ELECTRICAL, PHYSICAL AND CHEMICAL PERFORMANCE OF TRANSFORMER’S OIL, PAPER INSULATION AND GASKET WITH DIFFERENT ESTER OILS

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in partial fulfilment of the requirements for the degree of
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DECLARATION

I declare that this thesis entitled "ELECTRICAL, PHYSICAL AND CHEMICAL PERFORMANCE OF TRANSFORMER'S OIL, PAPER INSULATION AND GASKET WITH DIFFERENT ESTER OILS is the result of my own research except as cited in the references. The thesis has not been accepted for any degree and is not concurrently submitted in the candidature of any other degree.

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Date : 19/06/2024

APPROVAL

I hereby declare that I have checked this report entitled " ELECTRICAL, PHYSICAL AND CHEMICAL PERFORMANCE OF TRANSFORMER'S OIL, PAPER INSULATION AND GASKET WITH DIFFERENT ESTER OILS", and in my opinion, this thesis fulfils the partial requirement to be awarded the degree of Bachelor of Electrical Engineering with Honours

Signature :

Supervisor Name : Ts. Dr. Mohd. Shahril Bin Ahmad Khiar

Date : 19/06/2024

DEDICATIONS

To my beloved mother and father

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ABSTRACT

Power transformer insulation systems consist of liquid and solid insulation. Insulating paper and pressboard are used as the solid insulation while transformer insulating oil is used as the liquid insulation. Generally, the insulation system within the transformer that undergo ageing process during the operation will lead to insulation failure. Hence, monitoring the insulation system of transformer is crucial because a transformer's lifespan is assessed based on the performance of insulation system, especially the solid insulation because the lifespan of transformer is often associated with the mechanical properties of insulating papers. Therefore, this research aims to analyse the performance of different insulating papers in different insulating oils under thermal ageing process. Thermally upgraded kraft paper and kraft paper are used as the insulating papers in this research. FR3 (NEI), MIDEL 7131 (SE), pressboard and gaskets (NBR) are the other insulating materials are also used for this study. This research will be conducted by preparing 8 different samples. The first 4 samples will be using NEI as insulating oil and the rest are SE. The 4 samples of NEI will be divided into two categories where the first and second sample use thermally upgraded paper (TUK 1 and TUK 2) as insulating paper meanwhile the other two use kraft paper (KP 1 and KP 2) as insulating paper. The same condition is applied to SE. All the solid insulation materials will be immersed with insulating oil to undergo thermal ageing process. After the thermal ageing process, TUK showed better performance than KP by comparing its tensile strength. The dissolve decay product (DDP) and polarisation index (PI) of insulating oils, SE has better performance than NEI. However, the shore hardness of gasket displayed a better performance in NEI compared to SE.

ABSTRAK

Sistem penebat pengubah kuasa terdiri daripada penebat cecair dan pepejal. Kertas penebat dan papan akhbar digunakan sebagai penebat pepejal manakala minyak penebat transformer digunakan sebagai penebat cecair. Secara amnya, sistem penebat dalam pengubah yang mengalami proses penuaan semasa operasi akan membawa kepada kegagalan penebat. Oleh itu, pemantauan sistem penebat transformer adalah penting kerana jangka hayat transformer dinilai berdasarkan prestasi sistem penebat, terutamanya penebat pepejal kerana jangka hayat pengubah sering dikaitkan dengan sifat mekanikal kertas penebat. Oleh itu, penyelidikan ini bertujuan untuk menganalisis prestasi kertas penebat yang berbeza dalam minyak penebat yang berbeza di bawah proses penuaan haba. Kertas kraf dan kertas kraf yang dinaik taraf secara terma digunakan sebagai kertas penebat dalam penyelidikan ini. FR3 (NEI), MIDEL 7131 (SE), papan tekan dan gasket (NBR) adalah bahan penebat lain yang turut digunakan untuk kajian ini. Penyelidikan ini akan dijalankan dengan menyediakan 8 sampel yang berbeza. 4 sampel pertama akan menggunakan NEI sebagai minyak penebat dan selebihnya adalah SE. 4 sampel NEI akan dibahagikan kepada dua kategori di mana sampel pertama dan kedua menggunakan kertas dinaik taraf terma (TUK 1 dan TUK 2) sebagai kertas penebat manakala dua lagi menggunakan kertas kraft (KP 1 dan KP 2) sebagai kertas penebat. Keadaan yang sama digunakan untuk SE. Selepas proses penuaan haba, TUK menunjukkan prestasi yang lebih baik daripada KP dengan membandingkan kekuatan tegangannya. Produk pereputan terlarut (DDP) dan indeks polarisasi (PI) minyak penebat, SE mempunyai prestasi yang lebih baik daripada NEI. Walau bagaimanapun, kekerasan pantai gasket menunjukkan prestasi yang lebih baik dalam NEI berbanding SE.

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LIST OF SYMBOLS AND ABBREVIATIONS

NEI	-	Natural Ester Oil
SE	-	Synthetic Ester Oil
DDP	-	Dissolve Decay Product
KP	-	Kraft Paper
TUK	-	Thermally Upgraded Kraft Paper
PI	-	Polarisation Index
TS	-	Tensile Strength
PCB	-	Polychlorinated Biphenyls
MO	-	Mineral Oil
TGs	-	Triglycerides
FA	-	Fatty Chain
ASTM	-	American Society for Testing and Materials
BS	-	British Standard

CHAPTER 1

INTRODUCTION

1.1 Introduction

Transformer is a static machine that performs vital functions in electrical power systems. They assure the dependability of transmission and distribution networks by either stepping up or stepping down the voltage [1]. There are many types of transformers and each has its own application in electrical power system. One of the most important parts of electrical distribution networks is the power transformer. It provides an affordable means of transferring energy over large distances [2]. There are two types of power transformers, liquid filled (oil-filled) transformers and dry-type transformers depending on their design and applications. The main difference between these two transformers is liquid-filled transformers use insulating oil as insulation while dry-type transformers use air or gas.

Liquid insulation (insulating oil) and solid insulation (pressboard and paper) form the insulation system of an oil-immersed power transformer. The insulating oil reduces the possibility of oxidation, acts as a coolant system and an insulator for dielectric breakdown [3]. In contrast, the solid insulation serves as an insulator between the transformer's windings [3]. The structure of oil-immersed power transformer is shown in Figure 1.1.

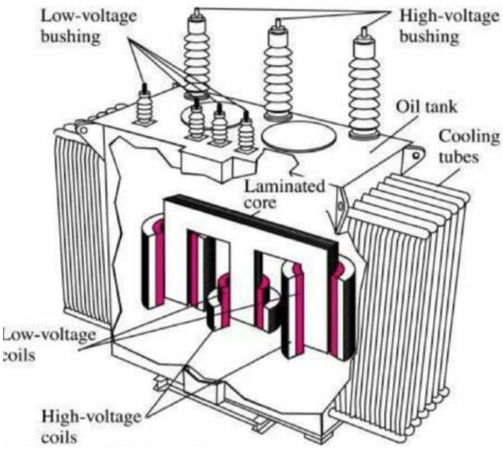


Figure 1.1 Power transformer [2]

According to manufacturers, the life expentancy of a power transformer to be between 25 and 40 years [4]. When some transformers in service are getting close to this age, they are more exposed to unforeseen failures and faulty [5]. For instance, when degradation occurs, insulation system can diminished. Even exposed to air and temperatures lower than 100 °C, oxidation can degrade the mechanical characteristics of insulating paper. When the deterioration process occurs over an extended length of time, insulating material will gradually deteriorate until it loses its ability to act as an insulator [6]. When such situation happens, it may lead to premature shutdown of transformers. Thus, it is highly desirable to predict the lifespan of insulating system of a power transformer .

1.2 Problem Statement

Based on a report provided by the International Association of Engineering Insurer (IMIA) in 2003, there were 94 cases of power transformers failures recorded within 1997 to 2001 in United State for transformers rated at 25MVA and above [7]. Figure 1.2 shows the percentage of failures and repair cost of the cases [2][7]. Based on the report, the largest cause of transformer failures and associated costs was insulation failures [7].

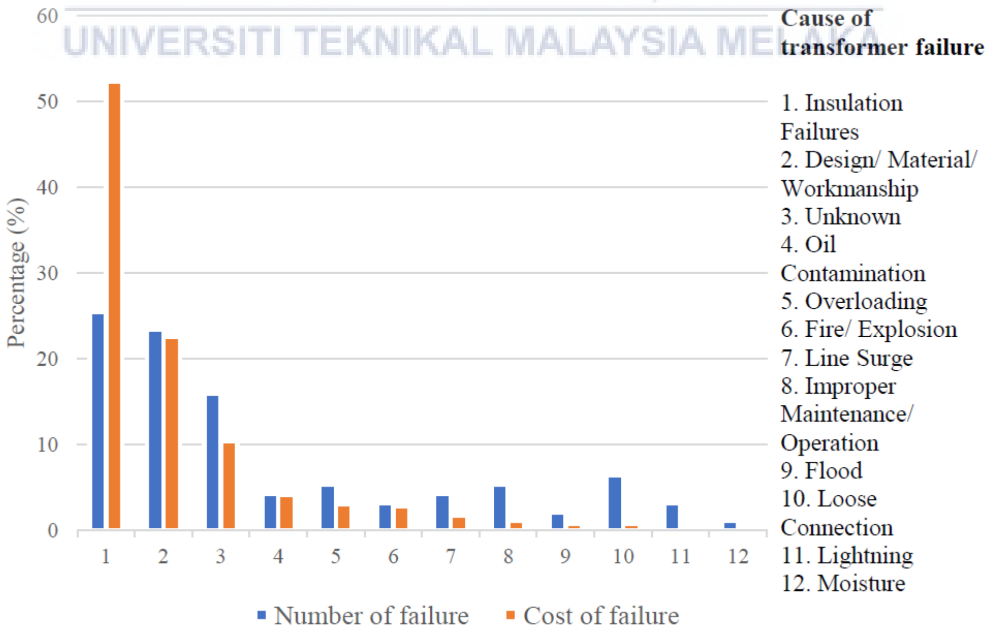


Figure 1.2 Cause of transformer failures [2][7]

These insulation failures happen due to the combination of thermal, chemical, electrical and mechanical stresses inside the transformers [2]. The liquid and solid insulation of transformer will deteriorate with time due to these stresses. When such a scenario happens, changing the deteriorated insulation system (liquid and solid insulation) is one of the desirable decisions. However, replacing the old solid insulation of a transformer with a new one is more challenging compared to the replacement of new liquid insulation. For liquid insulation, the old insulating oil will be drained out and replaced with a new insulating oil under retrofilling process [8] and this process can be done without significant disassembly. Meanwhile, it is difficult to replace solid insulation with a new one because the insulating papers and pressboard are often placed within the core and windings of the transformers and hard to access [9]. Although the idea of changing solid insulation is challenging, it still needs to take into consideration because the life of solid insulation will determine the life of a transformer [10].

Cellulose paper (kraft paper) has been used as the solid insulation of power transformers for at least the past 100 years [11]. It isolates the windings mechanically and dielectrically [3]. However, the kraft paper tends to degrade faster mainly due to its chemical composition. Besides, kraft paper also more prone to hydrolysis and oxidation [12]. This is because the cellulose in kraft paper contains numerous hydroxyl groups (-OH) in its polymer chains. Thus, in the presence of heat, oxygen and water, these groups can easily oxidize and hydrolyze. As a result, the kraft paper loses its abilities to protect the windings and fails to withstand abnormal (short-circuit) transformer [11].

1.3 Motivation

Regarding transformer winding failures, a case study about the analysis of transformer failures in Malaysia by Tenaga Nasional Berhad (TNB) was conducted in 2014 [13]. Figure 1.3 shows a post-mortem was conducted on 160 units of failed distribution to investigate the failure modes of transformers. Based on the study, arcing in windings as transformer's failure mode has the highest number. Hence, the transformer winding failure is a serious issue and this has motivates the project's study to investigate a better solid insulation (insulating papers) to protect transformer windings better than kraft paper.

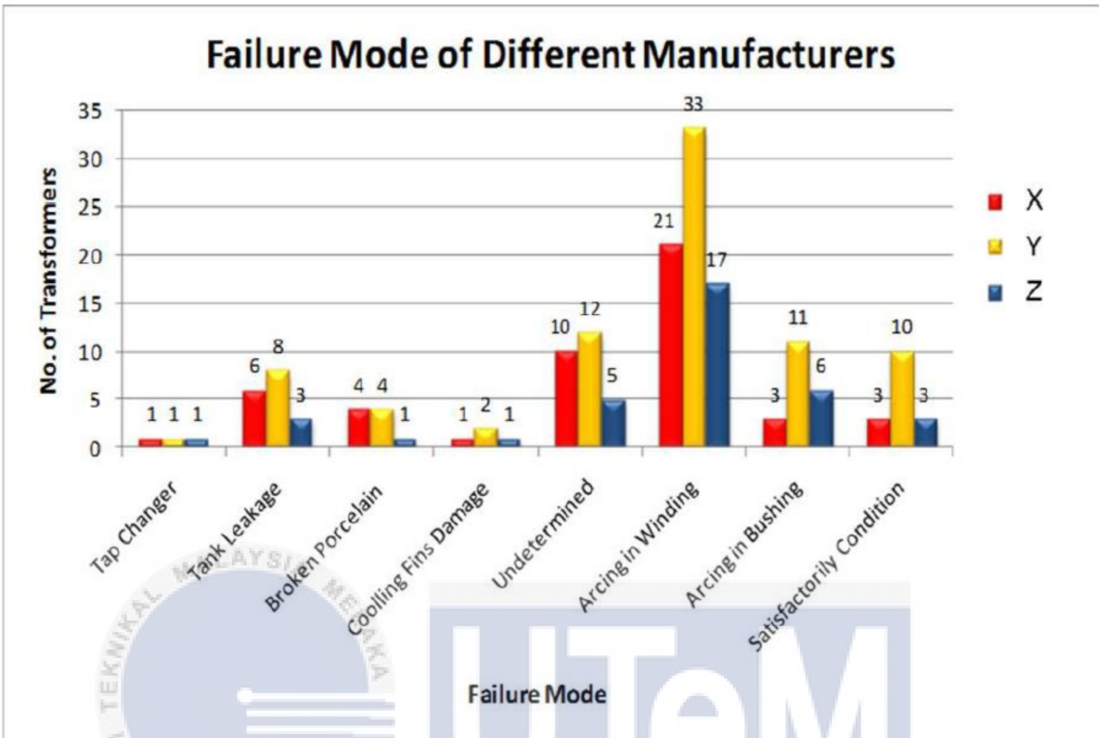


Figure 1.3 Failure modes of transformer [13]

1.4 Objectives

The objectives of this research are:

i. To investigate the physical performance of thermally upgraded kraft paper aged in ester oils via tensile strength measurements.

ii. To investigate the effect of thermally upgraded kraft paper on the physical properties of gasket aged in ester oils using shore hardness measurements.

iii. To analyze the electrical and chemical properties of ester oils immersed with different paper insulations based on the polarization index (PI) and dissolve decay product (DDP).

1.5 Scope

The scope of this study is including:

1. Liquid insulation used in this project:
    - Natural Ester Oil (FR3)
    - Synthetic Ester Oil (MIDEL 7131).
2. Solid insulation used in this project are:
    - Insulating papers: Thermally upgraded paper (TUK) and kraft paper (KP)
    - Pressboard
    - Gasket: Nitrile Butadiene Rubber (NBR)
3. Electrical test:
    - Polarization index test (PI) to check the insulation resistance of insulating oils
4. Chemical test:
    - Dissolve decay product (DDP) to check the amount of decay product in insulating oils
5. Physical test:
    - Weight of insulating papers and pressboard before and after drying
    - Tensile strength of insulating papers (TUK and KP)
    - Shore hardness of gasket

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter will discuss in detail the different properties of insulating papers. Initially, power transformer insulation materials will be reviewed in Section 2.2. This is followed by the description of liquid insulation and solid insulation properties in Section 2.3 and Section 2.4, respectively. Section 2.5 will discuss the effect of thermal ageing on the properties of insulation materials. Lastly, Section 2.6 will focus on the method of assessing insulation system degradation.

