TO STUDY THE CHARACTERIZATION AND EVALUATION OF CELLULOSIC BASED SOLID INSULATION HAVING LOW PERMITTIVITY

Dissertation submitted in partial fulfillment of the requirement
for the award of the degree of

Master of Technology
in
Chemical Engineering
At

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Submitted By:

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Under the guidance of

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July 2013

CERTIFICATE

This is certified that the dissertation entitled "**To study the characterization and evaluation of cellulosic based solid insulation having low permittivity**" is an authentic record of my own work carried out as requirements for the award of the degree of M. Tech. (Chemical engineering) at Thapar University, Patiala, under the guidance of **Dr. Rajeev Mehta** (Associate Professor, ChED) and **Dr. Sushil E. Chaudhari** (Crompton Greaves, Mumbai) during July 2012 to June 2013.

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TO WHOMSOEVER IT MAY CONCERN

This is to certify that Mr. AURNABH SINGH, student of Master of Technology in Chemical Engineering from Thapar University, Patiala, has undergone Project training in Dielectrics Laboratory of HVPTC Department, CG Global R& D centre during the period 1st November 2012 to 30th June 2013.

During the above mentioned period he has successfully completed the assigned task for following project:

To study the characterization and evaluation of cellulosic based solid insulation having low permittivity.

We found him sincere & hardworking during the above period.
We wish him all the success in future endeavors.

For Crompton Greaves Limited,

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ABSTRACT

The oil impregnated paper (OIP) insulation system is critical in the power transformer because the life of transformer is generally governed by life of insulation system. OIP is the basic insulation system used in transformers. Generally liquid insulation is mineral oil and solid insulation can be made of paper, pressboard, epoxy, and wood. Among them, kraft paper and pressboard is widely used as solid insulation in the transformer, which is made from unbleached softwood pulp through sulphate process. In service period of transformer these insulation system undergoes various stresses like thermal, mechanical, chemical and electrical.

Due to the difference in the permittivity (dielectric constant) of oil (DC is 2.2) and pressboard (DC is 4.4 – 4.6), electric stress is generated between them which causes the degradation of insulation. The good life of insulation requires reducing the electrical stress between cellulose as much as possible. The various methods are developed to reduce the permittivity of solid insulation with the help of filler and additives such as fibers, resins, inorganic insulating materials etc but it also alter the properties of OIP which is undesirable. So the characterization and evaluation of these modified pressboards are very important to decide their usability in transformer as solid insulation. Detailed discussion on the characterization and evaluation is included in this thesis report titled as:

“To study the characterization and evaluation of cellulosic based solid insulation having low permittivity”

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CHAPTER 1

INTRODUCTION

The purpose of this chapter is to present the objective of the thesis, approach taken to address this objective and a brief outline of the thesis.

1.1 Scope and Objective

Power transformer is one of the most important and expensive components of any power system utility. Research experience shows that high rating power transformers can have service life of 40 years. The life of a power transformer is primarily governed by the life of the insulation system. The life assessment of transformer is anticipated by the extent of degradation of the insulation system. It has been diagnosed that the main role plays in degradation of the insulation system is the high electric stress between solid and liquid insulation, temperature, moisture, oxygen and acids. So the research is required for improvement of solid insulation which helps in the reduction of electric stress between solid and liquid insulation system. Attempts have been made several researchers to prepare solid insulation using cellulose with synthetic fiber like PP, PET, PVOH, etc. The project thesis title is based on the objective of the improvement of cellulosic based insulation system by the characterization to evaluate the composite pressboard prepared using cellulose pulp and synthetic fiber.

1.2 Research Approach

The fast growth of usage of electricity asks improvement of power system equipments with high level of reliability and safety. Transformers are essential part in power system for voltage level conversion and maintaining the power flow. They are applied at four major regions

1. At power plants, where power is generated and raised to transmission.
2. At switching stations, where the transmission voltage is changed.
3. At distribution substations, where the incoming transmission-level voltage is reduced to distribution voltage.
4. At service transformers, where the voltage is reduced to utilization level for routing into consumers' homes and businesses.

Transformers may suffer from several conditions such as overload condition, insulation contamination, moisture content, etc. which might lead to transformer failures. Among all of the transformer components, the insulation system plays a significant role in the transformer life, because most of transformer failures were caused by insulation problems according to the statistics of transformer failures.

There are two basic transformer insulation types, solid and liquid. Solid insulation can be made of paper, pressboard, epoxy, and wood. Among them, Kraft paper is widely used as solid insulation in the transformer, which is made from unbleached softwood pulp and constructed through a sulphate process. Oil insulation provides two main purposes in the transformer operation, as the insulation material and the cooling medium.

The permittivity of cellulosic based solid insulation is high as compare to liquid insulation, due to this insulation system build a high electric stress in cellulose. For the long life of transformer, reduction in the electric stress between insulation systems is required. As permittivity of solid insulation is more than to that of liquid insulation so it is beneficial to reduce the permittivity of solid insulation.

There are various additives, fillers and other components which help to achieve the low permittivity of solid insulation, but it also alters the other properties of solid insulation which is undesirable. As per International standard and norms, this is difficult to play with properties of solid insulation such as tensile strength, compression, elongation, break down voltage, moisture content and other properties. So this is a big challenge to modify the solid insulation without altering the properties such as mechanical, electrical and chemical properties. The work deals with characterization and evaluation of composite cellulosic pressboard having low permittivity

1.3 Thesis outline

Chapter 2 gives brief explanation on research background that presents configuration of a typical power transformer along with the characterization of insulation system i.e. liquid and solid insulation. It also includes outlining of the standard test methods for determination of various properties such as chemical, mechanical and electrical properties. Chapter 3 contains literature review on characterization and evaluation of electrical grade insulation system. It also includes discussion of relevant patents towards the approach of this study. Chapter 4 explains laboratory scale experimental setups and standard test methods in detail. In this chapter the characterization and evaluation of composite pressboards are studied.

Chapter 5 contains experimental results performed at laboratory scale. Detailed discussion on results is also included. Following with the chapter 5 the overall conclusion of this study is given.

CHAPTER 2

RESEARCH BACKGROUND

The purpose of this chapter is to represent the background for the research that have been accomplished by a discussion on components of transformer insulation system, defining process for preparation of composite pressboard, characterization of pressboard and evaluation of pressboards. The explanation from this chapter shall be helpful in understanding the characterization and evaluation of composite pressboards.

2.1 Introduction to transformer

A transformer is essentially a static electromagnetic device consisting of two or more windings which link with a common magnetic field. Power transformers and distribution transformers are used in numerous public and private sector set-ups involved in electricity consumption, distribution and generation. The main purpose of power or distribution transformer is to transfer electric power from one voltage level to another.

The main components of the transformer are core, winding, insulation (solid or liquid) and tank. When the alternating voltage is applied to the primary winding, an alternating current will flow that will magnetize the magnetic core, first in one direction and then in the other direction. This alternating flux flowing around the entire length of the magnetic circuit induces a voltage in both the primary and secondary windings. Since both windings are linked by the same flux, the voltage induced per turn of the primary and secondary windings must be the same value ad same direction. This voltage opposes the voltage applied to the primary winding and is called counter- electromotive force (CEMF). An ideal transformer should have a negligible winding resistance; perfect coupling between windings and an ideal core (Figure 2.1).

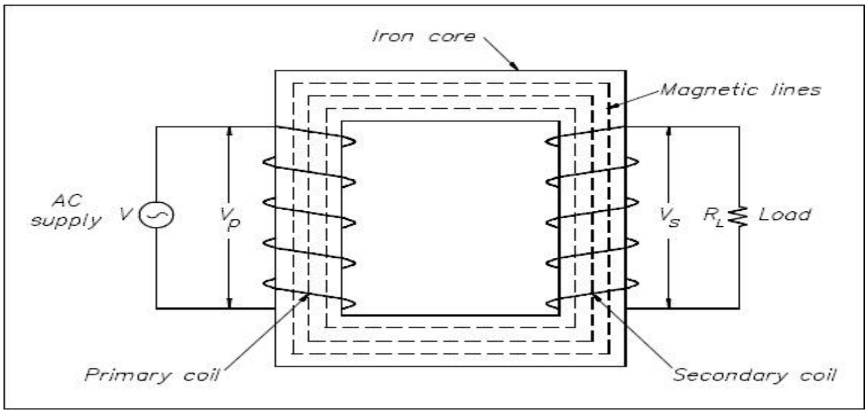


Figure 2.1: Sketch of an ideal transformer.

The fast growth of the use of electricity asks for an improvement of the power system equipment with a high level of reliability and safety. Transformer life management [1] is an essential part of a modern power operation system. Oil filled transformer technology has been used for more than 100 years. The principle of operation has not changed over many decades. A properly maintained power transformer can function for 50 to 75 years. However, the maintenance of the insulation system largely determines the extent of a transformer's life. The power system grid connects the power plants through transmission lines and distribution lines to the end users (Figure2.2). The main goal is providing electrical power to the consumers in ready to use form [2].

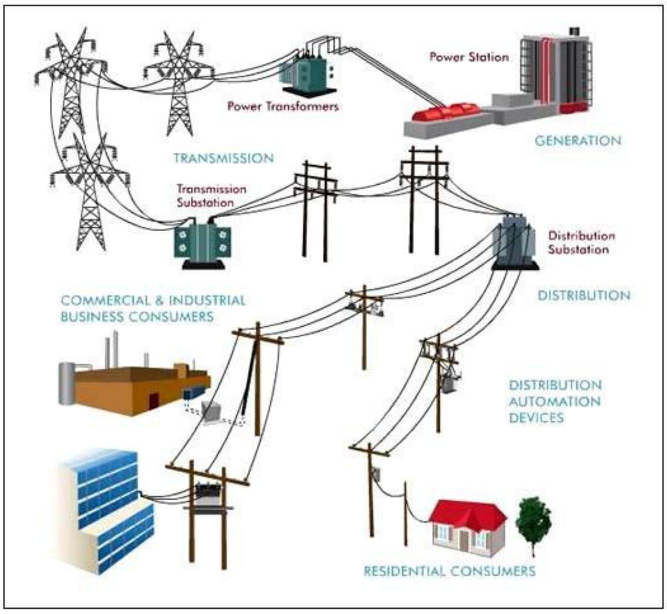


Figure 2.2: The power system grid.

Transformers are essential parts in the power system for voltage level conversion and maintaining the power flow. They are applied at four major regions [3, 4]

1. At power plants, where power is generated and raised to transmission;
2. At switching stations, where the transmission voltage is changed;
3. At distribution substations, where the incoming transmission level voltage is reduced to distribution voltage;
4. At service transformers, where the voltage is reduced to utilization level for routing into consumers' homes and businesses.

Transformers may suffer from several conditions such as overload condition, which might lead to transformer failures. Among all of the transformer components, the insulation system plays a significant role in the transformer life, because most of transformer failures were caused by insulation problems according to the statistics of transformer failures in USA from 1997 to 2001 [3, 4], as we can see from the transformer failure classification in figure 2.3.

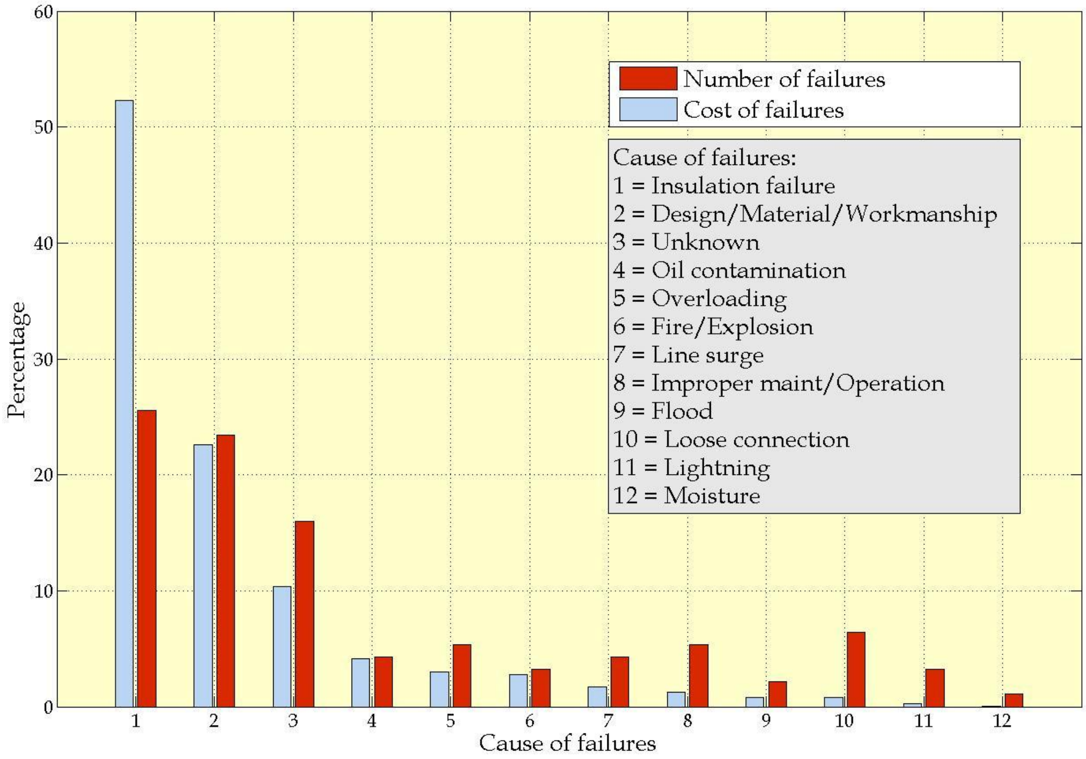


Figure 2.3: Number and cost of 25kV transformer failures in USA (1997 - 2001).

2.2 Insulating Materials

Transformer insulation is provided mainly through mineral oil and cellulose. Ferranti recognized their benefits for the transformer as far back as 1891.The life of a power transformer is primarily governed by the life of the insulation system. The insulation system is required to provide electrical insulation between the various current carrying components of the transformer and to provide mechanical support to the windings.

The two basic transformer insulation types are solid (cellulose insulation) and liquid (insulating oil). Solid insulation can be made of paper, pressboard, epoxy, and wood. Cellulose is widely used insulation material in the transformer, which is made from unbleached soft wood pulp and constructed through a sulphate process [9]. Oil insulation, provides two main purposes in the transformer operation, as the insulation material and the cooling medium.

These are the materials, which permit only a negligible current (order of pA) to flow in phase with the applied voltage. Insulating materials or insulants are extremely diverse in origin and properties. They are essentially non-metallic, organic or inorganic; uniform or heterogeneous in composition; natural or synthetic. Many of them are of natural origin such as paper, cloth, paraffin wax and natural resins whether the wide use is made up of many inorganic insulating materials such as glass, ceramics and mica. Many of the insulating materials are man-made products manufactured in the form of resins, glass, ceramics, etc. In the recent years wide use is made of new materials whose composition and properties place them in an intermediate position between inorganic and organic substances. These are the synthetic organo-silicon compounds, generally termed as silicones [15].

