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ABSTRACT

The availability of the raw materials needed to produce fibre is decreasing as demand for fibre increases over time. In an effort, to preserve natural biodiversity and improve waste management, this research aims to substitute available raw materials for wood fibres. Empty fruit bunch (EFB) is regarded as waste in the oil palm industry and is abundantly available as a renewable energy source, particularly in Southeast Asian countries. The primary objective of this study is to investigate the utilisation of EFB as a substitute for insulating paper in transformers. The morphology, degree of polymerization, tensile strength, thermal characteristics, permittivity, conductivity, and electrical properties (breakdown field strength and lightning impulse performance) of EFB were measured and compared to the propties of Kraft insulating paper. Using FESEM at a magnification of 500×, the morphological properties were examined. Based on FTIR measurement, the chemical bonding between Kraft and EFB samples varied slightly. Compared to EFB, Kraft-pulped insulating paper has a higher degree of polymerization and the ability to endure high temperatures. Furthermore, the breakdown field strength performance demonstrates that Kraft insulating paper is 20.30% higher than EFB insulating paper. In terms of tensile strength and lightning impulse, EFB insulating paper demonstrated comparable performance to conventional insulating paper. A new approach to the manufacturing of EFB insulating paper could result in improvements to the material’s insulation qualities.

CHAPTER 1

INTRODUCTION

Transformers are an important part of the equipment used to transmit and distribute electricity in small, medium, and large electrical distribution plants. It is a static device that transmits energy without frequency shift from one level to another. Transformer units' dependability is dependent heavily on the concept construction and reliability of their insulating system .

Presently in the electricity system, dry-type and oil-filled type transformers are most widely employed, with oil-filled transformers being more prevalent for distribution system.The available statistics on transformer failure indicate that the average lifespan of transformers approximately 18 years, which is almost half of the expected lifespan of 36 to 44 years, and that one-third of high voltage transformers have failed because of insulation system .

According to a statistical investigation of transformer accidents, the insulation failure of transformers is responsible for the majority, with oil–paper insulation failure being the most common cause . In a transformer, the solid insulation and insulating oil produce an inseparable insulation system. Paper, pressboard, and transformer board, which are composed of cellulose found in plants, are the most common solid insulation materials used in transformers. Since the 1890s, natural cellulose has been made to produce insulating paper and has been widely employed in all varieties of electrical equipment. Even in modern times, cellulose paper remains an important insulating product. The oldest transformer insulating paper was created from cotton fabric and paper coated or oil-boiling paper. In the 1920s, as transformer voltage class increased, cellulose-oil composite insulation of kraft paper-insulating oil emerged . Later, in the 1950s, synthetic materials have been produced and increasingly utilised in transformers. The performance of the composite insulating paper consisting of cellulose and synthetic material is likewise remarkable. It has been demonstrated that composite paper made from cellulose paper and polymer film exhibits excellent dielectric characteristics compared to pure cellulose paper .

Compared to composite insulating paper, e.g., Nomex types of insulating paper, natural cellulose insulating paper is less expensive, greener, and has a lower production cost. Because of the extensive length of natural cellulose, cellulose-based insulating paper has the advantages of strong mechanical strength and convenient size regulation. Besides, cellulose insulating paper has great electrical performance and excellent compatibility with transformers. The resistivity of dried cellulose is on the scale of 1018/cm, and dielectric strength is higher than the majority of dielectrics, reaching on the order of 2.5 million V/cm . Despite the various advantages of cellulose insulating paper, its performance will deteriorate irreversibly throughout the long-term operation of transformers because of a variety of elements, including temperature, electric field, humidity, oxygen, etc.

