POLYMER FIBRE AND CELLULOSE COMPOSITE PAPER WITH STARCH BINDER FOR ELECTRICAL INSULATION

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

degree of

MASTER OF TECHNOLOGY
IN
CHEMICAL ENGINEERING

By

ABHISHEK KUMAR PANDEY
(Roll No.601111003)

UNDER THE GUIDANCE OF

Dr. RAJEEV MEHTA

Head and Associate Professor

Department of Chemical Engineering

Thapar University, Patiala

Dr. P.K BAJPAI

Distinguished Professor

Department of Chemical Engineering

Thapar University, Patiala

Department of Chemical Engineering
Thapar University Patiala-147004,
Punjab, India.

July 2013

DECLARATION

*This is certified that the dissertations entitled "**POLYMER FIBRE AND CELLULOSE COMPOSITE PAPER WITH STARCH BINDER FOR ELECTRICAL INSULATION**" is an authentic record of my own work carried out as requirement for the award of the degree of **M.Tech.** (Chemical Engineering) at Thapar University, Patiala, under the guidance of Dr. Rajeev Mehta (Head and Associate Professor, ChED) and Dr. P.K. Bajpai (Distinguished Professor, ChED) during July 2012 to June 2013.*

Date- 15/07/2013

Abhishek Kumar Pandey
(Roll No-601111003)

It is certified that the above statement made by the student is correct and best of our knowledge & belief.

13.07.2013

Dr. Rajeev Mehta
Head & Associate Professor
Department of Chemical Engineering
Thapar University, Patiala

13.07.13

Dr. P.K. Bajpai
Distinguished Professor
Department of Chemical Engineering
Thapar University, Patiala

Counter signed by-

15/7/13

Dr. Rajeev Mehta
Head & Associate Professor
Department of Chemical Engineering
Thapar University, Patiala

Dr. S.K. Mohapartra
Dean Academic Affairs
Thapar University, Patiala

ACKNOWLEDGEMENTS

This dissertation is the end of my journey in obtaining my M.Tech. This work has been kept on track and been seen through to completion with the support and encouragement of numerous people including well wishers, my friends, colleagues and various institutions. At the end of my dissertation, I would like to thank all those people who made this dissertation possible and an unforgettable experience for me. It is a pleasant task to express my thanks to all those who contributed in many ways to the success of this study and made it an unforgettable experience for me.

It is a matter of extreme honor and privilege for me to offer my grateful acknowledgement to my supervisors **Dr. Rajeev Mehta** and **Dr. P.K. Bajpai** for providing me a chance to work under their guidance and supervision, assisting with all kinds of support and inspiration, excellent guidance, constant encouragement, sincere criticism and valuable suggestions which they proffered throughout this investigation and preparation of this report.

I am obliged to **Dr. P.K. Bajpai,** Dean Research and sponsored project, Thapar University, Patiala for his constant encouragement, technical support and needful help during various stages of the work.

I am grateful to **Dr. Rajeev Mehta,** Head, Department of Chemical Engineering, Thapar University, Patiala for his support in every moment of difficulty. His skills, constructive suggestions and constant inspiration to this work helped me to fulfill this effort.

I am very thankful to **Dr. Raj Kumar Gupta** my P.G. Coordinator (Chemical Engineering),Thapar University , Patiala for his terrific guidance regarding the thesis writing and sir has provided us much time to write this work.

I would like to thank all the faculty members of the Chemical Engineering Department, Thapar University, Patiala for their encouragement to complete this work.

Words are inadequate in expressing my sincere thanks to **Dr. Nishi K. Bhardwaj**, Deputy Director, Thapar Centre for Industrial Research and Development for allowing me to test hand sheets made at Thapar University in his research lab.

I would like to convey my sincere gratitude to **G. Selvamaharajan,** Thapar Centre for Industrial Research and Development for extending their valuable technical support from time to time.

I am also thankful to seniors and colleagues **Shilpa Narang, Toyesh Upreti, Mohit Garg, Shubham Kaushal, Amit Kamboj** and **Anil Kamboj** for their incomparable help during the experimental work.

Abhishek Kumar Pandey

Abstract

As per the demand of power transmission systems the life of transformer depends upon the insulating material used. The most important insulating materials of optimum dielectric strength properties that have been used in large high-voltage transformers through almost a century are the oil impregnated, cellulose-based products: primarily paper and pressboard. The chief disadvantage of cellulosic material for electrical use is that it is hygroscopic in nature and needs to be processed and maintained dry. For power transformers the process is quite elaborate and time consuming. To overcome this limitation, a new area to look forward to is blending of cellulose fibers with synthetic fibers. The most important property of these materials is their high thermal stability. Their dielectric strength is excellent, being above that of Kraft paper, and they retain this property for a sustained period even at high temperature for short periods of time. This work discusses the production of electrical grade composite paper from Kraft pulp, synthetic fibers and cationic starch as binder. The insulation paper produced by blending Kraft pulp with synthetic fibers, polyethylene terepthalate has good mechanical properties making it useful for electrical insulation in transformers.

Keywords Insulation, electrical grade kraft paper, synthetic fibers, cationic starch.

Table of Content

Abbreviations

ASTM	American Standard of Testing and Materials
CD	Cross Direction
DGA	Dissolved Gas Analysis
DMA	Dynamic Mechanical Analysis
DSC	Differential Scanning Calorimetry
EDXS	Energy Dispersive X-Ray Spectrometry
FTIR	Fourier Transform Infra-Red
MD	Machine Direction
pA	Pico Ampere
PVOH	Poly Vinyl Alcohol
SEM	Scanning Electron Microscope
TAPPI	Technical Association of Pulp and Paper Industry (USA)
TGA	Thermo Gravimetric Analysis
TMA	Thermal Mechanical Analysis
WDXS	Wave Dispersive X-Ray Spectrometry

List of Tables

List of Figures

Chapter 1: Introduction

1.1 Materials used for insulation

These are the materials permit only a negligible current (order of pA) to flow in phase with the applied voltage. Insulating materials 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 as, for example, paper, cloth, paraffin wax and natural resins. Wide use is made 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.

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 which is sustained at elevated temperatures
2. High resistivity
3. Good thermal conductivity
4. High tensile and shear strength of solid insulation
5. High degree of thermal stability

In addition to the above properties, the material should have other good mechanical properties such as ability to withstand moisture (it should be non-hygroscopic), vibration, abrasion and bending. Also, it should be able to withstand chemical attack, heat and other adverse conditions of service.

1.2 Cellulose paper insulation

Cellulose insulation has been the preferred choice for the solid insulation in power transformers, because it is available in plenty from natural renewable source - softwood.

Insulation grade paper is made by the delignification of wood pulp by the Kraft process. The major constituent of paper is cellulose, which is a natural polymer of glucose. It has about

90% cellulose, 6 to 7% lignin and the balance is hemicellulose. The natural water content of paper is 4 to 5% by weight and the insulation is dried after winding to less than 0.5%.

The dried paper is impregnated with insulating oil, which increases its dielectric strength and also serves to cool the windings. 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 to 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.

1.3 Degeneration of insulation

Heat, water and oxygen degrade (depolymerise) the cellulose, reducing the polymer molecular chain length and with it the mechanical strength of the material. 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. Thermal ageing of transformer insulating materials is associated with the chemical reactions occurring within the materials. These chemical reactions are caused by pyrolysis, oxidation and hydrolysis, and are accelerated by increased levels of temperature and of the oxygen and moisture contents. Apart from chemical reactions, there is a reduction in the mechanical properties of cellulose paper. The paper insulation becomes brittle to the point of almost falling apart, but it still retains an acceptable level of dielectric strength. Once in the transformer, the insulation begins to age over many years. Its water content increases because of the degradation of the molecular chain by thermal stresses and oxidative processes. Depolymerisation of the cellulose chain lowers the chain length and mechanical strength. The insulation finally becomes brittle and carbonaceous with no short circuit withstand capability. This stage is termed as an absolute end of life. Thus the combined action of temperature, oxygen and moisture cause the insulation to lose mechanical strength and become weak and brittle [1]. There are two main sources of moisture inside the transformer. One is ingress of atmospheric air into the tank. The amount of water into the transformer's tank strongly depends on the design of the transformer. The rate of water contamination in transformers with membrane-sealed conservator preservation systems is about 0.03 to 0.06% of water in cellulosic materials per year. But the rate of water contamination of transformers with an open-breathing conservator is even up to 0.2% per year [2,3]. The second source of moisture in the transformer is the aging processes of

insulation [4,5,6].