2.2.1 Properties of insulating materials

There are many properties, which characterize the insulating materials, e.g. resistivity, breakdown voltage, permittivity and dielectric loss, etc. An ideal insulating material should have:

1. High dielectric strength sustained at elevated temperature
2. High resistivity
3. Good thermal conductivity
4. High tensile and shear strength of solid insulation
5. High degree of thermal stability

2.3 Insulation system of transformer

When electrical energy is transformed from one voltage to another, heat is developed. This temperature must be within limits so that it will not adversely affect the dimensional stability of the materials used in the construction of the transformer. In power transformers, the high electrical stresses and amount of heat developed require both solid and liquid insulation, with the fluid conducting the generated heat away to cooling surfaces, where it gets dissipated. The combination of oil and cellulose products has remained unchanged for reasons of electric strength and cost. The amount of insulating oil and cellulose vary with different types of transformers based on function and voltage class.

The life of the transformer is actually the life of the internal insulation system. The most widely used systems are liquid insulation (transformer oil) and solid insulation (kraft paper, pressboard, wood i.e. cellulose products). The insulating oil provides approximately 80% of the dielectric strength of a transformer. Transformer oil is a good insulating medium and when impregnated in paper, board and cloth, increases the dielectric strength of it further. The low viscosity of oil also allows it to penetrate the solid insulation setting up convection currents for conveying the heat from the core materials to the radiators. The liquid insulation therefore also serves as a coolant and its oxidation stability allows it to operate at high temperatures for long periods.

2.3.1 Liquid Insulation

The insulating fluid that has the greatest use in electrical equipment is mineral oil. There are insulating materials that may be superior to mineral oil with respect to both dielectric and thermal properties; however, up to date, none has achieved the requisite combination of equal or better performance at an equal or better price. Consequently, mineral oil continues to serve as the major type of liquid insulation used in electrical equipment. Oil used for insulation in transformers is mineral oil and it is obtained by refining crude petroleum. Animal oils and vegetable oils are not used for this purpose as these form fatty acids on heating which are corrosive for the cellulosic paper used in insulation. Mineral oils have been in use as liquid dielectrics in electrical equipment for over hundred years now. Despite the availability of a variety of synthetic oils, with far more superior properties, mineral oils held its way, due to their abundant availability and economy [5].

Three properties that are fundamental to use of mineral oil as dielectric are:

1. High insulating property
2. Good oxidative
3. Ageing stability and good heat transferability.

The reliable performance of mineral insulating oil in an insulation system depends upon certain basic oil characteristics, which can affect the overall performance of the electrical equipment:

1. High electric strength to withstand the stresses in service
2. Sufficiently low viscosity so that its ability to circulate and transfer heat is not impaired

3. Adequate low temperature properties down to the extreme of climatic conditions expected at the installation site
4. Proper oxidation resistance to ensure long life in service
5. Good resistance to emulsion to prevent holding water in suspension in it
6. Free from inorganic acid, alkali and corrosive sulphur which causes corrosion of metal parts and insulation and accelerate the production of sludge
7. Free from slugging under normal separating conditions
8. High flash/fire points
9. Low pour point
10. Low water content

2.3.1.1 Composition of Oil

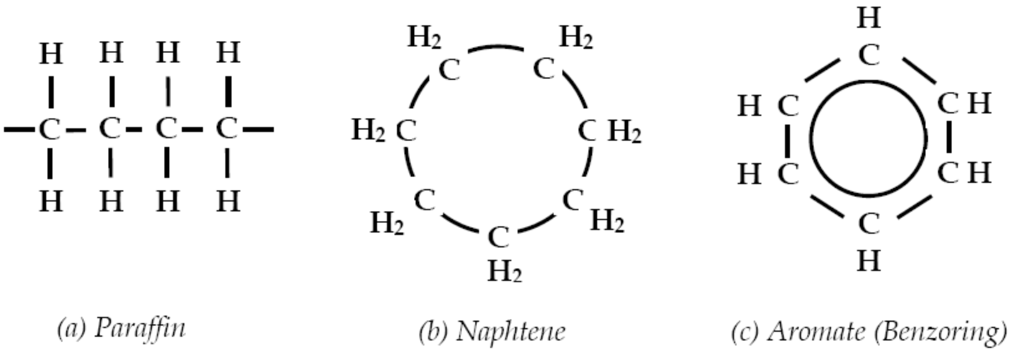
Mineral oil can vary greatly in its composition. All mineral oils are mixtures of hydrocarbon compounds with about 25 carbon atoms per molecule. The blend of compounds that is present in particular oil is dependent on several factors, such as the source of the crude oil and the refining process. Crude oils from different geographical areas will have different chemical structures (arrangement of the carbon atoms within the molecules). Crude oils from some sources are higher in paraffinic compounds, whereas others are higher in naphthenic compounds. Crude oils also contain significant amounts of aromatic and polyaromatic compounds. Some of the polyaromatic compounds are termed “heterocyclics” because, besides carbon and hydrogen, they contain other atoms such as nitrogen, sulfur, and oxygen. Some heterocyclics are beneficial (e.g., oxidation inhibitors), but most are detrimental (e.g., oxidation initiators, electrical charge carriers). The refining of crude oil for the production of dielectric fluids reduces the aromatic and polyaromatic content to enhance the dielectric properties and stability of the oil.

The terms paraffinic and naphthenic refer to the arrangement of carbon atoms in the oil molecule. Carbon atoms that are arranged in straight or branched chains, i.e., carbon atoms bonded to one another in straight or branched lines, are referred to as being paraffinic. Carbon atoms that are bonded to one another to form rings of generally five, six, or seven carbons are referred to as being naphthenic. Carbon atoms that are bonded as rings of benzene are referred to as being aromatic. Carbon atoms that are contained in “fused” benzene rings are referred to as being polyaromatic. These forms of bonded carbon atoms are depicted in figure 2.4. The straight lines represent the chemical bonds between carbon atoms that are present (but not depicted) at the ends and vertices of the straight lines. Figure 2.5 illustrates a typical oil molecule. Remember that particular oil will contain a mixture of many different molecular species and types of carbon atoms. Whether particular oil is considered paraffinic or naphthenic is a question of degree. If the oil contains more paraffinic carbon atoms than naphthenic carbons, it is considered paraffinic oil. If it contains more naphthenic carbons, it is considered naphthenic oil. The differences in the chemical composition will result in differences in physical properties and in the chemical behavior of the oils after they are put in service. The chemical composition has profound effects on the physical characteristics of the oil.

For electrical equipment, the main concerns are:

- Paraffinic oils tend to form waxes (solid compounds) at low temperature.
- Paraffinic oils have a lower thermal stability than that of naphthenic and aromatic oils.
- Paraffinic oils have a higher viscosity at low temperature than that of naphthenic and aromatic oils.

These factors can impair the performance of high-voltage electrical equipment. The first two factors have an unfavorable effect on the dielectric characteristics of the oil. The third factor unfavorably affects the heat/dissipation ability of the oil. Unfortunately, the availability of insulating oil is limited. Therefore, electrical equipment owners have a choice of only a few producers, who produce only a very few different products [14, 19].



(a) Paraffin (b) Naphtene (c) Aromate (Benzoring)

Figure 2.4: Hydrocarbon compounds in mineral oil.

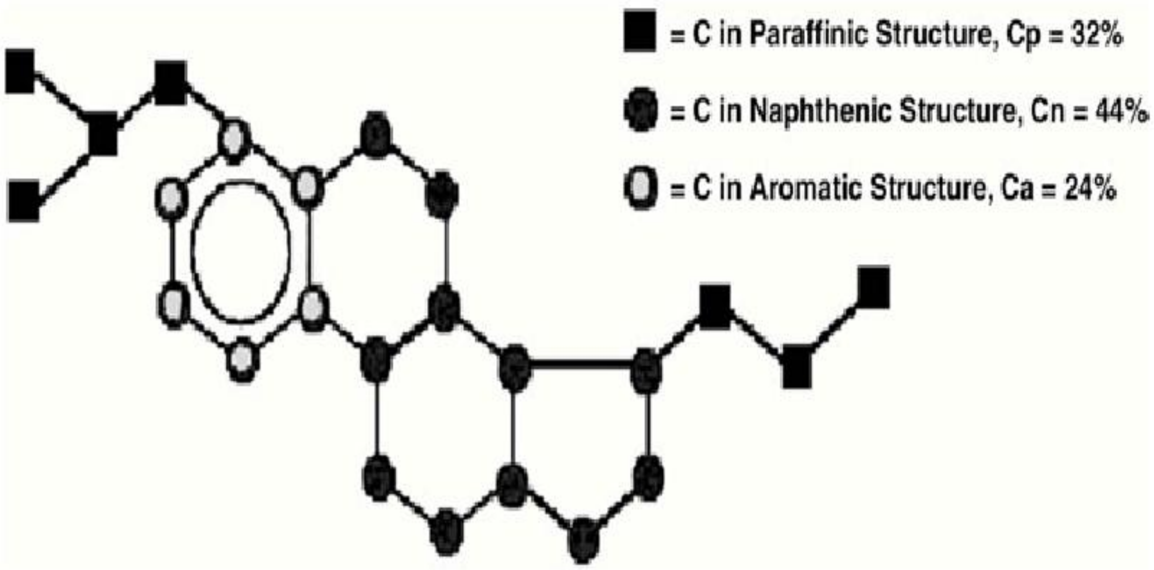


Figure 2.5: Schematic figure of typical oil molecule.

2.3.1.2 Oxidation Inhibitors

Oxidation inhibitors, such as DBPC (di-tertiary butyl paracresol) and DBP (di-tertiary butyl phenol), are often added to oil to retard the oxidation process. These compounds work by attracting oxygen molecules to themselves rather than allowing oxygen to bind with oil molecules. With time, the inhibitor gets consumed because of its preferential reaction with oxygen. As a result, the oil will then oxidize at a more rapid rate. The remedy is to add inhibitor to oil that has lost its antioxidant capabilities.

2.3.2 Functions of Oil

2.3.2.1 Electrical Insulation

The primary function of insulating oil is to provide a dielectric medium that acts as insulation surrounding various energized conductors. Another function of the insulating oil is to provide a protective coating to the metal surfaces within the device. This coating protects against chemical reactions, such as oxidation, that can influence the integrity of connections, affect the formation of rust, and contribute to the consequent contamination of the system. Insulating oil, however, is not a good lubricant. Despite this fact, it is widely used in load tap changers, circuit breakers, and transformers. Therefore, its use in these devices presents a challenge to the mechanical design of the system [5, 6].

2.3.2.2 Heat Dissipation

A secondary function of the insulating fluid is to serve as a dissipater of heat. This is of particular importance in transformers where localized heating of the windings and core can be severe. The oil aids in the removal of heat from these areas and distributes the thermal energy over a generally large mass of oil and the tank of the device. Heat from the oil can then be transferred by means of conduction, convection, and radiation to the surrounding environment. All mineral oils are comparable in their ability to conduct and dissipate heat. To ensure that given oil will perform satisfactorily with respect to heat dissipation, several specifications are placed on the oil. These specifications are based upon certain factors that influence the oil’s ability to dissipate heat over a wide range of possible operating conditions. These factors include such properties as viscosity, pour point, and ash point.

2.3.2.3 Diagnostic Purpose

The third function of the insulating fluid is to serve as an indicator of the operational condition of the liquid-filled equipment. The condition (both chemical and electrical) of the insulating fluid reflects the operational condition of the electrical device. In a sense, the fluid can provide diagnostic information about the electrical device much like blood can provide diagnostic information about the human body. The condition of the blood is important as it relates to its primary function of transporting oxygen and other chemical substances to the various parts of the body. Indeed the condition of the blood is symptomatic of the overall health of the body. For example, the analysis of the blood can be used to diagnose a wide variety of health problems related to abnormal organ function. In much the same way, insulating fluid can be viewed as serving its primary functions as an insulator and heat dissipater. It can also be viewed as serving another (and perhaps equally important) function as a diagnostic indicator of the operational health of liquid-filled equipment. This is possible because when faults develop in liquid-filled equipment, they cause energy to be dissipated through the liquid. This energy can cause a chemical degradation of the liquid. An analysis for these degradation products can provide information about the type of fault that is present.

2.3.3 Parameters that affect oil degradation

2.3.3.1 Heat

Just as temperature influences the rate of degradation of the solid insulation, so in same manner it also affects the rate of oil degradation. Although the rates of both processes are different, both are influenced by temperature in the same way. As the temperature rises, the rates of degradation reactions increase. For every 10° (Celsius) rise in temperature, reaction rates double.

2.3.3.2 Oxygen

Hydrocarbon-based insulating oil, like all products of nature, is subject to the ongoing, relentless process of oxidation. Oxidation is often referred to as aging. The abundance of oxygen in the atmosphere provides the reactant for this most common degradation reaction. The ultimate products of oxidation of hydrocarbon materials are carbon dioxide and water. However, the process of oxidation can involve the production of other compounds that are formed by intermediate reactions, such as alcohols, aldehydes, ketones, peroxides, and acids.

2.3.3.3 Partial Discharge and Thermal Faulting

Of all the oil degradation processes, hydrogen gas requires the lowest amount of energy to be produced. Hydrogen gas results from the breaking of carbon–hydrogen bonds in the oil molecules. All of the three fault processes (partial discharge, thermal faulting, and arcing) will produce hydrogen, but it is only with partial discharge or corona that hydrogen will be the only gas produced in significant quantity. In the presence of thermal faults, along with hydrogen will be the production of methane together with ethane and ethylene. The ratio of ethylene to ethane increases as the temperature of the fault increases.

2.3.3.4 Arcing

With arcing, acetylene is produced along with the other fault gases. Acetylene is characteristic of arcing. Because arcing can generally lead to failure over a much shorter time interval than faults of other types, even trace levels of acetylene (a few parts per million) must be taken seriously as a cause for concern.

2.3.3.5 Acid

High levels of acid (generally acid levels greater than 0.6 mg KOH/g of oil) cause sludge formation in the oil. Sludge is a solid product of complex chemical composition that can deposit throughout the transformer. The deposition of sludge can seriously and adversely affect heat dissipation and ultimately result in equipment failure.

2.3.4 Paper Insulation

Insulation grade paper is made by the delignification of wood pulp by the Kraft process. It contains about 90% cellulose, 6-7% lignin and, the balance is hemicelluloses. The natural humidity of paper is 4-5% by weight and the insulation is dried after winding to less than 0.5%. Cellulose is a linear polymer of glucose; consisting D-anhydroglucopyranose units joined together by glycosidic bonds (refer Figure 2.6). A single cellulose fiber is formed from a number of these chains held together by hydrogen bonds [8, 10].

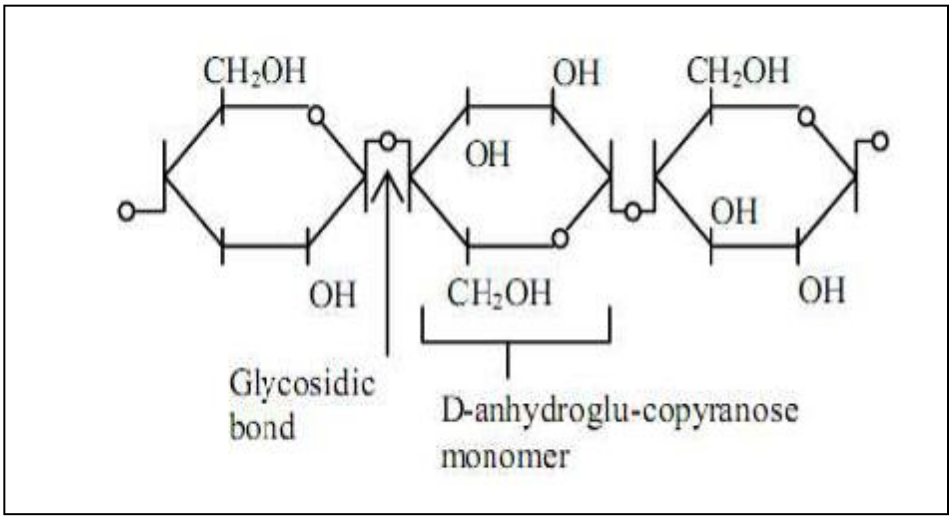


Figure 2.6: Structural formula of cellulose.