2.2 Power Transformer Insulation Materials

A power transformer's primary and secondary coils are essential in carrying out its main operation of converting voltage and current. Therefore, these coils are insulated to ensure safety and efficiency in their operation. However, sufficient insulation is not only required to isolate coils from one another, it is also necessary for different active parts of the transformer for its safe operation [9]. Hence, these active parts in transformers are divided into two different insulation systems according to the level of insulation required. There are major insulation and minor insulation. Table 2.1 shows the major and minor insulation system of a transformer [9].

Table 2.1 Major and minor insulation of transformer [9]

Insulation system	Parts in transformer
Major insulation	- Between top and bottom of winding yoke

	- Between HV and tank - Between core and low-voltage (LV) winding - Between LV and high-voltage (HV) winding - Bushings
Minor insulation	- Between turns - Between conductors - Between laminations - Between layers - Between joints and connections

Solid insulation is the key element for both major and minor insulation. The solid insulating materials (cellulose insulation) are composed of paper and pressboard. The paper insulation serves to isolate the windings mechanically and dielectrically [3]. Besides, pressboard is used in high potential regions such as between phase winding and connection lead outs because it provides excellent resistance to break under thermal, chemical and electrical stress [14].

During normal operation, various power losses cause the transformer’s windings and cores to get heated up and this can damage the insulation system within the transformer. Thus, liquid insulation such as insulating oil is used to improve heat dissipation within the transformer and heat energy is transferred to atmosphere according to the convection principle [14]. Besides, the insulating oil also offers better insulation between the transformer windings. It can reduce any potential oxidation-causing contact between transformer parts and oxygen [3]. In the meantime, it is important to prevent insulating oil from leaking out as it may bring environmental damage. Thus, gaskets are used to safely contain the oil within the transformer housing and these gaskets are also considered as solid insulation of a power transformer.

2.3 Liquid Insulation

For decades, liquid insulation has been used for smooth operation of power transformers. In the 1950s, polychlorinated biphenyls (PCBs) were first introduced as insulating oil. Due to its excellent chemical resistance, thermal stability and electrical insulating fluids, they had been extensively used in various application such as capacitors, heat transfer fluids and dielectric fluids in transformers [15]. However, the commercial production of PCBs in the United States was restricted in the early 1970s and ultimately ended in 1977 as repetitive health issues had been reported in 1960s due to the PCBs presence in environmental [16].

During the year from 1870s to 1990s, petroleum based oils or known as mineral oil (MO) has been used as insulating oil in power transformers [17]. Because of its excellent pouring points at low temperatures, outstanding thermal cooling capacity, low cost, high efficiency and availability on the market, naphthenic mineral oil has long been the most recommended insulating liquid for power transformers [18]. However, due to their poor biodegradability and low fire point, it is necessary to look for other insulating oil to replace MO [18].

Owing to several benefits, researchers focused on biodegradable and renewable alternative of MO [17]. Ester liquids have become an alternative option to MO in transformers, especially in situations where there is a need to reduce environmental risk or enhance fire safety [19]. Another factor that make the ester oils as an ideal choice is that the insulation systems in a transformer which composed of cellulose materials and ester liquids have been shown to operate with lower moisture content in insulation system and withstand greater temperatures that MO [20]. Therefore, in this research, the performance of solid insulation and ester liquids under thermal ageing is examined.

2.3.1 Ester Oils

Esters are a special class of compounds that can be used to make insulating oils more useful and environmentally friendly [21]. Ester oil is formed when alcohol (R’-OH) and carboxylic acid (R-COOH) combine under the chemical reaction known as esterification as shown in Figure 2.1 [22]. Esters come in five different varities, monoesters, dicarboxylic esters (Di esters), glycerin esters, polyesters and complex esters. Remarkably, complex esters and polyesters have a unique role in high-voltage transformers as insulators [17].

$$\underset{\textit{Carboxylic acid}}{\text{R-COOH}} + \underset{\textit{Alcohol}}{\text{HO-R'}} \leftrightarrows \underset{\textit{Ester}}{\text{R-COO-R'}} + \underset{\textit{Water}}{H_2O}$$

Figure 2.1 Esterification process of ester oil [22]

Esters' properties met the industry's demand for insulating oil in a smooth manner, providing a superior substitute for mineral oil. Ester oils belong to the exclusive K class of liquids, which is distinguished by its high flash and fire points due to their superior electrical and thermal properties. They are a better option in high-risk areas due to their environmental friendliness as well as improved fire safety [23]. Hence, in this research, natural ester and synthetic ester are used as the insulating oil.

2.3.2 Natural Ester Oil (NEI)

Natural ester dielectric liquids are vegetables oils that are made from plant crops such as sunflower, soybean, canola or rapeseed and others. The majority of naturally occurring esters are triglycerides, which are lipids that include fats and oils [22]. Triglycerides (TGs) are thus triesters generated from one glycerol and three fatty acids in biochemistry. According to the structure of natural esters as illustrated in Figure 2.2 [24], glycerol (or glycerin) is known as polyol compound with the presence of three hydroxyl groups (-OH) meanwhile fatty acids (FAs) are carboxylic acids which have a unbranched, long aliphatic carbon skeleton that can be either unsaturated or saturated [22].

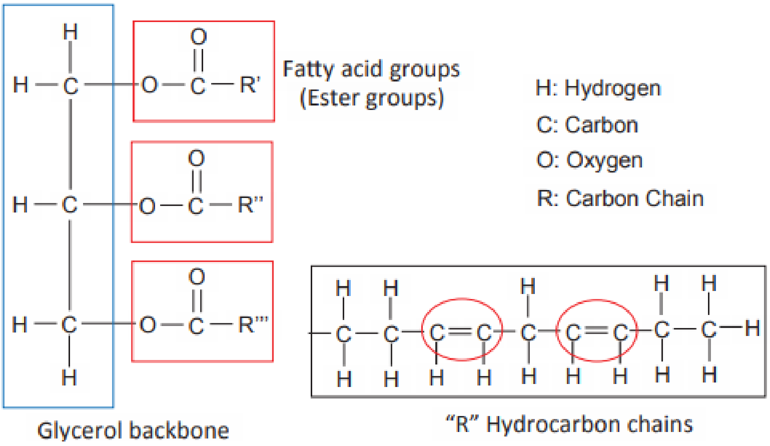


Figure 2.2 Example of a chemical structure of natural ester liquid [24]

The properties of TGs depend on three constitutive FAs and FAs are differentiate according to the number of hydrogen and carbon atoms in the formula as illustrated in Figure 2.3 [22].

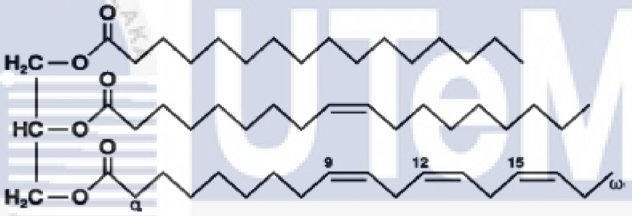


Figure 2.3 Triglyceride [22]

The carbon atoms create a flexible zigzag chain because they are each connected to two neighboring carbons. Longer chain fatty acids are more prone to intermolecular forces of attraction, which raises their viscosity and melting/pour point and, consequently, those of related fatty esters [22]. On the other hand, unsaturated triblock glycols (TGs) flow and freeze less readily and are usually liquid at normal temperature due to stiff kinks inserted by double bonds in the FA carbon chains as shown in Figure 2.3, which prevents them from stacking themselves in a closely packed arrangement like saturated TGs do. For instance, linseed oil (flax) is highly unsaturated and a viscous liquid, but animal fats (tallow and lard) have a high saturated fat content and are solids at room temperature [22].

Furthermore, unsaturated TGs are less stable than saturated ones and may break down or polymerize more quickly (tendency to go rancid or to harden) due to double bonds being more vulnerable to oxidative attack [22]. This suggests that a higher grade of molecule saturation corresponds to a higher level of oxidation stability. However, these highly saturated TGs also have high viscosities and pour points. Therefore, selecting the optimum natural esters for electro-technical applications requires careful evaluation of all these chemical factors.

2.3.3 Synthetic Ester Oil (SE)

As mentioned in Section 2.3.1, synthetic esters are produced when an alcohol molecule and a carboxylic acid molecule directly combine under a process known as esterification. In this reaction, polyols molecules with several hydroxyl groups are typically used. Every hydroxyl group has the ability to interact with another carboxylic acid molecule in the process. Consequently, the carbon chains formed from carboxylic acid molecules are joined by ester bonds to the backbone of a polyol molecule. Saturated molecules, which have only single bonds between carbon atoms, or unsaturated molecules, which have double or triple bonds between carbon atoms, can be used in the synthesis process. Saturated compounds are favored because they exhibit greater stability than those with unsaturated bonds [25].

Pentaerythritol ester is an example of a synthetic ester utilized in electrical applications [25]. It is made up of four ester groups, COOR, which are positioned at the end of the primary compound's cross structure. In this molecule, the alkyl (organic) groups from R_1 to R_3 are usually from C_5H_{11} to C_9H_{19} (with saturated carbon chains), but they might be different or the same [25]. The chemical structure of synthetic esters is what makes them a very stable substance [26]. The simplified structural formula of the mentioned ester is shown in Figure 2.4 [25].

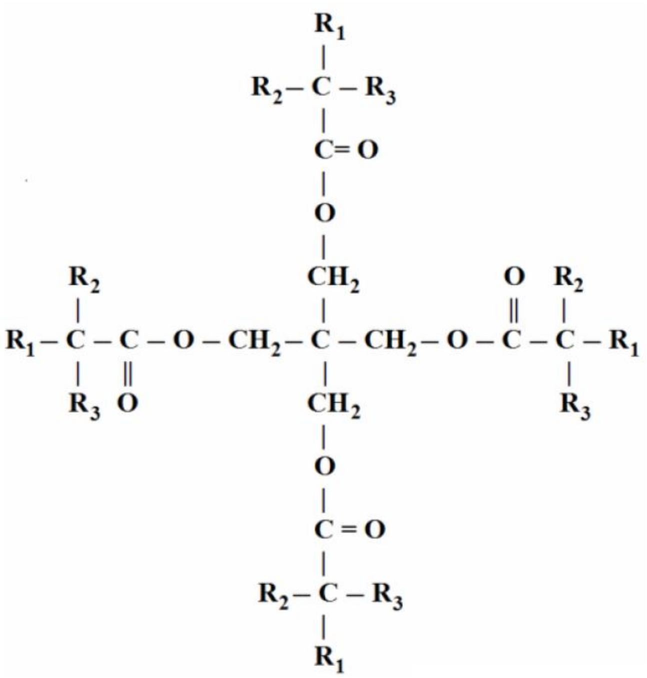


Figure 2.4 Simplified structural formula of pentaerythritol ester [25]

2.3.4 Comparison of Properties between NEI and SE

Even though both NEI and SE are created under same chemical reaction (esterificitaion), they can differ significantly in their properties due to the difference in their molecular structures. In terms of the environment, NEI is better than SE. Even though both esters are easily biodegrable and environmentally safe, only natural ester comes from plant crops that are widely available and naturally sustainable throughout the world. This indicates NEI has a much lower carbon footprint that SEI in addition to being more cost-effective [27]. Given the growing emphasis on sustainability and specifically zero carbon as a corporate requirement, NEI is undoubtedly the fluid of choice for the majority of end users.

The primary distinction between NEI and SE is the former’s proven ability to delay the ageing rate of cellulose paper insulation. In addition to operating temperature, high moisture content is a major factor in the degradation of cellulose paper. Due to its special double moisture removal actions through hydrolysis and absorption, NEI able to continuously dry the paper insulation in transformers [27][28][29]. Constant moisture removal not only increases the life expectancy of paper insulation but can also help to significantly lower the risk of dielectric breakdowns [27]. Although SE can absorb even more moisture than NEI due to its high moisture saturation point, but its capacity to chemically eliminate moisture has never been shown to be as effective in extending the life of cellulose paper. This is most likely because SE lacks the beneficial hydrolytic properties in eliminating moisture chemically [27]. A recent investigation on the ageing behaviour of insulating fluid under high humidity and air exposure [30] showed that even when hydrolysis eventually occurs in synthetic ester, the shorter chain fatty acids generated as a result are far more aggressive to the insulation paper. In contrast, the long chain fatty acids that are produced during the hydrolysis of natural ester are often non-aggressive and even aid in stabilising the cellulose structure of the paper, protecting it from deterioration [31]. Because of its exceptional moisture-handling qualities, NEI is therefore crucial for improving transformer reliability and lowering the amount of maintenance required for routinely drying both paper and liquid insulations.

Regarding their dielectric characteristics, NEI and SE typically because of their more polar chemical structure, have lower streamer inception voltage than MO under severly inhomogenous fields. It has been demonstrated that there would be no appreciable difference in the breakdown voltage limits for test electrodes down to 3 mm [27], so in practice, it would not be a major issue in the design of internal leads connecting the windings to the bushings and tap changers in power transformers, even though this means lower breakdown voltage from ester fluids in impulse tests using highly divergent electrode systems.

Even though NEI has higher moisture tolerance and better birodegradibility than SE, this oil suffer from poor oxidation stability compared to SE. This is because NEI has a lower level of oxidation resistance due to unsaturated double carbon-carbon bonds [32]. In the worst scenario, the fluid may polymerize into a solid due to the unsaturated linkages in the molecular structure being vulnerable to oxygen attack [32]. Due to that reason, NEI are nor recommended to be used in breathing transformers and SEI on the other hand are perfectly suited for both breathing and non-breathing transformers. In short, it is important to properly handle NEI and SE for electro-technical applications in power transformer.

In this research, FR3, a biobased natural ester dielectric coolant is used to represent NEI meanwhile MIDEL 7131 is selected to represent SE. Table 2.2 summarises the properties of NEI and SE used in this research.

Table 2.2 Properties of NEI and SE used in this research

Properties	Natural Ester Oil FR3	Synthetic Ester Oil MIDEL 7131
Colour	Light green	Light yellowish
Density (g/cm^3) at 20℃	≤ 1.0	< 1.0
Viscosity (mm^2/s) at 40℃	≤ 50	≤ 35
Flash point (℃)	≥ 250	> 250
Fire point (℃)	> 300	> 300
Water content (mg/kg)	≤ 200	< 200

2.4 Solid Insulation

Pressboards and electro-technical papers, often known as kraft papers, are two examples of cellulosic materials that represent most of the insulating system of a power transformer. Solid insulations improve the direction of oil flow and offer mechanical, thermal as well as electrical insulation [2]. When insulating oil is impregnated with this solid insulation, the dielectric strength of the insulating oil increases further [33]. Besides, gasket is another important material in solid insulation system of a transformer. Gasket is used to safely keep the insulating oil within the transformer housing, ensuring there are no oil leaks from the transformer. However, all these solid insulations will undergo degradation over time. Therefore, it is important to monitor these solid materials because the health of a power transformer is determined by the condition of its insulation system.

2.4.1 Insulating Paper

Insulating paper is made from cellulose fibrers, which are basically organic components. Since cellulose makes up the majority of the cells in plants including cotton, hemp, manila, straw, wood and deciduos trees, these materials can be acquired from vegetable sources [34]. Insulating paper is composed of 90% of cellulose, 6-7% of hemicellulose, lignin and pentosan [35]. Glucose residues are bonded together into chains to create the cellulose chains. The glucose units are connected in incredibly lengthly strands, as shown in Figure 2.5Figure **2.5** Chain structure of the glucose molecules, forming cellulose fibres [36].

