TRIBOLOGICAL PROPERTY OF ROAD MARKING PAINT

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DECLARATION

I hereby declare that this Final Year Project is my own work as a result of my own research. The work was done wholly in candidature for the honors degree in this university. This paper is the result of my own investigations and interpretations. Where I have quoted the works from others, the sources are always acknowledged by giving references. This paper has not been published in anywhere before subsmission.

Loh Yuan Ting

Sign: ……………………… (LOH YUAN TING)

Date: 29/5/2019………………………

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LIST OF SYMBOLS

Symbols	Descriptions
%	percent
°C	degree Celcius
mg	milligrams
mm	millimetre
m	metre
m/s	metre per second
kg	kilogram
rpm	revolution per minute
N	Newton
M_1	initial mass before wear test
M_2	mass after wear test
ΔW	wear mass loss
mm/min	millimetre per minute
µm	micrometre
MPa	megapascal

LIST OF ABBREVIATIONS

Abbreviations	Descriptions
COF	Coefficient of Friction
EDX	Energy Dispersive X-Ray
POD	Pin-On-Disc
SEM	Scanning Electron Microscope
L	applied load
S	sliding speed
D	sliding distance
Lub	lubricated
IRHD	International Rubber Hardness Degree
Signal to Noise Ratio	S/N Ratio
ANOVA	Analysis of Variance

ABSTRAK

Cat penanda jalan memainkan peranan penting dalam memastikan keselamatan jalan raya kerana cat penanda jalan memberikan maklumat penting kepada pengguna jalan raya. Ketahanan cat penanda jalan sangat penting terutamanya apabila kereta autonomi menjadi sebahagian daripada bandar pintar masa depan. Kenderaan berautonomi menavigasi dalam landasan dengan mengesan penanda jalan. Kenderaan berautonomi akan gagal untuk mengesan jalan raya sekiranaya cat penanda jalan pudar atau hilang. Ini boleh mengakibatkan kemalangan jalan raya. Oleh itu, ketahanan cat penanda jalan adalah amat penting dan mesti dikaji. Kajian ini adalah untuk menyiasat ciri-ciri tribologi cat penanda jalan jenis thermoplastic. Ujian haus dilakukan berdasarkan Taguchi L18 tatasusunan Orthogonal. Keadaan gelongsor (kering atau dilincirkan), beban (10-20 N), kelajuan (0.6283-1.0472 m/s) dan jarak (200-300 m) adalah input parameter manakala kehilangan berat kehausan dan purata koefisien geseran adalah output. Kombinasi input parameter yang optimum untuk mencapai kehilangan berat kehausan dan purata koefisien geseran minimum ditentukan dengan menggunakan kaedah Taguchi. Keadaan optimum untuk kehilangan beat kehausan minimum adalah dalam keadaan gelongsor kering, beban 10 N, kelajuan 1.0472 m/s dan jarak 200 m. Keadaan optimum untuk purata koefisien geseran minimum adalah dalam keadaan gelongsor kering, beban 15 N, kelajuan 1.0472 m/s dan jarak 250 m. Analisis Varians dikaji pada tahap kepercayaan 95% untuk menyiasat pengaruh setiap input parameter terhadap output. Hasil analisis menunjukkan bahawa kehilangan berat kehausan dan purata koefisien geseran sangat dipengaruhi oleh beban dan keadaan geser. Faktor yang paling berpengaruh yang mempengaruhi kehilangan berat kehausan dan purata koefisien geseran adalah beban, diikuti dengan keadaan geser, kelajuan dan jarak. Pemerhatian permukaan selepas ujian haus dilakukan dengan mikroskopi pengimbas electron untuk mengenal pasti mekanisme kehausan.

ABSTRACT

Road markings plays a crucial role in road safety because they provide significant information to road users. The durability of road markings is extremely important especially when autonomous vehicles are inseparable part of the smart cities of the future. Autonomous vehicles navigate on a close track by detecting the trafficway markings. With faded, or missing road markings, autonomous vehicles will fail to detect the trafficway resulting in road accidents. Therefore, the road markings durability is of significant importance and must be investigated. The present study investigates the tribological property of the thermoplastic road marking material. The rotary sliding wear test is carried out based on Taguchi L18 Orthogonal Array. Sliding condition (dry or lubricated), applied load (10-20 N), sliding speed (0.6283-1.0472 m/s) and sliding distance (200-300 m) are design parameters whereas wear mass loss and coefficeint of friction are responses. The optimal combination of design parameters to achieve minimum wear mass loss and coefficient of friction is determined using Taguchi method. The optimal condition for minimum wear mass loss is in dry sliding condition, applied load of 10 N, sliding speed of 1.0472 m/s and sliding distance of 200 m. The optimal condition for minimum coefficient of friction is in dry sliding condition, applied load of 15 N, sliding speed of 1.0472 m/s and sliding distance of 250 m. Analysis of Variance is studied at 95% level of confidence to investigate the influence of each design parameter on responses. The results show that the wear mass loss and coefficient of friction are significantly influenced by applied load and sliding condition. The most influential factor which affects the wear mass loss and coefficient of friction is applied load, followed by sliding condition, sliding speed and sliding distance. Scanning Electron Microscopy observations are carried out to identify the wear mechanism for the worn surfaces.

CHAPTER 1 : INTRODUCTION

1.1 Introduction on Thermoplastic Road Marking Paint

Road markings plays a crucial role in road safety because they provide significant information to road users. The road markings delineate the traffic path thus providing guidance to the road users and controlling the traffic. This ensure the safe movement of the traffic. Road without road markings would lead to accidents resulting in injuries and loss of life.

