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AN INVESTIGATION OF BICYCLE CHAIN LUBRICATION PERFORMANCE IN RAINY CONDITION

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ABSTRACT

A bicycle chain is one of the primary components in a drive train to transfer muscular power to mechanical energy to move a bike forward. Most bicycle drive train manufacturer produces chain with more than 100 links formed by side plates connected with pin and rollers. The chain connects the driving and driven sprockets for energy transfer. The bicycle chain has to be lubricated to improve efficiency; it is crucial to understand the basics of bicycle chain lubrication. Lubrication is achieved by introducing a lubricant substance to reduce friction between contacting moving surfaces. Every lubricant is formulated with a mix of substances, each serves a specific purpose. Therefore, understanding the working conditions such as the chain speed, environment temperature and contaminants is critical before formulating the composition and substance of the lubricant. Mixed grade lubricant was superior under the test of ASTM D445 Standard Test Method for Kinematic Viscosity of Transparent and Opaque Liquid and UV light penetration test.

1.0 INTRODUCTION

Every mechanical transmission system has its limitations and advantages. Chain drives are the oldest of basic machines elements and transportation industry including bicycles [1]. The design of the chain is comparatively straightforward and have been conceptually unchanged since the nineteenth century [2]. Chain drives are preferred in cycling for their high efficiency up to 98% and able to operate across every weather condition. Up to the present date, the chain is the most successful indirect drive system [3]. However, the chain drive is subjected to velocity fluctuations once it is elongated and requires regular lubrication. The chain wear by elongation will no longer align perfectly with the teeth of the sprocket. This elongation of chain pitches occurs when chain links consist of side plates and rollers being stretched by mechanical forces of the contacting sprocket teeth [4]. Components of a chain link is shown in Figure 1. A chain also needs to be properly measured before being installed on the bicycle. The length must be optimum to match the gearing ratio. There should be no slack in the chain if the length is correct.

The number of bicycles around the world is estimated to be more than 1 billion units and one of the very important components of every bicycle is the chain. The bicycle chain is one of the primary components in a drive train to transfer muscular power to mechanical energy to move a bike forward. The hope of marginal efficiency gains has driven the invention of various energy transfer mechanisms, but the success rate was below expectation. Most of the bicycle drive train manufacturer produces chain with more than 100 links formed by side plates connected with rollers. The chain connects the driving and driven sprockets for energy transfer. Utilization of chain allows the development of gearing ratio for greater mechanical advantage especially during a gear change to match their muscular power and the road inclination. It helps cyclists to achieve better efficiency by pedalling at a suitable cadence for variable speed. Every mechanical transmission system has its limitations and advantages. The study of mechanical

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efficiency encompasses lubrication, friction and wear. The energy-efficient system is increasingly recognized as the priority in a transmission system, optimized lubricants is an option to boost energy conservation corresponding to mechanical systems in a broad scope of application [5]. Chain drives are preferred in cycling for their high efficiency up to 98.6% and able to operate across every weather condition [6].

Another study found that cycling chain links that including pin and sleeve has an average efficiency of 98.8% [7]. There were studies conducted to experimentally and theoretically quantify the chain drive efficiency [8]. Up to the present date, the chain is the most successful indirect drive system [3]. However, the chain drive is subjected to velocity fluctuations once it is elongated and requires regular lubrication to function at high performance. The chain links wear occurs during contact with gear teeth which creates friction and elongation [9]. The combination of friction and elongation creates minor misalignment with the teeth of the sprocket. This irreversibility in deformation phenomena occurs when side plates and rollers being stretched by mechanical forces. Throughout consistent cyclic loading, the chain's elongation dampens the power transfer due to the poor surface contract. A chain also needs to be properly measured before being installed on the bicycle. The length must be optimum to match the gearing ratio so that there would be no slack in the chain. Gear ratio selection is a significant factor in peak power production [10]. The absence of optimized lubrication can greatly reduce the chain's efficiency due to scoring caused by the absence of lubricants between surface contacts. In this case, material loss occurs at the side plates, rollers and pins of the chain. Most metals also get oxidized in the air and create a thin oxide layer. The thin oxide coating creates a natural lubricant by allowing metal contact surfaces to shear under the application of load.