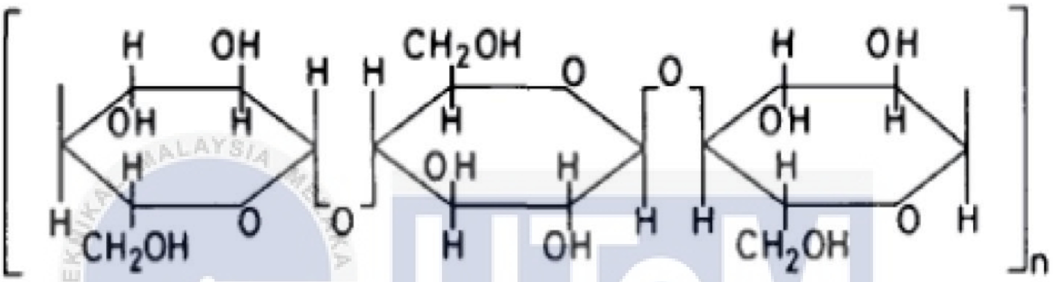


Figure 2.5 Chain structure of the glucose molecules, forming cellulose fibres [36]

Hydrogen bonds between the neighbouring molecules and the hydroxyl group (-OH group) hold these molecules together. Hydrogen bonds are created between the cellulose chains and the hydroxyl groups, binding the chains together to create a fibrous, insoluble polymer. The length of cellulose molecules is represented by the letter "n" in and is expressed in terms of the degree of polymerization (DP) [36].

The hemicellulose materials included in cellulose fibres have an impact on sheet strength as well. Because of the fiber-to-fiber connection caused by the hydrogen bridges forming hydroxyl groups, the sheet strength increases. Together with cellulose, lignin is a highly complex, polymeric natural material that is difficult to break down and makes up the majority of wood. Lignin functions as a binder between the cellulose fibres in a fibre composite, enhancing the strength of the wood [2]. Thus, depending on the type of transformer and its intended use, the insulating paper is selected based on the density and structure of the component [35].

According to the reasearh’s objectives, thermally upgraded kraft paper (TUK) and kraft paper (KP) are used as the insulating papers. As mentioned at earlier of this section, KP is cellulosed fibres that composed of 90% of cellulose, 6-7% of hemicellulose, lignin and pentosan. Meanwhile, TUK is an upgraded version of KP where the properties of TUK is customised by adding stabilizing agents such as melamine, dicyandiamide and polyacrylamide [37][38] to enhance the properties of the paper. The main properties that make TUK as better insulating paper is described in Table 2.3. All these properties reduce the aging rate of TUK compared to KP. Hence, the peformance of these two insulating papers will be investigated in this research.

Table 2.3 Properties of TUK [37][39]

Properties	Explanation
Thermal Stability	By adding the stabilizing agents to TUK, they stabilise the polymer structure of TUK and making it more resilient to high temperature compared to KP.
Moisture Resistance	The stabilizing agents enhance its moisture resistance, by reducing its hygroscopic nature (absorb mositure from the surroundings), thus lower the hydrolysis rate of cellulose.
Oxidation	TUK’s resistance to oxidative degradation is strengthened by the stabilizing agents. The cellulose chains are susceptible to severe damage from oxidation, but the stabilizing compounds work as antioxidants to prevent the cellulose fibres from breaking under oxidative stress.
Mechanical properties	Compared to KP, which is more prone to rapid degradation under similar conditions, TUK's stabilising chemicals lessen the negative effects of insulating oils on the paper's mechanical properties, resulting in a slower drop in tensile strength.

2.4.2 Pressboard

The main component of cellulose pressboard, sometimes referred to as transformer board, is many layers of laminated cellulose paper. Because of the thin layers of cellulose and insulating oil's breakdown strength, pressboard has a high dielectric strength. In contrast to soft insulating paper, the thin layers of cellulose give the pressboard dimensional stability [40].

Calendared pressboards and pre-compressed pressboard sheets are the two varieties of cellulose pressboards. Shaped objects and tubes are typically formed using calendared pressboards. Pressboards also serve as winding insulators. Pressboard sheets that have been pre-compressed are used to support heavy objects like laminated blocks and spacers. Typically, a hot press is used to dry and press the pre-compressed pressboard sheets. The many shapes of cellulose pressboards are depicted in Figure 2.6 [34].

Figure 2.6 Various shapes of cellulose pressboards [34]

2.4.3 Gasket

As mentioned in Section 2.4, gasket is used to safely keep the insulating oil within the transformer housing, ensuring there are no oil leaks from the transformer. The most used gasket material for liquid-filled equipment in the electrical sector is Buna-N, sometimes known as nitrile rubber. Nitrile rubber (NBR) is a copolymer of acrylonitrile and butadiene [41].It is reasonably priced, has extremely good low temperature capabilities, a strong track record of performance, and fair high temperature properties [42].

Similar to other solid materials, gaskets also deteriorate over time. Transformer gaskets can fail and become brittle. Besides, the incompatibility of the gasket and the insulating oil can lead to gasket degradation and oil contamination, which can impair the fluid's dielectric characteristics, shorten the transformer's usable life, and contaminate the environment through fluid leaks [41]. Therefore, it is important to monitor whether there is any leakage from transformer as the phenomena such as deterioration of gasket and insulating oil will occur.

2.5 Effect of Thermal Ageing on The Properties of Insulation Material

Thermal ageing is a process where the insulating material of a power transformer which is solid and liquid insulation are typically conditioned in a temperature-controlled chamber at either high or subambient temperatures. After few weeks or months, the residual properties of the insulation system will be measured by conducting ageing assessment. The thermal ageing mechanism significantly influences the electrical and physicochemical properties of solid and liquid insulation [43]. For liquid insulation, it causes an increase in the dielectric dissipation factor and a decrease in the resistivity, breakdown voltage and dielectric strength. Furthermore, it plays a part in the generation of dissolved gases in oil, which deteriorates the liquid’s physicochemical properties [43]. Meanwhile, the decrease in the paper's tensile strength (TS) and degree of polymerization (DP) accelerates the degradation of solid insulation [43]. In this section, the effect of thermal ageing mechanism on the properties of solid and liquid insulation is discussed.

2.5.1 Liquid Insulation

Thermal ageing mechanims deteriorate the properties of insulating oil. Based on many studies, thermal ageing contributed to an increase in the physicochemical properties of insulating oils (such as moisture content, acidity, viscosity, and furanic compounds), which had a detrimental effect on the electrical properties like the breakdown voltage [44][45][46]. Because of the molecular structure of ester oil, ester oils' ageing process can be linked to oxidation and hydrolysis. Ester oils are made up of single COOH valence bonds that encourage hydrolysis while double C–C valence bonds might cause oxidation [2]. Mineral oils and ester oils both undergo the same oxidation process. The process of esterification is reversed during hydrolysis, where the presence of water causes the formation of incomplete ester molecules (disconnected at the C–O bond) and free fatty acids. This mechanism is called an autocatalytic reaction because the hydrolysis process is accelerated by the free fatty acids themselves [2].

An increase in the water content, oil temperature, or the proportion of dissolved metals in the ester oil speeds up the hydrolysis process and raises the overall acid number. Due to the incomplete ester molecules polymerize at their cutting points, the viscosity also rises [44]. There are three steps in the hydrolysis of ester oils. The interactions between the triglycerides and water result in the formation of diglycerides in the first stage. The reactions between the diglycerides and water result in the formation of monoglycerides in the second stage. Lastly, as seen in Figure 2.7 [35], glycerol, the ultimate reaction product, is produced. All phases of the hydrolysis process result in the production of fatty acids as byproducts [47].

$$\underset{\text{triglyceride}}{C_3H_8(OOCR)_3} + \underset{\text{water}}{H_2O} \Leftrightarrow \underset{\text{diglyceride}}{C_3H_8(OH)(OOCR)_2} + \underset{\text{fatty acid}}{R\text{-}COOH}$$

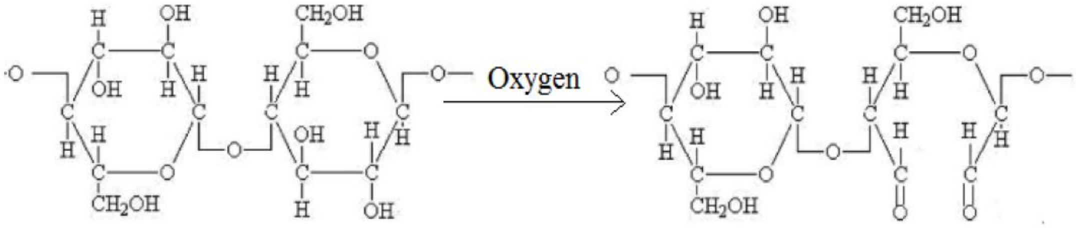
$$\underset{\text{diglyceride}}{C_3H_8(OH)(OOCR)_2} + \underset{\text{water}}{H_2O} \Leftrightarrow \underset{\text{monoglyceride}}{C_3H_8(OH)_2(OOCR)} + \underset{\text{fatty acid}}{R\text{-}COOH}$$

$$\underset{\text{monoglyceride}}{C_3H_8(OH)_2(OOCR)} + \underset{\text{water}}{H_2O} \Leftrightarrow \underset{\text{glycerol}}{C_3H_8(OH)_3} + \underset{\text{fatty acid}}{R\text{-}COOH}$$

Figure 2.7 Hydrolysis of ester oils [35]

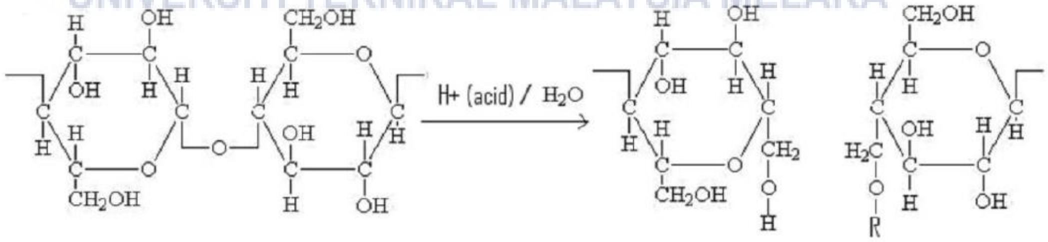
2.5.2 Solid Insulation

The three primary processes that lead to the deterioration of cellulose are pyrolysis, oxidation, and hydrolysis [48][49]. As illustrated in Figure 2.8 [48], oxidation starts when oxygen attacks the hydroxyl groups in the cellulose structure, weakening the glycosidic bond. As oxidation produces just CO_2 and water as byproducts, it is regarded as a slow type of combustion [2].



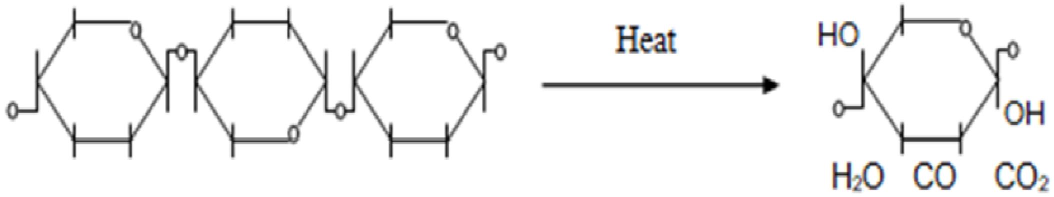
Oxidation mechanims of cellulose [48]

The main process that causes insulating paper in power transformers to deteriorate is called hydrolysis. As seen in Figure 2.9 [48], this mechanism causes the chain scission of the glycosidic linkages in cellulose polymers as a result of the attack by hydrogen ions that have separated from the acids [49]. Furanic substances like 2-furaldehyde and 5-hydroxymethylfuraldehyde are formed as a result of the multiple phases of hydrolysis of the free glucose rings [35][49].



Hydrolysis mechanism of cellulose [48]

At high transformer operating temperatures (>140°C), pyrolysis begins in the absence of moisture or oxidising factors [49]. As seen in Figure 2.10 [35], this mechanism can result in both chain scission and the opening of the glucose rings [49]. Carbon dioxide, water, glucose, and carbon monoxide are the byproducts of pyrolysis [50].



Pyrolysis mechanism of cellulose [35]

Other properties of cellulose material such as degree of polymerization (DP) and tensile strength (TS) are also affected due to thermal ageing mechanism. The evolution of DP and TS with respect to the ageing period can be used to provide trustworthy information regarding the degrading process of solid insulations because the data are gathered directly from the insulating paper sample. A correlation between the DP and TS has been found in multiple studies [51][52]. Both of these parameters decrease as the ageing time and ageing temperature increase. However, most of the insulating paper are assessed based on the DP while less on the TS measurement [2].

2.6 Method of Assessing Insulation System Degradation

Organisations and research institutions have developed a number of condition monitoring techniques (such as electrical and chemical analysis methods) over the years to evaluate the state of the insulating system in power transformers. The American Society for Testing and Materials (ASTM), the British Standard (BS), and the International Electrotechnical Commission (IEC) have published standards that outline these procedures. The development of technology and diagnostic approach expertise has been greatly aided by these organisations. For this reserach, some of the ASTM standards have been referred in order to assess the insulation system degrdation.

2.6.1 Electrical Test: Polarisation Index Test

To assess the state of insulation, such as cellulose paper and insulating oil, the polarisation index (PI) is used. The amount of insulation degradation is monitored to determine whether the insulating material still has useful life left in it or needs to be replaced. PI will drop as a result of insulation deterioration and high insulation sludge content [53]. Equation 2.1 illustrates that PI is a ratio of insulation resistance for 10 minutes to 1 minute. For this reaserch, the PI value for FR3 (NEI) and MIDEL 7131 (SE) will be measured to monitor the degradation rate of the insulating oils.

$$PI = \frac{IR\ (10\ mins)}{IR\ (1\ mins)} \tag{2.1}$$

2.6.2 Chemical Test: Dissolve Decay Product (DDP)

The ASTM D6802 [54] is typically used for Dissolved Decay Product (DDP) measurements, which use UV-Vis Spectrophotometry to determine the amount of dissolved decay product in insulating oil. As insulation oil ages, decay compounds that target cellulose will be absorbed by insulation paper, leading to a decomposition process that increases the amount of dissolved decay products in the insulating oil [55].

Insulating liquid is easily contaminated when the transformer is in operation, despite its high dielectric qualities and ability to function as a coolant [56]. Gas and sludge are produced as a result of a chemical reaction that is brought on by the oil. The ensuing sludge will reduce the insulating oil's ability to conduct heat. The insulating paper is likely to deteriorate as a result of the decay product that results from this process since it is not soluble in insulating oil. Typically, insulating oil will absorb small dispersed decay particles. Transformer failure can be attributed in large part to DDP [57]. In this research, the DDP of FR3 (NEI) and MIDEL 7131 (SE) will be measured to investigate which oil has lower DDP.

2.6.3 Physical Test

There are several type of physical tests for power transformers. However, the focus of this research is in conjuction to tensile strength and shore hardness tests.

2.6.3.1 Tensile Strength Test

According to ASTM D828-22 *Standard Test Method for Tensile Properties of Ppaer and Paperboard Using Constant-Rate-of Elongation Apparatus* [58], in order to perform this test technique, test specimens must meet specified dimensions of 25.4 cm ± 0.5 cm in width and approximately 254 mm in length to ensure there is enough specimen to fit into the instrument grips. The tested paper is placed in a vacuum and kept out of the water. The tested paper selected for the tensile test needs to be in good shape and free of any defects that could compromise the tensile strength measurement, such as folds, holes, and wrinkles. Tests are carried out in an atmospheric environment. Until the test item breaks, the test is conducted. Recorded is the greatest tensile force that was applied. Test piece readings that crack within 10 mm of the clamp line will not be accepted. In this research, the test will be conducted on kraft paper (KP) and thermally upgraded kraft paper (TUK).

