Study on physicochemical properties of Magnetorheological Elastomer Featuring Naphthenic Oil as Additive

by

Nasrullah Bin Abdullah Saloji
24785

Dissertation submitted in partial fulfilment of
the requirements for the
Bachelor of Mechanical Engineering
With Honours

FYP II
January 2020

Universiti Teknologi PETRONAS
32610 Seri Iskandar
Perak Darul Ridzuan

CERTIFICATION OF APPROVAL

Study on physicochemical properties of Magnetorheological Elastomer Featuring Naphthenic Oil as Additive

by

Nasrullah Bin Abdullah Saloji
24785

A project dissertation submitted to the
Mechanical Engineering Programme
Universiti Teknologi PETRONAS
in partial fulfilment of the requirement for the
BACHELOR OF MECHANICAL ENGINEERING
WITH HONOURS

Approved by,

____

(Dr Nurul Azhani Bt Yunus)

UNIVERSITI TEKNOLOGI PETRONAS

BANDAR SERI ISKANDAR, PERAK

January 2020

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

Nasrullah

Nasrullah Bin Abdullah Saloji

ABSTRACT

Magnetorheological (MR) materials are magnetically active materials whose physics or mechanical properties are often changed unceasingly, rapidly, and reversibly by applying a magnetic field. Magnetorheological elastomers (MREs) principally contain elastomers or rubbery materials and soft magnetic particles. MREs are often referred to solid analogue of previously developed magnetorheological fluids. The introduction of Petroleum based oil (PBO) as the additive has been discussed to increase the dispersion of the magnetic particles, thus increased the MR effect. MREs samples were fabricated by using natural rubber bas matrices, CI as magnetic particles and different ratio of naphthenic oil to aromatic oil as the additive which are 100:0, 70:30, 50:50 and 30:70, respectively. The microstructure of the samples were observed and the samples with 100:0 of NO to AO shows the best CIP dispersion. The thermal behavior was analyzed by using the Thermogravimetric analysis (TGA) where the sample of 100:0 start decomposing at the higher temperature compared to another sample. The magnetic saturation was analyzed and the sample with 100:0 ratio shows the highest magnetic saturation. The use of naphthenic oil is believed to be potentially useful in industry applications, such as vibration absorbers, base isolator etc.

TABLE OF CONTENTS

List of Tables

List of abbreviations

MR: Magnetorheological

MRE: Magnetorheological Elastomer

NR: Natural Rubber

CI: Carbonyl Iron

CIP: Carbonyl Iron Particles

FESEM: Field Emission Scanning Electron Microscopy

VSM: Vibrating Sample Magnetometer

TGA: Thermogravimetric Analysis

NO: Naphthenic Oil

AO: Aromatic Oil

1.0 Introduction

1.1 Background of study

Magnetorheological (MR) materials are magnetically active materials whose physics or mechanical properties are often changed unceasingly, rapidly, and reversibly by applying a magnetic field. Magnetorheological elastomers (MREs) principally contain elastomers or rubbery materials and soft magnetic particles.

The most well-known MR materials is MR fluids (MRFs) and it is used in the industries such as in the damping system etc. The MREs then was founded by (Rigbi and Jilken, 1983) an know to be as the solid analogue to MRF. The MRFs are usually have a lot of disadvantages due to its fluid form which always have leaking and sedimentation problems. The MREs can overcome the short coming and the weakness of the MRFs by replacing solid matrix.

MREs can be categorized into two types based on the fabrication method which are the isotropic and anisotropic. The MREs that has been produced in the absence of magnetic field is known as the isotropic MREs. Then, the MREs that has been produced in the presence of magnetic field which are known as anisotropic MREs where the chain like structure of the magnetic particles is formed and thus give more MR effect The chain like structure of the magnetic particles are formed when the individual particles are exposed to the magnetic field, the magnetic dipole moment that pointing on the direction of the field will be induced among them. Then, the north pole of the one particle will attract the neighbor of the south pole by magnetic force thus resulting on the chain columnar in the matrices. the particle will be back in its place during curing process.

Generally, MREs consist of three major components which are matrix, magnetic particle and additives. There are matrices that have soft elastic properties which mean these matrices can maintain the magnetic particles under zero magnetic field and can deform finitely under the magnetic field. There are a lot of polymetric rubber that can be suggested to be use such as silicone rubber, natural rubber, butadiene rubber, and epoxy rubber.

The second material for MREs is the magnetic particles. For this material, it has high permeability, high saturation magnetization, and low remnant magnetization that highly recommended due to the strong magnetic field sensitive effect. Some of the most used magnetic particles in fabricating the MREs is Carbonyl Iron (CI) since it has, high permeability, high saturation magnetization, and low remnant magnetization

One other component that is also a key when preparing the MREs is additives. This can be either from silicone oil (SO), carbon black, carbon nanotube silver nanowire. But the silicone is widely used for additives. The other additive that is also proven to be as softener is the Petroleum Based Oil (PBO) where this additive can increase the matrix molecule and decreased the conglutination of the molecules when the silicone oil enters the matrix. The additive can also increase the internal stress distribution thus making the MRE more stable.

1.2 Problem Statement

For a quite long time, many researchers and engineers were challenged for solving problem regarding the stiffness and damping mechanism which is used a lot in the MREs applications such as automobile and mechanical industries. This damping mechanism were countered by using the MRFs, but this fluid is facing difficulties including magnetic particles sedimentation and sealing. By using Natural rubber based MREs, the problem that were present on MRFs can be reduced.

However due to previous experiences with MR fluid, the issue of MR effect pertaining to a proper dispersion of magnetic particles is thoroughly studied. It is known that the introduction of dispersion aids will help in improving compatibility and provide better lubricant property between rubber molecular and magnetic particles within composite. Some examples of dispersing aids include Petroleum-Based Oils (PBO) and Silicon-Based Oil (SBO). For this study, the PBO was chosen as they are well known and proven softener and can act as extender process oils in rubbering processing. Some of PBO are paraffin, naphthenic, aromatic asphaltic oils.

1.3 Research objective

This project aims to study the effect of different ratio~~s~~ of petroleum-based oils corresponding to naphthenic oil on the physicochemical properties of MREs utilizing natural rubber as matrix.

The objectives of this research accordingly have the following aims:

(a) To fabricate ~~a~~ Natural rubber based MREs with different ratio~~s~~ of Naphthenic Oil and Aromatic Oil as additive.
(b) To analyze the effect of different ratio~~s~~ of Naphthenic Oil- and Aromatic Oil on the physicochemical of the NR-based MREs such as microstructure of the MRE, thermal behavior and magnetic properties.

1.4 Scope of study

There were three main elements that were focused in this study. The scope includes:

1. MREs samples were fabricated using the natural rubber as the matric, CIP as the magnetic particles and naphthenic oil as the additive
2. Different ratio of the naphthenic oil to aromatic oil were used as additive which are 100:0, 70:30, 50:50 and 30:70, respectively.
3. Physicochemical properties such as MREs samples were studied by using the Field Emission Scanning Electron Microscopy (FESEM), Thermogravimetric analysis (TGA) and Vibrating sample magnetometer (VSM)

2.0 Literature Review

2.1 Definition of Magnetorheological Elastomer

Magnetorheological elastomers (MREs) are one of the smart materials that has been developed in this modern era where its usage can have high advantages over its predecessor. This smart material is known as soft particles reinforced magneto active rubber where this rubber can change its physical and mechanical properties when the magnetic field is applied (Li, Li & Du, 2014). During the application of the magnetic field on the MREs, the material can induce a magnetorheological effect where the physical, rheological and mechanical properties can be adjusted depending on the magnetic field applied. For example, the modulus of the material can now be controlled because the sensitivity response from magnetic field. But when the field is removed, the MREs will return to its original state. the MREs that has been produced in the presence of magnetic field which are known as anisotropic MREs where the chain like structure of the magnetic particles is formed and thus give more MR effect The chain like structure of the magnetic particles are formed when the individual particles are exposed to the magnetic field, the magnetic dipole moment that pointing on the direction of the field will be induced among them

The first embryo of MRE were reported decades ago by Rigbi & Jiken (1983) but the basic magnetorheological effect was discovered in 1940s in the magnetic fluids. MRE can be described as a solid-state analog to magnetorheological fluids (MRFs) and often voted as better than the MRF (Ashour, Rogers & Kordonsky, 1996). This is because MR elastomers is the lack of sedimentation, as the ferromagnetic particles are embedded in a polymer matrix, which gives them a small range of motion. The achievable yield stress in MR fluids is also something that raises concern, as these smart fluids typically work in the post- yield region, while MR elastomers work in the pre-yield region. To add to that, MR elastomers do not need channels or seals to hold or prevent leakage, as they have a solid state of matter. Plus, the MRE is not only can be used in damping technology, but also very useful in other mechanism such as vibration isolation, medicine and many more (Deng & Gong, 2008).

2.2 Components in MRE

MRE usually will have ~~3~~ three basic components which are magnetic particles, matrix and additives. In this subtopic, each component was reviewed and discussed in depth.