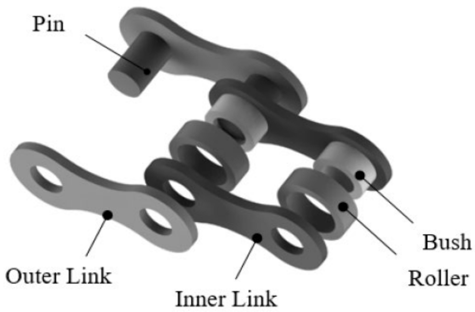

Fig. 1. Components of bicycle chain [7]

Lubrication is significantly utilized in many systems especially on moving surfaces to reduce erosion and friction loss [11]. Tribology is a complex study because it encompasses the combined relation of friction, lubrication, and wear between two moving surfaces [12]. Tribology's basic objectives are to contribute to the advancement of resources, energy and the environment. In the new era, the objectives have been expanded to "energy and material efficiency, emission reduction, shock absorption, reduce noise pollution, and enhance life quality" [13]. It was reported that 85 % of lubricants are extracted from petroleum-based oils being used worldwide [14]. Lubricants can be assigned into a few different categories namely plants oils, mineral oils, and synthetic oils. Mineral oil is a product from a series of crude oil refining processes that resulted in a wide spectrum of chemical components. It consists of a mixture of different hydrocarbons. Mineral oil is transparent and colourless oil composed mainly of alkanes and cycloalkanes. Mineral oil consists of three major elements namely, aromatics, naphthenic, and paraffins. Aromatics are excellent for solubility. Naphthenic has very good low-temperature properties. Paraffins is highly preferred for their high viscosity index, low sulphur content and inherent good oxidative stability. At cooler temperature, oils tend to form wax crystal and reduce their fluidity [15].

Base-oil lubricants from animal fats or plant oils also have been produced because their properties tend to lubricate the moving parts of the machine [16]. Besides, this type of base oil is more environmentally friendly, biodegradable and low toxicity compared to mineral oils. The production process of plant oils involves the extraction of oil from the seeds. Plant oils are considered as the alternative to non-biodegradable petroleum-based lubricants because most industries emit harmful lubricants to the environment. However, plant oils are not widely used in industries due to the limitations of becoming rancid over a relatively short period [17]. It also has lower oxidative stability and poor cold flow properties in a colder environment. Hence, the environmental aspect and application properties

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must be sustainable during the formulation phase of lubricant. One of the significant lubricant applications is to act as a seal against dust, dirt and water [18]. There are two types of lubricants: solid and liquid lubricants including oil-based type and emulsion-type [19]. Commonly, oil-based type is used as chain lubricants that tend to wash off in wet weather conditions and are also less effective in reducing friction after exposure to rainwater, sweat and dirt. Lubricants are made of two major substances, base oil and additives. Generally, the base oil is the determining factor of the properties such as the viscosity. The additives are added to modify the properties so that they can be tailored to fit the requirement.

Waxes have been derived from petroleum resources and are widely used in lubricants, polishes, coating and cosmetic products as well. Waxes are a mixture of esters of long-chain carboxylic acids and long-chain alcohol that crystallize as the temperature is lowered [20]. Waxes are formed in a solid state. Due to the presence of fatty acids esters in waxes, it also used as lubricant materials. Some lubricants were produced by both oil and wax to improve their characteristics to lubricate the moving surfaces. There might use different percentages of combination to make the lubricant more efficient depending on their usage or application. It was reported that oil drip feed lubricant provides the greatest wear protection between chain roller and pin. Meanwhile, wax and PTFE spray lubricants also provide lubrication chain roller and sprocket [1].

