ABSTRACT

CUERVO GARCIA, PAULA ALEJANDRA. Influence of Pressure and Specific Energy on the Structure of the Hydroentangled Fabrics. (Under the direction of Dr. Behnam Pourdeyhimi).

During the past decades, hydroentangling has become a very interesting technique to mechanically bond webs that can result into amazing nonwoven products with a wide range of applications in many industries globally. This bonding technique involves the use of high energetic water jets that impinge the web, entangling the fibers or the filaments. The fabrics made through hydroentangling are considered "3D" materials, due to the fact that the fibers may be entangled in the thickness direction. The fiber entanglement results in good performance – good strength, softness, low lint, etc.

The process provides controls the pressure and the types of nozzles employed. In turn, the weight of the material and the speed of the production determines the total imparted to the web. This work partially focuses on the relationship of pressure and specific energy in the hydroentangled fabrics with the aim to understand which of these two parameters "control" the degree of entanglement. We performed five specific design of experiments (Experiment) to establish the basis for entanglement and establish structure property relationships as a function of pressure, energy, line speed, and the types of nozzles employed. The Experiment and the results are shown in chapters 5 and 6. Several fabrics were produced; these include 50/50 blends of cotton, and polyester fibers (PET) as well as 100% cotton and 100% PET. These were chosen because blends of cellulosic fibers and PET and/or PP are very common. The performance was measured in terms of air permeability, density, burst strength and tear strength.

Overall, the results indicate that hydroentangling energy is what determines entanglement and that equivalent fabrics can be produced by using similar hydroentangling energy levels.

Further, it can be seen that the type of jet strips used and the nozzle to nozzle spacing can lead to structures that behave similarly if the total energy is kept constant. This can lead to potential process improvements such as using fewer nozzles, and less water leading to significant savings.

Influence of Pressure and Specific Energy on the Structure of the Hydroentangled Fabrics

by
Paula Alejandra Cuervo Garcia

A thesis submitted to the Graduate Faculty of
North Carolina State University
in partial fulfillment of the
requirements for the degree of
Master of Science

Textile Engineering

Raleigh, North Carolina

2018

APPROVED BY:

Dr. Behnam Pourdeyhimi Chair of Advisory Committee	Dr. Benoit Maze
Dr. Eunkyoung Shim	Dr. Hechmi Hamouda

DEDICATION

To my amazing family, especially my parents who have been supporting me in every aspect of my life, as well as my academic and professional career, caring about my development as a human being. I also want to thank to my siblings, important part of my life, they have been supportive with me and have tried to help me to make my dreams come true. I want to thank to Dr. Pourdeyhimi for offering me this opportunity that has completely changed my life, my possibilities in the future and who inspires me to be a better student and professional.

Also to my lovely nieces and nephews who inspire me every day to be a good role model for them.

BIOGRAPHY

Paula Alejandra Cuervo Garcia was born in Manizales, Colombia on December 20, 1989. She finished her bachelor degree in Engineering Physics at Universidad Nacional de Colombia in 2011. For about five years, she had the opportunity to work in the industry. In one of the experiences, she had the opportunity to work for a company that sells nonwovens materials to the hygiene market in Colombia, this experience showed her the great world of nonwovens and then she wanted to pursue a career in this area. For the past two years during her Masters in Textile Engineering, she has been studying the effect of changing different parameters in the hydroentanglement process to enhance the resultant fabrics and the process by itself.

ACKNOWLEDGMENTS

I would like to express special gratitude to Dr. Pourdeyhimi for his support to finish my Masters and the NWI staff and students.

Advising Committee

- Behnam Pourdeyhimi, Ph. D
- Eunkyoung Shim, Ph. D.
- Hechmi Hamouda, Ph. D.
- Benoit Maze, Ph. D.

Lab Managers and Technicians:

- Angelo Corino
- Amy Minton
- John Fry
- Bradley Scroggins

Friends, family and officemate

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CHAPTER 1: INTRODUCTION

1.1 PURPOSE

Nonwovens materials have shown an exponential growth the last decades and especially the hygiene products have the biggest participation in the market. This kind of materials have been used for many years, but with the introduction of nonwoven materials for its production, more applications have been found. One of the biggest application is wet and dry wipes not just for baby or adults, but also for household cleansing, antibacterial wipes, pets cleansing, personal care, such as make up remover, flushable wipes to replace or complement toilet paper, industrial wipes that can absorb different substances, like water, dust or thicker materials, such as oil, can be made using hydroentangling machine. This bonding technique allows the materials to have the characteristics required for wipes, as well as other hygiene products, or even products used in other applications, such as filtration, medical gowns or drapes, food packaging and so on. Either synthetic, natural or man-made fibers can be used to produce nonwovens through hydroentangling technique. The selection of the fibers or filaments is based on the cost of the raw materials, the application of the spunlaced fabric and the desired performance of the final product.

Thinking in the possibilities that this bonding technique offers, different fabrics have been produced, changing various process parameters and characterizing the final product, to see how those little variations, improve or change the product, in order to make the process as effective as possible, reducing costs and with a better material

The final fabric obtained should have different features, like basis weight, bulkiness, absorption performance, but with the different options to produce them, the idea is identified which parameters must be changed and which ones must be kept. Different fibers can be used and they will also determine the characteristics of the final product.

1.2 RESEARCH OBJECTIVES

Pressure and energy are the most remarkable variables involved in the hydroentanglement process. The pressure profile is related to water consumption required and also will determine the total energy imparted to the fabric (depending on the web weight and line speed). Hydroentanglement is a process that involves the transfer of kinetic energy to the web, entangling and intertwining the fibers and due to frictional forces, the fiber or filaments stay together. This study performed 5 different EXPERIMENTs (Design of Experiments) to determine the process variables that control the properties of the resulting fabrics, and decouple pressure from total kinetic energy. Analysis of variance (ANOVA) was performed to establish differences amongst fabrics tested.

Companies are always looking for processes that enhance the production rate and result in lower cost. Therefore, another objective was to determine if fabrics with similar properties can be produced by for example, using fewer hydroentangling manifolds or by using different nozzle geometries that lead to lower water consumption.

CHAPTER 2: REVIEW OF LITERATURE

2.1 WHAT ARE NONWOVENS

Nonwovens have many definitions; however, organizations such as INDA (North Americas' Association of the Nonwovens Fabrics Industry) or EDANA (The European Nonwovens Association) and some books like the Handbook of nonwovens have similar definitions. Nonwovens is a sheet, web or mat of fibers or filaments that have been bonded together by chemical, mechanical or thermally procedures that interlock the fibers or filaments present in the structure. The resulting sheets are of porous nature and usually flat, with unique characteristics that make them interesting for several applications in various industries. The fibers and filaments mentioned before can have natural, man-made or synthetic origin. They can also be separate fibers or molten plastics; this would depend on the web formation technique used. Nonwovens have gained a lot of fame through the past decades, because they are fabrics with special characteristics and many applications can be achieved thanks to the versatility of the processes; they can also be long lasting while others can be made for few uses or even single-use. Some specific functions of these fascinating materials are Absorbency, Bacterial barrier, cushioning, filtering, flame retardancy, liquid repellency, softness, strength, drapeability and some others that the research devoted in this area has been discovering.

The nonwovens processing has been inspired by other industries, such as pulp and paper, fiber and polymer extrusion and traditional textile.

These unique textiles are also called engineered fabrics; this is because the different web formation techniques and web bonding techniques can be combined to produce special and customized fabrics with features that seemed to be impossible to get before. Besides, they are lightweight and faster to produce when compared to traditional textiles. We can find from disposable to super resistant and high performance nonwovens. This versatility allows their usage in many industries and applications. They are often produced and converted to give place to many products that we use in a regular basis [1-3]

Many industries have found in nonwovens a solution for the big challenges they face in a growing world that each day requires more product that make life easier. Different products made out of nonwoven materials have been use for many companies to introduce, enhance or enlarge their current products with a good balance life-use and cost. Some of the fields that have taken advantage of the potential of nonwovens are: Food packaging, Hygiene market (Baby and adult diapers, feminine care, etc.), Wipes (Dry, wet,), Household, Filtration, Insulation, Automotive, Geotextiles, Apparel, Agriculture, Medical.

2.2 APPLICATIONS OF NONWOVENS

Many properties for different applications may be achieve thanks to the versatility of nonwovens; they can also be long lasting while other can have few uses or even single-use. Some specific functions of these engineered materials can be:

- Flame retardancy
- Absorbency
- Softness
- Washability
- Filtering
- Bacterial barrier
- Liquid repellency
- Among other properties that several industries find interesting because the wide range of applications

Many industries have found in nonwovens a solution for the big challenges they face in a growing world that each day requires more product that make life easier. Different products made out of nonwoven materials have been use for many companies to introduce, enhance or enlarge their current products with a good balance life-use and cost, some of the fields that have taken advantage of the potential of nonwovens are:

- Food packaging
- Hygiene market (Baby and adult wipes and diapers, feminine care, etc.)
- Household
- Filtration
- Insulation
- Automotive
- Geotextiles
- Apparel linings
- Agriculture
- Wall covering
- Household
- Roofing
- Building construction
- Medical/surgical products (Caps, masks, gowns, drapes, wound care, etc.) Other [1-2]

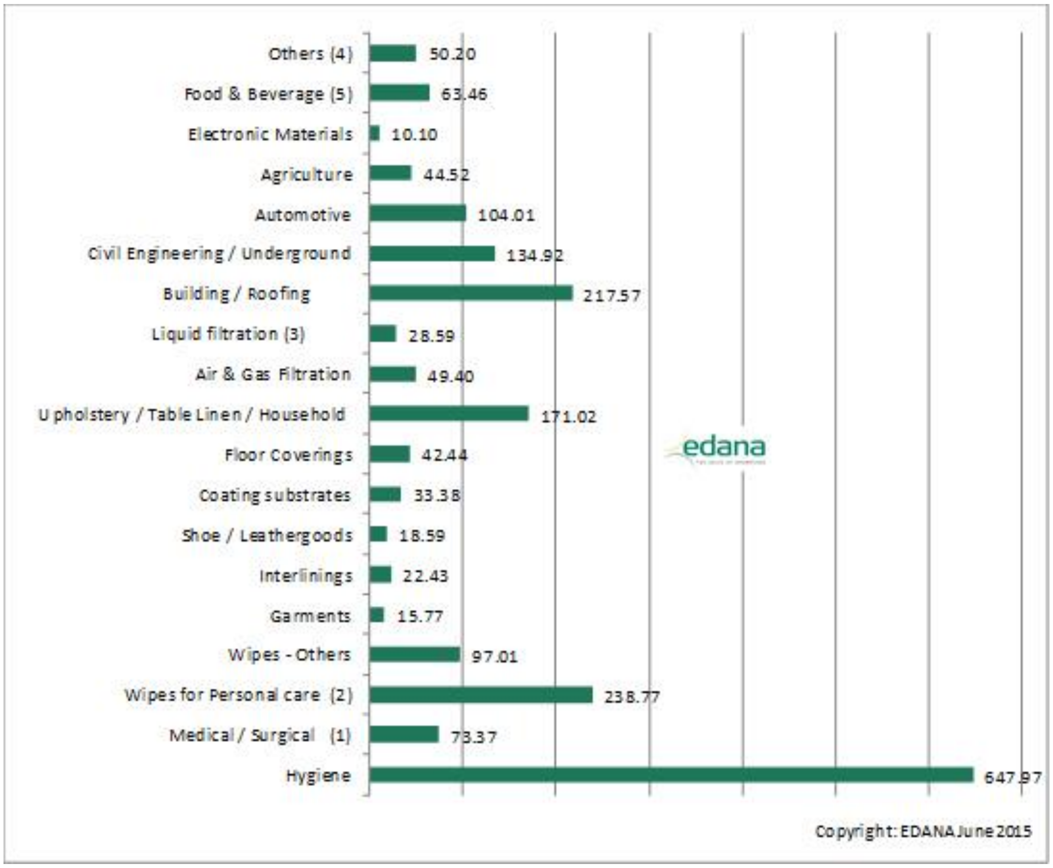

Figure 2.1: Nonwovens market in 2014 [2]

2.3 HOW NONWOVENS ARE MADE

Nonwovens have different steps to be produced; first, raw materials must be chosen, normally the fibers used for nonwovens production are polyester, polypropylene, bi-component fibers, cotton, viscose and so on, some have polymeric nature or are man-made and other fibers are natural, the second step is called web formation and there are some options for this: Dry-laid, wet-laid and spun-laid. The main purpose of the web formation step is to convert a bunch of fibers or filaments to a thick web that can be converted into a fabric through a process called web bonding. The third step is the web bonding and basically consist is bond the web that has been gotten during the web formation, the web is bonded through chemical, thermal or mechanical techniques. The most widely used thermal bonding thecniques are calendaring bonding and and as mentioned before, nonwovens can be bonded through chemical, thermal and mechanical procedures, the last step is finishing and converting with chemical or mechanical techniques that are widely used.

2.4 WEB FORMATION TECHNIQUES

As mentioned in the previous paragraph, there are several ways for web formation to take place, in this stage, webs with little mechanical integrity are obtained, and then web-bonding techniques must be used to get a strong and well-formed fabric. They are disclosed here:

2.4.1 Dry-laid

This web formation technique has become very popular in nonwovens production; it can be combined with bonding process to get good materials with many applications. It is particularly interesting, due to involves staple fibers that can be natural or man-made. The natural fibers are often obtained in staple form; however man-made fibers are usually obtained in filaments and they must be cut. Having the possibility to use natural and man-made fibers, make this technique ideal for any applications. The two main dry-laid processes are carding and air-laid, they both will be widely explain in the next paragraphs. [3]

2.4.1.1Carding

Carding is the most widely used method to form the web using fibers, either organic or inorganic, being polyester the most popular one, this wide usage is due to its convenient cost and suitability for many nonwovens goods. The basic principle of carding is to disentangle the fibers that have been previously selected and mix them to form the web, that must be homogenous and with uniform weight per unit area. Along the carding machines, we find several rollers with teeth, which purpose is to do the action described (open and mix). The machines can have different settings, but they all perform the same way and are supposed to form a uniform web from fiber bundles.

Although, every carding machine is different, some rollers must exist in all of them, independently to the setting.

The carding machines usually have a big cylinder and several rollers that work around it and have some functions that will be mentioned below.

The cylinder is the main component of the carding machine, and its functions is to distribute the fibers while the process takes place. There are other rollers called worker and stripper, they form pairs and are place around the cylinder, the way they operate allows them to have two functions, mixing and carding, due to this action, the fibers stay in these two rollers and then are place in the cylinder where the process continues. Other type of rollers are called the doffers, they have the function to remove fiber from the cylinder, but these fibers are not bundle anymore, but web. Nevertheless the doffers do not remove all the fiber in form of web, some of those fibers are taken again by the cylinder and are mix with either new fibers fed by the cylinder or recycled ones.

The ability of the carding machine to mix new fibers with recycled ones is what lets this technique to produce outstanding webs, with perfectly mixed fibers.

To have a better understanding of the explanations, the following shows a basic carding machine, as we mentioned before, every company has different setting, depending on their needs and type of fibers they mix for their products.

Each roller (Cylinder, doffer, stripper or worker) has small metallic teeth that allow them to break the fibers from the tuft, therefore the following steps, such a mixing and carding can take place. The rotary direction and the way that teeth in a roller are located with respect to the teeth in other roller, determines the success of the carding action and a correct distribution of the fibers along the web. The worker rotates in an opposite direction to the cylinder, this means that the point of the teeth in the worker cylinder oppose the teeth point in the cylinder. The worker rotates to a lower speed than the cylinder and we desire this kind of roller to be empty as long as possible. When the worker is full of fiber, it cannot catch new ones and the efficiency decreases. The speed is also a key factor, it cannot be to slow as people believed for long time, or otherwise it is not going to work optimally. [3]

The characteristics that carding process confers are unique and helps to enhance the performance of the final material, some of its benefits are.

- Well defined MD/CD ratio
- Good web uniformity
- It allows to mix appropriate the fibers
- Carding action allows the change of some parameters, such as speed that can lead in a process ideal for multiple applications. [4]

2.4.1.2 Air-laid

This process requires very specific features in the fibers that are intended to be use. They can be either natural or man-made fibers. Their weight must be in a range of 1 and 200 dtex and their length cannot be more than 120mm, so webs made out of short fibers are ideal to be produced with this technique; actually, pulp is widely used in air-laid. After passing through a rotating drum, these fibers get into a turbulent airflow, that arrange them in a randomly way, forming a three-dimensional web structure. Generally, latex emulsions, thermoplastic fibers or a combination of both are used to bond the fibers, as a result, the material looks like a paper, but thicker, softer and with better absorption capacity. At the same time, the strength and the integrity of the sheet is much better than paper, making this kind of material, ideal for disposable, absorbent applications:

- Wet hand wipes
- Household cleaning wipes

- Industrial wipes
- Baby diapers and wipes
- Feminine care products
- Other hygiene applications [5]

2.4.2 Wet-laid

Nonwovens industry has taken process from several industries, such as traditional textiles or papermaking, this last industry has a narrow relationship with wet-laid process. Either, natural, man-made or synthetic fibers with short length can be used in this process. Due to it is difficult to control the orientation in an aqueous environment; the fibers are randomly oriented in the web.

This process consists in the suspension of fiber into water, then they are dry in a mesh that filters the liquid and forms the web, the web is then transferred to a drying felt to later being cured with heat. [3] [12]

The materials produced with this web formation technique tend to be used for disposable application that requires very short useful life. High production rates and economical products are highly appreciated, even if the quality needs to be sacrificed. The most common applications include products for different areas, like medicine, food but that do not require high performance, such as tea bags, napkins, gloves and so on. [3]

2.4.3 Spunlaid

This web formation process involves the extrusion of a molten polymer through a system with spinnerets and a high-speed current of air or other gas. The fibers are formed and deposit in either, conveyor, scrim or screen drum to form the web. The extruded filaments can have defined orientation (prior web formation) in order to give the web higher strength. The web is then taken by a support to the station where the bonding process takes place. [3]

There are two famous processes for web formation of nonwovens; they are spunbond and meltblown. They are widely used for their multiple applications and have been widely studied. They will be described in the next paragraphs.

2.4.3.1 Spunbond

It is a process that involves the extrusion of polymers (Polypropylene, polyester, polyethylene, polyamide, polyurethane are most commonly used polymers) through a system that involves different steps, such as extruder, filament spinning that produces nonwovens with very good strength.

This kind of materials are not bulky, but they are uniform and possess good tensile and tearing strength. They have many applications, like geotextiles, filters, protective clothing and other industrial applications. [2]

PP spunbonds are hydrophobic, and can be used for hygiene applications, such as the backsheeet of a baby diaper. They can have different treatments that make them hydrophilic and this gives them more applications, for example the topsheet of a diaper that must be hydrophilic, in order to let the liquids to go from that layer to the superabsorbent materials. [6]

2.4.3.2 Meltblown

This process consists of the extrusion of melted thermoplastic polymers (PET, nylon, polypropylene, TPU, PLA and styrene are highly used) through an air current with high velocity, and then this material is collected for a device, forming a self-bonded web. With this technique, uniform fine fibers can be produced with good properties, such as softness and strength.

Meltblown is particularly interesting and widely used, because it is able to make fabrics with high surface are and a low cost.

When the thermoplastic is in a semi-molten strength, the fibers can be stretched to get the final diameter and due to there is not a method for drawing the thermoplastic before being deposited in the collector, they are materials with not very good strength. [8]

Both methods, spunbond and meltblown can be combined to get fabrics with amazing properties.

2.5 WEB BONDING TECHNIQUES

This step consolidates the web into the nonwoven fabric. With the use of different techniques, the web that was formed previously with one of the methods mentioned above, finally can be bonded and some properties, such as bulkiness and appearance change.

For web bonding there are 3 methods used, they are thermal (Calendering, through-air), chemical (adhesive bonding) and mechanical (Needlepunching and hydroentangling).

Brief explanation of thermal and chemical bonding technique will be given as follows and we will go deeper in the mechanical bonding techniques, especially hydroentangling which is the study of our interest.

2.5.1 Thermal bonding

As its name says, this technique involves heat to bond the fibers and there are several options, such as hot calendaring, area bonding, point bonding, embossing, through air bonding, ultrasonic bonding. We will focus in calendaring and through air bonding.

2.5.1.1 Calendaring

It involves three main types of hot calendaring.

Area bonding: A hot metal roll is in contact with felt made of wool, cotton or other material. In most cases more than one hot roll is involved, depending of the weight of the web and the degree of bonding that wants to be achieved. There are several configurations, like three rolls or four rolls configurations. In both systems, the hot roll is located in a different place. The four rolls configuration allows more versatility in the heat application, leading in a wider range of basis weight.The materials bonded this way are usually thin, smooth and stiff.

Point bonding: This method is the most used, and it is ideal for hygiene and disposable applications, such as diapers, sanitary and medical products. Two rolls are in contact, both can be heated or just one can be heated, they usually have patterns that will determined the point where the fabric has been bonded. The features of the fabric are determined for the temperature and the pressure used during the process, the pattern also plays an important role.

Belt calendaring: This process is a modification of the point bonding. This means that also involves hot roll, but the temperature and the pressure are much lower, about 1/10th of the point bonding. The heated roll bonds the web against a rubber blanket. The materials resulting are less dense than the ones obtained with area bonding or point boinding and can be compared to paper. [3]

2.5.1.2 Through air bonding

Hot air is applied to the surface of the web that has been formed. Negative pressure or suction pulls the hot air through an open conveyor that supports the nonwoven fabric and then it passes through an oven. To bond the web, a binder must be used that form molten droplets that are the ones that bond the fibers when cooling.

The fabrics made with this technique tend to be bulky, soft and strong, they have good absorbent and breathable properties. [3]

2.5.2 Chemical bonding

The fibers in the web are bonded with the use of a bonding agent. This agent normally is made out of the same polymer of the fibers to create bond between fibers.

Typical binders used are made with PVA (Polyvinyl alcohol), polyvinyl chloride, polyvinyl acetate and acrylic binders. Despite of the several options available, the binder is chosen according to the fibers that need to we bonded. [3]

2.5.3 Mechanical bonding

In the last decades, mechanical bonding has become very popular, due to the good properties of the fabrics, the range of basis weight that might be obtained, the types of fibers that can be used and the applications that require materials with such good characteristics. There are to techniques very used all over the world and the trend of their participation in the market is to continue growing.

2.5.3.1 Needle punching

This mechanical bonding technique uses steel needles to entangle the fibers in the web. It typically bonds dry-laid and spun-laid webs. Needle punching uses needles that punch the fibers through the web and when the fibers are displaced in a right way, they stay in the new place even when the needles have been withdrawn. Fibers can go up, down or in both directions

It has many applications in medical fabrics, geotextiles, automotive fabrics, clothing and furniture, filtration.

2.5.3.2 Hydroentangling

It is a technique to mechanically bond the fibers in a web, using high energetic waterjets as a high speed. Many parameters are involved, the fabrics gotten have many applications and it is growing in the nonwovens production.

The next chapter is dedicated to the whole process, its parameters, types of fibers used and the characteristics of the fabric.

CHAPTER 3: HYDROENTANGLING

One very interesting method for bonding fibers and producing nonwovens is called Hydroentangling and it is a technique to mechanically bond natural or synthetic fibers with high energetic waterjets. These water jets are driven out of thin-plate strips that usually have 40-50 nozzles per inch. The structure created with this method is a 3D structure, due to the waterjets move the fibers in different directions and also turn or twist such fibers. [9]

The kind of materials you can make with hydroentangling, are generally soft to the touch, uniform, bulky, low-lint with good absorption properties. They make this kind of materials, ideal for different applications, such as hygiene market, some popular products are baby wipes, household wipes, industrial wipes, feminine hygiene products, adult incontinence, as well as medical applications, like drapes, gowns, surgical masks, wound care and so on. This method is interesting for several reasons; one of them is the quality of the fabric, the fibers that can be used and the patterns can be achieved using embossing plates. Al of these possibilities can make unique and customized materials at the same time they improve the performance of the final product; for example a baby wet wipe with embossing pattern or also called structured surface has the capability of cleaning better and retain more liquid or different substances. The nonwovens product can be either environmental friendly, when 100% natural or man-made biodegradable are used fibers (Cotton, viscose, jute, hemp, bamboo) or they can have a percentage of polymeric fibers such as polyester, polyethylene or polypropylene, that is this case can be considered as the matrix of the fabric. The future trend for this market is to grow up and to open its path to different segments. [10]

The entangling of the fibers, takes place when the water jet impacts in the web, this means that the water jets transfer energy to the web, while entangling the fibers, The pressure applied to the web (supported on the drum or belt) depends only on the type of fibers and the web basis weight. Pressure is an important parameter and normally the number of manifold varies, depending of the degree of entangling we want to get. Normally in real production more than five manifolds are used, the pressure increases in each manifold; the first manifold has always the lowest pressure, in order to pre-wet and pre-entangle the fibers or filaments in the web and the last one uses the highest pressure, this arrangement prevents the fibers to jump out of the web. [11-16, 20-39]

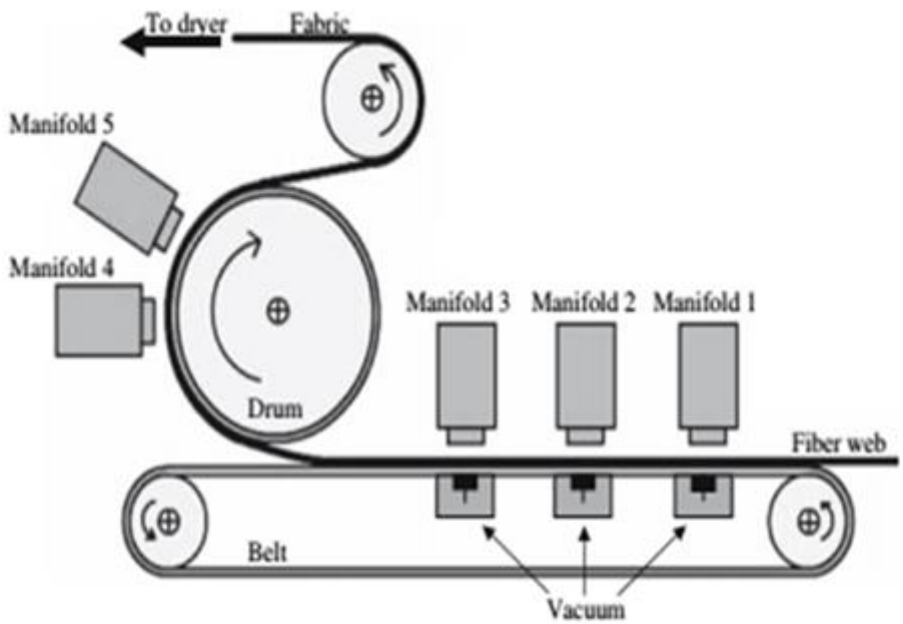

Figure 3.1 Fleissner Aquajet machine with 5 manifolds

The figure 3.1 shows the machine that was used to perform this research project. The machine is a “Fleissner Aquajet” with 5 manifolds. Manifold 1 is used to pre-wet and pre-entangle the fiber web and usually operates under low pressure, typically 30 bar. Manifolds 1, 2 and 3 are called the face manifolds, because they bond the web in the upper side, manifolds 4 and 5 are called the back manifolds, because they bond the web on the other side. It is necessary to have manifolds that reach both sides of the web, otherwise we can have a fabric that has been bonded in a non-homogenous way and the properties can be negatively affected. The machine has a forming wire or belt, this is the surface where the web is placed to be bonded. This belt together with the rotating perforated drum, carry the web throughout the whole systems, this interaction causes textures that remain in the resultant fabric. The belt and rum allow the fiber web to go under the different parts of the machine, where the bonding takes place. The machine also has vacuum boxes that are placed opposite to the manifolds underneath the belt and inside the drum. The purpose of the vacuum system is to extract the water from the fiber web, this way we can ensure that there is not remaining water affecting the entanglement, if this water stays in the web, the water ejecting from the nozzles would not be able to transfer enough energy to properly bond the fibers or filaments.

After the web has been bonded and has passed through the whole system is then ready for drying and winding process.

Due to the hydroentanglement is a process, where the water jet transfers kinetic energy to the web, this action makes the fibers turn, rotate, interlock and twist around each other, hence they stay together by frictional forces. It is a complex process that involves more than just the parts of the machine. The variables and parameters to consider will be disclosed in the following sections.

3.1 PARAMETERS USED DURING HYDROENTANGLING PROCESS

As mentioned before, many variables are involved during the production of hydroentangled fabrics. We must consider the web formation technique, the fibers and the experimental set up. In this section we will describe other parameters that must be considered for hydroentanglement and their impact or role during the process. They are: jet pressure, nozzle diameter and geometry, jet spacing, belt speed, velocity of the water jet and number of manifolds needed for a good procedure to take place. They will be explained as follows:

3.1.1 Number of manifolds

The hydroentangling system has several parts, manifolds is one of the most important parts of the machine and the process, and it also has a vacuum system that helps the web to be in its place during the production and absorbs the excess of water in the web. The vacuum box is for avoiding water to stay in the fabric and to keep waterjets energy and their transfer for the process to keep running. The air drums completely dry the resulting fabric and finally the web goes to the winding area, where the roll goods are formed.

The primary use of the first manifold is to pre-wet the web, it has the lowest pressure to pre-entangle the fibers in the way, and normally this value goes from 15 to 30 bar. Some hydroentangling machines for experimental work use only might have up to 5 manifolds, while in real production the machines normally have 8 or even more manifolds, in order to produce webs perfectly entangled. The more manifolds the better the level of entangling is. [9]

Manifolds also called injectors are one of the most important parts of the hydroentanglement machine. The jet strip is placed inside and also they are connected to the pumps that will apply the pressure chosen according to each production requirement. The number of manifolds change according to the machine, commercially we can find machines with 8 or more manifolds, to a lab scale we can find machines with 3 or 5 of them.

The first manifold is used to pre-wet and pre-entangle the fibers in the web; therefore the pressure is usually lower than the other manifolds. 30 Bar is a good way to start the process, it keeps the fibers in the web and the entanglement starts taking place.

Our previous machine has 5 manifolds, the first one uses the lowest pressure (30 – 50 Bar) and the next 4 manifolds gradually increase such pressure.

Manifolds 2 and 3 are called face manifolds and manifolds 4 and 5 are called back manifolds.

If we do not bond the web in both sides (Face and back) we are going to have a weak structure.

This is a schematic of the manifolds and jet strip that is placed inside the manifolds in the bottom part. It will be an explanation of it further in this document.

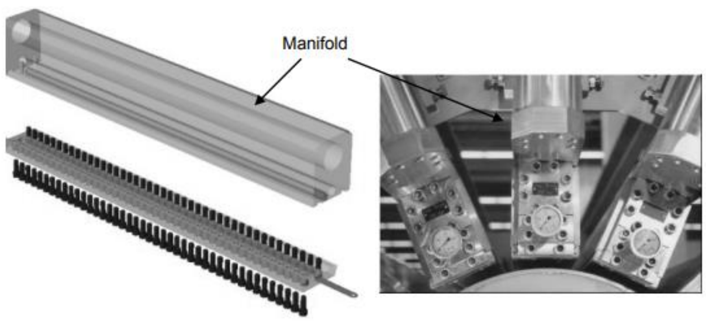

Figure 3.2 Inside view of the manifold and the jet strip

3.1.2 Number of passes

The number of manifolds or passes are important to determine the final structure of the fabric. For research purposes and machinery limitations some webs are passed more than once through the hydroentanglement line. This way, higher energy and pressure and different fabric structure can be achieved.

In the next example we can see how the same web (Same basis weight and fiber) formed with carding machine has been passed 2, 6, 8 and 12 times through a line with 3 manifolds. It is clear that the number of passes combined with the specific energy and pressure lead to a change in the ODF (Fiber orientation Distribution of the fabric)

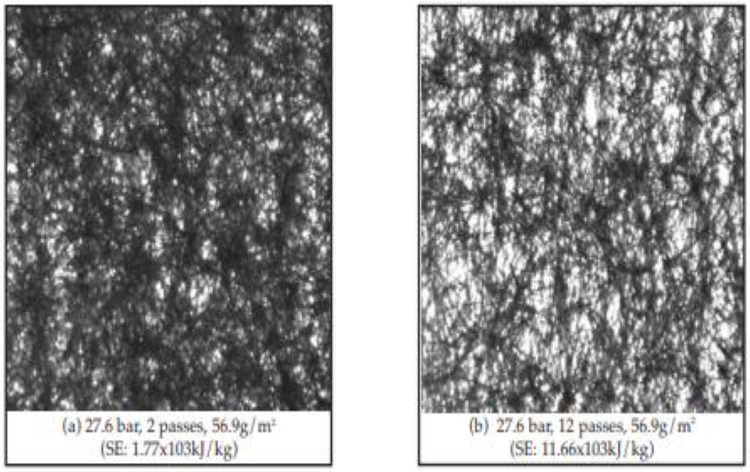

Figure 3.3 Fabric produced under same pressure and basis weight but different number of passes

3.1.3 Jet Strip

The jet strip is located at the bottom of the lower chamber, inside the manifold. The standard jet strip possess one row of nozzles, distributed through the whole length. However, jet strips with two or three rows of nozzles are common.

