PREPARATION AND CHARACTERIZATION OF POLYMER FIBRE AND CELLULOSE COMPOSITE PAPER FOR ELECTRICAL INSULATION

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By

RAMESH CHANDRASHEKAR
(Roll No. 601011008)

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.

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DECLARATION

This is certified that the thesis entitled ***"PREPARATION AND CHARACTERIZATION OF POLYMER FIBRE AND CELLULOSE COMPOSITE PAPER FOR ELECTRICAL INSULATION",*** *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 (Head and Associate Professor, ChED) and Dr. P.K.Bajpai (Distinguished Professor, ChED) during January to June 2012.*

Date:- 12-07-12

Ramesh Chandrashekar
(Roll no.601011008)

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

Rajeev Mehta
Dr. Rajeev Mehta 12.07.12
Head and Associate Professor
Department of Chemical Engineering
Thapar University, Patiala.

12-07-12
Dr. P.K.Bajpai
Distinguished Professor
Department of Chemical Engineering
Thapar University, Patiala.

Counter signed by:

Rajeev Mehta
12.07.12
Dr. Rajeev Mehta
Head and Associate Professor
Department of Chemical Engineering
Thapar University, Patiala.

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

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Abstract

With growing capacities, an ever-increasing reliability of products in service is demanded 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 fibres with synthetic fibres. 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 paper from kraft pulp and synthetic fibres. The insulation paper produced by blending kraft pulp with synthetic fibres, viz, polypropylene and polyethylene terepthalate has higher tensile, tear, burst strengths as compared to normal kraft paper making it useful for electrical insulation in transformers.

Keywords Insulation, electrical grade kraft paper, power transformers, cellulose fibres, synthetic fibres

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Abbreviations

ASTM	American Standard of Testing and Materials
CD	Cross Direction
CMC	Carboxy Methyl Cellulose
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
TGA	Thermo Gravimetric Analysis
TMA	Thermal Mechanical Analysis
WDXS	Wave Dispersive X-Ray Spectrometry

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Chapter 1: Introduction

1.1 Insulating materials

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 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, but not because it is best. In fact, it would have never been the preferred material if it was not 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 Degradation 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 Historical background of transformer

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 [8]. 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 [9]. 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 Transformer insulation development

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 [10].

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 20th century [10]. 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 fibre 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 [10].

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 [11]. 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 [12].

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 [13]. 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 [14]. 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 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.

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 a 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 fibre and cellulose composite paper for electrical insulation covers the process of production of paper from kraft pulp and synthetic fibres viz Recron 3s$^{©}$ (Polyethylene terepthalate (PET) fibres, a product of Reliance industries Limited, India), Polyimide P84$^{©}$ (Polyimide fibres, 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

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 is required. Some of the relevant studies on approaches to develop better fibre cellulose paper composites are discussed below

2.1 Inorganic fibres

2.1.1 E glass fibre 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 fibres in an aqueous slurry. The fibres 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 fibres held together by an equally random dispersed binder.

Labino and Ohio in their study described the production of glass paper [15]. The paper so formed had the characteristics that were not capable of reproduction by natural fibres 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 fibres had a tendency of self-adhesion which was witnessed by wetting the glass fibres in acid water and no binder was required for self adhesion of glass fibres. The resulting glass paper thus formed from glass fibres had high tensile strength.

The use of glass fibres and wood pulp to control dimensional stability has also been studied [16]. The composition of paper was 38-46% glass fibres, 24-32 % wood pulp, and around 22-38% binder. The pulp used was neutracel pulp which had following advantages over long fibre 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 fibres can also be obtained from recycled pulp which offers cost reduction properties without changes in mat structure.

A process for making fibre paper products comprising of cellulose pulp and coarse diameter glass wool has been studied by Singh [17]. The average diameter of glass wool fibres used varied from 5.5 to 11 µm. The composition of glass wool fibres 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 fibres 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 fibres 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 fibres**	**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.	[15]
2	Length: 1 mm dia: 10-50 µm	B017A, B018B (Source not specified)	Cellulosic pulp fibres (38-46%), E glass fibres (24-32%), binder (22-38%)	Increased dimensional stability of paper	[16]
3	Glass wool fibre dia: 5.2 µm	Ceramic/Clay/Plastic	10-25% glass wool fibres and 75-90% cellulose pulp fibres	Increase in tear resistance of paper	[17]

2.2 Organic polymer fibres

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 [18]. To overcome its hygroscopic nature cellulose is blended with synthetic polymer fibres, one such synthetic polymer fibre is polyamide fibre. The insulation paper generally includes a wood pulp fibre, a synthetic fibre and a binder material. The wood pulp fibre composition generally varies from 60-80% by weight (length 0.5-1.4 inch, diameter 10-15 µm), synthetic fibre 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 fibre 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 fibres [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 fibres. 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 fibre, a particulate binder substantially insoluble in water, an emulsion comprised of lecithin and fatty acid and a synthetic fibre has also been studied [22]. The binder used was BF Goodrich. The composition of cellulosic pulp fibre 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 fibre 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. [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 fibres and polymers has also been studied [24]. Short aramid fibres 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 fibres. The aramid fibres were continuously introduced in the extruder simultaneously heat was applied in the extruder so as to evaporate the water from fibres. The fibres were then subjected to shear force in the extruder. The polymer was blended with the fibres so as to form a uniform dispersion.

Kinsley [25] and Cornbower [26] in their studies varied: (a) the composition of cellulosic pulp fibre 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 fibres and the inner layer is comprised of polymeric binder, a synthetic fibre and cellulosic pulp fibre. 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 fibres 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 fibres	Binders	Composition	Properties	References
1	Not specified	No binder	Cellulosic pulp fibres (60-80%) and polyamide fibres (20-40%)	Paper has good water repellent properties	[20]
2	Length: 1-1.6 mm	No binder	Laminate of cellulosic pulp fibres, Nomex fibres and PET films	PET films unsuitable for temperature over 200°C	[21]
3	Not specified	BF Goodrich /Dow/ Acrylic	Cellulosic pulp fibre (60-90%), a latex binder (10-20%) and an emulsion of lecithin and fatty acid (1-10%), synthetic fibre (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 fibres (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 fibre (10-25%)	Increased thermal resistance of paper	[25]
7	Length of fibre : 0.25 to 0.75 inches, dia: 10-15 µm	Polyvinyl alcohol	Wood pulp fibre (70%), synthetic fibre (20%), binder material (10%)	Binder used has good thermal aging properties,adding synthetic fibre to wood pulp fibre increases papers thermal stability	[19]
8	Length: 0.25 inch	Polyvinyl alcohol	Cellulosic Pulp fibres (70 %), polyvinyl alcohol (20%), poly amide fibre (10 %)	Increased thermal resistance of paper	[26]

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 [27]. 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 fibres and polyolefin micro fibres along with cellulose fibre 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 fibres (composition: 10-70%, length 0.5-2 mm, diameter 10-50 µm), polypropylene fibres (composition: 3-35%, length 0.3-1 mm, diameter 10-30 µm) and polyolefin fibres (composition: 1-25%, length 0.1-5 mm, diameter 0.2-10 µm) and a layer B comprised of polypropylene fibres only. The paper was prepared by superimposing one layer over the other and they were heat treated from 110ºC to 180ºC so that the fibres 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 fibres with large diameters (up to 50 µm) resulted in paper having reduced mechanical strength and lower air permeability. Generally finer fibres 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 fibres. 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 fibres 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 fibres.

The above studies are summarised in Table 2.3

Table 2.3: Summary of polypropylene and cellulose paper composites

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

2.2.3 Polyvinyl alcohol and cellulose composite paper

Polyvinyl alcohol can be used in fibre form or even in powder form. Poly vinyl alcohol fibre 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 fibre 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 fibre 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 fibres are blended with polyvinyl alcohol to increase strength properties. The composition of polyvinyl alcohol varied from 3-10% and the composition of cellulosic pulp fibres 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 fibre, 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 fibre 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 fibre, 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 fibre 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 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.