The JKR Standard Specification for Road Works specified that the road marking materials shall be of thermoplastic type, road marking paints can only be used for temporary road markings. Thermoplastic is durable road marking materials. Thermoplastic is a blend of solid ingredients that become liquid when heated. The road marking materials shall comply with BS EN 1471 and BS EN 1436. BS EN 1436 specifies the performance for road markings as expressed by their reflection in daylight or under road lighting, retroreflection in vehicle headlamp illumination, color and skid resistance [1].

The thermoplastic road marking materials consists of filler material, glass beads, binder, pigments, and additives. The thermoplastic road marking materials is generally heated to an elevated temperature of 220°C in thermostatically controlled pre-heater and agitated continuously until a homogenised liquid is achieved [2]. The hot, melted liquid is applied onto the road surface by application vehicle. Drop-on glass beads are added on top to provide adequate visibility especially at night time. The road with marking completed is opened for traffic after required drying time of application and proper settling of thermoplastic material.

The road markings with good performances should have the following characteristics: good day and night visibility both in dry and wet conditions, adequate skid resistance, rapid drying time and low wear rate. However, the performances of road markings normally begin to deteriorate over a period of time. Road markings reach the end of service life when there is reduction of retroreflective properties due to bead loss, loss of color, reduction of skid resistance as well as chipping and abrasion causing the wear and damage of road markings [3].

There are a number of factors that influence the road markings lifespans. Traffic volume impacts how often and what types of road marking materials should be applied. The road markings on road with large traffic volume do not lasts as long as those with low traffic volume [4]. The overall intensity of the traffic on the road contributes to the abrasion of the road markings. The traffic composition impacts the durability of the road markings. Trucks and buses produce more wear on road markings than passenger cars. The thickness or amount of the road markings affects the road marking lifespans too. If a thicker layer of paint is applied, the marking will most likely to last longer. In addition, road marking lifespans depends on quality of materials. For example, the quality of beads is extremely important to achieve adequate retro-reflectivity. The application of road markings affects the durability of the road markings. For example, incorrect workmanship during application would lead to lack of adhesion of road markings to the road surface or colour variations when thermoplastic was overheated. Pavement surface and condition is significant for road marking application. The roughness of the pavement surface will influence the amount of the paint being applied. The same amount of paint will not cover a draining surface or a completely smooth surface to the same thickness.

1.2 Project Background

Autonomous vehicles are inseparable part of the smart cities of the future. An autonomous vehicle is also known as driverless transportation. It is an automobile equipped with advanced driver assistance system or even systems that are able to substitute the driver [5]. There are many benefits of autonomous vehicle deployment. Autonomous cars for example, will reduce instances of accidents caused by driver error or distracted drivers. Apart from that, deployment of autonomous cars will reduce traffic congestion because they are able to navigate through the fastest and the most efficient route.

Vehicle-to-infrastructure communication is critical for enabling autonomous driving [6]. The autonomous vehicle system obtains the information from the optical camera with lane detection capabilities to navigate the vehicle on a close track with road markings [7]. One of such necessary conditions is the quality of the road markings. The navigation system cannot discern faded, or missing road markings. Without proper navigation, the autonomous vehicle will fail to detect the lane resulting in road accidents. Therefore, the road markings quality is of significant importance and must be investigated to develop road markings which is more durable.

However, the conditions experienced by road markings are usually harsh. It is difficult for the road markings to have long lifespans. The deterioration of road markings is a common problem leading to the increase of road infrastructure maintenance costs.

The wear and friction of road markings influence the road markings durability. This summons the needs to investigate the tribological characteristics of road markings in order to improve the longevity of the road markings. In this study, the tribological properties of thermoplastic road marking paint are investigated by using the pin-on-disc tribometer. Wear mass loss and coefficient of friction are investigated under a specific range of applied load, sliding speed and sliding distance under dry and lubricated conditions.

1.3 Problem Statement

Road markings are very important for future autonomous driving vehicle and for the safety of passengers and passer-by. However, the road markings are continuously subjected to high frequency usage and aggressive motion that combine to wear them away. The worn-out road markings bring safety hazard to all the road users. Moreover, continuous remarking efforts and maintenance costs will be required. Many studies on road marking materials are related to their performances in terms of skid resistance and retroreflection. There is a lack of study on the tribological properties of road marking materials. Studies on tribological properties are significant to predict the durability performance of road marking materials. This suggests the importance to establish a study on the tribological properties of road marking materials to fill up the deficiencies of the research.

1.4 Objectives

The objectives of this research are stated below:

- To investigate the tribological properties of thermoplastic road marking paint which includes the wear mass loss and coefficient of friction of road marking materials under the effect of sliding condition, applied load, sliding velocity and sliding distance.
- To determine the optimal combination and the degree of significance of the design parameters that result in minimum wear mass loss and coefficient of friction.
- To identify the wear mechanism by examining the morphology of the worn surface.

CHAPTER 2 : LITERATURE REVIEW

Recently, the study of tribology has received huge attention as it has become evident that the potential savings offered by improved tribological knowledge. There is a lot of studies concerning the tribological properties of the materials as the understanding of friction and wear is critical for better performance of components.

S. Djebali et al. (2016) investigated the tribological behavior of pin on disc contact in dry sliding condition. The discs were made of carbon steel which undergoing heat treatment to achieve different hardness value while the pins made of bronze, virgin unsaturated polyester, and unsaturated polyester charged with graphite powder. The friction coefficient decreases with the increasing hardness value of the disc and the increasing graphite percentage. The observation shows that when the normal load and sliding speed increase, the friction coefficient increase [8]. The effect of the normal load on the friction coefficient is more significant than that of the sliding speed. When normal load increases, real contact area increases, the force required to shear the interfacial junction increases, thus the friction coefficient increases.