During the degradation of cellulose, the degree of polymerization decreases, resulting in the formation of different aged products. The mechanical and electrical qualities of cellulose insulating paper decrease gradually, and the life span of transformers will end when the cellulose insulating paper deteriorates . In 2001, Ferrito and Stegehuis [9] applied hightemperature fibres to improve cellulose insulating paper’s thermal ageing resistance and accelerated thermal ageing by severe overload cycles. It was discovered that conventional Kraft paper has lost the majority of its mechanical strength. Besides, with the rapid growth of the world’s power industry, the need for cellulose continues to increase, risking greater difficulty in terms of the shortage of softwood pulp. In addition to demanding a great deal of tree use, the production of paper has a negative impact on the environment and depletes the forest. Empty Fruit Bunch (EFB) is one example of a non-wood fibre resource that has the potential to be an effective substitute for the primary fibre resources used in the production of insulating paper.

The increase in production of EFB can be attributed to the fact that a growing number of countries, including Malaysia, Indonesia, Colombia, Ivory Coast, and Papua New Guinea, have begun to see the potential of palm oil, and are therefore harvesting it in mass quantities. Malaysia is the world's second-largest exporter of palm oil, following Indonesia, which supplies around 39 % of the world's palm crude oil production, and hence the palm oil sector is one of Malaysia's primary economic resources .

As one of the primary suppliers of palm oil, the feedstock for EFB is very inexpensive and readily available throughout the year. EFB contains a high percentage of cellulose, which can be utilised as a source for cellulose and cellulosic-derived. Cellulose has good mechanical strength and the ability to be elastic . EFB is produced when fruits are removed from oil palm bunches fruit (FFB) for oil extraction, leaving only the fruit's stem and spikelet as shown in Fig. 1. The combination of steam from the sterilising process of oil extraction and continued biological growth led to a high moisture content of up to 60% in the EFB . Similar to other natural fibres, EFB fibres comprise lignocellulosic fibres with cellulose (43-65%) and hemicellulose (17-33%) surrounded by a lignin (13-37%) matrix. The levels of lignin, cellulose, and hemicellulose were almost the same as those of softwoods and hardwoods, which means they could be used to make pulp and natural resource fibres

In this study, the capability and suitability of Empty Fruit Bunches (EFB), which is waste produced after the sterilised oil palm fruit are separated from the bunch stalk, has been investigated for the purpose of use as an alternative to cellulose insulation in transformer applications. Therefore, the morphology of EFB-based insulation paper as well as its degree of polymerization, tensile strength, thermal characteristics, permittivity, conductivity, and electrical properties are investigated (AC breakdown and lightning impulse breakdown strength). These findings are compared with the conventional insulating paper (Kraft insulating paper) that is commonly used in the transformer industry.

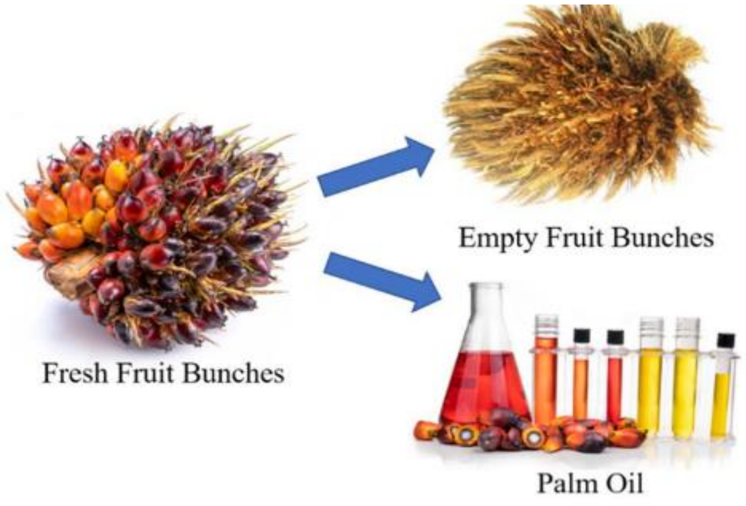

FIGURE 1.1 By-product/ biomass from the oil palm tree.

CHAPTER 2

LITERATURE REVIEW

"Evaluation of mechanical properties and aging behavior of oil palm empty fruit bunch paper composite insulation for power transformers" by J. M. L. Tavares et al. (2017).This study evaluated the mechanical properties and aging behavior of paper composite insulation made from EFB for use in power transformers. The results showed that the EFB paper composite had good mechanical properties and could withstand aging over time. However, the authors noted that further research was needed to optimize the insulation's electrical properties.