The temperature of a transformer has a major impact on the life of the insulation. The best technique for evaluating the ageing of such thermally resistant papers is the determination of the degree of polymerization (DP) of the constituting cellulose chains. However, the technique turns out to be impractical due to the difficulty in retrieving paper samples in the field [7]. Continuous on-line monitoring of the transformer oil temperature along with a thermal model of the transformer can give an estimate of the loss of life of the transformer due to overheating. Current industry standards limit maximum allowable hot spot temperatures in transformers to 140°C with conventional oil/paper insulation. The accelerated electric stress is an important factor considered in the oxidation of the oil. The weight and dimension restrictions of the transformer lead to a decrease in insulation clearances. Consequently, the oil ducts also become narrower and hence the strength of the electrical field increases which exerts a great effect on the oxidation process. Essentially, the electric stress supplies the energy (approximately 4 eV) required for the cleavage of a covalent bond. The mechanism by which the high voltage field interacts with the chemistry of insulating oil. The hidden source of energy capable of breaking covalent bonds consists of the electrons that escape from the conduction band and manage to leave the surface of the metal conductor, especially during very short but frequent communication voltage surges.

An accumulation of colloidal suspensions is of particular interest in sealed transformers, especially when dissolved gas analysis (DGA) indicates the existence of a hot spot or an incipient electrical failure. End of life may be dictated by any one factor or by a combination of factors. Much attention has been given to a paper ageing as a cause of transformer failure. While it is undoubtedly a factor in reducing life, it does not automatically lead to failure; some other influence is normally required, such as a mechanical shock.

1.4 History and background of transformer

A transformer is a device for stepping-up, isolating or stepping-down, the voltage of an alternating electrical signal and is widely used for transferring energy of an alternating current in the primary winding to that of one or more secondary windings [8] Transformers are complex devices consisting of an iron core around which are wrapped various coils of insulated wires, inside a tank filled with insulating oil, along with connectors, bushings and various other small components [9]. The design of transformers is based on the expected sustained and short-term power-frequency voltage stresses originating on the network and

those caused by lightning and switching surges. Besides, the growing geometrical dimensions, disposal of heat losses and the determination of local hot spots resulting from stray magnetic fields are factors of increasing concern in the design.

Technological advances in recent decades have accustomed the development engineer to rapid changes, a phenomenon that will have to be taken into account when considering the future of transformers. It seems that in near future, the transformer will still remain an important element of power systems. It is not easy to predict what new requirements will be raised in the years to come. In any case, the present state of the art is surely an important link in the chain leading into the future.

Like other machines, transformer too has limited life. However, unlike most other machines, it does not have any moving parts, except tap changers or cooling fan or pump motors. The outages, therefore, is not due to wear out. The transformers die because of deterioration of insulation over time. The insulation system in most power transformers consists of oil/paper on the copper windings, and there are also several oil-impregnated pressboard barriers between the high and low voltage windings, and sometimes also between windings and the core [10]. The insulation is subjected to a variety of stresses, such as thermal, mechanical, electromagnetic, etc. Under the influence of the these stresses and in the presence of oxygen and moisture, the insulation deteriorates continuously over a period of time, eventually leading to failure.

1.5 Development of transformer insulation

Transformer insulation had developed concurrently with the transformer development, but it took a few decades before the paper-oil combination became reliable and well accepted. In the early 1930s, kraft paper insulation began to be used in combination with insulating oil in transformers. This combination was used to satisfy the increasing insulation requirements as the voltage readings escalated. In the 1940s, kraft paper in combination with oil was the dielectric material of choice for high voltage transformers. Synthetic dielectric materials which slowly developed in the late 1950s, began to replace cellulosic insulation in power cables and capacitors. Mixtures of cellulosic and synthetic materials are now used in many transformer insulation applications [11].

1.5.1 Kraft paper and board

It is difficult to pinpoint the time when electrical grade paper was introduced, but it is known that such papers were used for capacitors and cables extensively before becoming the primary insulation in transformers. The use of resin impregnated paper for transformer was introduced at the turn of 20^{th} century [11]. The introduction of oil impregnation of paper led to the discontinuation of resin impregnated paper. By the late 1920s transformer board (now called pressboard) form kraft pulp could be easily fabricated into formed items. The calendered press board is ideal for washers and tubes used in power transformers.

The press board is used in electrical industry as spacing and insulating medium. These are made from rags or a mixture of rags and kraft in wet machine in thickness ranging from 0.0005 to 0.0125" (12.7-317.5 μm). Vulcanised fiber board is used as an insulation material in winding motor armatures. The desirable properties of paper for such use are good mechanical and high dielectric strength. Some of the grades of the low calliper are also known as fish paper.

1.5.2 Creped paper turn insulation

Although plain kraft paper is widely used for insulation in transformers in many countries, creped paper turn insulation is used in U.S.. Creped paper is a tear free paper for taping. The tough hemp kraft paper used for taping at the time had very little stretch. The creped paper has as much as 20% stretch (elongation). The introduction of the creped paper was a few years after thermal upgrading agents were put into paper so the creped paper could be thermally upgraded at the same time from non upgraded paper [11].

1.5.3 Thermal upgrading of paper

As the rating of transformers climbed, the transformers would occasionally became overloaded; the concern for transformer life, or rather, paper insulation life was raised. Thermal upgrading of paper insulation was considered as one remedy. The purpose of upgrading is to increase the insulation life [12]. Accelerated ageing studies confirmed that cellulose degradation is considerably slowed by upgrading agents. Westinghouse studies on insulating paper showed that upgraded paper could take a temperature rise of 20 to 30°C greater as compared with non upgraded paper [13].

1.5.4 Hygroscopic nature of polymer

Another attempted improvement of cellulosic paper was targeted at reducing its hygroscopicity. Dry paper can absorb a considerable amount of water which is a function of relative humidity and temperature [14]. Chemical modification with cyanoethylation not only improves thermal performance but also reduces hygroscopicity. In the mid 1990s efforts were made to reduce hygroscopicity by graft polymerization [15]. The grafted material had the lowest moisture absorption. However, the reduced moisture absorption came with a price: the paper was more brittle and the dissipation factor was higher than that for paper.

1.6 Categorization 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.

1.6.1 Electrical analysis

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

1.6.1.1 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.

1.6.1.2 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 contant and dielectric breakdown voltage. A voltage ramp rate of 5 kV/minute is typically used for material properties assessment.

1.6.1.3 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 resistivities.

1.6.2 Mechanical analysis

1.6.2.1 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.

1.6.2.2 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.

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

1.6.2.4 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.

1.6.3 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.

1.6.3.1 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.

1.6.3.2 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.

1.6.4 Thermal analysis

1.6.4.1 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 T_g temperature above the intended operating temperature. There is a significant drop in mechanical properties above the T_g temperature.

1.6.4.2 Glass transition method by DMA (ASTM El640): This is an excellent method to determine the glass transition temperature, T_g, for thermoset materials. The test procedure uses Dynamic Mechanical Analysis (DMA) methods. T_g 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 T_g temperature.

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

1.6.4.4 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.

1.6.4.5 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 behaviour 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.

Thus the topic preparation and characterization of polymer fiber and cellulose composite paper for electrical insulation covers the process of production of paper from kraft pulp and synthetic fibers viz Recron 3s© (Polyethylene terepthalate (PET) fibers, a product of Reliance industries Limited, India), Polyimide P84©(Polyimide fibers, a product of Evonik Iindustries, Austria). The paper thus produced has high thermal, mechanical and electrical resistance making it suitable for use in high power transformers.

Chapter 2: Literature Review

For the development in electrical power systems in recent years it has been desired to develop extra and ultra high voltage transformers. For this purpose, development of high quality insulating paper is required. Some of the relevant studies on approaches to develop better fiber cellulose paper composites are discussed below

2.1 Inorganic fibers

2.1.1 E glass fiber and cellulose composite paper

Glass papers were made by the wet-forming papermaking process. The first step in the production of glass paper is the dispersion of the glass fibers in an aqueous slurry. The fibers are treated with special sizing agents to provide good dispersion. The slurry is then deposited evenly across the width of a woven wire belt which moves at speeds as high as 305 meter per minute and is saturated with a binder. As this wet mat moves with the belt, water is pulled through the belt by vacuum to begin the drying process. Final drying is accomplished by inline ovens downstream from the wire former. Other ancillary processes such as an application of various chemical treatments, coating, and addition of scrims is done in line at convenient points in the machine. The product resulting from this process is a randomly dispersed web of fibers held together by an equally random dispersed binder.

Labino and Ohio in their study described the production of glass paper [16]. The paper so formed had the characteristics that were not capable of reproduction by natural fibers and thus making glass paper adaptable for special purposes like use in electrical appliances where thermal stability of paper required is quite high. The glass fibers had a tendency of self-adhesion which was witnessed by wetting the glass fibers in acid water and no binder was required for self adhesion of glass fibers. The resulting glass paper thus formed from glass fibers had high tensile strength.

The use of glass fibers and wood pulp to control dimensional stability has also been studied [17]. The composition of paper was 38-46% glass fibers, 24-32 % wood pulp, and around 22-38% binder. The pulp used was neutracel pulp which had following advantages over long fiber super soft pulp: a) it is less expensive and less required, b) since thickness is not critical, varying machine conditions have less of an effect on mat acceptability and c) short wood pulp fibers can also be obtained from recycled pulp which offers cost reduction properties without changes in mat structure.