Table 2.4: Summary of polyvinyl alcohol and cellulose paper composites

Sr No.	Dimensions of fibres	Binders	Composition	Properties	References
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 fibres	Increase in tear resistance, mechanical reistance and strength of paper	[32]
3	Length: 2-15 mm and dia: 10-15 µm, dia of microfibre 0.2-10µm	Polyvinyl alcohol powder	Cellulosic pulp fibre (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 fibre (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]

2.2.4 Liquid crystalline polymer and cellulose composite paper

Liquid crystalline polymer can be blended with cellulose fibres 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. [36]. The insulation paper was obtained by heat pressing paper composed of pulp component, a fibre 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 [37]. 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 2.5: Summary of liquid crystalline polymer and cellulose paper composites

Sr No.	Dimensions of fibres	Binders	Composition	Properties	References
1	Length of fibres: 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	[36]
2	Not specified	No binder	Liquid crystalline polymer	The spacers have low mositure absorption and low moisture regain characteristics	[37]

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 [38]. Nitrated wood cellulosic pulp fibres were blended with cellulosic pulp fibres and felting these fibres 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 [39]. 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 inch.

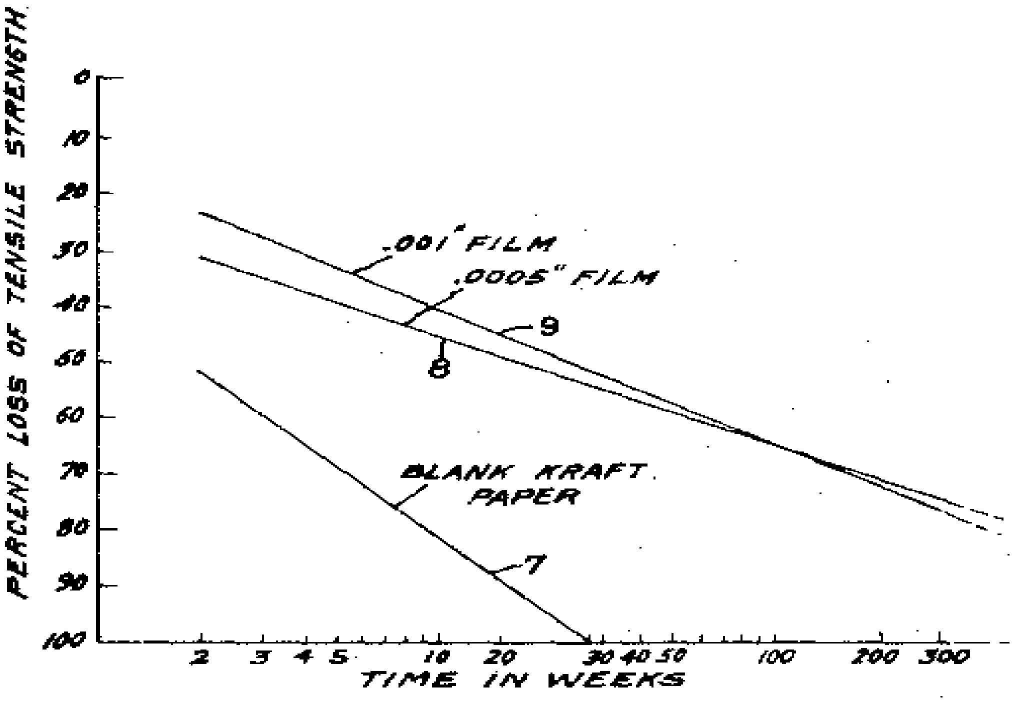

Figure 2.1: Percent loss in tensile strength vs time in weeks, Source: Ref 39

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 2.6.

Table 2.6: Summary of cellulose acetate used as a coating agent

Sr No.	Dimensions of fibres	Binders	Composition	Properties	References
1	Not specified	No binder	Cellulosic pulp fibres and cellulose acetate	Increase in tensile strength of paper	[38]
2	Not specified	No binder	Kraft paper coated with celulose acetate of 0.0005 inch	Increase in tensile strength of paper	[39]

2.2.6 Epoxy resin/Resin powder/Thermoset resin and cellulose composites

Cellulose paper tends to deteriorate when subjected to elevated temperatures. To overcome this cellulose fibres are blended with resins.

A process for the production of high strength paper having high impact tear and tensile strength, which could be used for special purposes was studied by Arledter [40]. The high strength paper comprised of 70-30 weight percent of cellulosic pulp fibres, resin powder varied from 30-70 weight percent, synthetic fibre varied from 7 to 35 weight percent and 1-20 weight percent of fine siliceous fibres, all in the length 6 mm to 15 mm and diameter 1-2 micron. Resin powders in particle size distribution 60 mesh to 300 mesh were used. The resin powders used, were: polyvinylchloride, polyethylene, polystyrene, cellulose acetate.

Sadler and Lapp in their study described the production of cellulose paper having improved thermal stability which could withstand the deteriorating action of heat over a period of time [41]. The cellulose fibre material (5-65%) was treated with an aqueous treating medium containing a dispersion of liquid (0.1-10%), uncured cross linkable thermosetting resin and an amine curing agent.

A process for the production of electrical device coil forms has also been studied [42]. Kevlar/Nomex fibres and polyethylene terepthalate were blended to form paper. The composition of synthetic pulp fibre varied from 15 to 70% and composition of polyethylene terepthalate varied from 20 to 30%. The paper so formed has high thermal stability, good mechanical strength, good heat resistance and good oil impregnation.

The above studies are summarised in Table 2.7.

Table 2.7: Summary of Epoxy resin/Resin powder/Thermoset resin and cellulose paper composites

Sr No.	Dimensions of fibres	Binders	Composition	Properties	References
1	Length: 6 mm to 15 mm, dia: 1-2 µm	No binder	Fibre: 70-30%, resin powder (filler): 30-70%, synthetic fiber: 7-35%, siliceous fibres 1-20%	Increase in tear, tensile and impact strength	[40]
2	Not specified	No binder	5-65% by weight of resin of dry paper, organic amine 0.1-10%	Increased thermal stability and strength of paper	[41]
3	Length < 0.75 inch	No binder	Nomex/Kevlar fibres (15-70%) and polyethlylene terepthalate (10-30%)	Increased thermal stability and strength of paper	[42]

2.2.7 Polyacrylate/Polyketone/Acrylonitrile/Rayon and cellulose composites

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

Ucci et al., in their study described the preparation of paper from wet spun fibres 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 fibres and large diameter rayon or polyvinyl formal fibres were studied by Selke et al., [44]. The composition of wood pulp fibres varied from 90 to 98% and the composition of polyvinyl formal fibres 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, embossability, resiliency, conformability, moisture and vapour 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 fibre paper which was comprised of aliphatic polyketone fibres [46]. The paper had high mechanical strength, high modulus of elasticity, excellent dimensional stability, chemical resistance, adhesiveness, heat resistance, low dielectricity and low water absorbance. The paper comprised of 1 to 100% by mass aliphatic polyketone fibres having length 1-3 mm and diameter variation of 5-50 µm.

The above studies are summarised in Table 2.8.

Table 2.8: Summary of Polyacrylate/Polyketone/Acrylonitrile/Rayon and cellulose paper composites

Sr No.	**Dimensions of fibres**	**Binders**	**Composition**	**Properties**	**References**
1	Diameter: 0.3 to 20 denier	Anti foaming agent: octlyl alcohol	Acrylonitryle 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 fibres (90-98%) and rayon/poly vinyl formal fibres (2-10%)	The paper produced is of low cost, has less porosity and high dielectric strength	[44]
3	Length: 1-2.2 mm	Polyacrylates	Cellulosic pulp fibres (30-70%), polyethlylene glycol	Moisture content of final paper is less than 5%, increase in strength in cross direction tear	[45]
4	Length of fibres: 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 dielectricity and water absorbance	[46]

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 fibres

Name of product: P84© polyimide fibres
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 fibres

Name of product: Recron3s© fibres
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 Carboxy methyl cellulose

Name of product: Finfixx 30
Name of the supplier: CIBA-BASF, India.
Percentage moisture: 6-8%.
pH: 5-8

3.1.5 Cationic starch

Name of the supplier: Bharat starch.

Degree of substitution: 0.0035

3.1.6 Polyvinyl alcohol

Name of the supplier: Loba Chemicals, Mumbai, India.

Degree of polymerization: 1700-1800.

pH (0.2% in water): 5-7

Hydrolysis (mole %): 98-99

Ash: 0.7%

3.2 Procedures

3.2.1 Preparation of fibre/pulp

The kraft paper is first torn into small pieces and soaked in water for at least 16 hours. Then working in small batches, blend the paper with plenty of water. The longer the paper is blended, the finer the fibers will be.