- Length: According to the machine (up to 5.5 m)
- Thickness: 0.6 to 1 mm
- Width: 12-25mm (2.5cm or 1 inch)
- Nozzle density: ~1600 holes per meter

For our research we have used a standard jet strip and a double row jet strip with the following dimensions: 25 inch length, 1mm thickness and 1 inch width.

An essential characteristic of the jet strip is the jet spacing (This is the nozzle to nozzle space), this distance is found to be 600µm in most cases, and however, this number can change, influencing the properties of the fabric.

Other jet strips with two or three rows, have a different jet spacing, for example the ones with two rows can have the double (1200 µm), but the fact that there are two rows, and sometimes the nozzles of one row have smaller diameter than the ones in the other row, leads to a fabric with less jet streaks, this means that not just the aesthetics of the fabric is better but also the physical performance improves, because less jet marks means less weak points that generate low tear strength.

Standard jet strip has a single row of nozzles, with a jet spacing of 600 microns and a nozzle diameter of 130 microns. Holes Density is around 1600 holes/m.

Where a is the jet spacing (Distance from nozzle to nozzle: 600 microns) and b is the nozzle diameter 130 microns

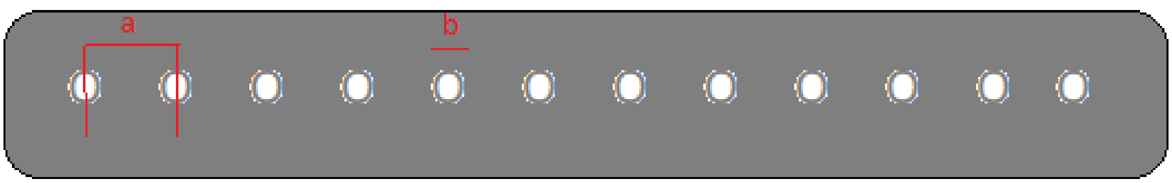

Figure 3.4 Standard jet strip with a single row of nozzles

The double row jet strip is highly used in the industry, due to it improves the fabric's tear strength about 30%, without affecting the tensile strength. [30]

The nozzle to nozzle distance (a) in each row is 600 microns, this means same as than standard jet strip, the nozzle diameter for a row is 130microns and for the other row the diameters can be smaller (From 100microns to 120micron) or the same (130microns).

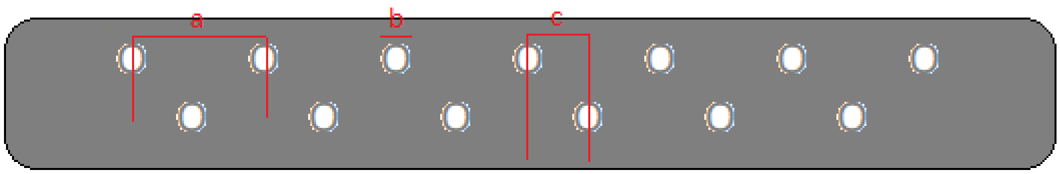

Figure 3.5 Jet strip with double row of nozzles

Where a is the nozzle to nozzle distance (600microns) in a row, b the nozzle diameter and C is the nozzle to nozzle distance from the first and second row (300microns).

3.1.4 Nozzle geometry

As mentioned before, the jet strip is a thin plate that contains the nozzles that let the water to come through and the process to take place. The geometry of the nozzle, as well as the diameter are essential to have an optimum energy transfer, a longer breakup length and therefore a fabric with all the features desired, such as homogenous appearance and high mechanical performance that can extend the useful time of the material.

The nozzles tend to wear as a consequence of different mechanism, like shear stress or corrosion, this change in the geometry causes the nozzle not to able to issue long breakup length, this has a negative impact in the energy transfer.

There are three geometries for the cone-capillary nozzle that have been studied and have an impact in the way the water is issued from them. The cone-down configuration has been found to be the geometry able to get the longest intact length and stability, although the cylindrical nozzles are able to achieve high intact length, the jet tends to not to be stable, due to the aspect ratio (length to diameter ratio) of 7.6 to 10. The cone-up configuration possess a short intact length.. [11-16]

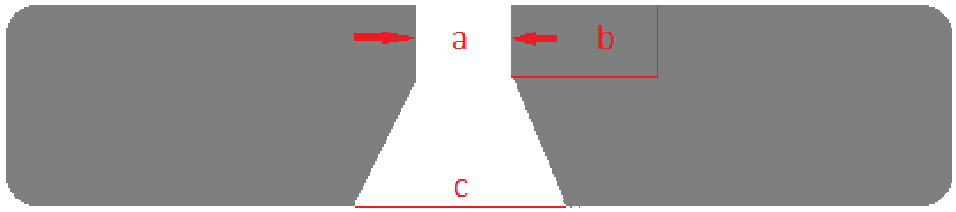

Figure 3.6 Parts of a cone-down nozzle

Where a is the capillary part, b is the distance from the nozzle to the age of the strip. a and b have the same value because the capillary part is a square and c in the width of the nozzle in the bottom part.

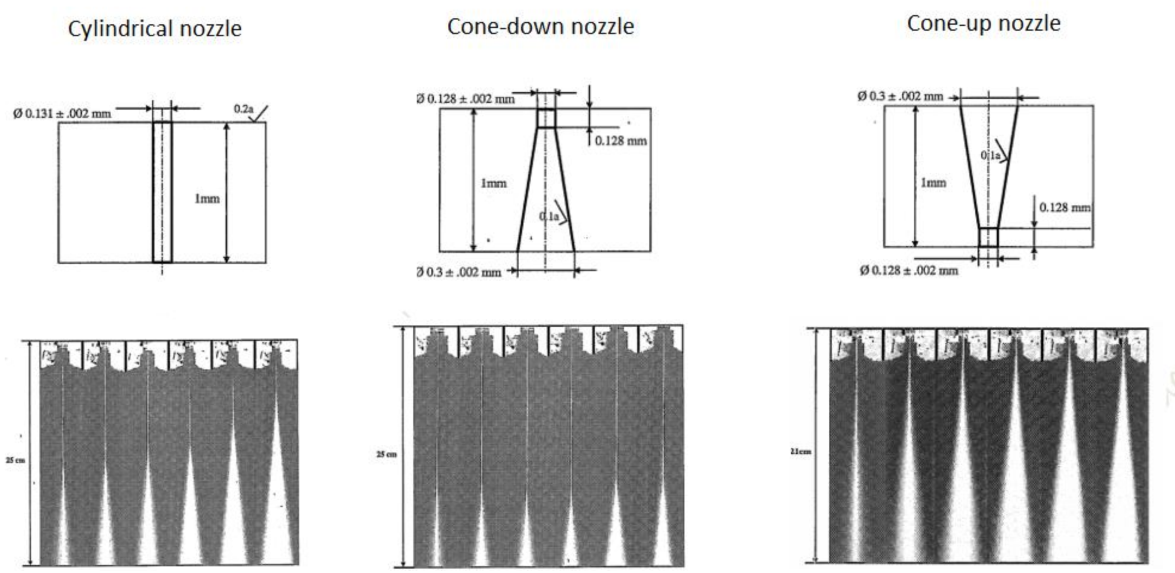

Figure 3.7 Typical nozzle geometries (a) cone-up nozzle, (b) cone-down nozzle, (c) cylindrical nozzle and their intact length [11]

3.1.5 Intact or breakup length

The fiber web needs to be bonded in the best possible way, that is why, the intact length of the water jet is the one able to properly transfer the energy and bond the fibers or filament in the web. When the jet starts to spread the water jet loses energy causing poor energy transfer and fabric with lower physical properties.

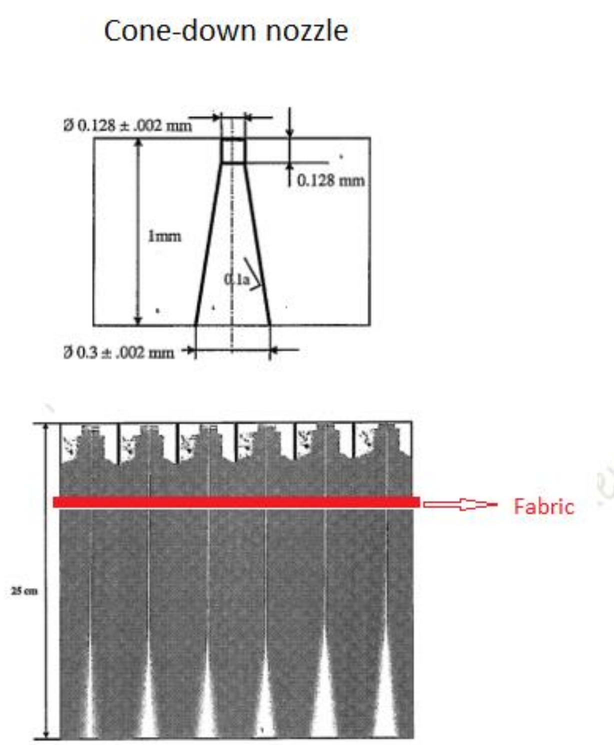

Figure 3.8 Intact length for a cone down nozzle and its influence of the fiber web

3.1.6 Jet Spacing

Jet spacing, is not widely mentioned; however, changing the spacing from nozzle to nozzle, can lead in a well-entangled fabric or non-well entangled fabric. Research has shown that the ideal jet spacing range goes from 600 µm to 1200 µm. What makes this distance so effective is that when the nozzles are very close to each other, the interaction between the jet starts to minimize the entangling actions, due to they interfere to each other. If a jet entangles the fibers, a very close jet next to it can do the opposite action that is disentangle the fibers.

When the jet spacing is in a higher range the level of entangle is really good, because the jet can penetrate better the fabric, leading in a very good entanglement index.

Some of these results have been studied as shown in some dissertations. [9]

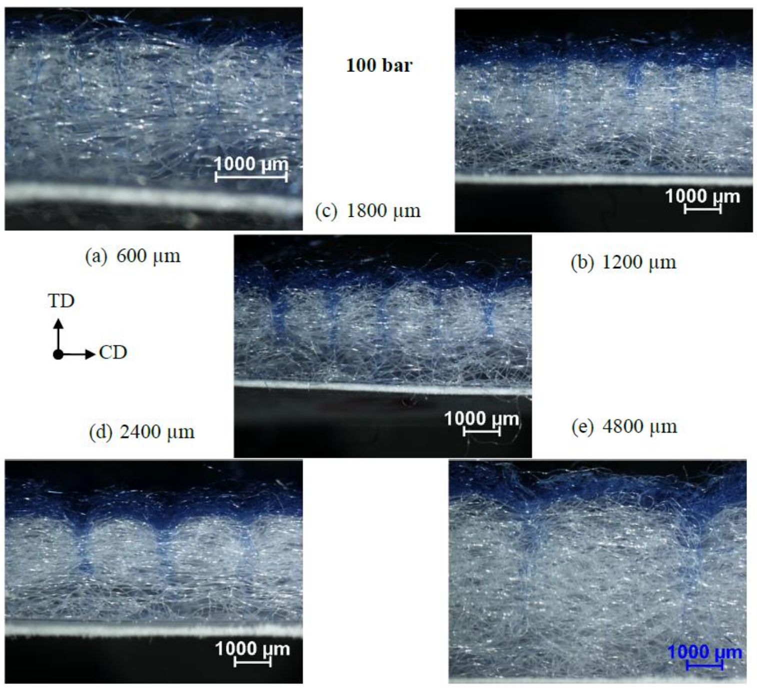

Figure 3.9: Hydroentangled fabric resulting from using different jet spacing (a) 600 µm, (b) 1200 µm, (c) 1800 µm, (d) 2400 µm, (e) 4800 µm [9]

3.1.7 Coefficient of discharge

The coefficient of discharge for standard process is around 0.60 to 0.66, being 0.62 highly reported in papers.

$$C_d = \frac{\dot{m}_{real}}{\dot{m}_{ideal}}$$

$$\dot{m}_{ideal} = \rho V A$$

Where

C_d = Coefficient of discharge

M = Mass flow rate (kg/m^3)

ρ = Density of the water, assumed to be 998 kg/m^3

V = Mean Velocity of the waterjet, m/s

A = Cross-sectional area of the nozzle, (m^2)

$$V = \sqrt{2\frac{P}{\rho}}$$

It is very important to know the geometry of the nozzles, because it determines the discharge coefficient.

The waterjets separates from the nozzle wall forming a collimated waterjet

The number mentioned in the previous slide (0.62) means that the water jet diameter is 0.62 times the width of the capillary portion.

3.1.8 Jet Pressure

This is one of the most important variables during the hydroentanglement process and the pressure is chosen based on the machine capability, the manifold (The first one usually has the lowest pressure to pre-entangle and pre-wet the web) and the level of entanglement we want to get.

The pressure profile changes according to the desired structure, belt speed and the energy have a very important role during the process, because these two variables combined with pressure, lead to different energy transferred, mechanical properties and structure.

The pressures found to be more used for commercial applications go from 25-250 Bar. However, technology has advanced so much that pressure up to 1000 bars are possible to get.

3.1.9 Specific energy

The key of the hydroentanglement process is the transfer of kinetic energy from the water jets to the webs and its constituents fibers. The efficiency of the process, fabric properties and degree of entanglements (Bonding) are highly related with this energy

The energy is dependent on several variables involved during the process, such as the pressure, discharge of coefficient, jet velocity, density of water, nozzle diameter and can be achieved using different pressure profiles during the production

However, the fabrics produced under same energy but different pressure profile, belt speed or nozzle diameter might have different structure.

The energy is calculated using the Bernoulli equation shown below. Where P is the pressure (pa) and ρ is the density of water in room temperature (998kg/m3).

$$V = \sqrt{2\frac{P}{\rho}}$$

The energy transferred from the waterjets can be calculated using the following equation. Where d is nozzle's capillary diameter (m), Cd is coefficient of discharge, ρ is the density of water in room temperature (998kg/m3), and V has been calculated with the previous equation.

$$\dot{E} = \frac{\pi}{8} \rho d^2 C_d V^3$$

Note: This equation corresponds to the enrgy of a single water jet, therefore we need to sum up the energy obtained for all the water jets (Depending on nozzle density) in order to get the total energy.

The specific energy is therefore obtained with this equation that uses de Energy transferred E and M the mass flow rate of the fabric in kg/s

$$SE = \frac{\dot{E}}{\dot{M}}$$

Specific energy is the energy transferred per kilogram of a web when it is impinged by a curtain of high-speed, fine water jets in hydroentangling process, which depends on number of jets and manifolds, employed pressure, processing speed and basis weights of the web.

The breakup length is an important parameter that is determined by the nozzle diameter, Reynolds number, coefficient of discharge and jet velocity.

3.1.10 Belt Speed

The belt speed will determine what is the residence time of the fabric under the water jets; therefore, lower belt speed leads to a higher specific energy transferred to the web, the opposite occurs with high belt speed. If we want to have high belt speed for high efficiency production purposes, the same energy as with low belt speed can be achieved, choosing higher pressure profile; however, if the same energy is achieved using different variables, such as nozzle diameter, belt speed or pressure profile, the mechanical properties of the fabric are going to be slightly different. Because the residence time under the water jets is going to be lower for higher belt speeds, or the energy transferred is different, when we change the diameter of the nozzle or the pressure.

- Belt Speed: 10-50m/min
- Basis weight: 15 -500 gsm
- Stainless steel strip with nozzles: 1mm thick, 2.5mm width and the length is according to the manifold
- Number or manifolds: 5 to 8 or even more in some companies
- Width of the machine: 1.2 to 6 meters, depending of the application
- Water should have neutral pH [9-10]

CHAPTER 4: FIBERS USED DURING THE PRODUCTION OF THE DIFFERENT MATERIALS

The first step for the production of any nonwoven fabric is the selection of the raw materials, depending of the methods used, we can select from polymers (In the case of spun melt processes) or staple fiber for the fiber based processes such as carding.

The staple fibers come in a compressed mass of fiber, for transportation purposes. Therefore, they need to be opened to facilitate their manipulation.

The opening step takes place before the carding process, this way we can ensure a correct opening, blending, individualization and parallelization of the fibers that will lead to the production of an appropriate carded web. However, not all the processes are suitable for all kind of fibers, properties like length, fineness, surface characteristics and crimp must be considered prior their usage. Some carding machines must be adapted depending on the type of fiber, some are customized to work exclusively with cotton, some for man-made fibers and some are capable to produce with either fiber, as long as they meet the requirements of the machine setting. [Batra, Pourdeyhimi 2012, p. 33-34]

For this specific research we have used two types of staple fibers, the first one is cotton, the most widely used natural fiber and the second fiber is PET, a man-made fiber, desired in many applications, due to it is cost-effective, . Three webs have been produced. One web is 100% cotton, the second we has 100% PET and the third web has 50% Cotton and 50% PET.

When the raw materials are selected, the next step is to break the bales, in order to have loosen fibers that can be easily blended.

Due to the production of nonwoven materials omits several steps that take place during the production of a traditional woven fabrics, such as roving, spinning, weaving or knitting, the selection of the fibers is really important. Depending on the nature of the fiber, they can provide different attributes and features to the final material, that will benefit the final user. [Batra, Pourdeyhimi 2012, p. 33-34]

4.1 Characteristics of Cotton

Cotton leads the world market of the natural fibers. It is widely used all over the world for different applications, including textile products manufacturing, beauty supplies, hygiene products, medical products and nonwovens production, which is the field of our interest. This fiber is interesting for several reasons, the first one it is that cotton is a renewable fiber that grows in special crops with the only purpose to provide good quality cotton and supply the needs of the human beings in the fields mentioned above.

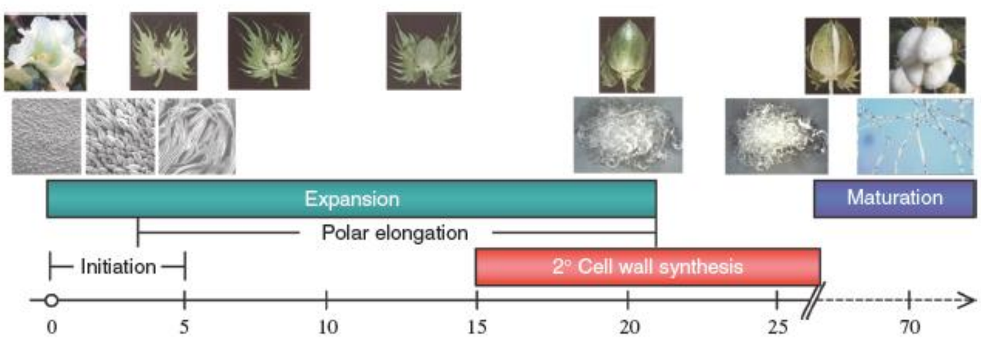

Figure 4.1: Stages of cotton development [17]

Other Reasons to choose cotton for nonwoven production, especially for hygiene applications, such as wet wipes or baby diapers is the softness that cotton can provide to the final product, this property makes this fiber ideal when the final product has contact with the skin. Avoiding any kind of allergy or irritation is a crucial property that this kind of hygiene products must have, that is why cotton must be used when we want a fiber that is hypoallergenic.

It also has different properties that significantly improves the performance of the final product, such as the strength; cotton is 3.7 times stronger than pulp and 1.3 times stronger than rayon. When the application requires absorbing certain liquids, cotton is the ideal fiber, it absorbs 24 grams of water per gram of fiber. [18]

Despite the advantages just mentioned for cotton fiber in the nonwovens production, when a hydroentangling fabric is made, blend are common, because combining different fiber give the material different features that cannot be achieved just with the used of one fiber. its use is less than 5% in the fabric made with hydroentangling, due to the high cost that implies to bleach this fiber, given its high cost, compared to polymeric fibers, like Polyester or polypropylene, whose performance in nonwovens products is good and will be disclosed as follows.

However, the process to bleach the cotton is high and make the process expensive, when this process is expected to have a high profit, especially because it is produced with an amazing speed rate. [19]

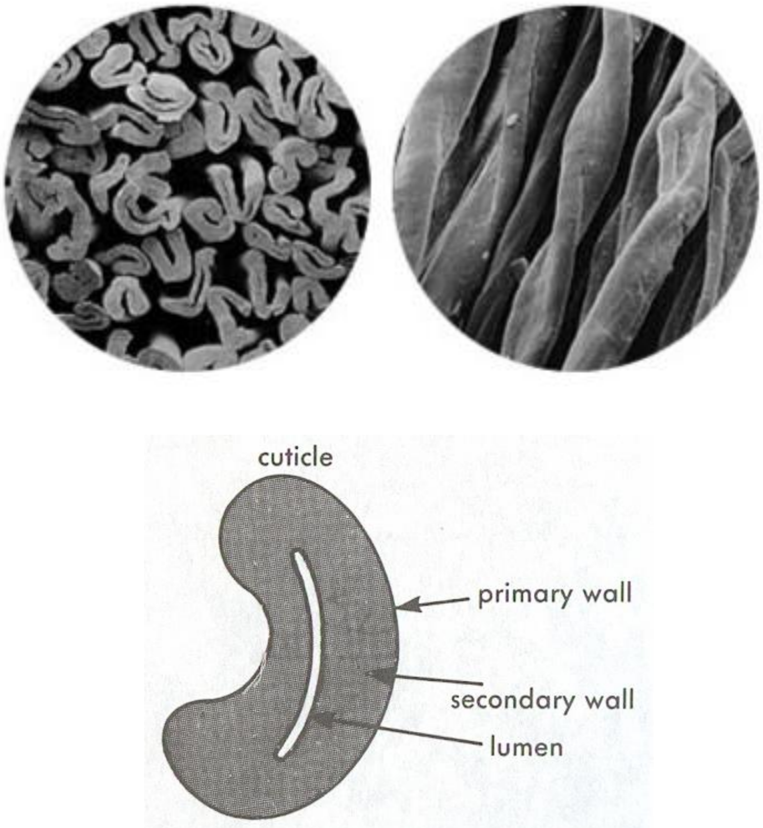

Figure 4.2 Cross section and longitudinal section of cotton fiber

Table 4.1 Characteristics of Cotton Fiber

Properties Cotton Fiber	
Type of cotton	unbleached
Fiber length (mm)	21-28
Fiber diameter (millitex)	135-230
Fiber strength (g/tex)	20-30
Fiber Elongation (%)	5-7.6
Tensile Strength (psi)	44.000-109.000
Breaking Elongation (%)	3-9.5
Breaking Tenacity (gf/den)	Dry:3-4.9, wet:3.3-6.7
Elastic Recovery	74% recovery after 2% elongation; 45% recovery after 5% elongation
Fiber Fineness (millitex)	135-230
Fiber Micronaire	3.8-5.2
Uniformity Index (%)	77-85
Average Stiffness (gf/den)	57-60
Specific Gravity	1.27
Moisture Regain (%)	7
Surface Finish	None
Moisture Absorbency (%)	24-27 at 95% relative humidity

Hydroentangled products used for hygiene applications are expected to have certain whiteness index, due to the cotton is unbleached naturally, it requires treatment to become bleached, this kind of processes are expensive, this is not very affordable for companies

Incorporating at least 60% of a man-made fiber like rayon or polymeric fiber like polyester, can significantly increase the overall whiteness of a fabric made with hydroentangling machine, at the point to look as white as a fabric made with bleached cotton, at a significant less expensive process. [29]

Polyester also works as a reinforcement fiber in the nonwoven fabric, due to its cost is lower than cotton, generally it proportion is more than 50%, reaching sometimes, 70%.

4.2 Characteristics of Polyester

The PET poly(ethylene-terephthalate) belong to the family of polyester. It can be found as a resin, continuous filament yarn and staple fiber. Due to its versatility is suitable for many processes. For example we can find it with different molecular weight (MW), additives and blends and other treatments are available to tailor the PET.

There are some properties of PET when is found as staple fiber. The typical length goes from 6 to 100mm and the fineness goes from 1 – 17 dtex. The density ranges go from 1.33 g/cm3 to 1.392 g/cm3; however, the most common value is 1.38 g/cm3. It is shape is usually circular, though the cross section shape can change. [Batra, Pourdeyhimi 2012, p. 317-318]

Due to its good strength (From 2.6 CN/dtex and 8.0 cN/dtex), its excellent abrasion resistance, elastic recovery (65-98%), good resistance to oxidizing agents, bleaches and solvents, mildew and bacteria. PET is one of the most widely produced fibers worldwide. We can find PET in various products that go from high performance to disposable ones.

PET fibers have some special properties that make them desirable for the production of nonwovens materials, these properties include low cost and durability. This fiber is mainly used as a fiber-fill, as well an in quilts, cushions and furniture. Due to it can be produced in various degrees of fineness, has high resistance to moisture and chemicals and it is suitable for several nonwovens production processes, PET is used in filtration, strong light-eight fiberwebs, coated fabrics, backing fabric, as well as other applications that require heavy-weight form, like automotive, and interlinings. It has been very used in hygiene products like baby and adults diapers, in medical applications, like surgical gowns and protective apparel, other applications include shoe reinforcement, battery separators and agriculture. [Batra, Pourdeyhimi 2012, p. 318 -319].

The PET can be used for the production of bi-component filaments and fibers that usually have a low-density polyethylene (PE) sheath component. The bi-component fibers or filaments remarkably increase the tensile strength of the fabric depending on the polymer ratio (low-density PE/ PET) [2016 Nonwoven Fabrics, p. 9]

Table 4.2 Characteristics of PET (Polyester)

Properties PET Fiber	
Fineness (Denier)	0.9
Specific Modulus (cN/tex)	700-800
Specific Tenacity (cN/tex)	36
Density (g/cm3)	1.39
Extension to break (%)	36
Modulus (GPa)	9-11.0
Tenacity (GPa)	0.5-1.1

The fibers mechanical properties determine the behavior of the fibers during the nonwoven manufacturing process, as well as the most important features of the final nonwoven fabric. [The Influences of Hydrophilic Finishing of PET Fibers on the Properties of Hydroentangled Nonwoven Fabrics]

The PET fibers are naturally hydrophobic making them difficult to be processed through hydroentanglement, because of the resultant fabric is hydrophobic, and therefore if we need a hydrophilic product made with PET, some treatments can be performed, such as plasma treatment that is able to decrease the water contact angle or deposition [2016 Nonwoven Fabrics, p. 224 - 225]. Some research has been devoted to this matter, due to the effectiveness of PET and its low cost make them a highly desirable fabric for nonwovens production.

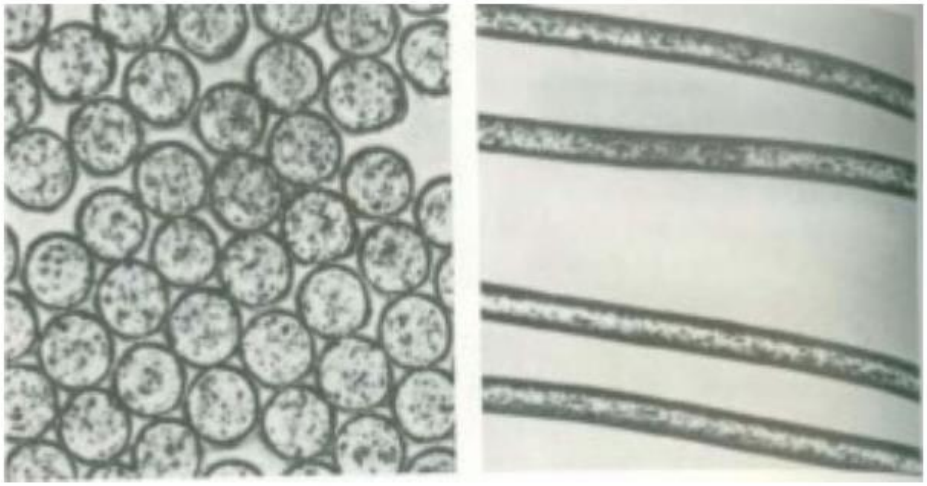

Figure 4.3 Cross section and longitudinal section of polyester fiber

CHAPTER 5: EXPERIMENTAL SETUP

This work has used two different fibers for the production of the hydroentangled fabrics, cotton and Polyester. Three webs were produced by using carding as a web formation technique and then they were bonded using hydroentangling as a web bonding technique. The process parameters were changed to establish structure-property-process relationships. The various Experiments are described below.

5.1 Design of experiment.

The webs were: 100% PET, 100% Cotton and 50%/50% PET/Cotton.

Five experiments were performed. These were:

1. Belt speed,
2. pressure,
3. type of manifolds (face and back),
4. number of manifolds (For some experiments we worked with three, four or five),
5. type of jet strip (single and double row) used

See Table 5.1 below

Table 5.1. Description of the variables used for each experiment

	Experiment 1	**Experiment 2**	**Experiment 3**	**Experiment 4**	**Experiment 5**
PARAMETERS					
FIBERS	100%Cotton 100%PET 50%Cotton/ 50%PET	100%Cotton 100%PET 50%Cotton/ 50%PET	100%Cotton 100%PET 50%Cotton/ 50%PET	100%Cotton 100%PET 50%Cotton/ 50%PET	100%Cotton 100%PET 50%Cotton/ 50%PET
BELT SPEED (m/min)	15, 30, 45	15, 30, 45	15, 30, 45	60	30
PRESSURE (Bar)	30, 50, 75, 100, 100	30, 50, 50, 100, 100	30, 50, 75, 100, 100	30, 100, 150, 200, 200	From 30 to 190
TYPE AND NUMBER OF MANIFOLDS	5 manifolds (3 on the face and 2 on the back)	1, 2 and 5 manifolds (2 on the face and 1 on the back)	5 manifolds (3 on the face and 2 on the back)	5 manifolds (3 on the face and 2 on the back)	5 manifolds (3 on the face and 2 on the back)
TYPE OF JET STRIP	Standard Jet Strip	Standard jet strip and double row jet strip	Standard jet strip and double row jet strip	Standard Jet Strip	Standard Jet Strip

The characteristics of the jet strips used are described in the following paragraphs:

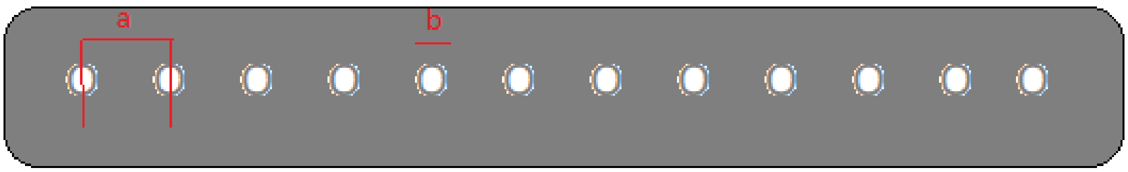

Figure 5.1: Standard Jet strip with a single row of nozzles

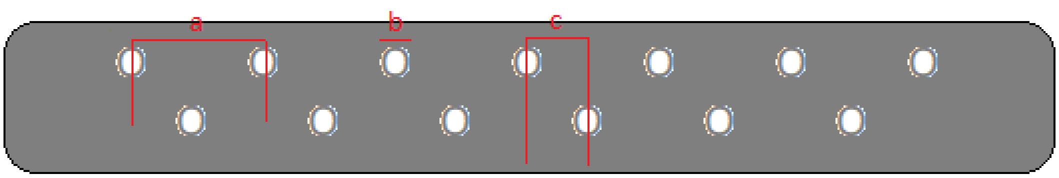

Figure 5.2: Double row jet strip with two rows of nozzles

Both jet strips have the same nozzle density of about 1666 jets per meter and the nozzle diameter in both cases is 130µm.

The three webs mentioned above were used during the 5 experiments. The 5 manifolds used pressures in the following range: from 30 – 200 bar.

In order to collect data, producing fabrics under various conditions, we designed five experiments, they all played with the type of jet strip, pressure, manifolds and belt speed. The way the experiments were set up is described below.

EXPERIMENT 1

Experiment1 is the basic design and the following Experiment are going to be compared with it:

1. Fabrics: 100%Cotton, 100%PET and 50%Cotton/50%PET
2. Belt speed: 15, 30, 45 m/min
3. Manifolds: We used the 5 manifolds
4. Pressure: 30, 50, 75, 100, 100 bars.
5. Jet strip: Standard Jet strip for the 5 manifolds

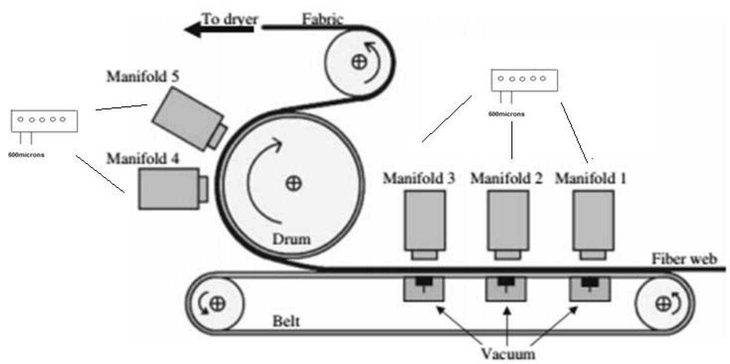

Figure 5.3: Set-up for Experiment1

9 fabric were produced:

- 3 fabrics 100% cotton produced at different speeds, 15, 30 and 45 m/min
- 3 fabrics 100% PET produced at different speeds, 15, 30 and 45 m/min
- 3 fabrics 50% Cotton/50% PET produced at different speeds, 15, 30 and 45 m/min.