A process for making fiber paper products comprising of cellulose pulp and coarse diameter glass wool has been studied by Singh [18]. The average diameter of glass wool fibers used varied from 5.5 to 11 µm. The composition of glass wool fibers varied from 1 to 25%, whereas the composition of cellulose pulp varies from 99-75%. The paper so formed was more air resistant and less hygroexpansive.

Glass fiber paper have better temperature performance (up to 200°C) but the presence of glass fibers which is necessary to impart dimensional and structural stability, shortens the life of the insulator since it precipitates partial discharges which result in breakdown of transformers. Hence, glass fibers can only be used in dry type transformers.

The above studies are summarised in Table 2.1.

Table 2.1: Summary of E glass and cellulose paper composite

Sr No.	**Dimensions of fibers**	**Binders**	**Composition**	**Properties**	**References**
1	Length: 1/8 to 3/8 inch, dia: 0.45-1 µm	Liquid synthetic resins	Glass fibers (80-99%) and liquid synthetic resin (20-1%)	Paper produced is smooth. Paper does not deteriorate at high temperature. The paper is non hygroscopic.	[16]
2	Length: 1 mm dia: 10-50 µm	B017A, B018B (Source not specified)	Cellulosic pulp fibers (38-46%), E glass fibers (24-32%), binder (22-38%)	Increased dimensional stability of paper	[17]
3	Glass wool fiber dia: 5.2 µm	Ceramic/Clay/Plastic	10-25% glass wool fibers and 75-90% cellulose pulp fibers	Increase in tear resistance of paper	[18]

2.2 Organic polymer fibers

2.2.1 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, have 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 [19]. 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 [20].

Thinius in his study described the production of mixed structures, foils, filaments and films consisting of polyamide and cellulose pulp fibers [21]. 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 [22]. 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 [23]. 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 were studied by Kato et al. [24]. 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 [25]. 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 [26] and Cornbower [27] 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 summarised in Table 2.2.

Table 2.2: Summary of polyamide and cellulose paper composite

Sr No.	Dimensions of fibers	Binders	Composition	Properties	References
1	Not specified	No binder	Cellulosic pulp fibers (60-80%) and polyamide fibers (20-40%)	Paper has good water repellent Properties	[21]
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	[22]
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	[23]
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	[24]
5	Not specified	No binder	Short aramid fibers (1-85%), extrudable polymer (20-30%)	Uniform dispersion gives Dimensionally stable paper	[25]
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	[26]
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	[20]
8	Length: 0.25 inch	Polyvinyl alcohol	Cellulosic Pulp fibers (70 %), polyvinyl alcohol (20%), poly amide fiber (10 %)	Increased Thermal resistance of Paper	[27]

2.2.2 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 [28]. Synthetic polymer and cellulose were mixed in microscopic molecular level hence the cracking and crazing caused in conventional plastic films were not created and the paper became more oil resistant. The heat resistance of the synthetic polymer was utilised 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 [29,30]. 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. [31]. 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 problem 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 2.3

Table 2.3: Summary of polypropylene and cellulose paper composites

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	[28]
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	[29]
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.	[30]
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	[31]

2.2.3 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 hydrolysed (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) [32]. 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 [33]. 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 [34]. 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 [35]. 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 [36]. 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 hydroxy containing polymer and multifunctional aldehyde in presence of catalyst. The

composition of aldehyde 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.

2.2.4. Liquid crystalline polymer and cellulose composite paper

Liquid crystalline polymer can be blended with cellulose fiber because of their superior mechanical properties and fire retardant nature. They are also non hygroscopic in nature which makes them suitable to be used as insulators in transformers.

A process for the production of low hygroscopic paper, which can be used for electric insulation was studied by Kumuda et al. [37]. The insulation paper was obtained by heatpressing paper composed of pulp component, a fiber component and a liquid crystalline polymer (polyester) exhibiting optical anisotropy in molten state. The paper formed had excellent heat resistance and mechanical strength and low hygroscopicity which made it useful for use in electrical insulation.

Marek et al. in their study described a process for making insulating spacer used in transformers by means of liquid crystalline polymer (LCP) generally polyester [38]. The spacers produced had low moisture absorption and moisture regain characteristics as compared to cellulose paper based spacers. LCPs could be used in spacers because of their fire retardant nature.

Table 2.4: Summary of liquid crystalline polymer and cellulose paper composites

Sr No.	**Dimensions of fibers**	**Binders**	**Composition**	**Properties**	**References**
1	Length of fibers: 1mm to 2.5 mm, dia: 2 µm	No binder	Cellulose pulp (70%), liquid crystalline polymer (30%)	The paper has low moisture absorption and low moisture regain characteristics	[37]
2	Not specified	No binder	Liquid crystalline polymer	The spacers have low mositure absorption and low moisture regain characteristics	[38]

2.2.5 Cellulose acetate used as coating agent

Cellulosic sheet material such as ordinary insulating paper when coated on exposed surfaces with superficial films such as cellulose esters, cellulose acetate and cellulose ethers give improved electrical properties.

The use of electrical insulating paper in transformers in oil-impregnated state was studied by Jones [39]. Nitrated wood cellulosic pulp fibers were blended with cellulosic pulp fibers and felting these fibers on ordinary paper machines or cylindrical machines to form a paper sheet. The paper so formed had good tensile, mechanical and shear strength.

Clark in his study described the production of improved sheet for electrical insulation in transformers [40]. The paper was passed through a solution of cellulose ether or cellulose ester. Acetone was used as solvent. The coated paper was then passed through an air-drying column of sufficient height to remove the solvent. The percent of cellulose acetate was 1-4% in acetone solution. The thickness of coating varied from 0.0005 inch to 0.00005.

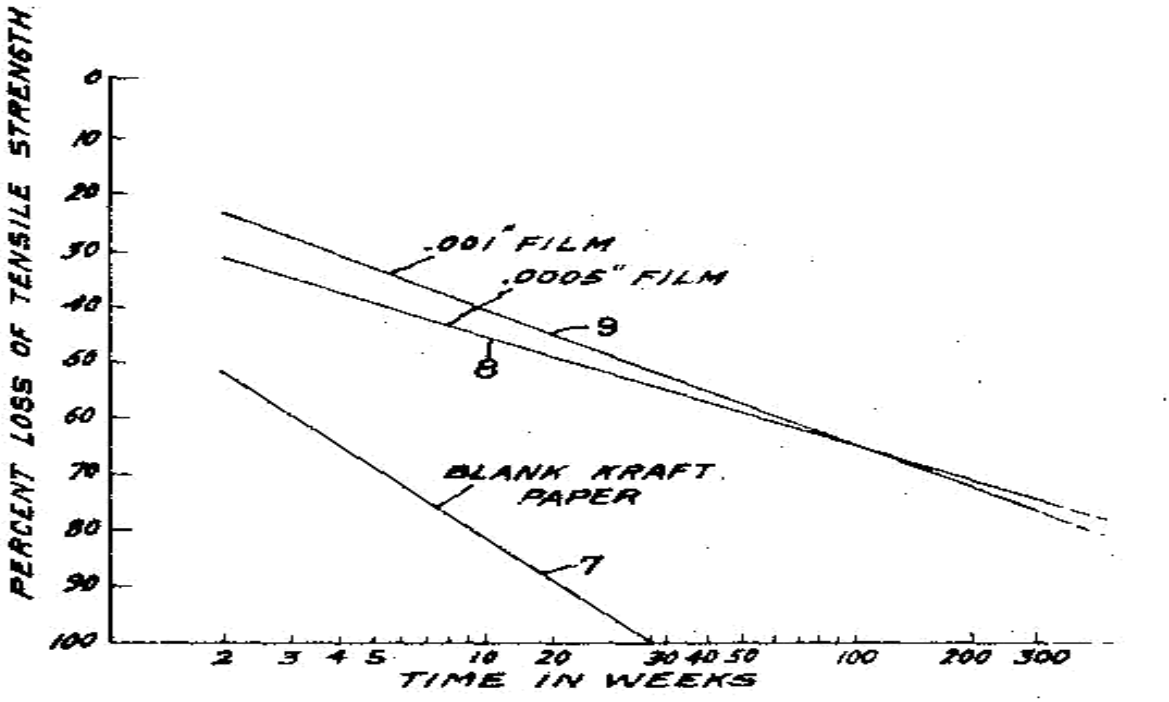

Figure 2.1: Percent loss in tensile strength vs time in weeks

From the Figure 2.1 it can been seen that the sheet material consisting of cellulose acetate was found to be more temperature resistant than fibrous cellulosic material. The application of cellulose acetate to electric paper was subjected to mechanical and other difficulties.

The above studies are summarised in Table 2.5.