2.6.3.2 Shore Hardness Test

The ASTM D2240-15 *Standard Test Method for Rubber Property-Durometer Hardness* [59] is used to conduct the shore hardness test, and up to five measurements will be made at various locations on the gasket. In order to provide provide an accurate reading, the temperature will be measured at room temperature, which is 23±2 °C. Should the durometer have an electronic indicator, the measurement ought to be documented at 1±0.3 s. A durometer with an analogue type indicator needs to have the reading recorded right away, while one without one needs to take the reading in less than 1 s. In this research, Nitrile Butadiene Rubber (NBR) gasket will be used for this test.

2.7 Summary

This chapter has discussed in detail the different properties of insulating papers by introducing the power transformer insulation materials in Section 2.2. This is followed by the description of liquid insulation and solid insulation properties in Section 2.3 and Section 2.4, respectively. Lasty, the effect of thermal ageing on the properties of insulation materials and the method of assessing is discussed.

CHAPTER 3

METHODOLOGY

3.1 Introduction

In this chapter, the overall methodology of this research will be explained. The flow of the research is categorized into four parts, Part A, B, C and D, as shown in Figure **3.1**. Each part will be explained in detail in Section 3.2, Section 3.3 and Section 3.4. Section 3.2 covers Part A, which is the preparation of sample. In Section 3.3, Part B and Part D of this research is discussed regarding the sample testing. Lastly, the thermal ageing process in Part C will be demonstrated in Section 3.4.

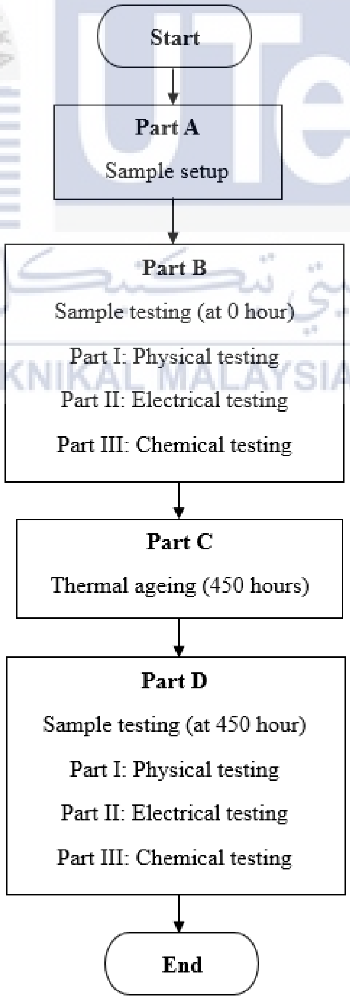


Figure 3.1 Flowchart of overall process

3.2 Part A: Sample Setup

Figure 3.2 shows the flowchart of the process for preparing the sample setup. The preparation begins with calculation of parameters for solid insulation, insulating oils and metal catalyst. Following with filtration and nitrogen treatment of insulating oils. For the solid insulation, it begins with cutting process, thickness measurement, weighing process and lastly, the drying process. Meanwhile, for metal catalyst, only the amount of catalyst use for thermal ageing is measured.

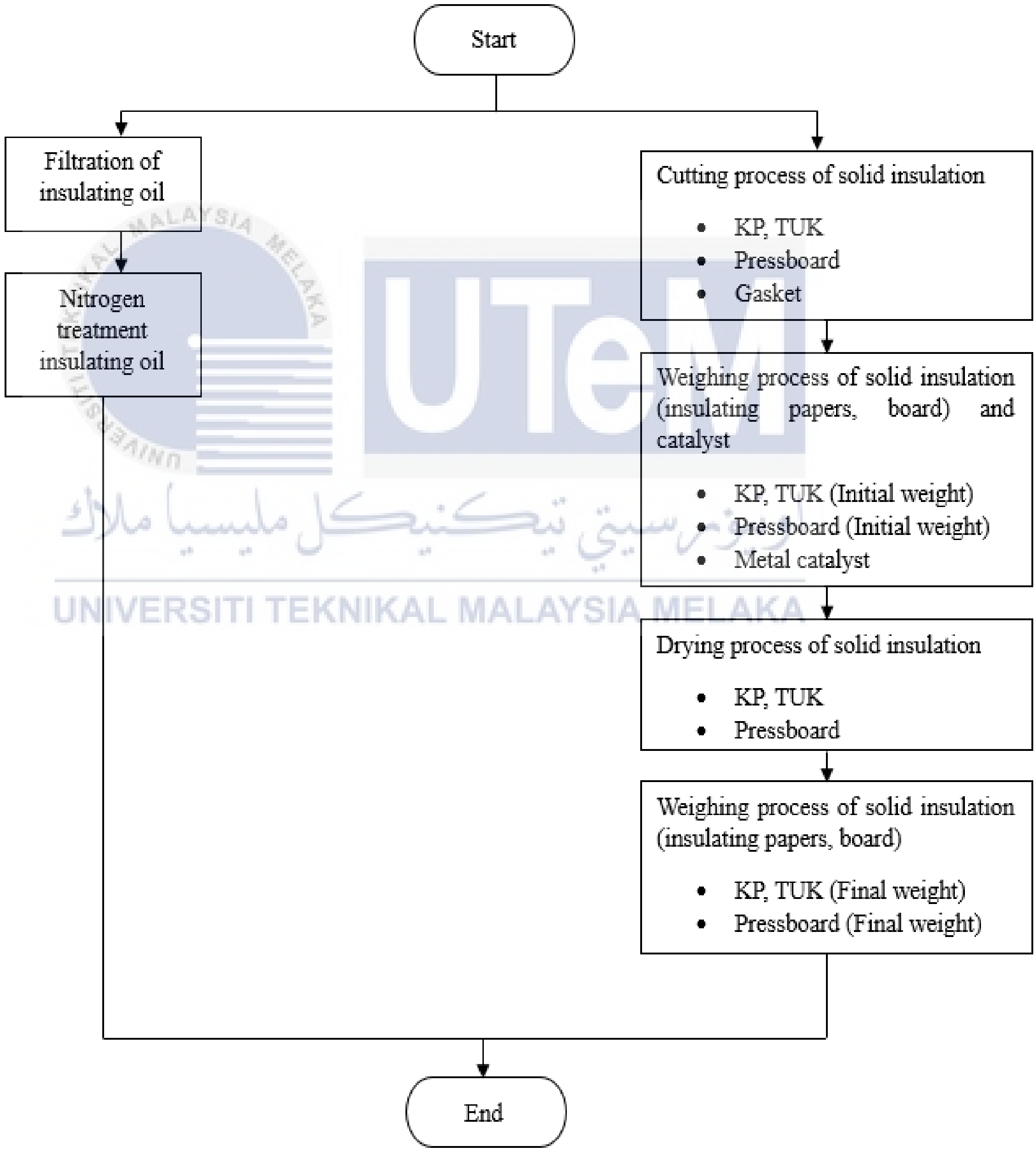


Figure 3.2 Flowchart of sample setup (Part A)

3.2.1 Calculation for Sample Setup

For this research, the study quantity of each insulating oil is 400ml. Hence, all the material measurements are calculated in accordance with the study quantity of insulating oils and referred to the ASTM standards and previous research. Table 3.1 shows the references used in calculating the weight of insulation materials and metal catalyst. For insulating papers, the weight of TUK is same as KP.

Table 3.1 Weight of insulation materials and metal catalyst

Material	References			
	Tenbohlen and Koch, 2010 [44]	Akmal et al., 2006	Nur Lidiya, 2020 [2]	Study quantity for this research (each sample)
Volume of oil (ml)	1000	1000	1000	400
Weight of pressboard (g)	100	80	80	32
Weight of KP (g)	100	-	20	8
Weight of metal catalyst (g)				
Copper, Cu	2.5	2.5	2.5	1
Iron, Fe	2.5	2.5	2.5	1
Zinc, Zn	0.5	0.5	0.5	0.2
Aluminum, Al	0.5	0.5	0.5	0.2

Table 3.2 shows the ASTM standards used in calculating the dimensions of TUK, KP, pressboard and gasket. When deciding the finalized dimension, it must be considered with the volume of insulating oil so that the materials can immerse fully in the oil.

Table 3.2 Dimension for solid insulation

Material	ASTM Standards	Finalized dimension (in accordance with 400ml of oil)
Gasket	ASTM D3455 – 02 [60]: A ratio of 65 cm^2 surface area per 800ml of oil.	A ratio of 32 cm^2 surface area per 400ml of oil. • Length × Width: 8cm × 2cm • Top surface area: 16 cm^2 • Bottom surface area: 16 cm^2
Pressboard	ASTM D3455 – 02 [60]: Not less than 52 cm^2 are used for 800 ml of oil if the test specimen can be measured.	For 400ml of oil, a minimum of 26 cm2 is needed. • Length × Width: 6 cm × 2.5 cm • Top surface area: 15 cm^2 • Bottom surface area: 15 cm^2 • Total surface area: 30 cm^2
KP and TUK	ASTM D828-22 [58]: A minimum of 254 mm in length is required to be clamped while conducting tensile test.	The dimension will be used: • Length: 28 cm • Width: 2 cm

After finalizing the measurements. All the materials will be inserted in 8 ageing bottles for the thermal ageing process (Part C). The ageing bottles will be labelled by referring to the types of insulating papers in the bottles, as shown in Table 3.3.

Table 3.3 Sample labelling for the research

Sample labelling	Types of insulating oil and its volume	Weight of insulating papers	Number of Gasket	Pressboard
TUK 1	NEI (400 ml)	8g of TUK	1	32
TUK 2	NEI (400 ml)	8g of TUK	1	32
KP 1	NEI (400 ml)	8g of KP	1	32
KP 2	NEI (400 ml)	8g of KP	1	32
TUK 1	SE (400 ml)	8g of TUK	1	32
TUK 2	SE (400 ml)	8g of TUK	1	32
KP 1	SE (400 ml)	8g of KP	1	32
KP 2	SE (400 ml)	8g of KP	1	32

3.2.2 Filtration of insulating oil

Based on Figure 3.3, insulating oil will be filtered to remove all contaminations presence in the oils. Membrane filtered paper with size of pore 0.22µm is used during this filtration process. Before starting the filtration process, the unfiltered insulating oil will be covered with aluminum foil to prevent dust from entering the oil. The FR3 (NEI) and MIDEL 7131 (SE) filtering process takes 80 minutes for every 300ml.

Figure 3.3 Process of filtering insulating oil

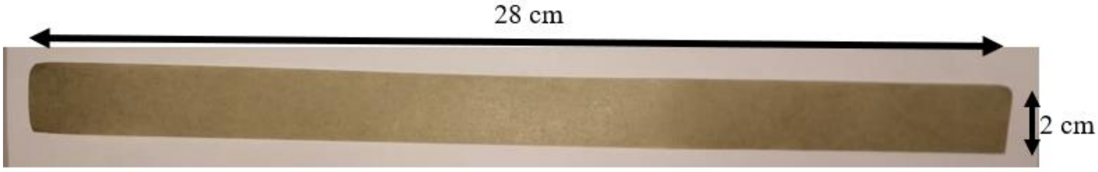
3.2.3 Nitrogen Treatment for Insulating Oil

The filtered insulating oil will undergo nitrogen treatment shown in Figure 3.4 to prevent the formation of gas, water or compounds that can affect the properties of insulating oil during thermal ageing process. The moisture content level for NEI and SE must be less than 200 ppm. Hence, the dry nitrogen will be bubbled for 30 minutes in each oil to obtain that level of moisture content.

Figure 3.4 Nitrogen treatment for insulating oil

3.2.4 Cutting Process for Solid Insulation

The width of the KP and TUK follows the orginal width, which is 2 cm. Based on Figure **3.5** and Figure **3.6**, KP and TUK will be cut into a length of 28 cm for the tensile stength test in accordance with ASTM D828 – 22 [58] because a minimum length of 25.4 cm is required so that the insulating papers can be clamped and griped well by the equipment. The dimension for both KP and TUK is 28 cm × 2 cm. The insulating papers will be



cut more than the required amount (which will be explained in Section 3.2.5) to avoid any shortage.

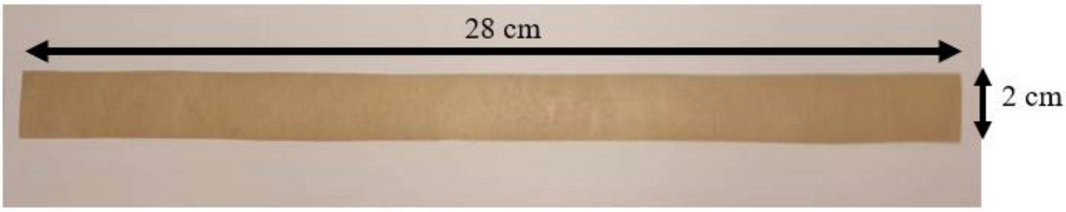


Figure 3.5 Size of TUK

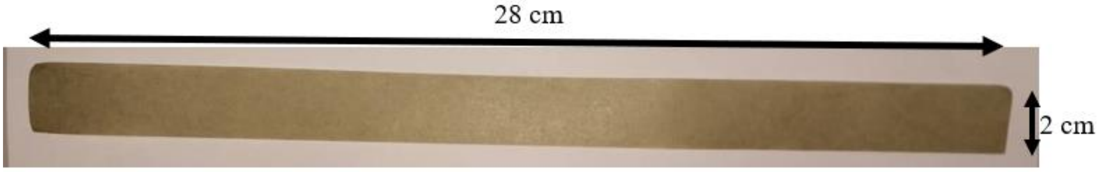


Figure 3.6 Size of KP

Based on Table 3.2, the pressboard is cut with a dimension of 6 cm × 2 cm so that the top and bottom surface area for a piece of pressboard will be 15 cm^2. Hence, a total surface area of 30 cm^2 can be obtained. Figure 3.7 shows the size of pressboard. Similar to insulating papers, pressboard will be cut more than the required amount (which will be explained in Section 3.2.6) to avoid any shortage.

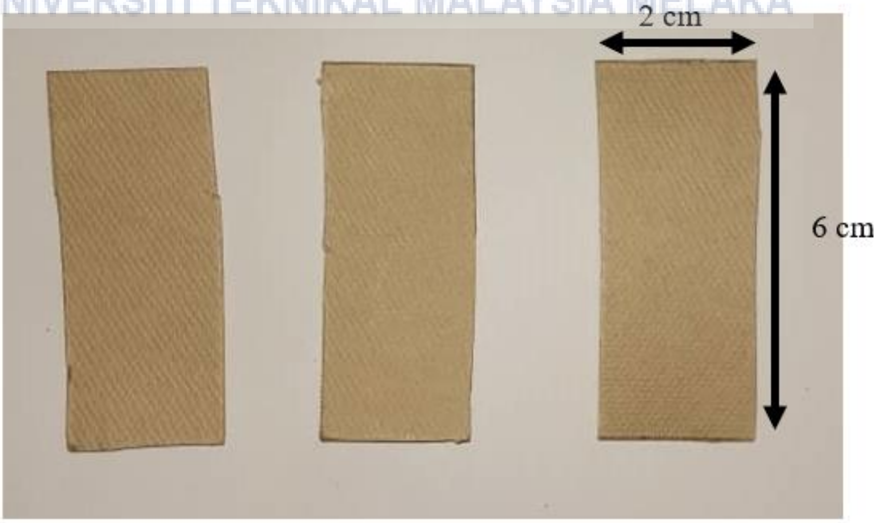


Figure 3.7 Size of pressboard

For NBR gasket, the gasket is cut with a dimension of 8 cm × 2 cm so a total surface area of 32 cm^2 can be obtained, as stated in Table 3.2. Figure 3.8 shows the size of NBR gasket. The thickness of gasket will be used is 3mm.