These are considered our "standard" or "control" fabrics with specific energies of 591.196, 886.794, 1773.588 kJ/kg.

EXPERIMENT 2

Experiment2 is kind of similar to Experiment1, with some exceptions:

1. Fabrics: Same as Experiment1
2. The belt speed is the same: Same as Experiment1
3. Manifolds: Instead of 5, we used 3. They are 1, 2 and 5
4. Pressure: 30, 50, 50, 100 and 100 bars. It is the same pressure used in the same manifolds for Experiment1
5. Jet strip: Fist manifold had standard and 2 and 5 had double row jet strip (Jet spacing of 1200microns)

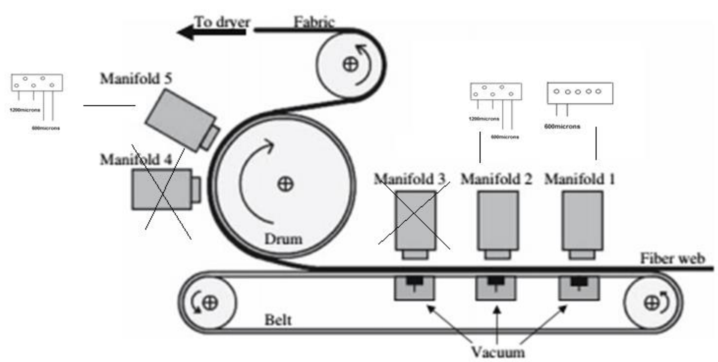

Figure 5.4: Set-up for Experiment2

Same conditions of the Experiment 1; with the difference, that manifolds 3 and 4 were not working, manifolds 2 and 5 had the double row jet strip and manifold 1 had the standard jet strip.

9 fabric were produced:

- 3 fabrics 100% cotton produced at different speeds, 15, 30 and 45 m/min
- 3 fabrics 100% PET produced at different speeds, 15, 30 and 45 m/min

- 3 fabrics 50% Cotton/50% PET produced at different speeds, 15, 30 and 45 m/min

The key question: Can we produce similar fabrics with different jet strips, a different number of manifolds, and at the same line speed?

EXPERIMENT 3

Experiment3 is very similar to Experiment1 and Experiment2, with few exceptions:

1. Fabrics: Same as Experiment1 and Experiment2
2. Belt speed: Same as Experiment1 and Experiment2
3. Manifolds: As Experiment1 we used the 5 manifolds
4. Pressure: Same pressure as Experiment1
5. Jet strip: Manifolds 1, 4 and 5 had standard and 2 and 3 had double row jet strip (Jet spacing of 1200microns)

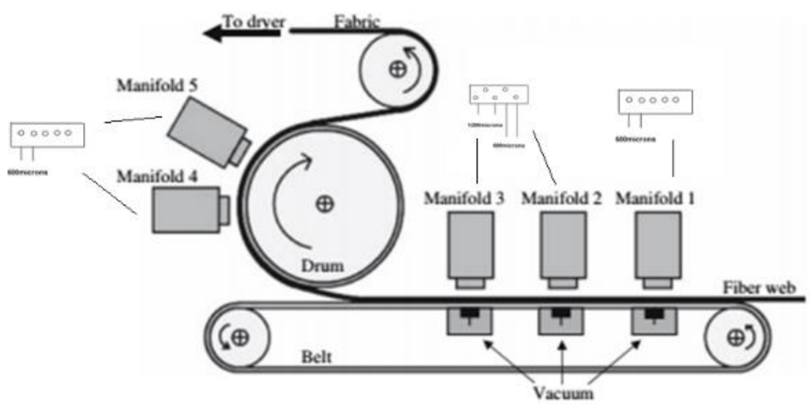

Figure 5.5: Set-up for Experiment3

9 fabric were produced:

- 3 fabrics 100% cotton produced at different speeds, 15, 30 and 45 m/min
- 3 fabrics 100% PET produced at different speeds, 15, 30 and 45 m/min

- 3 fabrics 50% Cotton/50% PET produced at different speeds, 15, 30 and 45 m/min

The total energies imparted to the fabrics were the same as those in Experiment1 except that two of the jet strips were double row and spaced at 1200 microns

The key question: Can we use similar fabrics with different jet strips, using the same number of manifolds, at the same line speed if we use wider double row strips but such that the total energy remains the same?

EXPERIMENT 4

Experiment4 is very similar to Experiment1 with few exceptions:

1. Fabrics: Same as Experiment1
2. Belt speed: 60 m/min (higher than before)
3. Manifolds: As Experiment1 we used the 5 manifolds with standard strips
4. Pressure is the double: 30, 100, 150, 200, 200 bars. Double the pressure to see the impact in the mechanical properties.
5. Jet strip: Same as Experiment1

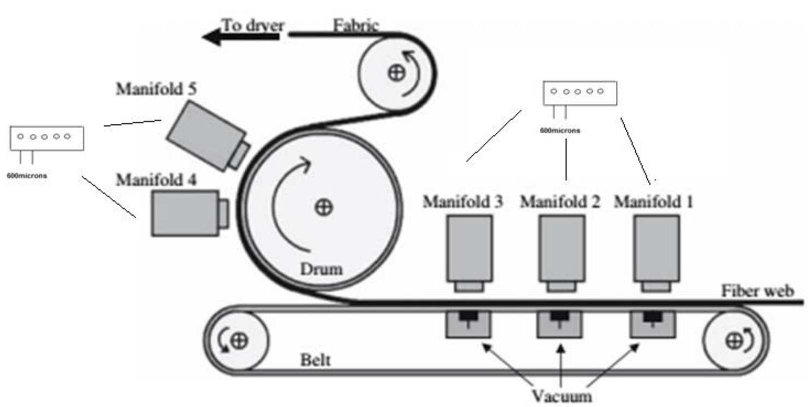

Figure 5.6: Set-up for Experiment4

3 fabric were produced:

- 3 fabrics 100% cotton produced at different speeds, 60 m/min
- 3 fabrics 100% PET produced at different speeds, 60 m/min
- 3 fabrics 50% Cotton/50% PET produced at different speeds, 60 m/min

The total energies imparted to the fabrics was 1212.058 kJ/kg.

The key question: Can we produce similar fabrics at higher speeds with a higher pressure profile (Double than Experiment1)?

EXPERIMENT 5

Experiment5 has been designed changing the pressure profile 3 times to achieve the same energy. Energy is around 1180 kJ/kg

1. Fabrics: Same as Experiment1
2. Belt speed: 30 m/min
3. Manifolds: We used the 5 manifolds, but not at the same time. Depending on the pressure profile we turn some off (Please see the chart in the next page)
4. Pressure: Changes according to the number and type of manifold used. (Please see the chart in the next slide)
5. Jet strip: Standard Jet strip for the 5 manifolds

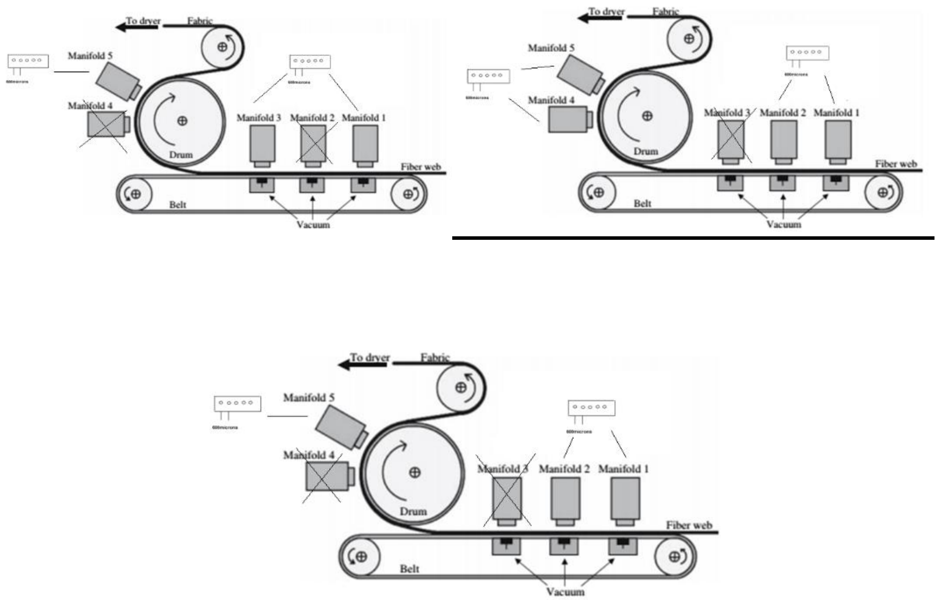

Figure 5.7: The three set-ups for Experiment5

We have divided this experiment in three different arrangements: The conditions are described in **Table 5.2** and the number of manifolds and jest strip used are describes in **Figure 5.7.**

Table 5.2: Conditions for experiment 5

Assumptions (Effect of types of manifolds)			
Belt Speed (m/min)	30	30	30
Orifices per meter	1666	1666	1666
Orifices capillary size (µm)	130	130	130
Basis weight (g/m2)	100	100	100
Pressure Settings			
Manifolds	Pressure (Bar)	Pressure (Bar)	
Head 1 - Face	30	30	30
Head 2 - Face	130	50	X
Head 3 - Face	x		150
Head 4 - Back	x	150	X
Head 5 - Back	190	150	170
Energy received by the web			
Total Energy (kJ/kg)	1194	1174	1181

The total energies imparted to the fabrics were similar (Around 1180 kJ/kg). The key question: Can we use different pressure settings and achieve similar fabrics provided that the total energy is similar?

CHAPTER 6: RESULTS AND FABRIC CHARACTERIZATION

Table 6.1 Specific Energies calculated for each experiment

Specific Energy (kJ/kg)	
591.196	Exp1
886.794	
1773.588	
535.954	Exp2
803.931	
1607.861	
591.196	Exp3
886.794	
1773.588	
1212.058	Exp4
1174	Exp5
1181	
1194	

6.1 Results Experiment1 (Air Permeability, Solid Volume Fraction, Normalized Burst Strength and Tear Strength)

Each Experiment is discussed seperately below.

We are presenting the data for each fiber separately.

For these control fabrics, it can be seen that as the energy increases, the structure becomes denser and stronger.

Table 6.2 Air permeability, Solid volume fraction and normalized burst strength for fabrics made with 100% Cotton

Cotton DOE1					
Fiber	Belt Speed (m/min)	Specific Energy (kJ/kg)	Air Permeability (ft3/min)	Solid Volume Fraction	Normalized Burst S.
100 cotton	45	591.196	141.4	9.594559651	142.2050719
	30	886.794	124.3	10.90290131	151.0008695
	15	1773.588	128.26	11.30029104	188.4535125

Cotton DOE2					
Fiber	Belt Speed (m/min)	Specific Energy (kJ/kg)	Air Permeability (ft3/min)	Solid Volume Fraction	Normalized Burst S.
100 cotton	45	535.954	208.7	6.765166596	93.90185412
	30	803.931	176.9	7.648752821	74.55440657
	15	1607.861	157.7	8.869445052	127.3722068

Cotton DOE3					
Fiber	Belt Speed (m/min)	Specific Energy (kJ/kg)	Air Permeability (ft3/min)	Solid Volume Fraction	Normalized Burst S.
100 cotton	45	591.196	157.6	8.675965725	173.0264274
	30	886.794	134.3	11.00220213	194.7548916
	15	1773.588	151.2	8.938948255	201.5979125

Cotton DOE4					
Fiber	Belt Speed (m/min)	Specific Energy (kJ/kg)	Air Permeability (ft3/min)	Solid Volume Fraction	Normalized Burst S.
100 cotton	60	1212.058	90.26	13.81022202	175.554257

Cotton DOE5					
Fiber	Belt Speed (m/min)	Specific Energy (kJ/kg)	Air Permeability (ft3/min)	Solid Volume Fraction	Normalized Burst S.
100 cotton	30	1174	95.74	13.27244661	167.2298871
	30	1181	96.04	12.21453452	159.1918904
	30	1194	108.48	12.05293147	177.2100819

Table 6.3 Air permeability, Solid volume fraction and normalized burst strength for fabrics made with 100% PET

PET DOE1					
Fiber	Belt Speed (m/min)	Specific Energy (kJ/kg)	Air Permeability (ft3/min)	Solid Volume Fraction	Normalized Burst S.
100 PET	45	591.196	184.1	7.161230063	799.021714
	30	886.794	165.7	8.209277306	744.1869659
	15	1773.588	162.6	8.762308069	727.8474651

PET DOE2					
Fiber	Belt Speed (m/min)	Specific Energy (kJ/kg)	Air Permeability (ft3/min)	Solid Volume Fraction	Normalized Burst S.
100 PET	45	535.954	177.9	6.717248122	705.2100036
	30	803.931	171.2	7.788273068	599.2762612
	15	1607.861	151	8.612121526	728.7982664

PET DOE3					
Fiber	Belt Speed (m/min)	Specific Energy (kJ/kg)	Air Permeability (ft3/min)	Solid Volume Fraction	Normalized Burst S.
100 PET	45	591.196	201.8	6.942909462	737.6769792
	30	886.794	144.1	8.493922529	767.8653033
	15	1773.588	139.5	8.423048926	750.0476161

PET DOE4					
Fiber	Belt Speed (m/min)	Specific Energy (kJ/kg)	Air Permeability (ft3/min)	Solid Volume Fraction	Normalized Burst S.
100 PET	60	1212.058	160.8	9.262500319	806.3301133

PET DOE5					
Fiber	Belt Speed (m/min)	Specific Energy (kJ/kg)	Air Permeability (ft3/min)	Solid Volume Fraction	Normalized Burst S.
100 PET	30	1174	151.2	9.022630175	693.2240538
	30	1181	132.1	10.56395711	671.5258063
	30	1194	156.7	9.136058087	715.6320852

Table 6.4 Air permeability, Solid volume fraction and normalized burst strength for fabrics made with 50% Cotton/50%PET (Blend)

Blend DOE1					
Fiber	Belt Speed (m/min)	Specific Energy (kJ/kg)	Air Permeability (ft3/min)	SVF	Normalized BS
50/50 COT/PET	45	591.196	153.2	9.156827588	483.9934517
	30	886.794	156.8	9.651618703	429.0188813
	15	1773.588	160.4	9.30742212	498.9943249

Blend DOE2					
Fiber	Belt Speed (m/min)	Specific Energy (kJ/kg)	Air Permeability (ft3/min)	SVF	Normalized BS
50/50 COT/PET	45	535.954	198.7	7.393078517	344.6623325
	30	803.931	190	8.025340783	368.9702641
	15	1607.861	189.7	8.40733323	363.6445714

Blend DOE3					
Fiber	Belt Speed (m/min)	Specific Energy (kJ/kg)	Air Permeability (ft3/min)	SVF	Normalized BS
50/50 COT/PET	45	591.196	182.8	8.443739317	406.1583018
	30	886.794	187.5	8.672249436	424.2308931
	15	1773.588	164.4	9.802796169	419.8315849

Blend DOE4					
Fiber	Belt Speed (m/min)	Specific Energy (kJ/kg)	Air Permeability (ft3/min)	SVF	Normalized BS
50/50 COT/PET	60	1212.058	138.6	10.47538629	429.7081637

Blend DOE5					
Fiber	Belt Speed (m/min)	Specific Energy (kJ/kg)	Air Permeability (ft3/min)	SVF	Normalized BS
50/50 COT/PET	30	1174	125.37	10.34305004	434.2805359
	30	1181	102.14	10.84919757	478.2463224
	30	1194	134.2	9.109470371	429.2396992

6.1.1 Results of Air permeability, solid volume fraction and normalized burst strength for each experiment

6.1.1.1 Graphs and analysis for Experiment1

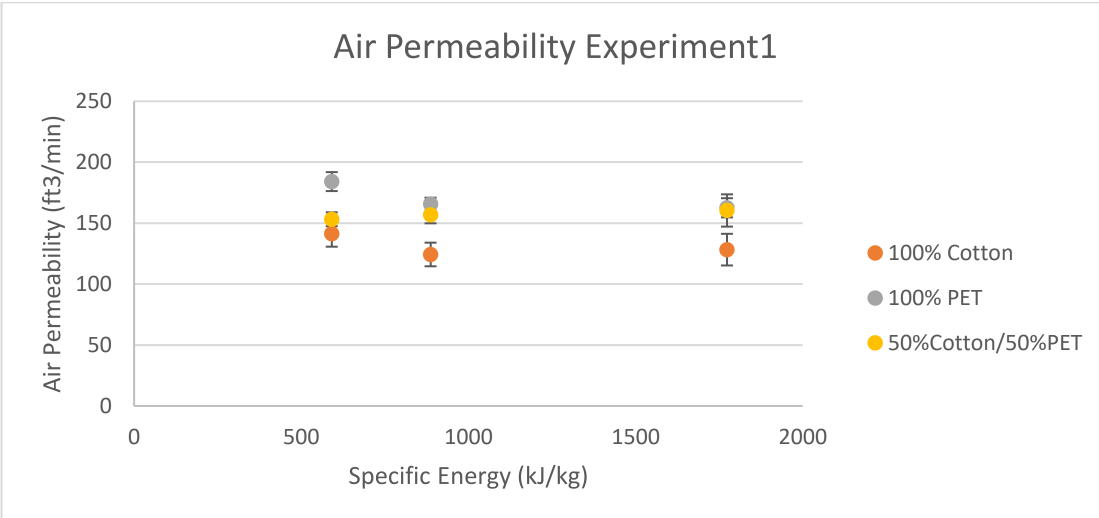

Figure 6.1 Air permeability (ft3/min/ft2) for Experiment1 in function of specific energy (kJ/kg)

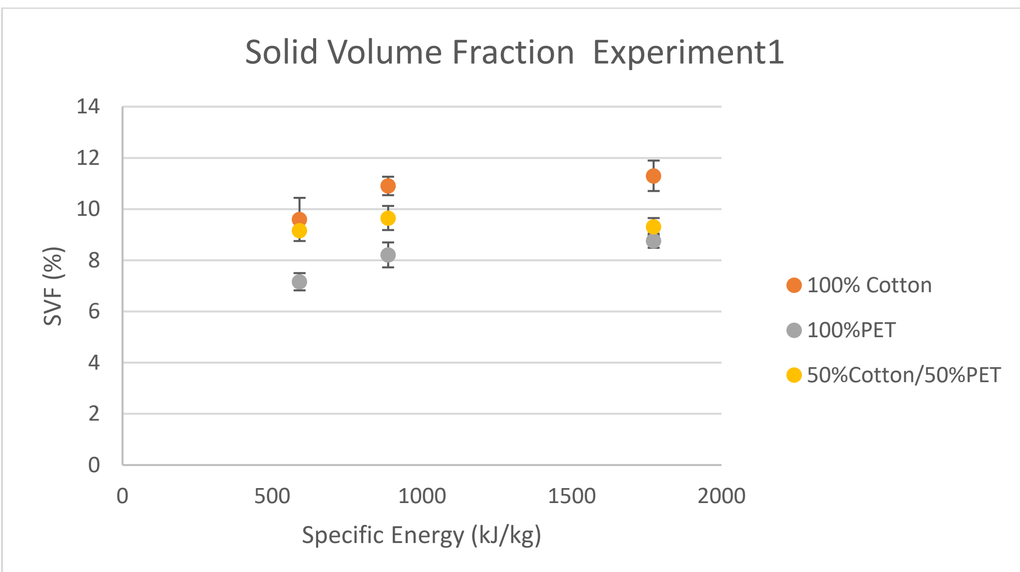

Figure 6.2 SVF (%) for Experiment1 in function of specific energy (kJ/kg)

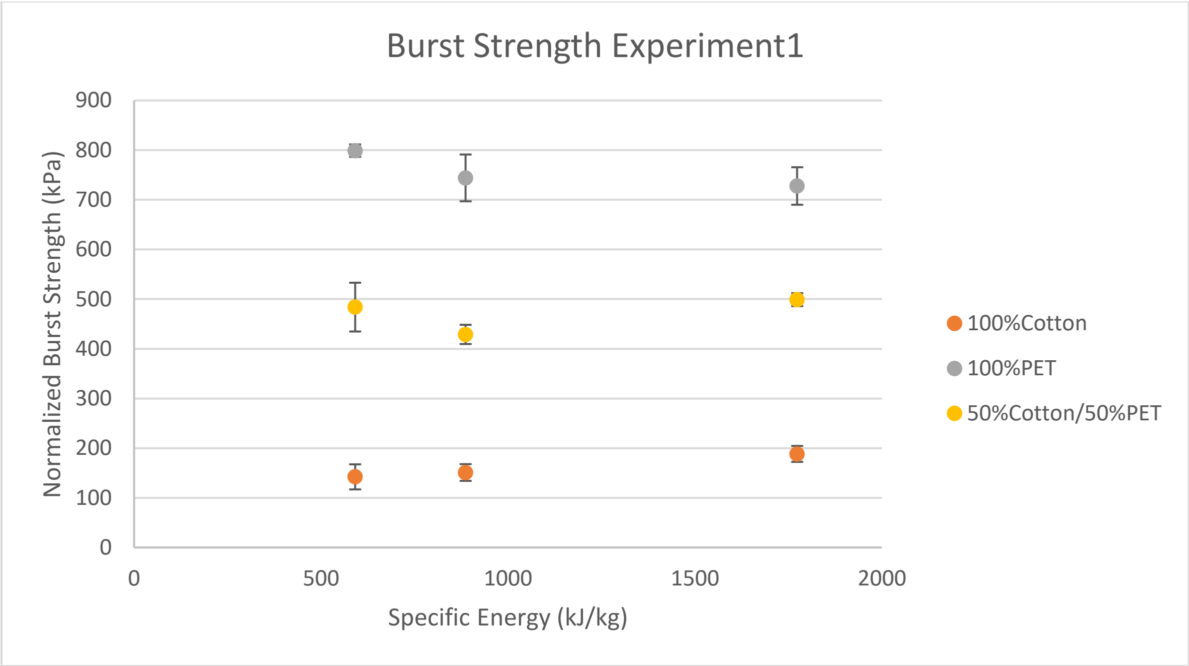

Figure 6.3 Normalized Burst strength (kPa) for Experiment1 in function of specific energy (kJ/kg)

For Experiment 1 the air permeability tends to decrease for the three types of fabrics (Cotton, PET and blend) and some error bars even overlap and as we would expect the solid volume fraction tends to be higher when the energy increases, for this attribute, cotton fabrics exhibit the highest values and PET the lowest. We can see that there is coherence for air permeability and solid volume fraction in terms of behavior and type of fabric. For normalized burst strength we can see how the values do not change dramatically for low and high energy values, for the three fabrics the values tend to remain in narrow ranges.

6.1.1.2 Graphs and analysis for Experiment2

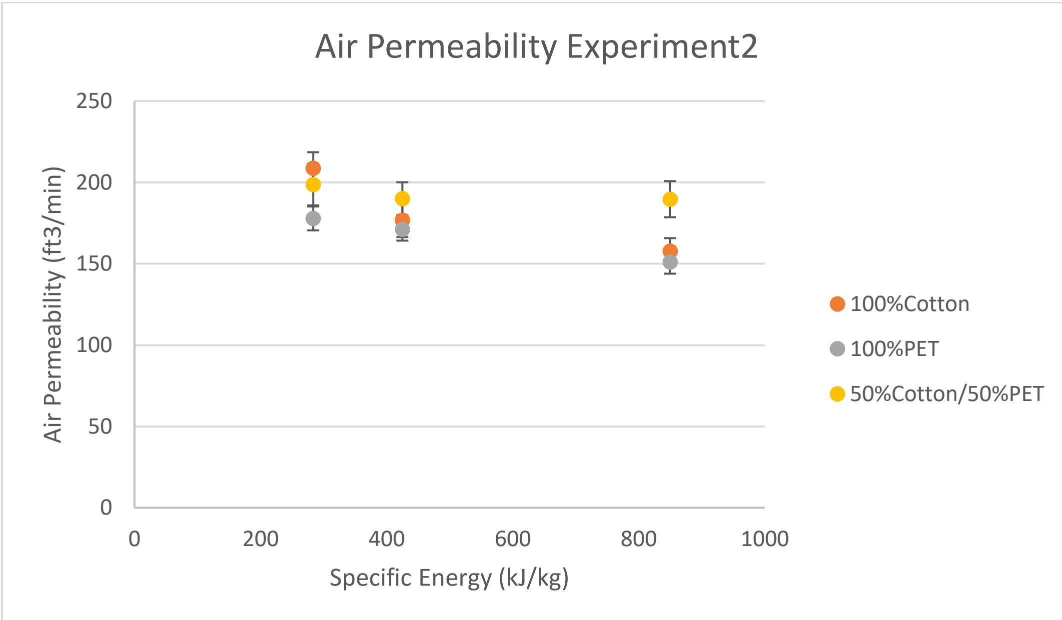

Figure 6.4 Air permeability (ft3/min/ft2) for Experiment2 in function of specific energy (kJ/kg)

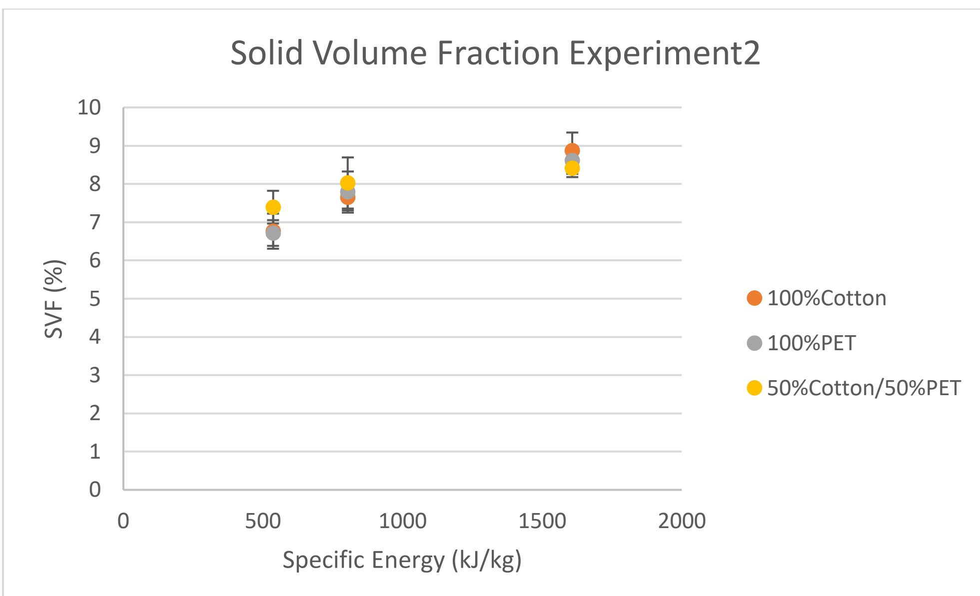

Figure 6.5 SVF (%) for Experiment2 in function of specific energy (kJ/kg)

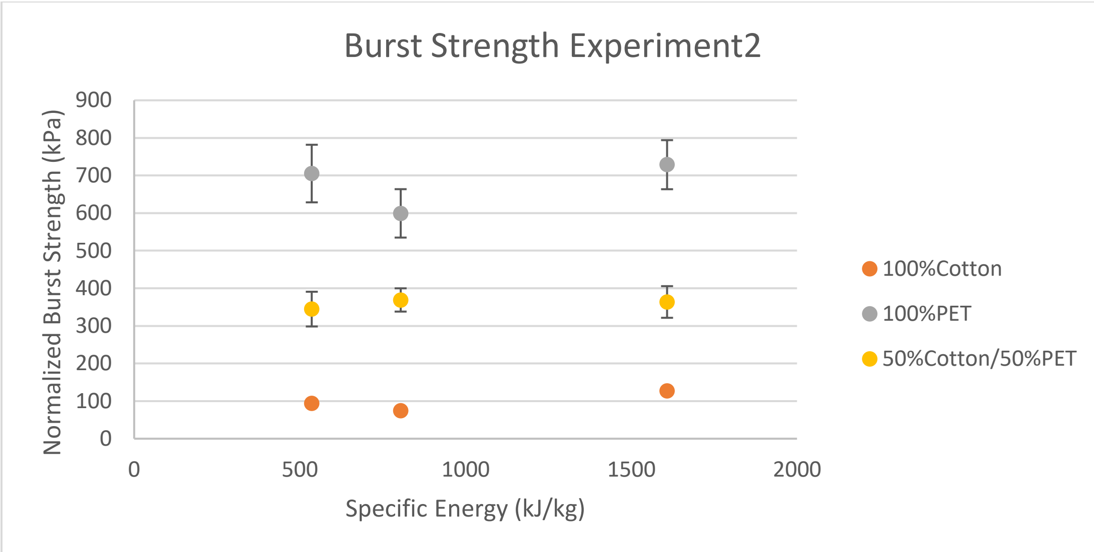

Figure 6.6 Normalized Burst strength (kPa) for Experiment2 in function of specific energy (kJ/kg)

As well as Experiment1, Experiment2 exhibits a relationship for air permeability and solid volume fraction. When the air permeability decreases, the density increases. For this experiment fabrics made of PET show the lowest values for air permeability, this means that for certain applications that need this type of attribute, this set up for this type of fabric is appropriate. Although the solid volume fraction tend to increase for all the fabrics, we can see that values remain very similar.

For all the fabrics the normalized burst strength tends to increase for higher energies, this behavior is evident especially for cotton, this could mean that the set up for Experiment2 is able to achieve cotton fabric with good mechanical properties.

6.1.1.3 Graphs and analysis for Experiment**3**

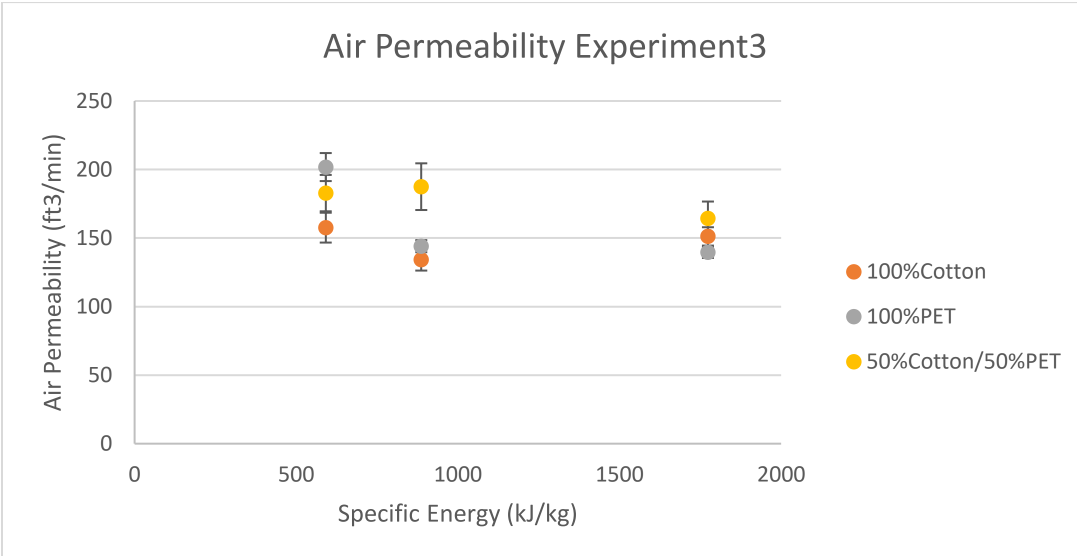

Figure 6.7 Air permeability (ft3/min/ft2) for Experiment3 in function of specific energy (kJ/kg)

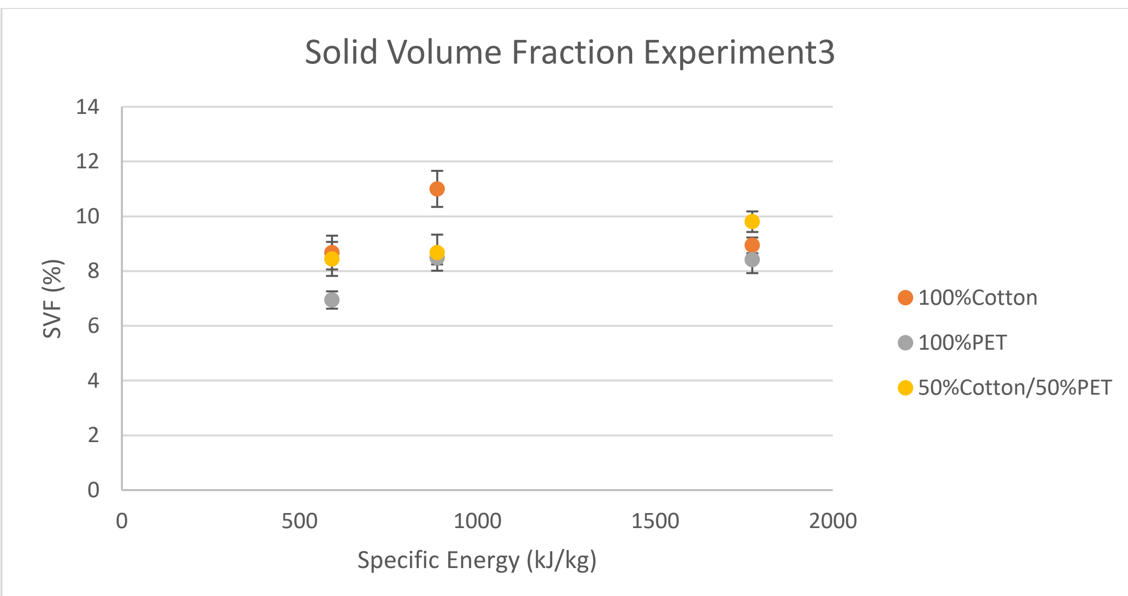

Figure 6.8 SVF (%) for Experiment3 in function of specific energy (kJ/kg)

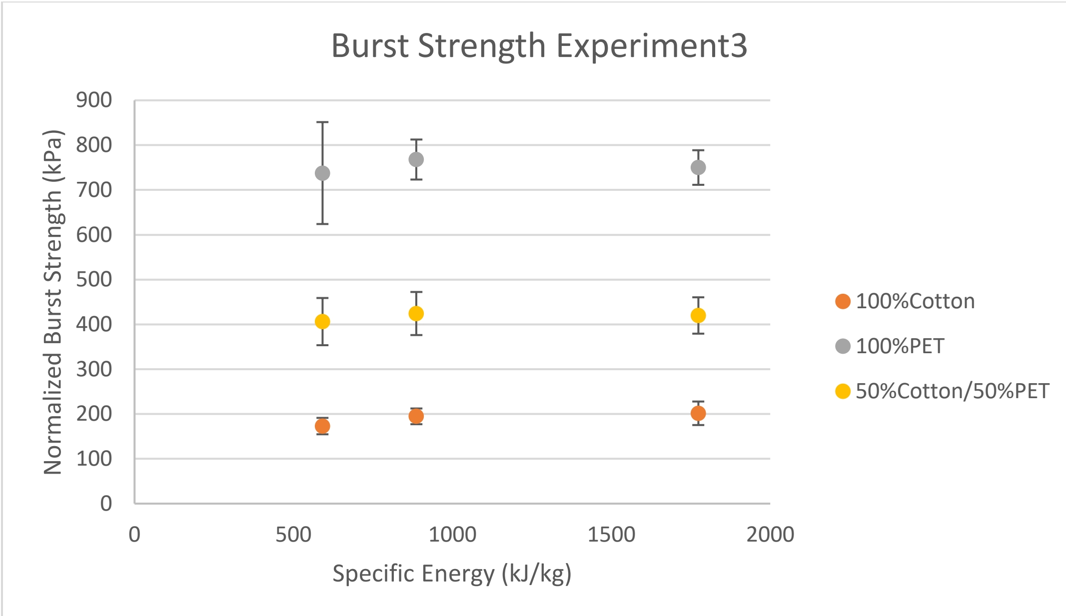

Figure 6.9 Normalized Burst strength (kPa) for Experiment3 in function of specific energy (kJ/kg)

Experiment3 is the most similar one to Experiment1, with the difference that two of the manifolds used double row jet strip with spacing of 1200microns. First we must noticed that the values for air permeability, solid volume fraction and normalized burst strength remain in similar ranges, which shows that this experiment set up does not significantly affect these numbers. The air permeability tends to decrease and the solid volume fraction increases for two of the fiber webs (except cotton), but the variation is minimum if we consider that the range is narrow and all the numbers are close to each other.