2.2.1 Magnetic particles

The second material for MREs fabrication is the magnetic particles. Magnetic particles can be further divided into two categories which are soft magnetic and hard magnetic particles. Soft magnetic particles are particles that have smaller area enclosed to their hysteresis loop while hard magnetic particles are particles that has larger area enclosed to their hysteresis loop. Soft magnetic particles usually have low remnant magnetization while hart magnetic particles have high remnant magnetization. Soft magnetic materials that has, high permeability, high saturation magnetization, and low remnant magnetization is highly recommended because of its strong magnetic field sensitive effect. Some of the most used magnetic particles in fabricating the MREs is Carbonyl Iron (CI) due to its high permeability, high saturation magnetization and low remnant magnetization. Figure 1(a) shows the macroscopic image of the CI powder. CI powder is a very fine powder material. Figure 1 (b) and (c) on the other hand shows the microscopy images with different magnetization and it can be seen there are several types of diameter for that material. For most magnetic particles, the diameter size is usually ranged from several micrometers up to hundreds of micrometers (Lokander & Stenberg, 2003).

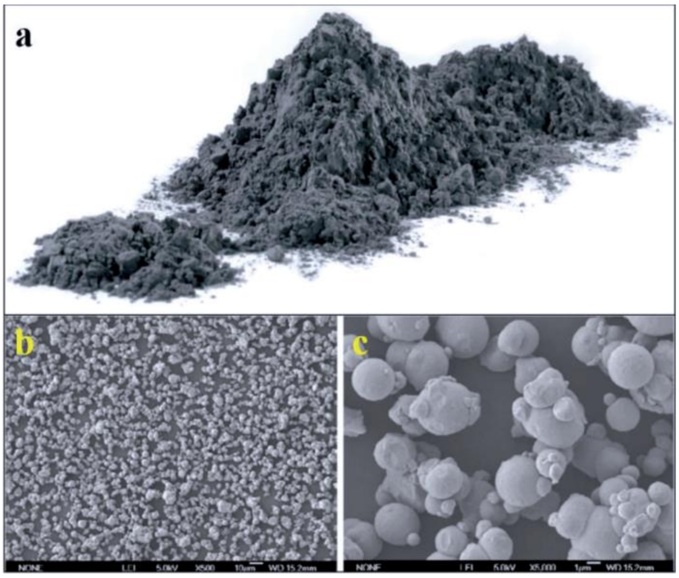

Figure 1: Carbonyl iron (Zhu, 2010)

The saturation magnetization values of CIP can reach more than 600 kA/m and when the magnetic field is removed, the remnant of magnetization is very small. This is because the CIP contain about 97.5% of the Fe element thus improving the magnetic properties. The CIP is also widely used in other fabrication such as steel fabrication industries and not limited to MRE only.

2.2.2 Elastomer Matrices

One of the matrices properties requirement to fabricate the MRE is ~~is~~ that the matrices must have a soft elastic property so that the magnetic particle can be hold stably by the matrices when no magnetic field is applied and when there is the application of magnetic field, the matrices can have a finite deformation. There are lots of rubbers that can be considered for matrices such as natural rubber, butadiene rubber, butyl rubber etc. Figure 2 shows the images of silicone rubber and its application.

Figure 2: Silicone rubber and its products (Stepanov et al., 2006)

Each matrix has different modulus from each other such as silicone rubber might have a modulus lower than 1.0 MPa (Bose, 2007) while natural rubber on the other hand can have several more MPa (Chen et al., 2007). Usually the shear modulus of PDMS range around 0.1-3.0 MPa but it may differ depending on the preparation condition.

Based in the Figure 2, Silicone rubber can be described as low modulus, have good chemical stability, nontoxic, non-polluting and very friendly for daily use. Thus, it is safe to say that this rubber is very suitable to be used in MRE preparation. But other type of rubber also can be used for MRE materials such as natural rubber.

2.2.3 Additives

One other component that is also a key when preparing the MRE is additives. This can be either from silicone oil, carbon black, carbon nanotube silver nanowire and etc. But the silicone is widely used for additives. This additive can increase the matrix molecule and decreased the conglutination of the molecules when the silicone oil enters the matrix. The additive can also increase the internal stress distribution thus making the MRE more stable. There also some study by Chan, In & Hyung (2018) where additives from petroleum-based oil such as naphthenic oil can increased the MR effect of the MRE.

2.3 Preparing Method

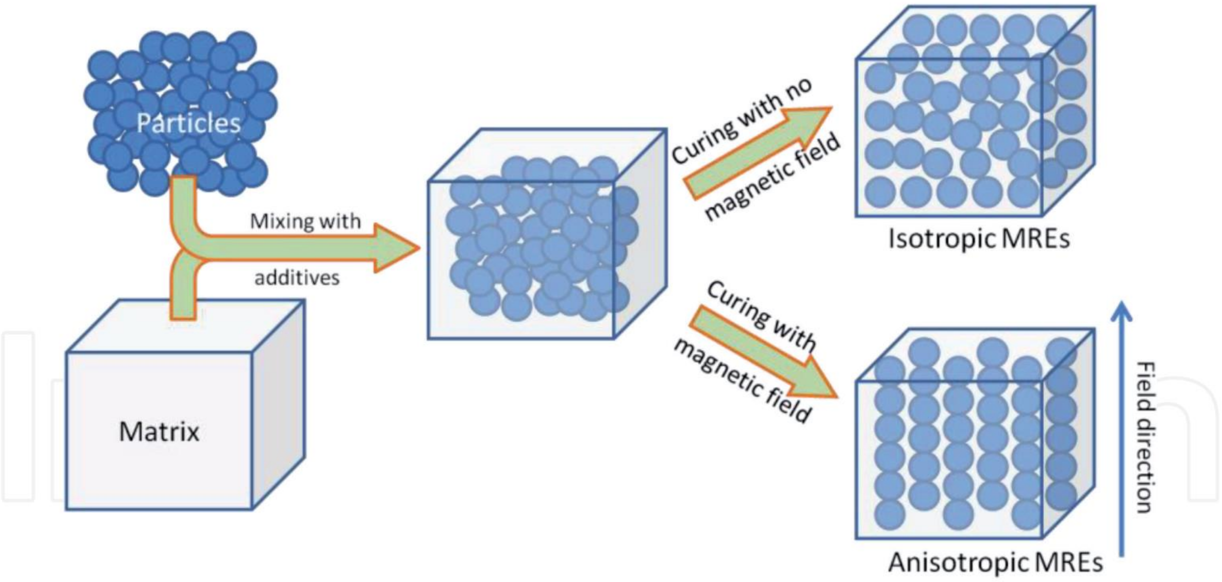

Figure 3: MRE preparation process (Lee at al, 2018)

Figure 3 shows the simplified process of MRE preparation. The MRE components which are matrices and the magnetic particle are usually mixed with some addition of additives. The process produced a mixture that can be easily deform due to the low yield stress, and it then will creep by itself. The mixture then will go through vulcanizing process where mixture will be vulcanized in room temperature or high room temperature (Zhu, 2010). During this process, if the magnetic field applied, the magnetic particle will move into the matrix and will form a chain like structure according to the direction of the field. The process will produce an anisotropic MRE while if the curing is done without applying magnetic field, the magnetic particle will disperse uniformly thus producing an isotropic MRE. Figure 4 (a) and (b) shows the MRE sample that has been prepared.

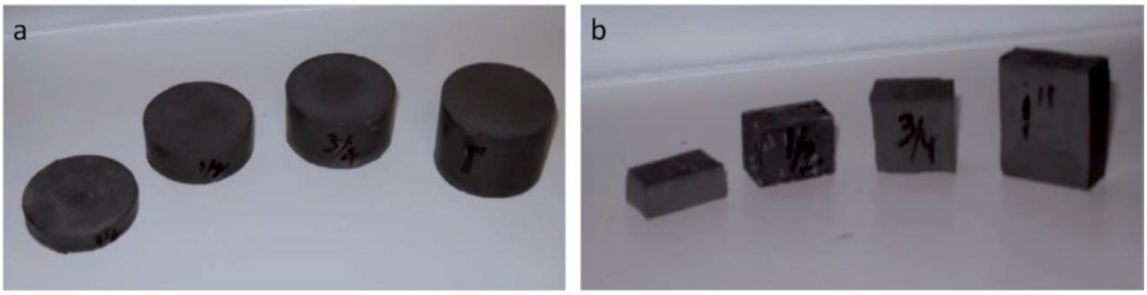

Figure 4 (a) and (b): Sample of MRE (Lee et al., 2018)

2.4 Microstructure and macroscopic properties of MRE

2.4.1 Microstructure of MREs

One of the studies of MREs properties that is really important is the study of microstructures of the MREs. Figure 9 show the images of carbonyl iron powder embedded with natural rubber based MRE microstructure with different magnification. In figure 5 (a) the carbonyl iron dispersed randomly in the matrix ~~because~~ due to the absence magnetic field was applied on the sample. This is the typical images that will showed if it is an isotropic MRE. On the other hand, a chain like structure was formed due to the application of magnetic field in figure 5 (b) and this is known as Anisotropic MRE. The higher or stronger the magnetic field applied during curing process, the longer the and thicker the chain structure thus increasing the magnetic interaction.