The dried paper is impregnated with insulating oil, which increases its dielectric strength and also serves to cool the windings. The major constituent of paper is cellulose, which is a natural polymer of glucose. Power transformer conductor windings are insulated by paper impregnated with insulating oil, which is expected to last the life of the transformer (25 years minimum at an operating temperature of 65-95 ° C). A typical 600 MVA transformer contains 12 t of paper, 30-120 µm thick (density 0.7-0.8 g/cm^3), and 45 t (40,000 l) of oil. Heat, water and oxygen degrade (depolymerise) the cellulose, reducing the polymer molecular chain length and with it the mechanical strength of the material. Local mechanical failure could lead to short the turns or paper fragments or fibers in the oil ducts and hence to dielectric or thermal failure of the insulation system. Changes in the compliance and tension of the windings with time may result in distortion and an increased susceptibility to short-circuit force failure of the aged insulation or even of the winding itself. Water is a product of ageing. Its presence in the insulation increases conductivity and the likelihood of gas bubble formation, reducing the thermal stability of the insulation system during overload conditions [10, 15].

In order to serve as a good insulant, paper should have the following properties:

1. Good breakdown voltage
2. High resistivity
3. Low dissipation factor
4. Low conductivity of extract
5. Good tensile strength
6. High degree of polymerization
7. Low cost

2.3.4.1 Composition of paper- Cellulose

Paper and pressboard are composed primarily of cellulose, which is a naturally occurring polymer of plant origin. From a chemical perspective, cellulose is a naturally occurring polymer. Each cellulose molecule is initially composed of approximately 1000 repeating units of a monomer that is very similar to glucose. As the cellulose molecule degrades, the polymer chain ruptures and the average number of repeating units in each cellulose molecule decreases. With this reduction in the degree of polymerization of cellulose, there is a decrease in the mechanical strength of the cellulose as well as a change in brittleness and color. As a consequence of this degradation, cellulose will reach a point at properly function as an insulator separating conductors. When cellulose will reach its end of life as an insulator depends greatly on the rate at which it degrades properly function as an insulator separating conductors. When cellulose will reach its end of life as an insulator depends greatly on the rate at which it degrades [9].

2.3.4.2 Parameters that affect degradation of Cellulose

Several chemical reactions contribute to the degradation of cellulose. Oxidation and hydrolysis are the most significant reactions that occur in oil-filled electrical equipment. These reactions are dependent on the amounts of oxygen, water, and acids that are in contact with the cellulose. In general, the greater the level of these components, the faster is the degradation reactions [8].

2.3.4.2.1 Heat

The rates of the degradation reactions are greatly dependent on temperature. As the temperature rises, the rates of chemical reactions increase. For every 10°C rise in temperature, reaction rates double. Consequently, the useful life of cellulose and oil is markedly reduced at higher temperatures. Paper and oil subjected to an increased temperature of 10°C will have their lives reduced by a factor of 50%. Elevations in temperature can result from voluntary events such as increased loading, or they can result from a large number of involuntary events, such as the occurrence of fault processes (partial discharge, thermal faulting and arcing) will produce hydrogen, but it is only with partial discharge or corona that hydrogen will be the only gas produced in significant quantity. In the presence of thermal faults, along with hydrogen will be the production of methane together with ethane and ethylene. The ratio of ethylene to ethane increases as the temperature of the fault increases.

2.3.4.2.2 Oxygen

The cellulose that is present in paper, pressboard, and wood oxidizes readily and directly to carbon oxide. The carbon dioxide and carbon monoxide that are found in oil-filled electrical equipment result primarily from the cellulose material. This has very important consequences, since the useful life of major electrical devices such as power transformers is generally limited by the integrity of the solid insulation — the paper. It is now possible to determine more closely the extent and the rate of degradation of the cellulose by observing the levels of the carbon oxides in the oil as a function of time. As cellulose reacts with oxygen, carbon dioxide, water, and possibly carbon monoxide are produced. Carbon monoxide is produced if there is an insufficient supply of oxygen to meet the demands of the oxidation reaction. The levels of these products in the oil continue to increase as oxidation continues. However, they never exceed concentrations in the oil that are referred to as their solubility limits, which are temperature and pressure dependent. After the solubility limit of each has been reached, further production cannot increase their concentration in the oil. If carbon monoxide and carbon dioxide were to ever exceed their solubility limits, they would form bubbles that would be lost to the atmosphere or to a gas blanket; this rarely happens. Any water that forms will fall to the bottom of the tank or be adsorbed into the solid insulation (the cellulose).

2.3.4.2.3 Moisture

Cellulose has a great affinity for holding water (notice how well paper towels work). Water that is held in the paper can migrate into the oil as the temperature of the system increases, or the reverse can happen as the temperature of the system decreases. In a typical large power transformer, the quantity of cellulose in the solid insulation can be several thousand pounds. For new transformers, the moisture content of the cellulose is generally recommended to be no more than 0.5%. Water distributes between the oil and the paper in a constant ratio, depending on the temperature of the system. As the temperature increases, water moves from the paper into the oil until the distribution ratio for the new temperature is achieved. Likewise, as the temperature decreases, water diffuses in the opposite direction. In addition to the water that is in the paper and the oil at the time a transformer is put into service, there is also water introduced into the system because of the ongoing oxidation of the cellulose. Water is a product of the oxidation of cellulose, and it is therefore always increasing in concentration with time. Even if the transformer were perfectly sealed, the moisture concentration of the paper would continue to increase. The rate of generation of water is determined primarily by the oxygen content of the oil and the temperature of the system. An increase in either of these factors increases the rate of water generation.

2.3.4.2.4 Acid

Cellulose can degrade by a chemical process referred to as hydrolysis. During hydrolysis, water is consumed in the breaking of the polymeric chains in the cellulose molecules. The process is catalyzed by acids. Acids are present in the oil that is in contact with the cellulose. Carboxylic acids are produced from the oil as a result of oxidation. The acid content of the oil increases as the oil oxidizes. With an increase in acidity, the degradation of the cellulose increases.

2.4 Characterization of insulation materials

The modern power industry uses a great variety of electrical insulating materials and systems to meet challenges and requirements of the present day science and technology. The advancement in science and the changes in the industrial environment have led to rapid progress in the field of insulation engineering. This has resulted in availability of an abundant variety of new generation materials. Thus for design of an insulation system for any specific application many alternatives are available. Though many new materials and systems are available, their properties especially the ageing in service due to various factors like thermal, mechanical and electrical stresses is not well understood. Therefore, the process of evaluation and testing of insulating materials and systems plays a vital role in determining the quality and also reliability of the power that is delivered.

2.4.1 Electrical analysis

There are several test methods used to measure common properties of electrical insulating materials.

2.4.1.1 AC loss characteristics and dielectric constant for electrical insulation materials (ASTM D150): The dielectric constant and dissipation factor is typically measured as per ASTM D150. Standard test conditions for ASTM D150 are 60 Hz, 25°C and 1.0 kV/AC.

2.4.1.2 Dielectric breakdown voltage and dielectric constant for electrical insulation materials at commercial power frequencies (ASTM D149): The ASTM D149 method is used to determine the dielectric constant and dielectric breakdown voltage. A voltage ramp rate of 5kV/minute is typically used for material properties assessment.

2.4.1.3 DC resistance of insulating materials (ASTM D257): The insulating resistance to electrical charge is defined by surface resistivity and volume resistivity. The two material properties are related; however, most insulation materials are conducting along the surface rather than through the bulk thickness. ASTM D257 covers the DC voltage testing of volume and surface resistivity.

2.4.2 Mechanical analysis

2.4.2.1 Flexural properties of electrical insulating materials (ASTM D790): ASTM D790 3 point flexural strength test method differs from ASTM 06272 four point flexural property test method. The three point loading creates a shear stress concentration at the center loading position. The shear stress concentration affects the sample stress state, therefore, 3 point loading does not create pure flexural loading. Four point bending eliminates the shear load concentration in the test span, thus, pure flexural strength and modulus measurements are obtained for test spans greater than or equal to 16 times the sample thickness.

2.4.2.2 Compressive properties of rigid plastics (ASTM D695): ASTM D695 tests materials with compressive loading to determine compressive strength, strain to failure and compressive modulus. An ideal compressive failure for rigid, elastic materials would have the sample fail with 45° degree prism pieces.

2.4.2.3 Tensile properties of plastics (ASTM D638): Tensile strength, modulus and strain to failure can be determined by ASTM D638.

2.4.2.4 Shear properties of insulating materials (ASTM D5379): The shear strength, shear modulus and shear strain to failure for rigid laminates and structural composites can be determined using ASTM D5379.

2.4.3 Chemical analysis

There are many methods for determining the chemistry of electrical insulating materials. The constituent atomic elements of solid materials can be determined by Scanning Electron Microscopy (SEM), Energy Dispersive X-Ray Spectrometry (EDXS) or Wave Dispersive X-ray Spectrometry (WDXS). The energy of the electron beam excites electrons in each atom impacted. The excited electrons in each atom will return to a lower energy level, a photon of unique wavelength is released from the material. Each atomic element will emit a unique x-ray photon for each possible electrical transition within the atom. These characteristic photon wavelengths have been determined for all common atomic elements; hence, identification of the various elements present can readily be determined.

2.4.3.1 Fourier Transform Infra-Red (FTIR) spectroscopy (ASTM E1252): FTIR spectrometry is often used to determine the identity of polymers present in solid or liquid materials with insulating properties. The sample is exposed to a range of infra-red light energy. Each polymer molecule bond within the molecule absorbs photons with a specific wavelength. Analytical FTIR spectrometers are equipped with a reference library with common characteristic waves for polymer materials for faster identification. It's also possible to store the test results for future comparisons.

2.4.3.2 Gas chromatography (GC) (ASTM 01428): It is used to determine the types of small sized organic molecules present in materials. The low molecular weight polymeric molecules are extracted by solvent based distillation and then vaporized into a gas vapor where a chromatograph records the absorbance time on the detector. The absorbance time measured corresponds to known molecules. The extractable ions are dissolved in a water solution and detected using ion chromatography.

2.4.4 Thermal analysis

2.4.4.1 Thermal expansion by TMA (ASTM E831): This is a common test procedure for measuring the coefficient of thermal expansion (CTE) using thermal mechanical analysis (TMA) equipment. Most material designs for electrical insulation use polymer materials that have a Tg temperature above the intended operating temperature. There is a significant drop in mechanical properties above the Tg temperature.

2.4.4.2 Glass transition method by DMA (ASTM El640): This is an excellent method to determine the glass transition temperature, Tg, for thermoset materials. The test procedure uses Dynamic Mechanical Analysis (DMA) methods. Tg by DMA plots shows the change in apparent modulus versus temperature. Most thermoset and thermoplastic materials lose a significant amount of physical strength above the Tg temperature.

2.4.4.3 Glass transition method by DSC (ASTM E1356): This method is frequently used to determine thermal transitions in polymeric materials using a Differential Scanning Calorimeter (DSC) technique.

2.4.4.4 Resistance to thermal transmission of materials by guided heat flow (ASTM E1530): The heat dissipation of electrical insulating materials is critical to machine efficiency in electrical generator applications. The amount of heat that can be conducted per unit area through a known thickness is typically measured using ASTM E1530 thermal conductivity method.

2.4.4.5 Rapid thermal degradation of solid insulating material by TGA (ASTM D3850): Thermal limits related to material temperature stability or thermal decomposition can be determined by ASTM D3850 method for rapid thermal degradation of solid electrical insulating materials by Thermo Gravimetric Analysis (TGA). The procedure determines precise weight loss of a material when heated in inert gas environment. Heating can also be done in an air environment to measure the effects on thermal stability.

Since reliability of high voltage equipments and systems depend on the quality and proper choice of the insulation, it is not only desirable but also mandatory to acquire a sound knowledge of the behavior of insulating materials that are used. Thus, process of testing and evaluation of insulating materials plays a vital role in quality assurance and maintenance of high voltage equipments and systems.

CHAPTER 3

LITERATURE REVIEW

To meet the ever increasing demand for electrical power in recent years it has been desired to develop extra and ultra high voltage transformers. For this purpose, development of high quality insulating paper/ pressboard/ paperboard is required. A number of investigations made regarding to develop better fiber cellulose paper composites are discussed below

3.1 Polypropylene and cellulose composite paper

Polypropylene, with its low loss factor and high thermal stability was earlier considered to be one of the most hopeful polymers as a substitute for kraft pulp in making composite insulating paper.

Nakao et al. in their study described the production of electric insulating paper with a low dielectric constant, low dielectric loss tangent, high dielectric strength and sufficient oil passage due to its porous nature as compared to conventional paper [27]. Synthetic polymer and cellulose were mixed in microscopic molecular level hence the cracking and crazing caused in conventional plastic films was not created and the paper became more oil resistant. The heat resistance of the synthetic polymer was utilized so that the paper could endure higher temperatures than normal electrical insulating paper and it could be used for a longer period of time than conventional insulating electric paper.

The use of polypropylene fibers and polyolefin micro fibers along with cellulose fiber to produce an electrical grade insulating paper has also been studied [28, 29]. The electrical insulating layer comprised of two layers, a layer A comprised of a mixture of kraft pulp fibers (composition: 10-70%, length 0.5-2 mm, diameter 10-50 μm), polypropylene fibers (composition: 3-35%, length 0.3-1 mm, diameter 10-30 μm) and polyolefin fibers (composition: 1-25%, length 0.1-5 mm, diameter 0.2-10 μm) and a layer B comprised of polypropylene fibers only. The paper was prepared by superimposing one layer over the other and they were heat treated from 110ºC to 180ºC so that the fibers get thermally adhered with each other. The electrical insulating paper produced had outstanding electrical properties, mechanical properties, oil resistance and amenability to impregnation with oil which was well suited to the insulation of extra and ultra high voltage filled electric power apparatus, especially power cables. Using polypropylene fibers with large diameters (up to 50 μm) resulted in paper having reduced mechanical strength and lower air permeability. Generally finer fibers gave better results. Excess usage of polyolefin microfibers adversely affected the oil resistance of paper.

A process for production of lower permittivity pressboard was described by Kamta et al. [30]. Reducing the permittivity reduces the insulating distance in transformers which would result in uniform electric field distribution in oil paper press board insulation systems. A low permittivity press board was produced by blending poly methyl pentene with cellulosic pulp fibers. The paper produced had permittivity of 3.5 which is less than 4.7 for normal press board paper.