3.2.2 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

3.2.3 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

Addition of synthetic fibers: The fibers are first completely soaked in a solution containing a synthetic binder and the solution is made uniform by mixing it in a lab stirrer for 15 minutes. This solution is then added in the pulp disintegrator and blended for about 5000 revolutions.

3.2.4 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

3.2.5 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

3.2.6 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.

3.2.7 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.

3.2.8 Testing and analysis

Hand sheets were made by blending kraft pulp with synthetic fibre 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.

3.2.8.1 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.

3.2.8.2 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).

3.2.8.3 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 kNm/kg.

3.2.8.4 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

The difference in mechanical strength properties of paper made in machine and paper made from same material in hand sheet maker can be seen in Table 4.1 and Table 4.2. Tables 4.3 to 4.30 demonstrate mechanical properties of various formulations that have been tested and compared to normal kraft paper (Table 4.2). These tests were performed according to TAPPI standards.

When non-cellulosic synthetic fibers are incorporated with the kraft pulp fibre, an unusal phenomenon occurs. Synthetic fibers which are non-cellulosic in nature are generally stronger in tensile strength than are the wood fibers but are less bonded in a sheet than a cellulose fiber. When sheet is torn, the synthetic fibers do not rupture but pull out of the sheet structure. This requires more work than simple fiber rupture. This means that the tear strength will improve as the synthetic fiber content is increased (Table 4.9 to 4.30; Figure 4.2, 4.4, 4.6, 4.8 & 4.9). At some point, however, the quantity of synthetic fibers will cause a loss in tensile strength (Table 4.4, 4.6 & 4.7; Figure 4.2, 4.4, 4.6, 4.8 & 4.9). It is desirable therefore to add sufficient amount of synthetic fiber to increase the tear strength without disrupting the sheet structure to the point the tensile strength is decreased below the acceptable level. Fiber length is an important parameter related to tear strength. The long synthetic fibers having a length of 6 mm (Recron 3s, 6) impart higher stretch to the paper as compared to short synthetic fibers of length less than 3 mm. However, this comes at a cost that the burst strength and tensile strength reduce considerably as compared to short fibers (Table 4.16 to 4.30, Figure 4.6, 4.8). If the amount of synthetic fiber incorporated into the wood pulp/synthetic fiber sheet structure is constant, the tear strength will increase with the length of the fiber. It is important to note however that as length increases, the number of times synthetic fibers is contacted by wood fiber increases. Since each fiber contact as an area of bonding, the total amount of synthetic fiber bonding increases as length increases. At some point, however, the fibers become so bonded that they will break rather than pull out of the sheet during tear test. This phenomenon decreases the tear strength since it takes less energy to break a fiber than it does to pull it out of the sheet structure.

Binder is added to improve the bonding of wood pulp fiber and the synthetic fibers, since the synthetic fibers interfere with wood pulps bonding ability. The binder corrects for that interference so that wood pulp and synthetic fibers will bond. Even with a binder present, the addition of a synthetic fiber to cellulose fiber may not improve the tensile strength (Table 4.8, 4.9, 4.16 to 4.19) to a great extent.

Table 4.1: Mechanical properties of original kraft paper

		Test					
Sr.No	**Kraft Paper Original**	**Basis Weight (gsm)**	**Thickness (μm)**	**Air Permeance (sec/100 ml)**	**Tear Resistance (mN)**	**Burst Strength (kPa)**	**Tensile Strength (kNm/kg)**
1	100%	59.85	75.5	196	601	356	106.1
2		59.90	77.6	198	603	374	110.8
3		60.02	78.2	199	600	382	107.2
4		59.88	76.1	201	604	371	107.1
Average		**59.91**	**76.8**	**199**	**602**	**370**	**107.8**

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

Base		**Test**					
Sr.No	**Kraft Paper Repulped**	**Basis Weight (gsm)**	**Thickness (μm)**	**Air Permeance (sec/100 ml)**	**Tear Resistance (mN)**	**Burst Strength (kPa)**	**Tensile Strength (kNm/kg)**
1	100%	61.1	96.06	19.6	776	164	49.29
2		61.1	96.13	21.8	820	163	42.23
3		61.1	96.31	23.6	838	158	42.23
4		61.1	95.93	20.1	919	155	43.96
Average		**61.1**	**96.10**	**21.3**	**838**	**160**	**44.42**

4.1. Effect of blending kraft pulp and polyimide fibres

The first experiments were conducted using polyimide fibres and kraft pulp. The weight percentage of polyimide fibres was varied from 5 to 30% and the kraft pulp weight percentage was varied from 95 to 70%. The variation in mechanical strength properties after addition of polyimide fibres can be seen from Table 4.3 to 4.7. Polyimide fibres were blended with kraft pulp using polyvinyl alcohol as a binder. The effect of binder addition on mechanical strength properties is shown in Table 4.8.

Table 4.3: Mechanical properties of 70% kraft pulp + 30% polyimide fibres (A)

A	**Test**					
Sr.No	**Basis Weight (gsm)**	**Thickness (μm)**	**Air Permeance (sec/100 ml)**	**Tear Resistance (mN)**	**Burst Strength (kPa)**	**Tensile Strength (kNm/kg)**
1	62.4	152.33	1.34	621	85	19.99
2	62.8	158.66	1.42	679	85	22.33
3	62.3	159.77	1.66	661	97	18.44
4	62.7	156.33	1.12	668	89	22.46
Average	**62.5**	**156.77**	**1.38**	**658**	**89**	**20.80**

Table 4.4: Mechanical properties of 80% kraft pulp + 20% polyimide fibres (B)

B	**Test**					
Sr.No	**Basis Weight (gsm)**	**Thickness (µm)**	**Air Permeance (sec/100 ml)**	**Tear Resistance (mN)**	**Burst Strength (kPa)**	**Tensile Strength (kNm/kg)**
1	62.10	147.77	1.85	800	101	23.58
2	60.90	148.44	1.64	700	100	29.55
3	61.00	149.97	1.82	704	103	25.45
4	61.45	149.60	1.87	774	96	28.63
Average	**61.36**	**148.95**	**1.79**	**745**	**100**	**26.81**

Table 4.5: Mechanical properties of 85% kraft pulp + 15% polyimide fibres (C)

C	**Test**					
Sr.No	**Basis Weight (gsm)**	**Thickness (µm)**	**Air Permeance (sec/100 ml)**	**Tear Resistance (mN)**	**Burst Strength (kPa)**	**Tensile Strength (kNm/kg)**
1	60.32	133.25	3.75	912	146	27.63
2	60.93	132.65	3.81	861	151	30.58
3	60.86	133.97	3.86	929	167	39.43
4	60.45	134.35	3.82	796	150	40.51
Average	**60.64**	**133.55**	**3.81**	**875**	**154**	**34.53**

Table 4.6: Mechanical properties of 90% kraft pulp + 10% polyimide fibres (D)

D	**Test**					
Sr.No	**Basis Weight (gsm)**	**Thickness (µm)**	**Air Permeance (sec/100 ml)**	**Tear Resistance (mN)**	**Burst Strength (kPa)**	**Tensile Strength (kNm/kg)**
1	60.90	115.45	10.8	779	176	36.92
2	61.11	116.10	11.7	672	183	43.83
3	61.39	116.64	11.1	958	168	36.39
4	61.44	115.34	10.8	889	164	43.3
Average	**61.21**	**115.88**	**11.1**	**825**	**173**	**40.11**

Table 4.7: Mechanical properties of 95% kraft pulp + 5% polyimide fibres (E)

E	**Test**					
Sr.No	**Basis Weight (gsm)**	**Thickness (μm)**	**Air Permeance (sec/100 ml)**	**Tear Resistance (mN)**	**Burst Strength (kPa)**	**Tensile Strength (kNm/kg)**
1	60.90	115.45	10.8	779	176	36.92
2	61.11	116.10	11.7	672	183	43.83
3	61.39	116.64	11.1	958	168	36.39
4	61.44	115.34	10.8	889	164	43.30
Average	**61.21**	**115.88**	**11.1**	**825**	**173**	**40.11**

Table 4.8: Mechanical properties of 70% kraft pulp + 20% polyimide fibres +10% PVOH (EA)

EA	**Test**					
Sr.No	**Basis Weight (gsm)**	**Thickness (μm)**	**Air Permeance (sec/100 ml)**	**Tear Resistance (mN)**	**Burst Strength (kPa)**	**Tensile Strength (kNm/kg)**
1	60.11	140.70	1.59	968	139	25.30
2	59.88	138.00	1.86	760	118	26.95
3	59.92	138.15	1.27	970	117	18.15
4	59.22	137.25	1.82	712	119	21.17
Average	**59.78**	**138.52**	**1.63**	**853**	**124**	**22.89**

It is desirable to add sufficient amount of synthetic fiber to increase tear strength without disrupting the sheet structure to the point the tensile strength is decreased. From the figure 4.2, it is clear that the amount of synthetic fiber to be incorporated should be about 10-15% by weight of paper. Although a good combination of tensile and tear is achieved by polyimide fibers, it proved to be not desirable due to two disadvantages a) the air permeance of paper polyimide composite paper is less than normal kraft paper indicating poor bonding between polyimide fibers and cellulose pulp (Figure 4.1), moreover a lot a loose fibers are observed on the surface of paper sheet indicating poor bonding and b) polyimide fiber is very expensive.