Figure 3.8 Size of NBR gasket

3.2.5 Weighing Process for Solid Insulation and Metal Catalyst

Based on Table 3.1, the weight required for insulating papers (KP and TUK) and pressboard for each sample of insulating oil is 8g and 32g. Figure 3.9 shows the process of measuring the TUK. After measuring the weight for solid insulation, 19 pieces of each insulating paper are needed for 8g (in total of 64 g for 8 samples) meanwhile 20 pieces of pressboard are needed for 32g (in total of 256g for 8 samples). In total, the numbers of KP and TUK required is 152 pieces each and 160 pieces for pressboard. However, it is advisable to cut more pieces than the stated amount (152 pieces and 160 pieces) because after the drying process (Section 3.2.6), the weight of materials will be decreased and it will be difficult to obtain 64g and 256g. Both the initial and final weight (after drying process) of solid insulation will be recorded to analyse the decrement of weight.

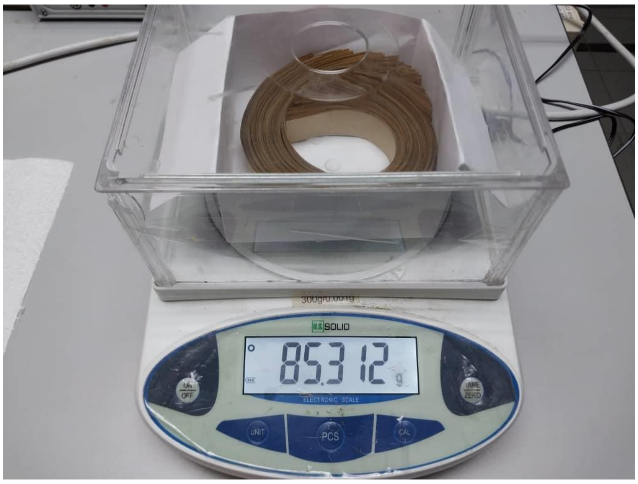


Figure 3.9 Measuring the weight of TUK

According to Table 3.1, the amount of weight required for copper (Cu) and iron (Fe) is 1g each while the weight of zinc (Zn) and aluminum (Al) is 0.2g each. After the weighing process, all four metal catalyst will be placed on a filter paper with a diameter of 12 cm before wrapping it to prevent the catalyst from spilling during the immersion and the thermal ageing process as shown in Figure 3.10. Since there are 8 samples for this research, 8 packs of metal catalysts will be prepared.

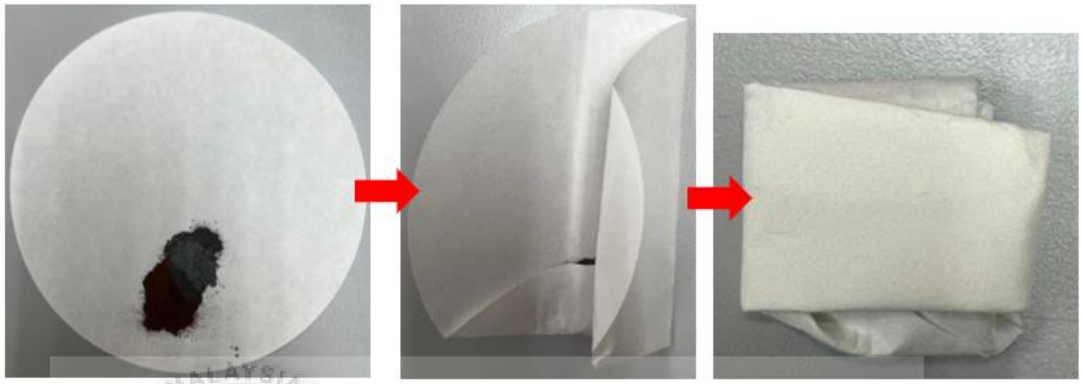


Figure 3.10 Steps to a wrap filter paper

3.2.6 Drying Process for Solid Insulation (Insulating Papers and Pressboard)

The purpose of drying the insulating papers and pressboard is to reduce the moisture content in the materials. This is because the moisture in the materials can affect the ageing process. Hence, TUK, KP and pressboard will be undergo a drying process in accordance to BS EN 60641-2:2004 60641-2:2004 *Pressboard and Presspaper for Electrical Purposes – Part 2: Method of Tests* [61].

Each sample thickness will be measured using an electronic digital caliper for the purpose of determining the time required for the drying process, as shown in Table 3.4. The thickness of TUK and KP is 0.075 mm and the thickness of pressboard is 0.790 mm.

Table 3.4 Duration for material drying [61]

Thickness, T (mm)	≤ 0.5	0.5 < T ≤ 1.5	1.5 < T ≤ 5	> 5
Duration, h	12	24	48	72

Figure 3.11 and Figure 3.12 shows the arrangement of TUK, KP and pressboard in the oven for drying process. The KP and TUK will be dried at 105°C for 12 hours while

the pressboard will be dried for 24 hours. After the drying process, all the insulating papers and pressboard will be weighed according to Table 3.1. Later, the weighed materials will be placed and sealed in a vacuum bag to prevent them from being exposed to the environment where the moisture can be absorbed into the insulating papers and pressboard.

Figure 3.11 Arrangement of KP and TUK in oven

Figure 3.12 Arrangment of pressboard in oven

3.3 Part B and Part D: Sample Testing (at 0 hour and 450 hours)

In this part, physical, electrical and chemical tests for this research will be explained in detail. Basically, the sample tesing at 0 hour refers to examine the initial condition of the materials before thermal ageing process. Meanwhile, sample testing at 450 hours is examining the final condition of materials after thermal ageing process for 450 hours. By conducting these tests, the difference between the conditions of solid insulations (KP, TUK, pressboard and gaskets) and insulating oils (NEI and SE) can be investigated.

3.3.1 Physical Test

The physical properties of solid insulations will be performed by comparing the weight of KP, TUK and pressboard (before and after drying), shore hardness of gaskets (before and after thermal ageing process) and investigation of the tensile strength of KP and TUK (before and after thermal ageing process).

3.3.1.1 Weight of Insulating Papers and Pressboard

To make sure KP, TUK, and pressboard are thoroughly dried, their weights will be noted both before and after the drying process. When there are no weight changes, the materials are considered to be dried out. In order to prevent the ambient air from affecting the water content in the materials, the weighing procedure is done at room temperature. The following procedures are followed in order to complete the measurements:

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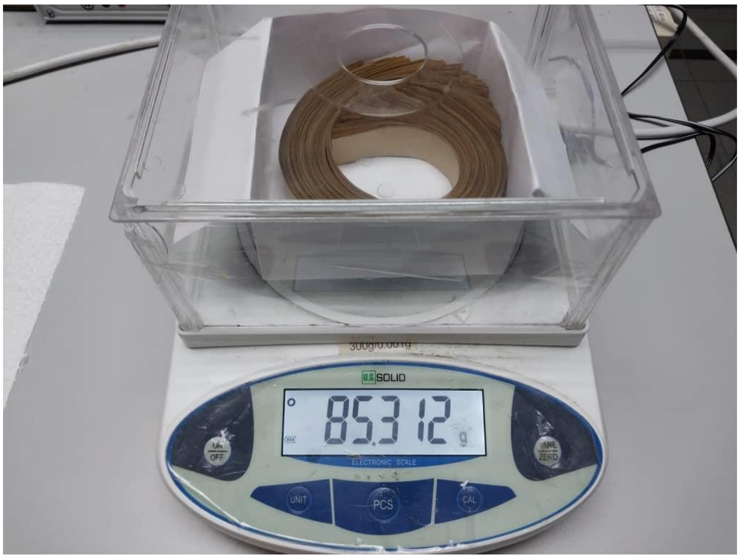


Figure 3.13 Measuring the initial weight of TUK

Step 1: Turn on the scale and make sure that the reading value is zero.
Step 2: Place the TUK on the scale.
Step 3: Properly cover the scale (as shown in Figure 3.13) with its cover to avoid any external interference that can affect the reading value.
Step 4: Record the initial weight of the TUK.
Step 5: Repeat steps 1 to 4 to measure the initial weight of KP and pressboard.
Step 6: Repeat step 1 to 4 o measure the final weight of TUK, KP and pressboard.
Step 7: The difference in weight of KP, TUK and pressboard is calculated using the formula:

$$\Delta\ of\ weight\ (g) = Initial\ weight\ (g) - Final\ weight(g) \qquad (3.1)$$

3.3.1.2 Tensile Strength Test

According to ASTM D828-22 [58], the measurement of tensile strength for insulating papers (KP and TUK) need to be carried out for 10 times to get their average value. The tensile strength test at 0 hour and 450 hours is carried out according to the following steps:

Step 1: Turn on the tensile machine. Make sure that the software in the computer opened.
Step 2: Set the distance between upper and lower clamper to 260mm before placing the TUK on the clamper as in Figure 3.14.

Step 3: Make sure that TUK is clamped correctly (i.e., the angle of the kraft paper and the upper surface of the clamper is 90 ± 1° to get the true value of the tensile strength).

Step 4: Make sure that the readings of the tensile strength and the elongation zero (in the software) before the measurement is done.

Step 5: Run the machine until the TUK is torned as shown in Figure **3.15**. Record the tensile strength of TUK.

Step 6: Repeat step 2 to step 5 for 10 times to get the average reading of tensile strength for TUK.

Step 7: The changes of tensile strength of TUK at 0 hours (initial) and 450 hours (final) can be calculated using formula:

$$\Delta\ (MPa) = Initial\ Tensile\ Strength - Final\ Tensile\ Strength \tag{3.2}$$

Step 8: Repeat step 2 to step 7 for KP.

Figure 3.14 TUK set up in tensile machine

Figure 3.15 Torned TUK after tensile test

3.3.1.3 Shore Hardness of Gaskets

The shore hardness of NBR gasket will be measurd using a durometer as shown in Figure 3.16. The gasket at 0 hour and 450 hours will be measured to make a comparison. The following steps are:

Figure 3.16 Measuring shore hardness of NBR gasket

Step 1: Make sure the surface of the gasket is clean and wipe the surface of the gasket until it is completely dried (gaskets after aging).

Step 2: After the durometer is turned on, press the zero button to confirm that the shore value hardness before the measurement is zero.

Step 3: Place the durometer on the gasket and press to it.

Step 4: Record the value for shore hardness, (press the H" button to hold the reading).

Step 5: Repeat step 3 and step 4 for 5 times at different position of gasket. Calculate the average value.

Step 6: The changes of shore hardness of gasket at 0 hour and 450 hours is obtained using the formula:

$$\Delta\ (HA) = Initial\ shore\ hardness\ (HA) - Final\ shore\ hardness\ (HA) \quad (3.3)$$

3.3.2 Electrical Test: Polarization Index Test (PI)

The PI test for insulating oils does not have a set standard. Mushroom shaped electrode with 1 mm gap is used. Voltage 500 V will be injecting into the insulating oils at 0 hour and 450 hours. The PI test is carried out by following steps:

Step 1: Insert 500ml of the insulating oil into the chamber until it submerges the electrode as shown in Figure 3.17.

Step 2: Connect the live and neutral cable to the electrode and tester.

Step 3: Turn on the polarization index tester.

Step 4: Set mode to PI and up the voltage to desired level.

Step 5: Push the test button until the red light is turn on.

Step 6: Record the reading after 10 mins.

Figure 3.17 Chamber for PI testing

3.3.3 Chemical Test: Dissolve Decay Product (DDP)

According to ASTM D6802 (2010) [54], the wavelength is set from 360 nm to 600 nm. The process is done at room temperature, which is 25 ± 5 °C. To make sure the cuvette is not contaminated, it is first cleaned and dried at 110 °C for 30 minutes. To make sure that there is no pollution obstructing the UV rays as they are emitting into the samples, it is imperative to make sure the bright side of the cuvette is cleansed. To make sure that the oil samples are exposed to all of the UV rays released, the oil samples will be poured into the cuvette until it reaches the 41 mm (Figure 3.18).

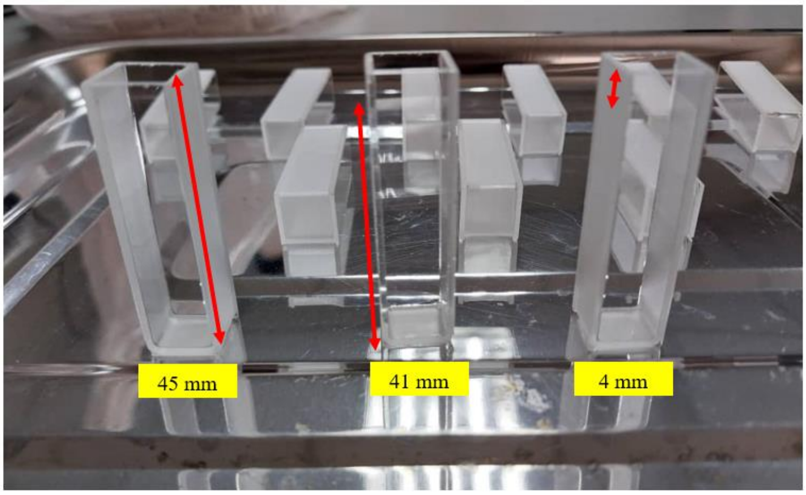


Figure 3.18 Measurement of cuvette height

The measurement of DDP is carried out using Ultraviolet-visible spectroscopy according to the following steps:

Step 1: Turn on the software and UV – V is spectroscopy. Wait until the UV – V is spectroscopy is ready before performing the measurement.

Step 2: Press “Enter” and “PC Control” to control UV – V is spectroscopy using the software.

Step 3: Press the “Connect” button in the software to connect the software with UV – V is spectroscopy.

Step 4: The cuvette containing the insulating oil (NEI) before aging will be placed in the cuvette reference and sample place, as shown in Figure 3.19.

Step 5: Close the cover and press auto zero until the absorbance and wavelength values become zero.

Step 6: Set wavelength to 360 – 600nm.

Step 7: Baseline will be pressed as the baseline for this oil specimen to be recorded.

Step 8: The cuvette containing the aging insulating oil (NEI) will be placed in the cuvtte sample place and press start to obtain a graph of absorbance, a.u versus wavelenth, nm.

Step 9: Save the obtained graph in the form of a point pick table.

Step 10: Repeat step 8 and step 9 for SE.