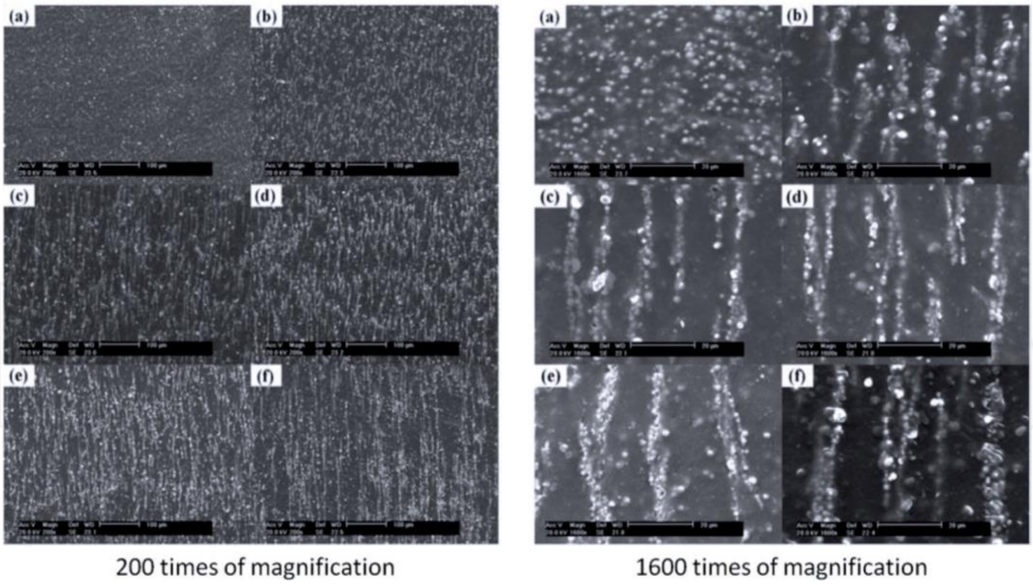

Figure 5: Microstructure of MRE (Chen, Gong and Li, 2007)

2.4.2 Macroscopic properties

One of the most important properties in MRE study is macroscopic properties or mechanical properties. This is because the MRE macroscopic physical can be changed according to the magnetic field application.

A lot of the study about the MRE are more concentrate to the MRE damping or the modulus change by the induced magnetic field (Li, Li & Du, 2014). There is an equipment that will be used to measure the shear storage and the los modulus which called the Dynamic mechanical analyzer (DMA). Figure 6 below describe about the damping and the shear storage modulus of the MRE samples.

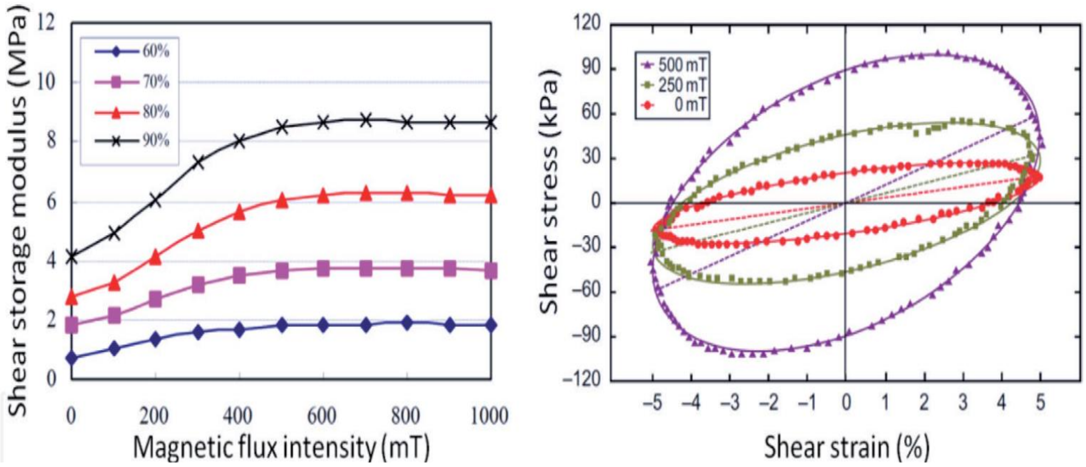

Figure 6: Relationship between shear strain and shear stress under different magnetic strength (Chen et al. 2007)

2.5 Applications

MREs is a smart material that can be used in a lot application such as vibration absorber, vibration isolator, sensors, controllable valves and adaptive beam structure.

2.5.1 Vibration Isolator

Vibration isolator is a device where it is used to isolate the equipment from the vibration. There are two categories of this device which are base isolation and force isolation (Ibrahim, 2008). Figure 7 shows a layout design of the base isolator where it can work in squeeze or elongation-shear mode.

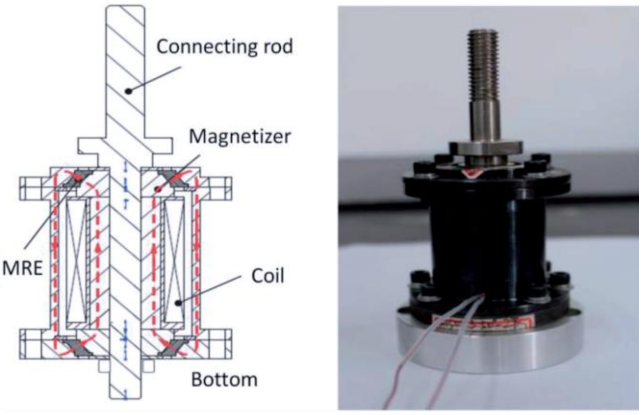

Figure 7: Base isolator (Yu et al., 2016)

3.0 Methodology

The methodology of the research was started by materials selection and followed by samples or MRE fabrication, and rheological testing as well as analysis. Figure 3.1 shows the process flow of this project.

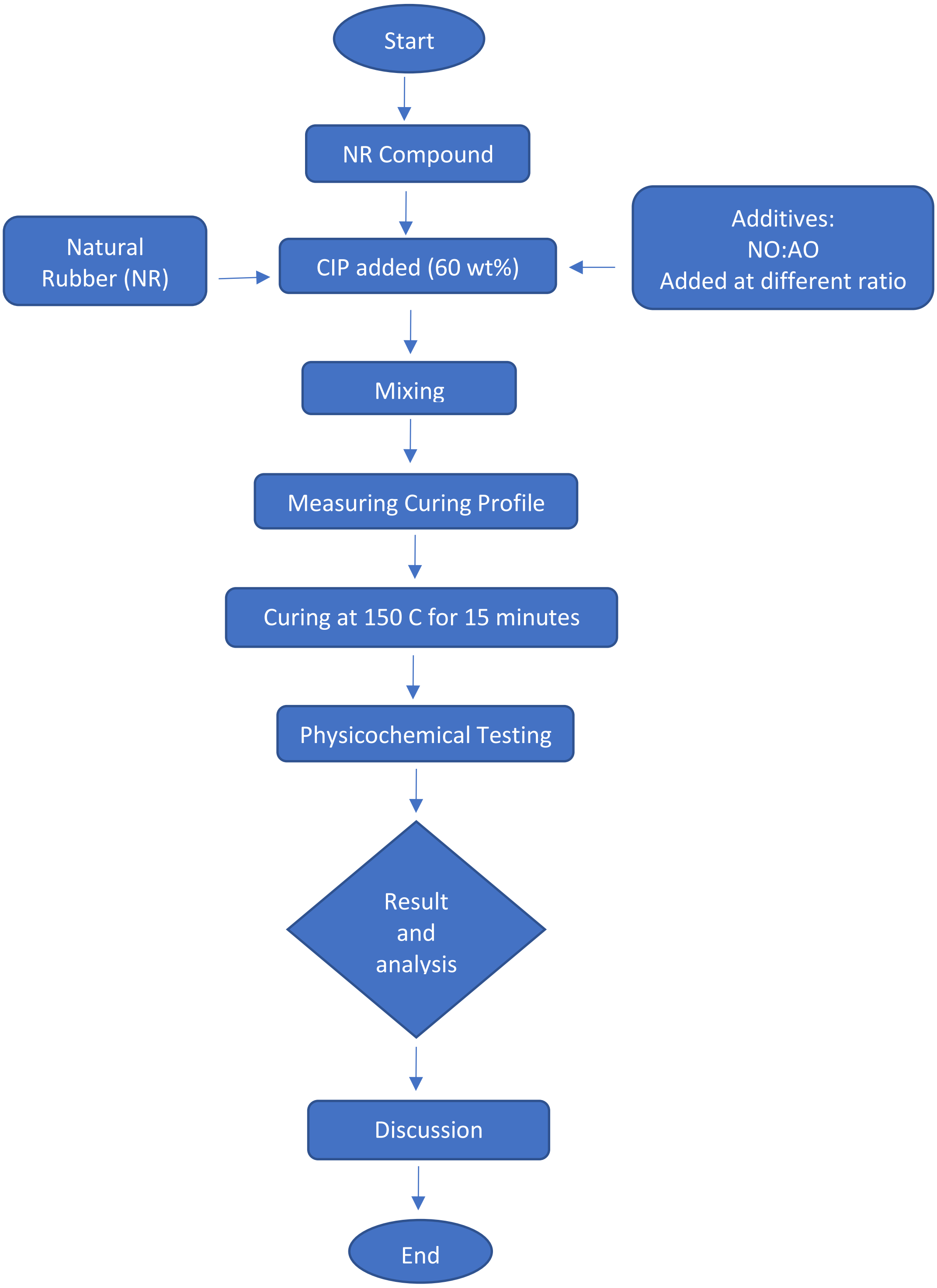

Figure 8: Flowchart of the project works

3.1 Materials

The materials that were used in this study was prepared or purchased. These materials are usually easy to be obtained and can also be prepared quite simply in the laboratory. The materials were listed as in the table 1 below;