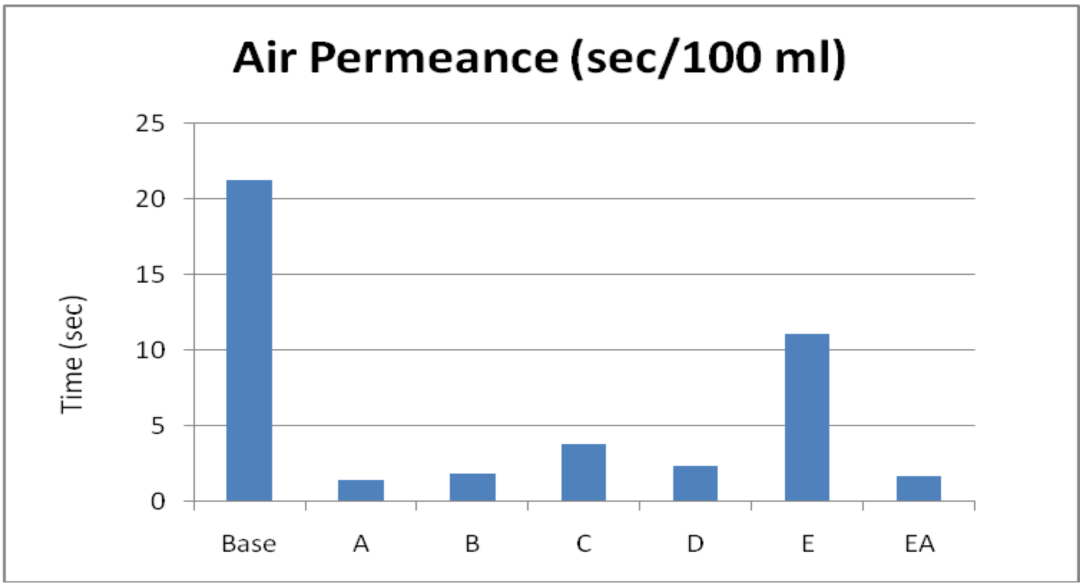

Fig 4.1: Air permeance of polyimide cellulose composite paper in comparison to normal kraft paper.

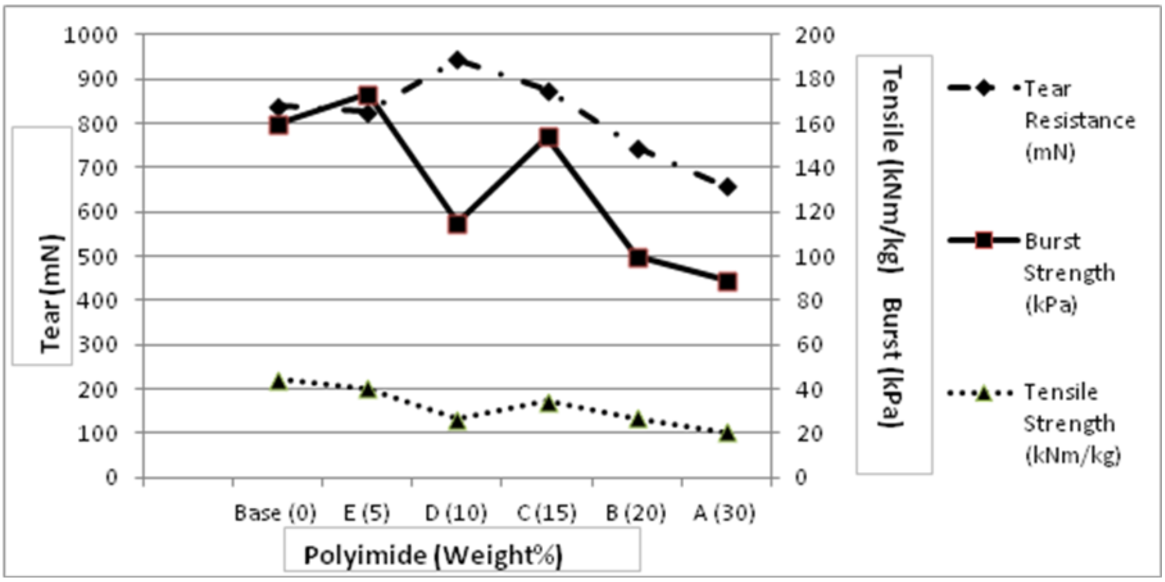

Fig 4.2: Effect of (weight %) polyimide loading on tear, tensile and burst strength of paper in comparison to normal kraft paper.

4.2. Effect of blending of kraft pulp and polypropylene fibres

Polypropylene, with its low loss factor and high thermal stability is considered to be one of the most hopeful polymers as a substitute for kraft pulp in making composite insulating paper. Experiments were conducted using polypropylene fibres and kraft pulp with binders. The weight percentage of polyimide fibres was varied from 5 to 25% and the kraft pulp weight percentage was varied from 94 to 74% and binder percent by weight was generally

1%. Polyvinyl alcohol (PVOH), starch and carboxy methyl cellulose (CMC) were used as binders (Table 4.9 to 4.15, Figure 4.3).

Table 4.9: Mechanical properties of 85% kraft pulp + 5% polypropylene fibres + 10% PVOH (A)

A	**Test**					
Sr.No	**Basis Weight (gsm)**	**Thickness (µm)**	**Air Permeance (sec/100 ml)**	**Tear Resistance (mN)**	**Burst Strength (kPa)**	**Tensile Strength (kNm/kg)**
1	59.14	133.2	4.04	801	128	25.68
2	59.33	137.4	4.07	770	135	27.22
3	59.98	140.1	4.72	812	145	28.45
4	60.04	133.6	4.04	791	135	27.86
Average	**59.62**	**136.1**	**4.21**	**793**	**135**	**27.30**

Table 4.10: Mechanical properties of 89% kraft pulp + 10% polypropylene fibres + 1% PVOH (B)

B	**Test**					
Sr.No	**Basis Weight (gsm)**	**Thickness (µm)**	**Air Permeance (sec/100 ml)**	**Tear Resistance (mN)**	**Burst Strength (kPa)**	**Tensile Strength (kNm/kg)**
1	61.45	137.1	5.2	1213	168	36.12
2	61.87	137.4	5.3	1301	135	35.44
3	61.13	135.3	4.9	1223	144	35.12
4	61.41	136.2	5.1	988	157	33.87
Average	**61.46**	**136.5**	**5.1**	**1181**	**151**	**35.13**

Table 4.11: Mechanical properties of 89% kraft pulp + 10% polypropylene fibres + 1% starch (C)

C	**Test**					
Sr.No	**Basis Weight (gsm)**	**Thickness (µm)**	**Air Permeance (sec/100 ml)**	**Tear Resistance (mN)**	**Burst Strength (kPa)**	**Tensile Strength (kNm/kg)**
1	57.55	138.6	3.89	871	112	31.01
2	57.11	139.4	3.70	880	116	34.62
3	58.85	139.1	3.67	991	132	30.88
4	58.34	138.2	3.49	912	129	31.22
Average	**57.96**	**138.8**	**3.68**	**913.5**	**123**	**31.94**