Normalized burst strength shows similar data points when the energy increases for cotton and the blend, the change is more evident for PET.

6.1.1.4 Graphs and analysis for Experiment4

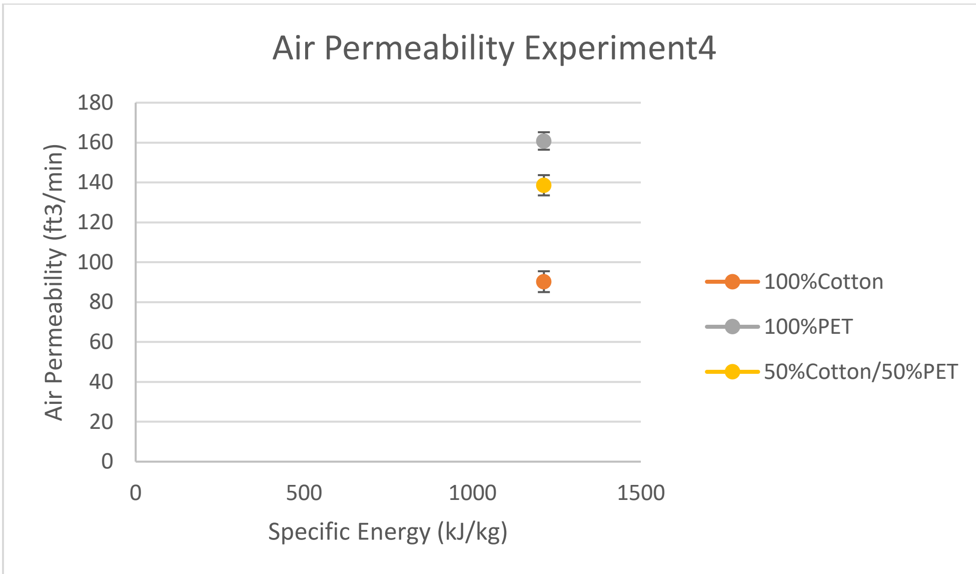

Figure 6.10 Air permeability (ft3/min/ft2) for Experiment4 in function of specific energy (kJ/kg)

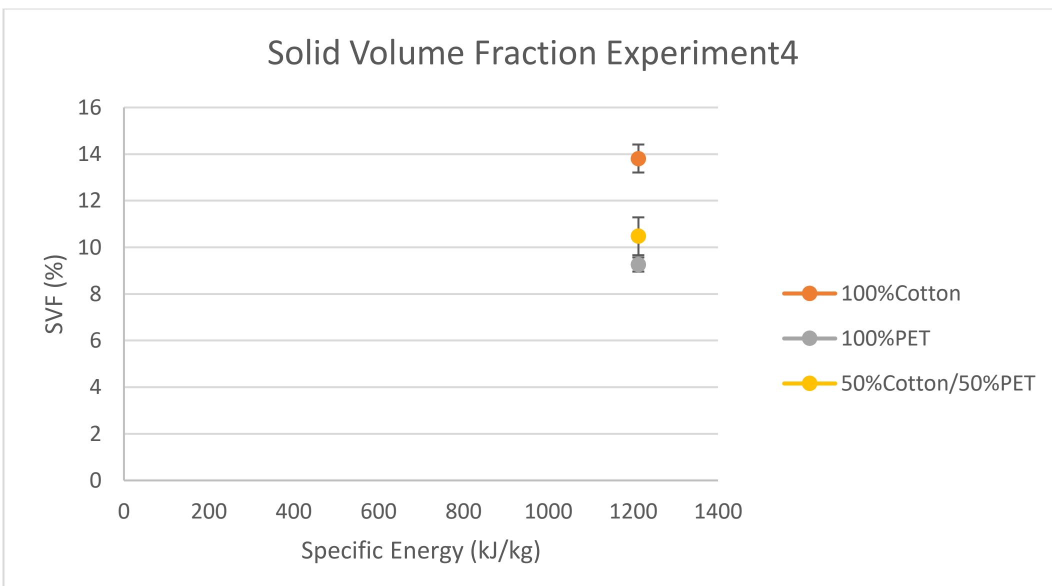

Figure 6.11 SVF (%) for Experiment4 in function of specific energy (kJ/kg)

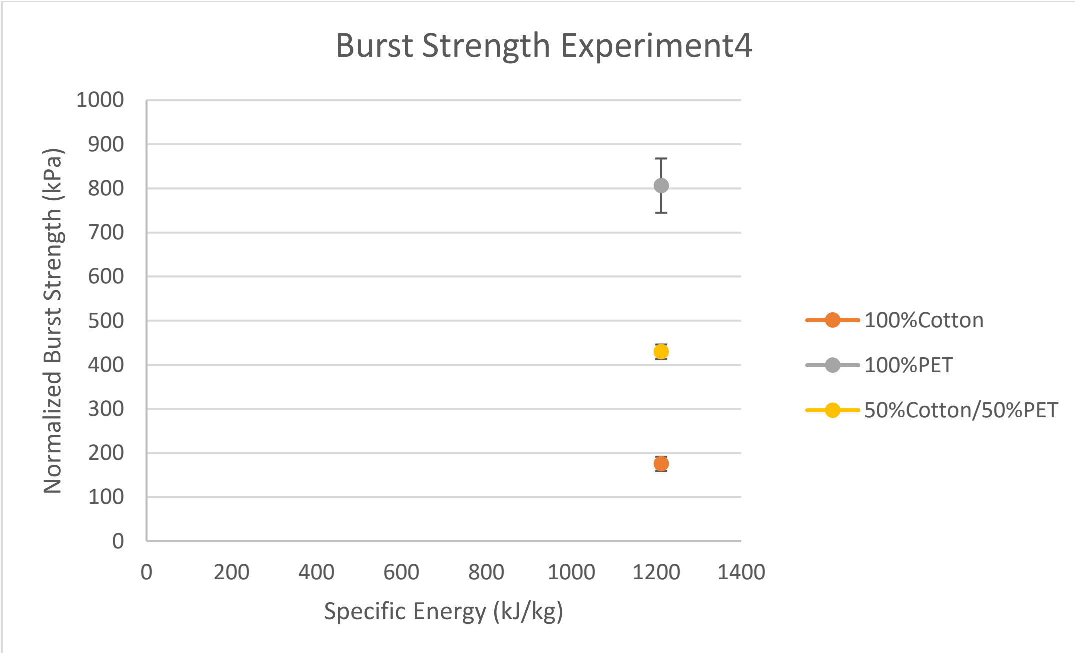

Figure 6.12 Normalized Burst strength (kPa) for Experiment4 in function of specific energy (kJ/kg)

These experiment has been performed with a constant belt speed of 60m/min. Solid volume fraction and air permeability show the data we would expect for the type of fibers used. We can see how cotton fabrics exhibit a denser structure and therefore lower air permeability, the opposite happens to PET, the fabric is less dense, hence the air permeability is higher. Normalized burst strength also shows typical results, where PET has higher value and cotton has the lowest.

Due to Experiment4 has just one point (just a belt speed was used), we will compare it with Experiment1 in the following section. The data will be shown in function of specific energy.

6.1.1.5 Graphs and analysis for Experiment1+Experiment4

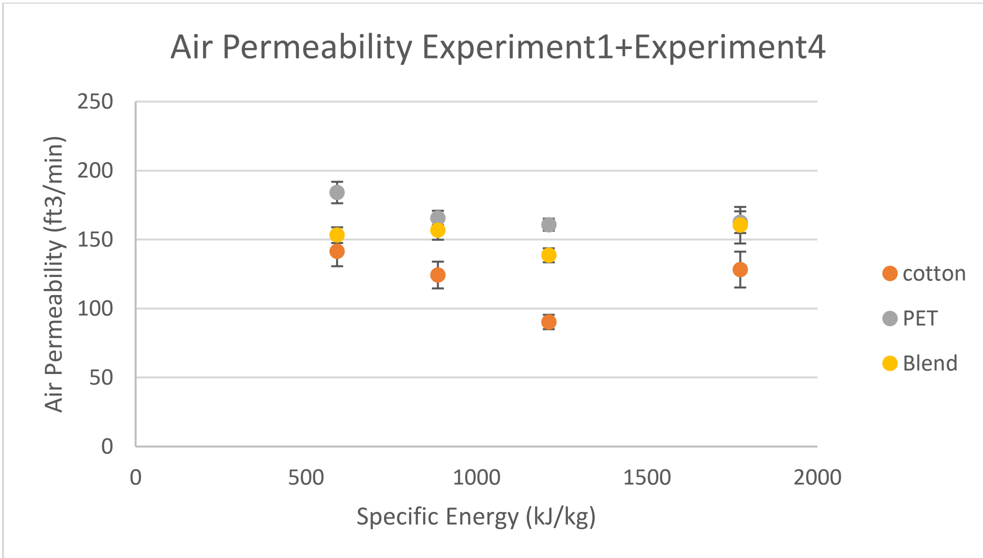

Figure 6.13 Air permeability (ft3/min/ft2) for Experiment1+Experiment4 in function of specific energy (kJ/kg)

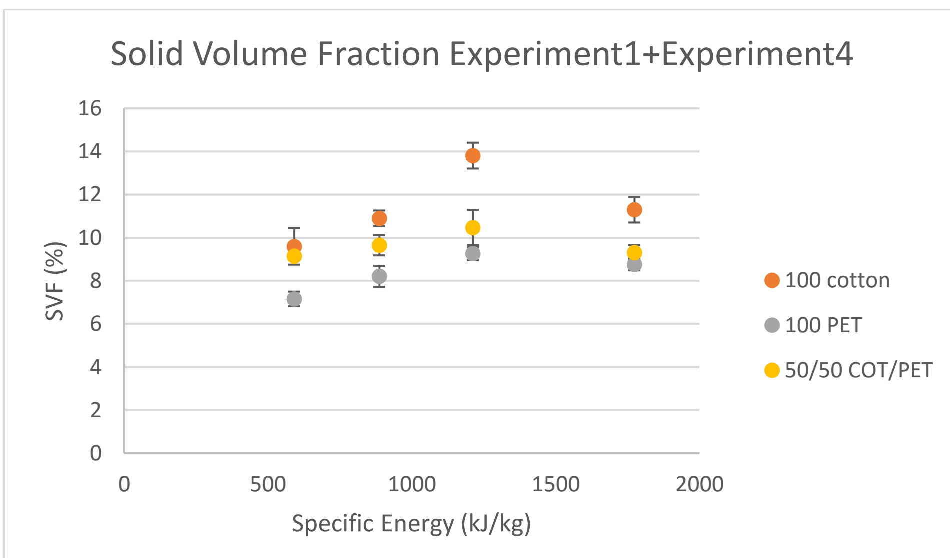

Figure 6.14 SVF (%) for Experiment1+Experiment4 in function of specific energy (kJ/kg)

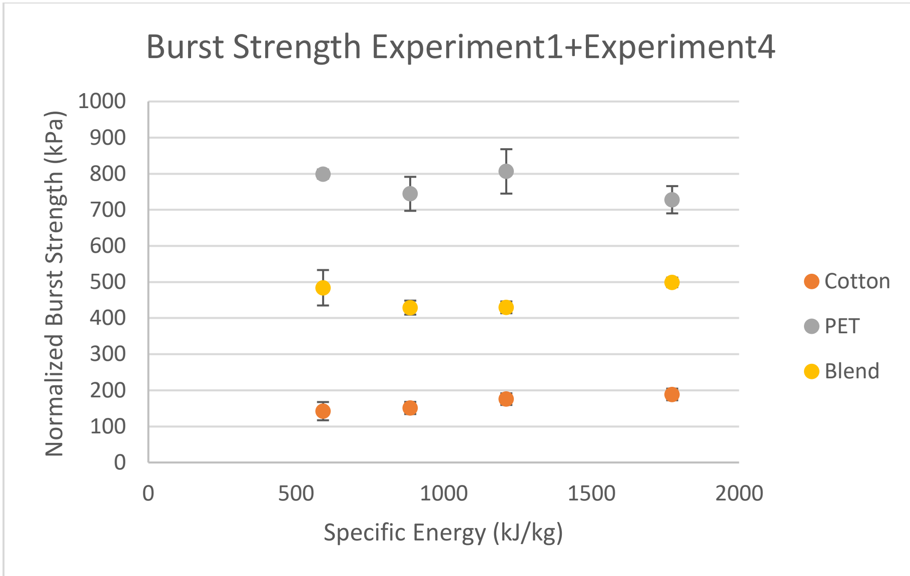

Figure 6.15 Normalized Burst strength (kPa) for Experiment1+Experiment4 in function of specific energy (kJ/kg)

Experiment1 and Experiment4 have been combined two show what happens with the fabrics when we double the belt speed (60m/min) and double the pressure profile (30,100,150,200,200 bar). Because the energy is not the same as Experiment1 (It is 1212.058kJ/kg for Experiment4), the graphics are compared. We can see that air permeability decreases and the solid volume fraction increases for Experiment4, this means that having higher speed and higher jet pressure lead to denser structures with very good performance for some type of applications that require this kind of attributes. The normalized burst strength does not have a significant change when we have higher belt speed and higher pressure profile. The normalized burst strength slightly increases for Experiment4.

6.1.1.6 Graphs and analysis for Experiment5

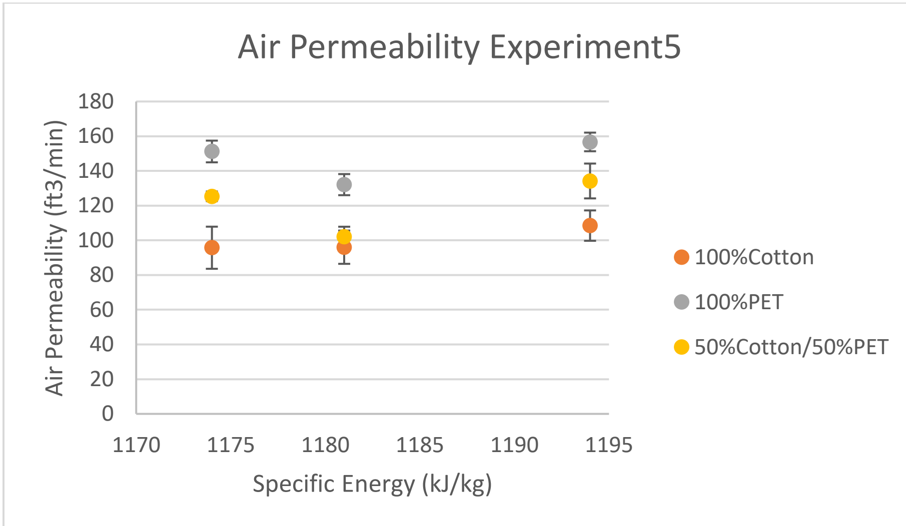

Figure 6.16 Air permeability (ft3/min/ft2) for Experiment5 in function of specific energy (kJ/kg)

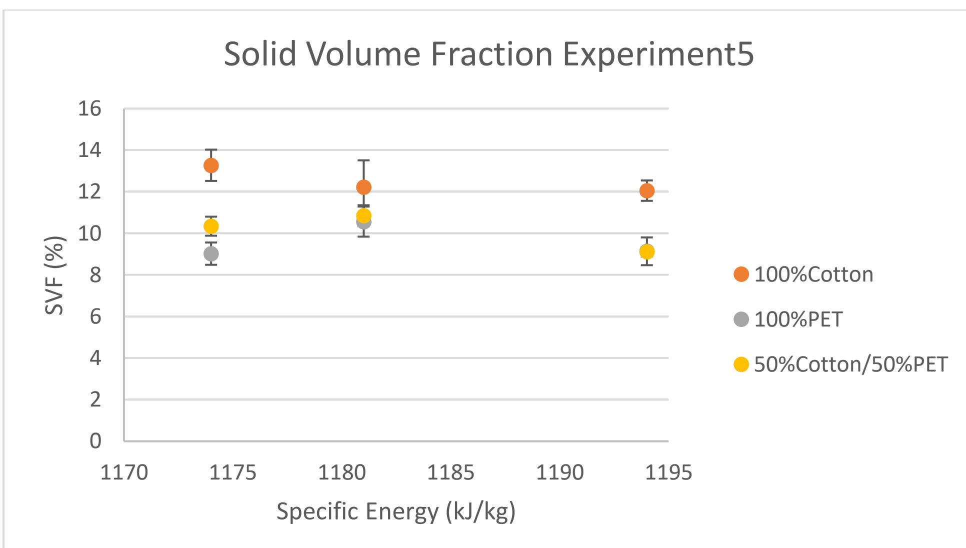

Figure 6.17 SVF (%) for Experiment5 in function of specific energy (kJ/kg)

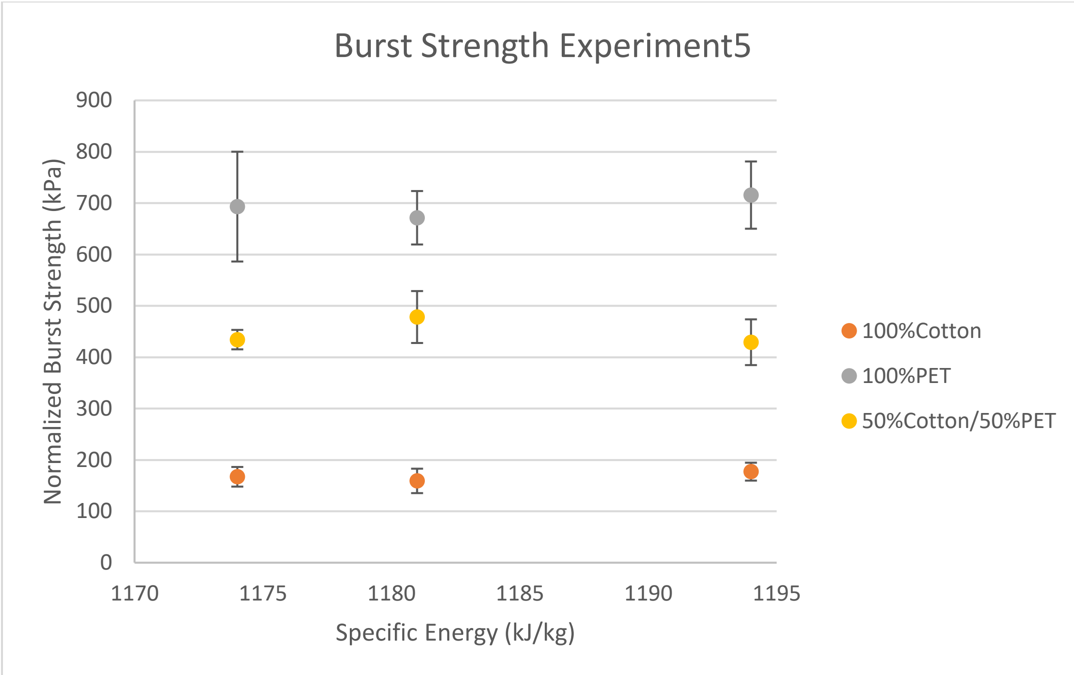

Figure 6.18 Normalized Burst strength (kPa) for Experiment5 in function of specific energy (kJ/kg)

Experiment5 has kept the energy constant, changing the number of manifolds and pressure profile. The air permeability and solid volume fraction have a direct relationship; when the air permeability increases the density decreases. All the fibers show a coherent behavior, where cotton has the lowest values for air permeability, but the higher numbers for solid volume fraction. This Experiment has the opposite results than Experiment1 where air permeability tends to decrease and solid volume fraction increases.

Normalized burst strength exhibits slightly higher values for cotton and PET but remains almost constant for the blend.

6.1.2 Results of tear strength (MD and CD) for each Experiment

The tear strength in MD and CD has been performed under the test method ASTM D2261 Tongue Tear Test. The test procedure, consisted in 5 rectangular specimens cut in the MD (Machine direction) and 5 cut in the CD (Cross direction), then they were placed into the tester, that consist in two jaws (upper and lower), one side of the rectangular specimen cut end is placed in the lower jaw, and the other end is placed in the upper jaw. The aforementioned jaw are moved apart at a constant rate, then the fabric starts to tear and the apparatus stop when the fabric breaks. This test method allows to determine the resistance of the fabrics to tearing, this gives us an idea of the conformation of the fabric. During the experiment, it was clear that the fabric made with 100%Pet are stronger and therefore more time an strength were necessary to tear them and break them, the opposite happened to the fabrics made with 100%Cotton. They teared easily and fast, the fabrics made with the blend exhibited a good behavior, they are not as easy to tear as the 100%cotton ones but not as difficult as the 100%PET ones.

In the following chart we can see the results for the 39 samples produced using the 5 Experiment, the data for the test done in MD and CD can be visualized as well as the graphs obtained.

Table 6.5 Tear strength in MD and CD for fabrics made with 100% Cotton

MD DOE1					
Fiber	Belt Speed (m/min)	Specific Energy (kJ/kg)	Peak Load (N) MD	Strain at break (%)	Confidence Int. (P. Load N)
100 cotton	45	591.196	7.425	368.525	0.644
	30	886.794	6.788	363.058	0.558
	15	1773.588	7.764	380.792	0.697

CD DOE1					
Fiber	Belt Speed (m/min)	Specific Energy (kJ/kg)	Peak Load (N) CD	Strain at break (%)	Confidence Int. (P. Load N)
100 cotton	45	591.196	10.796	471.058	0.698
	30	886.794	9.542	278.258	0.327
	15	1773.588	10.153	375.591	1

MD DOE2					
Fiber	Belt Speed (m/min)	Specific Energy (kJ/kg)	Peak Load (N) MD	Strain at break (%)	Confidence Int. (P. Load N)
100 cotton	45	535.954	5.172	398.125	0.808
	30	803.931	7.663	394.258	0.605
	15	1607.861	7.276	388.925	0.607

CD DOE2					
Fiber	Belt Speed (m/min)	Specific Energy (kJ/kg)	Peak Load (N) CD	Strain at break (%)	Confidence Int. (P. Load N)
100 cotton	45	535.954	7.485	362.925	1.254
	30	803.931	9.311	382.925	1.024
	15	1607.861	9.575	390.258	1.072

MD DOE3					
Fiber	Belt Speed (m/min)	Specific Energy (kJ/kg)	Peak Load MD	Strain at break (%)	Confidence Int. (P. Load N)
100 cotton	45	591.196	7.063	367.592	0.402
	30	886.794	5.959	353.859	0.42
	15	1773.588	6.405	347.192	0.319

CD DOE3					
Fiber	Belt Speed (m/min)	Specific Energy (kJ/kg)	Peak Load CD	Strain at break (%)	Confidence Int. (P. Load N)
100 cotton	45	591.196	9.878	402.659	0.926
	30	886.794	9.282	234.792	1.281
	15	1773.588	9.387	342.658	1.289

MD DOE4					
Fiber	Belt Speed (m/min)	Specific Energy (kJ/kg)	Peak Load MD	Strain at break (%)	Confidence Int. (P. Load N)
100 cotton	60	1212.058	4.241	272.792	0.377

CD DOE4					
Fiber	Belt Speed (m/min)	Specific Energy (kJ/kg)	Peak Load CD	Strain at break (%)	Confidence Int. (P. Load N)
100 cotton	60	1212.058	7.522	371.059	0.432

MD DOE5					
Fiber	Belt Speed (m/min)	Specific Energy (kJ/kg)	Peak Load MD	Strain at break (%)	Confidence Int. (P. Load N)
100 cotton	30	1174	3.675	240.659	0.382
	30	1181	4.845	345.192	0.678
	30	1194	4.988	335.725	0.528

CD DOE5					
Fiber	Belt Speed (m/min)	Specific Energy (kJ/kg)	Peak Load CD	Strain at break (%)	Confidence Int. (P. Load N)
100 cotton	30	1174	7.098	341.992	0.79
	30	1181	8.409	389.192	0.71
	30	1194	9.402	406.658	0.488

Table 6.6 Tear strength in MD and CD for fabrics made with 100% PET

MD DOE1					
Fiber	Belt Speed (m/min)	Specific Energy (kJ/kg)	Peak Load (N) MD	Strain at break (%)	Confidence Int. (P. Load N)
100 PET	45	591.196	42.095	296.925	3.304
	30	886.794	40.204	334.125	2.779
	15	1773.588	46.584	438.258	3.047

CD DOE1					
Fiber	Belt Speed (m/min)	Specific Energy (kJ/kg)	Peak Load (N) CD	Strain at break (%)	Confidence Int. (P. Load N)
100 PET	45	591.196	33.671	395.991	1.994
	30	886.794	35.894	354.791	2.347
	15	1773.588	34.307	524.258	2.92

MD DOE2					
Fiber	Belt Speed (m/min)	Specific Energy (kJ/kg)	Peak Load (N) MD	Strain at break (%)	Confidence Int. (P. Load N)
100 PET	45	535.954	42.664	420.992	4.286
	30	803.931	48.227	420.125	1.106
	15	1607.861	47.706	334.525	4

CD DOE2					
Fiber	Belt Speed (m/min)	Specific Energy (kJ/kg)	Peak Load (N) CD	Strain at break (%)	Confidence Int. (P. Load N)
100 PET	45	535.954	32.222	403.325	3.501
	30	803.931	35.725	463.458	2.524
	15	1607.861	35.296	411.458	1.577

MD DOE3					
Fiber	Belt Speed (m/min)	Specific Energy (kJ/kg)	Peak Load MD	Strain at break (%)	Confidence Int. (P. Load N)
100 PET	45	591.196	37.3	363.992	2.031
	30	886.794	47.505	436.125	2.652
	15	1773.588	46.515	395.058	2.516

CD DOE3					
Fiber	Belt Speed (m/min)	Specific Energy (kJ/kg)	Peak Load CD	Strain at break (%)	Confidence Int. (P. Load N)
100 PET	45	591.196	30.668	481.458	1.416
	30	886.794	33.64	483.059	3.103
	15	1773.588	34.572	489.858	2.697

MD DOE4					
Fiber	Belt Speed (m/min)	Specific Energy (kJ/kg)	Peak Load MD	Strain at break (%)	Confidence Int. (P. Load N)
100 PET	60	1212.058	37.103	384.792	3.143

CD DOE4					
Fiber	Belt Speed (m/min)	Specific Energy (kJ/kg)	Peak Load CD	Strain at break (%)	Confidence Int. (P. Load N)
100 PET	60	1212.058	29.733	493.592	3.239

MD DOE5					
Fiber	Belt Speed (m/min)	Specific Energy (kJ/kg)	Peak Load MD	Strain at break (%)	Confidence Int. (P. Load N)
100 PET	30	1174	26.681	438.125	3.108
	30	1181	25.733	413.192	3.569
	30	1194	31.115	420.525	4.074

CD DOE5					
Fiber	Belt Speed (m/min)	Specific Energy (kJ/kg)	Peak Load CD	Strain at break (%)	Confidence Int. (P. Load N)
100 PET	30	1174	24.769	455.327	1.861
	30	1181	20.772	443.992	0.612
	30	1194	29.178	486.125	2.662

Table 6.7 Tear strength in MD and CD for fabrics made with 50% Cotton/50%PET (Blend)

MD DOE1					
Fiber	Belt Speed (m/min)	Specific Energy (kJ/kg)	Peak Load (N) MD	Strain at break (%)	Confidence Int. (P. Load N)
50/50 COT/PET	45	591.196	26.459	480.471	1.644
	30	886.794	26.077	477.725	1.852
	15	1773.588	25.999	445.325	2.331

CD DOE1					
Fiber	Belt Speed (m/min)	Specific Energy (kJ/kg)	Peak Load (N) CD	Strain at break (%)	Confidence Int. (P. Load N)
50/50 COT/PET	45	591.196	23.179	509.058	1.275
	30	886.794	21.849	495.191	1.236
	15	1773.588	21.688	400.125	1.148

MD DOE2					
Fiber	Belt Speed (m/min)	Specific Energy (kJ/kg)	Peak Load (N) MD	Strain at break (%)	Confidence Int. (P. Load N)
50/50 COT/PET	45	535.954	17.775	472.792	1.998
	30	803.931	21.287	395.592	2.524
	15	1607.861	23.154	387.06	1.652

CD DOE2					
Fiber	Belt Speed (m/min)	Specific Energy (kJ/kg)	Peak Load (N) CD	Strain at break (%)	Confidence Int. (P. Load N)
50/50 COT/PET	45	535.954	18.599	468.925	1.613
	30	803.931	19.225	436.792	1.916
	15	1607.861	22.508	469.992	2.335

MD DOE3					
Fiber	Belt Speed (m/min)	Specific Energy (kJ/kg)	Peak Load MD	Strain at break (%)	Confidence Int. (P. Load N)
50/50 COT/PET	45	591.196	24.386	366.792	2.307
	30	886.794	21.601	293.592	2.539
	15	1773.588	22.322	307.592	2.535

CD DOE3					
Fiber	Belt Speed (m/min)	Specific Energy (kJ/kg)	Peak Load CD	Strain at break (%)	Confidence Int. (P. Load N)
50/50 COT/PET	45	591.196	25.125	482.912	2.903
	30	886.794	21.228	424.659	3.228
	15	1773.588	23.246	411.886	6.224

MD DOE4					
Fiber	Belt Speed (m/min)	Specific Energy (kJ/kg)	Peak Load MD	Strain at break (%)	Confidence Int. (P. Load N)
50/50 COT/PET	60	1212.058	21.583	392.792	1.844

CD DOE4					
Fiber	Belt Speed (m/min)	Specific Energy (kJ/kg)	Peak Load CD	Strain at break (%)	Confidence Int. (P. Load N)
50/50 COT/PET	60	1212.058	19.119	442.125	0.637

MD DOE5					
Fiber	Belt Speed (m/min)	Specific Energy (kJ/kg)	Peak Load MD	Strain at break (%)	Confidence Int. (P. Load N)
50/50 COT/PET	30	1174	18.271	414.432	0.25
	30	1181	16.307	377.059	1.377
	30	1194	20.375	390.525	1.302

CD DOE5					
Fiber	Belt Speed (m/min)	Specific Energy (kJ/kg)	Peak Load CD	Strain at break (%)	Confidence Int. (P. Load N)
50/50 COT/PET	30	1174	16.937	459.093	0.562
	30	1181	17.019	422.925	1.045
	30	1194	18.532	447.459	1.041

6.1.2.1 Graphs and analysis for Experiment1

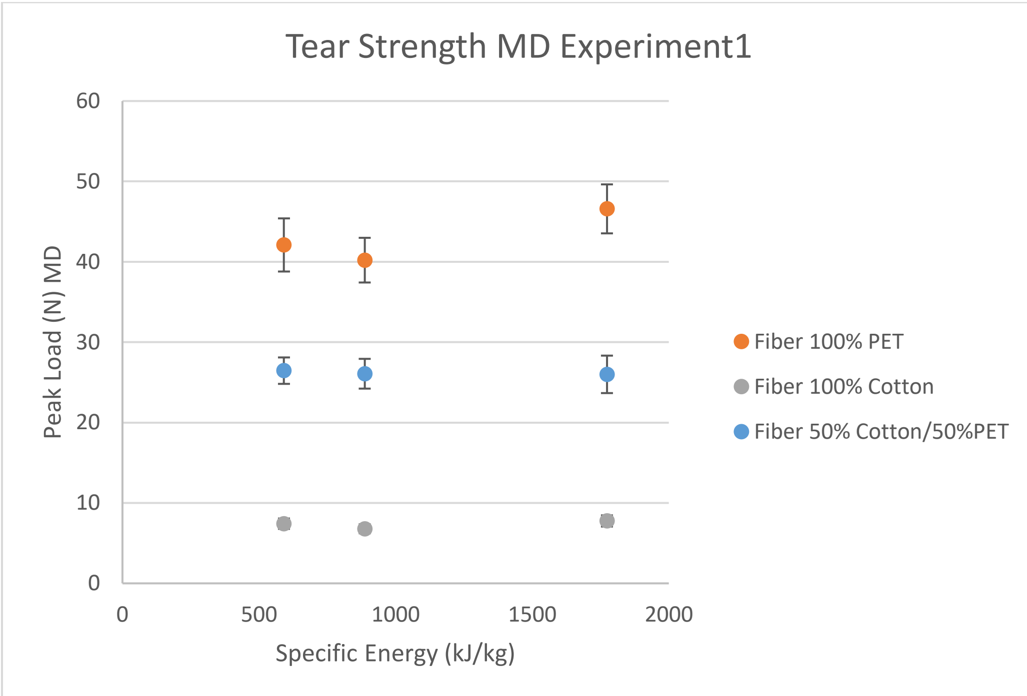

Figure 6.19 Tear strength MD for Experiment1 in function of specific energy (kJ/kg)

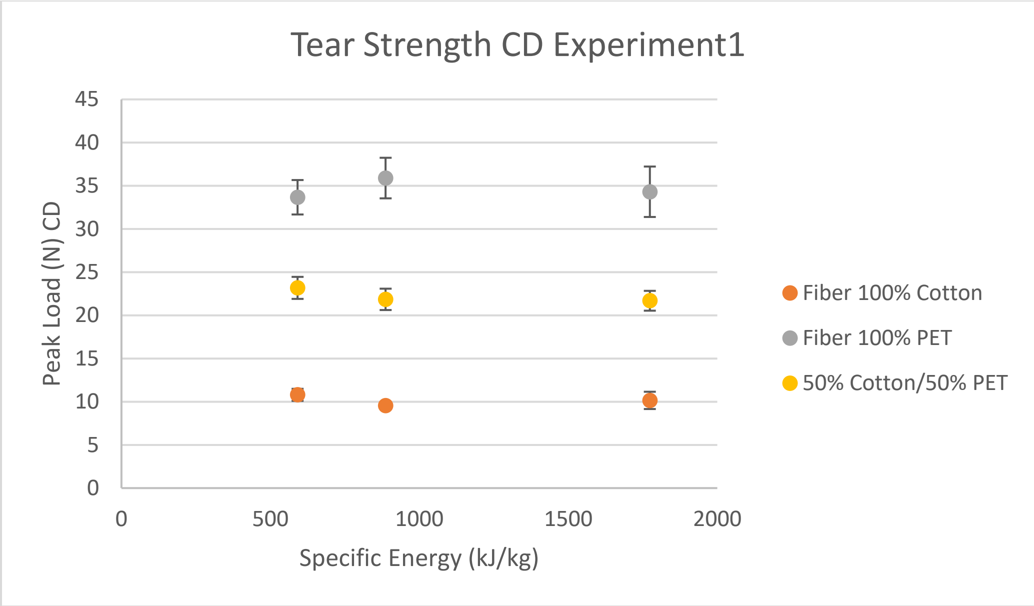

Figure 6.20 Tear strength CD for Experiment1 in function of specific energy (kJ/kg)

For Experiment1 we can see that tear strength for cotton the values are very similar for both MD and CD and the values remain the same even with higher energies.