One of the major problems of blending cellulose fibers with polypropylene is the loss of elastic modulus during prolonged use in oil impregnated state. Another significant problem encountered is that on attempting to lower the dielectric loss factor also reduces its mechanical strength due to low bonding between cellulose and polypropylene fibers. The above studies are summarized in Table 3.1

Sr No.	**Dimensions of fibers**	**Binders**	**Composition**	**Properties**	**References**
1	Not specified	No binder	Wood pulp fiber (60-80%), synthetic fiber (40-20%)	Low dielectric loss tangent, high dielectric strength	[27]
2	Length: 2-15 mm and dia: 10-15 µm, dia of microfiber 0.2-10 µm	No binder	Kraft pulp (80-85%), polypropylene (10-15%) and polyolefin microfibers (2-3%)	Increased thermal resistance of paper	[28]
3	Diameter: 10-30µm, dia of microfibers 0.2-10 µm	No binder	Polypropylene (3-35%), polyolefin microfibers (1-25%), cellulose fibers (10-80%)	Increased diameter of polypropylene fibers reduces mechanical strength of paper.	[29]
4	Not specified	No binder	Cellulosic pulp fibers and polymethlypentene fibers	The permittivity of the paper so formed is 3.5 which is less than 4.7 for normal press board paper	[30]

Table 3.1: Summary of polypropylene and cellulose paper composites

3.2 Polyamide and cellulose composite paper

The current standard insulating material used in transformers are cellulosic materials of various thickness and density. Cellulose based insulating materials commonly known as Kraft paper, has been widely used in transformers since early 1900’s. Despite of its shortcomings, Kraft paper has been used continuously in transformers because of its low cost, easy availability and reasonably good performance [18]. To overcome its hygroscopic nature cellulose is blended with synthetic polymer fibers, one such synthetic polymer fiber is polyamide fiber. The insulation paper generally includes a wood pulp fiber, a synthetic fiber and a binder material. The wood pulp fiber composition generally varies from 60-80% by weight (length 0.5-1.4 inch, diameter 10-15 µm), synthetic fiber varying from 5-20% by weight (length 0.1-1 inch, diameter 10-15 µm) and polymeric binder 10-30% by weight. Ideally the binder and synthetic fiber have good long term aging properties and are compatible with common dielectric fluids [19].

Thinius in his study described the production of mixed structures, foils, filaments and films consisting of polyamide and cellulose pulp fibers [20]. The paper produced had good heat resistance, good water repellent properties and high thermal stability. Blending of cellulose and its derivatives with polyamide resulted in increased flexibility, higher stability on heating and better dyeing characteristics.

Insulating structures in transformers were studied by Schroeder and Michel [21]. Electrical apparatus such as transformer have certain portions insulated by solid means. The solid means may be a film formed by polyethylene terepthalate, which is surrounded by a layer of paper having a fibrous web formed by aromatic polyamide fibers. Dielectric films such as polyester films are unsuited for solid insulation in transformers because these films embrittle at a temperature of more than 200ºC and also plastic flow at temperature and pressure experienced during short circuit of transformers.

Production of paper which comprised of cellulosic pulp fiber, a particulate binder substantially insoluble in water, an emulsion comprised of lecithin and fatty acid and a synthetic fiber has also been studied [22]. The binder used was BF Goodrich. The composition of cellulosic pulp fiber varied from 60 to 90%, the composition of binder which was insoluble in water varied from 10 to 20%, the composition of emulsion of lecithin and fatty acid varied from 1 to 10% and the composition of synthetic fiber varied from 5 to 25%. The study dealt with improving the strength properties of paper like dry strength, wet strength and folding endurance of paper.

Smoothening of the surface of aramid paper so that it can be used as electrical insulation paper was studied by Kato et al. [23] the paper produced was heat resistant and had high thermal stability. For making the aramid paper smooth it was coated with fibrids of poly metaphenylene isothalamide {Length 0.2-1 mm and aspect ratio (length to width ratio) of 5:1 to 10:1}, which had 100% weight of poly metaphenylene isothalamide, a coating ratio of 97% and a coat weight of 10 gsm on one side.

A process for making a uniform dispersion of aramid fibers and polymers has also been studied [24]. Short aramid fibers were continuously combined with extrudable polymers to yield substantially uniform composition paper which comprised of 15 to 99 weight percent polymer and 1 to 85 weight percent aramid fibers. The aramid fibers were continuously introduced in the extruder simultaneously heat was applied in the extruder so as to evaporate the water from fibers. The fibers were then subjected to shear force in the extruder. The polymer was blended with the fibers so as to form a uniform dispersion.

Kinsley [25] and Cornbower [26] in their studies varied: (a) the composition of cellulosic pulp fiber from 50-80% by weight, (b) the aramid component from 5 to 25% by weight and (c) the polymeric binder (polyvinyl alcohol) from 10 to 25% by weight to produce E board paper. The E board paper produced comprised of three layers. The outer two layers were comprised of cellulosic pulp fibers and the inner layer is comprised of polymeric binder, a synthetic fiber and cellulosic pulp fiber. E board paper could be used as an insulator in transformers because of its excellent dielectric properties, good mechanical strength, high thermal stability, good heat resistance, good oil impregnation and its ability to withstand temperatures upto 220ºC.

Electric insulation paper made from combination of polyamide and cellulose fibers have outstanding electrical, mechanical and thermo-chemical properties. However, the desired insulator shape must be stamped out of aramid paper sheets resulting in significant handling and labour costs and also resulting in considerable waste of material in the non-used trimmings which adds to transformer costs. The above studies are summarized in Table 3.2.

Sr No.	**Dimensions of fibers**	**Binders**	**Composition**	**Properties**	**Reference**
1	Not specified	No binder	Cellulosic pulp fibers (60-80%) and polyamide fibers (20-40%)	Paper has good water repellent properties	[20]

2	Length: 1-1.6 mm	No binder	Laminate of cellulosic pulp fibers, Nomex fibers and PET films	PET films unsuitable for temperature over 200°C	[21]
3	Not specified	BF Goodrich /Dow/ Acrylic	Cellulosic pulp fiber (60-90%), a latex binder (10-20%) and an emulsion of lecithin and fatty acid (1-10%), synthetic fiber (5-20%)	Increase in dry strength and tensile strength of paper	[22]
4	Length: 1 mm, Aspect ratio 5:1 to 50:1	No binder	Polymetaphenalene isothalamide and fibrids	Increase in surface smoothness of paper and also increase in heat resistance	[23]
5	Not specified	No binder	Short aramid fibers (1-85%), extrudable polymer (20-30%)	Uniform dispersion gives dimensionally stable paper	[24]
6	Length: 5 mm to 25 mm	Polyvinyl alcohol	Cellulose pulp (50-80%), polymeric binder (5-25%), aramid fiber (10-25%)	Increased thermal resistance of paper	[25]
7	Length of fiber : 0.25 to 0.75 inches, dia: 10-15 µm	Polyvinyl alcohol	Wood pulp fiber (70%), synthetic fiber (20%), binder material (10%)	Binder used has good thermal aging properties, adding synthetic fiber to wood pulp fiber increases papers thermal stability	[19]
8	Length: 0.25 inch	Polyvinyl alcohol	Cellulosic Pulp fibers (70 %), polyvinyl alcohol (20%), poly amide fiber (10 %)	Increased thermal resistance of paper	[26]

Table 3.2: Summary of polyamide and cellulose paper composite

3.3 Polyvinyl alcohol and cellulose composite paper

Polyvinyl alcohol can be used in fiber form or even in powder form. Poly vinyl alcohol fiber with low solubilisation temperature should be used for medium basis weight paper.

For high basis weight papers polyvinyl alcohol with high solubilisation temperature can be used. Polyvinyl alcohol when used in powder form should be fully hydrolyzed (99% or higher) and the polymer should be ground to a particle size of 100 mesh or smaller. The powder can be added to wood fiber prior to refining or it can be added to the system after refining. It should also be noted that the process water used to dissolve polyvinyl alcohol fiber or powder should not be more than 60°C as hot water will dissolve the polymer and most bonding characteristics will be lost.

Suter et al. in their study described the coating of electrical grade paper with a material insoluble in liquid dielectrics and is substantially free of alkali metals (polyvinyl alcohol/starch) [31]. The coating material is present in 2-15% of total weight of coated paper. For a coating which increases coat weight per unit area by less than 4 % could increase the dielectric constant by 25%.

A process for internally strengthening the paper or board during their manufacture so that they can have enhanced strength properties have also been studied [32]. The cellulosic pulp fibers are blended with polyvinyl alcohol to increase strength properties. The composition of polyvinyl alcohol varied from 3-10% and the composition of cellulosic pulp fibers varied from 97-90%. The paper so formed had increased tear resistance and mechanical resistance.

Kinsley in his study described the production of paper which comprised of cellulosic pulp fiber, a particulate binder substantially insoluble in water and an emulsion comprised of lecithin and fatty acid [33]. The binder used was polyvinyl alcohol powder. The composition of cellulosic pulp fiber varied from 60 to 90%, the composition of binder which was insoluble in water varied from 10 to 20% and the composition of emulsion of lecithin and fatty acid varied from 1 to 10%. The invention dealt with improving the strength properties of paper like dry strength, wet strength and folding endurance of paper. Kinsley in his study described the production of paper which comprised of cellulosic pulp fiber, a particulate binder substantially insoluble in water and an emulsion comprised of lecithin and fatty acid [34]. The binder used was AIRVOL 165SF (product of Air products and Chemicals Inc). The composition of cellulosic pulp fiber varied from 60 to 90%, the composition of binder which was insoluble in water varied from 10 to 20% and the composition of emulsion of lecithin and fatty acid varied from 1 to 10%. The invention dealt with improving the strength properties of paper like dry strength, wet strength and folding endurance of paper. This method was cost effective method of producing paper.Additives were used to improve paper strength properties [35]. Additives may be added to paper pulp slurry prior to sheet formation or after sheet formation depending on the properties desired such as wet strength, dry strength, folding endurance, oil resistance and stain resistance. The invention dealt with improving the folding endurance of paper by treating paper with hydroxyl containing polymer and multifunctional aldehydes in presence of catalyst. The composition of aldehydes was 100 to 800 weight percent of the polymer and the catalyst was present in the weight ratio of about 1:0.2 to 1:1 aldehyde: catalyst.

Sr No.	**Dimensions of fibers**	**Binders**	**Composition**	**Properties**	**Reference**
1	Not specified	No binder	The electrical insulating paper is coated with starch/polyvinyl alcohol/ protein in range of 2-15%	For a coating which increases coat weight per unit area less than 4 % can increase the dielectric constant by 25%	[31]
2	Not Specified	No binder	3-5% polyvinyl alcohol and rest cellulosic pulp fibers	Increase in tear resistance, mechanical reistance and strength of paper	[32]
3	Length: 2-15 mm and dia: 10-15 µm, dia of microfiber 0.2-10µm	Polyvinyl alcohol powder	Cellulosic pulp fiber (60-90%), a binder insoluble in water (10-20%) and an emulsion of lecithin and fatty acid (1-10%)	Increase in dry strength of paper	[33]
4	Not specified	Airvol 165SF	Cellulosic pulp fiber (50-75%), a binder insoluble in water (15-25%) and an emulsion of lecithin and fatty acid (1-10%)	Cost effective method of paper making	[34]

5	Not specified	Polyvinyl alcohol	10% of polyvinyl alcohol is added on oven dry basis at wet end. Paper used is kraft paper of 65 gsm.	Increase in dry strength, wet strength and folding endurance of paper.	[35]

Table 3.3: Summary of polyvinyl alcohol and cellulose paper composites

3.4 Polyacrylate/Polyketone/Acrylonitrile/Rayon and cellulose composites

Cellulose fibers are blended with these fibers to increase their thermal stability.

Ucci et al., in their study described the preparation of paper from wet spun fibers from a physical blend of acrylonitrile polymer and cellulose fatty acid ester fibrids [43]. The fibrids were first beaten to fibrillate them; these were then sheeted out to form a sheeted article and finally dried to form paper. The paper so formed had improved physical properties. The composition of acrylonitrile polymer varied from 1-18% and the composition of cellulose fatty acid ester varied from 85 to 98%.

A process for the production of dielectric paper from wood pulp fibers and large diameter rayon or polyvinyl formal fibers was studied by Selke et al., [44]. The composition of wood pulp fibers varied from 90 to 98% and the composition of polyvinyl formal fibers varied from 2 to 10%. The paper produced had low dielectric constant, low dielectric loss tangent, a high dielectric strength and sufficient oil passage due to its porous nature as compared to conventional paper.

The use of polymer reinforcement to improve the properties of paper such as dimensional stability, resistance to chemical and environmental degradation, resistance to tearing, emboss ability, resiliency, conformability, moisture and vapor transmission, and abrasion resistance have also been studied [45]. Polymer reinforced paper was prepared by 50% dry weight of pulp and 15 to 50% by weight of bulking agent containing polymer such as polyacrlylates, styrene-butadiene copolymers. The paper so formed had improved tear strength in machine cross direction.

Shiratori et al., in their study described polyketone fiber paper which was comprised of aliphatic polyketone fibers [46]. The paper had high mechanical strength, high modulus of elasticity, excellent dimensional stability, chemical resistance, adhesiveness, heat resistance, low dielectric and low water absorbance. The paper comprised of 1 to 100% by mass aliphatic polyketone fibers having length 1-3 mm and diameter variation of 5-50 µm. The above studies are summarized in Table 3.4.

Sr No.	Dimensions of fibers	Binders	Composition	Properties	Reference
1	Diameter: 0.3 to 20 denier	Anti foaming agent: octlyl alcohol	Acrylonitrile polymer (1-18%) and cellulose fatty acid ester (85-97%)	Improved paper having highly valuable physical properties	[43]
2	Length:0.25 inch, Dia: 1 to 15 µm	No binder	Wood pulp fibers (90-98%) and rayon/poly vinyl formal fibers (2-10%)	The paper produced is of low cost, has less porosity and high dielectric strength	[44]
3	Length: 1-2.2 mm	Poly acrylates	Cellulosic pulp fibers (30-70%), polyethylene glycol	Moisture content of final paper is less than 5%, increase in strength in cross direction tear	[45]
4	Length of fibers: 0.5 mm to 10 mm, Dia: 1-20 µm	No binder	Aliphatic Polyketone fiber (70-100%)	The paper produced has excellent heat resistance, abrasiveness, chemical resistance, low dielectric and water absorbance	[46]

Table 3.4: Summary of Polyacrylate/Polyketone/Acrylonitrile/Rayon and cellulose paper composites

CHAPTER 4
EXPERIMENTAL SETUP

The scope of this chapter contains the characterization techniques to evaluate the composite pressboard prepared using cellulose pulp and synthetic fiber. The evaluation of pressboard generally contains properties like dielectric constant, tensile strength, compression strength, break down voltage, volume/surface resistivity, etc. In order to evaluate these properties, it is required to follow standard test procedure which is described in IEC, ASTM, etc.

4.1 Characterization of pressboard

In this chapter a brief description of experimental setup and test methods are discussed under various test conditions.

4.1.1 Drying setup

Unless otherwise specified, the following drying procedure as per the IEC 60641-2 should be used. Dry the test pieces in a ventilated oven at 105 °C ± 5 K. the minimum drying time as a function of the thickness (Th) expressed in millimeters should be as follows:

Nominal thickness ,Th , (mm)	≤ 0.5	0.5 < Th ≤ 1.5	1.5 < Th ≤ 5	> 5
Time (hrs)	12	24	48	72

Table 4.1: Minimum drying time with respect to thickness of pressboard (IEC 60641-2)

For prepared composite pressboard with thickness 1.5 mm the following drying procedure is followed.