Table 4.12: Mechanical properties of 89% kraft pulp + 10% polypropylene fibres + 1% starch (D)

D	**Test**					
Sr.No	**Basis Weight (gsm)**	**Thickness (μm)**	**Air Permeance (sec/100 ml)**	**Tear Resistance (mN)**	**Burst Strength (kPa)**	**Tensile Strength (kNm/kg)**
1	58.98	162.2	1.98	903	157	22.22
2	62.12	161.3	1.66	1001	138	24.46
3	61.03	163.5	1.89	1033	146	24.92
4	60.88	164.1	1.75	939	151	27.01
Average	**60.75**	**162.7**	**1.82**	**969**	**148**	**24.62**

Table 4.13: Mechanical properties of 84% kraft pulp + 15% polypropylene fibres + 1% CMC (E)

E	**Test**					
Sr.No	**Basis Weight (gsm)**	**Thickness (μm)**	**Air Permeance (sec/100 ml)**	**Tear Resistance (mN)**	**Burst Strength (kPa)**	**Tensile Strength (kNm/kg)**
1	64.9	155.4	3.55	1193	140	29.76
2	63.88	153.2	3.92	1162	168	31.46
3	64.05	154.1	3.69	1004	162	27.77
4	64.56	153.8	3.87	1131	165	29.76
Average	**64.34**	**154.1**	**3.75**	**1122**	**159**	**29.68**

Table 4.14: Mechanical properties of 89% kraft pulp + 10% polypropylene fibres + 1% CMC (F)

F	**Test**					
Sr.No	**Basis Weight (gsm)**	**Thickness (μm)**	**Air Permeance (sec/100 ml)**	**Tear Resistance (mN)**	**Burst Strength (kPa)**	**Tensile Strength (kNm/kg)**
1	62.30	136.7	3.87	1059	106	29.32
2	61.24	137.1	3.92	992	130	31.70
3	62.02	137.5	3.67	981	140	30.11
4	61.55	137.3	4.10	1012	122	29.77
Average	**61.77**	**137.1**	**3.89**	**1011**	**125**	**30.22**

Table 4.15: Mechanical properties of 94% kraft pulp + 5% polypropylene fibres + 1% CMC (G)

G	**Test**					
Sr.No	**Basis Weight (gsm)**	**Thickness (µm)**	**Air Permeance (sec/100 ml)**	**Tear Resistance (mN)**	**Burst Strength (kPa)**	**Tensile Strength (kNm/kg)**
1	62.24	118.4	4.98	981	158	31.06
2	62.56	118.9	5.11	763	171	32.22
3	61.87	118.1	4.18	781	148	28.91
4	62.98	120.1	5.02	812	162	31.12
Average	**62.41**	**118.8**	**4.82**	**834**	**160**	**30.82**

There is a considerable increase in tear resistance of composite paper as compared to normal kraft paper which can be observed from Figure 4.4. However there is an increase in porosity of paper which shows that polypropylene fibres are not compatible with cellulose fibres which is clear from Figure 4.3. The porosity of paper has decreased considerably by using CMC as binder instead of using PVOH and starch as binder.

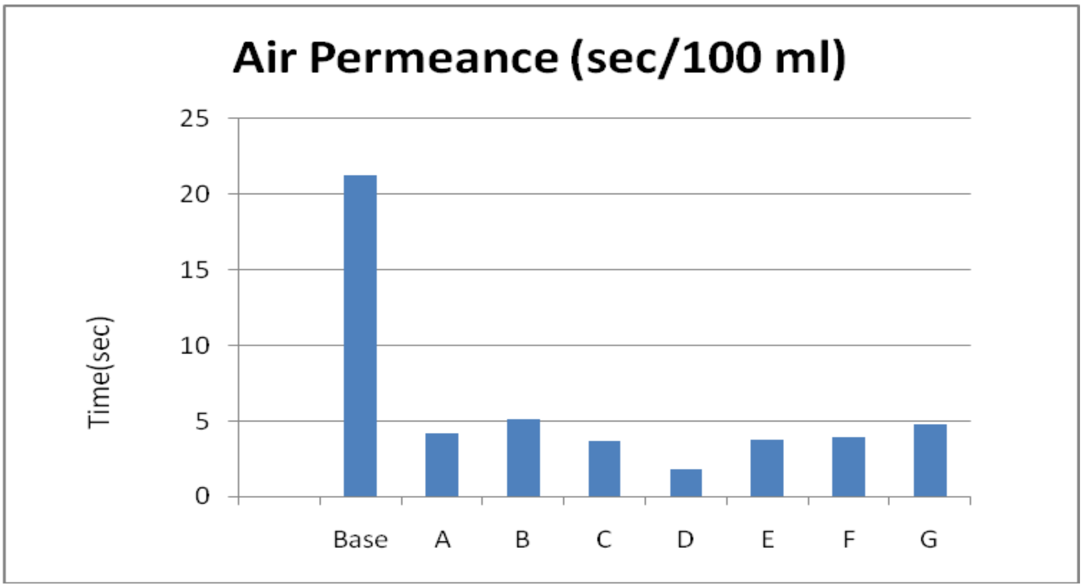

Fig 4.3: Air permeance of polypropylene cellulose composite paper in comparison to normal kraft paper.

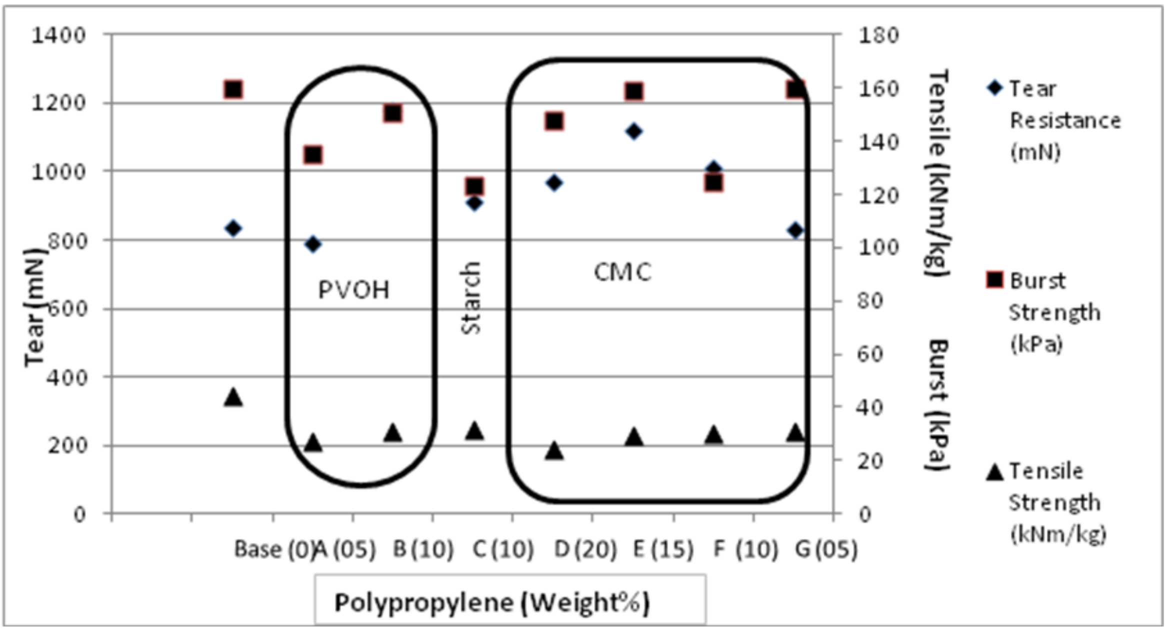

Fig 4.4: Effect of (weight %) polypropylene loading on tear, tensile and burst strength of paper in comparison to normal kraft paper.

4.3. Blending of kraft pulp and Recron 3s 6mm (PET) fibres

Experiments were conducted using Recron 3s, 6mm fibres and kraft pulp with binder. The weight percentage of synthetic fibres was varied from 5 to 20% and the kraft pulp weight percentage was varied from 85 to 70% and binder percent by weight was generally 10%. PVOH. The strength properties of paper were relatively low in spite of high binder addition (Table 4.16 to 4.19), this may be due to large aspect ratio of the fibres making it incompatible with cellulose pulp (Figure 4.5).