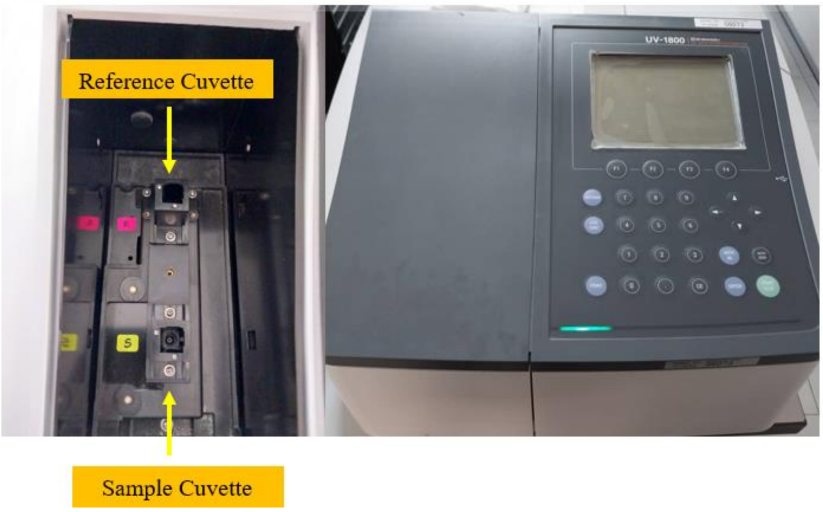
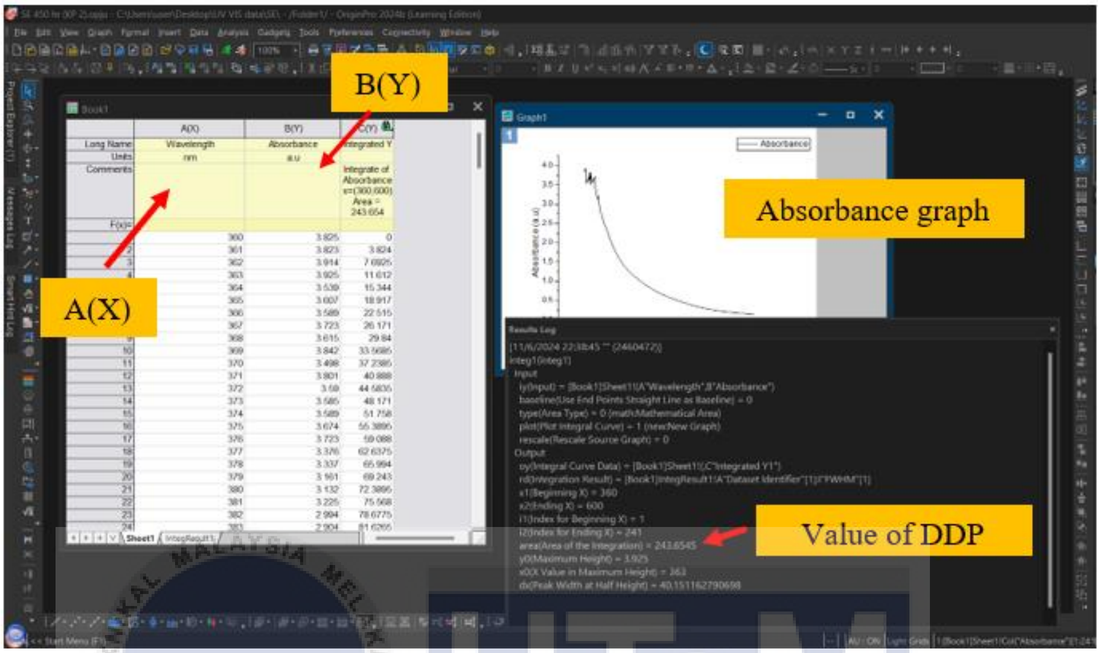


Figure 3.19 Ultraviolet-visible spectroscopy

The DDP value of insulating oils will be obtained using Microsoft Origin. The steps are:



	A(X)	B(Y)	C(Y)
Long Name	Wavelength	Absorbance	Integrated Y
Units	nm	a.u	
Comments			Integrate of Absorbance x=[360,600] Area = 243.654
F(x)=			
1	360	3.825	0
2	361	3.823	3.824
3	362	3.914	7.6925
4	363	3.925	11.612
5	364	3.539	15.344
6	365	3.607	18.917
7	366	3.589	22.515
8	367	3.723	26.171
9	368	3.615	29.84
10	369	3.842	33.5685
11	370	3.498	37.2385
12	371	3.801	40.888
13	372	3.59	44.5835
14	373	3.585	48.171
15	374	3.589	51.758
16	375	3.674	55.3895
17	376	3.723	59.088
18	377	3.376	62.6375
19	378	3.337	65.994
20	379	3.161	69.243
21	380	3.132	72.3895
22	381	3.225	75.568
23	382	2.994	78.6775
24	383	2.904	81.6265

```
[11/6/2024 22:38:45 "" (2460472)]
integ1(integ1)
 Input
  iy(Input) = [Book1]Sheet1!(A"Wavelength",B"Absorbance")
  baseline(Use End Points Straight Line as Baseline) = 0
  type(Area Type) = 0 (math:Mathematical Area)
  plot(Plot Integral Curve) = 1 (new:New Graph)
  rescale(Rescale Source Graph) = 0
 Output
  oy(Integral Curve Data) = [Book1]Sheet1!(,C"Integrated Y1")
  rd(Integration Result) = [Book1]IntegResult1!A"Dataset Identifier"[1]:J"FWHM"[1]
  x1(Beginning X) = 360
  x2(Ending X) = 600
  i1(Index for Beginning X) = 1
  i2(Index for Ending X) = 241
  area(Area of the Integration) = 243.6545
  y0(Maximum Height) = 3.925
  x0(X Value in Maximum Height) = 363
  dx(Peak Width at Half Height) = 40.151162790698
```

Figure 3.20 Microsoft Origin

Step 1: Insert the saved data (A(X) for wavelength, nm and B(Y) for absorbance (a.u) as shown in Figure 3.20.

Step 2: Go to plot and select line.

Step 3: Go to analysis and select mathematics then select integration.

Step 4: Record the obtained value of Dissolved Decay Product (DDP).

Step 5: Repeat Step 1 until Step 4 with another data to make a comparison.

3.4 Part C: Thermal Ageing Process

After completing the procedures in Part A and testing in Part B at 0 hour, all the sloid insulation (TUK, KP, gaskets and pressboard) are immersed in the insulating oils (NEI and SE) for 24 hours. This is to make sure all the solid insulation are soaked and immersed well in the insulating oil. The immersion process will be starting with inserting 400 ml of insulting oil in the ageing bottle, following with insulating papers, gasket, pressboard and metal catalyst, as shown in Figure 3.21. After immersing for 24 hours, all the samples will be placed in the oven and the thermal ageing process begins (Figure 3.22). Then temperature oven is set to 120℃ for 450 hours. In order to achive the 450 hours, the thermal ageing process will be conducted for days.

Figure 3.21 Immersion process for 24 hours

Figure 3.22 Thermal ageing process

3.5 Summary

This chapter has discussed the methodology of this research. Firstly, the flow of the experiment is explained in Section 3.1. In Section 3.2, a detailed explanation regarding the preparation of for solid insulation and insulating oils has been presented. The method of assessing the insulation system degradation has elaborated in Section 3.3. Lastly, the thermal ageing process has been explained and presented in Section 3.4.

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1 Introduction

This chapter will briefly describe the results of this research. Initially, the results of the physical test will be explained in Section 4.2. Section 4.3 will briefly describe the results of the electrical test. Lastly, Section 4.4 explains the detailed results of the chemical test of this research.

4.2 Physical Test

Section 4.2.1 presents the obtained weight of kraft paper (KP), thermally upgraded kraft paper (TUK) and pressboard (before and after drying process in convection oven). Section 4.2.2 reveals the results of tensile strength for KP and TUK before as well as after the ageing process. Section 4.2.3 describes the shore hardness of NBR gasket before and after the ageing process. Lastly, Section 4.2.4 illustrates the visual conditions of the pressboard.

4.2.1 Weight of Insulating Paper and Pressboard

Figure 4.1 shows the weight of KP (160 pcs), TUK (200 pcs) and pressboard (20 pcs) before and after drying process meanwhile Figure 4.2 represents Δ value of weight of the papers and pressboard. The Δ represents the amount of weight reduced after the drying process. The weight of KP decreased by 3.925g from 69.378g to 65.453g while the weight of TUK decreased by 3.63g from 85.312g to 81.682g. In the meantime, the pressboard’s weight decreased by 4.978g from 36.467g to 31.489g. The significant decrement in the weight of paper and pressboard revealed that initially, there was a presence of water in both insulations.

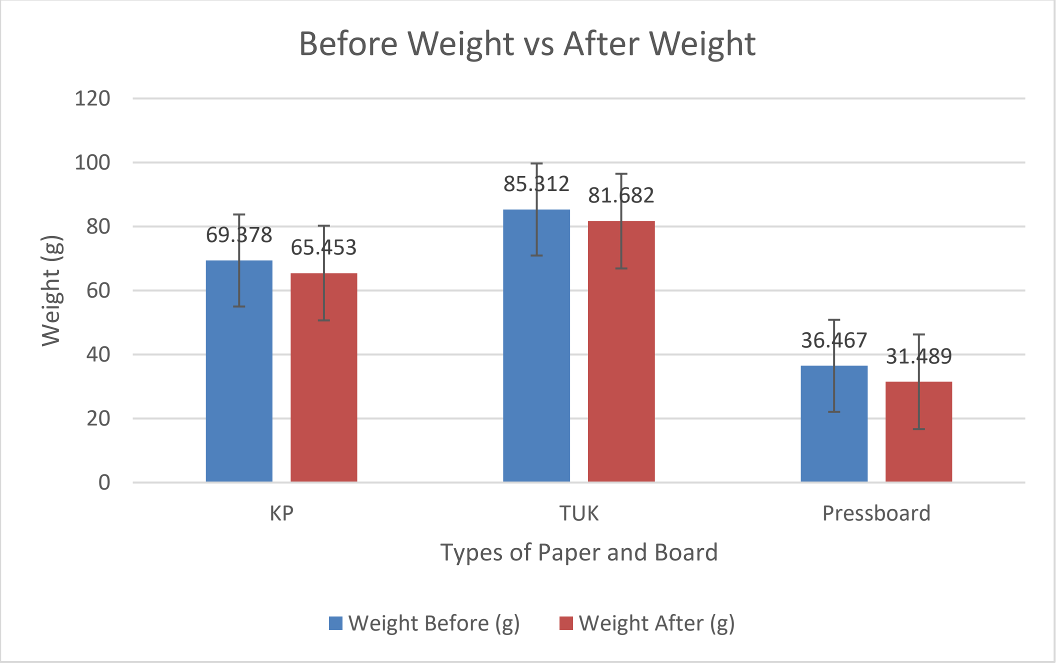


Figure 4.1 Graph for weight of KP, TUK and pressboard before and after drying process

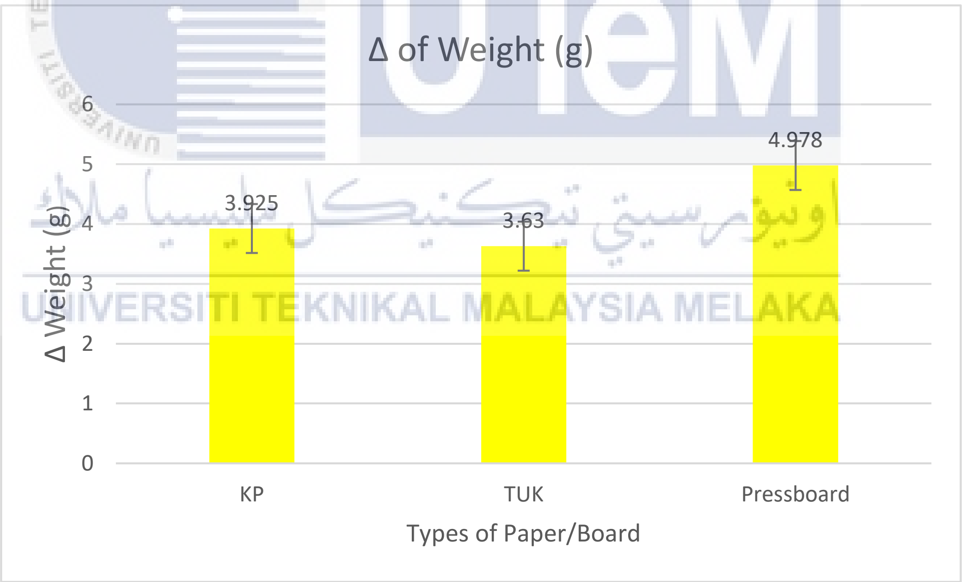


Figure 4.2 Difference in weight of KP, TUK and pressboard

4.2.2 Tensile Strength Test

This tensile strength is conducted on KP and TUK. The initial tensile strength of KP is 112.31Mpa while the initial tensile strength of TUK is 49.39Mpa. Figure 4.3 shows the Δ value of TUK and KP in NEI and SE.

Based on Figure 4.3, the Δ value of TUK in NEI (Sample 1 = 5.54MPa and Sample 2 = 2.3Mpa) is smaller than the Δ value of KP in NEI (Sample 1 = 14.24MPa and Sample 2 =16.12MPa). The same trend happened in SE where the Δ value of TUK in SE (Sample 1 = 6.95MPa and Sample 2 = 8.66Mpa) is smaller than the Δ value of KP in NEI (Sample 1 = 14.12Mpa and Sample 2 =12.21MPa). This proves the degradation rate of TUK is slower compared to KP because TUK is more resilient to moisture and high temperature. Hence, TUK tensile strength after thermal ageing is better than KP.

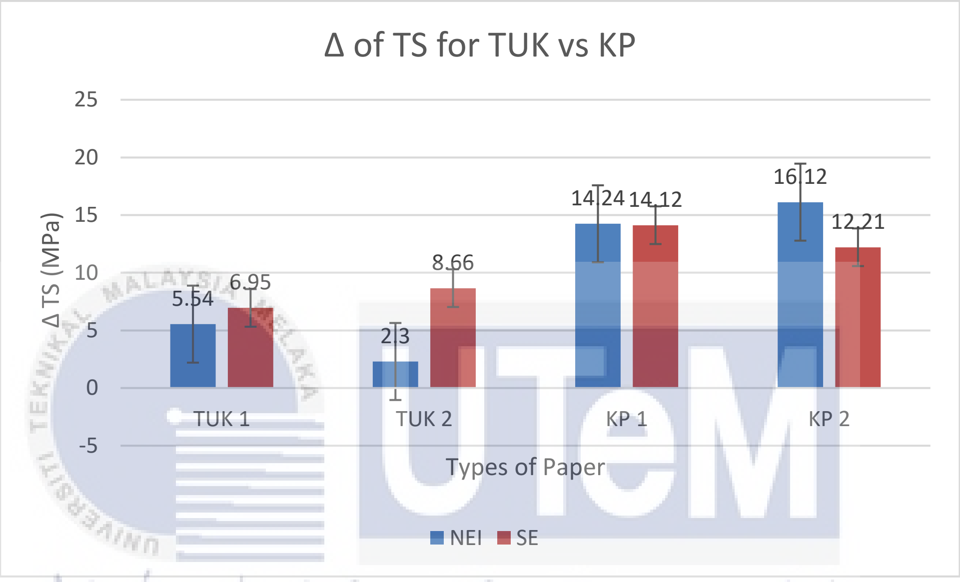


Figure 4.3 Δ of tensile strength for TUK and KP

Figure 4.4 and Figure 4.5 shows the comparison of KP and TUK in NEI and SE before and after ageing process. In both NEI and SE, the colour of TUK after ageing is still similar to its initial state because of its chemical changes that increase its resistance to thermal degradation [37]. These modification slow down the rate of cellulose decomposition and prevents the formation of water. However, for KP, its colour in both NEI and SE changed because the cellulose fibres in KP undergo depolymerization (long chains of cellulose molecules break into shorter chains) [62] when it exposes to heat for a longer period of time (thermal ageing).