Viscosity and viscosity-temperature response are crucial in choosing lubrication's application [11]. Since the operating temperature can alter the viscosity and lubrication film thickness, polymers such as viscosity modifiers are introduced to the formula. Low viscosity causes lubricant to heat up and insufficient film thickness to reduce wear, high viscosity reduces fluidity and affects effective lubrication. Viscosity is the measure of resistance to the flow of a liquid that impacts the ability of the lubricant to be circulated on the contacting surface [21]. The main lubricant's performance parameter is viscosity, and its performance is highly dependent on the operating temperature [22]. Hence, viscosity modifiers keep the fluidity at the expected level which is specified at the high and low extremities of operating temperature. Most of the mineral base oils, synthetic base oils, and fully formulated single grade oils are Newtonian fluids where the fluid viscosity is constant [23]. A limited study was conducted on mixed grade chain lubricant due to its non-Newtonian behaviour. The complexity of mixed grade chain lubricant creates limitations and greater challenges to predict its behaviour.

Losing the thin film of lubrication causes rubbing contact between two metal surfaces which is the main contributor to energy losses along with the transmission system. The high viscosity of lubricants is the limiting factor to penetrate deep enough between the tight gap of the chain rollers and side plates. Loss of material on the surface creates a higher coefficient of friction which amplifies the wear rate. Research on lubrication also has great implications for the economy by reducing unnecessary wear of material in the industry. Thus, the objective of this study is to investigate the properties and performance of rain-resistant chain lubricant.

2.0 MATERIALS AND METHODS

In this study, the combination of wax and oil are used for lubricant formulation to achieve the desired properties in optimized viscosity and rain resistance. The general properties of paraffin wax and mineral oil are in Table 1. Paraffin wax is solid at room temperature and poses a variable melting point between 50 °C to 69 °C. As the temperature increase towards the melting point, paraffin wax transition from solid to liquid like other petroleum-based waxes. It is also insoluble in water and changes form during water contact to return to solid form. At lower temperatures, paraffin wax has a high viscosity and eventually will no longer flow as it solidifies. Paraffin wax is white at room temperature and has good material stability under normal conditions. Paraffin as the solid lubricant breaks easily from the metal surface at room temperature. The flaky texture hinders the lubricant from cushioning metal to metal surfaces.

Mineral oil is a liquid product of the crude oil refining process. It is a liquid form at room temperature and retains its liquid form up to 100 °C. The viscosity of mineral oil is almost constant and does not display extreme viscosity change as the temperature increase. Mineral oil also has a wide range of temperature stability and the ability to displace heat, making it a good option for a medium of heat transfer. Since it is an incompressible fluid, mineral oil also can be used as a hydraulic fluid to transfer energy. Solely using mineral oil as chain drive lubricant offers great penetration between tight gaps between metal-to-metal surfaces because of its low viscosity. However, mineral oil gets removed from the metal surface during rainwater contact by gravity separation.

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Table 1. General properties of paraffin wax and mineral oil

Properties	Paraffin wax	Mineral oil	Mixed grade
Viscosity (cSt) at 35 °C	-	8.35 cSt	-
Colour	White	Colourless	White
Physical State	Solid	Liquid	Semi-Solid
Solubility in Water	Insoluble	Insoluble	Insoluble

The combination of paraffin wax and mineral oil produces a new property that is favourable for the operating environment of the bicycle chain transmission system. In this study, a weight ratio of 80 % paraffin wax and 20 % mineral oil was mixed. The mixing portion for paraffin wax and mineral oil can be adjusted to suit the operating temperature range. It is also relatively inexpensive and easy to handle and remarkably longer lasting than the commonly used chain oil lubricant. The newly formulated chain lubricant tends to be very viscosity-sensitive to temperature. The characteristic of lubricant plays a significant role in ensuring continuous chain drive lubrication, especially during rainy days. Hence, the lubricant must retain on every metal-to-metal contact surface to reduce wear and increase efficiency.