Materials

1. Heater
2. Silicon oil
3. Temperature controller
4. Inert Gas (For purging purpose)
5. Clamps
6. Teflon ring
7. Vacuum grease
8. Vacuum desiccator
9. Vacuum pump (max. 0.02 mbar)

10. Silicon sealant

- Glass wares

1. Oil bath
2. Two neck 3 liter flat bottom cylindrical vessel

Procedure

The procedure of drying process for pressboard with thickness 1.5 mm is as follows:

1. In oil bath take silicon oil and put heater and temperature controller in it as shown in figure 4.1

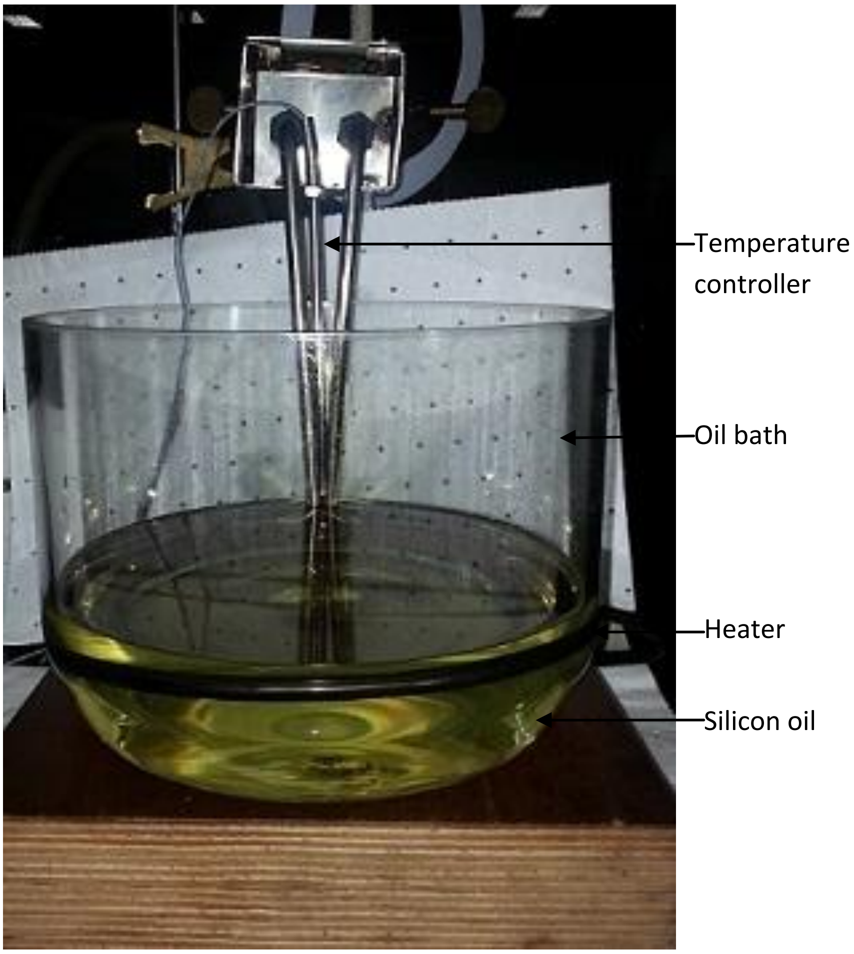


Figure 4.1: Schematic picture of oil bath.

2. Maintain the temperature about 130°C ± 5 °C of oil bath.
3. Take samples in cylindrical vessel having temperature sensor and air tight it.
4. Make sure that there is no leakage in cylindrical vessel.
5. Put the cylindrical vessel into oil bath having temperature 130 °C (adjustable).
6. Check the temperature of samples (through temperature sensor) and make sure it will not exceed to 105 °C ± 5 °C.
7. When heating of samples start check thoroughly for the moisture in the assembly.

8. When water droplets (vapors condensed at the top of assembly) are observed, vacuum is applied in the assembly for the removal of moisture.
9. For better drying it is required to take inert gas break (mainly N_2) for 5 minutes in the time interval of 1 hour.
10. Carry out this process at least for 24 hours.

After the drying period has passed, the samples should be cooled in vacuum desiccator and tested within 3 min of removal from the desiccator. The schematic picture of drying assembly in which oil bath, vacuum chamber, vacuum line, heater and samples are shown in figure 4.2

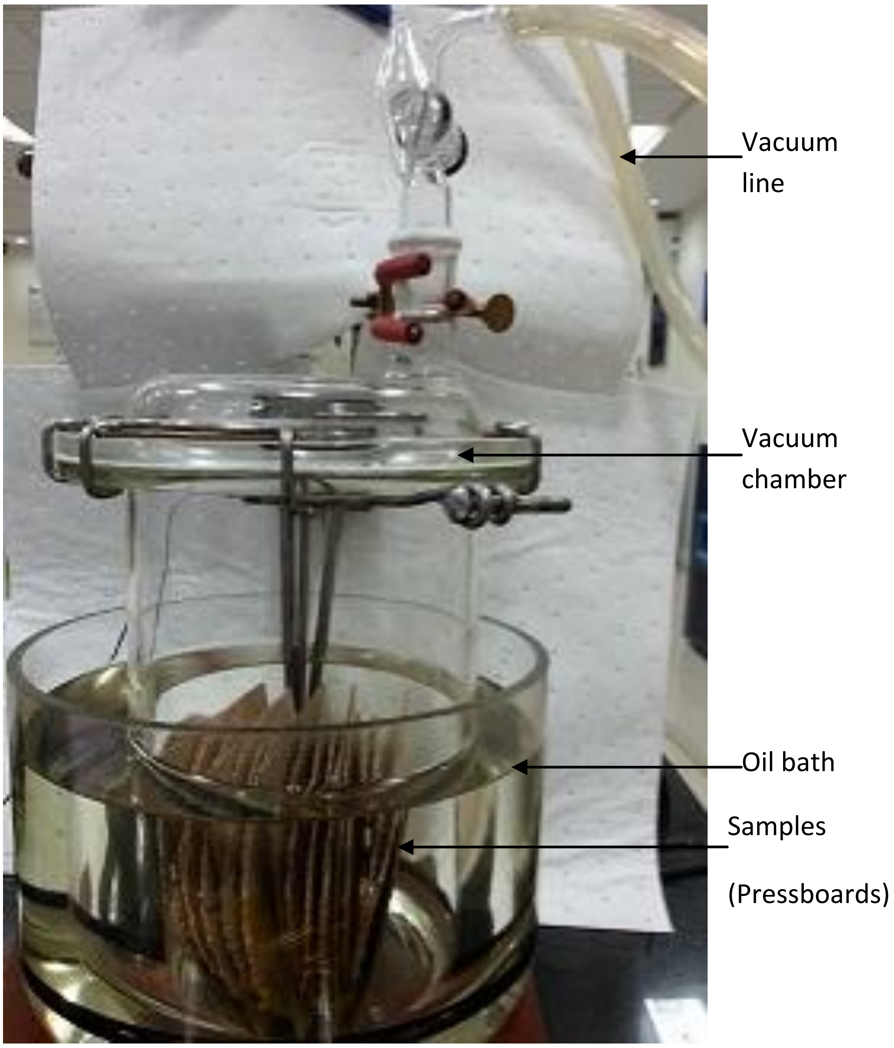


Figure 4.2: Schematic picture of drying assembly.

4.1.2 Moisture Content setup

The moisture content of material should be measured in accordance with ISO 287 (oven drying method). The method consists of weighing the test pieces at the time of sampling and again after a drying period, which led to a constant mass of the test piece. The drying should be carried out as described in 4.1.1. The mass of test piece should be at least 20 g and its area is 100 cm^2. Three test pieces should be taken and report all values. The central value should be taken as result.

Apparatus

1. Computrac® MAX® 4000XL (Arizona Instrument LLC).

Principle

The MAX® 4000XL moisture analyzer, as shown in figure 4.3, works on the principle of weight loss as a function of temperature.

Figure 4.3: MAX® 4000XL moisture analyzer.

The percentage of moisture based on the original sample weight is calculated as follows

Moisture, % = [(W_1- W_2) / W_1] x 100

Where, W_1 = original weight of the sample

W_2 = weight of the sample after drying

As the sample is heated, it loses weight due to moisture evaporation. During the entire testing process, the sample’s weight loss is monitored and is fitted to a standard drying curve.

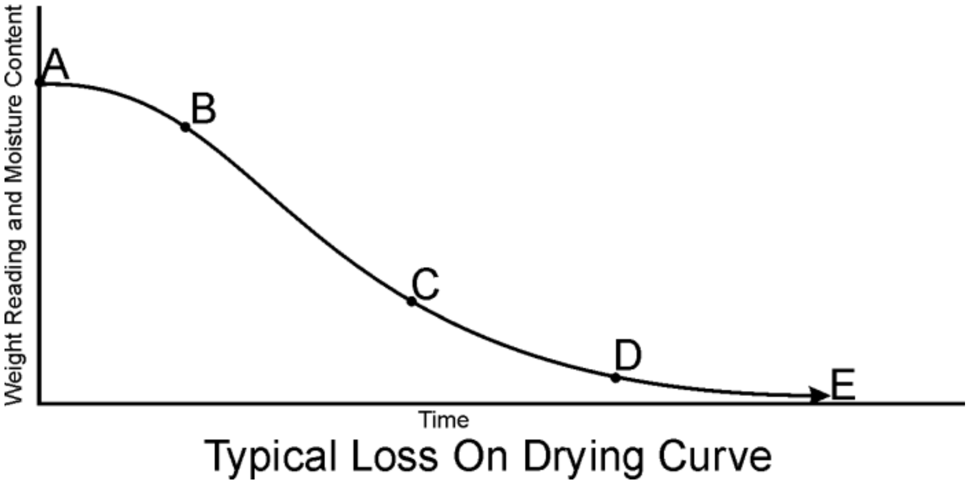


Figure 4.4 Graph between Moisture content and Time.

The graph of moisture content w.r.t. time is shown in figure 4.4; section (A-B) represents the sample's weight loss as it heats from room to testing temperature. Section (B-C) is linear, representing moisture loss from the interior of each particle of the tested sample. Section (C-D) is exponential in nature and represents the final evolution of moisture from within the particle. The point (E) at which no additional weight loss occurs represents the complete evolution of water from the original sample. Section (D-E) is longest and time-consuming portion of the entire testing process. The sample's decreasing weight is compared to the initial sample weight and the calculated moisture concentration appears on the display. The final moisture concentration is extrapolated from the curve and results are available within minutes.

Procedure

The Computrac® MAX® 4000XL is a simple and user friendly instrument. For performing the measurement, the following steps should be followed

1. Switch ON the instrument from the switch board and an ON/OFF button located at the back of the instrument.
2. Open the lid. Place a clean aluminum pan sample holder on the pan support. Alternately the pan can be cleaned and used for successive measurement. Close the lid
3. Perform the Weight Test. Click on PROGRAM, (Factory) WEIGHT and START. After the pan tare, open the lid. Place 3g and 5 g weight at the center of the

aluminum pan. Close the lid. After 0.04 minute, gently remove the 3 g weight from the pan and close the lid. The weights handling should be done with help of a tweezers.

4. The instrument gives three beeps after the measurement is over. The test result values (% moisture) should essentially be in the range of 37.480% and 37.520%. The in-built fan starts cooling the test chamber automatically.
5. For sample measurement, click on PROGRAM, CGL and START. If the test parameters such as temperature, sample size are to be changed then click on PARAM. Note that if the parameters for a particular program are to be changed then it should be done only after entering the said program. (CGL in this case)
6. Select the parameter (temperature), click ENT, edit the value, and click ENT. Then click ESC. Similarly the other parameters such as sample size, sample name can be edited. Now the instrument is ready for performing the test as per requirement.
7. Click on PROGRAM, CGL and START. Open the lid and gently place the sample with tweezers at the center of the aluminum pan.
8. The sample is heated up to the desired programmed temperature. The LCD screen displays the heating process and the subsequent change in the sample weight, time, rate of moisture evaporation, result (% moisture).
9. After the measurement is over, the instrument gives three beeps. Click on GRAPH. The graph is displayed as Time (X-axis) vs. Moisture (Y-axis) and Rate of moisture removed (Y-axis). The graphical representation can also be viewed during the measurement.
10. Click on DATA to get the Test Result.

The result is displayed in the following forms:

1. % Moisture: percentage of weight lost.
2. % Solids: percentage of weight remaining.
3. % Dry Weight: moisture on a dry weight basis.

The instrument results are precise to better than:

1. 0.002% SD typical for < 0.020% moisture
2. 10% RSD from 0.020% - 0.100% moisture
3. 20% RSD from 0.100% - 100% moisture

(SD: Standard deviation, RSD: Relative Standard deviation)

4.1.3 Oil impregnation setup

The oil absorption process was carried out in between 70 °C – 90 °C under vacuum of 1 kPa .Oil conforming with the requirements of IEC 60296, preheated to 70 °C to 90 °C should be admitted at a rate slow enough to ensure that the proper impregnation of pressboards, monitor the process carefully. When the test pieces are completely submerged in the oil and the oil is 2 inch above the pressboard, switch off the vacuum. Stand time of 6-8 hrs should be given. The test pieces are then taken out of the oil and the surplus of oil wiped with filter paper, if required.

Materials

1. Naphthenic Oil (fresh oil of 22-25ppm)
2. Oil filtration unit
3. Heater
4. Temperature controller
5. Strap heater
6. Silicon oil
7. Inert Gas (For purging purpose, mainly N_2)
8. Clamps
9. Teflon ring
10. Vacuum grease
11. Vacuum desiccator
12. Vacuum pump (max. 0.02 mbar)
13. Silicon sealant
14. Silicon pipe
15. Filter paper
16. Viasala moisture analyzer

- Glass wares

1. Oil bath
2. Two neck 3 liter flat bottom cylindrical vessel
3. Two neck 3 liter flat bottom bottle
4. Two way vacuum stop cock

Procedure

1. After drying of pressboard, moisture content and dielectric constant of the pressboards are measured;

2. Dried pressboards are again kept in the vacuum chamber and heat the chamber at temperature max. 90 °C ± 5 °C. This step must be taken because the dried pressboards are exposed to air when taken for measuring dielectric constant and it absorbed some moisture from the atmosphere.
3. Carry out heating at least for 1 hr.
4. Simultaneously, filter fresh naphthenic oil with the help of oil filtration unit, as shown in figure 4.5 till the oil ppm reaches below 5 ppm.

Figure 4.5: Schematic figure of oil filtration unit.

5. Connect the filtered naphthenic oil (< 5 ppm) reservoir (two neck 3 liter flat bottom bottle) and start heating with the help of strap heater up to 80 °C ± 10 °C.
5. The preheated oil should be admitted slowly to assembly containing pressboard. The oil should fill drop by drop in the assembly so that the oil can fill the voids present in the pressboard.

Figure 4.6: Full experimental set up for oil impregnation.

6. When the pressboards are completely submerged and the oil is 2 inch above the pressboards, the vacuum is released by inert gas (mainly N_2) and the pressboards are allowed to stand immersed in oil at a temperature 90 °C ± 5 °C at least for 24 hrs.
7. The pressboards are then cooled to room temperature while completely immersed in oil.
8. The pressboards are then taken out and the surplus of oil is wiped with filter paper and preserves the pressboard in vacuum desiccator.

After completing the above said process the pressboards are tested for DC with minimum exposure to the outer environment.

4.1.4 Dielectric constant setup

These test methods measures the capacitance of pressboards. Dielectric constant of oil impregnated pressboards is measured.

Calculation

As it is well known that the dielectric constant of a material is defined as the ratio of its capacitance and the capacitance of the media in which the material capacitance is measured. In this report the media is air in which the samples capacitance is measured. So the mathematical relation used for calculating the dielectric constant is described in Eq 4.1.

$$\kappa = \frac{C_s}{C_a} \qquad \textbf{(Eq 4.1)}$$

Where,

C_s is the sample capacitance;

C_a is the air capacitance.