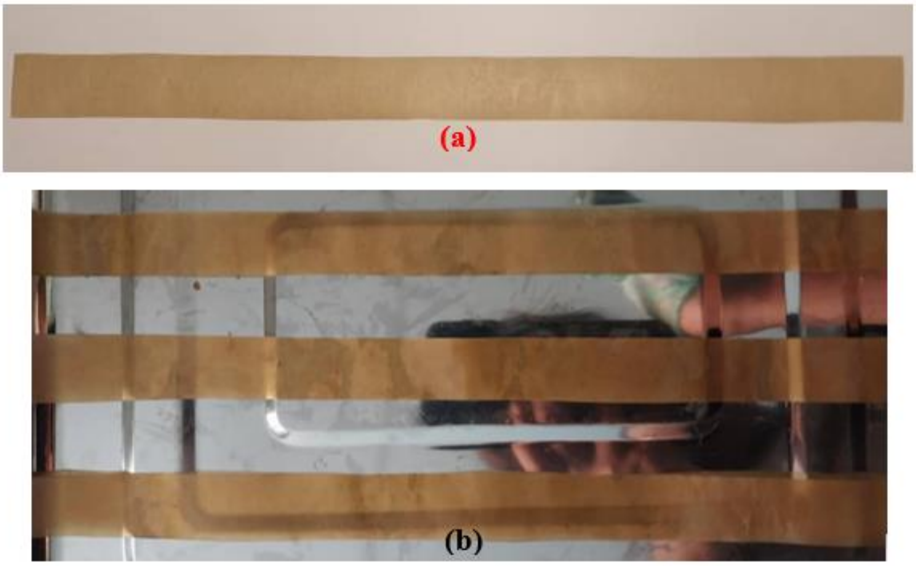


Figure 4.4 (a) TUK before ageing (b) TUK after ageing

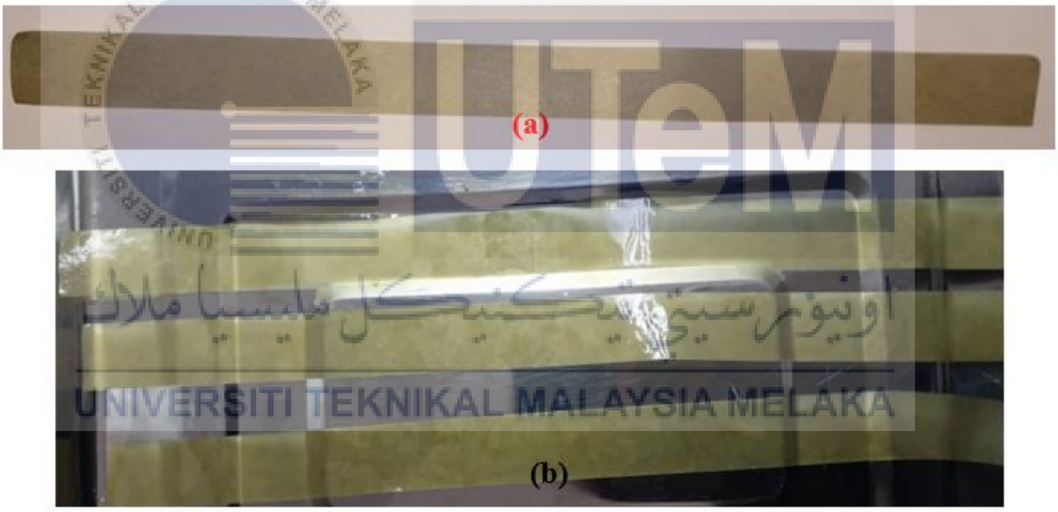


Figure 4.5 (a) KP before aging (b) KP after ageing

4.2.3 Shore Hardness of Gasket

This test is conducted on 8 NBR gaskets since this research has 8 samples. The readings are taken five times to obtain the averange readings to improve the measurement accuracy. The initial values of shore hardness is recorded and the values are in range between 67 HA and 74 HA. Figure 4.6 shows the Δ value of shore hardness of NBR gasket in NEI and SE. Δ value indicates the changes of shore hardness of gaskets after ageing process.

By comparing the Δ of shore hardness of NBR gaskets in both insulating oils, the samples in NEI (Sample 1 = 53.6HA, Sample 2 = 56 HA, Sample 3 = 59.1 HA, Sample 4 = 60.5 HA) is smaller than the samples in SE (Sample 1 = 70.5HA, Sample 2 = 70.2 HA, Sample 3 = 69.7HA, Sample 4 = 67HA). The higher Δ value shows the degradation of NBR gaskets after thermal ageing is large. Based on Δ of shore hardness, TUK effect on gaket in NEI is not significant compared to TUK effect on gasket in SE. The gasket immersed in NEI shows better results because NEI is derived from the vegetable oils. Hence, the chemical compunds in NEI do not influence the properties of gasket material.

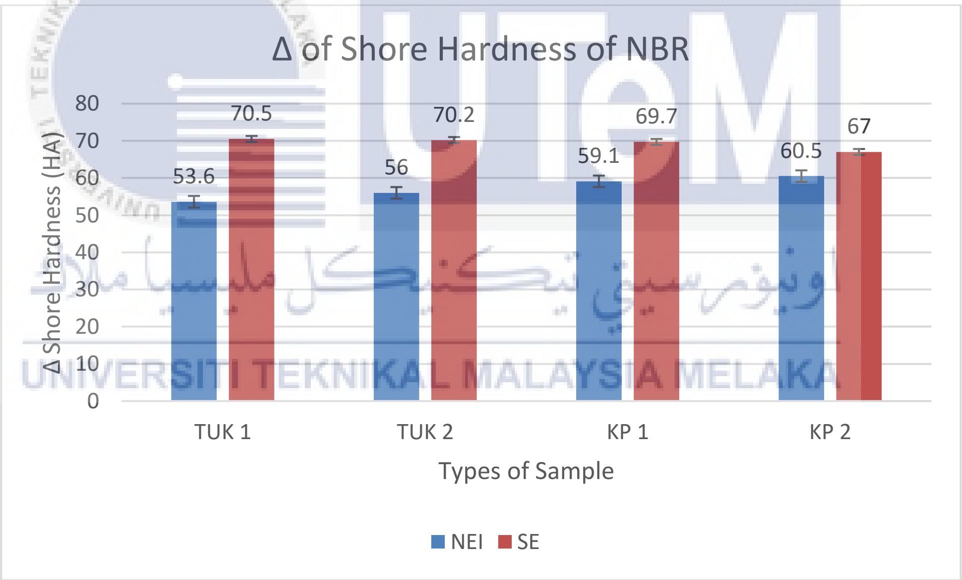


Figure 4.6 Δ of shore hardness of NBR gaskets in NEI and SE

Figure 4.7 shows the comparison of NBR gaskets; (a) initial condition (before aging), (b) final condition in NEI and (c) final condition in SE (after ageing). The condition of gasket in SE (c) is brittle and crake meanwhile the surface of gasket in NEI (b) is not brittle and crake. The surface of the gaskets that comes out has seeped into the insulating oil and caused the insulating oil become darker.

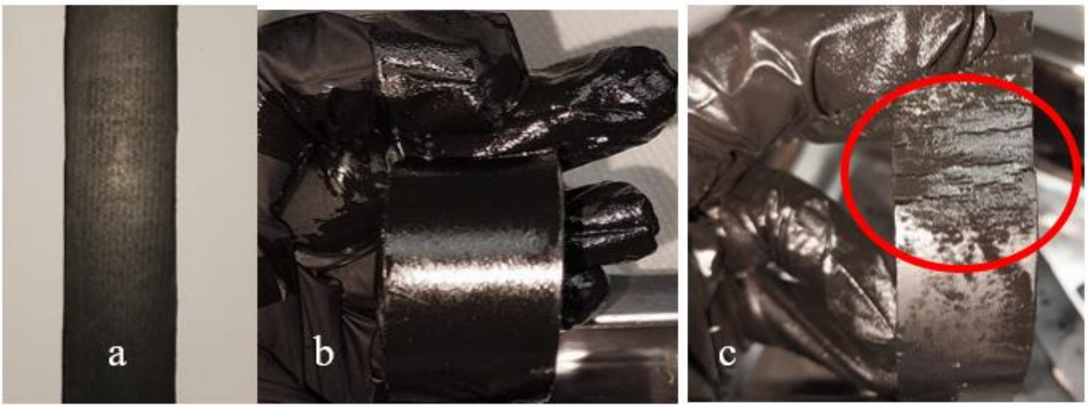


Figure 4.7 The surface of NBR gasket (a) initial condition (before ageing), (b) final condition in NEI (after ageing) and (c) final condition in SE (after ageing)

4.2.4 Visual Observation of Pressboard

Figure 4.8 shows the condition of pressboard before and after ageing process in NEI and SE: (a) shows the initial state of pressboard, (b) displays the condition of pressboard immersed with TUK after the ageing process and (c) illustrates the condition of pressboard immersed with KP after the ageing process. The colour of the pressboard changed from milky white to brown and there is no colour difference for the pressboard after the ageing process in NEI and SE. This colour changes indicates the temperature plays a vital role in degrading the condition of pressboard. Sludge that generated from the ageing process has been absorbed into the pressboard and it can reduces the properties of the pressboard.

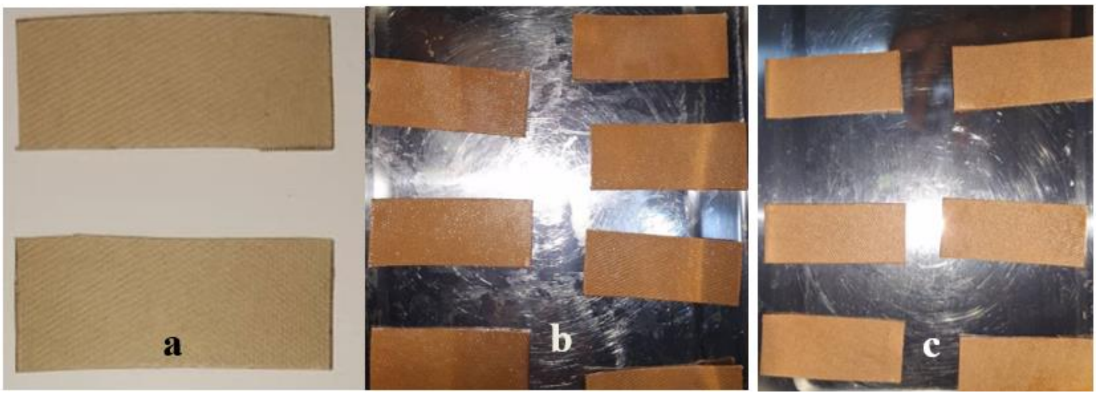


Figure 4.8 (a) Initial condition of pressboard (b) Final condition of pressboard immersed with TUK (c) Final condition of pressboard immersed with KP

4.3 Chemical Test: Dissolve Decay Product (DDP)

Figure 4.9 represents the colour of SE for a) before ageing process, b) after ageing process (immersed with KP) and c) after ageing process (immersed with TUK). Before the ageing process (a), the colour of SE is clear because SE is still in good condition without any contamination. Meanwhile, the colour of SE in (b) and (c) clearly showed that the colour of SE after the ageing process becomes brown yellowish. This is due to the presence of dissolve decay product in SE due to the reaction between solid insulation (i.e, gasket, KP, TUK and pressboard) and insulating oil itself. However, the colour of SE in (b) is darker compared to the (c). This shows that the dissolve decay product of SE immersed with KP is higher than SE immersed with TUK.

Figure 4.10 shows the colour of NEI for a) before ageing process, b) after ageing process (immersed with TUK) and c) after ageing process (immersed with KP). Before the ageing process (a), the colour of NEI is clear and bright green because NEI is still in good condition without any contamination. Meanwhile, the colour of NEI in (b) and (c) clearly showed that the colour of NEI after the ageing process becomes brownish. This is due to the presence of dissolve decay product in NEI due to the reaction between solid insulation (i.e, gasket, KP, TUK and pressboard) and insulating oil itself. However, the colour of NEI in (b) is lighter compared to the (c). This shows that the dissolve decay product of NEI immersed with TUK is lower than NEI immersed with KP. Interestingly, the colour for both SE and NEI immersed with TUK after the ageing process is lighter compared to the colour of SE and NEI immersed with KP.

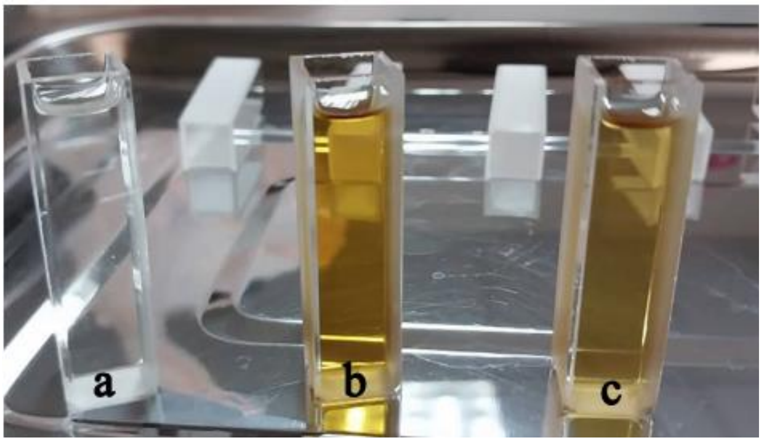


Figure 4.9 Colour of SE for a) before ageing process, b) after ageing process (immersed with KP) and c) after ageing process (immersed with TUK)

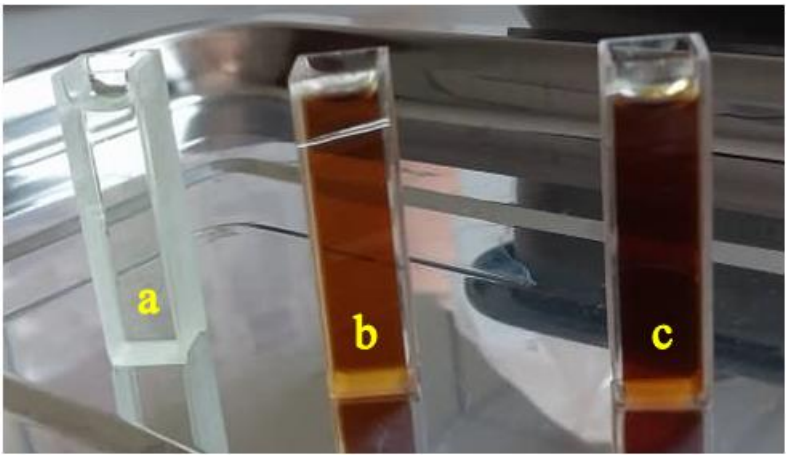


Figure 4.10 Colour of NEI for a) before ageing process, b) after ageing process (immersed with TUK) and c) after ageing process (immersed with KP)

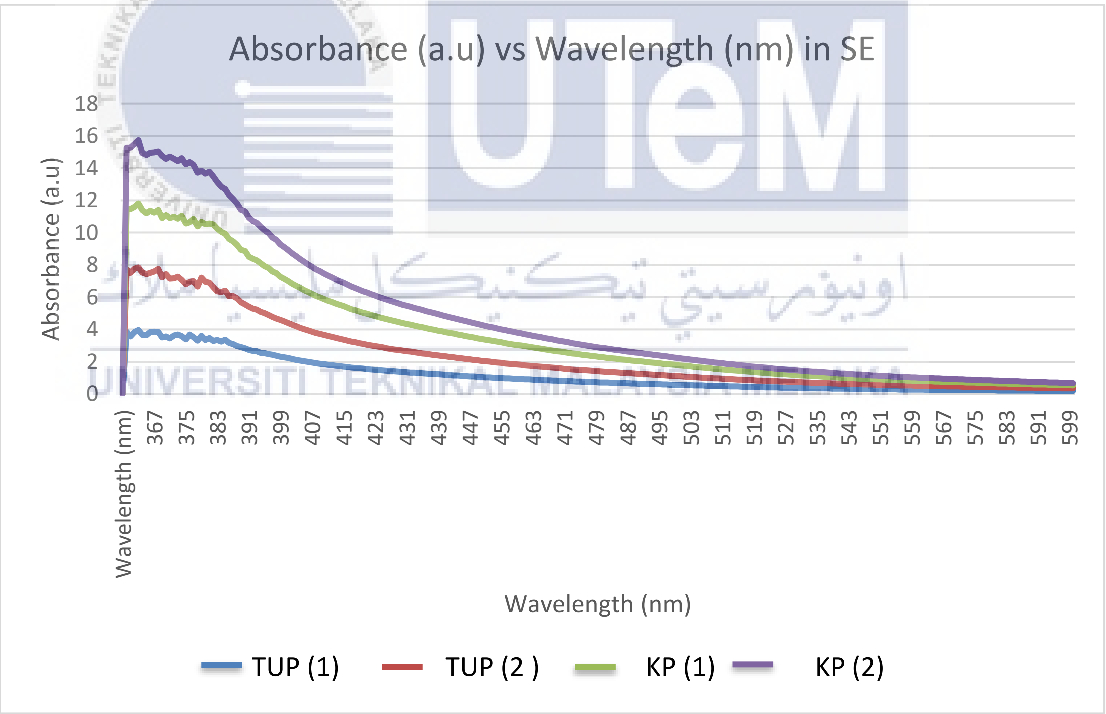


Figure 4.11 and Figure 4.12 shows the quantitative analysis to confirmed the qualitative analysis performed through visual observations. Based on