Compound Ingredients	Ratio of Naphthenic Oil (NO): Aromatic Oil (AO)			
	100:0	70:30	50:50	30:70
	Amount in phr (parts per hundred rubber)			
Natural Rubber (NR)	100	100	100	100
Carbon Black	19	19	19	19
Zinc Oxide	5	5	5	5
Stearic Acid	2	2	2	2
Sulphur	2.3	2.3	2.3	2.3
CBS	0.8	0.8	0.8	0.8
NO	10	7	5	3
AO	0	3	5	7

Table 1: Compounding for the MRE samples

All this material was formulated in rubber compound formulation with each sample will have varies of the mixing ratio of matrices, magnetic particles and additives.

3.2 MRE Preparation

The MRE components which are matrices and the magnetic particle are usually mixed with some addition of additives. The process was produced a mixture that can be easily deform due to the low yield stress. This MRE preparation process can done by following the method that has been proposed below;

1. Firstly, the compounding was started with softening the rubber on its own in the two-roll mill (mastication).
2. After 2–3 minutes the rubber became invested on the hot roll and additives were then added followed by iron sand
3. addition of accelerators and Sulphur were delayed to the last part of the process to prevent premature vulcanization during compounding
4. After that, the cure time at 150°C was determined
5. Compounded rubber samples were placed in a mold
6. The Isotropic MREs were subjected

3.3 Physicochemical Properties Analysis

For this specific study, the microstructure and the physicochemical properties of the NR-based MRE samples with different NO to AO were conducted. The microstructure of the MRE was observed in order to investigate the CIP behavior when different ratio is used. The thermal behavior of the MRE also was investigated as the samples with different ratio of NO to AO is used. Finally, NR-based MRE was studied with different ratio of NO to AO whether they change their behaviors when using different ratio of the additive.

3.4 Observation of Microstructure of the MRE

In order to observe the microstructure of the NR- based MRE with different ratio of NO to AO, the Field Emission Scanning Electron Microscopy (FESEM) were used and the image then was captured at an accelerating voltage of 5kV. All the samples images were taken at 500X and 3000X,

Figure 9: Field Emission Scanning Electron Microscopy (FESEM)

3.5 Thermal Behavior Analysis

The thermal behavior of the NR-based MRE with different ratio of NO to AO were investigated by conducting the Thermal Gravimetric Analysis (TGA) using the Thermal Gravimetric Analyzer. The samples were heated from the ambient temperature from 25 C up to 900 C. The process of heating the samples were conducted at constant 10 C per minute in the environment filled with nitrogen gas.

Figure 10: Thermogravimetric Analysis (TGA)

3.6 Magnetization Curves Analysis

For this study, the magnetization curves of the NR-based MRE with different ratio of NO to AO were measured at the room temperature by using the Vibrating Sample Magnetometer (VSM). The samples were weighted around 50mg. The samples then were continuously vibrated, and the magnetic field of 8000 G were applied during the process.

Figure 11: Vibrating Sample Magnetometer

3.7 FYP 1 Gantt Chart and Key Milestone

Task	**Academic Week**													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Weekly Meetings with FYP Supervisor to update on progress as well as getting clarification on any project queries.	🟦 🎯	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
Collecting information to gain clearer insight of project and past research in field.		🟩	🟩	🟩	🟩	🟩	🟩	🟩						
Understanding materials from research journals and submission of draft literature review			🟥 🎯	🟥	🟥	🟥	🟥	🟥						
Extended proposal report submission & Progress Assessment 1						📊								
Proposal Defence mock presentation with FYP Supervisor								🟪						
Proposal Defence								📊						
Progress Assessment 2 Submission									🟪					
Preparation & Submission of Draft Interim Report FYP I										🟩	🟩	🟩	🟩	
Submission of Final Interim Report FYP I														📊

Table 2: FYP1 Gantt chart and Key Milestone

📊 Key Milestone

3.8 FYP 2 Gant Chart and Key Milestone

Task	Academic Week													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Fabrication of the MRE samples	🎯													
Physicochemical properties testing of the samples and data collection		🟦	🟦											
Progress report submission							📊							
Comparison of the rheological properties for different ratio of naphthenic oil to aromatic oil (70:30, 50:50, 30:50)				🎯	🟦	🟦								
Pre-SEDEX										📊				
Final report draft submission											📊			
Soft bound dissertation submission												📊		
Technical paper submission												📊		
Viva													📊	
Hard bounded project dissertation submission														📊

Table 3: FYP2 Gantt Chart and Key Milestone

4.0 Result and Discussion

4.1 Morphology

One of the studies of MRE properties that is important is the study of microstructures of the MRE. The Microstructure is observed the inner structure and CIPs distribution to see the properties change of the MRE.

In this study, four MREs samples has been prepared with different ratio of NO and AO where different ratio~~s~~ of the oil are 100:0, 70:30, 50:50 and 30:50, respectively. Different ratio~~s~~ were prepared in order to investigate the performance of the MREs relative to the amount of NO to AO since that oils can reduce the viscosity of the matrix and make the sample become elastic and flexible.

4.1.2 Microstructure of MRE sample with 100:0 of NO to AO

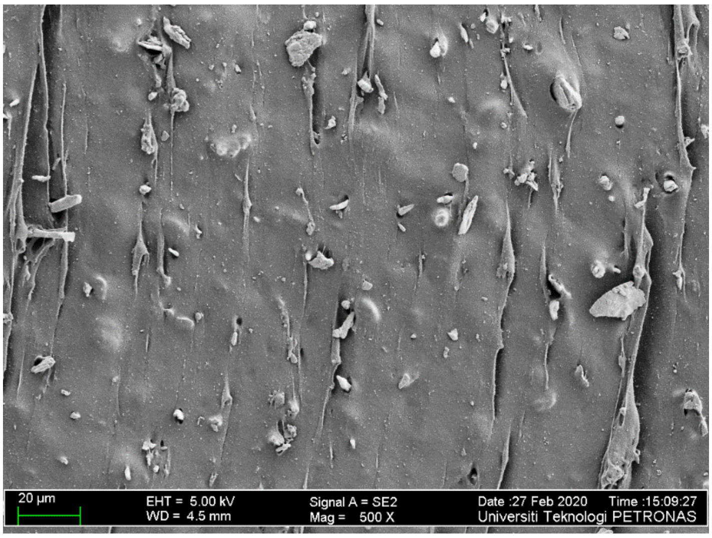

Figure 12: FESEM image of the NR-based MRE with 100:0 NO to AO at 500X magnification

In this sample, the ratio of the NO is 100:0 and there was no mixture with the AO. From the micrograph in Figure 12, the sample can clearly be described as an isotropic MRE since the CIP are dispersed uniformly in the matrix. It also can be seen that the addition of the naphthenic oil has improved the dispersion of the CIP in the matrix. In the figure 13, the sample also showed only small aggregates are formed in the fractured surface of the MRE sample.

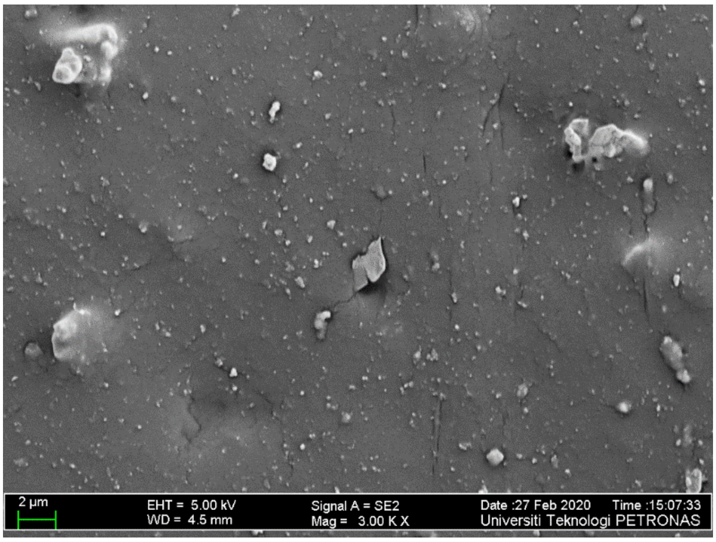

Figure 13: FESEM image of the NR-based MRE with 100:0 NO to AO at 3000X magnification

All this result indicates that the introduction of the NO as the additive has improved the dispersion of the Isotropic MRE because the incorporation of NO may reduce the viscosity of the matrix and increase the CIP dispersion in the matrix. The increase of dispersion is due to the reduced resistance of the CIP orientation in the pre-polymer, resulting a better dispersion in the matrix and gives a better rheological behavior and properties.