For PET fabrics the values for MD are higher than the values for CD. In MD the tear strength tends to increase while the tear strength in CD remains almost constant.

Fabric made with the blend, have similar values for MD and CD, being the ones in MD slightly higher, in general they do not change significantly for higher energies.

6.1.2.2 Graphs and analysis for Experiment2

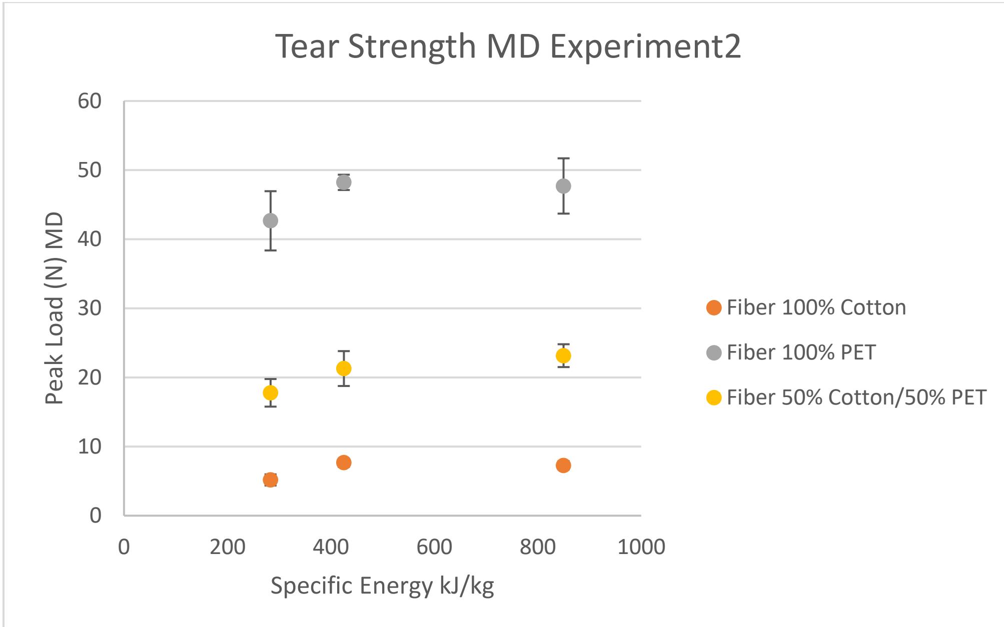

Figure 6.21 Tear strength MD for Experiment2 in function of specific energy (kJ/kg)

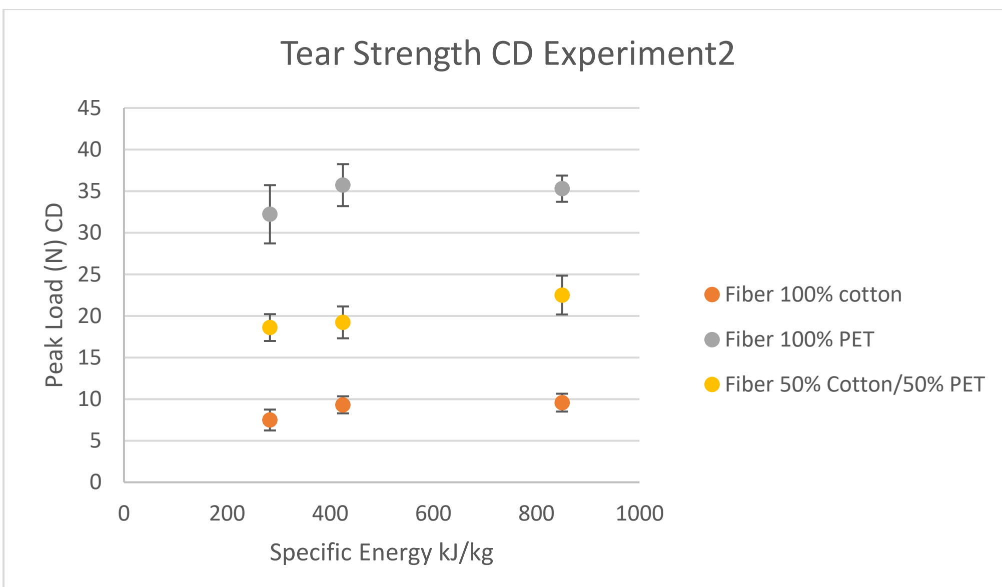

Figure 6.22 Tear strength CD for Experiment2 in function of specific energy (kJ/kg)

Experiment2 has lower energies than Experiment1, because we used 3 manifolds instead of 5. Two of those manifolds used double row jet strip with spacing of 1200microns.

Cotton shows very similar values in MD and CD, those values tend to be higher for higher energies, but they are similar to each other.

The tear strength for PET fabrics is higher for MD and as well as cotton, the last two point are higher when the energy increases.

For the blend, values for MD and CD are very similar, the values of tear strength show an increase when the energies are higher. This behavior is evident for both directions.

6.1.2.3 Graphs and analysis for Experiment3

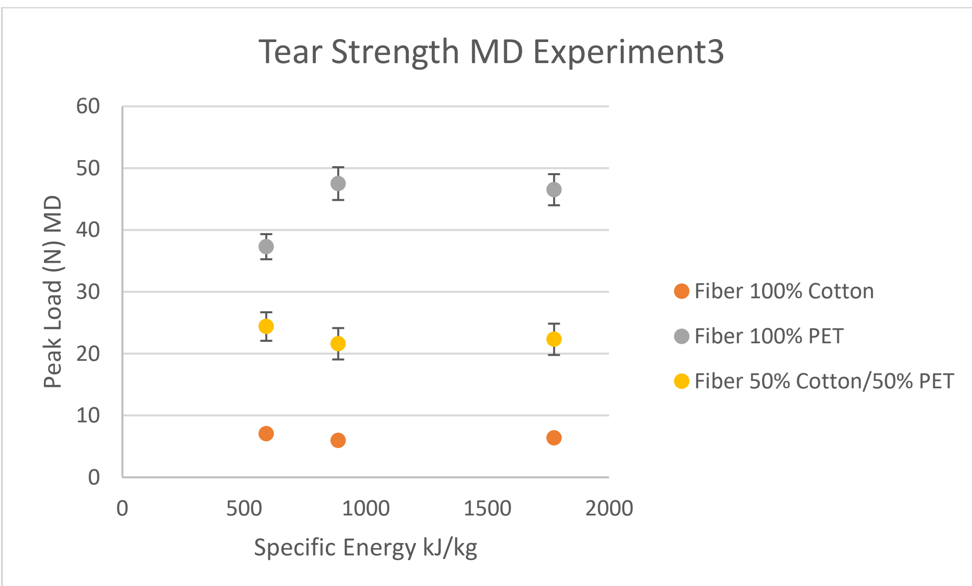

Figure 6.23 Tear strength MD for Experiment3 in function of specific energy (kJ/kg)

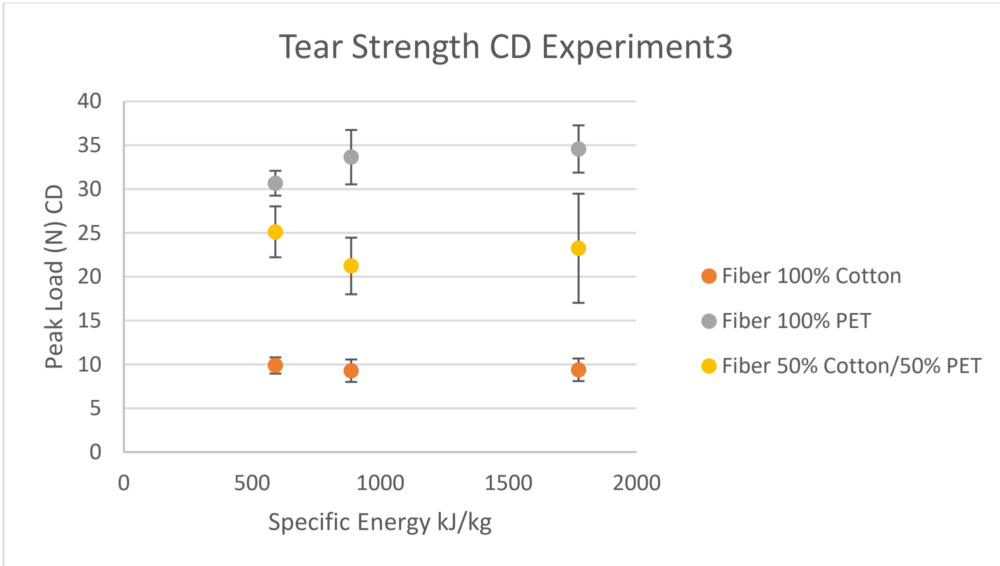

Figure 6.24 Tear strength CD for Experiment3 in function of specific energy (kJ/kg)

As we have mentioned before, this Experiment is highly comparable with Experiment1, the only difference is that 2 and 3 operated with double row jet strip (Spaced 1200microns), but the energy and pressure profile were the same as Experiment1.

Fabrics made with cotton, show higher values for CD and for both MD and CD they tend to decrease when the energy increases; however, this change is not dramatic and the values are very similar.

The opposite happens to PET, the tear strength increases for higher energies and the last two numbers are similar to each other. PET exhibits higher values for MD than CD.

The blend has a behavior similar to cotton, values for MD and Cd are similar and these values decrease with higher energies.

6.1.2.4 Graphs and analysis for Experiment4

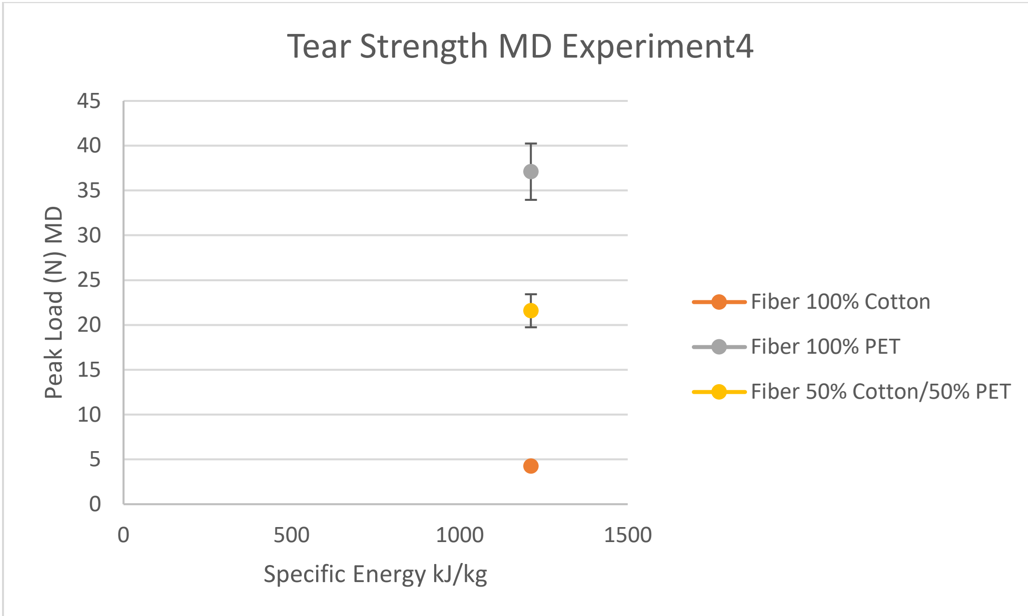

Figure 6.25 Tear strength MD for Experiment4 in function of specific energy (kJ/kg)

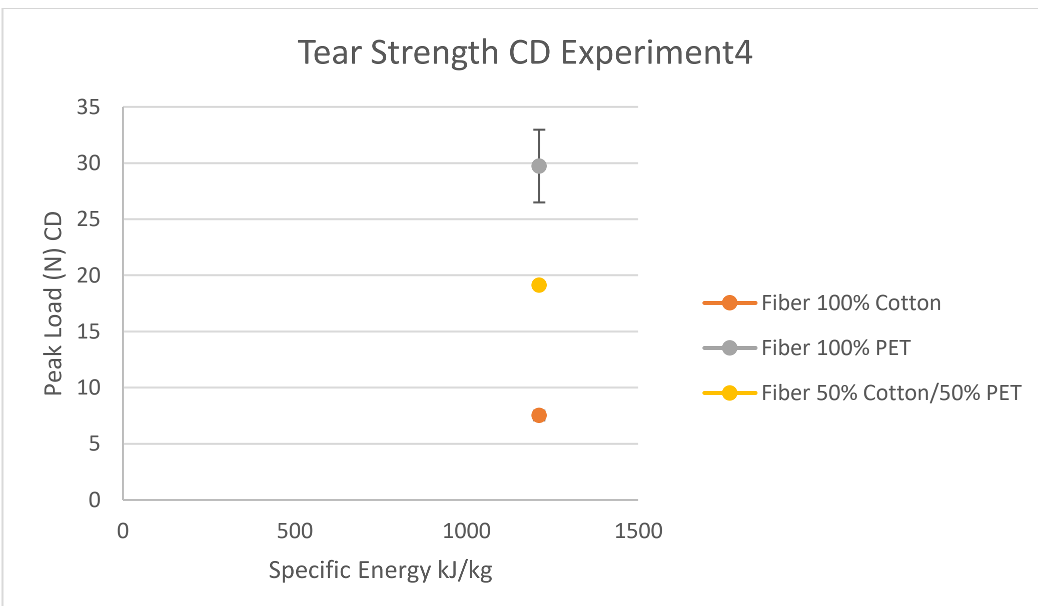

Figure 6.26 Tear strength CD for Experiment4 in function of specific energy (kJ/kg

Experiment4 has used one belt speed (60m/min), which is higher than the belt speeds for Experiment1 and the pressure profile used has values that double the ones used for Experiment1.

We have found a point for each property measure. PET fabric shows higher values for MD and this values is higher than cotton and the blend.

Cotton fabric, also has a higher value for CD and it is the lowest value compared to PET and the blend.

The blend exhibits higher value for MD.

Due to we do not have more than one point in this experiment, we have plotted with Experiment1

6.1.2.5 Graphs and analysis for Experiment1+Experiment4

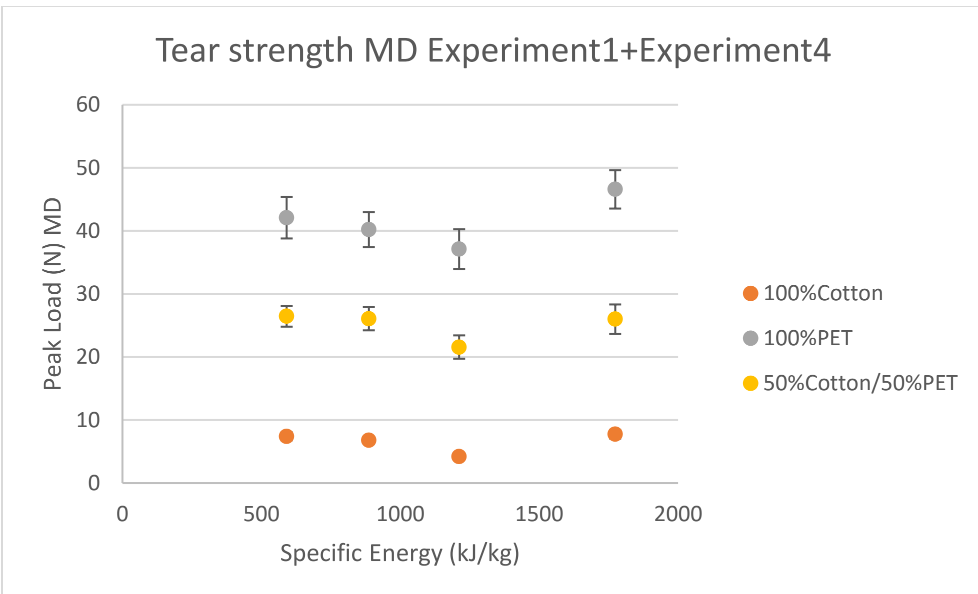

Figure 6.27 Tear strength MD for Experiment1+Experiment4 in function of specific energy (kJ/kg)

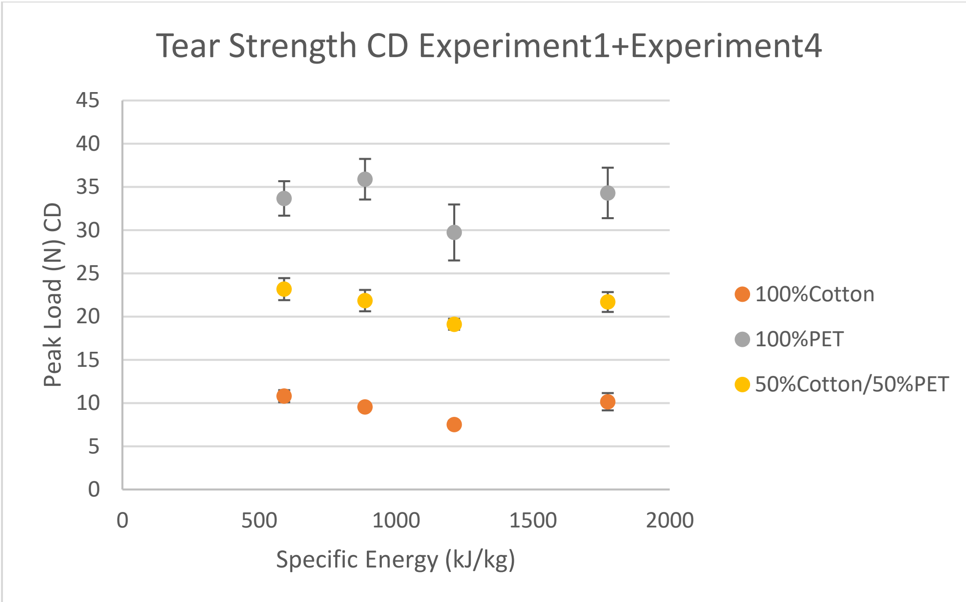

Figure 6.28 Tear strength CD for Experiment1+Experiment4 in function of specific energy (kJ/kg)

Because Experiment1 and Experiment4 have similar set ups, we have plotted them together. The main differences are that Experiment4 used higher belt speed and the pressure profile was the double.

We can see that for both MD and CD, the trend is that the tear strength decreases with higher belt speed and pressure profile.

Values for cotton are higher for CD and although they remain very similar, the last point, the one with higher speed and pressure, shows a more drastic decrease.

For PET, the values are higher for MD and as well as cotton, the tear strength decreases.

The blend exhibits higher values for MD and for Experiment1, the points do not show a significant change, but for Experiment4, we can see a decrease, for MD and CD this value is around 20N.

6.1.2.6 Graphs and analysis for Experiment5

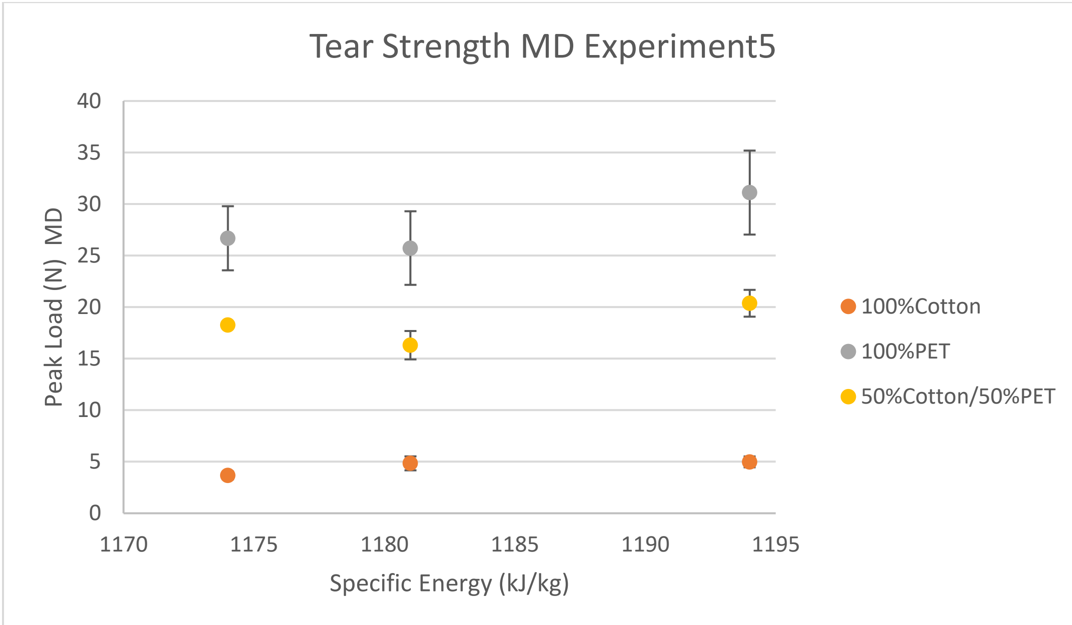

Figure 6.29 Tear strength MD for Experiment5 in function of specific energy (kJ/kg)

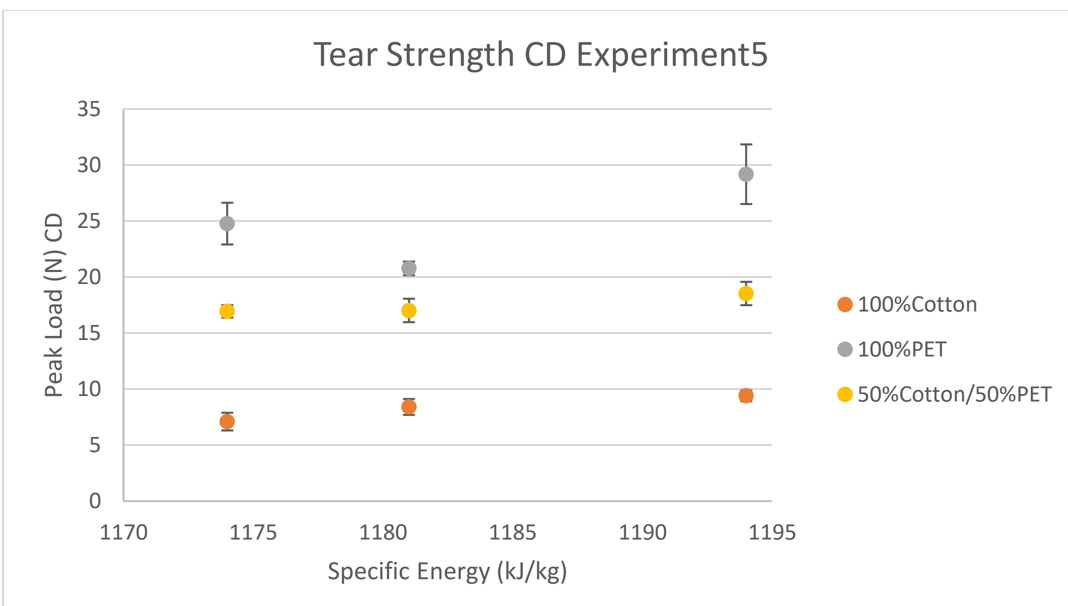

Figure 6.30 Tear strength CD for Experiment5 in function of specific energy (kJ/kg)

This Experiment changed some conditions like pressure profile and number of manifolds, but the specific energy was kept constant (around 1180kJ/kg).

Fabric made with cotton, have higher values for CD and these values increase with the energy, but due to the energy is constant, the values for MD are almost the same, they increase is more evident for CD.

PET has higher values for MD and for both MD and CD, we can see how the value of tear strength when the energy is the highest (1194kJ/kg) dramatically increases. We must notices that this energy was achieved with three manifolds, 1,2 and 5, but manifolds 2 and 5 have high pressures. 130 and 190 bar respectively. The fabrics made with the blend, has very similar values for MD and CD and same as PET, the last points with the highest energy, exhibit the higher tear strength in MD and CD.

6.1.3 Air permeability

In this section we are presenting the data and its analysis for each fiber separately. The values found were shown in table 6.1 to table 6.6.

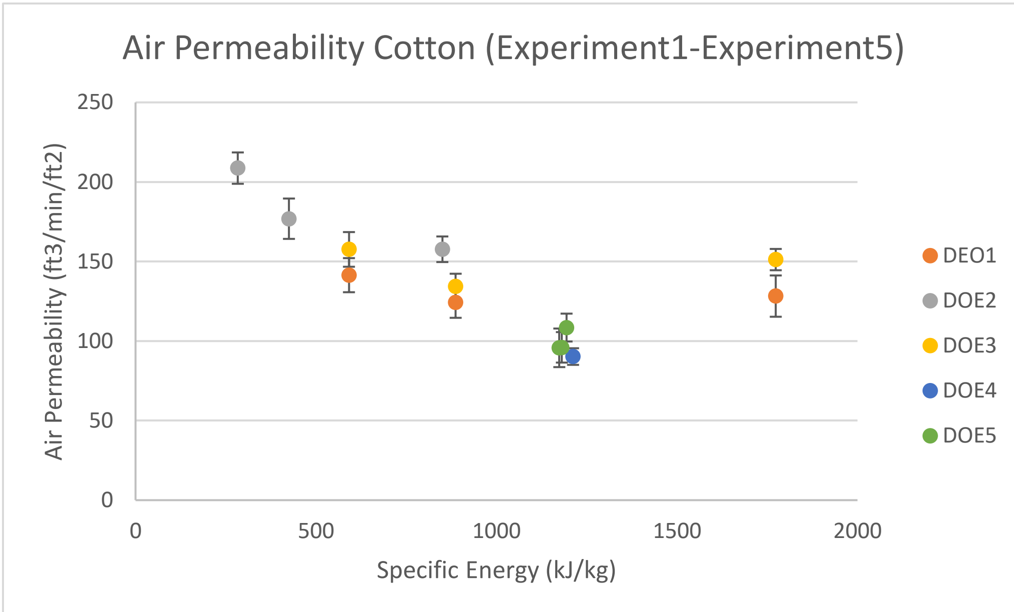

Figure 6.31 Air permeability (ft3/min/ft2) for fabrics made with 100% Cotton in function of specific energy (kJ/kg)

In the graphic we can see how the air permeability tends to decrease for fabrics made 100% Cotton when the specific energy increases, especially for Experiment2, this might be, because just three manifolds were working and two of them used double row jet strip; however, this fabric has the highest air permeability, this can be significant if we consider that we are using less water and getting fabrics with good mechanical properties that can be useful for many applications that require higher air permeability. ExperimentT1 and Experiment3 have similar results, although Experiment shows higher values, the error bars overlap indicating that they are the same point. Experiment4 that has used significantly higher belt speed (60 m/min) exhibits one of the lowest air permeability that can be comparable with the data for Experiment5 that has used in some cases less manifolds and lower belt speed (30m/min)

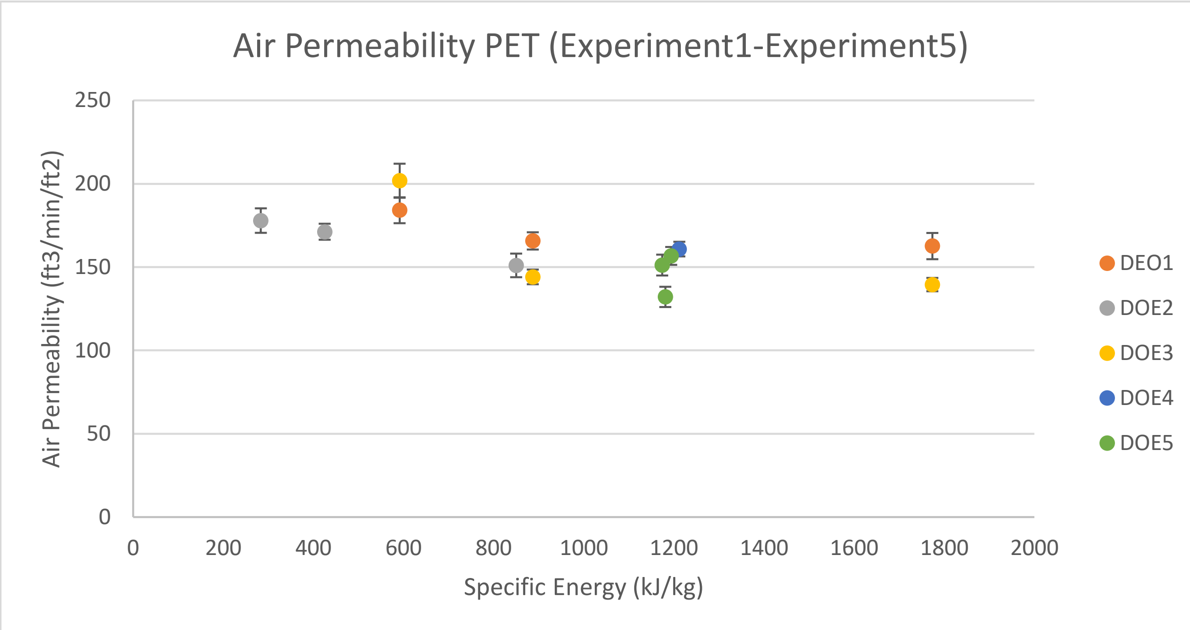

Figure 6.32 Air permeability (ft3/min/ft2) for fabrics made with 100% PET in function of specific energy (kJ/kg)

In general the values of Air Permeability for fabrics made 100% PET is higher than the values gotten by the fabrics 100% Cotton. This might be due to the geometry of the fibers, PET tend to have a round shape, therefore, the structure is less compact and the air permeability is higher.