H. Unal et al. (2003) studied the the tribological behaviour of polyamide 6, POM and UHMWPE polymers at dry condition on a pin-on-disc arrangement. These tests were carried out varying sliding speeds (0.88 and 1.76 m/s) and loads (20-40 N). The specific wear rates were deduced from the mass loss. The sliding speed has stronger effect on the wear rate of polyamide 6, UHMWPE and POM than the applied load. The coefficient of friction increases slightly with the increase in load. In fact, for polymer, the variation of coefficient of friction with load follows the equation $\mu = K \times N^{(n-1)}$ where μ is the coefficient of friction, N is the load, K is a constant, n is a constant with its value $2/3 < n < 1$. According to this equation, the coefficient of friction decreases with the increase of load [9]. When load increase to the limit load value of the polymer, the friction and wear increase, the temperatue of the friction surfaces increases leading to the relaxation of polymer molecule chains.

Reaching at optimized balance of wear characterisitcs under a set of dynamically varying applied load, sliding velocity and sliding distance is still an unsolved research field. Hence, tailoring the wear characteristics of materials would be critical for engineering applications. Taguchi tools are used to analyse the influence of design parameters on the responses and to evaluate the optimum combination of the design parameters. Annappa A R et al. (2013) investigated the dry sliding wear characteristics of glass-epoxy composites filled with tamarind kernel powder. The filler which acts as solid lubricant reduces the wear volume loss thus improving the wear resistance. He identified the effect of design parameters such as filler volume fraction (0-6%), applied load (20-60 N), sliding velocity (3-5 m/s) and sliding distance (1000-3000 m) on wear volume loss using Taguchi approach experimental design. The results of Taguchi analysis indicate that sliding distance is found to be the prominent parameter affecting wear volume loss compared to other wear parameters [10]. The regression model demonstrates a feasible way to evaluate the dry sliding wear of the test samples because the error percentages for all the experiments vary from 3.83 to 13.3%. This variation may be due to the machine vibrations, environmental conditions and human error.

The road markings usually have lower friction than the road surface. When road markings covers a large area of the road surface, braking distance could increase when driving a split friction surface, the accident risk could increase too [11]. The friction of road markings can be measured with Portable Skid Resistance Tester as shown in Figure 2.1.

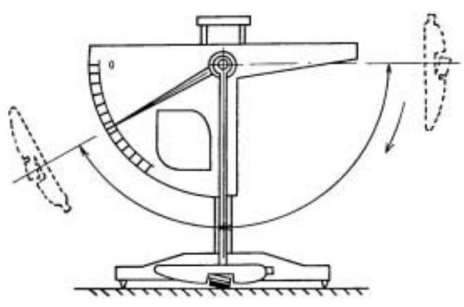

Figure 2.1 Portable Skid Resistance Tester [11]

The European standard for road marking material, EN1436 specifies that the SRT value should be higher than 45. The performance of road marking materials are evaluated based on skid resistance.

Ali Siyahi et al. (2014) studied the effect of addictive materials such as waste glass powder, silica granules and Lika on the skid resistance, abrasion resistance, reflectivity and adhesive properties of the road marking paint [12]. The test specimen was prepared by applying the marking paint with thickness of 800 microns on asphalt specimen. A laboratory-scale tool was used to apply the same thickness of paint on the asphalt specimen. Required amount of paint was uniformly poured on the surface. The tool placed on top of the specimen surface was moved with a constant velocity until the entire surface was equally covered with the paint. The specimens were kept at 25 °C for 72 hours under laboratory conditions until the paint was completely dry afterward. The skid resistance values of the specimens are determined by using a British Pendulum Skid Resistance Tester. The results show that the addition of addictive improve the skid resistance but causing the reduction in the abrasion resistance. The application of waste glass powder by 10 % of the weight of the paint improve the skid resistance without impose much negative effect on abrasion resistance and other properties.

The performance of the road marking materials can be tested in laboratory or on-road. The laboratory performance tests measure properties such as color, luminance, heat stability, softening point and flow resistance. The on-road performance tests measure the durability of the material in-service. The tests measure properties such as degree of wear, skid resistance, retroreflectivity, luminance and color. Although the results of in-laboratory test are reliable and repeatable, but they may not directly reflect the in-service use of the materials. The in-situ test performed under actual traffic and weather conditions provides more accurate results than those obtained in laboratory.

Timothy J. Gates (2003) evaluated the performance of pavement marking materials on asphalt and concrete in terms of durability and retroreflection. The field testing was carried out by placing multiple beaded transverse lines for each pavement marking materials. Durability was determined by estimating the percentage of the stripe remaining (non-exposed substrate) at each line [13]. The durability ratings were reported on an integral scale from 0 to 10. This research revealed the bonding mechanism of thermoplastic paint to pavement surface. Thermoplastic materials bond to asphalt through a thermal-bonding process which creates a very tight bond between the thermoplastic and asphalt.

Andres Coves Campos et al. (2018) done the in-situ study of road marking durability. The study found out the effect of drop-on materials such as glass microbeads, transparent antiskid aggregates (sodium-calcium glass particles) and non-transparent antiskid aggregates (white marble sand) on the luminance, retroreflectivity and skid resistance of road marking. It is found out that the relation between skid resistance is opposite to daytime and nighttime visibility. The samples with non-transparent aggregates have higher skid resistance but have lower values of luminance and retroreflectivity because the rougher mixtures capture dirt and rubber particles, darkening the markings surface [14].

Troger apparatus as shown in Figure 2.2 was used to determine the wear resistance of road marking materials by simulating the wear from studded tyres [15].