The capacitance can be calculated by a general formula which is as follows:

$$C = \frac{\varepsilon_0 \times \varepsilon_a \times A}{t} \qquad \text{(Eq 4.2)}$$

Where,

C is the capacitance, in F;

A is the Area of overlap of the two electrodes, in mm^2;

ε_0 is the electric constant ($\varepsilon_0 \approx 8.854\times10^{-12}$ F m^{-1});

ε_a is the relative permittivity of material between the electrodes;

t is the separation between the plates.

So the calculations that are made for calculating the dielectric constant of samples are as follows:

1. Air Capacitance measurement

With the help of equation 4.2 the air capacitance can be calculated as:

$$C_a = \frac{\varepsilon_0 \times \varepsilon_a \times A}{t} \qquad \text{(Eq 4.3)}$$

Where,

C_a is the capacitance of air, in pF;

A is the area of overlap of the two electrodes (A = 2375 mm^2);

ε_0 is the electric constant ($\varepsilon_0 \approx 0.008854$ pF mm^{-1});

ε_a is relative permittivity of vacuum between the electrodes(for vacuum, $\varepsilon_a = 1$);

t is the separation between the plates.

So Eq 4.2 becomes

$$C_a = \frac{0.008854 \times 2375}{t} \qquad \textbf{(Eq 4.4)}$$

The Eq 4.3 is used for calculating the air capacitance of experiments throughout the whole period. The value of “t” is taken as the corresponding thickness of the pressboard. The value obtained from the Eq 4.4 is the corresponding air capacitance C_a.

2. Sample Capacitance measurement

The two – electrode system was used for measuring the sample capacitance. The following procedure should be followed:

Apparatus

1. Aplab 4190 LCR meter (inductance, capacitance and resistance) with remote cord as shown in figure 4.7.

Figure 4.7: Figure of LCR meter with remote cord.

2. Electrodes (dia. 55 mm) as shown in figure 4.8.

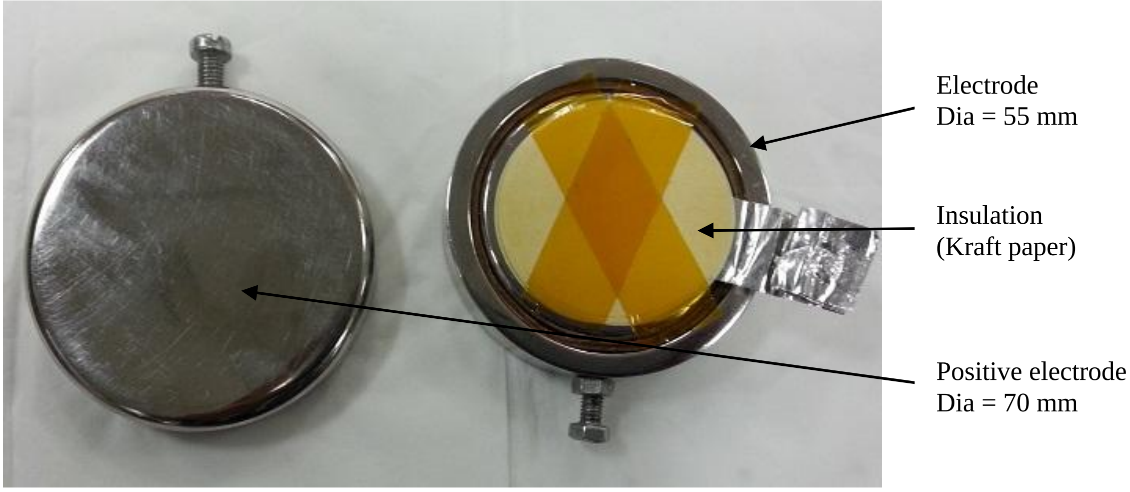


Figure 4.8: Schematic figure of electrodes.

3. Hydraulic press (only for applying pressure)
4. Vacuum desiccator
5. Dehumidifier (for controlling Temperature and Humidity)

Procedure

For controlling the surrounding environment around the experimental setup (full setup is shown in figure 4.9), dehumidifier is used. The controlled environment around the experimental setup requires the temperature below 50 °C and humidity below 40%.

Figure 4.9: Schematic figure of full experimental setup for measuring sample capacitance.

The following steps are taken during performing the experiment:

1. **1.** First of all apply the insulation (kraft paper) on the top and bottom platform of the hydraulic press which is used for only applying the pressure.
2. **2.** Now mount the electrodes in between the plates of hydraulic press.
3. **3.** Connect the electrodes with LCR meter through remote cord.
4. **4.** Before performing the experiment, ensure the connection and environmental conditions.
5. **5.** Now take out sample from vacuum desiccator and wipe off excess of oil from its surface
6. **6.** Place the pressboard in between the two electrodes such that both the electrodes are at the centre of pressboard. It will avoid the creepage current.
7. **7.** Apply pressure 2 kgf/cm^2 so that there is no air gap between the sample and electrode. Pressure is applied so that there is no air gap as well as any movement of sample occurs between the electrodes.
8. **8.** Note down the reading shown in the LCR meter.

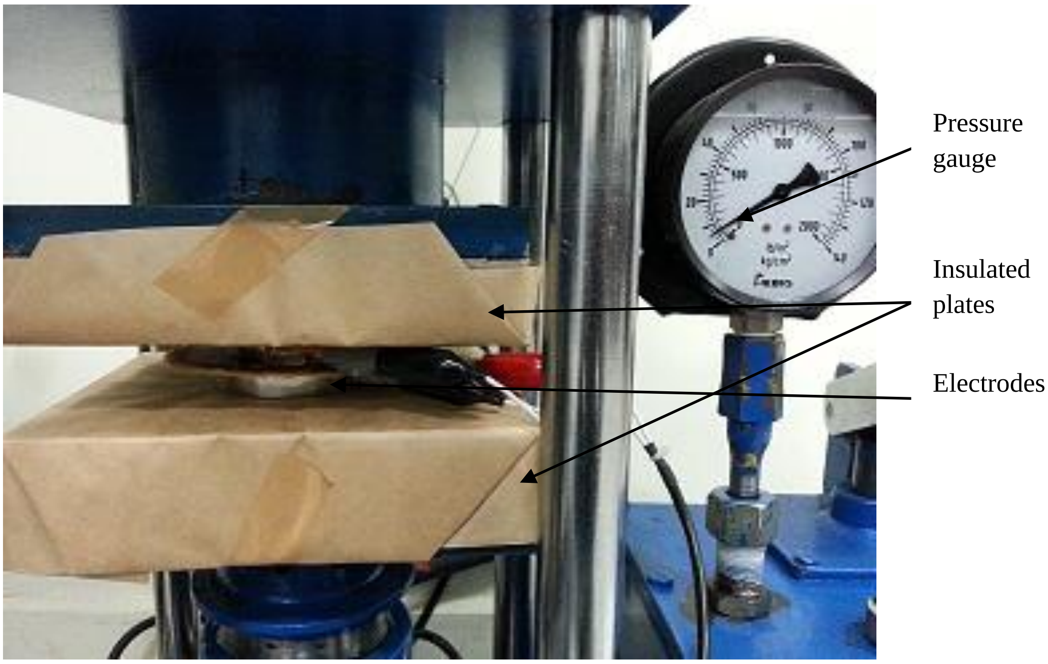


Figure 4.10: Figure of DC measurement experiment.

This reading is considered as a sample capacitance C_s. Now the value of C_a and C_s is used in Eq 4.1 to find out the dielectric constant of a sample (pressboard).

4.1.5 Tensile Strength setup

The tensile strength of a pressboard is one of the most important properties. Measurement of the tensile force required under standardized conditions to cause failure of the samples 15 mm × 250 mm cut from both direction of the sample. The tensile strength, in MPa, is calculated by the formula:

$$\sigma = \frac{F}{w \times A} \qquad \textbf{(Eq 4.5)}$$

Where,

F is the force, in N;

W is the width of the sample, in mm;

A is the thickness of sample, in mm.

As the laboratory made composite pressboard does not meet the dimension requirement as per the standard IEC 60641-2 so it is necessary to resize the sample according to ratio method i.e. if 250 mm sample require 180 mm gauge length then 100 mm sample require 72 mm gauge length. All others parameter such as width of the sample, gauge speed, etc were kept as per standard requirements.

Apparatus

1. Llyod UTM machine with 50 KN load as shown in figure 4.11.

Figure 4.11: Schematic figure of UTM.

Procedure

1. Cut the sample in dimension 150 mm × 250 mm.
2. Set the machine setup according to standard ISO 1924-2 i.e. gauge speed is 20 mm/min and gauge length 72 mm (calculated by ratio method).
3. Hang the sample between the jaws of the UTM machine and start the test.
4. Note down the readings on the machine, in MPa.
5. Compare the results with standard readings.

4.1.6 Compressibility

According to IEC 60641 – 2, the pressboards with a thickness ≥ 0.5 mm was tested for compressibility.

Principle

To determine the compressibility of pressboard, a stack of samples is subjected to a low pressure (bedding pressure) 1 MPa, followed by an increase of the pressure to a defined value (final pressure) 20 MPa. The percentage change in the thickness of the stack is a measure of the compressibility of the material.

Apparatus

1. Universal testing machine designed to compress a test piece of given dimensions at an appropriate constant rate of compression and to measure the compressive force and the deflection of sample.
2. A test rig with parallel steel plates and area greater than the area of samples itself.

Sample preparation

1. Cut a sufficient number of square samples with an edge of 25 ± 5 mm the number of samples should be chosen so that three stack of a height of 25 mm to 50 mm can be made.
2. All edges of the sample should be free of burrs.
3. The sample should be dried in an oven at 105 °C ± 5 °C for 4 to 24 hrs.
4. Subsequently the oven should be evacuated at approximately 1 kPa.
5. The complete drying period should be 24 hrs to 48 hrs.

Procedure

1. Place a stack of sample between the plates of the test rig.
2. Apply a bedding pressure of 1 MPa for at least 5 min. and then measure the height h_o of the stack with an accuracy of ± 0.1 mm.

3. Increase the pressure to 20 ± 0.1 MPa. During this operation, the rate of displacement of the moving plate should be 5 ± 1 mm/min.
4. Maintain this pressure for 5 min minimum and then measure the height $h_{1.}$
5. Measure the difference in height Δh_1 from h_o of the stack with an accuracy of ± 0.1 mm.
6. Reduce the pressure to 1 MPa and keep it for not less than 5 min.
7. Measure the difference in height Δh_2 from h_o of the stack with an accuracy of ± 0.1 mm after the bedding pressure has been restored.

Calculation

Compressibility (in %)

$$\text{Cm} = \frac{\Delta \text{h1}}{\text{h0}} \times 100 \qquad \text{(Eq 4.6)}$$

CHAPTER 5
RESULTS AND DISCUSSIONS

The purpose of this chapter is to provide experimental results performed at lab scale and their discussions in detail.

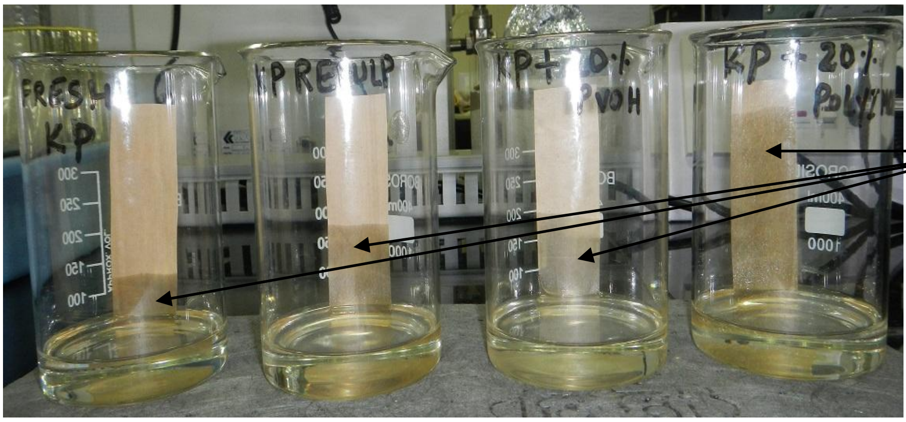
5.1 Fiber loading

The optimization of fiber loading in composite pressboard is very important aspect because the properties of pressboard are affected due to the different loading of fibers. The composite pressboards of no load, 10 %, 15 %, 20 %, 25% and 30% of fiber loading are prepared, tested and compare their properties. The reduction in dielectric constant of 10% and 15% are approx. 1.5 % and 7% respectively which is very less so that they are not considerable while in 30% loading the compressibility of pressboard exceed the standard limit. So it is observed that the 20% and 25 % of fiber loading is giving good result.

5.2 Oil Impregnation

Oil impregnation is one of the most important because in power transformer the solid insulation is fully immersed in liquid insulation (i.e. mineral oil) and it withstands more electric stress. The absorption ability of pressboard is very good as it is porous in nature. Due to oil absorption the variation in all the properties of pressboard are observed. So it is very important to study the characterization of pressboard under oil impregnation condition.

During oil impregnation it is observed that the oil is absorbed by the capillary effect as shown in figure 5.1. Due to capillary action, the oil molecules replaces the air from the voids and due to this the variation in properties are observed. For proper oil impregnation it is required that the rate of impregnation is slow enough so that the maximum air voids are replaced by oil.



Rate of oil absorption at different composition

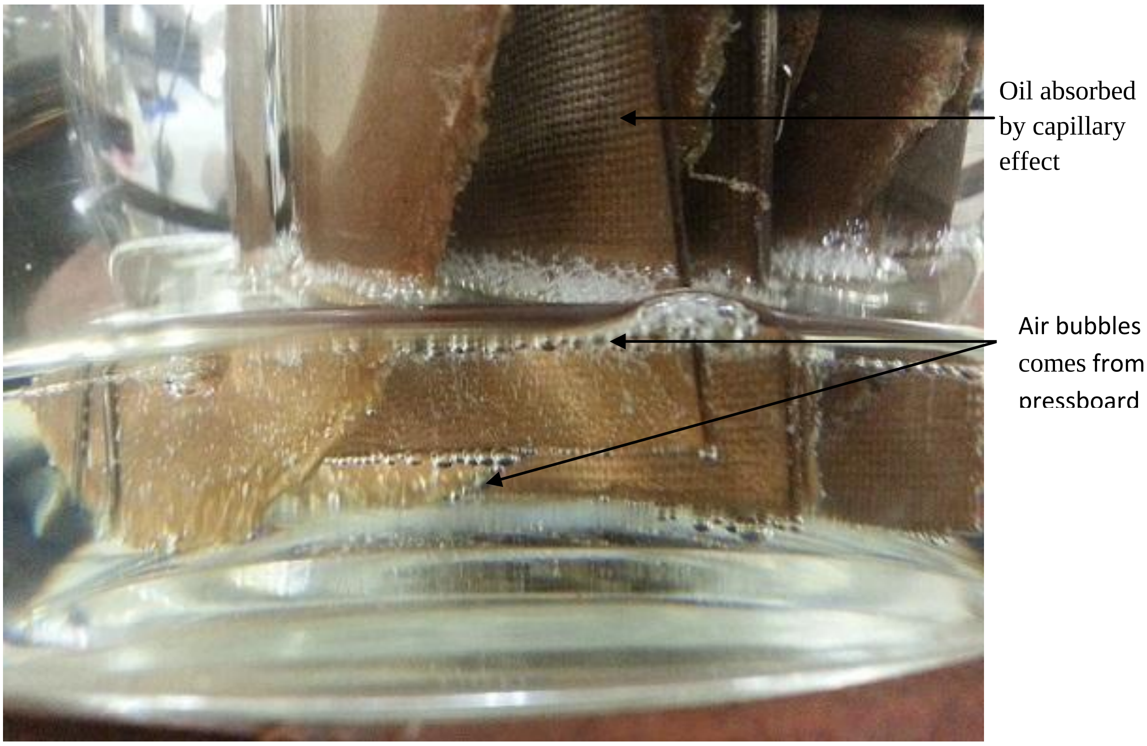
Figure 5.1: Capillary action during oil impregnation.