In this sample, the NO is used as the additive and the result of matrix have less viscosity and the dispersion of CIP become easier. The NO is known as a favorable grease in the industries due to its high viscosity and high solubility

4.1.3 Microstructure of MRE sample with 70:30 of NO to AO

For this sample, the ratio of the NO and AO is 70:30 was used to investigate the microstructure of the sample with NO and AO as the additive. Like the sample that has been discussed before, this sample is also an isotropic MRE since the CIP is dispersed uniformly in matrix

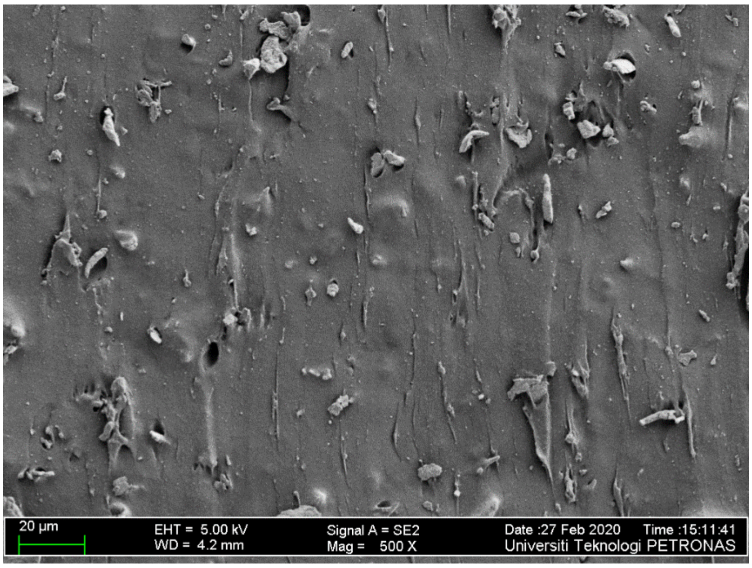

Figure 14: FESEM image of the NR-based MRE with 70:30 NO to AO at 500X magnification

In the figure 14, the additive did improve the dispersion of the CIP, but it was seen to be more less dispersed compared to the sample with 100:0 of NO to AO. Then, the aggregate formed in the fractured MRE surface sample is also small as seen in the figure 15 but when compared it with the sample with 100:0, it is clear that the previous sample, there are less aggregate formed on the fractured MRE surface.

This is probably because the matrix viscosity has been slightly increased compared to the sample before since the NO naturally have a higher solubility and viscosity level compared to the AO. This resulting the sample to have a slightly less dispersion performance as the resistance of CIP orientation has also slightly increased due to the presence of AO in the sample.

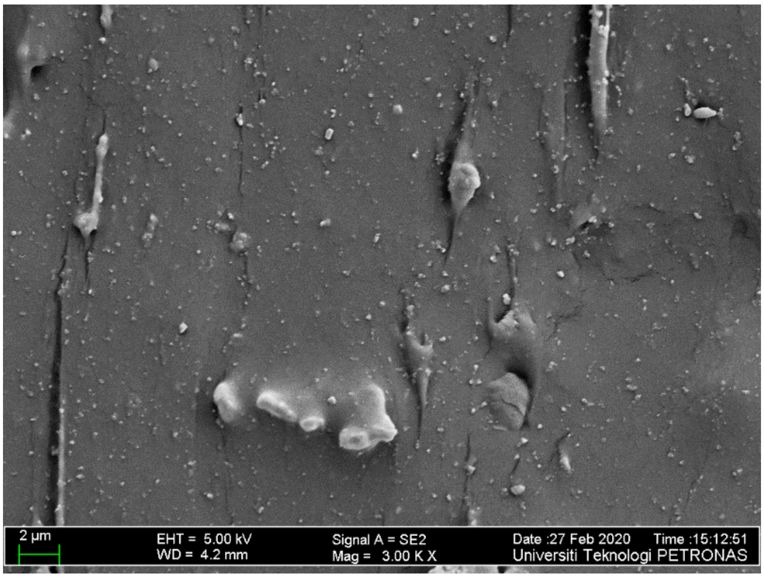

Figure 15: FESEM image of the NR-based MRE with 70:30 NO to AO at 3000X magnification

All this result shows that the ratio of this AO and NO mixture incorporated in the mixture has increased the viscosity of the matrix making the sample become slightly less flexible and less elastic. There are possibilities that by changing the ratio of the NO and AO can improved the rheological behavior of the MRE.

4.1.4 Microstructure of MRE sample with 50:50 of NO to AO

For this sample, the ratio of the NO and AO is set to 50:50 in order to investigate the MRE microstructure with different ratio of NO to AO. Firstly, like the sample that has been discussed before, this sample is also an isotropic MRE since the CIP is dispersed uniformly in matrix.

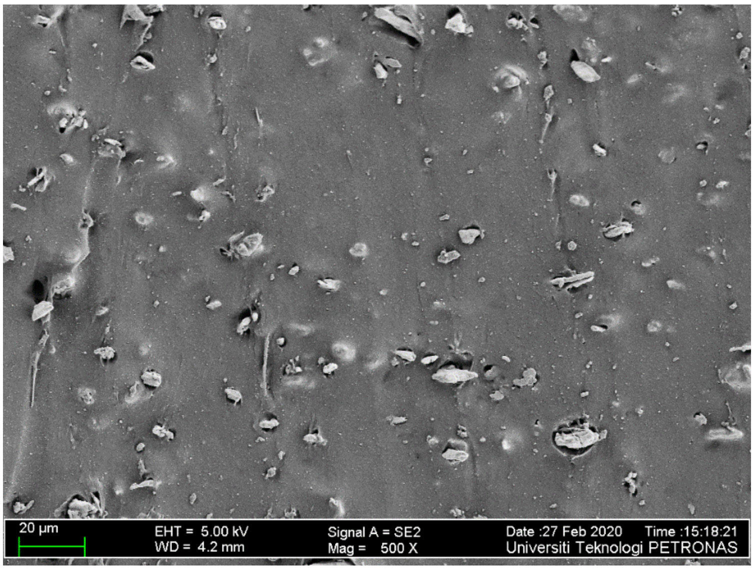

Figure 16: FESEM image of the NR-based MRE with 50:50 NO to AO at 500X magnification

In the figure 16, the additive improves the dispersion of the CIP and it was showed to be even less well dispersed compared to the sample with 100:0 and 70:30 of NO to AO. Then, the aggregate formed in the fractured MRE surface sample is also has increased as seen in the figure 17 and when compared it with the sample with 100:0 and 70:30, it is clear that the previous sample has bigger aggregate on the fractured MRE surface.

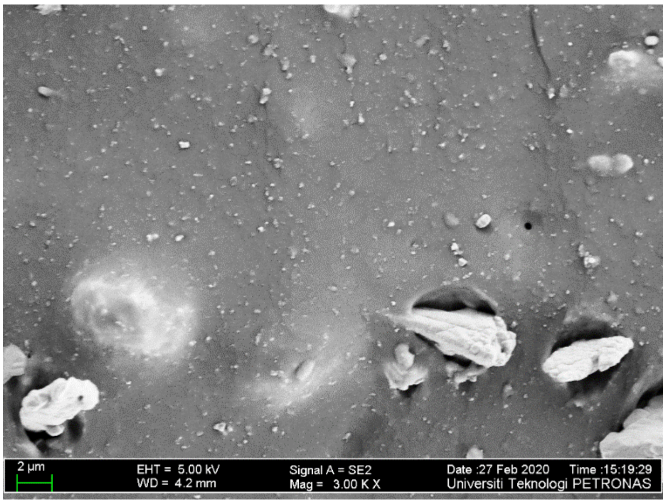

Figure 17: FESEM image of the NR-based MRE with 50:50 NO to AO at 3000X magnification

This is probably because the ratio of NO to AO is less compatible with the NR-based MRE which resulting a decrement in crosslinking density. This affecting the sample to have a lower dispersion performance as the resistance of CIP orientation has also slightly increased due to the presence of AO in.

All this result shows that the ratio of this AO and NO mixture incorporated in the mixture has reduced the viscosity of the matrix making the sample become less flexible and less elastic.

4.1.5 Microstructure of MRE sample with 30:70 of NO to AO

For this sample, the ratio of the NO and AO is set to 30:70 which has the least amount of NO compare to the other samples Firstly, like the sample that has been discussed before, this sample is also an isotropic MRE since the CIP is dispersed uniformly in matrix.