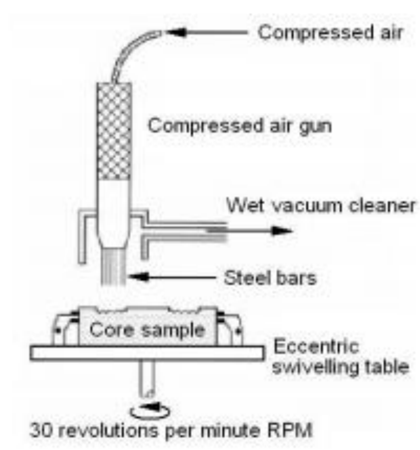

Figure 2.2 Troger apparatus [15]

The sample is mounted on a rotating table with speed of 30 rpm. Wear is produced by a vertical group of needles striking the sample driven by compressed air. Testing comprises

16 periods of 40 s with a 32 s pause after each period. Troger wear is defined as the loss of mass after the testing.

Maryam Taheri et al. (2018) investigated the wear resistance and scratch resistance of nanocomposite traffic marking paint. Wear resistance measures the ability of the dried film to withstand wear from traffic and from objects rolled or pulled across the surface [16]. Wear resistance was determined by pouring abrasives on to a dry film on a glass panel until the paint was removed. Scratch resistance was determined by penetrating the tipped needle under increasing load. The penetration of the needle may be either to the substrate or to an intermediate coat. This research concluded that nanosized particles when correctly dispersed in coatings, enhance the wear and scratch resistance of traffic marking paint.

In the past, a number of studies on the abrasion resistance of the road marking paint have been carried out. Ali Siyahi et al. (2014) studied the abrasion resistance of road marking paint using Wet Track Abrasion Tester (WTAT). The specimens were submerged in a water bath of 25°C for 60 to 75 minutes. Subsequently, the specimens were removed from the water bath and the abrasion resistance were tested. The abrasion resistance was evaluated by examining the amount of the paint remained intact on the surface [12].

Studies on abrasion resistance of road making paint under dry and wet condition have been carried using Taber abraser as shown in Figure 2.3. The test specimen is mounted on a rotating turnable. Two loaded wheels on an axis that is offset from the turnable axis are used to cause abrasion to the test specimen surface [17]. The abrading wheels with different levels of aggressiveness can be used. The load on them can be controlled. The standard loads are 0.25 kg, 0.5 kg or 1 kg. S. M. Mirabedini et al. (2012) determined the abrasion resistance using Taber abrasion tester. The weight loss after 1000 rotation with 1 kg load was recorded as the abrasion resistance value according to ASTM D4060 [18].

Figure 2.3 Taber Abraser [18]

W. Lee Shoemaker et al. (1988) studied the abrasion resistance of types of paint marking using Taber Abraser under dry and submerged condition. The results show that the alkyd resin paint exhibits lower wear in submerged condition than dry condition [19]. A. C. Aznar et al. (1997) carried out the dry and wet abrasion tests using Taber Abraser. The dry wearing was determined after 100 revolutions. After finishing the dry wear test, distilled water was added to the track to carry out the wet wear test for 100 revolutions. The results show that the wearing values are three times greater in wet wear test than dry wear test [20]. The retained moisture of the thermoplastic traffic material after immersion is considered as a harmful property to the wearing resistance.

A. C. Aznar et al. (1997) measured the shore A hardness of thermoplastic traffic marking according to ASTM D2240 at the temperature between 40 °C and 70 °C at an increment of 5 °C [20]. The samples were stabilized to the test temperature for at least one hour before being tested its hardness value. The hardness decreases as the temperature increases. Above the critical temperature of 55 °C, the hardness values reduce abruptly.

W. Lee Shoemaker et al. (1988) done the tensile testing of paint marking at room condition at load rate of 0.2 in/min. The paint markings were categorized according to their percent elongation. The paint with percent elongation of greater than 50 % is ductile, the paint with percent elongation of less than 10 % is brittle, otherwise the paint is classified as average ductility. The alkyd resin is classified as brittle paint marking. Brittleness of the paint marking will cause the cracking. The tensile stress is induced at the paint-pavement interface when the pavement expands and contracts with the temperature [19]. As a result, the brittle paint marking cracks. More ductile paint marking can tolerate the tensile stress and conform to pavement better.

S. M. Mirabedini et al. (2012) optimized the composition and performance of the thermoplastic road markings using mixture experimental design [21]. The key factors include the resin, titanium dioxide, talc, and plasticizer at different levels. The key responses include the softening point temperature and its change after heat stability test, abrasion resistance, color difference after weathering resistance test and heat stability test. The results were analyzed using Analysis of Variance (ANOVA) as shown in Figure 2.4. ANOVA shows the best model to fit the correlation between the design parameters and responses. Value of 'Prob>F' less than 0.05 means that the model term is significant. In this case, AC and CD are significant model terms.

ANOVA of T_{sp} response for thermoplastic road marking samples.

Source	Sum of squares		d_f	Mean square		F-Value		Prob > F		A	B
	A^a	B^a		A	B	A	B	A	B		
Model	812.81	398.73	9	90.31	44.30	16.05	12.04	0.0216	0.0324	Significant	
Linear mixture	788.96	248.99	3	262.99	83.00	46.73	22.55	0.0051	0.0147		
AB	1.44	31.52	1	1.44	31.52	0.26	8.56	0.6478	0.0612		
AC	0.025	79.90	1	0.025	79.90	0.005	21.71	0.9506	0.0187		
AD	0.017	5.33	1	0.017	5.33	0.003	1.45	0.9594	0.3153		
BC	1.14	26.03	1	1.14	26.03	0.20	7.07	0.6827	0.0764		
BD	4.33	34.59	1	4.33	34.59	0.77	9.40	0.4448	0.0548		
CD	2.50	67.63	1	2.50	67.63	0.44	18.38	0.5531	0.0233		
Residual	16.88	11.04	3	5.63	3.68						
Cor total	829.69	409.77	12								

[a] A and B represent response results for rosin ester and hydrocarbon based formulations, respectively.