Table 2.5: Summary of cellulose acetate used as a coating agent

Sr No.	Dimensions of fibers	Binders	Composition	Properties	References
1	Not specified	No binder	Cellulosic pulp fibers and cellulose acetate	Increase in tensile strength of paper	[39]
2	Not specified	No binder	Kraft paper coated with celulose acetate of 0.0005 inch	Increase in tensile strength of paper	[40]

2.3 *Treatment of fiber surface with NaOH*

Thermoplastic poly(ethylene terepthalate) (PET) fibers have been used to toughen an intrinsically brittle epoxy resin with high glass transition temperature. The morphologies and chemical properties as-received and the surface modified PET fibers are comparatively investigated by scanning electron microscopy (SEM)and strong fiber matrix adhesion is successfully achieved by optimizing surface modification of PET fiber with NaOH.

Compared with neat epoxy resin the fracture toughness of PET fibers filled epoxy composites is almost double when loading only 1% with chemically treated fiber.
The short fibers with an average diameter of 20 μm and an average length of 2-3 mm are hydrolyzed with alkali at (50 % w/v) at 80°C for different length of time (from 0-30 min).
Then by washing with distilled water until all the sodium hydroxide was eliminated and the water used for washing the fiber no longer gave any alkalinity reaction. Subsequently the surface treated fibers would be dried at 60°C for 24 hrs in a vacuum oven. [41]

The following figure shows the difference between NaOH treated PET fiber and non treated PET fiber.

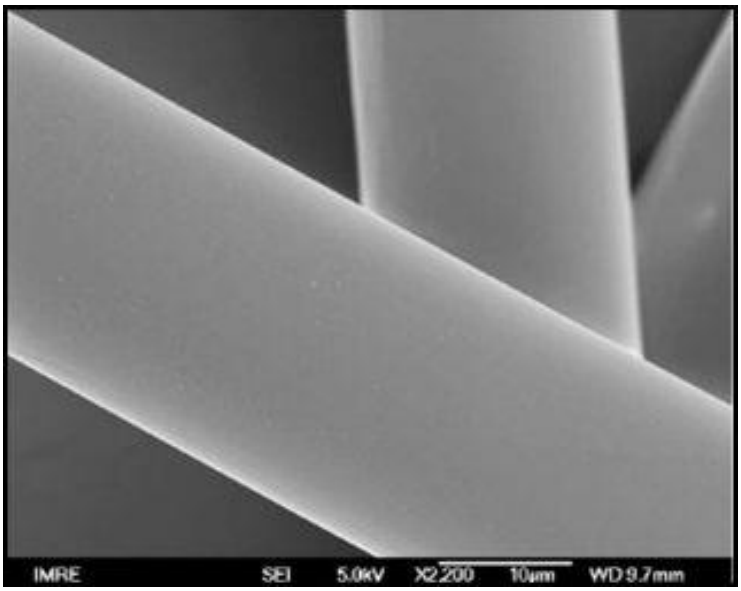

Figure 2.2: PET fiber surface

Figure 2.3: NaOH treated fiber surface

2.4: *PVOH fiber*

Polyvinyl alcohol (PVOH) is commodity polymer which is used in wide variety of different applications. However PVOH is generally regarded as non thermoplastic. PVOH has a melting point of about 200 °C depending on degree of hydrolysis as PVOH is heated near its melting point, yellowing and discoloration occurs. Therefore, when using PVOH as a base material for thermoplastic applications, PVOH must usually be modified.

Modified PVOH is used in many different water- dispersible thermo formable articles, such as fibers, films and fabrics which maintain their integrity and strength when in use but dissolve and disperse when placed in contact with water. PVOH fibers are discontinuous and generally have a length ranging from 3 to 15mm and a diameter from 7 to 20 μm [42].

In its unmodified form, PVOH has not been used for thermoplastic applications. Typically, some modification of the PVOH, such as chemical grafting or addition of plasticizer, is necessary to achieve melt processability for PVOH. The commercially available PVOH according to following properties.

1. The composition or % hydrolysis of the PVOH
2. The molecular weight of the PVOH
3. The solution viscosity of the PVOH
4. The melt viscosity of PVOH

The selected grades of PVOH have demonstrated thermoplsticity, allowing for continuous, melt extrusion or conversion into thin films in a continuous, extrusion process [42].

Chapter 3: Experimental Procedure and Materials

3.1 Materials

3.1.1 Kraft paper

Name of product: PHOENIX AL-L-250

Name of the supplier: Kotlas pulp and paper, Russia

Basis weight: 60 gsm

Paper category: Non flammable paper

3.1.2 Polyimide fibers

Name of product: P84© polyimide fibers

Name of the supplier: Evonik Industries, Austria

Diameter: 16.9 µm

Length: 2.5 mm

Specific gravity: 1.25

Glass transition temperature (T_g): 310°C

3.1.3 Polyethylene terepthalate fibers

Name of product: Recron3s© fibers

Name of the supplier: Reliance Industries Limited, India.

Diameter: 15 µm

Length: 3 & 6 mm

Specific gravity: 1.36

Glass transition temperature (T_g): 180°C

Dispersion in water: Excellent

3.1.4 Cationic starch

Name of the supplier: Bharat starch.

Degree of substitution: 0.035

3.2 Procedures

3.2.1 Preparation of fiber/pulp

Firstly we will take craft paper then it will torn into small pieces and soaked in water for minimum 16 hours. Then working in small batches, blend the paper with plenty of water .The longer the paper is blended, the finer the fiber will be.

3.2.2. *Cooking of Starch*

We take 5gm cationic starch in 100 ml water then cook it up to 80-85°C for at least 30 min. Then take sufficient amount of this cooked starch for experimental purpose.

3.2.3. *NaOH fiber Treatment*

Take the PET fiber and treat it with NaOH for different time intervals then wash it with plenty of DM water so that all the NaOH washed out .after that put the treated fiber into vacuum oven for 24 Hrs.

3.2.4. *Freeness of the pulp (TAPPI T 227)*

Blending is followed by checking the freeness of pulp. The general standard accepted value for freeness is 425-500 CSF (25-30 °SR).

Figure 3.1: Freeness tester

3.2.5 Pulp disintegration (TAPPI T 205)

A pulp sample is said to be completely disintegrated when it is subjected to mechanical treatment in water so that interlaced fibers, which were free in the pulp stock, are again separated from one another without appreciably changing their structural properties.

Figure 3.2: Pulp disintegrator

3.2.6 Stock preparation

Water is added in a large bucket, to the blended fibers to make a consistency of 0.4%. A lab stirrer is then placed inside the bucket so that the pulp does not settle and it will also allow uniform mixing.

Figure 3.3: Stock preparation

3.2.7 Hand sheet preparation

Once a uniform dispersion is formed then hand sheets of paper are made on sheet maker. The sheet machine container is firmly placed in position, and firmly clamped by pulling the handles of clamping lever in upward direction. The drain valve and needle valve are closed and container is filled with water and pulp slurry is added. The perforated stirrer is then inserted, and moved steadily up and down six times and the stirrer is gently withdrawn. After a pause of 6 seconds when liquid becomes motionless, the drain valve is opened with a rapid movement. A sheet is then obtained which is transferred and air dried.

Figure 3.4: Hand sheet maker

3.2.8 Hand sheet pressing and drying (TAPPI T 402)

The sheet is to be couched from the wire using blotters of suitable quality, using the couch roll. Then the sheet is laid, on the attached blotter, in the press on an initial pad of two blotters, a polished drying plate is centred over the sheet and add two more blotters. Repeat procedure for second sheet. The stack from top to bottom will then consist of two blotters, drying plate, test sheet, and two blotters. This process of assembling the blotters, plates, and

test sheets has to be kept in the press until up to four sets have been accumulated. The top sheet is then covered with two blotters. Finally the cover of the press is put on and hand-tightened by two of the diagonally opposite, or all four, wing nuts. The pressure is then raised as indicated by the gage to 50 psig, on the sheet in 30 s from the time the needle begins to move and is maintained for 5 mins ± 15 secs. The stack of blotters, plates, and sheets is then removed from the press. A sheet of 185-mm filter paper is then laid on the test sheet with light hand pressure and the assembled plate, test sheet, and filter are fitted into a set of drying rings. The piles of rings are then clamped together. The test sheets are then dried in atmosphere in accordance with TAPPI T 402.

3.2.9 Hand sheet making calculations

4g in 1000ml = 0.4% consistency

Area of sheet = 0.02 m^2

For 60 gsm sheet

60 g → 1 m^2

X g → 0.02 m^2

Therefore X = 1.2 g

4 g → 1000 ml

1.2 g → Y ml

Therefore Y = 300 ml

To prepare 60 gsm sheet 300 ml pulp slurry is required.

Prepare consistency sheet and weight it

Suppose its weight is 1.153 g

Then 1.153 g → 300
ml 1.2 g → Z ml

Z = 312.22 ml

So use 312.22 ml to prepare 60 gsm sheets.

3.2.10 Testing and analysis

Hand sheets were made by blending kraft pulp with synthetic fiber and binder. All hand sheets were made at 60 ± 1.5 gsm. The paper was conditioned as per TAPPI standards (paper sheet was conditioned in chamber in a temperature of 20-25 °C and relative humidity of 60-65% for four hours), the conditioning of sheets were followed by their mechanical testing which included measuring the thickness, air permeance, tear resistance, burst strength and tensile strength.