"The effect of oil palm empty fruit bunch fiber content on the physical and mechanical properties of paper for electrical insulation" by N. N. Nor et al. (2017).This study investigated the effect of EFB fiber content on the physical and mechanical properties of paper for electrical insulation. The results showed that increasing the EFB fiber content improved the paper's mechanical properties, but decreased its dielectric strength. The authors concluded that a balance needed to be struck between the mechanical and electrical properties of the insulation.

"Evaluation of the suitability of oil palm empty fruit bunch paper as insulation in distribution transformers" by S. S. Sivarao et al. (2016).This study evaluated the suitability of EFB paper as insulation in distribution transformers. The results showed that EFB paper had good mechanical properties and could withstand electrical stresses. However, the authors noted that further research was needed to optimize the insulation's thermal properties.

"Properties and application of oil palm empty fruit bunch fiber-reinforced composite paper for transformer insulation" by J. Li et al. (2015).This study investigated the properties and application of EFB fiber-reinforced composite paper for transformer insulation. The results showed that the composite paper had good mechanical, electrical, and thermal properties, making it a promising material for transformer insulation.

CHAPTER 3

PROPOSED SYSTEM

The Xuchang Yuneng Electrical Insulation Material Co. Ltd. has processed and manufactured the Kraft insulating paper. The sample of Empty Fruit Bunches (EFB) consisted of fibrous strands that were squeezed to extract the palm oil and eliminate moisture, respectively. Following this, the strands were shredded, then dried, and finally bales were formed. To prepare EFB bundles for the pulping process, short fibres were removed from the bundles, washed, and then pre-steamed. The pulping process has been done using a rotary digester. EFB has been fed into the rotary digester cylinder and then cooked for eight hours, while Sodium Hydroxide (NaOH), a strong alkali, has been utilized to remove the dissolved lignin from the fibre surface. Following the pulping procedure, the pulp has been washed to remove pulping chemicals and screened with a fibre Somerville fractionator.

The pulp was then rinsed with distilled water, dried using a spin dryer, and stirred to get a homogeneous consistency. In accordance with the TAPPI Standard T248 , the EFB pulp is beaten using a NORAM PFI mill. The procedure of beating is the most basic phase in the manufacturing of paper because it guarantees that the pulp that is generated from beaten stock is sturdy, thick, and has a firm consistency. In each beating run, a 24 g sample of pulp was collected from a representative sample, and the disintegrator tank was rotated at 2,000 rpm while 2 litres of water were added. This has been done in order for the bundled pulp to be dispersed. After the procedure was complete, the disintegrated pulp was loaded into the PFI mill, which rotates at various speeds. This investigation will utilize a pound with a speed of rotation of 12,000 rpm. Prior to any testing or measurements, the handsheet was couched, pressed, and dried for 24 hours at a temperature of 23 ◦C±1 ◦C and relative humidity of 50%±2.