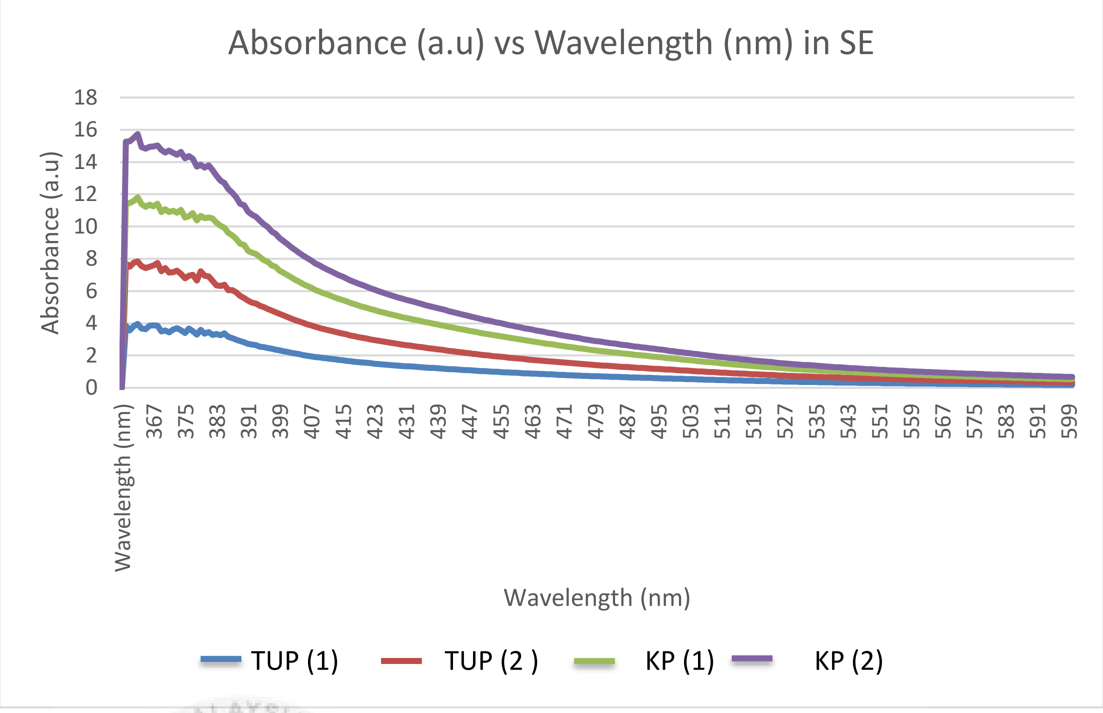


Figure **4.11**, the absorbance values in SE immersed with TUK has lower value compared to absorbance values in SE immersed with KP. The same trend also shown in Figure 4.12 where the absorbance values in NEI immersed with TUK is lower compared to the NEI immersed with KP. This absorbance value indicates the amount of DDP in insulating oil. Hence, the higher the level of DDP in the insulating oil, the higher the absorbance value. When the level of DDP is high, the insulating oil is more contaminated and lower the brerakdown voltage of the insulating oil. This proves that the amount of dissolve decay product in SE and NEI immersed with KP is higher than the SE and NEI immersed with TUK.

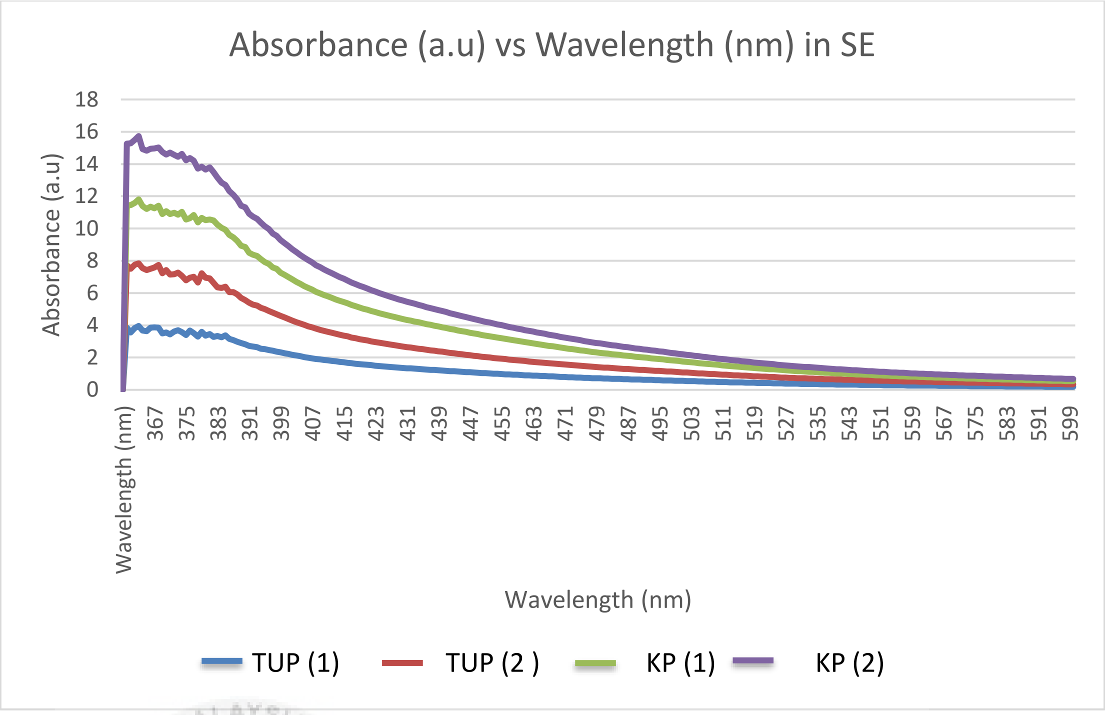


Figure 4.11 The absorbance characteristics in SE immersed with TUK and KP

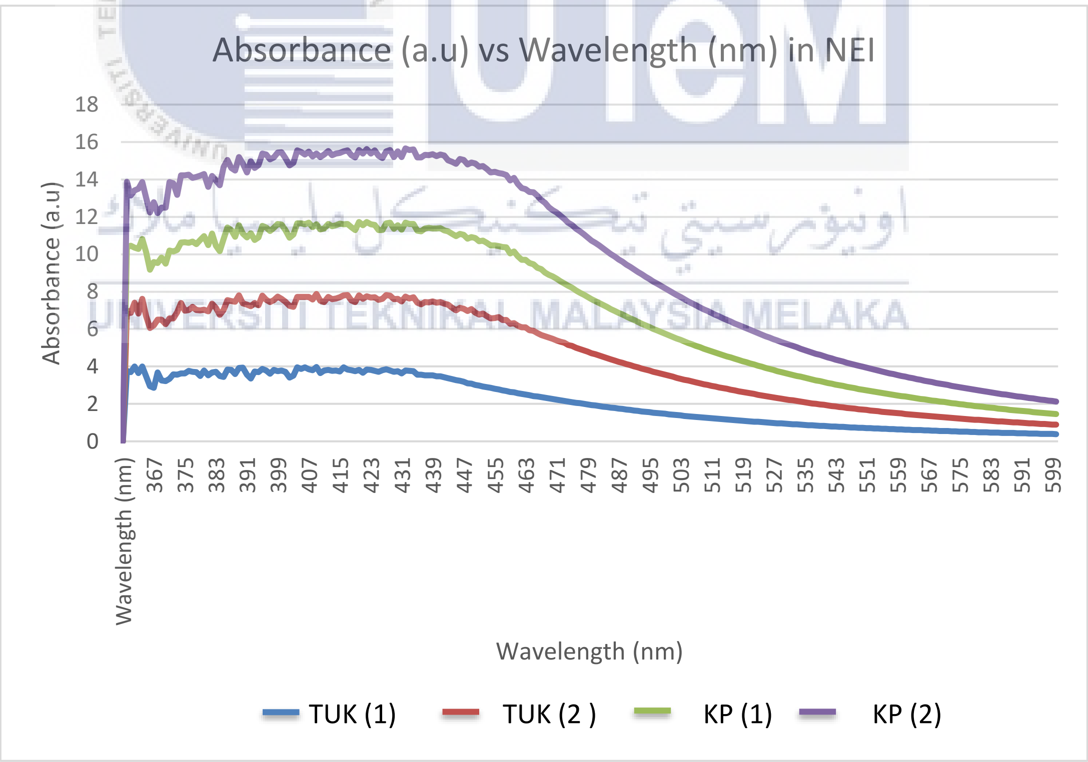


Figure 4.12 The absorbance characteristics of NEI immersed with TUK and KP

Figure 4.13 shows the DDP in SE and NEI after the ageing process. In general, new insulating oil is essentially transparent, no visual absorption can be seen [63]. Thus, the DDP value of insulating oil before the ageing process is 0. Based on obtained data, the DDP value when insulating oils immersed with TUK (Sample NEI TUK 1 = 512.774, Sample NEI TUK 2 = 590.5855, Sample SE TUK 1 = 276.9375 and Sample SE TUK 2 = 270.3545) is smaller compared to DDP value when SE and NEI immersed with KP (Sample NEI KP 1 = 608.6155, Sample NEI KP 2 = 629.4055, Sample SE KP 1 = 319.7775 and Sample SE KP 2 = 243.6545). According to the data, DDP values in all samples of NEI are higher compared to the samples in SE. The degradation of solid materials (gaskets, insulating paper and pressboard) and insulating oil influences the DDP in oil. When the solid materials degrade, water molecules as a by-product are released into the oil. NEI has lower tolerance to moisture compared to SE. Hence, the moisture from the solid insulations migrates into the NEI and accelerates degradation. As a result, the DDP value of NEI is higher than SE.

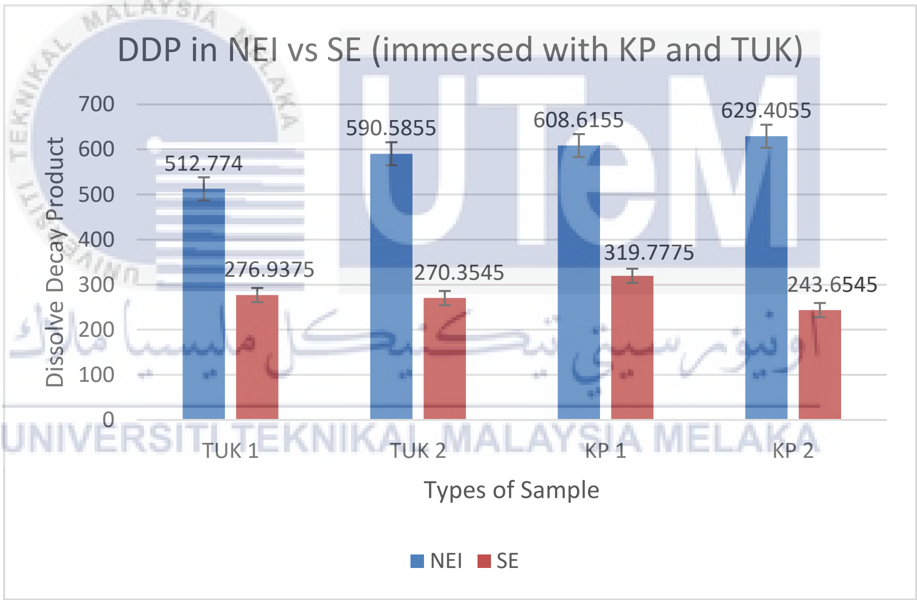


Figure 4.13 DDP value in NEI and SE

4.4 Electrical Test: Polarization Index Test (PI)

Figure 4.14 shows the results of polarization index test (PI) for all samples in NEI and SE (after ageing). The initial PI value for NEI is 1.27 meanwhile the initial PI value of SE is 1.75. After the ageing process, the final PI values of all samples in NEI and SE have reduced but not less than 0.9. The reduction in PI values indicates the insulation resistance in NEI and SE decrease after the ageing process. However, the insulation resistance of SE after the ageing process is better than NEI. This is because when the

NEI has unsaturated double carbon-carbon bonds that are vulnerable to oxygen attack. Hence, the oil can easily oxidize and produce acidic compounds and water. This will increase the conductivity of NEI and reduce its insulation resistance.

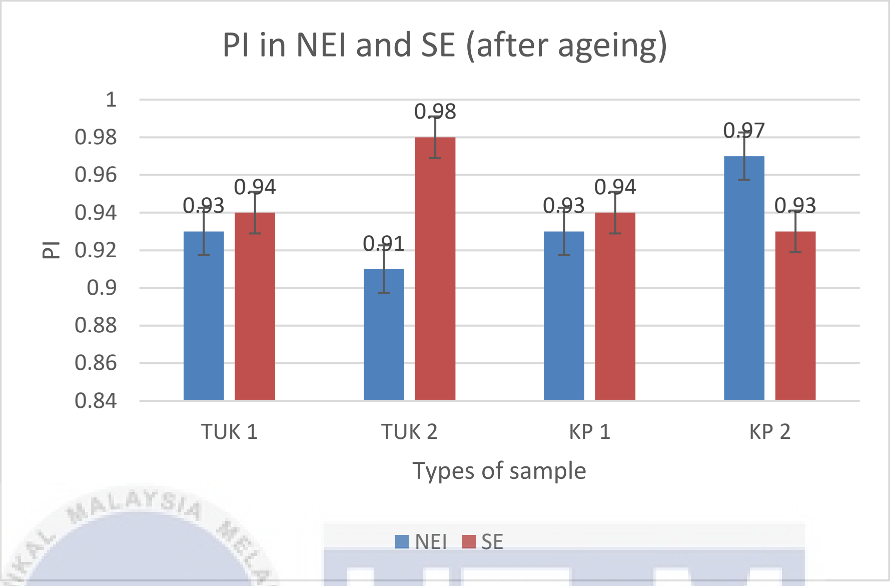


Figure 4.14 Results of polarization index in NEI and SE after the ageing process

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

In conclusion, the objective of this research study has been achieved. The changes of properties of insulation materials such as thermally upgraded kraft paper, kraft paper, pressboard, NBR gasket and insulating oil show changes for the before and after thermal ageing process. Thermal ageing process has greatly impacted the electrical, chemical and physical characteristics of both solid and liquid insulation. In comparison to kraft paper, thermally upgraded kraft paper shows better performance which has a good tensile strength and compatible in NEI and SE. This also proves the degradation rate of thermally upgraded kraft paper is slower than the kraft paper. By comparing the insulating oil, SE shows better performance than NEI in the aspects of electrical and chemical test. The DDP value in SE is lower than NEI and the insulation resistance of SE is still higher than NEI after the thermal ageing process. However, the condition and hardness of gasket is better in NEI compared to SE. Overall, thermally upgraded kraft paper as an insulating paper is very much compatible with both ester oils.

5.2 Recommendations

Further research should be carried out to identify the ways to improve the properties of NEI as better insulating oil than SE. This is because the main drawback of NEI is its poor oxidation stability. In order to improve its properties, study over a longer period of time at various temperatures should be carried out. By doing so, the possibility of NEI to perform well when immerse with TUK can be done while maintaining its properties Tests performed on insulating oil and material should not be limited and expanded to see the ability of the oil to maintain the performance of transformers.

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