Figure 2.4 ANOVA of softening point temperature [18]

There is a scarcity of literatures related to the thermoplastic road marking paint in the tribological field. In this study, thermoplastic road marking paint will be tested for its tribological properties under rotary pin-on-disc sliding configuration. The wear mass loss and coefficient of friction of the thermoplastic road marking paint specimen are investigated under different sliding condition (dry/lubricated), applied load, sliding speed, and sliding distance. The morphology of the worn surface after tribological tests will be studied using Scanning Electron Microscope in order to identify the wear mechanism.

CHAPTER 3 : RESEARCH METHODOLOGY

3.1 Overview

The fabrication of specimen is done for various tesiting purpose. The mechanical properties, such as hardness and ductility of the thermoplastic road marking paints are investigated. The wear tests are carried out using DUCOM Pin-On-Disc Tester based on Taguchi L18 Orthogonal Array. Sliding condition, applied load, sliding speed and sliding distance are design parameters whereas wear mass loss and coefficient of friction are responses used. The optimal combination of design parameters for mininum wear mass loss and coefficient of friction is determined using Taguchi Analysis technique. Analysis of Variance (ANOVA) is done to investigate the significance of the design parameters. Finally, scanning electron microscope (SEM) is used to examine the worn surface of the specimen in order to identify the wear mechanisms.

3.2 Scope of Works

The friction and wear characteristics of thermoplastic road marking paints are investigated by conducting pin-on-disc wear test. The study does not attempt to represent the real application condtion. The study is done to investigate the tribological characteristics for a specific range of applied load, sliding speed and sliding distance being explored in this study.

The flowchart of the experimental and analytical works is shown in Figure 3.1.

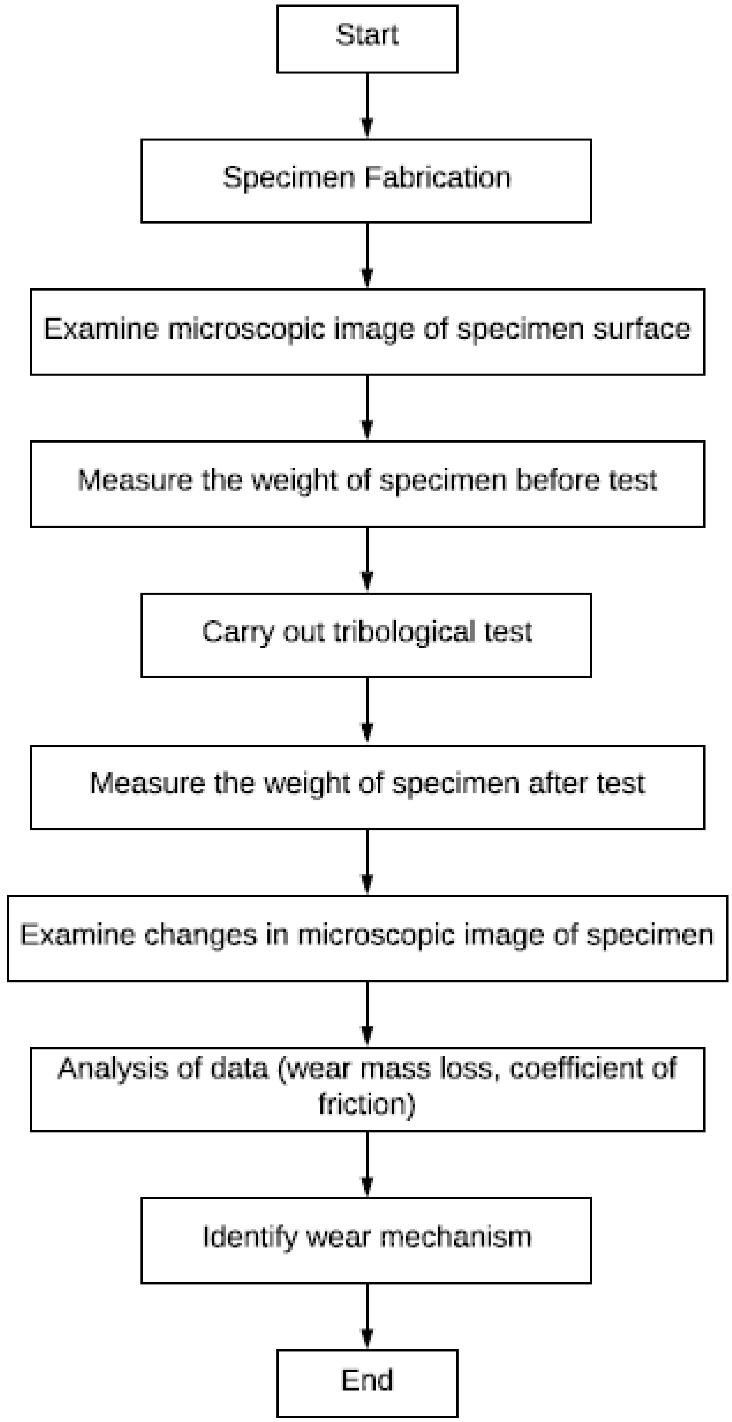

Figure 3.1 Flowchart of experimental and analytical works

3.3 Fabrication of Test Specimen

3.3.1 Raw Materials for Fabrication of Test Specimen

The thermoplastic road marking materials is shown in Figure 3.2. Thermoplastic road marking materials are dry homogenously mixes of filler, glass beads, binder, pigments and additives.