Experiment1, Experiment2 and Experiment3, exhibit a similar behavior, all of them tend to decrease when the specific energy increases, but they still remain in close ranges, especially Experiment1 and Experiment3 show a very similar trend and the error bars of some point overlap, meaning that they are the same. Considering that Experiment3 used two of the manifolds with double row jet strip, we would expect the mechanical properties to have a significant improvement, due to this jet strip has been proved to reduce the jet marks in the fabric, the graph show us that this is not the case and we might need to have all the injectors with double row jet strip in order to have a significant improvement in the air permeability. Experiment4 and Experiment5 have similar values and the air permeability remains close to the values for the other Experiment.

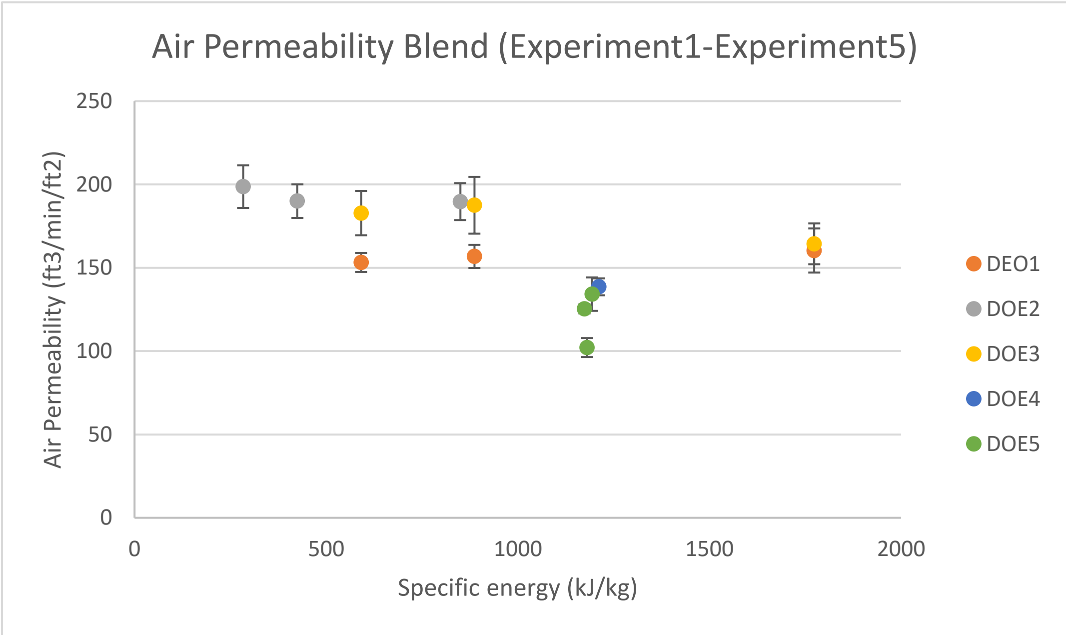

Figure 6.33 Air permeability (ft3/min/ft2) for fabrics made with 50% Cotton/50%PET (Blend) in function of specific energy (kJ/kg)

The fabrics made with cotton and polyester have significant advantages in terms of cost-effectiveness, as well as properties. We can see that for Experiment1 and Experiment3 the points have the same behavior and they do not tend to change much, with the specific energy, even for Experiment3 the three point remain very constant with no significant change in function of energy. Once again, we can see that Experiment4 and Experiment5 can get a very similar air permeability, this means that using less manifolds but lower belt speed or all the manifolds but higher belt speed we can achieve similar values for air permeability; therefore we can choose what conditions are more appropriate or suitable.

6.1.4 Solid Volume Fraction

The density was calculated measuring the basis weight of the fabric and the thickness. In the following paragraphs a wider explanation is given.

For the basis weight, 5 round samples with a diameter of 10 cm were obtained from each piece of fabric, then they were weighed in the digital weight, to find the mean, the standard deviation and with this values, being able to calculate the density.

The basis weight uniformity is a very important factor when we are studying nonwovens, because it explains the different properties of the fabrics. Even though the basis weight is chosen according to the requirements of the product or the client. We desire to have basis weight uniformity, this means that if we have a fabric that is supposed to be 100gsm, we want to have almost the same basis weight, all over the fabric, otherwise when the uniformity is not consistent, this could indicate, that the production process had some mistakes and the fabric possess defects.

To measure the thickness, the same round samples used in the weight, were tested with a machine that tests two different point of the sample , this means that with the 5 samples, we get 10 values which were processed later to find the mean and standard deviation. These values, combined with the basis weight led to get the density of the samples, which is one of the four main parameters that we have deeply analyzed, graphic and evaluated. In the case of hydroentangled fabrics, the thickness is highly related to the basis weight. The higher the basis weight is the thicker the fabric will be. According to the numbers, that can be seen in the tables in the Appendices section for each sample, we can conclude that the web formation and web bonding processes were done in a correct way, due to the samples showed a similar thickness in the point that we measured.

The density was found dividing the basis weight into the thickness.

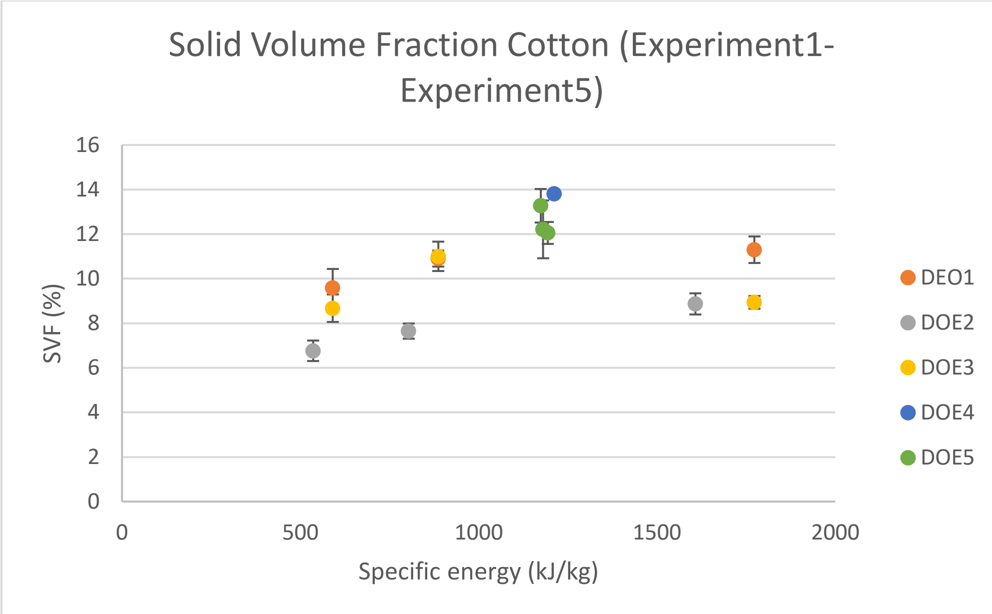

Figure 6.34 SVF (%) for fabrics made with 100% Cotton in function of specific energy (kJ/kg)

For the all the Experiment is clear that there is not a significant change in density in function of specific energy, all the values remain between 0.1 and 0.2, and although the range is narrow, the five Experiment show an increase in the density for higher energies, being Experiment4 and Experiment5 the ones that express the highest value and therefore the more compact structure. Experiment1 and Experiment3 have a similar behavior and the error bars of two point overlap, this means that they are exactly the same. Experiment2 shows the lowest values, due to this experiment used just 3 manifolds with low pressure profile. We can conclude from this graph that for fabrics made of 100% Cotton, lower pressure profiles, lead to less compact structures.

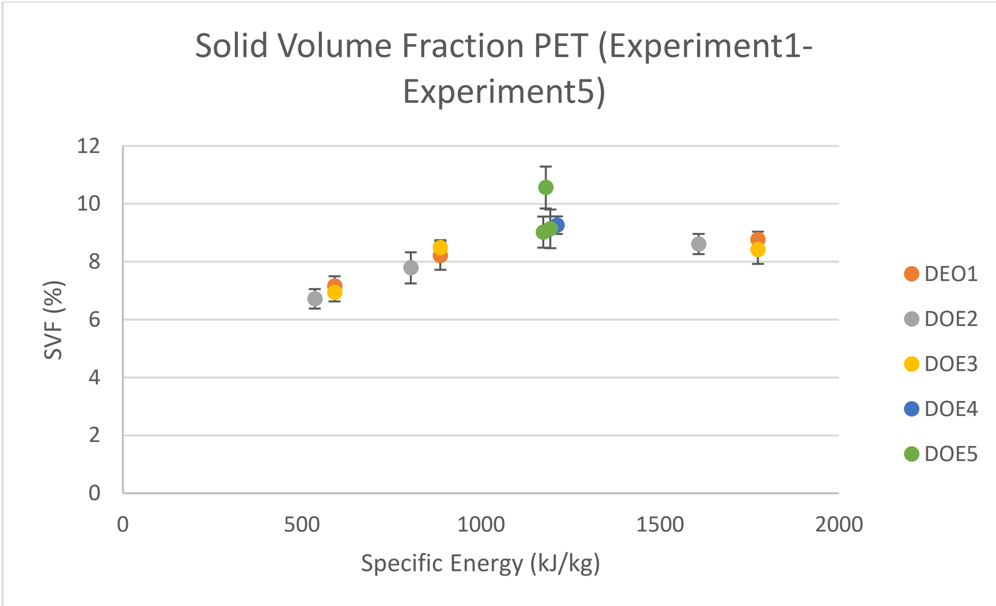

Figure 6.35 SVF (%) for fabrics made with 100% PET in function of specific energy (kJ/kg)

For fabrics made with 100% PET fiber, we can see that density remains very constant for all the experiments, once again we can see that Experiment1 and Experiment3 have basically the same behavior and the error bars prove that the points are the same. This let us conclude that changing the jet strip is not necessary to improve density for this type of fiber. Experiment2 exhibits some increase but the values are very close to each other (around 0.1). Experiment4 and Experiment5 have the higher pressure profiles, among all the Experiment and they clearly show the highest values for density, in fabrics made with 100%PET. From this graph we can see that using less manifolds, can lead to a fabrics with lower density, but still the density is close and appropriate for many applications.

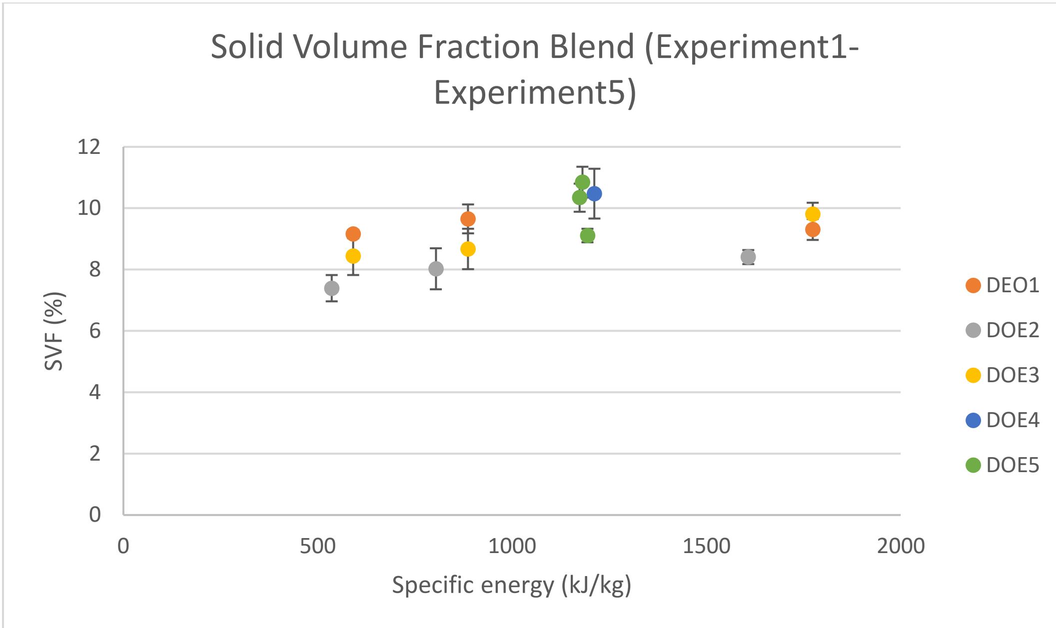

Figure 6.36 SVF (%) for fabrics made with 50% Cotton/50%PET (Blend) in function of specific energy (kJ/kg)

Considering the analysis done for the other two fabrics (100%Cotton and 100%PET), we can see that the fabric made with 50% Cotton and 50% PET exhibits values very close to each other. The density remains almost in the same values (From 0.1 to 0.15), Experiment1 and Experiment3 could be considered to be the same, and this means the two double row jet strips do not have a significant impact on the density. Surprisingly, Experiment2 shows similar values for Experiment1 and Experiment3 but using less water and consuming less energy (Two manifolds were off). Experiment4 and Experiment5 have very similar values as well. This has been a constant for the three fabrics.

6.1.5 Normalized Burst Strength

We have measured the burst strength using the standard method ASTM D 3786-06. This is an important measure for nonwoven fabric, because it let us know the resistance of the nonwovens to bursting. The equipment uses a hydraulic diaphragm.

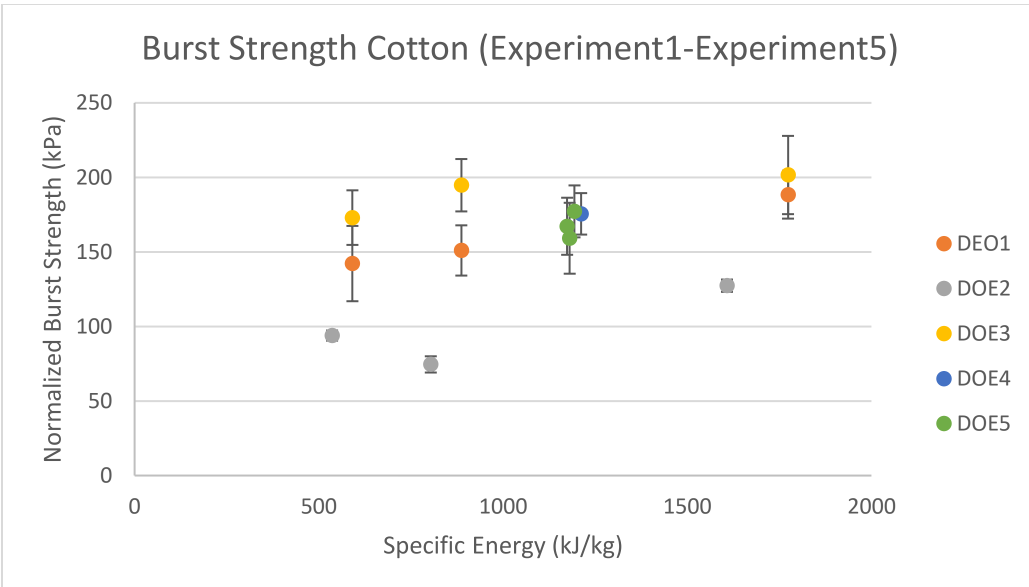

Figure 6.37 Normalized Burst strength for fabrics made with 100% Cotton in function of specific energy (kJ/kg)

The burst strength has a significant difference for some Experiment, while Experiment1 and Experiment3 seem to have the same behavior, as well as the same points, if we consider the error bars overlap for the three points, Experiment2 has the lowest values, especially for lower specific energies and therefore higher belt speeds. Experiment4 and Experiment5 exhibit similar values, but in general we could say that for all the Experiment the trend of the burst strength is to increase when the specific energy increases. This is the case for fabrics made with 100% cotton, in the following graphs, we will see the data obtained for the other two fabrics (100%PET and the blend).

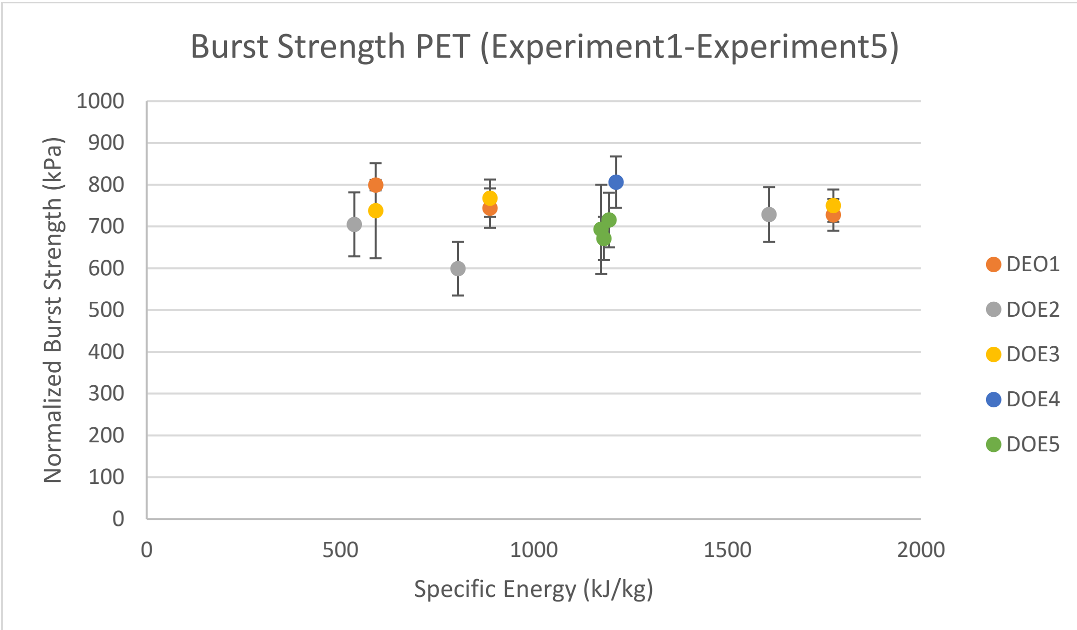

Figure 6.38 Normalized Burst strength for fabrics made with 100% PET in function of specific energy (kJ/kg)

For the fabrics made 100%PET, the values of burst strength are between 500 to 700 kPa, these values are higher than the values for the fabrics made with 100% cotton, this is because the PET fibers are usually longer and round shaped, also the bending rigidity and fiber properties play an important role. Although, there is a point that is different for Experiment1 and Experiment3, the other two point are the same and error bars overlap. Experiment5 exhibits some of the lowest values, together with Experiment2. Experiment4 has one of the highest values, and some other Experiment like 1, 2 and 3 have some points similar to Experiment4, this means that for fabrics made with 100%PET, we can use different pressure profiles and belt speed to achieve similar properties, therefore, companies can select which arrangement is more suitable for them in terms of cost, speed and mechanical properties.

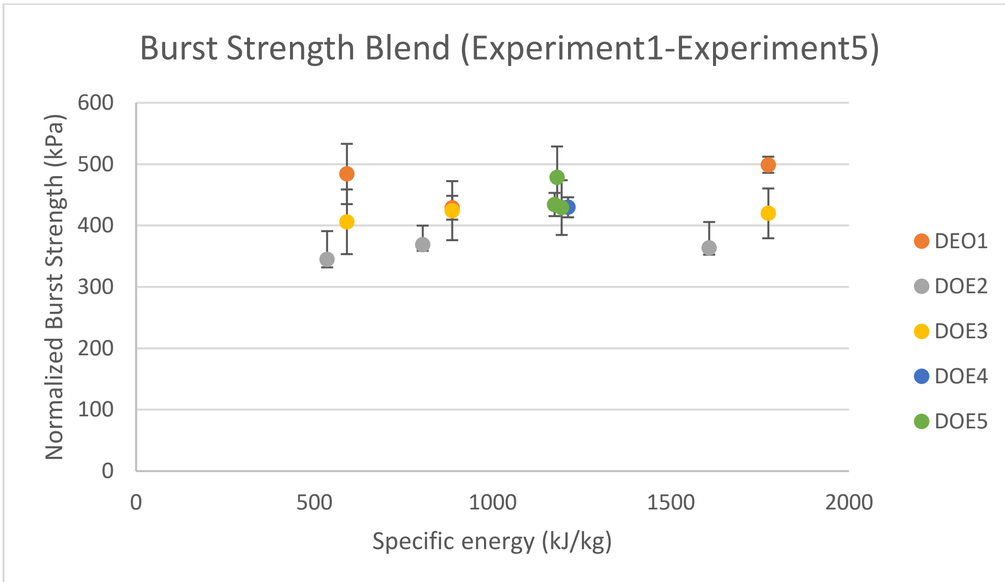

Figure 6.39 Normalized Burst strength for fabrics made with 50% Cotton/50%PET (Blend) in function of specific energy (kJ/kg)

The burst strength results for fabrics made with the blend, are in a range from 250 to 450 kPa, with Experiment2 exhibiting the lowest values, but still they show some increase when the specific energy increases. Experiment1 and Experiment3 seem to be less consistent that the point gotten for cotton and PET, just one of the point overlap and Experiment1 has a significant decrease for the middle point (30m/min belt speed and 886 kJ/kg), but the first and last point have very close values, despite they have been produce with 45m/min and 15m/min respectively. We could say that having higher speed and therefore lower specific energy we can produce fabrics with similar mechanical properties, but the production can significantly improve. Experiment5 has some of the highest values but surprise how close they are to the ones obtained by Experiment1. Experiment4 has a good values, close to Experiment1 and Experiment5.

6.1.6 Tear Strength MD and CD

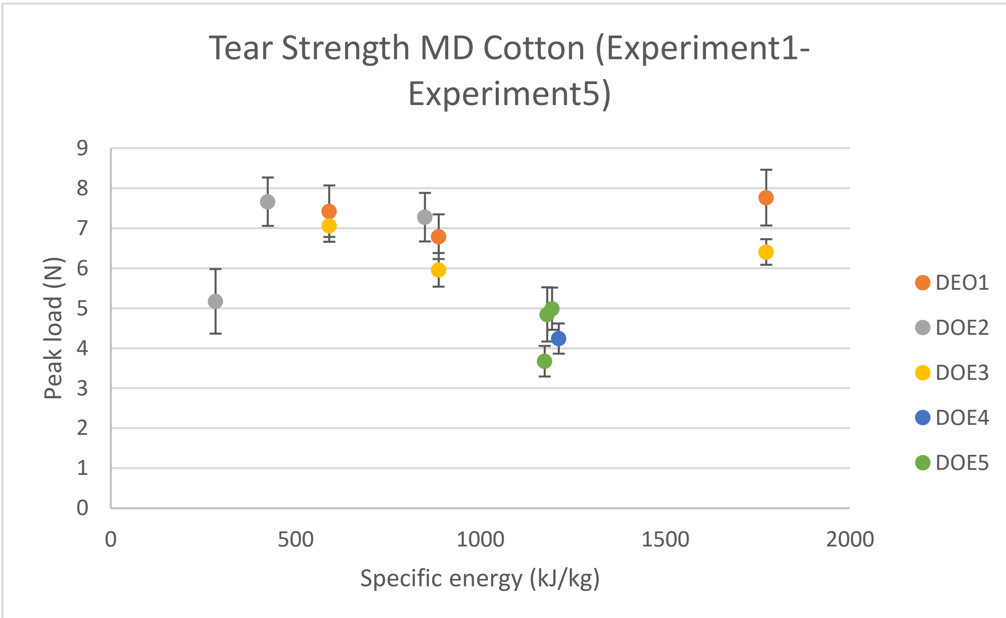

Figure 6.40 Tear strength MD for fabrics made with 100% Cotton in function of specific energy (kJ/kg)

The tear strength for fabrics made with 100%cotton in the MD direction Experiments not show consistency for the different Experiment with values from 3 to 8N. Experiment1 and Experiment3 have similar behavior, two of the point overlap, and for both the tear strength tends to decrease but rises again for the highest energy. Experiment3 has a significant rise when the specific energy increases and for the last two point, the values are comparable to the ones obtained for Experiment1 and Experiment3. Experiment4 and Experiment5 have the lowest values, this means that the belt speed and pressure profile for these experiments (which are higher) negatively impact the mechanical properties of the hydroentangled fabrics.

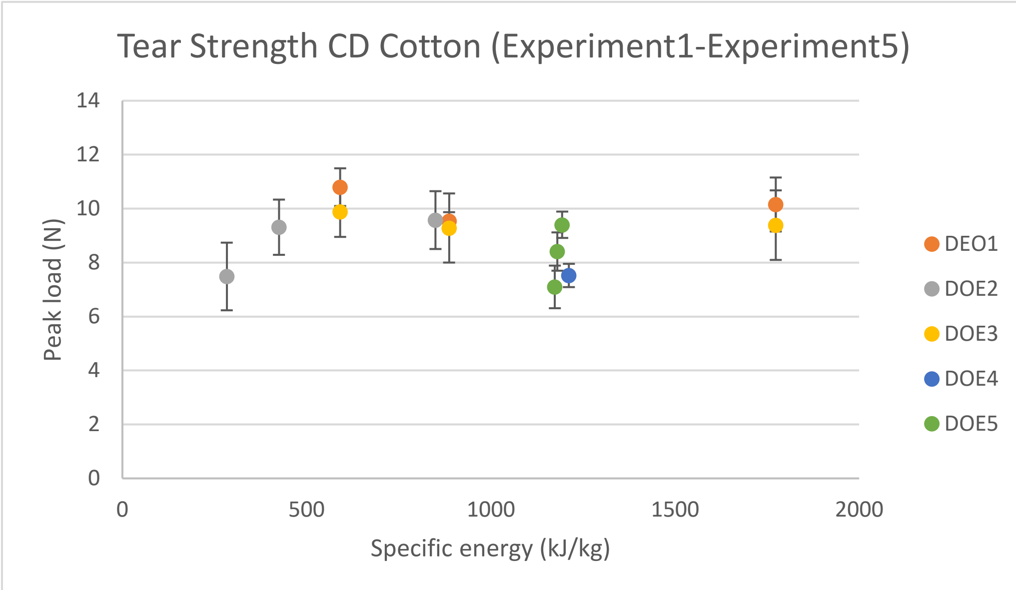

Figure 6.41 Tear strength CD for fabrics made with 100% Cotton in function of specific energy (kJ/kg)

As we were expecting the tear strength for CD direction achieved higher values, due to the resistance in the fiber orientation. Values go from 7 to 11 and the Experiment behave very similar for Cd and MD. In this graph we can see that the pressure profile in Experiment4 and Experiment5 do not affect the CD as dramatically as it affects the tear strrengthin MD. Here we can see that Experiment1 and Experiment3 have the same behavior and points, while Experiment3 increases when the energy increases. For Experiment4 and Experiment5 the values do not drop that much and they remain between 7 to 9N.

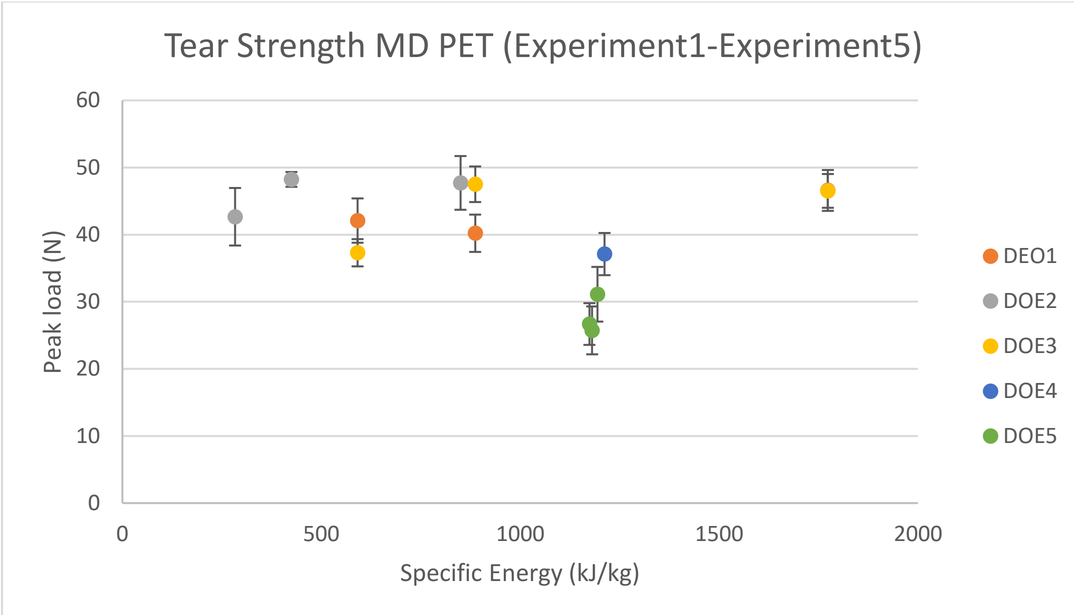

Figure 6.42 Tear strength MD for fabrics made with 100% PET in function of specific energy (kJ/kg)

As mentioned before, the fabrics made of 100%PET were really difficult to break and they needed more time and strength. The values are significantly higher going from 24 to 50N. For Experiment, Experiment2 and Experiment3, the trend is to have higher values when the energy is higher as well. Again Experiment1 and Experiment3 let us see that having double raw jet strip Experiments not significantly improve the mechanical properties of the fabric. Same that happened with the fabrics made with 100%cotton, the lowest values go for Experiment4 and Experiment5. We can conclude that the pressure profile and belt speed used for both Experiment has a negative impact in the tear strength in the MD.

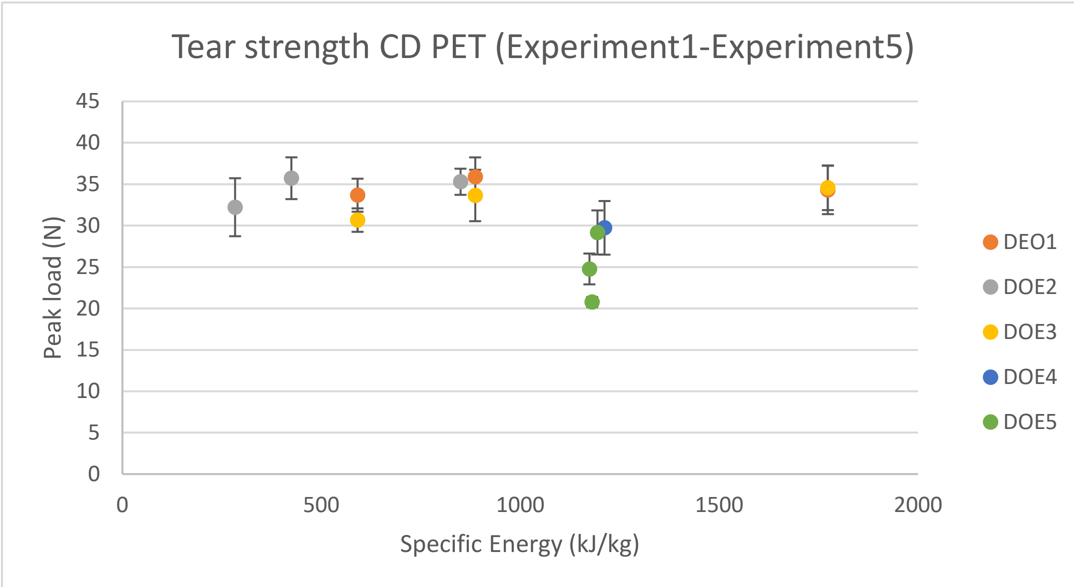

Figure 6.43 Tear strength CD for fabrics made with 100% PET in function of specific energy (kJ/kg)

The previous graph (MD) and this graph let us visualize that the Experiment have a similar impact for CD direction when the fabrics are made 100%PET. The main difference is that the values are lower, they go from 20 to 35, which is surprising, but during the testing the specimens tended to break by not going all the way through the sample but breaking in one side. Experiment1 and Experiment3 again exhibits same behavior with the error bar overlapping. Experiment2 keeps the values very close to each other, but there is an increasing when the energy is higher. Experiment4 and Experiment5 once again prove that their pressure profile and belt speed affect in a negative way the tear strength of a hydroentangled fabric.