The investigation involves the simulation of elements faced by cyclists riding on the road and subject to different weather conditions. Effective lubrication requires properties that can overcome the negative effects of rainwater throughout the ride. The critical parameters are viscosity, lubricant penetration and resistance to rainwater. The challenges of chain lubrication were listed down to identify suitable test protocols based on the available engineering standards. The weight ratio of 80 % paraffin wax and 20 % mineral oil mixing was labelled as "mixed grade" and compared with commonly used mineral oil in an experiment conducted. The compliance to test protocols used in the study aims to simulate the real-world application and dynamic elements that bicycle chain lubrication has to undergo throughout the ride. The list of test protocols is as follows:

- Water immersion test to simulate rainwater condition.
- ASTM D445 standard test method for kinematic viscosity of transparent and opaque liquids.
- DIN 2275 standard test method for feeler gauge method.
- UV light test to observe chain lubricant penetration.

2.1 Water Immersion Test

For the water immersion test to simulate rainwater condition, distilled water compliant to ISO3696 (Water for analytical laboratory use – Specification and test methods) was used in this process to reduce the possibility of a chemical reaction between contaminants in water and the lubricant's ingredient. The water was clear, colourless liquid and comply with Grade 3 requirements. Lubricants were applied on sheet metal surface and submerged in water bath at room temperature for 10 minutes. Visual observation of lubricant retaining on the sheet metal surface determines the test result.

2.2 ASTM D445 Standard Test Method For Kinematic Viscosity Of Transparent And Opaque Liquids

This test was conducted by recording the time for a volume of liquid to flow by gravitational force through a calibrated glass capillary viscometer submerged in a viscosity bath. When injecting the lubricant at targeted temperature into the glass capillary, all bubbles within the tube must be released for better accuracy. The bath temperature rises at the interval of 5 °C starting from 65 °C to 100 °C while the viscosity of lubricant is recorded. Temperature control and timing accuracy is crucial to achieve reliable and repeatable result.

2.3 DIN 2275 Standard Test Method for Feeler Gauge Method

Feeler gauges have a minimum length of 100 mm. The specific dimension and tolerance of the steel blades allow measurement to be taken at tight tolerance. All gaps between the roller and side plates of the chain were randomly measured along the chain links to identify the gaps. Since the total number of links on different bikes varies, 8 links from each of the 11 reputable chain manufacturers available in the market were randomly picked as the sample. Every link stands equal and fair chance to be selected in the study.

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2.4 UV Light Detection

UV dye was injected into mixed grade lubricant to observe penetration on the tightest tolerance chain-link measured by DIN 2275 Standard Test Method for Feeler Gauge Method. Lubricants were heated at temperature at rising interval of 5 °C from 65 °C to 100 °C. During lubricant application through a tube fitted on the bicycle's rear frame, the lubricant was considered "filled" when both sides of the chain gaps are filled with lubricant and "miss" if the rollers are partially or not filled with lubricant.

3.0 RESULT AND DISCUSSIONS

3.1 Water Immersion Test

Based on the observation, all lubricants had been removed from the metal surface upon immersion in distilled water. The lubricant floats on the water forming an oily surface due to gravitational force acting on the density difference between oil and water. Only the mixed grade is retained on the sheet metal surface by changing form from the clear liquid into a white greasy coating on the surface. The water surface was clear without any sign of floating oil nor residue of lubricant left at the bottom. The transformation happened almost immediately during contact with water as recorded in Table 2.

Table 2. 10 minutes water immersion test for chain lubricant

Lubricant	Form	Result	Observation
Finish Line Ceramic Lubricant	Liquid	Washed Off	Total washed off in 1 minute 35 seconds.
Muc Off Hydrodynamic	Liquid	Washed Off	Total washed off in 2 minutes 15 seconds.
Mineral Oil	Liquid	Washed Off	Total washed off in 5 minutes 25 seconds.
Deutch Wet Lube	Liquid	Washed Off	Total washed off in 2 minutes 34 seconds.
Mixed grade	Liquid / Quasi Solid	Retained	Retained on the metal surface until the end of the test at 10 minutes.

3.2 ASTM D445 Standard Test Method For Kinematic Viscosity Of Transparent And Opaque Liquids

Based on the observation, the viscosity of mixed grade gradually decreases as the temperature rises at the interval of 5 °C starting from 65 °C to 100 °C. The highest viscosity of 5.01 cSt was recorded at 65 °C and the lowest viscosity of 2.62 cSt was recorded at 100 °C referring to Table 3. The state of lubricant remains as a liquid before the test, appear to be stratified into two layers of limpid and grey throughout the test. Test equipment set up is shown in Fig 2.