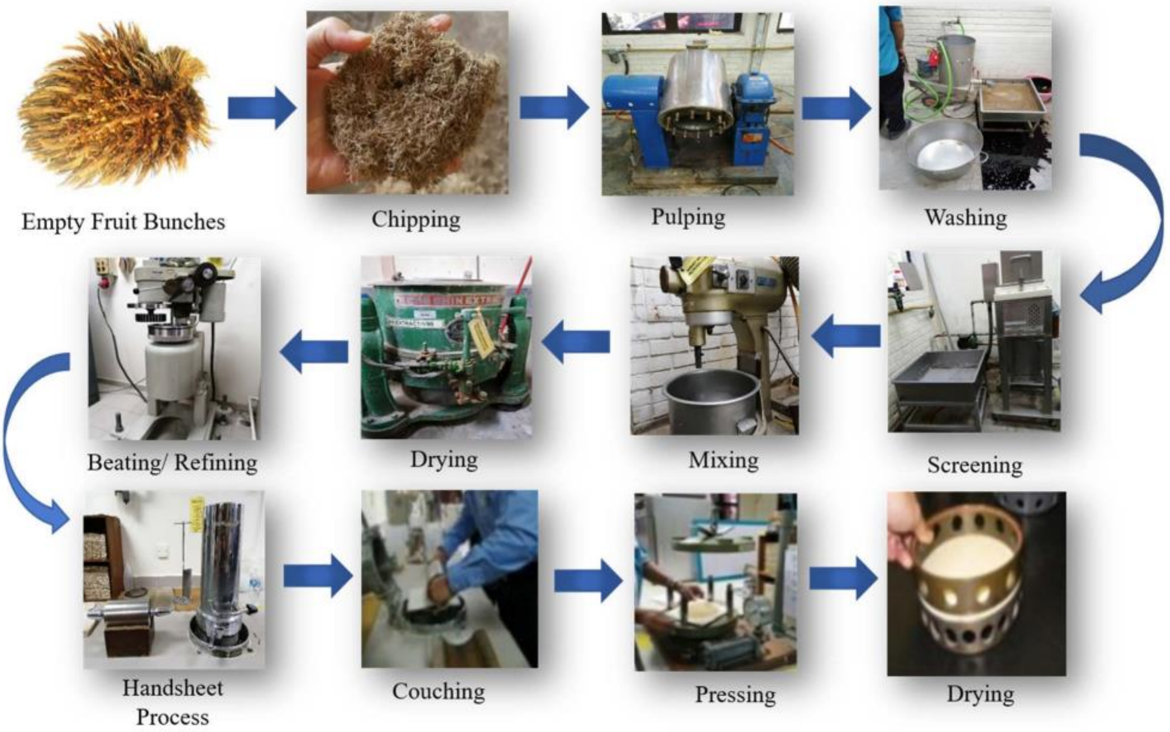

FIGURE 3.1 Process for producing paper from empty fruit bunches

Insulating paper made from Empty Fruit Bunches (EFB) was cut to width and length parameters of 70 mm and 120 mm, respectively. The EFB insulating papers range in thickness from 0.08 mm to 0.11 mm. The thickness and width of Kraft paper measuring 0.09 mm and 70 mm with a weight of 52 g/m2 were also evaluated for comparison purposes. Individually, the Kraft paper was cut to a length of 120 mm. In this investigation, all papers were impregnated with petroleumbased mineral oil (MO) supplied by Hyrax Sdn. Bhd. Company.

Field Emission Scanning Electron Microscope (FESEM) has been utilised to examine the morphologies of Kraft and EFB insulating papers at a 500x magnification. FESEM is a cutting-edge technique for capturing images of the microstructure of materials. Each sample had been plated with gold and then cut into 9 mm × 9 mm squares before the experiment was conducted. FESEM is usually done in a high vacuum because gas molecules tend to mess up the electron beam and the secondary and backscattered electrons that are used to make an image. With a resolution of 2 cm^{-1} , Fourier Transform Infrared Spectroscopy (FTIR) is utilised to obtain an infrared spectrum of insulating paper samples' absorption or emission, ranging from 4000cm^{-1} to 650cm^{-1} .