Figure 3.2 Thermoplastic road marking materials

Table 3.1 shows the constituents of the thermoplastic road marking materials and their functions [21][22]. Application requires heating of the thermoplastic road marking materials to an elevated temperature as specified by the manufacturer and then extruding a certain thickness of coating onto the road surface.

Table 3.1 Constituents of thermoplastic road marking materials

Constituent	Weightage	Function	Materials
Binder	18% min.	Hold components together. Provide adhesion to the road surface.	Hydrocarbon, alkyd resin

Glass beads	30% min.	Create the retroreflection which improves road marking visibility.	
Pigment	10% min	Impart colour and opacity to the mixture.	Titanium dioxide, zinc oxide, lead, lithopone
Filler	Less than 42 %	Provide mechanical strength. Ensure wear resistance.	Calcium carbonate, silicates, silica, mica, barytes
Additives		Increase the plasticity of the coating. Aids in dispersion and improve anti-settling.	Plasticizer

3.3.2 Fabrication Process for Test Specimen

The thermoplastic road marking materials was heated using a gas stove. The melting point of the thermoplastic road marking materials was observed to be 200 °C as measured by Oakton Infrared Thermometer. After all the thermoplastic road marking materials had been melted, it was poured into the mold. Thermoplastic road marking materials reverted to a solid state upon cooling. The specimens of size 8 mm x 8 mm of length 35 mm as shown in Figure 3.3 were made for tribological testing purpose.

Figure 3.3 Test specimen

3.4 Mechanical Properties

3.4.1 Hardness Test

The hardness of the specimen was measured using TECLOCK GS-706G Type A Durometer as shown in Figure 3.4 according to Test Method D2240. ASTM D2240 is a test method to test the depth of an indentation in the material being tested. The depth of indentation is proportional to the material hardness. The indentor was held in contact with the specimen by applying force manually. The resistance to indentation was displayed on the dial gage. The test was repeated three times to obtain an average hardness value.

Figure 3.4 TECLOCK GS-706G Type A Durometer

3.4.2 Tensile Test

Tensile test was carried out by using Instron 3367 Universal Testing Machine as shown in Figure 3.5. Tensile test applies tensile force to the specimen and measures the elongation of the specimen. The force required to break the specimen and the extent to which the specimen elongates that breaking point is measured. The specimen was placed in the grips at a certain grip separation. The specimen had a gage length of 100 mm. The test speed was set to be 1 mm/min and the specimen was pulled until failure. The elongation was measured by the extensometer to determine the tensile profile of the specimen. The test was repeated two times to obtain an average tensile value.

Figure 3.5 Instron 3367 Universal Tensile Machine

3.5 Surface Morphology Study

Surface morphology uses sophisticated microscopes of high spatial resolution to produce image of the specimen that cannot be seen with the naked eye. Surface morphology study of the specimen was carried out using Scanning Electron Microscope and USB Optical Microscope.

Hitachi S-3400 Scanning Electron Microscope (SEM) shown in Figure 3.6 was used to examine the surface of the specimen before and after the wear test in order to identify the wear mechanism.

Figure 3.6 Hitachi S-3400 Scanning Electron Microscope

Energy Dispersive X-ray (EDX) analysis was carried out for the elemental analysis of the specimen. The surface of the specimen was coated with a thin layer of gold using Quorum SC7620 Sputter Coater before analyzed. EDX characterization capabilities come from the interaction of the X-Ray source with the samples. The presence of unique set of peaks on electromagnetic emission spectrum reflects the unique atomic structure of each element. The elements present in the specimen were confirmed using EDX analysis.

USB Optical Microscope shown in Figure 3.7 was used together with Dino Capture software to examine the worn surface of the specimen. The LED lights on USB optical microscope was turned on. The magnification was adjusted to 80X to observe the worn surface of the specimen in a broader view.

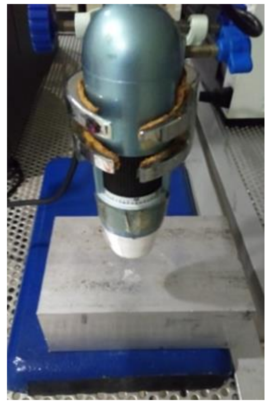

Figure 3.7 USB Optical Microscope

3.6 Surface Profilometry

Profilometry is a techinique used to extract topographical data, such as surface roughness of a surface. It can be a line scan or a full three dimensional (3D) scanner. The surface profilometry was done by using the stylus profilometer and optical profilometer.

The surface roughness measurement was conducted across the surface of the specimen before and after the wear test using Surfcom 130A Surface Profile Measuring Instrument as shown in Figure 3.8. The evalution length was set to be 4 mm and measure range was set to be 400 μm.

Figure 3.8 Surfcom 130 Stylus Profilometer

The surface rougness measurement of abrasive paper was conducted using Alicona InfiniteFocus measurement instrument as shown in Figure 3.9. This measuring instrument combines dimensional metrology and surface roughness measurement in one system. The measurement results have high repeatability and resolution up to 10 nm.

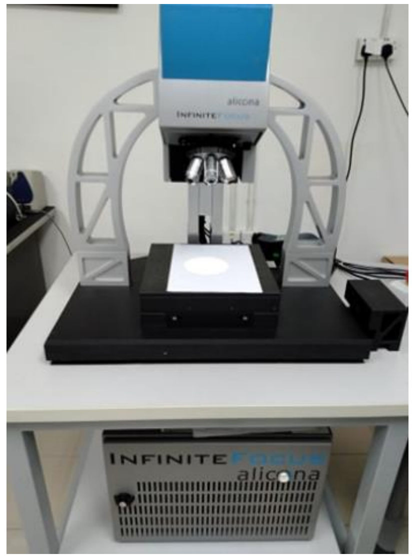

Figure 3.9 Alicona InfiniteFocus Measuring Instrument

3.7 Wear Test

The pin-on-disc test rig used to conduct the wear test is schematic illustrated in Figure 3.10. The stationary pin is normally loaded against the rotaing disc. The unidirectional motion of the disc is provided by a speed motor. The pin is held in a specimen holder which is rigidly attached to a pivoted loading arm. During the test, friction force is measured by a transducer mounted on the loading arm. Wear rates can be calculated from the mass loss during the test. The amount of wear depends on the applied load, sliding speed, sliding distance, material properties and its environment.