Table 3. Kinematic viscosity for mixed grade lubricant (Adreno)

Temperature	Form	Appearance	Viscosity (cSt)
100°C	Liquid	Stratified into 2 layers of limpid and grey	2.62
95°C	Liquid	Stratified into 2 layers of limpid and grey	3.11
90°C	Liquid	Stratified into 2 layers of limpid and grey	3.16
85°C	Liquid	Stratified into 2 layers of limpid and grey	3.60
80°C	Liquid	Stratified into 2 layers of limpid and grey	3.75
75°C	Liquid	Stratified into 2 layers of limpid and grey	4.17
70°C	Liquid	Stratified into 2 layers of limpid and grey	4.55
65°C	Liquid	Stratified into 2 layers of limpid and grey	5.01

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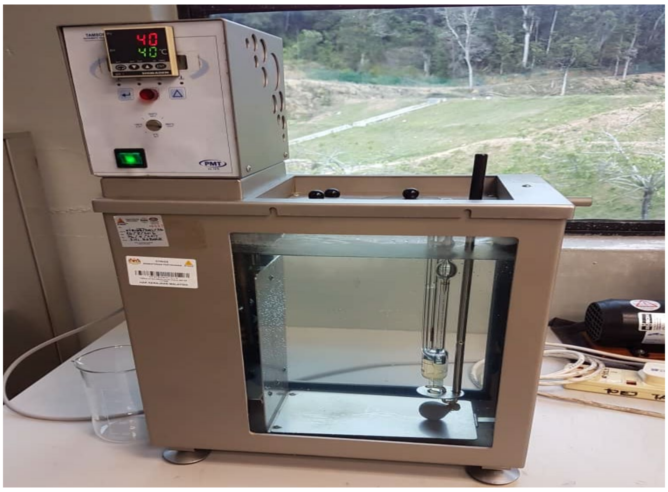

Fig. 2. Calibrated glass capillary viscometer to perform kinematic viscosity of the lubricant

3.3 DIN 2275 Standard Test Method for Feeler Gauge Method

Based on the measurement, the narrowest gap was recorded by Ultegra HG CN6701at 0.14 mm whereas the widest gap was recorded by KMC X11SL GOLD at 0.26 mm based on Table 4. The narrowest chain gap was used for the subsequent UV Light Penetration Test.

Table 4. Chain gap measured with DIN 2275 (mm)

	Link 1	Link 2	Link 3	Link 4	Link 5	Link 6	Link 7	Link 8
DGXMC	0.18	0.19	0.19	0.20	0.19	0.20	0.20	0.20
KMC DLC	0.19	0.18	0.19	0.19	0.19	0.18	0.18	0.18
SUMC	0.16	0.17	0.17	0.16	0.18	0.18	0.18	0.18
SHIMANO X11 CN HG701	0.19	0.18	0.19	0.19	0.19	0.18	0.18	0.19
SHIMANO X11 CN HG901	0.18	0.17	0.18	0.16	0.17	0.16	0.16	0.16
KMC X11 BLACK	0.21	0.21	0.22	0.23	0.22	0.22	0.22	0.21
KMC X11SL GOLD	0.22	0.24	0.25	0.22	0.26	0.25	0.25	0.25
SRAM PC X1	0.19	0.16	0.16	0.17	0.18	0.17	0.18	0.17
SRAM PC XX1	0.19	0.16	0.16	0.17	0.18	0.17	0.18	0.18
ULTEGRA HG CN6701	0.19	0.18	0.18	0.19	0.17	0.17	0.18	0.17
ULTEGRA HG CN6701	0.17	0.14	0.14	0.14	0.16	0.16	0.15	0.16

3.4 UV Light Detection

Tightest tolerance chain-link Ultegra HG CN6701 was measured at 0.14 mm using DIN 2275 standard test method for Feeler Gauge Method. At the highest temperature of 100 °C, viscosity recorded was 2.62 cSt whereas the lowest test temperature of 65 °C recorded 5.01 cSt. Based on the test result in Table 5, the lowest viscosity of 2.62 cSt scored the best penetration for observation under UV light. Out of 114 links, 111 links were filled with lubricants and only 3 links were partially lubricated. Higher viscosity at 5.01 cSt scored lesser penetration for observation under UV light. Example of UV Light Detection shown in Fig. 3.