The Attenuated Total Reflection (ATR) mode of the FTIR spectra enables the user to simultaneously collect high-resolution spectral data over a large spectral range. The ATR method is particularly effective for determining the spectra of insulating paper samples that absorb infrared light to a notable degree. The proportion of the entirely reflected light that is attenuated is caused by the insulating paper samples absorbing radiation of a specific frequency. Typically, the laser beam will penetrate the sample between 0.5 and 31 μm. The degree of polymerization (DP) is the number of monomer units present in the molecule. It can be determined by dividing the total molecular weight of a polymer by the total molecular weight of the repeat unit. For excellent mechanical qualities, a higher DP is particularly applicable . In order to measure the DP using the viscometric method, 25 mg of milled paper sample was placed in a 150 mL Erlenmeyer flask with a thin neck and 22.5 mL of distilled water was added. Then, the fluid is manually shaken to disperse and completely soak the paper. Following that, 22.5 mL of Cupriethylenediamine solution was added, and the insulating paper samples were magnetically agitated for at least three hours until entirely dissolved. The resulting solution was subsequently allowed to remain at 20◦C ± 0.1◦C for one hour. The solution was then delivered to the viscometer's reservoir for measurement. According to IEC 60450 , three assessments are performed on each sample, and DP is calculated. In accordance with IEC 60641 , the tensile strength of insulating paper is measured using the Zwick RoellZ005 testing machine with 5kN load in tensile/ compression, accuracy class 0.5 and crosshead speed from 0.0005-1500 mm/ mi. The machine was built with tensile grips, and the TestXpert II software was utilized for test setup and data post-processing. In this experiment, the test's measuring gap length was adjusted to 100 mm±1 mm. The sample of paper had a length of 100 mm and a width of 15 mm. The speed of the crosshead has been set to 20 mm/min. This experiment has been conducted a temperature 23◦C±1 ◦C and a relative humidity of 50%±2%. Thermogravimetric analysis (TGA) was used to analyse the thermal properties and decomposition features of insulating paper samples. The measurements were carried out with a Perkin Elmer STA 8000 equipped with the Pyris software and a constant 100 ml/min nitrogen gas flow.

The samples were initially cut into small pieces weighing between 10 and 25 mg for TGA analysis. It was then stabilised for 5 minutes at 30◦C before being heated to 800◦C at a rate of 10◦C/min. As part of this investigation, impedance analyzer equipment was used to determine the relative permittivity and conductivity of insulating paper samples. Impedance analyzers assess frequency-dependent electrical impedance. This involves measuring current and voltage phase-sensitively while varying the measurement frequency. This incorporates phase-sensitive measurements of voltage and current applied to a sample while the measurement frequency is altered. Impedance analyzers provide highly precise impedance measurements with a basic tolerance of up to 0.05% and a frequency measurement range of µHz to GHz . Within the measured impedance values are absolute impedance, the real and imaginary components.

On the basis of a replacement circuit model, model-derived impedance parameters including conductance, inductance, and capacitance are computed and displayed. When referring to insulating materials, the electrical breakdown capability of the material is of great concern. Therefore, the electric breakdown field strength for Kraft and EFB insulating paper must be conducted in accordance with IEC 60243 specifications .

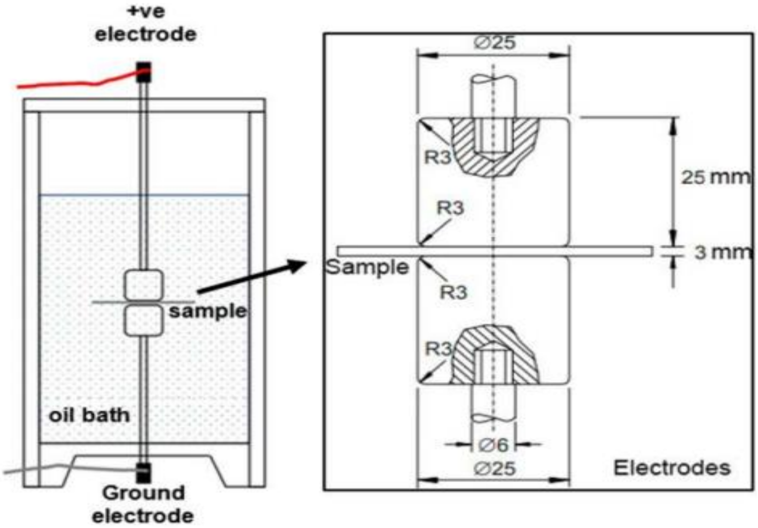

FIGURE 3.2 The test cell designed and produced specifically for AC and lightning impulse breakdown tests