The rate of oil absorption at different composition is shown in figure 5.1. The rise in the level of absorbed oil in compositions is due to the different fiber % loading. The rise in the level of oil absorption is directly depending upon the %fiber present in it. If the % level of fiber is high then the corresponding composition has fast impregnation.

It is necessary that the proper oil impregnation of samples is performed so that the results of other test methods are obtained accurately. The important steps taken for proper impregnation are as follows

1. During impregnation check that there is no air bubbles are come along with oil.
2. Rate of impregnation is slow so that the voids are filled with oil.
3. Vacuum is lifted only when there is no air bubbles are coming out from the samples.

During impregnation, as shown in figure 5.2, the air bubbles are coming out form samples indicates that air removal from the voids by oil and implies that the proper impregnation is carried out.



Oil absorbed by capillary effect

Air bubbles comes from pressboard

Figure 5.2: Oil impregnation of pressboards.

5.3 Dielectric Constant measurement

The dielectric constant of virgin pressboards and composite pressboards are measured in both medium i.e. in air and after oil impregnation. The dielectric constants of virgin pressboards are compared with composite pressboard with different percentage (%) of fiber loading. The results of dielectric constant of pressboards in air are summarized as follows:

The dielectric constant of oil impregnated pressboard (OIP) in three electrode system is measured. The dielectric constant of oil impregnated virgin, 10%, 15%, 20%, 25%, and 30% of fiber loading pressboards is summarized in table 5.1.

Sample No	Thickness (mm)	Dielectric constant
Virgin pressboard		
V 1	1.56	4.72
V 2	1.55	4.6
V 3	1.53	4.53
V 4	1.55	4.52
V 5	1.54	4.51
10% fiber loading		
AHP 1	1.59	4.49
AHP 2	1.52	4.42
AHP 3	1.46	4.38
AHP 4	1.53	4.35
AHP 5	1.44	4.28
15% fiber loading		
BHP 1	1.44	4.34
BHP 2	1.6	4.23
BHP 3	1.45	4.19
BHP 4	1.45	4.13
BHP 5	1.58	4.11
20% fiber loading		
CHP 1	1.5	4.19
CHP 2	1.5	4.1
CHP 3	1.58	4.09
CHP 4	1.55	4.08
CHP 5	1.53	3.98
25% fiber loading		
DHP 1	1.42	3.93
DHP 2	1.68	3.88
DHP 3	1.52	3.76
DHP 4	1.47	3.69
DHP 5	1.68	3.61

30% fiber loading		
EHP 1	1.55	3.66
EHP 2	1.5	3.6
EHP 3	1.62	3.55
EHP 4	1.62	3.49
EHP 5	1.53	3.41

Table 5.1: Dielectric constant of composite pressboard in three electrode system.

The comparison of dielectric constant of oil impregnated virgin, 10%, 15%, 20%, 25%, and 30% of fiber loading pressboards is shown in figure 5.1.

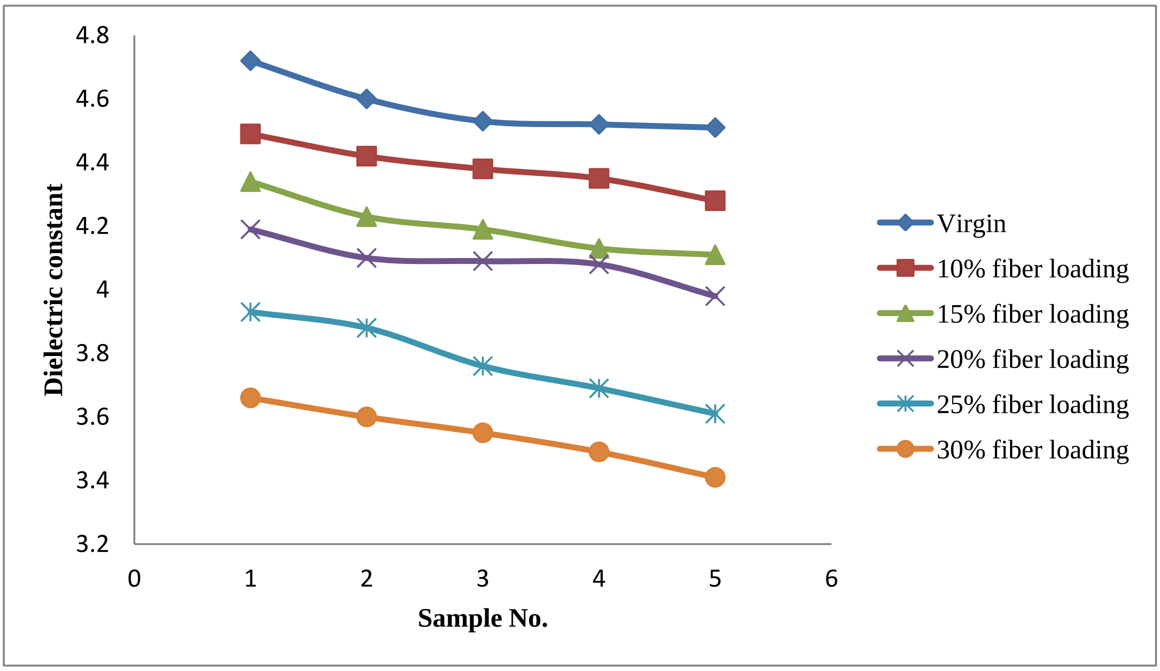


Figure 5.3: Comparison of dielectric constant of oil impregnated composite pressboard in three electrode system.

In figure 5.3 it is clearly shown that the dielectric constant of oil impregnated pressboard is reduced as the fiber loading in pressboard is increased. Approximately 20% reduction in oil impregnated composite pressboard having 30% fiber loading is observed. This dielectric constant is measured in three electrode system where the stray capacitance in neglected. To observe the effect of stray capacitance on dielectric constant the experiment is performed in two electrode system and the detailed result is discussed below.

5.3.1 Dried pressboard

The dielectric constant of pressboards in air are summarized and discussed below as well as compare the variation in the values of different kind of pressboards. The dielectric constant of virgin pressboards is summarized in table 5.2.

Sample No.	Thickness (mm)	Dielectric constant
V1	1.55	3.65
V2	1.54	3.68
V3	1.55	3.61
V4	1.56	3.67
V5	1.55	3.62
V6	1.6	3.78
V7	1.62	3.91
V8	1.59	3.82
V9	1.61	3.97
V10	1.6	3.83

Table 5.2: Dielectric constant of virgin pressboards in Air

As we see the variation in the dielectric constant with respect to the thickness of the pressboards. It is easily observed that the approximate thickness 1.55 mm of pressboards have dielectric constant of 3.61-3.68 while the pressboards having the approximate thickness of 1.6 mm have dielectric constant of 3.78-3.97. The thickness of pressboard is directly proportional to the dielectric constant when all other parameters are kept constant. So it is important to maintain the thickness of composite pressboard with accuracy for measuring accurate dielectric constant. The lab made pressboards, having no fiber loading but prepared with repulp process, shows reduction in dielectric constant, see table 5.3.

Sample No.	Thickness (mm)	Dielectric constant
LHP 1	1.58	3.33
LHP 2	1.56	3.32
LHP 3	1.55	3.29
LHP 4	1.52	3.22
LHP 5	1.56	3.38

Table 5.3: Dielectric constant of lab made (without fiber loading) pressboards in Air.

In table 5.3, it is clearly observed that the range of dielectric constant of lab made pressboard with thickness of 1.56 mm is 3.22-3.38

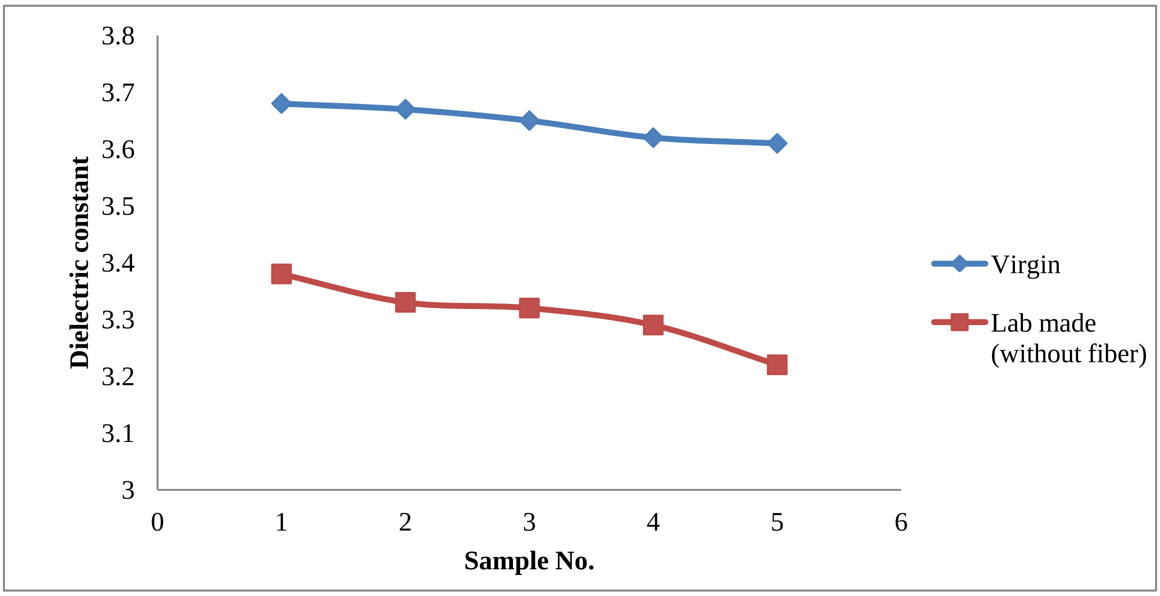


Figure 5.4: Comparison of DC between Virgin and lab made pressboard in Air.

It is observed that there is a reduction of 9.5% in dielectric constant between virgin and lab made (without fiber) pressboards as shown in figure 5.4. The drop in dielectric constant in lab made pressboard may be occurred due to the presence of large amount of air voids in it. The dielectric constant of composite pressboard having loading of 20% and 25% Crompt 150 fibers is summarized in table 5.4.

Where,

CHP is 20% Crompt 150 fibers and kraft paper

DHP is 25% Crompt 150 fibers and kraft paper.

Sample No.	Thickness (mm)	Dielectric constant
20% Crompt 150 + Kraft paper		
CHP 1	1.55	3.25
CHP 2	1.46	3.32
CHP 3	1.3	3.13
CHP 4	1.52	3.3
CHP 5	1.68	3.3
25% Crompt 150 + Kraft paper		
DHP 1	1.56	2.99
DHP 2	1.54	3.03
DHP 3	1.55	2.99
DHP 4	1.54	3.09
DHP 5	1.55	2.98

Table 5.4: Dielectric constant of composite pressboards in Air.

From the table 5.4 it is clearly observed that the dielectric constant is reduces with the increment of loading of Crompt 150 fibers. The reduction in dielectric constant is due to the presence of Crompt 150 fibers in pressboard. The comparison of dielectric constant between virgin, lab made and composite pressboard are shown in figure 5.3.

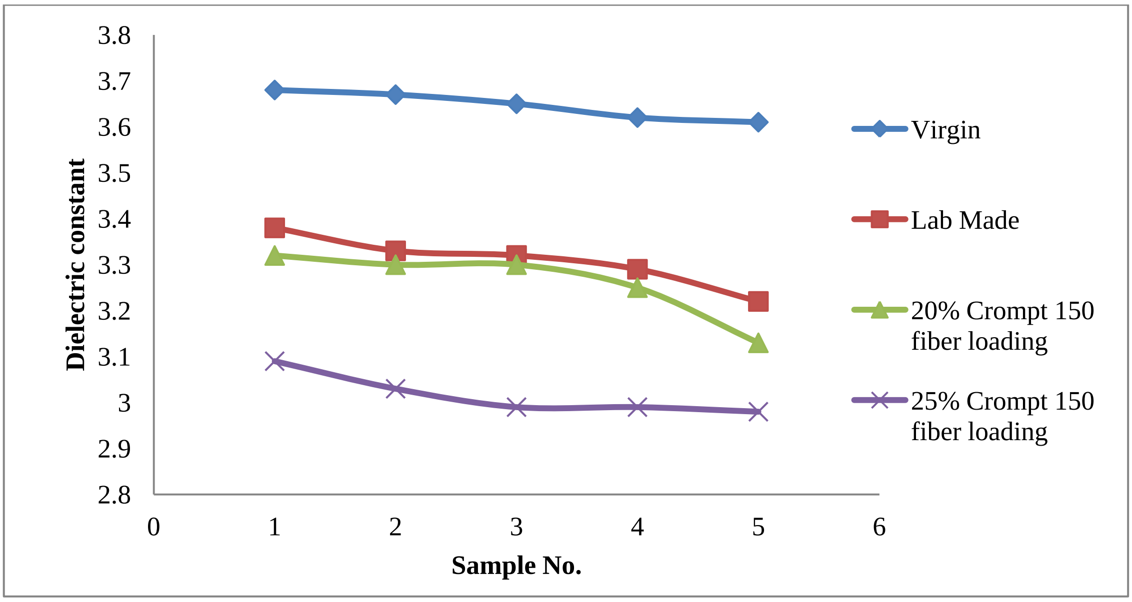


Figure 5.5: Comparison of Dielectric constant between virgin and composite pressboard in Air.

A large amount of reduction in the dielectric constant of composite pressboard as compared to virgin pressboard is shown in figure 5.5. The range of the dielectric constant of 20% and 25% loading of pressboard is 3.1 to 3.3 and 2.98 to 3.09 respectively. 25% of loading of fibers in the virgin pressboard, the reduction of DC by 18 % – 20 % is achieved.

But these pressboards are used in transformer as a solid insulation where oil is also present as a liquid insulation and both of them take as a part of insulation system. The result regarding dielectric constant as discussed above is in air (dried) not in oil so it is necessary to check the dielectric constant of oil impregnated pressboard.

5.3.2 Oil impregnated pressboard

The dielectric constant of pressboards is hampered when immersed in oil. So the scope of this section is to analyze the variation in dielectric constant of different type of pressboards. Table 5.5 shows the summarized values of dielectric constant of virgin pressboards.

Sample No.	Thickness (mm)	Dielectric constant
V25	1.55	4.2
V26	1.54	4.31
V27	1.55	4.31
V28	1.56	4.27
V29	1.55	4.19
V20	1.6	4.4
V21	1.62	4.48
V22	1.59	4.33
V23	1.61	4.38
V24	1.6	4.36

Table 5.5: Dielectric constant of oil impregnated virgin pressboard.