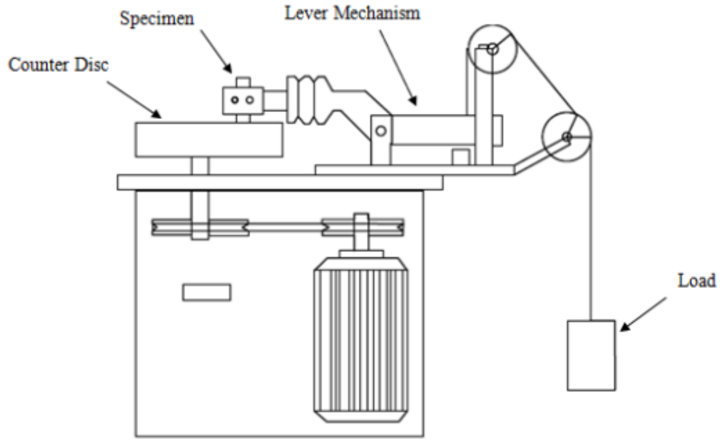

Figure 3.10 Pin-On-Disc test rig [23]

3.7.1 Experimental Procedure for Wear Test

In this work, wear tests were conducted by using DUCOM Pin-On-Disc tester model TR-20. Figure 3.11 shows the DUCOM Pin-On-Disc tester model TR-20. The wear tests were carried out according to ASTM G99 standards. The pin specimen of size 8 mmm x 8 mm of length 35 mm was tested against the abrasive paper of grade 1000 sticking on top of the steel disc.

Figure 3.11 DUCOM Pin-On-Disc tester model TR-20

Prior to the wear test, the pin specimen was rubbed over a 600 grade abrasive paper to ensure contact of the flat surface with the steel disc. Then, the initial mass of the specimen, M_1 was weighed using a digital analytical balance, SHIMADZU Balance AUW220D as shown in Figure 3.12 which has a precision of 0.00001g.

Figure 3.12 SHIMADZU Balance AUW220D

Abrasive paper of grade 1000 was stick on top of the steel disc. The wear track diameter was adjusted to 100 mm. The pin specimen was inserted securely in the specimen holder. The pin was held pressed against the counterface by applying dead weight on the loading pan. Figure 3.13 and 3.14 show the set up of the experiment.