Two distinct types of stainless steel with their edges rounded to a 3 mm radius make up electrodes that are equivalent to one another. The specific test cell design that was used for this test is shown in Fig. 3.2, with 25 mm diameter electrodes. A total of ten distinct breakdowns have been obtained for each test. Initially, the MO was filtered three times with a 0.2 µm pore size Nylon membrane filter. To remove the moisture content, the filtered MO and insulating paper samples were dried in a vacuum oven at 90◦C for 48 hours. Then, the dried insulating papers are impregnated with dried MO for twenty-four hours at 90◦C in a vacuum oven, with a weight ratio of twenty to one . The lightning breakdown strength (LI) test has been conducted using the identical test cell depicted in Fig. 3. However, a different configuration is employed, beginning with a DC charging unit that is connected to an impulse voltage generator and a test cell. Using an impulse generator FIGURE 3.2 The test cell designed and produced specifically for AC and lightning impulse breakdown tests from TERCO, a standard lightning impulse of 1.2/50 µs has been applied. Then, the capacitive voltage divider with weak damping is connected to a generator for measuring the fullwave voltage of the lightning impulse. The test begins with a charging voltage of 10 kV and gradually increases by 1 kV until breakdown occurs. Continue to half the breakdown voltage with a steady 2 kV increase until breakdown occurs. In accordance with IEC 60243-1 , the minimum required thickness of insulating paper for this study is 3 mm.

CHAPTER 4
RESULT AND DISCUSSION

A. MORPHOLOGY CHARACTERIZATION

The surface morphologies of Kraft and Empty Fruit Bunches (EFB) insulating paper as revealed by FESEM are depicted in Figure 4.1.The micrographs show that the surfaces of both Kraft and EFB fibres are relatively smooth and flat, and their tubular forms have been slightly elongated. This is because the refining phase in the papermaking process collapses the lumen and smoothes the surface of the fibres. However, it is noticed that Kraft cellulose is denser and has lower airflow resistance than EFB cellulose. The surface of Kraft insulating paper is also considerably denser compared to EFB insulating paper, and the barriers between the strong lignocellulose clusters are blurred, which may reduce the pore count. Consequently, the bonding strength of the cellulose cluster increased, resulting in an increase in tensile strength.

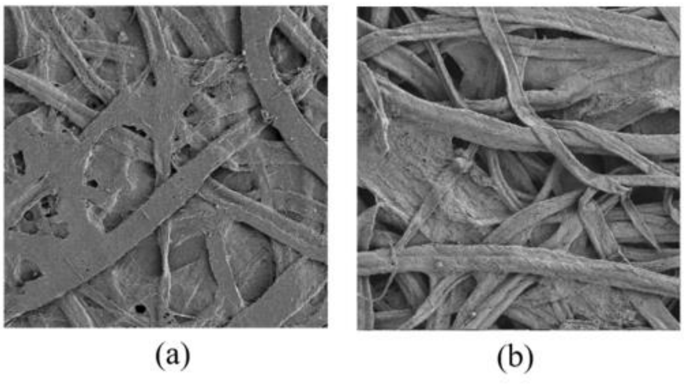

FIGURE 4.1 Morphologies of (a) Kraft and (b) Empty Fruit Bunches cellulose

This study examines FTIR analysis to determine the functional group of Kraft and EFB insulating paper. The FTIR spectrum is typically separated into three sections based on wavenumber: less than 400 cm^{-1} , 400-4000 cm^{-1} , and 4000-13000 cm^{-1} . The wavenumber range between 400 and 4000 cm^{-1} is the most prevalent for sample analysis and is further subdivided into four regions: the single bond region (2500-4000 cm^{-1}), the triple bond region (2000-2500 cm^{-1}), the double bond region (1500-2000 cm^{-1}) and the fingerprint region (600-1500 cm^{-1}). The appearance of peaks at around ∼3340 cm^{-1} and ∼2906cm^{-1} in single bond region for Kraft and EFB insulating paper may correspond to the stretching of -OH bonding and symmetrical stretching of -CH bonding. A wide absorption band between ∼3650 cm^{-1} and ∼3250 cm^{-1} , indicates a hydrogen bond and confirms the presence of hydrate (H_2O), hydroxyl (OH), ammonium (NH_4), or amino (NH_2). Both insulating papers are observed to have a complete absence of peaks in the triple bond region. In Kraft insulating paper, there is an absorption peak at ∼1650 cm^{-1} for the double bond region, which corresponds to carbonyl compounds containing the carbonyl group C=O bonding. In addition, the absorption peak near ∼1448 cm^{-1} in Kraft and EFB insulating paper is attributed to the bending of the -CH methyl group. The stretching of the CO-O-CO group is indicated by the presence of a high absorption peak in the region approximately at ∼1040 cm^{-1} band, which may be found in both Kraft and EFB insulating paper. Focusing on EFB insulating paper, a medium absorbance peak is found at 1639.90 cm^{-1} , however Kraft paper appears to lack this absorbance peak, which indicates stretching of C=N organic compounds.