Table 4.16: Mechanical properties of 85% kraft pulp + 5% Recron 3s, 6mm fibres + 10% PVOH (A)

A	**Test**					
Sr.No	**Basis Weight (gsm)**	**Thickness (μm)**	**Air Permeance (sec/100 ml)**	**Tear Resistance (mN)**	**Burst Strength (kPa)**	**Tensile Strength (kNm/kg)**
1	61.31	112.10	9.24	1003	178	32.89
2	61.96	111.72	9.28	1247	184	44.47
3	61.34	112.75	10.7	1123	168	39.31
4	60.99	107.22	10.8	1127	196	30.22
Average	**61.40**	**110.94**	**10.0**	**1125**	**182**	**36.72**

Table 4.17: Mechanical properties of 85% kraft pulp + 5% Recron 3s, 6mm fibres + 10% PVOH (B)

B	**Test**					
Sr.No	**Basis Weight (gsm)**	**Thickness (μm)**	**Air Permeance (sec/100 ml)**	**Tear Resistance (mN)**	**Burst Strength (kPa)**	**Tensile Strength (kNm/kg)**
1	60.42	115.50	4.61	1020	135	34.22
2	60.57	112.60	4.65	1142	159	29.41
3	61.20	118.40	3.94	927	189	30.21
4	60.45	117.34	4.56	1210	154	29.41
Average	**60.66**	**115.96**	**4.44**	**1075**	**160**	**30.81**

Table 4.18: Mechanical properties of 75% kraft pulp + 15% Recron 3s, 6mm fibres + 10% PVOH (C)

C	**Test**					
Sr.No	**Basis Weight (gsm)**	**Thickness (μm)**	**Air Permeance (sec/100 ml)**	**Tear Resistance (mN)**	**Burst Strength (kPa)**	**Tensile Strength (kNm/kg)**
1	61.11	137.5	1.91	1425	131	25.35
2	61.45	138.6	1.83	1607	175	29.41
3	61.54	136.7	1.71	1207	129	30.21
4	61.12	136.5	2.00		160	29.41
Average	**61.30**	**137.3**	**1.86**	**1413**	**150**	**28.59**

Table 4.19: Mechanical properties of 70% kraft pulp + 20% Recron 3s, 6mm fibres + 10% PVOH (D)

D	**Test**					
Sr.No	**Basis Weight (gsm)**	**Thickness (μm)**	**Air Permeance (sec/100 ml)**	**Tear Resistance (mN)**	**Burst Strength (kPa)**	**Tensile Strength (kNm/kg)**
1	60.89	141.68	3.61	1348	159	31.22
2	60.44	143.22	2.89	1365	160	32.37
3	59.97	139.96	2.78	1500	151	31.57
4	60.11	140.23	2.89		160	35.85
Average	**60.35**	**141.27**	**3.04**	**1404**	**158**	**32.76**

Moreover, Figure 4.5 shows that the porosity of paper has increased indicating that the synthetic fibre is not compatible with kraft paper. This may be due to large aspect ratio of synthetic fibre.

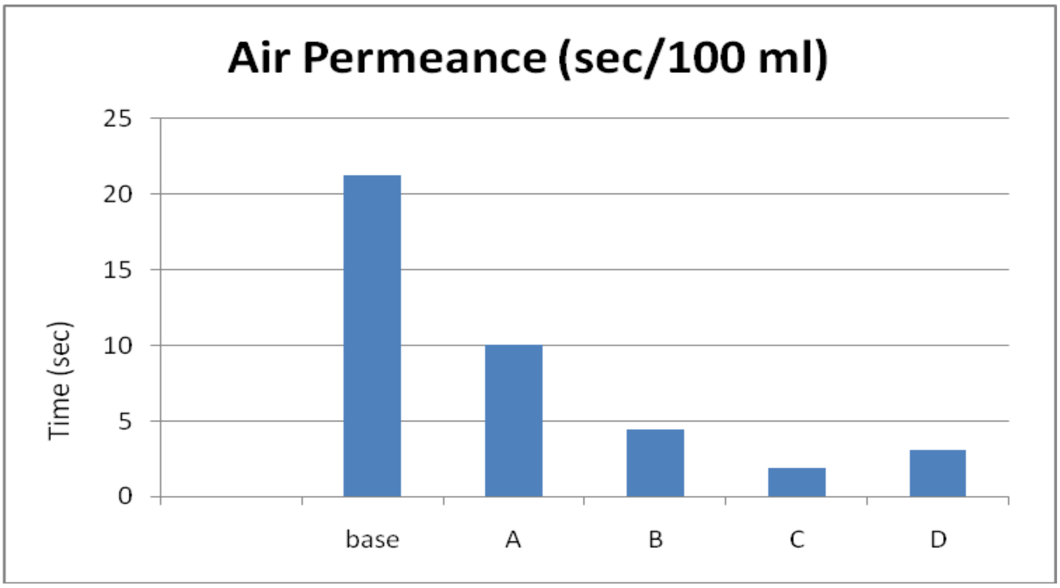

Fig 4.5: Air permeance of Recron 3s, 6 mm (PET) cellulose composite paper in comparison to normal kraft paper.

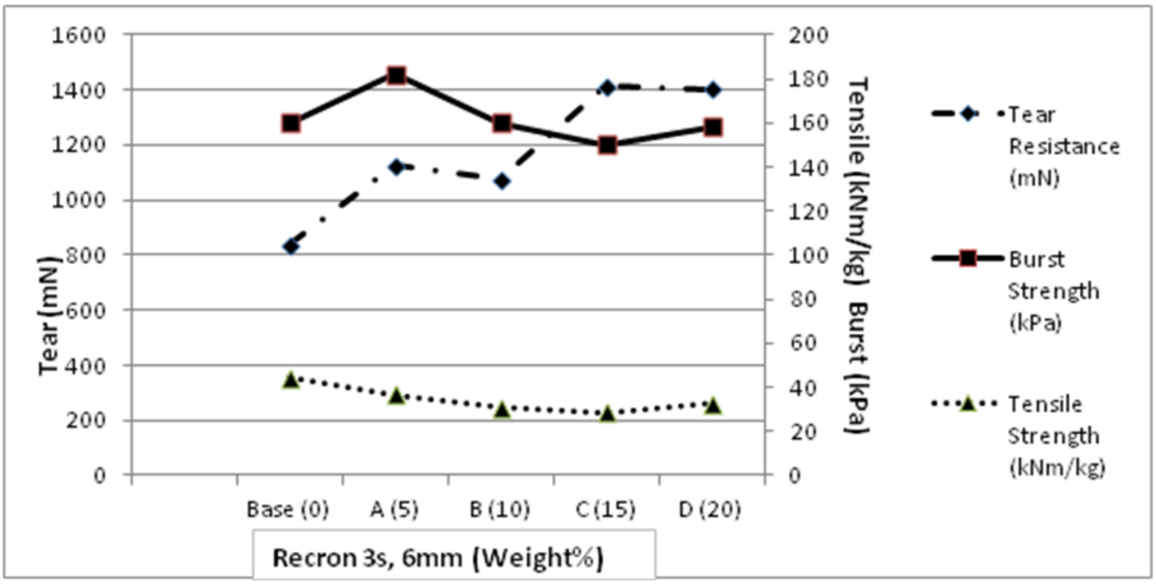

Fig 4.6: Effect of (weight %) Recron 3s, 6 mm loading on tear, tensile and burst strength of paper in comparison to normal kraft paper.

4.4. Blending of Kraft pulp and Recron 3s 3mm (PET) fibres

Experiments were carried out by using Recron 3s (Length=3 mm) with various binders viz PVOH, CMC, cationic starch. The weight percentage of synthetic fibres was varied from 5 to 20% and the kraft pulp weight percentage was varied from 94 to 79%. The variation in mechanical strength properties after addition of Recron 3s fibres can be seen from Table 4.21 to 4.30.

4.4.1 No binder addition

Kraft pulp was blended with Recron 3s without binder, so as to see the effect of binder addition on compatibility between cellulose pulp and synthetic fibres and also the effect of no binder addition on mechanical strength properties of paper (Table 4.20).

