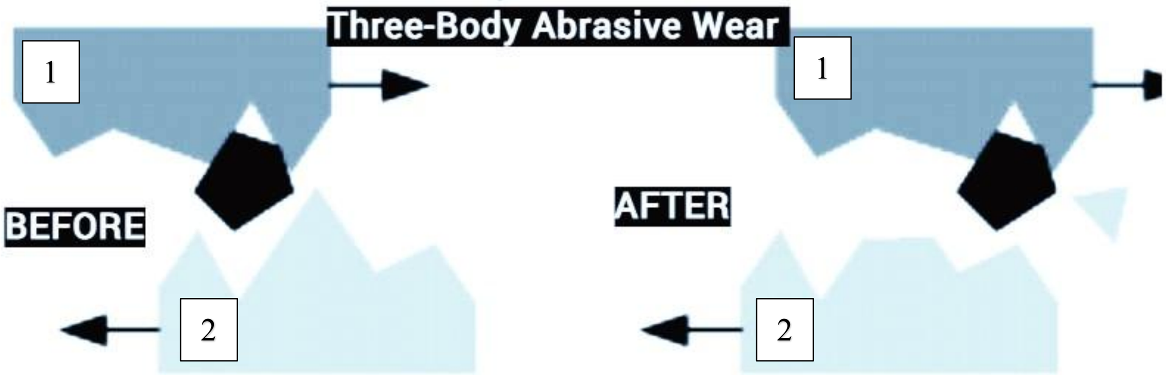


Figure 15: The Cross-sectional views of Three-Body Abrasive Wear (Salot, 2016).

The cross-sectional view of two contact surfaces separated by unwanted impurity-containing grease is shown in Figure 15 above. The dark spot in the above figure defines the contaminants (nano-particels) that potentially damage the second surface. When the nanoparticles come into touch with the second surface. They smash through the surface's peak, slightly scratching the surface before they could cause wear effects. The layer designated as the WSD is where the scratches first emerged.

CONCLUSIONS

TWCO can be used to make grease when it is properly mixed with the right thickener to transition from a liquid to a semi-solid state. This conversion not only produces a useful product but also supports environmental sustainability by reducing reliance on non-renewable mineral oils and diverting WCO away from landfills and water systems, where its improper disposal could harm ecosystems. By recycling and repurposing WCO, this study aligns with the principles of a circular economy, promoting the responsible use of resources and minimizing waste. The addition of additives such as graphite and MoS_2 further enhances the grease's performance. Graphite aids in maintaining the grease's structure at high temperatures, while MoS_2 reduces wear and friction to improve efficiency and durability. However, treating WCO to eliminate moisture and impurities is crucial, as improper treatment can lead to issues like increased abrasion from residual particles, raising the WSD value. While these greases meet ASTM criteria, $SG_{58}M$ stands out as the most effective option due to its lowest WSD and COF values, demonstrating superior performance and durability. By utilizing TWCO in this manner, this study not only developed high-quality grease but also contributed to reducing dependence on traditional mineral oil-based products, fostering a sustainable approach to waste management, and advancing efforts toward a cleaner, greener future.

ACKNOWLEDMENTS

The authors wish to acknowledge the financial support from the Ministry of Higher Education Malaysia through the grant RDU210147 (FRGS/1/2021/TK0/UMP/02/76) and from University Malaysia Pahang Al-Sultan Abdullah through the grants PGRS180396 and PGRS200356.

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