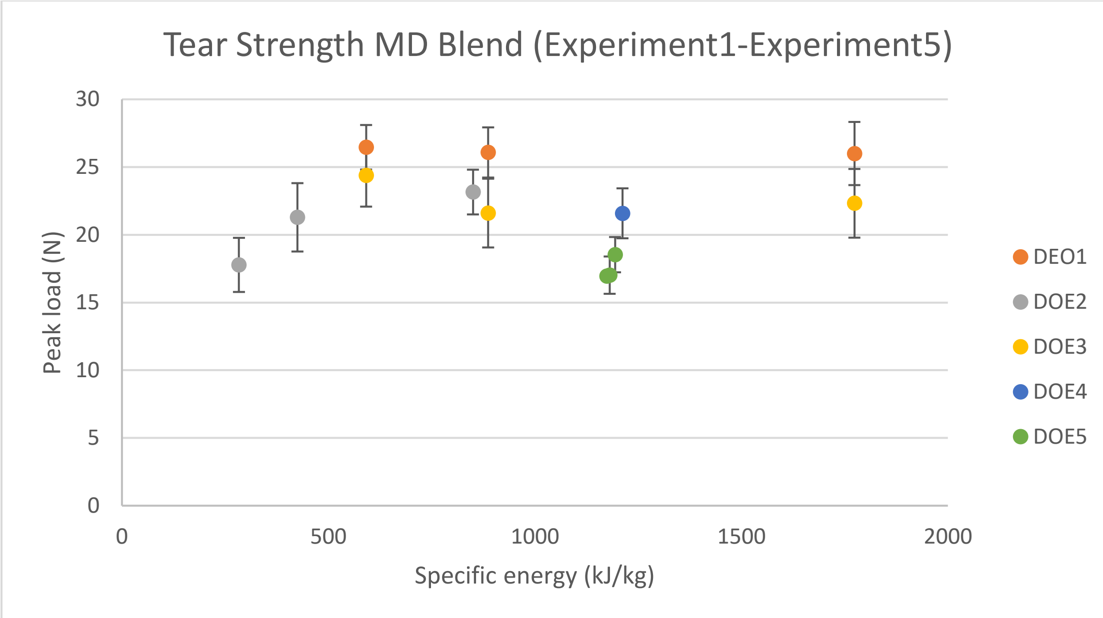

Figure 6.44 Tear strength MD for fabrics made with 50% Cotton/50%PET (Blend) in function of specific energy (kJ/kg)

According to the previous graphs that we analyzed, the five Experiment show a similar behavior. There are some differences in the values found, for instance in this graph we can see that the peak load changes a lot, going from 18 to 27N, this is a huge range. Experiment1 and Experiment3 show a slightly decreasing in the tear strength, but not too significant and the values are very close to each other, the error bars overlap. Experiment2 values increase when the specific energy increases, this behavior has been constant for all the data obtained for tear strength. Experiment4 shows higher value than Experiment5, but lower than Experiment1. Experiment5 has the lowest values, this means that the pressure profile set for this experiment affects the tear strength of the fabrics made with PET and Cotton.

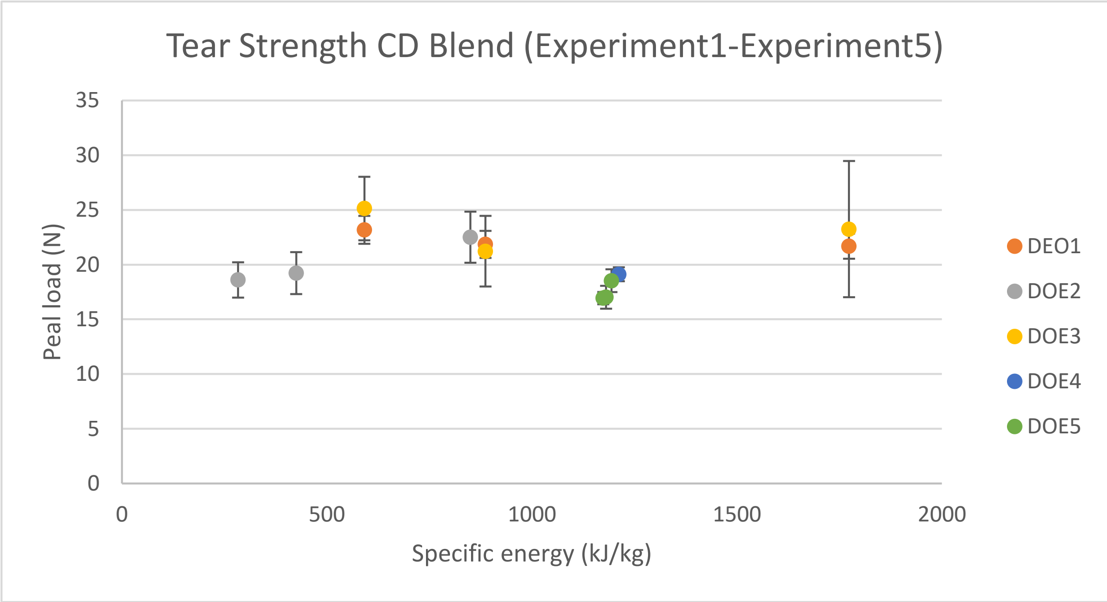

Figure 6.45 Tear strength CD for fabrics made with 50% Cotton/50%PET (Blend) in function of specific energy (kJ/kg)

The last analysis was performed to the fabrics made with blend of PET and Cotton. All the values for the five Experiment remain very close to each other, from 19 to 25N, this means that for the blend in the CD direction we can see that the mechanical properties remain consistent, although for some of them less manifolds were used. Experiment1 and Experiment3 exhibit the same behavior and the points are the same. For Experiment3, the peak load slightly increases with the energy. Experiment4 and Experiment5 have the lowest values.

According to all the graphs for tear strength in the MD and CD direction, the best Experiment, are Experiment1 and Experiment3, Experiment2 has good results and in most cases the peal load tends to increase, while Experiment4 and Experiment5 have the lowest results.

CHAPTER 7: CONCLUSIONS

1. The energy is what controls the properties of the fabrics. As noted, we use many different conditions in Experiment 1 through Experiment 5, and as long as the energy remains constant, the properties are similar.

2. The pressure has an important role in the process in that it allows us to balance the total energy required by adjusting the pressure.

3. Using higher energy, not always lead to better fabric performance; it is clear that strength evolves quickly and then plateaus and that most properties reach a maximum and then remain relatively constant or decrease slightly. Over entangling actually may result in de-entangling and damage to the structure.

4. The air permeability is lower for samples made with 100% cotton, because cotton especially when wet, has a lower bending modulus and can entangle more readily resulting in a denser structure.

PET appears to be better than the blend of PET/cotton and the blend appears to be superior to the 100% cotton in terms of mechanical properties. However, cotton can be entangled more readily and this means that similar structures made of cotton can be produced at lower energies.

5. The burst strength for PET is much higher than the one for just cotton or the 1:1 blend. This is because this type of fiber is longer that cotton, so the interaction and the friction are stronger and the level of entanglement is better, we also need to consider that the basis weight has also influence, because 100gsm is high and the samples have high density. In the case of the fabric made of 100% cotton, the burst strength is lower, this indicates that the small size of the fiber, highly influence in the level of entanglement.

6. As mentioned in the results, the density and the air permeability have an inverse relationship. The more density the fabric has, the lower the air permeability is. This is exactly the case for the fabric made of 100% cotton, and we can see that the air permeability graphics and density fabrics show this behavior.

7. When the belt speed increases, the air permeability increases, this could be an indicator that the more speed and therefore energy is used, the level of entanglement tend to decrease, but the fabric still perform good and can be used for the same purpose.

8. As we would expect from the previous conclusion if the air permeability increases with the belt speed, the density gets lower, generally speaking for the samples measured.

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9. **APPENDICES**

Appendix A (Air Permeability, Density and Burst Strength)

Table 9.1: Sample 1: 100% Cotton, belt speed 15 m/min (Experiment1)

Sample 1	Air Permeability (ft3/min)	Solid volume Fraction	Normalized Burst strength
Sample 1 (100% Cotton, belt speed 15 m/min)	146	11.71780369	168.8437079
	98.6	11.01494051	208.7753012
	122	11.92182394	185.1313043
	144	11.60047949	173.3983333
	137	10.24640758	206.1189157
	104		
	122		
	135		
	109		
	165		
Mean	128.26	11.30029104	188.4535125
Standard Deviation	20.95	0.678754064	18.35266663
Standard Error	6.624971698	0.303548046	8.20756203
Confidence Interval (95%)	12.98494453	0.594954169	16.08682158

Table 9.2: Sample 2: 100% PET, belt speed 15 m/min (Experiment1)

Sample 2	Air Permeability (ft3/min)	Fiber volume Fraction	Normalized Burst strength
Sample 2 (100% PET, belt speed 15 m/min)	182	8.669459339	723.6698936
	167	8.299157589	742.3394382
	160	8.738855504	784.9955056
	163	9.002338585	665.3882022
	181	9.101729329	722.8442857
	166		
	154		
	162		
	150		
	141		
Mean	162.6	8.762308069	727.8474651
Standard Deviation	12.70345535	0.314841514	43.06843172
Standard Error	4.017185305	0.140801406	19.2607882
Confidence Interval (95%)	7.873683199	0.275970755	37.75114488

Table 9.3: Sample 3: 50% Cotton/ 50% PET, belt speed 15 m/min (Experiment1)

Sample 3	Air Permeability (ft3/min)	Fiber volume Fraction	Normalized Burst strength
Sample 3 (50% Cotton/ 50% PET, belt speed 15 m/min)	135	9.281520828	504.5472289
	133	9.849294211	514.8045882
	146	9.452576316	475.9643678
	164	9.168374501	506.2123529
	156	8.785344743	493.4430864
	188		
	172		
	196		
	169		
	145		
Mean	160.4	9.30742212	498.9943249
Standard Deviation	21.37080043	0.389636051	14.95070459
Standard Error	6.758040479	0.174250539	6.686158353
Confidence Interval (95%)	13.24575934	0.341531057	13.10487037

Table 9.4: Sample 4: 100% Cotton, belt speed 30 m/min (Experiment1)

Sample 4	Air Permeability (ft3/min)	Fiber volume Fraction	Normalized Burst strength
Sample 4 (100% Cotton belt speed 30 m/min)	103	10.21068037	143.0495238
	101	11.09701595	125.6881053
	118	11.05859315	146.3157303
	108	10.88094553	174.0107778
	133	11.26727154	165.9402105
	134		
	128		
	138		
	144		
	136		
Mean	124.3	10.90290131	151.0008695
Standard Deviation	15.62796639	0.410590426	19.22596064
Standard Error	4.941996897	0.183621621	8.598110984
Confidence Interval (95%)	9.686313919	0.359898377	16.85229753

Table 9.5: Sample 5: 100% PET, belt speed 30 m/min (Experiment1)

Sample 5	Air Permeability (ft3/min)	Fiber volume Fraction	Normalized Burst strength
Sample 5 (100% PET belt speed 30 m/min)	171	7.555630526	811.8182558
	164	7.753396685	789.6404494
	148	8.406026357	726.895
	161	8.397959006	692.4845977
	173	8.933373957	700.0965263
	162		
	177		
	173		
	166		
	162		
Mean	165.7	8.209277306	744.1869659
Standard Deviation	8.353974437	0.555362086	53.74970783
Standard Error	2.641758673	0.248365475	24.03760009
Confidence Interval (95%)	5.177847	0.486796332	47.11369619

Table 9.6: Sample 6: 50% Cotton/ 50% PET, belt speed 30 m/min (Experiment1)

Sample 6	Air Permeability (ft3/min)	Fiber volume Fraction	Normalized Burst strength
Sample 6 (50% Cotton/ 50% PET belt speed 30 m/min)	151	9.746611312	447.1117857
	142	10.11138611	434.5397727
	152	9.779746146	432.5115476
	165	9.895811244	390.8434524
	150	8.724538704	440.0878481
	149		
	160		
	165		
	181		
	153		
Mean	156.8	9.651618703	429.0188813
Standard Deviation	11.19325194	0.537571769	22.07893538
Standard Error	3.539617054	0.240409404	9.874000075
Confidence Interval (95%)	6.937649426	0.471202431	19.35304015

Table 9.7: Sample 7: 100% Cotton, belt speed 45 m/min (Experiment1)

Sample 7	Air Permeability (ft3/min)	Fiber volume Fraction	Normalized Burst strength
Sample 7 (100% Cotton belt speed 45 m/min)	146	10.41328692	121.8442105
	125	9.863279768	122.3542857
	166	8.336459506	180.6164286
	125	8.855255125	165.8463529
	149	10.50451694	120.3640816
	170		
	130		
	147		
	136		
	120		
Mean	141.4	9.594559651	142.2050719
Standard Deviation	17.28326101	0.96176066	28.80967604
Standard Error	5.465447018	0.430112443	12.88407881
Confidence Interval (95%)	10.71227616	0.843020387	25.25279446

Table 9.8: Sample 8: 100% PET, belt speed 45 m/min (Experiment1)

Sample 8	Air Permeability (ft3/min)	Fiber volume Fraction	Normalized Burst strength
Sample 8 (100% PET belt speed 45 m/min)	194	7.346868461	815.3958621
	178	7.529592153	804.7206818
	177	7.124790709	777.2219565
	176	7.281529021	803.0413793
	180	6.523369973	794.7286905
	169		
	170		
	197		
	195		
	205		
Mean	184.1	7.161230063	799.021714
Standard Deviation	12.54724405	0.384973182	14.23383421
Standard Error	3.967786957	0.172165241	6.365564176
Confidence Interval (95%)	7.776862435	0.337443872	12.47650578

Table 9.9: Sample 9: 50% Cotton/ 50% PET, belt speed 45 m/min (Experiment1)

Sample 9	Air Permeability (ft3/min)	Fiber volume Fraction	Normalized Burst strength
Sample 9 (50%Cotton/ 50% PET belt speed 45 m/min)	169	9.335041139	422.7736047
	152	9.210437918	518.6954118
	148	9.245661527	519.7944186
	141	9.015080943	535.3694048
	159	8.977916414	423.3344186
	156		
	145		
	155		
	143		
	164		
Mean	153.2	9.156827588	483.9934517
Standard Deviation	9.186947262	0.153807449	56.01966571
Standard Error	2.905167809	0.068784782	25.05275612
Confidence Interval (95%)	5.694128906	0.134818174	49.103402

Table 9.10: Sample 10: 100% Cotton, belt speed 15 m/min (Experiment2)

Sample 10	Air Permeability (ft3/min)	Solid volume Fraction	Normalized Burst strength
Sample 10 (100% Cotton, belt speed 15 m/min)	156	8.452964852	134.7285542
	166	9.470354633	125.0917778
	173	9.119258089	125.8173913
	159	9.144383857	122.3723913
	148	8.16026383	128.8509195
	140		
	146		
	182		
	149		
	158		
Mean	157.7	8.869445052	127.3722068
Standard Deviation	12.98760092	0.542098697	4.714827712
Standard Error	4.107040026	0.242433907	2.108535053
Confidence Interval (95%)	8.049798452	0.475170458	4.132728705

Table 9.11: Sample 11: 100% PET, belt speed 15 m/min (Experiment2)

Sample 11	Air Permeability (ft3/min)	Solid volume Fraction	Normalized Burst strength
Sample 11 (100% PET, belt speed 15 m/min)	144	8.906259004	640.2971569
	148	9.138605771	660.9671569
	156	8.18750948	782.7765263
	165	8.341408527	808.0357447
	143	8.486824847	751.9147475
	144		
	133		
	150		
	172		
	155		
Mean	151	8.612121526	728.7982664
Standard Deviation	11.4212278	0.397801047	74.43135767
Standard Error	3.611709352	0.177902037	33.28671508
Confidence Interval (95%)	7.07895033	0.348687992	65.24196156

Table 9.12: Sample 12: 50% Cotton/ 50% PET, belt speed 15 m/min (Experiment2)

Sample 12	Air Permeability (ft3/min)	Solid volume Fraction	Normalized Burst strength
Sample 12 (50% Cotton/ 50% PET belt speed 15 m/min)	160	8.850295722	366.4371264
	219	8.366679544	347.0518519
	186	8.254704659	342.1451899
	177	8.381442815	443.9916
	208	8.183543412	318.5970886
	200		
	202		
	189		
	185		
	171		
Mean	189.7	8.40733323	363.6445714
Standard Deviation	17.88885438	0.260727908	48.0371232
Standard Error	5.656952458	0.116601065	21.48285459
Confidence Interval (95%)	11.08762682	0.228538088	42.10639499

Table 9.13: Sample 13: 100% Cotton, belt speed 30 m/min (Experiment2)

Sample 13	Air Permeability (ft3/min)	Solid volume Fraction	Normalized Burst strength
Sample 13 (100% Cotton, belt speed 30 m/min)	184	7.078553178	72.55253012
	167	7.458983969	80.82202247
	214	7.717835919	81.50556818
	159	7.994146894	68.60043478
	190	7.994244144	69.29147727
	176		
	193		
	158		
	184		
	144		
Mean	176.9	7.648752821	74.55440657
Standard Deviation	20.45835879	0.38877167	6.220075783
Standard Error	6.469501097	0.173863976	2.781702455
Confidence Interval (95%)	12.68022215	0.340773393	5.452136812

Table 9.14: Sample 14: 100% PET, belt speed 30 m/min (Experiment2)

Sample 14	Air Permeability (ft3/min)	Solid volume Fraction	Normalized Burst strength
Sample 14 (100% PET, belt speed 30 m/min)	179	8.596959084	554.7139
	172	8.262191516	554.0285263
	162	7.317052891	595.5935227
	175	7.57867245	564.9042857
	167	7.1864894	727.1410714
	156		
	177		
	175		
	169		
	180		
Mean	171.2	7.788273068	599.2762612
Standard Deviation	7.743097284	0.613737775	73.44652222
Standard Error	2.448582356	0.274471877	32.84628328
Confidence Interval (95%)	4.799221418	0.537964879	64.37871523

Table 9.15: Sample 15: 50% Cotton/ 50% PET, belt speed 30 m/min (Experiment2)

Sample 15	Air Permeability (ft3/min)	Solid volume Fraction	Normalized Burst strength
Sample 15 (50% Cotton/ 50% PET belt speed 30 m/min)	206	8.365722462	354.1618391
	178	7.178634947	336.232
	203	7.462934094	427.6584722
	192	8.008429926	353.9284211
	184	9.110982485	372.8705882
	162		
	182		
	189		
	220		
	184		
Mean	190	8.025340783	368.9702641
Standard Deviation	16.30950643	0.762885251	35.27342743
Standard Error	5.157518783	0.341172656	15.77475631
Confidence Interval (95%)	10.10873682	0.668698406	30.91852236

Table 9.16: Sample 16: 100% Cotton, belt speed 45 m/min (Experiment2)

Sample 16	Air Permeability (ft3/min)	Solid volume Fraction	Normalized Burst strength
Sample 16 (100% Cotton, belt speed 45 m/min)	212	6.414558086	95.32428571
	226	6.307256907	92.56917647
	203	6.431544057	99.82097561
	212	7.303288727	92.37142857
	188	7.369185203	89.42340426
	229		
	212		
	178		
	207		
	220		
Mean	208.7	6.765166596	93.90185412
Standard Deviation	15.90981528	0.524005132	3.912609619
Standard Error	5.031125344	0.234342219	1.749772215
Confidence Interval (95%)	9.861005673	0.45931075	3.429553542

Table 9.17: Sample 17: 100% PET, belt speed 45 m/min (Experiment2)

Sample 17	Air Permeability (ft3/min)	Solid volume Fraction	Normalized Burst strength
Sample 17 (100% PET, belt speed 45 m/min)	190	6.077651428	827.1167816
	164	6.786792901	760.596087
	163	7.072452221	631.6302041
	172	6.939074922	623.2042857
	171	6.710269139	683.5026596
	175		
	179		
	180		
	183		
	202		
Mean	177.9	6.717248122	705.2100036
Standard Deviation	11.85514422	0.383844433	87.3770768
Standard Error	3.748925772	0.171660449	39.07621668
Confidence Interval (95%)	7.347894513	0.33645448	76.58938469

Table 9.18: Sample 18: 50% Cotton/ 50% PET, belt speed 45 m/min (Experiment2)

Sample 18	Air Permeability (ft3/min)	Solid volume Fraction	Normalized Burst strength
Sample 18 (50% Cotton/ 50% PET, belt speed 45 m/min)	204	6.585879874	339.6195833
	194	7.803369941	283.4742857
	167	7.565169204	310.56675
	223	7.302238737	418.894557
	202	7.70873483	370.7564865
	227		
	192		
	165		
	213		
	200		
Mean	198.7	7.393078517	344.6623325
Standard Deviation	20.66693548	0.489237846	52.73339349
Standard Error	6.535458838	0.218793816	23.58309051
Confidence Interval (95%)	12.80949932	0.42883588	46.22285739

Table 9.19: Sample 19: 100% Cotton, belt speed 15 m/min (Experiment3)

Sample 19	Air Permeability (ft3/min)	Solid volume Fraction	Normalized Burst strength
Sample 19 (100% Cotton belt speed 15 m/min)	153	8.680592313	232.4954878
	149	9.279485298	193.7911494
	168	9.266981744	155.2710714
	137	8.893691482	204.374625
	146	8.573990438	222.0572289
	158		
	134		
	148		
	155		
	164		
Mean	151.2	8.938948255	201.5979125
Standard Deviation	10.79917692	0.326175422	29.9502741
Standard Error	3.414999593	0.145870083	13.39416976
Confidence Interval (95%)	6.693399203	0.285905363	26.25257274

Table 9.20: Sample 20: 100% PET, belt speed 15 m/min (Experiment3)

Sample 20	Air Permeability (ft3/min)	Solid volume Fraction	Normalized Burst strength
Sample 20 (100% PET belt speed 15 m/min)	133	9.052313319	708.9121
	143	8.58468384	735.6344211
	134	7.608866638	824.8646067
	139	8.114545978	746.4907527
	139	8.754834858	734.3362
	132		
	136		
	139		
	151		
	149		
Mean	139.5	8.423048926	750.0476161
Standard Deviation	6.467869304	0.567945484	44.03678246
Standard Error	2.045319861	0.253992942	19.69384782
Confidence Interval (95%)	4.008826927	0.497826166	38.59994172

Table 9.21: Sample 21: 50% Cotton/ 50% PET, belt speed 15 m/min (Experiment3)

Sample 21	Air Permeability (ft3/min)	Solid volume Fraction	Normalized Burst strength
Sample 21 (50% Cotton/ 50% PET belt speed 15 m/min)	142	9.946615633	465.4674684
	158	9.618023406	362.414
	169	10.02586419	378.4267089
	127	9.156838327	451.8002667
	172	10.26663929	441.0494805
	158		
	188		
	169		
	167		
	194		
Mean	164.4	9.802796169	419.8315849
Standard Deviation	19.78327015	0.429242451	46.27626925
Standard Error	6.256019324	0.19196306	20.69537676
Confidence Interval (95%)	12.26179787	0.376247598	40.56293844

Table 9.22: Sample 22: 100% Cotton, belt speed 30 m/min (Experiment3)

Sample 22	Air Permeability (ft3/min)	Solid volume Fraction	Normalized Burst strength
Sample 22 (100% Cotton belt speed 30 m/min)	136	11.68911783	197.5925287
	122	11.27973463	166.0404938
	124	10.72797313	188.6434483
	152	11.49293185	200.1231818
	146	9.821253192	221.3748052
	153		
	140		
	120		
	129		
	121		
Mean	134.3	11.00220213	194.7548916
Standard Deviation	12.91897829	0.751587498	20.04592791
Standard Error	4.085339643	0.336120147	8.964811496
Confidence Interval (95%)	8.007265701	0.658795489	17.57103053

Table 9.23: Sample 23: 100% PET, belt speed 30 m/min (Experiment3)

Sample 23	Air Permeability (ft3/min)	Solid volume Fraction	Normalized Burst strength
Sample 23 (100% PET belt speed 30 m/min)	159	8.505137103	783.8644211
	151	8.514261388	741.7983696
	145	8.949596988	745.6271875
	148	8.25904882	848.9576136
	141	8.241568344	719.0789247
	142		
	143		
	139		
	134		
	139		
Mean	144.1	8.493922529	767.8653033
Standard Deviation	7.109461614	0.285931348	50.95602056
Standard Error	2.248209164	0.127872386	22.78822517
Confidence Interval (95%)	4.406489961	0.250629877	44.66492133

Table 9.24: Sample 24: 50% Cotton/ 50% PET, belt speed 30 m/min (Experiment3)

Sample 24	Air Permeability (ft3/min)	Solid volume Fraction	Normalized Burst strength
Sample 24 (50% Cotton/ 50% PET belt speed 30 m/min)	227	8.773772884	440.2347368
	167	9.071940488	383.5713415
	181	9.653475135	386.5871084
	214	8.052361986	513.5620896
	184	7.809696688	397.1991892
	226		
	158		
	161		
	199		
	158		
Mean	187.5	8.672249436	424.2308931
Standard Deviation	27.47625237	0.751851301	54.85697848
Standard Error	8.688753906	0.336238123	24.53278659
Confidence Interval (95%)	17.02995766	0.659026722	48.08426171

Table 9.25: Sample 25: 100% Cotton, belt speed 45 m/min (Experiment3)

Sample 25	Air Permeability (ft3/min)	Solid volume Fraction	Normalized Burst strength
Sample 25 (100% Cotton belt speed 45 m/min)	177	9.66586516	142.5997753
	150	8.163495669	160.9367901
	189	8.75216069	192.05875
	139	8.9369191	180.5785714
	143	7.861388007	188.95825
	161		
	132		
	157		
	159		
	169		
Mean	157.6	8.675965725	173.0264274
Standard Deviation	17.57017675	0.70355626	20.88676401
Standard Error	5.556177743	0.314639925	9.340844831
Confidence Interval (95%)	10.89010838	0.616694253	18.30805587

Table 9.26: Sample 26: 100% PET, belt speed 45 m/min (Experiment3)

Sample 26	Air Permeability (ft3/min)	Solid volume Fraction	Normalized Burst strength
Sample 26 (100% PET belt speed 45 m/min)	239	6.829461981	611.0468605
	180	7.278057769	582.2455294
	210	6.667892117	845.7009459
	200	6.572467471	811.0791549
	201	7.366667972	838.3124051
	183		
	212		
	196		
	200		
	197		
Mean	201.8	6.942909462	737.6769792
Standard Deviation	16.49107503	0.359731776	129.7870066
Standard Error	5.214935815	0.160876941	58.04251385
Confidence Interval (95%)	10.2212742	0.315318804	113.7633272

Table 9.27: Sample 27: 50% Cotton/ 50% PET, belt speed 45 m/min (Experiment3)

Sample 27	Air Permeability (ft3/min)	Solid volume Fraction	Normalized Burst strength
Sample 27 (50% Cotton/ 50% PET belt speed 45 m/min)	185	8.345722526	475.970814
	170	7.28542894	456.6538889
	184	8.68448357	400.1639474
	162	9.156838327	333.906625
	201	8.746223222	364.0962338
	209		
	150		
	192		
	213		
	162		
Mean	182.8	8.443739317	406.1583018
Standard Deviation	21.41027791	0.708740913	60.10209194
Standard Error	6.770524352	0.316958572	26.87847263
Confidence Interval (95%)	13.27022773	0.621238801	52.68180636

Table 9.28: Sample 28: 100% Cotton, belt speed 60 m/min (Experiment4)

Sample 28	Air Permeability (ft3/min)	Solid volume Fraction	Normalized Burst strength
Sample 28 (100% Cotton belt speed 60 m/min)	84.6	14.22909435	174.5466667
	84.3	12.93919423	149.9323913
	81.2	13.34178313	191.7455682
	90.9	13.88266906	194.6239785
	82.2	14.65836932	166.9226804
	98.7		
	86.3		
	91.6		
	108		
	94.8		
Mean	90.26	13.81022202	175.554257
Standard Deviation	8.42643987	0.685233694	18.42425161
Standard Error	2.664674256	0.306445824	8.239575808
Confidence Interval (95%)	5.222761541	0.600633815	16.14956858

Table 9.29: Sample 29: 100% PET, belt speed 60 m/min (Experiment4)

Sample 29	Air Permeability (ft3/min)	Solid volume Fraction	Normalized Burst strength
Sample 29 (100% PET belt speed 60 m/min)	163	9.670154161	755.1588172
	153	9.008068363	823.355
	159	8.871773303	922.0691358
	162	9.197766615	761.345
	174	9.564739154	769.7226136
	169		
	153		
	162		
	152		
	161		
Mean	160.8	9.262500319	806.3301133
Standard Deviation	7.083627445	0.346093789	70.12068007
Standard Error	2.240039682	0.154777848	31.35892145
Confidence Interval (95%)	4.390477777	0.303364581	61.46348604

Table 9.30: Sample 30: 50% Cotton/ 50% PET, belt speed 60 m/min (Experiment4)

Sample 30	Air Permeability (ft3/min)	Solid volume Fraction	Normalized Burst strength
Sample 30 (50% Cotton/ 50% PET belt speed 60 m/min)	130	11.38068628	402.2213265
	134	10.40538076	433.075567
	143	11.15253103	434.1432979
	134	10.42745537	425.3220225
	138	9.010878016	453.7786047
	137		
	159		
	141		
	132		
	138		
Mean	138.6	10.47538629	429.7081637
Standard Deviation	8.194849331	0.926023178	18.60887154
Standard Error	2.591438897	0.414130155	8.32214035
Confidence Interval (95%)	5.079220238	0.811695103	16.31139509

Table 9.31: Sample 31: 100% Cotton, belt speed 30 m/min. Manifolds 1, 2, 5 (Experiment5)

Sample 31	Air Permeability (ft3/min)	Solid volume Fraction	Normalized Burst strength
Sample 31 (100% Cotton belt speed 30 m/min Manifolds 1, 2, 5)	114	12.5607101	201.6194949
	101	11.36363636	182.6553061
	125	11.53286868	186.8538043
	109	12.33432179	151.0776042
	92.3	12.47312043	163.8442
	93.9		
	119		
	86.6		
	124		
	120		
Mean	108.48	12.05293147	177.2100819
Standard Deviation	14.1301726	0.561064047	19.87476092
Standard Error	4.468352916	0.25091547	8.88826329
Confidence Interval (95%)	8.757971714	0.491794321	17.42099605

Table 9.32: Sample 32: 100% PET, belt speed 30 m/min. Manifolds 1, 2, 5 (Experiment5)

Sample 32	Air Permeability (ft3/min)	Solid volume Fraction	Normalized Burst strength
Sample 32 (100% PET belt speed 30 m/min Manifolds 1, 2, 5)	154	8.361960752	606.5631765
	147	8.30416988	789.4791667
	175	9.350163628	755.1760465
	162	9.737452597	672.2671429
	155	9.926543578	754.6748936
	147		
	151		
	161		
	152		
	163		
Mean	156.7	9.136058087	715.6320852
Standard Deviation	8.654478609	0.762175919	74.69605459
Standard Error	2.736786437	0.340855433	33.40509114
Confidence Interval (95%)	5.364101416	0.668076649	65.47397864

Table 9.33: Sample 33: 50% Cotton/50% PET, belt speed 30 m/min. Manifolds 1, 2, 5 (Experiment5)

Sample 33	Air Permeability (ft3/min)	Solid volume Fraction	Normalized Burst strength
Sample 33 (50% Cotton/50% PET belt speed 30 m/min Manifolds 1, 2, 5)	138	8.782438281	505.0602247
	116	9.237040333	449.6280645
	124	9.381284728	421.581875
	117	9.24005867	375.2511579
	128	8.906529842	394.6771739
	137		
	128		
	139		
	172		
	143		
Mean	134.2	9.109470371	429.2396992
Standard Deviation	16.1919047	0.25265851	50.82423277
Standard Error	5.12032985	0.11299232	22.72928788
Confidence Interval (95%)	10.03584651	0.221464948	44.54940424

Table 9.34: Sample 34: 100% Cotton, belt speed 30 m/min. Manifolds 1, 2, 4, 5 (Experiment5)

Sample 34	Air Permeability (ft3/min)	Solid volume Fraction	Normalized Burst strength
Sample 34 (100% Cotton belt speed 30 m/min Manifolds 1, 2, 4, 5)	106	12.51538074	139.3955789
	73.6	13.49336182	164.2945361
	77.5	14.01476222	187.1065625
	76.2	14.10653132	154.3653191
	96.3	12.23219693	190.987439
	80.4		
	120		
	86.4		
	120		
	121		
Mean	95.74	13.27244661	167.2298871
Standard Deviation	19.57317893	0.858894845	21.84242204
Standard Error	6.189582646	0.384109452	9.768228096
Confidence Interval (95%)	12.13158199	0.752854525	19.14572707

Table 9.35: Sample 35: 100% PET, belt speed 30 m/min. Manifolds 1, 2, 4, 5 (Experiment5)

Sample 35	Air Permeability (ft3/min)	Solid volume Fraction	Normalized Burst strength
Sample 35 (100% PET belt speed 30 m/min Manifolds 1, 2, 4, 5)	167	9.467967836	824.4213095
	149	7.957221975	826.8
	152	9.169831916	631.8046988
	141	9.386781229	593.2610465
	148	9.131347917	589.8332143
	148		
	170		
	148		
	138		
	151		
Mean	151.2	9.022630175	693.2240538
Standard Deviation	10.09730437	0.612273255	121.9732133
Standard Error	3.193048004	0.273816924	54.54807925
Confidence Interval (95%)	6.258374088	0.536681171	106.9142353