3.2.11 Air Permeance (TAPPI T 460)

Air permeance of paper is nothing but its ability to allow fluids (liquids and gases) to pass through it. A test which measures the time required for a given amount of air (100 ml) to flow through a sheet of paper; defines how open or tight the sheet of paper is with respect to the passage of air through the sheet.

3.2.12 Tearing resistance (TAPPI T 414)

Tearing resistance or tear strength of paper is the ability of the paper to withstand any tearing force when it is subjected to. It is measured in both machine direction (MD) and cross direction (CD), expressed in mN (milli newtons).

3.2.13 Tensile strength (TAPPI T 494)

Tensile strength of paper is nothing but the tensile force required to produce a rupture in a strip of paperboard, measured in MD & CD, expressed in MPa.

3.2.14 Burst Strength (TAPPI T 403)

Burst strength is the maximum hydrostatic pressure required to rupture the sample by constantly increasing the pressure applied through a rubber diaphram on 1.20 inch diameter sample.

CHAPTER 4: Results and Discussion

There is difference in mechanical strength properties of machine made and in laboratory handmade sheets it can be seen in Table 4.1 and Table 4.2.

The above properties are reference for our experiments and the various formulations have been tested and compared to normal Kraft paper (Table 4.2).These tests were performed according to TAPPI standards.

1. With PET fiber Recron 3s with different cut length of fiber and with varying quantity of binder (cooked) cationic starch the various observations are made. With increasing quantity of synthetic (PET) fiber the tensile strength get decreases while tear resistance get increases. It is desirable to add sufficient amount of synthetic fiber to increases the tear resistance without disrupting the sheet structure to the point the tensile strength is decreased below the standard level.
2. The NaOH treatment of PET Recron 3s fibers does not give the significant change in mechanical properties especially in Tensile strength and tear resistance but burst strength increases with respect to base Kraft paper.
3. Further the higher weight percent of binder quantity gives the significant change in mechanical properties of the composite paper as the tensile strength and air permiance get increases with increased quantity of binder. The higher percentage of Kraft pulp and lower percentage of fiber gives the improved mechanical properties.
4. The different cut lengths of PET fiber Recron 3s 3mm and 6mm have almost equal effect of tensile properties as in experiments we don’t have a great difference in tensile strength (Table 4.13 to 4.15).

Table 4.1: Mechanical properties of original Kraft paper

		Test					
Sr.No	**Kraft Paper Original**	**Basis Weight (gsm)**	**Thickness (mm)**	**Air Permiance (sec/100 ml)**	**Tear Resistance (mN)**	**Burst Strength (kPa)**	**Tensile Strength (MPa)**
1	100%	59.85	0.078	196	601	356	95.00
2		59.90	0.081	198	603	374	88.00
3		60.02	0.077	199	600	382	98.00
4		59.88	0.071	201	604	371	105.00
Average		**59.91**	**0.076**	**199**	**602**	**370**	**96.5**

Table 4.2: Mechanical properties of re-pulped Kraft paper (Base reading)

Base		**Test**					
Sr.No	**Kraft Paper Repulped**	**Basis Weight (gsm)**	**Thickness (mm)**	**Air Permeance (sec/100 ml)**	**Tear Resistance (mN)**	**Burst Strength (kPa)**	**Tensile Strength (MPa)**
1	100%	61.20	0.11	11.5	776	164	19.00
2		61.10	0.12	12.0	820	163	19.80
3		61.10	0.12	11.8	838	158	20.00
4		59.97	0.11	12.5	919	155	19.50
Average		**60.80**	**0.115**	**11.95**	**838**	**160**	**19.57**

4.1: *Effect of blending Kraft paper and PET fiber*

Table 4.3: Mechanical properties of 85% Kraft pulp+15% Recron 3s, 6mm fibers +5 % cationic starch 5% of Recron 3s

A	**Test**				
Sr.No.	**Basis Weight (gsm)**	**Thickness (mm)**	**Tear Resistance (mN)**	**Burst Strength (kPa)**	**Tensile Strength (MPa)**
1	61.10	0.126	1230	175	14.5
2	61.90	0.125	1190	180	15.2
3	60.12	0.124	1220	165	14.2
4	60.25	0.122	1212	172	15.7
Average	**60.79**	**0.124**	**1213**	**173**	**14.92**

Table 4.4: Mechanical properties of 90% Kraft pulp+10% Recron 3s, 6mm fibers +5 % cationic starch of 10% Recron 3s

B	**Test**				
Sr.No.	**Basis Weight (gsm)**	**Thickness (mm)**	**Tear Resistance (mN)**	**Burst Strength (kPa)**	**Tensile Strength (MPa)**
1	61.11	0.103	1080	190	14.5
2	61.90	0.112	990	215	15.2
3	60.12	0.110	1020	200	14.2
4	60.10	0.110	1110	215	15.7
Average	**60.80**	**0.108**	**1050**	**205**	**19.65**

Table 4.5: Mechanical properties of 95% Kraft pulp+5% Recron 3s, 6mm fibers +5 % cationic starch of 5% Recron 3s

C	**Test**				
Sr.No.	**Basis Weight (gsm)**	**Thickness (mm)**	**Tear Resistance (mN)**	**Burst Strength (kPa)**	**Tensile Strength (MPa)**
1	61.11	0.083	1080	325	27.10
2	61.90	0.09	990	295	26.82
3	60.12	0.10	1020	310	27.5
4	60.10	0.09	1110	330	27.7
Average	**60.80**	**0.090**	**933**	**315**	**27.28**

It can be seen from figure 4.10 that Recron 3s,6mm is compatible with cellulose when cationic starch is used as binder moreover it is also clear that tear resistance and burst strength of paper increases by cationic starch as binder .

It is also observed that addition of fiber decreases the tensile strength but increases the tear resistance.

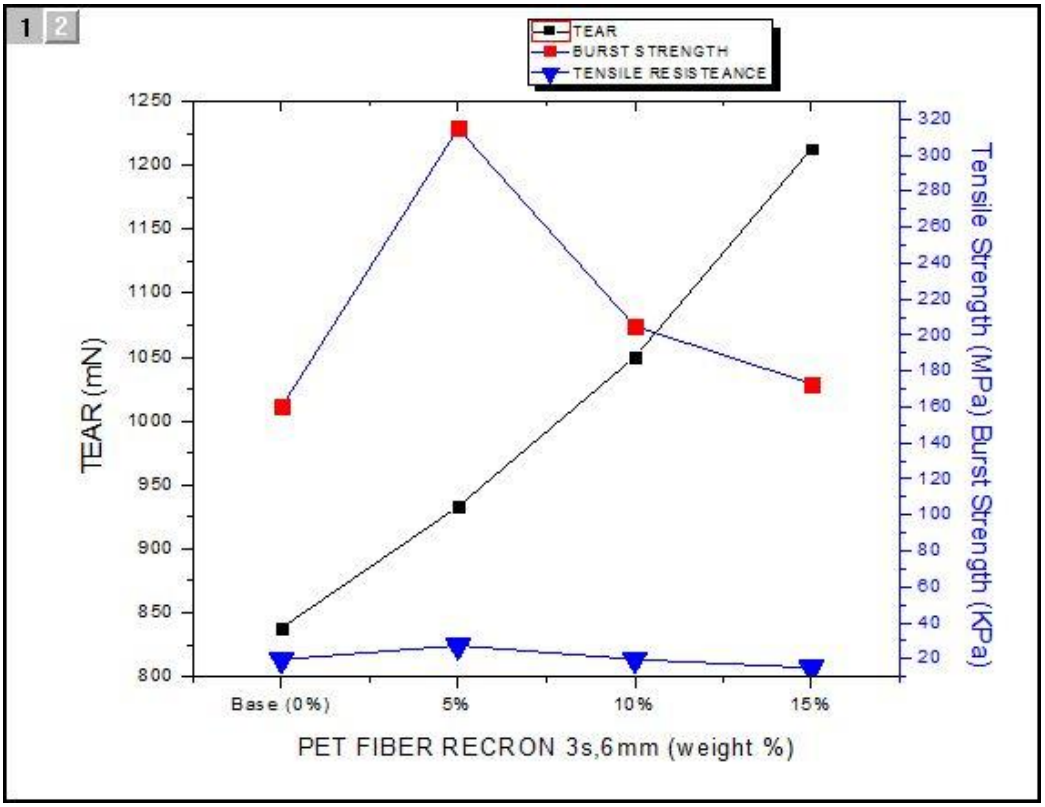

Figure 4.10: Effect of (weight %) Recron 3s, 6mm loading on tear, tensile and burst strength of paper in comparison to normal Kraft paper by using cationic starch as a binder.