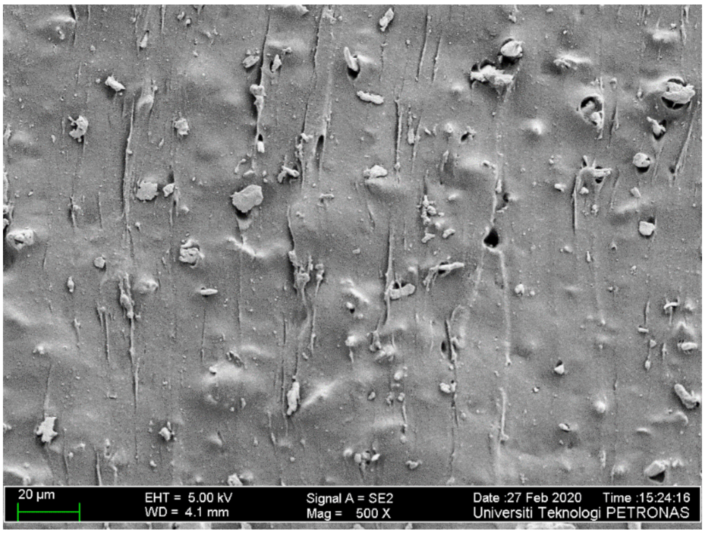

Figure 18: FESEM image of the NR-based MRE with 30:70 NO to AO at 500X magnification

In the figure 18, the additive improves the dispersion of the CIP but the it is seemed to be the least well dispersed compared to the sample with 100:0,70:30 and 50:50 of NO to AO. Then, the aggregate formed in the fractured MRE surface sample is also the large as seen in the figure 19 and when compared it with the sample with 100:0, 70:30 and 50:50, it is clear that the previous sample has smaller aggregate on the fractured MRE surface.

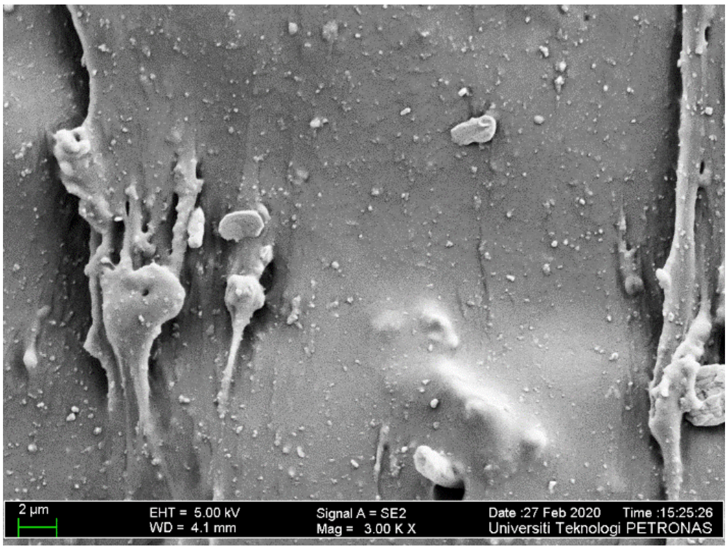

Figure 19: FESEM image of the NR-based MRE with 30:70 NO to AO at 3000X magnification

This is probably because the ratio of NO to AO is least compatible with the NR-based MRE which resulting a significant decrement in crosslinking density. This affecting the sample to have the lowest dispersion performance as the resistance of CIP orientation has also increased due to the presence of AO in pre-polymer. The NO is a more soluble type of grease when compared to the AO and has higher viscosity. The less amount of NO has reduced the solubility and increased the matrix viscosity.

All this result shows that the ratio of this AO and NO mixture incorporated in the mixture has increased the viscosity of the matrix making the sample become less flexible and less elastic.

4.2 Thermal Behavior Analysis

For this test, four samples of NR based MREs were prepared with different ratio of NO to AO. TGA test is conducted in order to investigate the thermal characteristic of the NR based samples with different ratio of NO to AO. The starting decomposition temperature was observed and the amount of the residue at temperature 500 C will then be collected.

This is important because the understanding of the thermal stability are critical in the field of developing a quality polymer-based product technology in high temperature condition.

4.2.1 MRE sample with 100:0 of NO to AO

In this sample, the ratio of the NO is set to 100:0 in the compounding of NR-based MRE so there will be no mixture with the AO. The thermal characteristic of the sample was tested using TGA in the nitrogen atmosphere. Figure 20 show the illustration of the thermal gravimetric curve of the MRE.

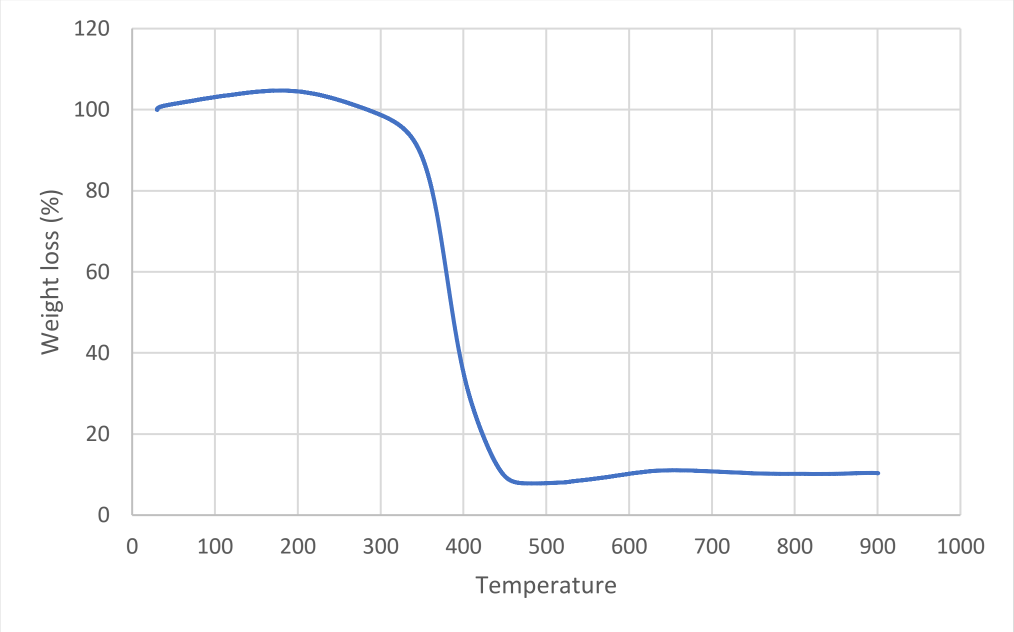

Figure 20: Thermal gravimetric curve for NR-based MRE with 100:0 of NO to AO

At the beginning of the decomposition process, the sample has gained a slight weight in the curve. This is probably due to the oxidation reaction of the surface material with the gaseous contaminants in the purge nitrogen gas. The other reason that can be discussed is due to the b buoyancy effect that has been caused by the decrease of the atmosphere density in the balance with the temperature increase.

For this sample, the material decomposition starts at temperature 283 C and increase rapidly afterward. The amount of the residue was observed after the temperature hit 500 C and it shows that the sample has about 7.79% of the weight. With the NO incorporation, the decomposition of the MRE can be reduced since that the crosslinked polymer chain has become more difficult to be destructed as the CIP occupies the voids and act as a barrier. The other sample with different ratio will need to be tested in order to find the best ratio of NO to AO of NR-based MRE.

4.2.2 MRE sample with 70:30 of NO to AO

In this sample, the ratio of the NO to AO is used at 70:30 in the compounding of NR-based MRE so there will be mixture of NO with the AO. The thermal characteristic of the sample was tested using TGA in the nitrogen atmosphere. Figure 21 show the illustration of the thermal gravimetric curve of the MRE.