The range of dielectric constant of oil impregnated virgin pressboard is 4.2 to 4.5 as shown in table 5.5. When the pressboard is impregnated with the oil, the oil replaces the air voids present. This replacement of oil helps in the increment in dielectric constant of pressboard because the dielectric constant of air is 1 while transformer oil is 2.1. The dielectric constant of lab made pressboard with no fiber loading and various fibers loading of pressboard such as 20% (CHP) and 25 % (DHP) are summarized in table 5.6. The range of the value of dielectric constant of oil impregnated composite pressboards is as follows:

1. No loading of fiber is 4.06 – 4.23
2. 20% Fiber loading is 3.78 – 4.03
3. 25% fiber loading is 3.69 – 3.82

Sample No.	Thickness (mm)	Dielectric constant
Without fiber		
LHP 1	1.58	4.23
LHP 2	1.56	4.06
LHP 3	1.55	4.2
LHP 4	1.52	4.09
LHP 5	1.56	4.12
20% Crompt 150 fiber + Kraft Paper		
CHP 1	1.55	4.03
CHP 2	1.46	3.98
CHP 3	1.3	3.78
CHP 4	1.52	3.92
CHP 5	1.68	3.94
25 % Crompt 150 + Kraft paper		
DHP 1	1.56	3.69
DHP 2	1.54	3.79
DHP 3	1.55	3.72
DHP 4	1.54	3.76
DHP 5	1.55	3.82

Table 5.6: Dielectric constant of oil impregnated composite pressboards.

Comparison of dielectric constant between Virgin and composite oil impregnated pressboards are shown in figure 5.6. The reduction in the value of dielectric constant is approx. 8 % for 20% fiber loading and approx 15 % for 25 % of fiber loading.

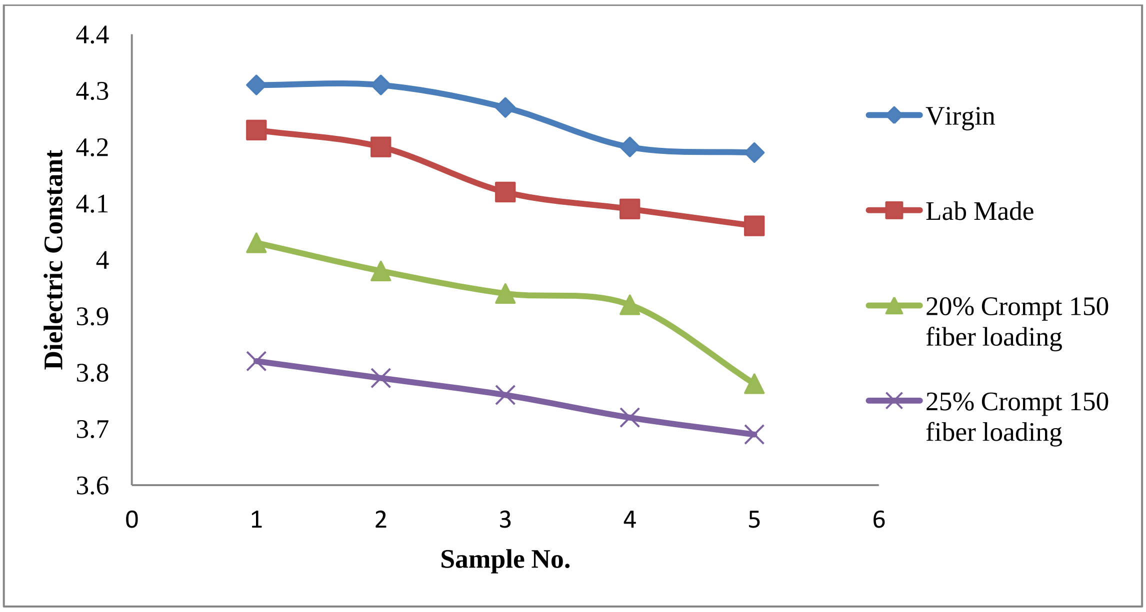


Figure 5.6: Comparision of DC between oil impregnated virgin and composite pressboards.

Other composition of pressboards is also prepared and compares their properties with respect to virgin pressboards. Table 5.7 summarized the value of Crompt 150 fiber having different cut length and different denier in kraft paper.

Sample No.	Thickness (mm)	Dielectric constant
20% Crompt 150 (6$, 12mm) + Kraft paper		
612CHP 1	1.72	3.98
612CHP 2	1.51	3.88
612CHP 3	1.43	3.82
612CHP 4	1.53	3.76
612CHP 5	1.54	3.78
612CHP 6	1.64	3.79
20% Crompt 150 (3$, 12 mm) + Kraft paper		
312CHP 1	1.32	3.58
312CHP 2	1.64	3.79
312CHP 3	1.57	3.61
312CHP 4	1.45	3.78
312CHP 5	1.64	4.00
20% Crompt 150 (malice anhydride grafted) + Kraft paper		
MGC 1	1.4	3.38
MGC 2	1.48	3.51
MGC 3	1.6	3.69
MGC 4	1.38	3.63
MGC 5	1.57	3.62

Table 5.7: Dielectric constant of 20% modified fiber loading pressboards.

Where,

612 CHP is 6 denier and 12 mm cut length of Crompt 150 fiber with 20 % loading in kraft paper 312 CHP is 3 denier and 12 mm cut length of Crompt 150 fiber with 20 % loading in kraft paper

MGC is malice anhydride grafted Crompt 150 fiber with 20 % loading in kraft paper

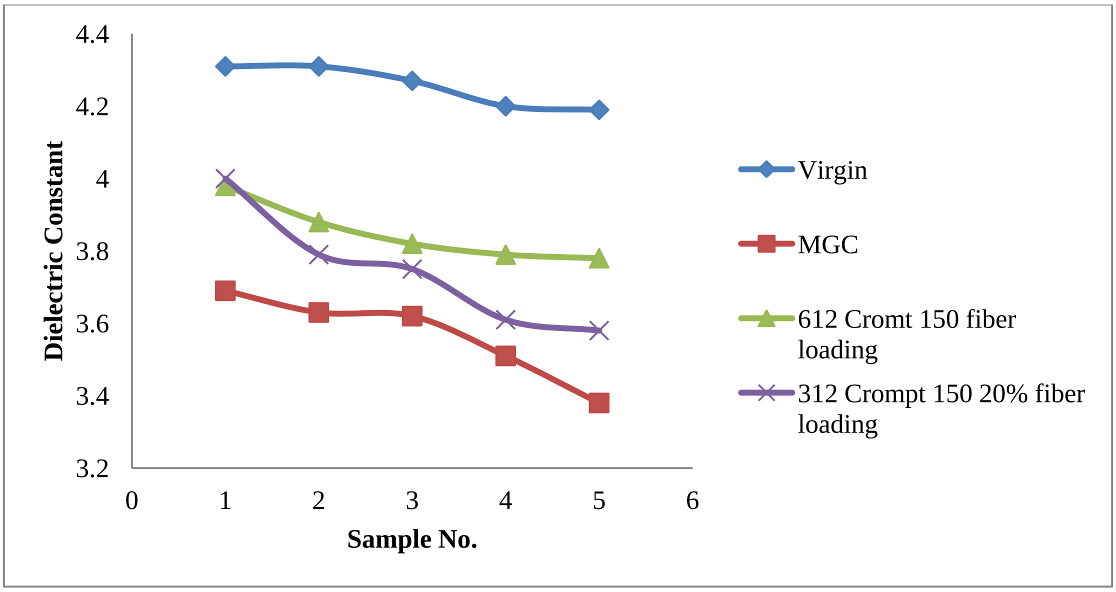


Figure 5.7: Comparision of DC between oil impregnated virgin and 20% modified fiber loading pressboards.

The comparison of dielectric constant with virgin pressboard and various compositions of composite pressboards are shown on figure 5.7. The range of dielectric constant is as follows:

1. 612 Crompt 150 fiber and kraft paper is 3.98 – 3.76
2. 312 Crompt 150 fiber and kraft paper is 4.00 – 3.58
3. MGC Crompt 150 fiber and kraft paper is 3.69 – 3.38

5.4 Tensile Strength

The difference in tensile strength properties of virgin pressboards and composite pressboards are shown in table 5.7. these tests were performed according to IEC 60641-2 standard. Generally the tensile strength of virgin pressboard used in power transformer is 88 – 90 MPa (IEC 60641-2). All the experiments are performed in machine direction and values of tensile strength are summarized in table 5.7.

Where;

V stands for virgin pressboard,
LHP stands for no fiber loading,
CHP stands for 20 % Crompt 150 fiber loading in kraft paper and
DHP stands for 25 % Crompt 150 fiber loading.

Sample No	Tensile Strength (Mpa)
Virgin pressboard	
V1	86.95
V2	88.45
V3	88.55
V4	89.29
V5	90.61
V6	91.04
V7	91.71
V8	91.99
No Fiber Loading	
LHP1	53.83
LHP2	54.07
LHP3	56.38
LHP4	59.13
LHP5	61.06
LHP6	62.31
LHP7	62.82
LHP8	63.78
20% Fiber loading	
CHP 1	45.05
CHP 2	45.36
CHP 3	45.39
CHP 4	46.4
CHP 5	49.48
CHP 6	51.27
CHP 7	52.72
CHP 8	53.91
CHP 9	55.71
CHP 10	55.91
CHP 11	56.73
CHP 12	57.72

25% Fiber Loading	
DHP1	40.52
DHP2	41.91
DHP3	43.18
DHP4	45.45
DHP5	47.47
DHP6	49.73
DHP7	50.14
DHP8	50.36
DHP9	53.43
DHP10	54.06
DHP11	54.06
DHP12	54.66
DHP13	54.88

Table 5.8: Tensile strength of virgin and composite pressboards.

The comparision of tesile strength between the virgin and composite pressboards are shown in figure 5.8. When the amount of fiber loading is increased there is the reduction in the tensile strength is observed.

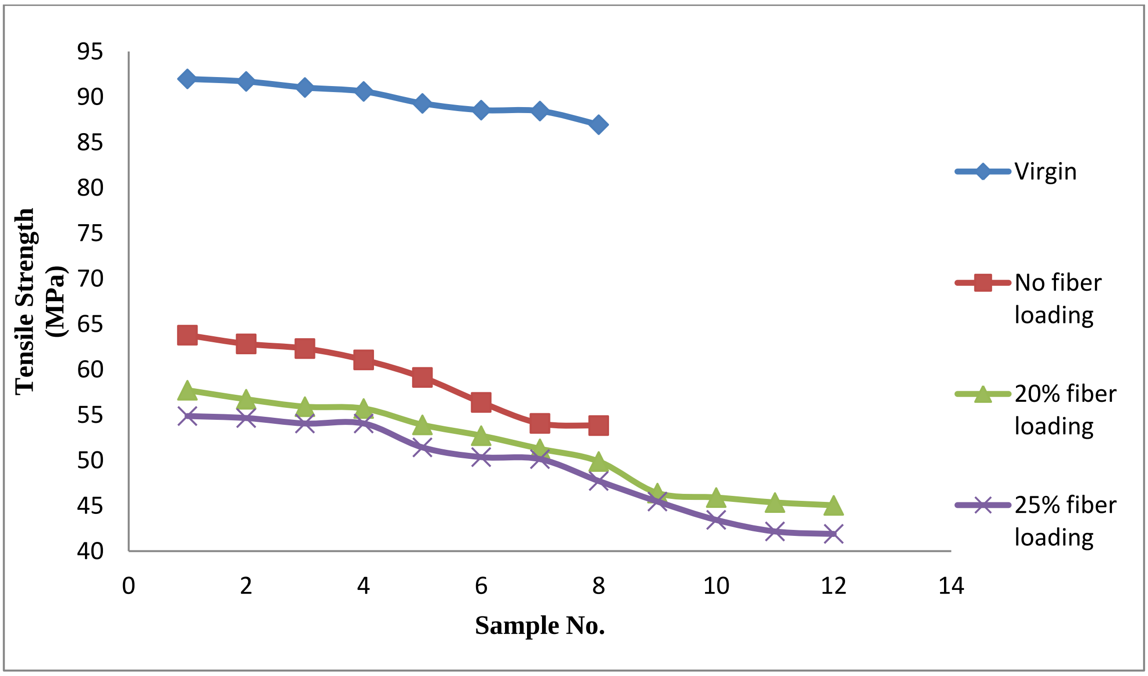


Figure 5.8: Comparision of tensile strength between virgin and composite pressboards.

5.5 Compressibility

The study of compressibility of pressboard is also necessary as it is one of the most important mechanical properties. According to standard value the allowable compressibility of pressboard in power transformer is approx. 8%. The compressibilty of composite pressboard is measured according to the standard IEC 60641-2. The experimental results and the variation in the compressibility of composite pressboard with respect to virgin pressboard is shown in table 5.9.

Sample No	**Initial Height Hi (mm)**	**Height & Load of Sample**						**Compressibility (%)**
		Lo (kg)	**Ho (mm)**	**L1 (kg)**	**H1(mm)**	**L2 (kg)**	**H2 (mm)**	
Virgin pressboards								
V 1	25.07	60	21.77	1272	19.87	64	22.07	8.72
V 2	24.8	58	20.6	1276	19	68	21.8	7.76
V 3	24.29	61	20.89	1268	19.39	72	21.49	7.18
V 4	24.55	58	23.25	1274	20.35	65	23.25	12.47
20 % Crompt 150 + Kraft Paper								
C 1	24.52	59	22.52	1276	18.02	62	19.82	19.98
C 2	25.53	58	24.03	1280	19.13	66	21.33	20.39
C 3	24.76	62	22.56	1272	15.76	66	19.77	30.14
30% Crompt 150 + Kraft Paper								
E 1	25.12	64	22.12	1270	16.32	65	18.92	26.22
E 2	24.65	64	21.96	1272	16.66	62	18.76	24.13
E 3	25.28	59	22.48	1272	17.68	67	19.68	21.35

Table 5.9: Compressibility value of virgin and composite pressboards.

CONCLUSION

Earlier it was discussed how solid insulation degrades gradually because of high electric stress between solid and liquid insulation. To reduce this electric stress, it is advisable to reduce the permittivity (dielectric constant) of solid insulation. With the help of different fillers and additives such as organic fibers, inorganic fibers, glass fibers, etc it is achievable to reduce the permittivity of the solid insulation with the limitation of altering the other properties. So the characterization of these pressboards is very important.

1. In the dissertation, characterization of pressboard of different percentage of fiber loading is studied. After studying the properties of modified pressboard, it is concluded that the dielectric constant (permittivity) is reduced when the %of fiber loading is increased. The study of properties with 0%, 10%, 15%, 20%, 25% and 30% of fiber loading is done. It is also concluded that due to the presence of air voids (having dielectric constant 1) in between the cellulose, the dielectric constant of composite pressboard is less with respect to virgin (original) pressboard.

   The pressboard having 25% of fiber loading with kraft paper gives the best result as the dielectric constant of oil impregnated pressboard is reduced to 3.7 – 3.8 from virgin (original) pressboard having dielectric constant 4.2 – 4.8.
2. However, the tensile strength composite pressboard shows a reduction of at least 50% as compared to virgin (original) pressboard.
3. The compressibility of composite pressboard increases by 8% to 10% as compared to virgin (original) pressboard.

RECOMMENDATION FOR FUTURE WORK

1. It is advisable that for more reliable and overall size reduction of power transformer, the target should be to reduce the electric stress between insulation system about 10% to 15%.
2. To study the relationship between processing variables and dielectric as well as mechanical properties.

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