4.2: *NaOH Treated PET Fiber*

Table 4.6: Mechanical properties of 85% Kraft pulp+15% Recron 3s, 3mm fibers (20min treated) +15 % cationic starch of 15% Recron 3s

D	**Test**				
Sr.No.	**Basis Weight (gsm)**	**Thickness (mm)**	**Tear Resistance (mN)**	**Burst Strength (kPa)**	**Tensile Strength (MPa)**
1	61.10	0.15	1210	250	19.10
2	61.80	0.14	1150	295	18.60
3	60.12	0.15	1322	211	18.10
4	60.10	0.15	1250	220	19.16
Average	**60.78**	**0.147**	**1233**	**244**	**18.74**

Table 4.7: Mechanical properties of 85% Kraft pulp+15% Recron 3s, 3mm fibers (2.5min treated) +15 % cationic starch of 15% Recron 3s

E	**Test**				
Sr.No.	**Basis Weight (gsm)**	**Thickness (mm)**	**Tear Resistance (mN)**	**Burst Strength (kPa)**	**Tensile Strength (MPa)**
1	61.20	0.16	1050	252	17.90
2	59.90	0.16	1020	298	17.94
3	60.12	0.16	992	220	17.20
4	60.10	0.16	1010	230	17.60
Average	**60.33**	**0.16**	**1018**	**250**	**17.66**

Table 4.8: Mechanical properties of 90% Kraft pulp+10% Recron 3s, 3mm fibers (2.5min treated) +10 % cationic starch of 10% Recron 3s

F	**Test**				
Sr.No.	**Basis Weight (gsm)**	**Thickness (mm)**	**Tear Resistance (mN)**	**Burst Strength (kPa)**	**Tensile Strength (MPa)**
1	61.20	0.15	540	272	18.10
2	59.90	0.15	522	210	18.74
3	59.84	0.15	520	220	18.70
4	60.10	0.15	550	230	19.10
Average	**60.26**	**0.15**	**533**	**233**	**18.66**

Table 4.9: Mechanical properties of 85% Kraft pulp+15% Recron 3s, 3mm fibers +15 % cationic starch of 15% Recron 3s

G	**Test**				
Sr.No.	**Basis Weight (gsm)**	**Thickness (mm)**	**Tear Resistance (mN)**	**Burst Strength (kPa)**	**Tensile Strength (MPa)**
1	61.20	0.15	1270	272	17.50
2	59.80	0.16	1240	285	17.90
3	59.84	0.15	1260	275	17.62
4	60.15	0.14	1250	240	18.10
Average	**60.24**	**0.15**	**1255**	**268**	**17.78**

It is observed from figure 4.11 that NaOH treated PET Recron 3s, 3mm fiber and for same quantity of binder (cationic starch) for different time interval have not very significant change on tensile strength with respect to base paper but burst strength decreases significantly with NaOH treated fiber as treatment time increases .Moreover we are getting better burst strength with respect to Base Kraft paper. While tear strength is minimum with 2.5 min NaOH treated PET fiber.

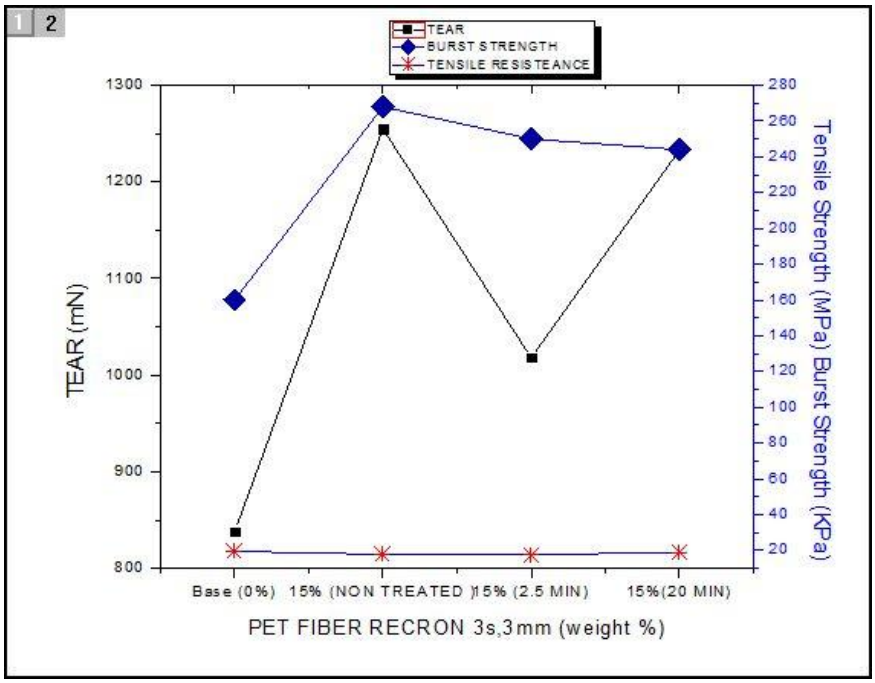

Figure 4.2: Effect of NaOH treated Recron 3s, 3mm loading for different time interval on tear, tensile and burst strength of paper in comparison to normal Kraft paper by using cationic starch as a binder.

4.3: *Effect of blending Kraft paper with higher percentage of binder (CATIONIC STARCH) and PET fiber*

Table 4.10: Mechanical properties of 80% Kraft pulp+20 % (COOKED) cationic starch

H		**Test**				
Sr.No.	**Basis Weight (gsm)**	**Air Permiance (Sec/100ml)**	**Thickness (mm)**	**Tear Resistance (mN)**	**Burst Strength (kPa)**	**Tensile Strength (MPa)**
1	61.30	11.00	.07	540	355	59
2	59.80	9.85	0.08	517	380	58
3	59.80	9.05	0.08	525	347	55
4	60.15	11.5	0.08	550	350	48
Average	**60.26**	**10.35**	**0.077**	**533**	**358**	**55**

Table 4.11: Mechanical properties of 80% Kraft pulp+10% Recron 3s, 3mm fibers +10 % cationic starch

I		**Test**				
Sr.No.	**Basis Weight (gsm)**	**Air Permiance (Sec/100ml)**	**Thickness (mm)**	**Tear Resistance (mN)**	**Burst Strength (kPa)**	**Tensile Strength (MPa)**
1	61.30	11.00	0.12	690	255	25.10
2	60.10	9.85	0.11	754	178	24.50
3	59.80	9.05	0.10	650	245	22.9
4	60.15	11.5	0.11	590	210	23.50
Average	**60.33**	**2.22**	**0.11**	**671**	**222**	**24**

Table 4.12: Mechanical properties of 95% Kraft pulp+5% Recron 3s, 3mm fibers +5 % cationic starch

J		**Test**				
Sr.No.	**Basis Weight (gsm)**	**Air Permiance (Sec/100ml)**	**Thickness (mm)**	**Tear Resistance (mN)**	**Burst Strength (kPa)**	**Tensile Strength (MPa)**
1	61.30	11.00	0.12	775	320	32
2	60.10	9.85	0.11	733	310	32.5
3	59.80	9.05	0.12	740	288	37.50
4	60.20	11.5	0.11	780	290	38
Average	**60.35**	**4.31**	**0.115**	**757**	**302**	**35**

It is observed that with higher percentage of binder (cooked starch) there is significant improvement in air permiance of the composite paper. From figure: 6.3 the figure it is very clear that by adding sufficient amount of binder and keeping the higher percentage of Kraft paper (weight %) basis the air permiance increases.

Moreover, the very high percentage (weight %) basis the air permiance and tensile properties of the composite paper get improved a lot. It is desirable to add sufficient amount of binder (cooked cationic starch) for the improvement of these properties but also keep the hygroscopic nature of starch in mind so that the moisture will not affect the paper quality.

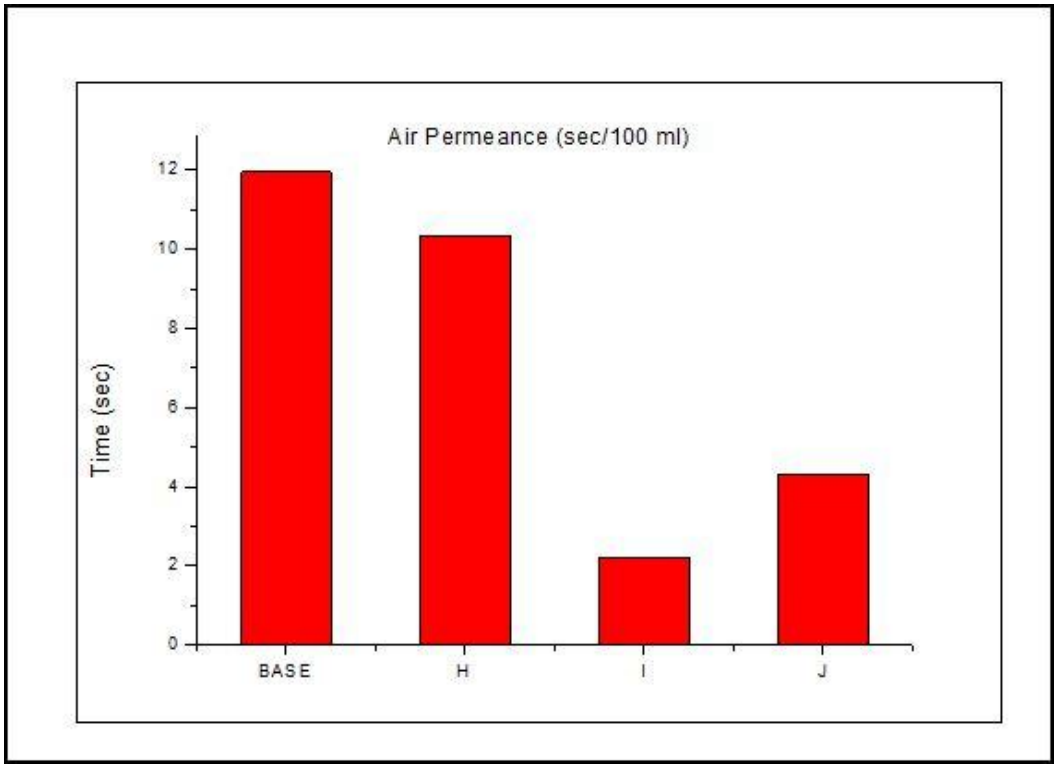

Figure 4.3: Air permiance of PET fiber cellulose composite paper in comparison to normal Kraft paper