Table 4.20: Mechanical properties of 95% kraft pulp + 5% Recron 3s, 3mm fibres (A)

A	**Test**					
Sr.No	**Basis Weight (gsm)**	**Thickness (μm)**	**Air Permeance (sec/100 ml)**	**Tear Resistance (mN)**	**Burst Strength (kPa)**	**Tensile Strength (kNm/kg)**
1	61.28	120.2	4.8	746	144	33.81
2	62.34	121.3	4.6	842	156	33.55
3	62.66	122.3	4.9	868	142	32.88
4	61.94	124.5	4.7	791	139	32.66
Average	**62.05**	**122.1**	**4.7**	**811.75**	**145**	**33.22**

4.4.2 PVOH as a binder

Table 4.21: Mechanical properties of 89% kraft pulp + 1% Recron 3s, 3mm fibres + 10% PVOH (B)

B	**Test**					
Sr.No	**Basis Weight (gsm)**	**Thickness (μm)**	**Air Permeance (sec/100 ml)**	**Tear Resistance (mN)**	**Burst Strength (kPa)**	**Tensile Strength (kNm/kg)**
1	61.54	106.4	11.8	1308	163	43.04
2	62.45	107.1	11.6	1410	191	38.84
3	62.12	106.3	12.2	1345	178	35.43
4	61.89	107.5	12.0	1367	167	34.48
Average	**62.00**	**106.3**	**11.9**	**1357.5**	**174**	**37.94**

Table 4.22: Mechanical properties of 87% kraft pulp + 3% Recron 3s, 3mm fibres + 10% PVOH (C)

C	**Test**					
Sr.No	**Basis Weight (gsm)**	**Thickness (µm)**	**Air Permeance (sec/100 ml)**	**Tear Resistance (mN)**	**Burst Strength (kPa)**	**Tensile Strength (kNm/kg)**
1	62.86	110.4	9.81	998	181	38.21
2	62.55	112.5	11.20	748	186	39.25
3	61.14	111.4	11.87	824	172	33.50
4	62.01	112.6	10.96	994	188	34.78
Average	**62.14**	**111.7**	**10.96**	**891**	**181**	**36.43**

Table 4.23: Mechanical properties of 83% kraft pulp + 7% Recron 3s, 3mm fibres + 10% PVOH (D)

D	**Test**					
Sr.No	**Basis Weight (gsm)**	**Thickness (µm)**	**Air Permeance (sec/100 ml)**	**Tear Resistance (mN)**	**Burst Strength (kPa)**	**Tensile Strength (kNm/kg)**
1	59.84	138.2	5.79	1022	168	37.15
2	59.11	138.6	5.68	968	176	36.07
3	60.72	140.4	5.96	1002	188	37.43
4	60.06	139.5	6.15	981	169	36.34
Average	**59.94**	**139.1**	**5.89**	**993**	**175**	**36.74**

Table 4.24: Mechanical properties of 80% kraft pulp + 10% Recron 3s, 3mm fibres + 10% PVOH (E)

E	**Test**					
Sr.No	**Basis Weight (gsm)**	**Thickness (µm)**	**Air Permeance (sec/100 ml)**	**Tear Resistance (mN)**	**Burst Strength (kPa)**	**Tensile Strength (kNm/kg)**
1	61.66	130.8	8.98	904	131	31.34
2	61.19	131.2	11.2	886	128	29.31
3	60.87	133.1	10.4	891	133	28.81
4	61.12	131.6	10.2	876	142	28.50
Average	**61.21**	**131.6**	**10.19**	**889**	**133**	**29.49**

Table 4.25: Mechanical properties of 75% kraft pulp + 15% Recron 3s, 3mm fibres + 10% PVOH (F)

F	**Test**					
Sr.No	**Basis Weight (gsm)**	**Thickness (µm)**	**Air Permeance (sec/100 ml)**	**Tear Resistance (mN)**	**Burst Strength (kPa)**	**Tensile Strength (kNm/kg)**
1	64.11	145.4	7.8	1132	165	29.06
2	63.08	143.1	8.4	992	146	31.01
3	63.11	142.2	8.3	970	151	27.53
4	62.87	145.1	8.2	912	149	27.06
Average	**63.29**	**143.9**	**8.1**	**1001**	**153**	**28.66**

4.4.3 Carboxy Methyl Cellulose as binder

Table 4.26: Mechanical properties of 94% kraft pulp + 5% Recron 3s, 3mm fibres + 1% CMC (G)

G	**Test**					
Sr.No	**Basis Weight (gsm)**	**Thickness (µm)**	**Air Permeance (sec/100 ml)**	**Tear Resistance (mN)**	**Burst Strength (kPa)**	**Tensile Strength (kNm/kg)**
1	62.22	128.6	15.20	1194	176	37.17
2	63.08	129.7	15.62	1067	205	36.62
3	62.91	130.1	16.11	1132	177	38.81
4	62.18	131.2	15.97	1081	191	39.22
Average	**62.59**	**129.9**	**15.72**	**1118**	**187**	**37.95**

Table 4.27: Mechanical properties of 89% kraft pulp + 10% Recron 3s, 3mm fibres + 1% CMC (H)

H	**Test**					
Sr.No	**Basis Weight (gsm)**	**Thickness (µm)**	**Air Permeance (sec/100 ml)**	**Tear Resistance (mN)**	**Burst Strength (kPa)**	**Tensile Strength (kNm/kg)**
1	63.14	126.5	16.1	1232	188	38.21
2	63.88	121.3	15.3	966	172	40.22
3	62.94	123.5	16.2	1132	191	39.18
4	63.44	125.1	16.8	1031	201	40.11
Average	**63.35**	**124.1**	**16.1**	**1090**	**188**	**39.43**

Table 4.28: Mechanical properties of 89% kraft pulp + 10% Recron 3s, 3mm fibres + 1% CMC (I)

I	**Test**					
Sr.No	**Basis Weight (gsm)**	**Thickness (μm)**	**Air Permeance (sec/100 ml)**	**Tear Resistance (mN)**	**Burst Strength (kPa)**	**Tensile Strength (kNm/kg)**
1	63.11	136.7	13.8	902	168	36.33
2	62.28	137.2	14.6	859	174	35.81
3	61.67	135.8	14.7	1088	159	39.20
4	62.78	138.1	14.3	1034	164	37.14
Average	**62.46**	**136.9**	**14.35**	**970**	**167**	**37.12**

Table 4.29: Mechanical properties of 84% kraft pulp + 15% Recron 3s, 3mm fibres + CMC 1.5% of Recron 3s (J)

J	**Test**					
Sr.No	**Basis Weight (gsm)**	**Thickness (μm)**	**Air Permeance (sec/100 ml)**	**Tear Resistance (mN)**	**Burst Strength (kPa)**	**Tensile Strength (kNm/kg)**
1	61.10	118.1	14.6	914	239	41.11
2	61.90	121.2	14.2	926	240	43.02
3	60.12	119.5	13.4	1088	236	42.86
4	60.05	118.6	13.9	1022	230	44.51
Average	**60.79**	**119.3**	**14.2**	**988**	**236**	**42.90**

Table 4.30: Mechanical properties of 84% kraft pulp + 15% Recron 3s, 3mm fibres + Cationic Starch 1.5% of Recron 3s (K)

K	**Test**					
Sr.No	**Basis Weight (gsm)**	**Thickness (μm)**	**Air Permeance (sec/100 ml)**	**Tear Resistance (mN)**	**Burst Strength (kPa)**	**Tensile Strength (kNm/kg)**
1	61.20	122.2	15.1	906	261	48.96
2	60.03	123.1	14.7	929	264	44.61
3	59.97	119.6	15.2	1110	251	46.43
4	61.11	125.1	14.9	914	259	46.01
Average	**60.57**	**122.5**	**15.5**	**965**	**258**	**46.50**

It can be seen from Figure 4.7 that Recron 3s, 3mm is highly compatible with cellulose when CMC and cationic starch are used as binder. Moreover, from Figure 4.7 and Figure 4.9, it is clear that tear resistance and burst strength of paper increases by binder addition more so by using CMC and cationic starch as a binder. Figure 4.9 shows that there is an increase in tensile strength of paper while using cationic starch indicating it is compatible with Recron 3s.