Table 5: UV light detection test.

Temperature	Viscosity	Test 1		Test 2	
		Filled	Miss	Filled	Miss
100 °C	2.62	110	4	111	3
95 °C	3.11	111	3	111	3
90 °C	3.16	110	4	110	4
85 °C	3.60	109	5	110	4
80 °C	3.75	110	4	110	4
75 °C	4.17	110	4	109	5
70 °C	4.55	106	8	106	8
65 °C	5.01	104	10	104	10

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Fig. 3. UV dye injected into lubricant for better observation

Lubrication of bicycle chain transmission is critical in ensuring the reliability and efficiency of chain transmission. Continuous full film lubrication is critical to prevent contact between metal surfaces. The experiments result shows that water resistance and viscosity play an important role in lubricant parameter selection. Mineral oil was separated from the chain immersed in water because of gravitational force. Mixed grade's thermal sensitivity changed its initial liquid form into a white greasy coating to retain on the surface. These properties have shown potential replacement to oil-based lubricant for transmission systems operating in prolonged wet weather for more efficient lubrication. Inadequate lubrication due to washing off reduces the capacity of lubricant to manage the friction between contacting surfaces. Furthermore, unnecessary friction also results in excessive heat and premature wear of transmission components.

The data collected from the ASTM D445 standard test method for kinematic viscosity of transparent and opaque liquids has shown an increment of temperature lowers the viscosity of lubricants. The thermal sensitivity of mixed grade allows the lowest viscosity of 2.62 cSt at 100 °C to be achieved. This information suggests that pre-heated lubricant during the application phase can improve penetration. Lubricant viscosity decreases dramatically with increasing temperature, lubricant viscosity also increases as the temperature decreases. Besides, variable viscosity changes the thickness of the lubricating film and allows lubricant to set in to resist rainwater wash off through form transformation from liquid to quasi solid for mixed grade chain lubricant. Since mixed grade chain lubricant contains thermal sensitive wax, this method has optimized lubricant's resistance to flow and enhances the ability for lubricant to remain on the surface. Compared to thicker lubricants with higher resistance to flow, the surface void was created, and the full potential of lubricant was unable to be utilized.

The optimization of viscosity by increasing the temperature before application on bicycle chain has proven to score high penetration performance under the UV Light Test, leading to a better coating of lubricant around the chain components as required in the narrowest gap from the result of DIN 2275 standard test method for Feeler Gauge Method. The lowest viscosity mixed grade chain lubricant was tested on 114 chain links in total, the lubricant filled up 110 links for the first test and 111 links for the second test under the observation of UV Light.

4.0 CONCLUSION

This study has proven potential added value by providing concrete benefits in all chain lubrication aspects. The existence of lubricant is crucial to managing friction between uneven contacting surfaces. This can reduce unexpected broken chains in races to improve safety. Athletes and coaches can make better decisions in lubricant selection based on racing conditions. Future studies can explore the potential of solid additives to be added into chain lubricants to improve longevity and efficiency. This study tested important properties required for rain-resistant chain lubricant and discovered that Mixed Grade lubricant performs better in multiple tests conducted in this study. The properties of Mix Grade lubricant such as rain-resistant, viscosity, and penetration were proven to be favourable in the rainy operating

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environment. Preheating of multi-viscosity grade lubricant helps to improve penetration of lubricant during the application phase, and the change of viscosity improves the rain-resistance of chain lubricant to retain on the contacting surfaces. This study concludes that mixed grade chain lubricant's special properties have the advantage to overcome the adverse effect of unnecessary friction along with the transmission system through properties optimization in wet conditions.

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