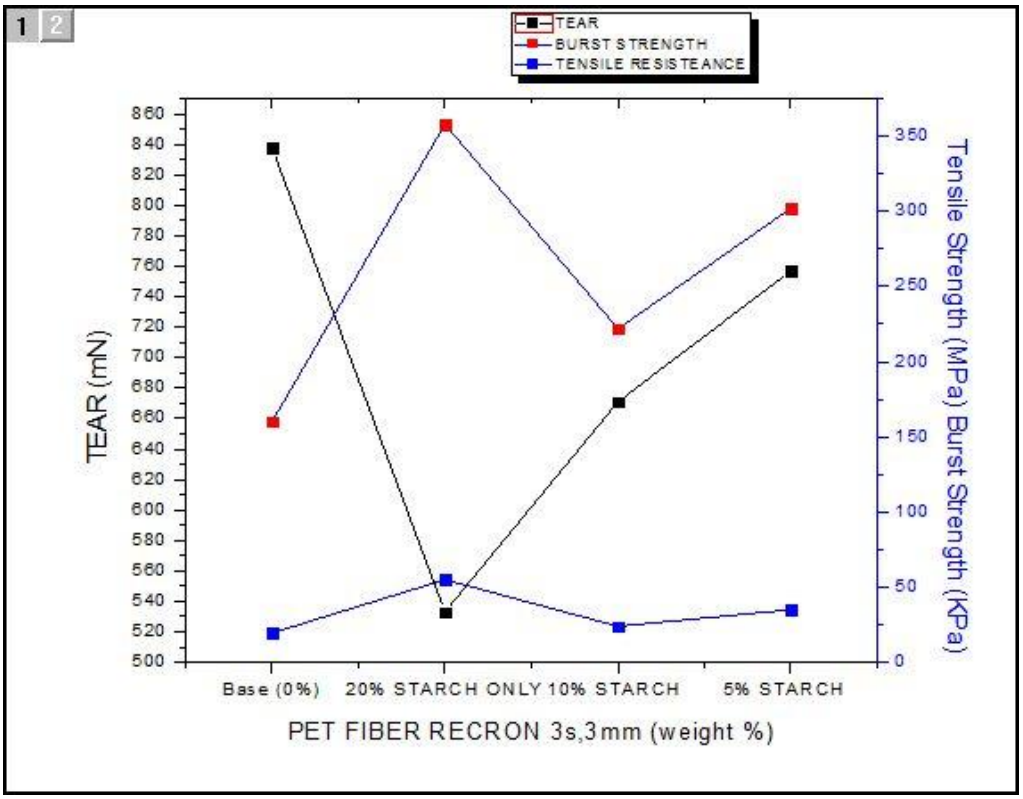

Figure 4.4: Effect of (weight %) PET fiber loading with higher percentage of binder (cationic starch) with equal (weight %) percentage of PET fiber.

4.4: *Comparison between PET Recron fiber 3s for different cut length 3mm and 6mm (Tensile Strength)*

Table 4.13: Mechanical properties of 95% Kraft pulp+2.5% Recron 3s, 3mmand 6mm fibers +2.5 % cationic starch

K	**Test**			
Sr.No	**Basis Weight (gsm)**	**Thickness (mm)**	**Tensile Strength (MPa) 3mm**	**Tensile Strength (MPa) 6mm**
1	60.11	0.14	36.5	36.5
2	60.15	0.13	37	39.5
3	59.5	0.14	37.5	38
Average	**59.92**	**0.1366**	**37**	**38**

Table 4.14: Mechanical properties of 95% Kraft pulp+5% Recron 3s, 3mm and 6mm fibers +5 % cationic starch of 5% Recron 3s

L	**Test**			
Sr.No	**Basis Weight (gsm)**	**Thickness (mm)**	**Tensile Strength (MPa) 3mm**	**Tensile Strength (MPa) 6mm**
1	60.10	0.14	36.5	36.5
2	60.20	0.14	37	39.5
3	59.50	0.14	37.5	38
Average	**59.93**	**0.14**	**27**	**27**

Table 4.15: Mechanical properties of 95% Kraft pulp+5% Recron 3s, 3mm and 6mm fibers +5 % cationic starch

M	**Test**			
Sr.No	**Basis Weight (gsm)**	**Thickness (mm)**	**Tensile Strength (MPa) 3mm**	**Tensile Strength (MPa) 6mm**
1	60.50	0.14	29.5	31
2	60.20	0.14	30	32
3	59.30	0.14	30.5	33
Average	**60**	**0.14**	**30**	**32**

It is very interesting that there is not very much change in tensile properties by using different cut lengths of fiber as with 3 mm and 6 mm cut length of Recron 3s fiber gives us almost same result.

It is also very interesting that we are getting decreased tensile strength by adding more quantity of fiber so far as we get the maximum tensile strength for 95% Kraft pulp +2.5% fiber+2.5% binder Which is just double of repulped base Kraft paper.

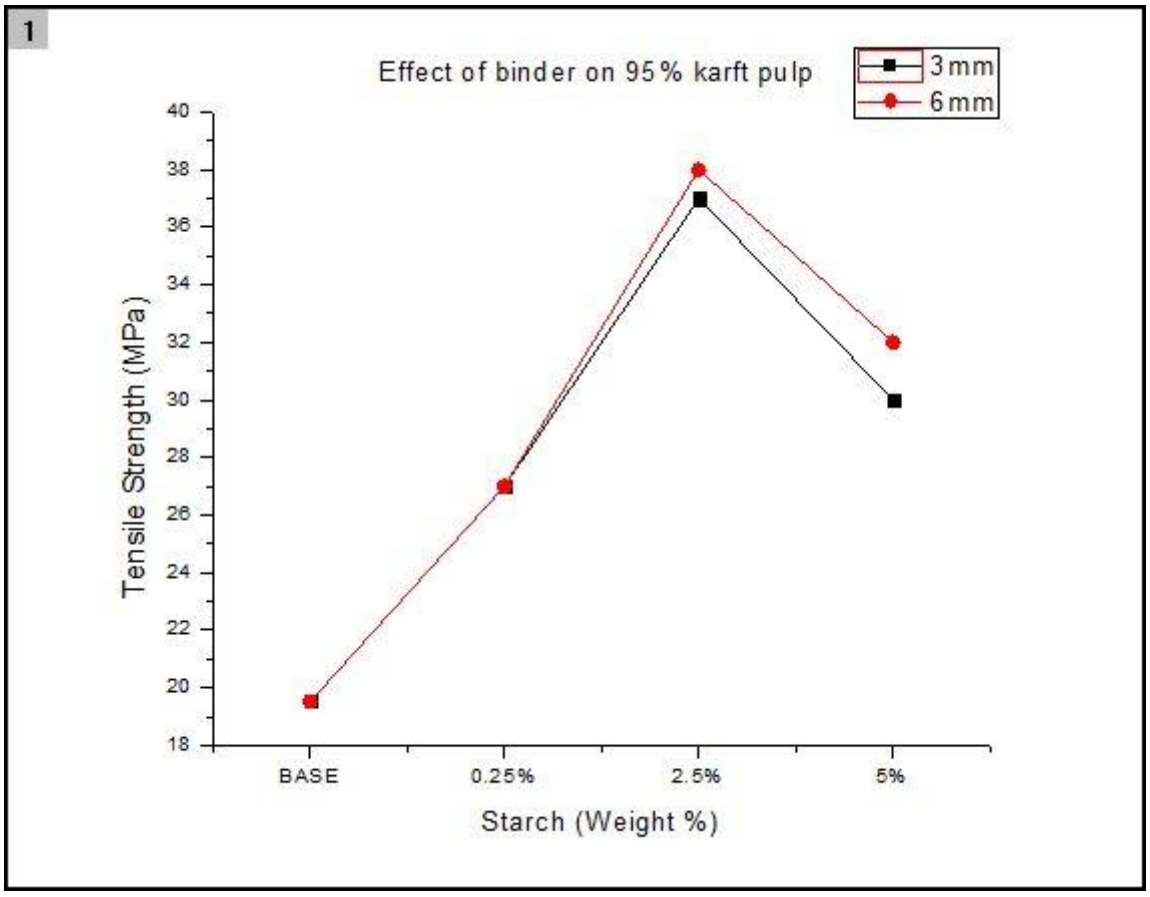

Figure 4.5: Effect of binder on 95% Kraft pulp

The oil used in transformers for cooling purpose has a relative dielectric constant 2.2 and the acceptable range for dielectric constant of insulating paper is between 2.2 to 3.5 of the dielectric constant for original Kraft paper is more than 4 and by adding the different fibers we get reduced value up to 50%. This also indicates to have an addition of synthetic fiber up to an optimized range so that mechanical as well as electrical properties are lie in acceptable range.