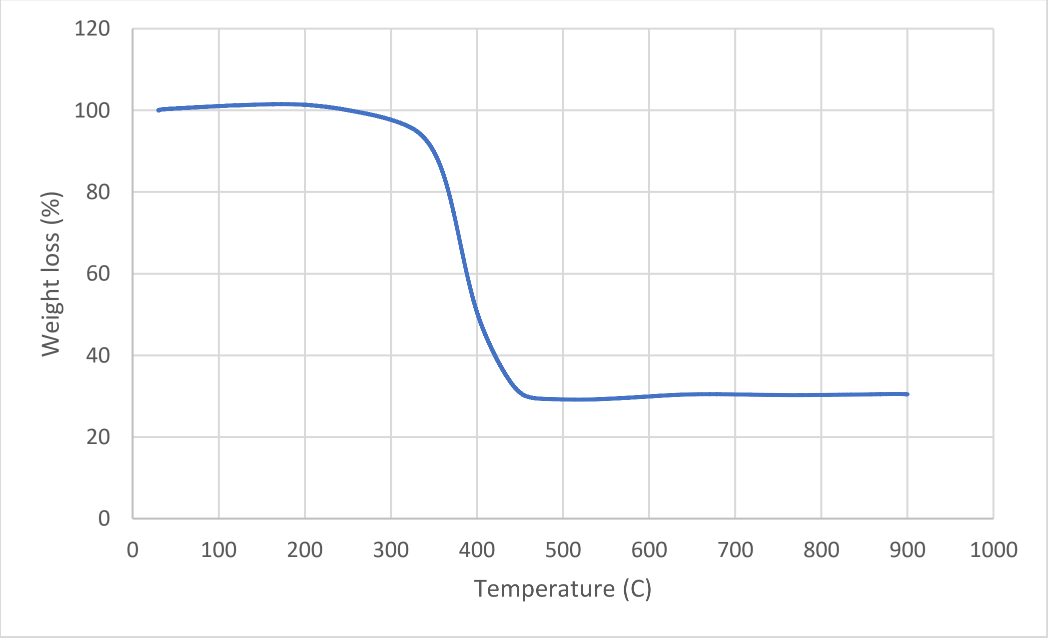

Figure 21: Thermal gravimetric curve for NR-based MRE with 70:30 of NO to AO

At the beginning of the decomposition process, the sample has gained a slight weight in the curve. This is probably due to the oxidation reaction of the surface material with the gaseous contaminants in the purge nitrogen gas. The other reason that can be discussed is due to the b buoyancy effect that has been caused by the decrease of the atmosphere density in the balance with the temperature increase.

For this sample, the material decomposition starts at temperature 251 C and increase rapidly afterward. The amount of the residue was observed after the temperature hit 500 C and it shows that the sample has about 29.52% of the weight which is a significant improvement compared to the previous sample. With the NO incorporation, the decomposition of the MRE can be reduced since that the crosslinked polymer chain has become more difficult to be destructed as the CIP occupies the voids and act as a barrier.

This NO to AO ratio has shown the decomposition reduction has been improved based the result that has been observed on the morphology study.

4.2.3 MRE sample with 50:50 of NO to AO

In this sample, the ratio of the NO to AO is used at 50:50 in the compounding of NR-based MRE so there will be mixture of NO with the AO. The thermal characteristic of the sample was tested using TGA in the nitrogen atmosphere. Figure 22 show the illustration of the thermal gravimetric curve of the MRE.

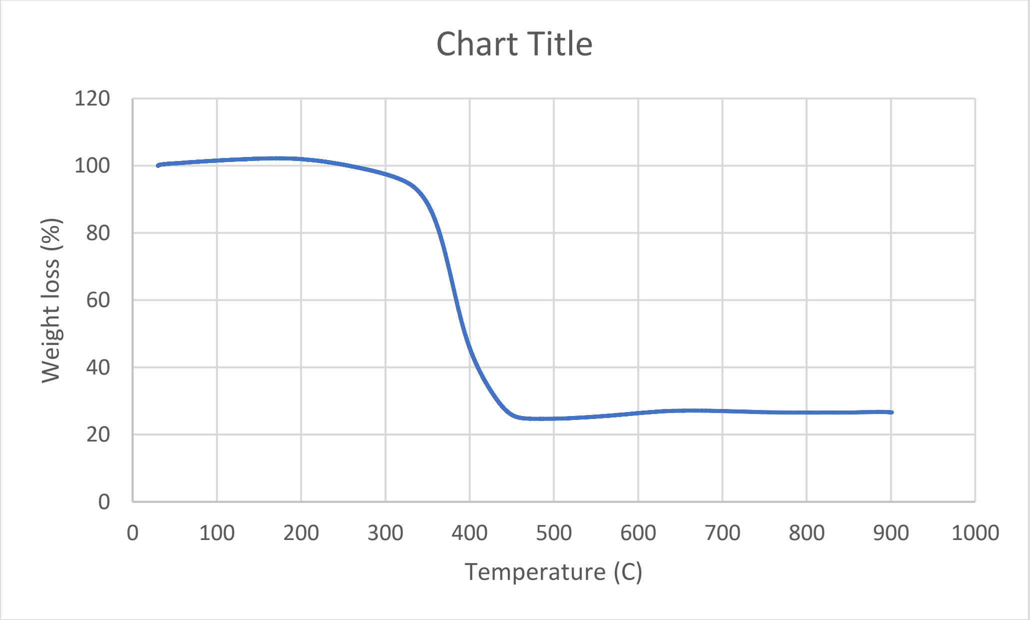

Figure 22: Thermal gravimetric curve for NR-based MRE with 50:50 of NO to AO

At the beginning of the decomposition process, the sample has gained a slight weight in the curve. This is probably due to the oxidation reaction of the surface material with the gaseous contaminants in the purge nitrogen gas. The other reason that can be discussed is due to the buoyancy effect that has been caused by the decrease of the atmosphere density in the balance with the temperature increase.

For this sample, the material decomposition starts at temperature 256 C and increase rapidly afterward. The amount of the residue was observed after the temperature hit 500 C and it shows that the sample has about 24.59% of the weight which is a slight reduced performance compared to the previous sample. With the NO incorporation, the decomposition of the MRE can be reduced since that the crosslinked polymer chain has become more difficult to be destructed as the CIP occupies the voids and act as a barrier.

This NO to AO ratio has shown the decomposition reduction has been reduced compared to the sample with 70:30 NO to AO and this tally with the result that has been observed on the morphology study.

4.2.4 MRE sample with 30:70 of NO to AO

In this sample, the ratio of the NO to AO is used at 30:70 in the compounding of NR-based MRE so there will be mixture of NO with the AO. The thermal characteristic of the sample was tested using TGA in the nitrogen atmosphere. Figure 23 show the illustration of the thermal gravimetric curve of the MRE.

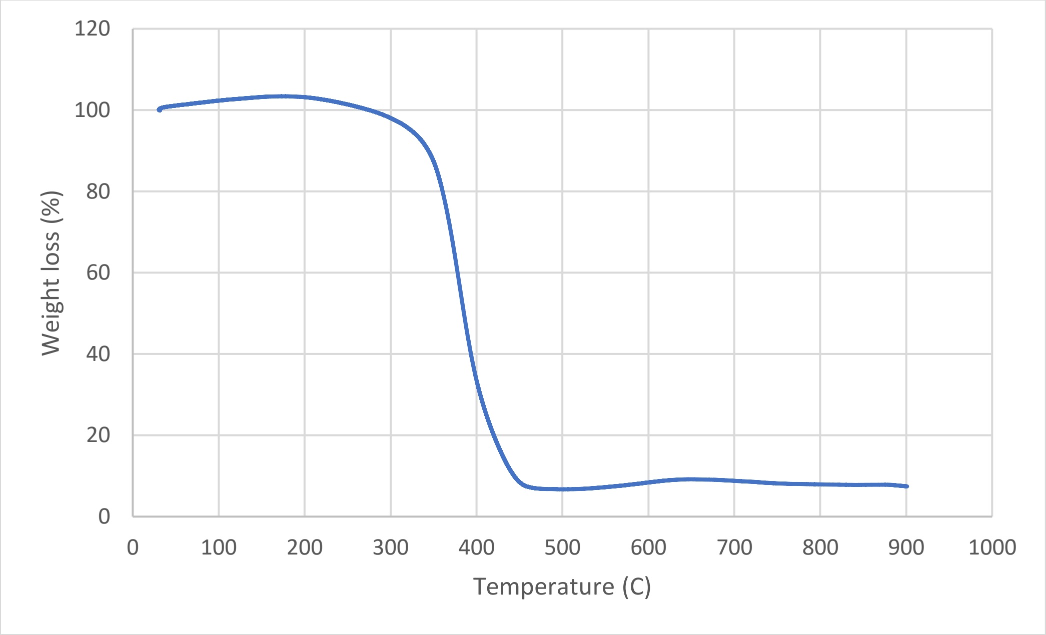

Figure 23: Thermal gravimetric curve for NR-based MRE with 30:70 of NO to AO

At the beginning of the decomposition process, the sample has gained a slight weight in the curve. This is probably due to the oxidation reaction of the surface material with the gaseous contaminants in the purge nitrogen gas. The other reason that can be discussed is due to the buoyancy effect that has been caused by the decrease of the atmosphere density in the balance with the temperature increase.

For this sample, the material decomposition starts at temperature 275 C and increase rapidly afterward. The amount of the residue was observed after the temperature hit 500 C and it shows that the sample has about 6.72% of the weight which is the least amount of weight compared to the previous sample. With the NO incorporation, the decomposition of the MRE can be reduced since that the crosslinked polymer chain become more difficult to destruct as the CIP occupies the voids and act as a barrier.

This NO to AO ratio has shown the decomposition reduction has been reduced and tally with the result that has been observed on the morphology study. The sample shows the worst performance when compared to previous sample.

4.3 Magnetization Curves analysis

The magnetic properties of the NR-based MRE with different No to AO ratio were ~~all~~ investigated using the VSM. When magnetic field is applied, the CIP will be induced on the NR-based MREs. All the MREs samples exhibit narrow magnetic hysteresis loops if it took on the soft magnetic characteristics.