B. DEGREE OF POLYMERIZATION

The degree of polymerization (DP) test is one of the most effective methods for determining the extent of cellulose paper deterioration and remaining life. The cellulose molecule is composed of a long chain of glucose rings, which determine their mechanical strength. DP is the number of these rings that present on an average throughout the molecule. Kraft paper has a higher DP value (932) than EFB insulation paper (866). For a brand-new transformer, the average number of glycoside rings per cellulose polymer chain is between 1000 and 1200 . Due to heat deterioration mechanisms, the DP of operating transformers reduces gradually, along with the mechanical strength of the insulating paper.

When the DP drops to 200, it is estimated that the tensile strength would also have decreased to 50% of its initial value; this is one of the conditions for the expiration of the transformer’s life. Both Kraft and EFB insulating papers have a lower DP value than the standard in this study. The degree of cellulose polymerization in low yield pulps and bleached pulps is important, since treatment will reduce the degree of cellulose polymerization to the point that paper strength qualities are negatively impacted. The number of these rings will decrease as time passes or as the insulating paper is degraded by elements such as heat, acids, oxygen, and water. When estimating the DP using a single indicator as the only basis, the resulting DP values for the same oil-paper sample are inconsistent. This is because the developed mathematical and artificial intelligence models that correlate these individual indicators with the DP value have a low level of accuracy.

C. TENSILE STRENGTH

The strength of the insulating paper is dependent not only on the strength of the fibres but, more significantly, the strength of the links between the fibres . Insulating paper made from EFB has a tensile strength that is comparable to that of insulating paper made from Kraft. Due to the fact that insulating paper is an aggregate of millions of pulp fibres and is primarily made up of cellulose micro-fibrils embedded inside a matrix of hemicellulose and lignin, this structure contributes to the strength of insulating paper. Insulating paper is a material with a high degree of heterogeneity and consists of an infinite number of cracks of different dimensions .

D. THERMAL PROPERTIES

The data collected from thermogravimetric (TGA) and derivative of thermogravimetric analysis (DTGA) are depicted in Fig. 4.2, which displays weight loss curves for Kraft and EFB insulating papers as a function of temperature rise at a constant heating rate. TGA-DTGA has been extensively utilised to characterise and determine the thermal stability of materials.

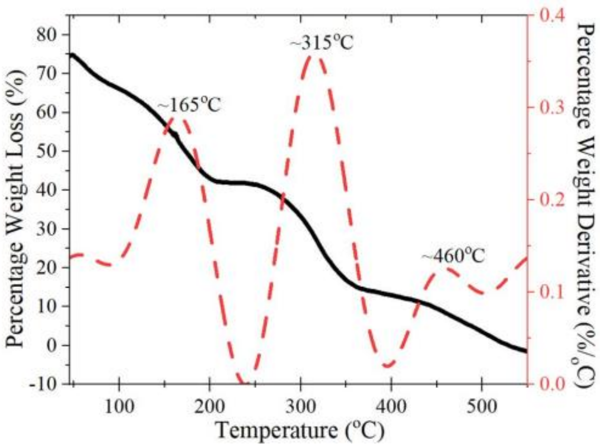

Figure 4.2 Empty Fruit Bunches insulating paper based on derivative of thermogravimetric analysis.