Chapter 5: Conclusion

The strength of composite paper is exceeded with the Kraft pulp quantity or binder quantity and it get decreases with increases of fiber quantity but the excess use of binder may affect the moisture absorption as the binder use in experiments is cationic starch which is hygroscopic in nature so the optimized quantity of all the three components can give the best results.

1. The tensile strength and burst strength are in correlations while tear resistance is in inverse relations. As these mechanical properties depend on the structure of the sheet so the fiber loading is very important characteristic.
2. The best result for mechanical properties of the paper is observed with 20% cationic starch (55 MPa) but in absence of fiber the electctrical properties does not affected and also starch is hygroscopic in nature so with higher percentage of Kraft and optimized quantity of fiber and binder will give us the better mechanical properties .
3. The nature of synthetic fiber and its bonding with cellulose fiber is an important factor affecting the structure and uniformity of composite paper and its mechanical properties.
4. The preferred range for fiber quantity is in between (0-5%) and the binder quantity is on overall basis as well as with respect to fiber (weight %). By doing several experiments with NaOH for different time interval the mechanical properties not so much affected So far with several experiments no doubt the higher quantity of cationic starch increases the tensile property but it must be minimized with respect to overall basis.
5. The best result so for achieved with cationic starch as binder and polyethylene terepthalate fibers (3mm) with composition Kraft pulp 95% fiber composition 2.5% and binder is 2.5%.results the tensile strength 37 MPa.(binder quantity is on overall basis)which is just double than our base Kraft paper strength.
6. When binder quantity is on fiber basis the best result achieved is 95% Kraft pulp and 5% fiber and the binder is 5% of fiber i.e. 0.25% overall basis results tensile strength 27MPa which is approximately 38% higher than repulped base Kraft paper.

References

[1] Jalbert J, Gilbert R, Te´treault P, Morin B, Lessard-De´ziel D Roland G, Pierre T, Brigitte M, Denise L.D (2007) Identification of a chemical indicator of the rupture of 1,4-β-glucosidic bonds of cellulose in an oil impregnated insulating paper system. Cellulose 14: 295.

[2] Sokolov V, Vanin B (1995) In-service assessment of water content in power transformers. Proc. the 62nd Annual Intern. Conf. Doble Clients, Section 8-6.

[3] Sokolov V, Vanin B (1996) Evaluation of power transformer insulation through measurement of dielectric characteristics. Proceedings of the 63rd Annual Intern. Conf. Doble Clients, Section 8-7.

[4] Cigré Brochure (2007) Aging of cellulose in mineral-oil insulated transformers. pp 323.

[5] Moser HP, Dahinden V (1987) *Transformerboard II*, Weidmann AG, Rapperswil.

[6] Shroff DH, Stannett AW (1985) A review of paper aging in power transformers. IEE Proc., 132: 312.

[7] Gilbert R, Jalbert J, Ducheshe S, Te´treault P, Morin B, Denos Y (2010), Kinetics of the production of chain-end groups and methanol from the depolymerization of cellulose during the ageing of paper/oil systems. Part 2: Thermally-upgraded insulating papers. Cellulose 17: 223.

[8] Richard P.Marek, Jean-Pierre Jackob and Giorgio Patrizio Vercesi(2008) Insulators for Transformers. US Patent No:2008/0061919 A1.

[9] Takami KM, Mahmoudi J (2008) A novel study on power transformer losses in relation to CO_2 capturing technology. International Journal of Energy Research, 32: 1151.

[10] Linhjell D, Lundgaard LE, Gafvert U (2007) IEEE Transactions on Dielectrics and Electrical Insulation. 14: 156.

[11] Prevost TA, Oommen TV (2006) Cellulose insulation in oil filled power transformers. IEEE Electrical Insulation Magazine 22: 28.

[12] Ford FG, Lockie AM, Leonard MG (1960) A new and improved heat stabilised insulation. Conf Paper 60-936, Summer Meeting of the A.I.E.E., Atlantic City, NJ.

[13] Westinghouse (2010), "Insuldur" ABB brochure.

[14] Oommen TV (2003), Moisture equilibrium curves—use and misuse. Doble Conf. Paper.

[15] Oommen TV, Andrachy TL (1996) Graft polymerisation and other methods to reduce the hygroscopicity of cellulose insulation. IEEE Conf Paper pp 538.

[16] Labino D, Ohio M (1959) Method for making glass paper. US Patent No: 2,919,221.

[17] Brandon RE (1994) Fibrous mat with cellulose fibers having a specified canadian freeness. US Patent No: 5,318,844.

[18] Singh TM (2004) Enhancement of a cellulose based paper product with glass fibers. US Patent No: 0,231,814 A1.

[19] Weinberg M (2010), Polyamide electrical insulation for use in liquid filled transformers. US Patent No: 0,039,199 A1.

[20] Rolling DJ, Stegehuis RL, Marusinec RM, Ferrito SJ (2005) Electrical apparatus with synthetic fiber and binder reinforced Cellulose insulation paper. US Patent No: 6,980,076.

[21] Thinius K (1944) Mutual percipitation of polyamides and cellulose. US Patent No: 2,347,525.

[22] Schroeder SM, Michel GP (1978) Transformer with improved Insulator. US Patent No: 4,095,205.

[23] Kinsley JR (1995) Process for making a paper based product employing a polymeric latex binder. US Patent No: 5,466,366.

[24] Kato I, Kimura Y and Hesler LJ (1997), Aramid paper with high surface smoothness. US Patent No: 5,667,900.

[25] Vercesi GP, Jakob JP and Maurox NC (2000) Process for making a uniform dispersion of aramid fibers and polymers. US Patent No: 6,068,922.

[26] Kinsley JR (2004) High temperature paper containing aramid component. US Patent No: 0140,072.

[27] Cornbower T (2006) High temperature paper. US Patent No: 7,112,259 B2.

[28] Nakao O, Hirose J, Nakamura T, Yamamoto H, Matsuda S, Suzuki H (1971) Electrical insulation paper and its production process. US Patent No: 3,617,438.

[29] Fujita H, Itoh H (1978) Electrical insulating paper and method of making the same. US Patent No: 4,096,313.

[30] Dainichi Nippon Cables LTD (1979) Electrical insulating paper and method of making same. US Patent No: 1,544,044.

[31] Kamata Y, Ohe E, Endow K, Furukawa S, (1991) Development of low permittivity pressboard and its evaluation in oil immersed EHV power transformers. IEEE Transactions on Electrical Insulation 26: 4.

[32] Suter K, Mathews JH, Lee, Mass (1975) Coated electrical insulating paper and method of making it. US Patent No: 3,903,352.

[33] White BM (1989) Process for internally strengthening the paper and board products and products resulting therefrom. US Patent No: 4,865,691.

[34] Kinsley JR (1994) Process for making a paper based product containing a binder. US Patent No: 5,328,567.

[35] Kinsley JR (1996) Process for making a paper based product containing a binder. US Patent No: 5,498,314.

[36] Yang CQ, Xu G (2002) Polymer aldehyde additives to improve paper properties. US Patent No: 6,379,499.

[37] Kumuda H, Yamaguchi T (2002) Low hygroscopic paper and method of producing the same. US Patent No: 153111 A1.

[38] Marek RP, Jakob JP, Verseci GP (2008) Insulators for transformers. US Patent No: 0061919 A1.

[39] Jones BW, (1937) Manufacture of partially soluble felted fibrous articles. US Patent No: 2,069,763.

[40] Clark FM (1950) Cellulose coated dielectric paper for electrical devices. US Patent No: 2,526,330.

[41] The Su Fern, Liu Tianxi, Lei Wang, He Chaobin (2004), Fracture behavior of PET fiber toughened epoxy composite,Composites:Part A 36(2005) 1167-1173.

[42] Wang,J.H. , Schertz,D.M. ,Roswell,G.A., Pomplun ,W.S. (2001) Unmodified polyvinyl alcohol fiber. US Patent No: 6,203,903 B1