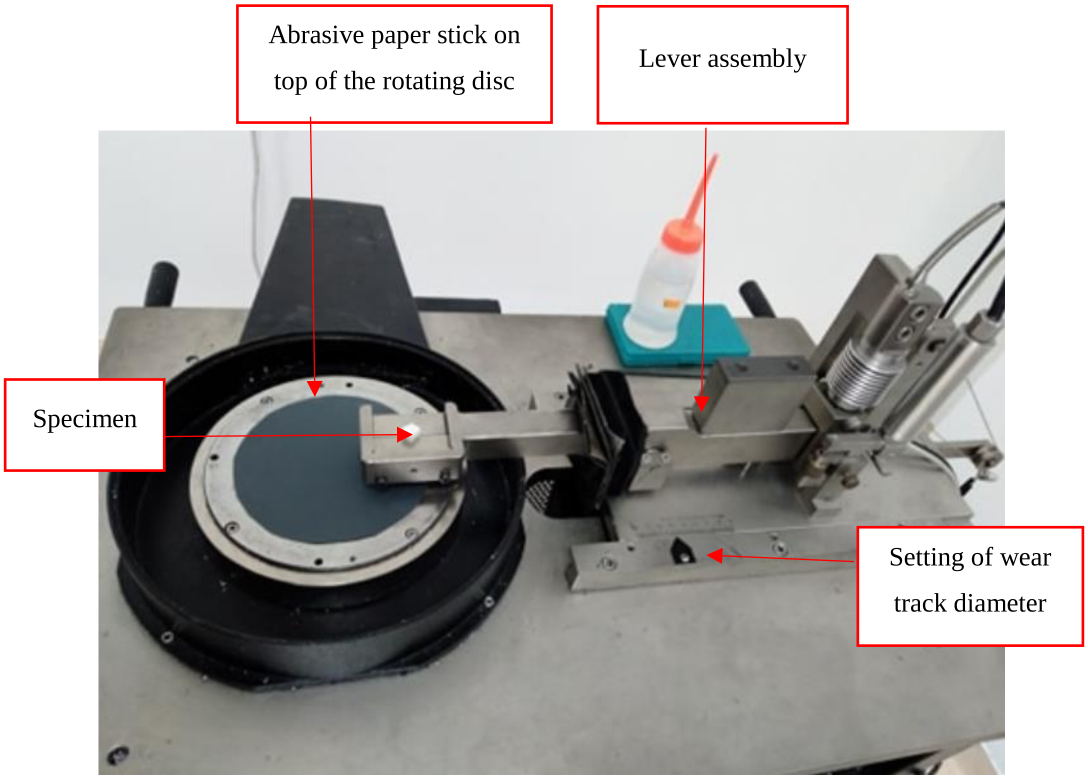

Figure 3.13 Experimental setup

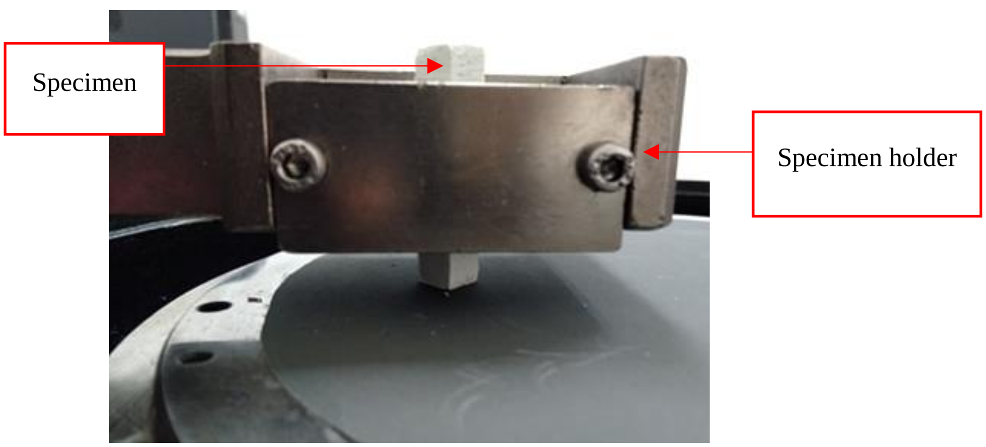

Figure 3.14 Experimental setup showing the insertion of specimen in the specimen holder

The WINDUCOM 2010 software was opened and the details were entered as follows as shown in Figure 3.15:

Select ROTARY > Enter speed: 120 RPM > Enter normal load applied: 1 kg > Enter track diameter: 100 mm > Enter test duration: 00:05:19 > Click on ACQUIRE > Click zero button to initialize the wear and frictional force display zero > Click RUN button to begin test

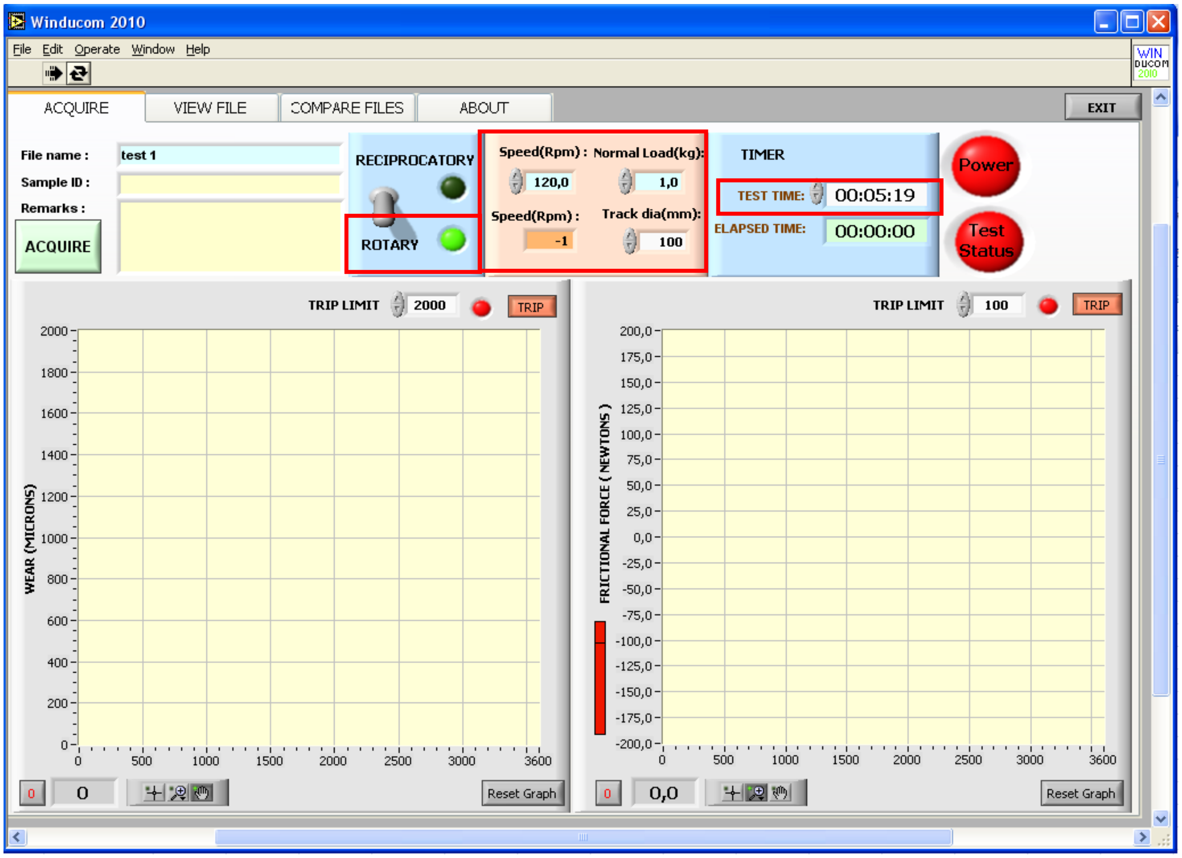

Figure 3.15 WINDCOM 2010 software

The test automatically stopped after the completion of test duration. The specimen was removed and any loose wear debris was cleaned off. The mass of the specimen after wear test, M_2 was measured again using the digital analytical balance. The wear mass loss, ΔW is calculated by using Equation 3.1 [24].

$$\Delta W = M_2 - M_1 \quad (3.1)$$

The wear tests were conducted under different contact condition, varying applied load, sliding speed and sliding distance. For the wear test under lubricated condation, water was added to the sliding surface in a dropwise manner ensuring the presence of thin layer