TGA shows how much material is lost as a function of temperature in percentage points, while DTGA shows how much material is lost in %/ ◦C. Based on the DTGA analysis of Kraft insulating paper one weight loss has been detected at Kraft insulating paper starting at approximately 250◦C, which is attributable to the pyrolysis of paper with a weight loss of around 41.96% and a maximum decomposition temperature of 360◦C temperature. The first weight loss is related to the decomposition and vaporisation of insulating oil, with a maximum decomposition temperature of 165 ◦C, and a weight loss of about 25.5%. The second weight loss was approximately 27.36%, and the highest temperature of decomposition was 315 ◦C. A small peak at approximately 460 ◦C and a 14.24% weight loss in the third step may be attributable to the combustion of compounds. Based on the results of this study, it can be concluded that Kraft insulating paper is more stable at high temperatures than EFB insulating paper

E.PERMITTIVITY AND CONDUCTIVITY :

Permittivity in alternating current electric field is defined as complex relative permittivity (εr), which depends on the angular frequency ($\omega = 2\pi f$) as shown in Equation 1.

$$\varepsilon_r(\omega) = \varepsilon'(\omega) + j\varepsilon''(\omega) \qquad (1)$$

where

ε_r: complex real permittivity
ε': real permittivity component
ε'': imaginary permittivity component
j: imaginary unit
ω: angular frequency

E. ELECTRICAL BREAKDOWN FIELD STRENGTH

The breakdown strength of an insulating material is one of the fundamental aspects that must be taken into consideration for a transformer to function properly. It has been observed that the breakdown field strength results achieved by Kraft insulating paper are significantly higher than those achieved by EFB insulating paper. Insulating paper made from Kraft has an average breakdown voltage of 47.19 kV/mm, while insulating paper made from EFB has an average breakdown voltage of 37.61 kV/mm. This is due to Kraft insulating paper has a higher percentage of fibres compared to EFB insulating paper.

F. LIGHTNING IMPULSE BREAKDOWN VOLTAGES

In dielectric testing, a significant amount of lightning impulse breakdown strength (LI) is recommended to assess the electrical characteristic for transformer insulation system design. Fig. 10 shows the scattering measurements value of the LI for insulating paper samples. The result indicates that the LI value for EFB insulating paper yields greater results than the results obtained by Kraft insulating paper. Furthermore, the average value of the number of LI application for EFB insulating paper is 21.37% higher than Kraft insulating paper. It is possible to make the assumption that EFB insulating. paper is able to withstand lightning overvoltage's that may occur while the transformer is in service and maintain secure insulation.

CHAPTER 5

CONCLUSION

This research revealed that the surface of Kraft insulating paper is significantly denser compared to Empty Fruit Bunches (EFB) insulating paper. According to FTIR analysis, there is an extra peak at 1639.90 cm^{-1} in the region of EFB insulating paper, which indicates stretching of the C=N chemical compound. Compared to EFB, Kraft-pulped insulating paper has a greater degree of polymerization and the ability to endure high temperatures. However, EFB insulating paper demonstrated equivalent tensile strength to Kraft insulating paper. Both insulating papers exhibit a decrement pattern in the real and imaginary portions of permittivity with increasing frequency. In contrast to the conduction phenomenon, where the higher frequency pattern indicates moisture content of insulating paper samples. The breakdown field strength performance also indicates that Kraft insulating paper is 20.30% superior than EFB insulating paper because of the higher proportion of fibres presented in Kraft insulating paper. However, the EFB insulating paper is considerably more able to protect transformer insulation and withstand lightning overvoltage that may occur during service. In conclusion, alternative insulating paper manufactured by EFB is still deficient in several areas. Nevertheless, the results are still relatively comparable, and there is space for development. It is indeed possible that the insulation characteristics could be improved with a new method of producing EFB insulating paper. The characteristics of paper could be altered by the addition of a supporting agent or by a modification in the papermaking procedure. In theory, increasing the cellulose content of EFB through pre-treatment could make it more amenable to bond between fibres and improve the qualities of EFB insulating paper.

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