Figure 24 shows the hysteresis loops of the samples and it has been measured under magnetic field up to 8000 G~~.~~

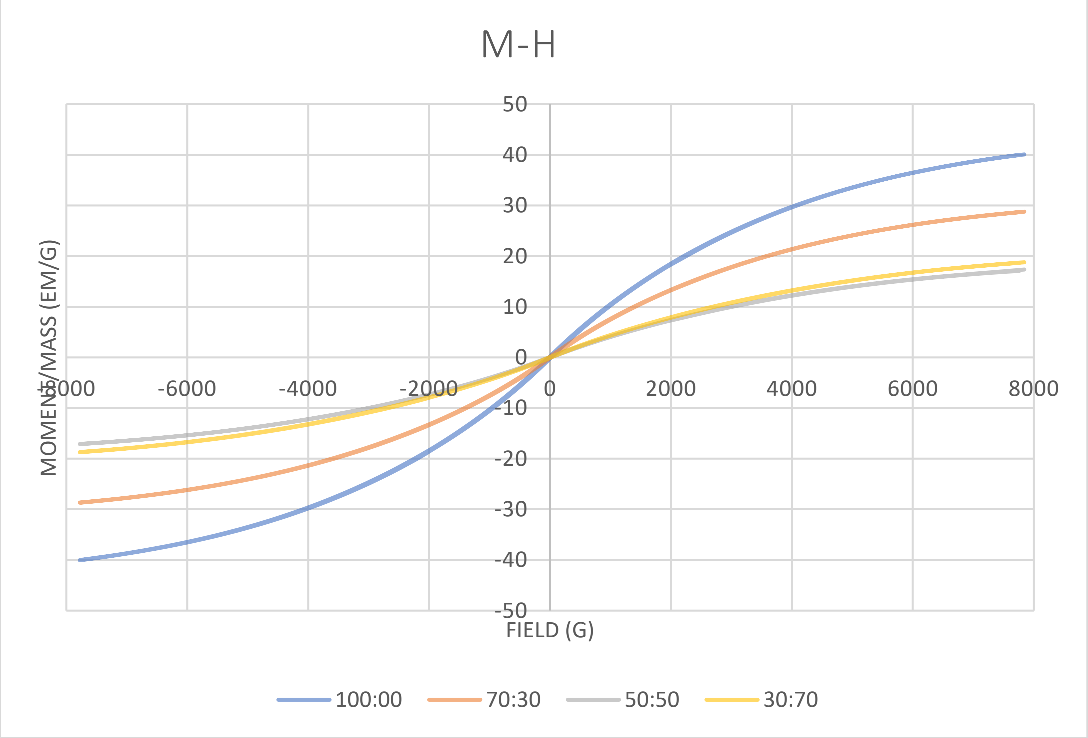

Figure 24: Magnetization curves for NR-based MRE with different ratio of NO to AO

All the details of the magnetic behavior of the NR- based MRE with different ratio of NO to AO were investigated experimentally and the parameters of the magnetic properties have such as magnetic saturation Ms, coercivity Hc and retentivity magnetization MR.

Sample	MS (emu/g)	MR (emu/g)	Hc (g)
100:0	40.067	0.18939	16.386
70:30	28.734	0.13184	15.575
50:50	17.230	0.07878	16.776
30:50	18.748	0.07878	16.367

Table 4: Magnetic properties of NR-based MRE with different ratio of NO to AO

Based on the table 4, MRE sample with the 100:0 give the highest magnetic saturation when compared to the sample with 70:30, 50:50 and 30:70. The 100:0 sample showed the highest value of Ms followed by the sample 70:30, 30: and 50:50 with 40.067, 28.734, 18.748 and 17.230 emu/g for each of them.

The ~~main~~ reason of the sample with 100:0 NO to AO has the highest magnetic saturation is because of the advantages of the NO~~.~~ The NO gives a better CIP dispersion in the MRE and a superior compatibility compared to the sample with mixture ratio of NO to AO. This is because the NO has higher viscosity compared to the AO and this reduced the matrix viscosity. The CIP dispersion also has been increased due the less friction in CIP orientation in the matrix.

This result can be confirmed by referencing the morphological image and study that has been discussed before where the sample with 100:0 shows the most well dispersed CIP in the MRE.

5.0 Conclusion and Recommendation

The study will cover three important aspects which are MRE fabrication using natural rubber based MREs with different ratio of naphthenic oil and aromatic oil as the additive and the physicochemical properties study of the MRE

The aims of the project are to fabricate NR based MREs with different ratio of naphthenic oil to aromatic oil. The ratio to be used has been decided which are 100:0, 70:30, 50:50 and 30:70,respectively and the physicochemical properties such as the microstructure of the MRE, the thermal behavior of the MRE and ~~the~~ Magnetization properties were analyzed in order to determine the best result of physicochemical properties based on different ratio of NO to AO . This additive increased the dispersion of the magnetic particles thus increased the MRE performance. The use of naphthenic oil has potential in industry applications, such as vibration absorbers, base isolator ~~etc~~. Based on the preliminary study done, the following can be concluded:

- The author has begun to understand the theory and the concept of the MRE such as the NO as the dispersant can improve the physicochemical properties of the NR-based MRE by improving the CIP dispersion.
- The literature review of the MRE and the physicochemical properties of NR-based MRE with different ratio of NO to AO was conducted. The author managed to understand the testing and experimental procedures of the physicochemical properties' analysis.

References

1) Li YC, Li JC, Li WH, Du HP. (2014)
   A stateof-the-art review on magnetorheological elastomer devices.
   Smart Materials and Structures, **23** (123001)

2) Rigbi Z, Jilkén L. (1983)
   The response of an elastomer filled with soft ferrite to mechanical and magnetic influences.
   Journal of Magnetism and Magnetic Materials, **37**, pp. 267-276.

3) Ashour O, Rogers CA, Kordonsky W. (1996)
   Magnetorheological fluids: Materials, characterization, and devices.
   Journal of Intelligent Material Systems and Structures, **7**, pp. 123-130

4) Deng HX, Gong XL. (2008)
   Application of magnetorheological elastomers to vibration absorber. Communications in Nonlinear Science and Numerical Simulation, **13**, pp. 1938-1947.

5) Lokander M, Stenberg B. (2003)
   Performance of isotropic magnetorheological rubber materials.
   Polymer Testing, **22**, pp. 245-251.

6) Chen L, Gong XL, Li WH. (2008)
   Effect of carbon black on the mechanical performances of magnetorheological elastomers.
   Polymer Testing, **27**, pp. 340-345.

7) Bose H, Rabindranath R, Ehrlich J. (2011)
   Soft magnetorheological elastomers as new actuators for valves.
   Journal of Intelligent Material Systems and Structures, **23**, pp. 989.

8) Zhu H. (2010)
Fabrication of practical magnetorheological fluids and their properties [thesis].
Hefei: University of Science and Technology of China

9) Ibrahim RA. (2008)
Recent advances in nonlinear passive vibration isolators.
Journal of Sound and Vibration, **314**, pp. 371-452.

10) Chan WH, In HK, Hyung JJ. (2018)
Fabrication and Characterization of Natural Rubber-based Magnetorheological Elastomer at Large Strain for Base Isolator.
Shock and Vibration, 2018, pp. 1-12

11) Zhu H. (2010)
Fabrication of Practical Magnetorheological fluids and their properties's thesis
Hefei: university of Science and Technology.

12) Stepanov GV, Abramchuck SS, Grishin DA, Nikitin LV, Kramarenko EY and Khokhlov AR (2006)
Effect of a Homogeneous Magnetic field on the Viscoelastic Behavior of Magnetic elastomer.
Polymer, 2007, pp. 488-495

13) Lee CJ, Kwon SH, Choi HJ, Chung KH, Jung JH (2018)
Enhanced Magnetorheological Performance of Carbonyl Iron/Natural rubber Composite elastomer with Gamma-ferrite Additive.
Colloid and Polymer Science, 2018, pp. 296

14) Chen L, Gong XL and Li WH, (2007)
Microstructure and Viscoelastic properties of Anisotropic Magnetorheological elastomer.
Smart Materials and Structures, 2007, pp. 2645-2650

15) Yu M, Zhao LJ, Zhu M. (2016)
Thermal Effects on the Laminated Magnetorheological Elastomer Isolator.
Smart Materials and Structures, 2016, pp. 25

16) Liao GJ, Gong XL, and Xuan SH. (2014)
Phase Based Stiffness Tuning Algorithm for a Magnetorheological Elastomer Dynamic Vibration Absorber.
Smart Materials and Structures, 2014, pp. 23

17) Bastola AK, Paudel M, and Li L. (2018)
Development of Hybrid Magnetorheological Elastomers by 3D printing
Polymer, 2018, **149**, pp 213-228

18) Chen L, Gong XL, Jiang WQ, Yao JJ, Deng HX, Li WH. (2007)
Investigation on Magnetorheological Elastomer Based on Natural Rubber
Journal of Material Science, 42, pp. 483-5489