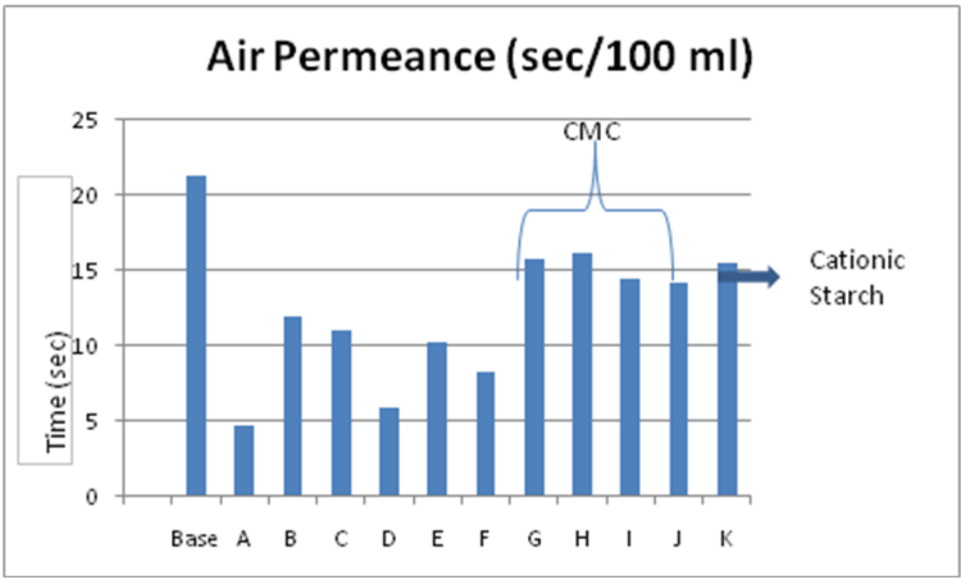

Fig 4.7: Air permeance of Recron 3s, 3 mm (PET) cellulose composite paper in comparison to normal kraft paper by using PVOH and CMC as binders.

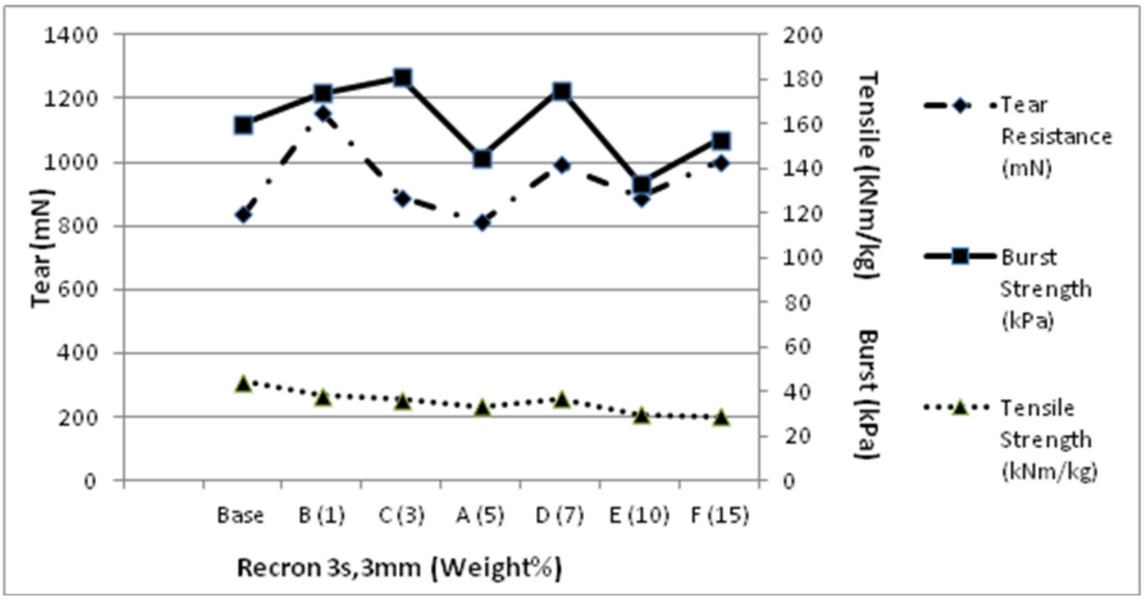

Fig 4.8: Effect of (weight %) Recron 3s, 3mm loading on tear , tensile and burst strength of paper in comparison to normal kraft paper by using PVOH as a binder.

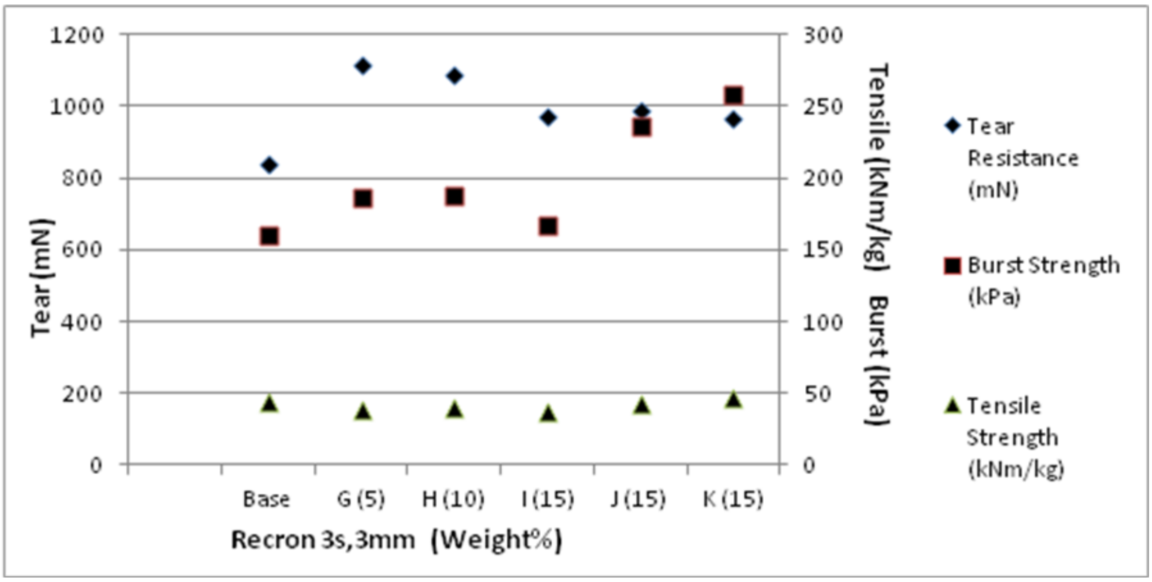

Fig 4.9: Effect of (weight %) Recron 3s, 3mm loading on tear , tensile and burst strength of paper in comparison to normal kraft paper by using CMC and cationic starch as a binder.

The transformer oil has a relative dielectric constant of 2.2, the ideal range for the dielectric constant of the insulating paper should be 2.2 to 3.5. The dielectric constant of kraft paper is more than 4, by adding synthetic fibres, viz, polyimide, polypropylene and polyethylene terepthalate, the value of dielectric constant is reduced by half.

Chapter 5: Conclusions

The strength of the non-cellulosic fiber exceeds the strength of non-cellulosic fiber bonding to the wood pulp fiber such that the non-cellulosic fiber tends to pull out of the paper rather than rupture when the paper product is torn with the tensile strength being substantially maintained. The tensile properties and tear resistance of paper depend on its structure. There is a tendency for tensile properties to increase with increasing paper density, whereas tear resistance of paper depends upon the synthetic fiber loading content.

A high tear strength and burst strength paper product comprised of wood pulp fiber in an amount from about 85% to 60% by weight, a non cellulosic synthetic fiber having length of from about 1 mm to about 3 mm in an amount of 5% to 30% by weight and a binder material in an amount from about 1% to about 10% by weight. It is desirable to add a sufficient amount of synthetic fiber to increase the tear strength without disrupting the sheet structure to the point the tensile strength is decreased. It is preferred that the amount of synthetic fiber should be 10 to 15 % of total weight of paper. The binder addition should be on basis of synthetic fiber. The nature of synthetic fiber and its bonding with hydrophilic cellulose fiber is an important factor affecting the structure and uniformity of composite paper and its mechanical properties. The preferred binder composition would be from 1-5 % by weight of synthetic fiber. Best results were achieved by blending polyethylene terepthalate fibers (Length: 3 mm) with kraft pulp by using cationic starch as binder. The composition of kraft pulp was 90% by dry weight, the synthetic fiber composition was 10% was by dry weight and the binder composition was 1.5% by dry weight of synthetic fiber.

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