Table 9.36: Sample 36: 50% Cotton / 50% PET, belt speed 30 m/min. Manifolds 1, 2, 4, 5 (Experiment5)

Sample 36	Air Permeability (ft3/min)	Solid volume Fraction	Normalized Burst strength
Sample 36 (50% Cotton/50% PET belt speed 30 m/min Manifolds 1, 2, 4, 5)	130.62	9.612703134	464.2042857
	121.45	11.01921984	418.2592632
	125.93	10.61737844	445.9121875
	127.69	10.25565893	410.3065306
	126.82	10.21028987	432.7204124
	120.18		
	127.46		
	132.24		
	122.32		
	118.94		
Mean	125.37	10.34305004	434.2805359
Standard Deviation	4.470590938	0.522286018	21.59047369
Standard Error	1.413724985	0.233573408	9.655553369
Confidence Interval (95%)	2.770900971	0.45780388	18.9248846

Table 9.37: Sample 37: 100% Cotton, belt speed 30 m/min. Manifolds 1, 3, 5 (Experiment5)

Sample 37	Air Permeability (ft3/min)	Solid volume Fraction	Normalized Burst strength
Sample 37 (100% Cotton belt speed 30 m/min Manifolds 1, 3, 5)	108	13.21129781	158.3898837
	96.3	14.26036253	185.0556566
	112	11.77767633	119.1898969
	92.5	10.92388781	183.44625
	92.1	10.8994481	149.8777647
	93.2		
	76.4		
	77.9		
	126		
	86		
Mean	96.04	12.21453452	159.1918904
Standard Deviation	15.44576173	1.480288451	27.13283986
Standard Error	4.884378728	0.662005121	12.13417487
Confidence Interval (95%)	9.573382306	1.297530036	23.78298274

Table 9.38: Sample 38: 100% PET, belt speed 30 m/min. Manifolds 1, 3, 5 (Experiment5)

Sample 38	Air Permeability (ft3/min)	Solid volume Fraction	Normalized Burst strength
Sample 38 (100% PET belt speed 30 m/min Manifolds 1, 3, 5)	150	9.496610173	659.1713415
	125	11.77365824	592.6850526
	131	10.41112097	756.3340909
	139	10.78986733	690.7225
	146	10.34852882	658.7160465
	129		
	127		
	119		
	126		
	129		
Mean	132.1	10.56395711	671.5258063
Standard Deviation	9.81438853	0.825137861	59.35811944
Standard Error	3.10358216	0.36901287	26.54575802
Confidence Interval (95%)	6.083021033	0.723265225	52.02968571

Table 9.39: Sample 39: 50% Cotton / 50% PET, belt speed 30 m/min. Manifolds 1, 3, 5 only (Experiment5)

Sample 39	Air Permeability (ft3/min)	Solid volume Fraction	Normalized Burst strength
Sample 39 (50% PET/50% Cotton belt speed 30 m/min Manifolds 1, 3, 5)	92.7	11.10350793	555.3660465
	99.2	11.33662552	503.6514286
	90.7	10.48139387	438.8567368
	109	11.29877115	406.9234
	117	10.02568935	486.434
	93		
	110		
	95.8		
	106		
	108		
Mean	102.14	10.84919757	478.2463224
Standard Deviation	9.013964475	0.573982036	57.65936186
Standard Error	2.850465849	0.25669257	25.78605053
Confidence Interval (95%)	5.586913064	0.503117438	50.54065904

Appendix B (Tear Strength in MD and CD direction)

Table 9.40: Tear strength in MD and CD for Sample 1: 100% Cotton, belt speed 15 m/min (Experiment1)

Sample 1MD	Peak Load (lbf)	Peak Load (N)	Strain to break (%)
Sample 1 (100% Cotton, belt speed 15 m/min)	1.772	7.88224584	374.792
	1.941	8.63399502	379.459
	1.632	7.25949504	384.791
	1.878	8.35375716	390.791
	1.504	6.69012288	374.125
Mean	1.7454	7.763923188	380.7916
Standard Deviation	0.17866393	0.794736468	7.039136652
Standard Error	0.079900939	0.355416953	3.147997611
Confidence Interval (95%)	0.15660584	0.696617229	6.170075318

Sample 1CD	Peak Load (lbf)	Peak Load (N)	Strain to break (%)
Sample 1 (100% Cotton, belt speed 15 m/min)	2.137	9.50584614	324.791
	2.325	10.3421115	554.125
	1.953	8.68737366	344.124
	2.637	11.72995614	381.458
	2.36	10.4977992	273.458
Mean	2.2824	10.15261733	375.5912
Standard Deviation	0.256526412	1.141085916	107.1339963
Standard Error	0.114722099	0.510309135	47.91177967
Confidence Interval (95%)	0.224855314	1.000205905	93.90708815

Table 9.41: Tear strength in MD and CD for Sample 2: 100% PET, belt speed 15 m/min (Experiment1)

Sample 2MD	Peak Load (lbf)	Peak Load (N)	Strain to break (%)
Sample 2 (100% PET, belt speed 15 m/min)	10.725	47.7071595	541.458
	11.597	51.58600734	546.125
	10.018	44.56226796	325.458
	10.503	46.71965466	528.791
	9.52	42.3470544	249.458
Mean	10.4726	46.58442877	438.258
Standard Deviation	0.78150707	3.476315378	140.4021312
Standard Error	0.349500587	1.554655499	62.78974191
Confidence Interval (95%)	0.68502115	3.047124778	123.0678941

Sample 2CD	Peak Load (lbf)	Peak Load (N)	Strain to break (%)
Sample 2 (100% PET, belt speed 15 m/min)	8.406	37.39173732	534.125
	6.458	28.72660476	517.458
	7.886	35.07866292	526.125
	8.111	36.07951242	512.791
	7.702	34.26019044	530.792
Mean	7.7126	34.30734157	524.2582
Standard Deviation	0.748953804	3.331511288	8.961983915
Standard Error	0.334942323	1.489897142	4.00792105
Confidence Interval (95%)	0.656486954	2.920198398	7.855525257

Table 9.42: Tear strength in MD and CD for Sample 3: Blend, belt speed 15 m/min (Experiment1)

Sample 3MD	Peak Load (lbf)	Peak Load (N)	Strain to break (%)
Sample 3 (50% Cotton/50% PET, belt speed 15 m/min)	6.168	27.43662096	443.458
	5.334	23.72680548	438.792
	6.714	29.86534908	448.791
	5.699	25.35040578	450.125
	5.309	23.61559998	445.458
Mean	5.8448	25.99895626	445.3248
Standard Deviation	0.597750533	2.658925877	4.506568062
Standard Error	0.267322165	1.189107802	2.015398506
Confidence Interval (95%)	0.523951444	2.330651291	3.950181073

Sample 3CD	Peak Load (lbf)	Peak Load (N)	Strain to break (%)
Sample 3 (50% Cotton/50% PET, belt speed 15 m/min)	5.233	23.27753526	408.791
	5.008	22.27668576	445.458
	4.599	20.45736378	331.458
	4.995	22.2188589	528.124
	4.543	20.20826346	286.792
Mean	4.8756	21.68774143	400.1246
Standard Deviation	0.294385462	1.309491298	94.96505966
Standard Error	0.131653181	0.585622312	42.46966578
Confidence Interval (95%)	0.258040234	1.147819731	83.24054492

Table 9.43: Tear strength in MD and CD for Sample 4: 100% Cotton, belt speed 30 m/min (Experiment1)

Sample 4MD	Peak Load (lbf)	Peak Load (N)	Strain to break (%)
Sample 4 (100% Cotton belt speed 30 m/min)	1.341	5.96506302	348.125
	1.679	7.46856138	369.458
	1.45	6.449919	369.458
	1.66	7.3840452	368.791
	1.5	6.67233	359.458
Mean	1.526	6.78798372	363.058
Standard Deviation	0.143214874	0.637051265	9.364050646
Standard Error	0.064047639	0.284897987	4.187730758
Confidence Interval (95%)	0.125533371	0.558400054	8.207952285

Sample 4CD	Peak Load (lbf)	Peak Load (N)	Strain to break (%)
Sample 4 (100% Cotton belt speed 30 m/min)	2.278	10.13304516	330.791
	2.17	9.6526374	329.458
	2.102	9.35015844	173.458
	2.061	9.16778142	241.458
	2.115	9.4079853	316.125
Mean	2.1452	9.542321544	278.258
Standard Deviation	0.083843306	0.372953472	69.19600021
Standard Error	0.037495866	0.166789863	30.94539205
Confidence Interval (95%)	0.073491898	0.326908132	60.65296841

Table 9.44: Tear strength in MD and CD for Sample 5: 100% PET, belt speed 30 m/min (Experiment1)

Sample 5MD	Peak Load (lbf)	Peak Load (N)	Strain to break (%)
Sample 5 (100% PET belt speed 30 m/min)	9.217	40.99924374	242.125
	8.056	35.83486032	347.458
	9.221	41.01703662	483.458
	8.712	38.75289264	377.458
	9.985	44.4154767	220.125
Mean	9.0382	40.203902	334.1248
Standard Deviation	0.712905814	3.171161901	107.0232015
Standard Error	0.318821172	1.418186716	47.86223076
Confidence Interval (95%)	0.624889498	2.779645963	93.80997229

Sample 5CD	Peak Load (lbf)	Peak Load (N)	Strain to break (%)
Sample 5 (100% PET belt speed 30 m/min)	8.879	39.49574538	189.458
	8.438	37.53408036	515.458
	8.033	35.73255126	324.791
	7.543	33.55292346	353.458
	7.453	33.15258366	390.791
Mean	8.0692	35.89357682	354.7912
Standard Deviation	0.602015116	2.67789568	117.6293572
Standard Error	0.269229345	1.197591355	52.60544775
Confidence Interval (95%)	0.527689515	2.347279056	103.1066776

Table 9.45: Tear strength in MD and CD for Sample 6: Blend, belt speed 30 m/min (Experiment1)

Sample 6MD	Peak Load (lbf)	Peak Load (N)	Strain to break (%)
Sample 6 (50% Cotton/50% PET belt speed 30 m/min)	5.109	22.72595598	468.125
	5.935	26.4001857	487.458
	6.29	27.9793038	488.125
	6.228	27.70351416	480.125
	5.75	25.577265	464.791
Mean	5.8624	26.07724493	477.7248
Standard Deviation	0.474873983	2.11234395	10.81780529
Standard Error	0.212370101	0.944668933	4.837869597
Confidence Interval (95%)	0.416245399	1.851551108	9.482224411

Sample 6CD	Peak Load (lbf)	Peak Load (N)	Strain to break (%)
Sample 6 (50% Cotton/50% PET belt speed 30 m/min)	5.25	23.353155	484.791
	4.906	21.82296732	487.458
	4.724	21.01339128	483.458
	4.492	19.98140424	490.124
	5.187	23.07291714	530.125
Mean	4.9118	21.848767	495.1912
Standard Deviation	0.316878841	1.409546799	19.69569384
Standard Error	0.141712526	0.630368492	8.808182056
Confidence Interval (95%)	0.277756551	1.235522244	17.26403683

Table 9.46: Tear strength in MD and CD for Sample 7: 100% Cotton, belt speed 45 m/min (Experiment1)

Sample 7MD	Peak Load (lbf)	Peak Load (N)	Strain to break (%)
Sample 7 (100% Cotton belt speed 45 m/min)	1.54	6.8502588	370.125
	1.471	6.54333162	362.791
	1.753	7.79772966	374.791
	1.7	7.561974	363.458
	1.882	8.37155004	371.459
Mean	1.6692	7.424968824	368.5248
Standard Deviation	0.165250416	0.735070206	5.219778654
Standard Error	0.073902233	0.32873339	2.33435598
Confidence Interval (95%)	0.144848376	0.644317444	4.57533772

Sample 7CD	Peak Load (lbf)	Peak Load (N)	Strain to break (%)
Sample 7 (100% Cotton belt speed 45 m/min)	2.387	10.61790114	506.125
	2.731	12.14808882	538.125
	2.254	10.02628788	310.125
	2.383	10.60010826	506.125
	2.38	10.5867636	494.791
Mean	2.427	10.79582994	471.0582
Standard Deviation	0.178948317	0.796001481	91.40576738
Standard Error	0.08002812	0.355982684	40.87790188
Confidence Interval (95%)	0.156855115	0.697726061	80.12068769

Table 9.47: Tear strength in MD and CD for Sample 8: 100% PET, belt speed 45 m/min (Experiment1)

Sample 8MD	Peak Load (lbf)	Peak Load (N)	Strain to break (%)
Sample 8 (100% PET belt speed 45 m/min)	10.51	46.7507922	205.458
	10.102	44.93591844	230.791
	9.379	41.71985538	454.124
	8.463	37.64528586	296.792
	8.863	39.42457386	297.458
Mean	9.4634	42.09528515	296.9246
Standard Deviation	0.847287614	3.768921708	96.76226721
Standard Error	0.37891854	1.685513028	43.27340143
Confidence Interval (95%)	0.742680339	3.303605535	84.8158668

Sample 8CD	Peak Load (lbf)	Peak Load (N)	Strain to break (%)
Sample 8 (100% PET belt speed 45 m/min)	8.099	36.02613378	198.791
	8.097	36.01723734	540.126
	6.957	30.94626654	546.792
	7.429	33.04582638	151.458
	7.266	32.32076652	542.792
Mean	7.5696	33.67124611	395.9918
Standard Deviation	0.511281527	2.274292715	202.3305473
Standard Error	0.22865205	1.017094622	90.48497155
Confidence Interval (95%)	0.448158018	1.993505459	177.3505442

Table 9.48: Tear strength in MD and CD for Sample 9: Blend, belt speed 45 m/min (Experiment1)

Sample 9MD	Peak Load (lbf)	Peak Load (N)	Strain to break (%)
Sample 9 (50%Cotton/50 % PET belt speed 45 m/min)	5.754	25.59505788	475.458
	6.642	29.54507724	496.792
	5.984	26.61814848	477.458
	5.526	24.58086372	483.458
	5.835	25.9553637	470.791
Mean	5.9482	26.4589022	480.7914
Standard Deviation	0.421728823	1.875942584	10.0336268
Standard Error	0.188602863	0.838947028	4.487174318
Confidence Interval (95%)	0.369661612	1.644336175	8.794861663

Sample 9CD	Peak Load (lbf)	Peak Load (N)	Strain to break (%)
Sample 9 (50%Cotton/50 % PET belt speed 45 m/min)	5.056	22.49020032	438.125
	5.619	24.99454818	496.791
	4.765	21.1957683	535.458
	5.208	23.16632976	538.125
	5.406	24.04707732	536.791
Mean	5.2108	23.17878478	509.058
Standard Deviation	0.32689402	1.454096516	43.28088364
Standard Error	0.14619145	0.650291731	19.35579959
Confidence Interval (95%)	0.286535242	1.274571793	37.9373672

Table 9.49: Tear strength in MD and CD for Sample 10: 100% Cotton, belt speed 15 m/min (Experiment2)

Sample 10MD	Peak Load (lbf)	Peak Load (N)	Strain to break (%)
Sample 10 (100% Cotton, belt speed 15 m/min)	1.626	7.23280572	399.459
	1.528	6.79688016	370.791
	1.757	7.81552254	392.125
	1.446	6.43212612	378.792
	1.822	8.10465684	403.458
Mean	1.6358	7.276398276	388.925
Standard Deviation	0.155805006	0.693054945	13.81966796
Standard Error	0.069678117	0.309943594	6.180343397
Confidence Interval (95%)	0.136569109	0.607489444	12.11347306

Sample 10CD	Peak Load (lbf)	Peak Load (N)	Strain to break (%)
Sample 10 (100% Cotton, belt speed 15 m/min)	2.221	9.87949662	285.458
	2.3	10.230906	523.458
	1.7	7.561974	140.792
	2.418	10.75579596	544.125
	2.124	9.44801928	457.458
Mean	2.1526	9.575238372	390.2582
Standard Deviation	0.275003273	1.223275058	172.590164
Standard Error	0.122985202	0.547065237	77.18466779
Confidence Interval (95%)	0.241050997	1.072247864	151.2819489

Table 9.50: Tear strength in MD and CD for Sample 11: 100% PET, belt speed 15 m/min (Experiment2)

Sample 11MD	Peak Load (lbf)	Peak Load (N)	Strain to break (%)
Sample 11 (100% PET, belt speed 15 m/min)	11.117	49.45086174	312.791
	9.44	41.9911968	362.791
	9.981	44.39768382	452.792
	11.036	49.09055592	260.792
	12.05	53.601051	283.458
Mean	10.7248	47.70626986	334.5248
Standard Deviation	1.026008138	4.563909921	76.32629065
Standard Error	0.458844789	2.041042565	34.13415487
Confidence Interval (95%)	0.899335786	4.000443428	66.90294355

Sample 11CD	Peak Load (lbf)	Peak Load (N)	Strain to break (%)
Sample 11 (100% PET, belt speed 15 m/min)	7.457	33.17037654	447.458
	8.211	36.52433442	535.458
	8.407	37.39618554	276.792
	8.012	35.63913864	362.791
	7.587	33.74864514	434.792
Mean	7.9348	35.29573606	411.4582
Standard Deviation	0.404498702	1.799299217	97.10803777
Standard Error	0.180897319	0.804671072	43.42803472
Confidence Interval (95%)	0.354558745	1.577155301	85.11894806

Table 9.51: Tear strength in MD and CD for Sample 12: Blend, belt speed 15 m/min (Experiment2)

Sample 12MD	Peak Load (lbf)	Peak Load (N)	Strain to break (%)
Sample 12 (50% Cotton, 50% PET, belt speed 15 m/min)	5.431	24.15828282	274.792
	4.899	21.79182978	332.125
	4.694	20.87994468	533.465
	5.239	23.30422458	321.458
	5.763	25.63509186	473.458
Mean	5.2052	23.15387474	387.0596
Standard Deviation	0.42377848	1.88505991	110.4814678
Standard Error	0.189519498	0.84302442	49.40881444
Confidence Interval (95%)	0.371458215	1.652327863	96.8412763

Sample 12CD	Peak Load (lbf)	Peak Load (N)	Strain to break (%)
Sample 12 (50% Cotton, 50% PET, belt speed 15 m/min)	4.978	22.14323916	470.792
	4.721	21.00004662	480.125
	6.113	27.19196886	480.791
	4.79	21.3069738	394.792
	4.698	20.89773756	523.458
Mean	5.06	22.5079932	469.9916
Standard Deviation	0.598831779	2.663735498	46.72683716
Standard Error	0.267805713	1.191258729	20.89687685
Confidence Interval (95%)	0.524899198	2.33486711	40.95787863

Table 9.52: Tear strength in MD and CD for Sample 13: 100% Cotton, belt speed 30m/min (Experiment2)

Sample 13MD	Peak Load (lbf)	Peak Load (N)	Strain to break (%)
Sample 13 (100% Cotton, belt speed 30 m/min)	1.844	8.20251768	394.125
	1.532	6.81467304	390.125
	1.913	8.50944486	402.791
	1.633	7.26394326	390.125
	1.691	7.52194002	394.125
Mean	1.7226	7.662503772	394.2582
Standard Deviation	0.155197616	0.690353139	5.172302311
Standard Error	0.069406484	0.30873531	2.313123914
Confidence Interval (95%)	0.136036708	0.605121207	4.533722871

Sample 13CD	Peak Load (lbf)	Peak Load (N)	Strain to break (%)
Sample 13 (100% Cotton, belt speed 30 m/min)	1.849	8.22475878	392.791
	2.199	9.78163578	327.458
	2.498	11.11165356	432.791
	2.014	8.95871508	527.458
	1.906	8.47830732	234.126
Mean	2.0932	9.311014104	382.9248
Standard Deviation	0.262681747	1.168466199	110.3307238
Standard Error	0.117474848	0.52255397	49.3413997
Confidence Interval (95%)	0.230250703	1.024205781	96.70914342

Table 9.53: Tear strength in MD and CD for Sample 14: 100% PET, belt speed 30m/min (Experiment2)

Sample 14MD	Peak Load (lbf)	Peak Load (N)	Strain to break (%)
Sample 14 (100% PET, belt speed 30 m/min)	10.741	47.77833102	197.459
	10.541	46.88868702	486.792
	10.831	48.17867082	549.458
	11.309	50.30491998	371.458
	10.787	47.98294914	495.458
Mean	10.8418	48.2267116	420.125
Standard Deviation	0.283741432	1.262144311	140.3524128
Standard Error	0.126893026	0.564448095	62.76750716
Confidence Interval (95%)	0.248710331	1.106318267	123.024314

Sample 14CD	Peak Load (lbf)	Peak Load (N)	Strain to break (%)
Sample 14 (100% PET, belt speed 30 m/min)	8.953	39.82491366	546.792
	7.445	33.1169979	555.458
	8.155	36.2752341	141.458
	7.552	33.59295744	538.791
	8.051	35.81261922	534.792
Mean	8.0312	35.72454446	463.4582
Standard Deviation	0.599728439	2.667724035	180.1777983
Standard Error	0.268206711	1.193042457	80.57796101
Confidence Interval (95%)	0.525685154	2.338363217	157.9328036

Table 9.54: Tear strength in MD and CD for Sample 15: Blend, belt speed 30m/min (Experiment2)

Sample 15MD	Peak Load (lbf)	Peak Load (N)	Strain to break (%)
Sample 15 (50% Cotton/50% PET, belt speed 30 m/min)	4.162	18.51349164	260.125
	4.154	18.47790588	482.125
	5.437	24.18497214	292.125
	4.712	20.96001264	535.458
	5.463	24.30062586	408.125
Mean	4.7856	21.28740163	395.5916
Standard Deviation	0.647380336	2.87969016	118.6004451
Standard Error	0.289517288	1.28783659	53.03973148
Confidence Interval (95%)	0.567453884	2.524159717	103.9578737

Sample 15CD	Peak Load (lbf)	Peak Load (N)	Strain to break (%)
Sample 15 (50% Cotton/50% PET, belt speed 30 m/min)	4.869	21.65838318	364.125
	4.271	18.99834762	454.125
	4.188	18.62914536	551.459
	3.602	16.02248844	392.792
	4.68	20.8176696	421.458
Mean	4.322	19.22520684	436.7918
Standard Deviation	0.491510427	2.186346512	72.28516138
Standard Error	0.219810145	0.977763885	32.32690692
Confidence Interval (95%)	0.430827885	1.916417214	63.36073757

Table 9.55: Tear strength in MD and CD for Sample 16: 100% Cotton, belt speed 45m/min (Experiment2)

Sample 16MD	Peak Load (lbf)	Peak Load (N)	Strain to break (%)
Sample 16 (100% Cotton, belt speed 45 m/min)	1.021	4.54163262	407.459
	1.227	5.45796594	413.458
	1.391	6.18747402	396.792
	0.882	3.92333004	373.458
	1.292	5.74710024	399.459
Mean	1.1626	5.171500572	398.1252
Standard Deviation	0.207271079	0.921987357	15.28268447
Standard Error	0.092694444	0.412325281	6.834624272
Confidence Interval (95%)	0.181681111	0.808157551	13.39586357

Sample 16CD	Peak Load (lbf)	Peak Load (N)	Strain to break (%)
Sample 16 (100% Cotton, belt speed 45 m/min)	1.344	5.97840768	184.792
	1.62	7.2061164	334.125
	2.193	9.75494646	273.458
	1.508	6.70791576	530.125
	1.749	7.77993678	492.125
Mean	1.6828	7.485464616	362.925
Standard Deviation	0.321702813	1.431004888	145.9568684
Standard Error	0.143869872	0.639964841	65.27389592
Confidence Interval (95%)	0.281984949	1.254331088	127.936836

Table 9.56: Tear strength in MD and CD for Sample 17: 100% PET, belt speed 45m/min (Experiment2)

Sample 17MD	Peak Load (lbf)	Peak Load (N)	Strain to break (%)
Sample 17 (100% PET, belt speed 45 m/min)	8.871	39.46015962	442.792
	10.021	44.57561262	493.458
	9.638	42.87194436	428.125
	8.271	36.79122762	346.125
	11.133	49.52203326	394.459
Mean	9.5868	42.6441955	420.9918
Standard Deviation	1.098360688	4.885749978	54.96932923
Standard Error	0.491201832	2.184973814	24.58303137
Confidence Interval (95%)	0.962755591	4.282548676	48.18274148

Sample 17CD	Peak Load (lbf)	Peak Load (N)	Strain to break (%)
Sample 17 (100% PET, belt speed 45 m/min)	7.114	31.64463708	276.792
	8.145	36.2307519	398.126
	5.832	25.94201904	417.458
	7.878	35.04307716	550.125
	7.25	32.249595	374.125
Mean	7.2438	32.22201604	403.3252
Standard Deviation	0.897835842	3.993771351	98.28561871
Standard Error	0.401524395	1.786068846	43.95466493
Confidence Interval (95%)	0.786987815	3.500694937	86.15114326

Table 9.57: Tear strength in MD and CD for Sample 18: Blend, belt speed 45m/min (Experiment2)

Sample 18MD	Peak Load (lbf)	Peak Load (N)	Strain to break (%)
Sample 18 (50% Cotton, 50% PET, belt speed 45 m/min)	4.108	18.27328776	490.792
	3.189	14.18537358	503.459
	3.846	17.10785412	488.125
	4.478	19.91912916	344.125
	4.359	19.38979098	537.459
Mean	3.996	17.77508712	472.792
Standard Deviation	0.512441704	2.279453437	74.55968005
Standard Error	0.229170897	1.019402567	33.34410259
Confidence Interval (95%)	0.449174958	1.998029032	65.35444108

Sample 18CD	Peak Load (lbf)	Peak Load (N)	Strain to break (%)
Sample 18 (50% Cotton/50% PET, belt speed 45 m/min)	3.708	16.49399976	313.459
	3.897	17.33471334	474.125
	4.391	19.53213402	500.792
	4.151	18.46456122	529.459
	4.76	21.1735272	526.792
Mean	4.1814	18.59978711	468.9254
Standard Deviation	0.413710406	1.840274902	89.75686281
Standard Error	0.185016918	0.822995956	40.14048934
Confidence Interval (95%)	0.36263316	1.613072073	78.67535911

Table 9.58: Tear strength in MD and CD for Sample 19: 100% Cotton, belt speed 15m/min (Experiment3)

Sample 19MD	Peak Load (lbf)	Peak Load (N)	Strain to break (%)
Sample 19 (100% Cotton belt speed 15 m/min)	1.396	6.20971512	355.459
	1.571	6.98815362	340.125
	1.455	6.4721601	344.125
	1.422	6.32536884	352.125
	1.356	6.03178632	344.126
Mean	1.44	6.4054368	347.192
Standard Deviation	0.081703733	0.36343618	6.352698482
Standard Error	0.03653902	0.162533601	2.841013129
Confidence Interval (95%)	0.07161648	0.318565857	5.568385733

Sample 19CD	Peak Load (lbf)	Peak Load (N)	Strain to break (%)
Sample 19 (100% Cotton belt speed 15 m/min)	2.102	9.35015844	335.459
	2.434	10.82696748	465.458
	2.432	10.81807104	522.792
	1.679	7.46856138	184.125
	1.904	8.46941088	205.458
Mean	2.1102	9.386633844	342.6584
Standard Deviation	0.330499924	1.470136374	151.2749778
Standard Error	0.147804059	0.657464973	67.65222674
Confidence Interval (95%)	0.289695957	1.288631348	132.5983644

Table 9.59: Tear strength in MD and CD for Sample 20: 100% PET, belt speed 15m/min (Experiment3)

Sample 20MD	Peak Load (lbf)	Peak Load (N)	Strain to break (%)
Sample 20 (100% PET belt speed 15 m/min)	9.455	42.0579201	272.792
	10.853	48.27653166	438.125
	11.162	49.65103164	523.458
	10.368	46.11914496	512.125
	10.447	46.47055434	228.792
Mean	10.457	46.51503654	395.0584
Standard Deviation	0.645342157	2.870623891	136.6010308
Standard Error	0.288605786	1.283782032	61.08983814
Confidence Interval (95%)	0.565667342	2.516212782	119.7360828

Sample 20CD	Peak Load (lbf)	Peak Load (N)	Strain to break (%)
Sample 20 (100% PET belt speed 15 m/min)	6.993	31.10640246	489.458
	7.351	32.69886522	473.458
	7.559	33.62409498	502.791
	8.686	38.63723892	498.125
	8.271	36.79122762	485.459
Mean	7.772	34.57156584	489.8582
Standard Deviation	0.691709477	3.076875928	11.44636382
Standard Error	0.309341882	1.376020747	5.118969519
Confidence Interval (95%)	0.606310089	2.697000663	10.03318026

Table 9.60: Tear strength in MD and CD for Sample 21: Blend, belt speed 15m/min (Experiment3)

Sample 21MD	Peak Load (lbf)	Peak Load (N)	Strain to break (%)
Sample 21 (50% Cotton/50% PET belt speed 15 m/min)	3.921	17.44147062	202.125
	5.2	23.130744	438.792
	5.011	22.29003042	225.459
	5.36	23.8424592	214.126
	5.599	24.90558378	457.459
Mean	5.0182	22.3220576	307.5922
Standard Deviation	0.650212811	2.892289632	128.7231221
Standard Error	0.290784009	1.293471245	57.56673025
Confidence Interval (95%)	0.569936658	2.535203641	112.8307913

Sample 21CD	Peak Load (lbf)	Peak Load (N)	Strain to break (%)
Sample 21 (50% Cotton/50% PET belt speed 15 m/min)	8.04	35.7636888	433.459
	4.89	21.7517958	522.792
	4.302	19.13624244	152.126
	4.672	20.78208384	556.925
	4.226	18.79817772	394.126
Mean	5.226	23.24639772	411.8856
Standard Deviation	1.596260004	7.100515674	159.3679092
Standard Error	0.713869176	3.175447145	71.27149566
Confidence Interval (95%)	1.399183584	6.223876404	139.6921315

Table 9.61: Tear strength in MD and CD for Sample 22: 100% Cotton, belt speed 30m/min (Experiment3)

Sample 22MD	Peak Load (lbf)	Peak Load (N)	Strain to break (%)
Sample 22 (100% Cotton belt speed 30 m/min)	1.383	6.15188826	356.125
	1.373	6.10740606	354.126
	1.318	5.86275396	354.792
	1.168	5.19552096	350.126
	1.456	6.47660832	354.126
Mean	1.3396	5.958835512	353.859
Standard Deviation	0.107774301	0.479403802	2.240709263
Standard Error	0.048198133	0.214395898	1.002075646
Confidence Interval (95%)	0.09446834	0.42021596	1.964068266

Sample 22CD	Peak Load (lbf)	Peak Load (N)	Strain to break (%)
Sample 22 (100% Cotton belt speed 30 m/min)	2.231	9.92397882	169.459
	2.469	10.98265518	238.792
	1.804	8.02458888	232.792
	2.243	9.97735746	384.125
	1.686	7.49969892	148.792
Mean	2.0866	9.281655852	234.792
Standard Deviation	0.328589866	1.461640013	92.17476034
Standard Error	0.146949855	0.653665286	41.22180599
Confidence Interval (95%)	0.288021717	1.28118396	80.79473974

Table 9.62: Tear strength in MD and CD for Sample 23: 100% PET, belt speed 30m/min (Experiment3)

Sample 23MD	Peak Load (lbf)	Peak Load (N)	Strain to break (%)
Sample 23 (100% PET belt speed 30 m/min)	10.612	47.20451064	545.458
	9.728	43.27228416	397.458
	11.024	49.03717728	552.792
	10.472	46.58175984	542.125
	11.562	51.43031964	142.792
Mean	10.6796	47.50521031	436.125
Standard Deviation	0.680156453	3.025485536	176.3095854
Standard Error	0.304175213	1.353038264	78.84804359
Confidence Interval (95%)	0.596183417	2.651954998	154.5421654

Sample 23CD	Peak Load (lbf)	Peak Load (N)	Strain to break (%)
Sample 23 (100% PET belt speed 30 m/min)	6.79	30.2034138	470.792
	8.723	38.80182306	474.792
	6.856	30.49699632	462.125
	7.864	34.98080208	538.126
	7.58	33.7175076	469.458
Mean	7.5626	33.64010857	483.0586
Standard Deviation	0.795906276	3.540366215	31.12240601
Standard Error	0.355940107	1.583299904	13.91836309
Confidence Interval (95%)	0.69764261	3.103267812	27.27999166

Table 9.63: Tear strength in MD and CD for Sample 24: Blend, belt speed 30m/min (Experiment3)

Sample 24MD	Peak Load (lbf)	Peak Load (N)	Strain to break (%)
Sample 24 (50% Cotton/50% PET belt speed 30 m/min)	5.622	25.00789284	236.792
	4.161	18.50904342	234.792
	4.314	19.18962108	310.125
	4.759	21.16907898	441.459
	5.424	24.12714528	244.792
Mean	4.856	21.60055632	293.592
Standard Deviation	0.651071809	2.896110641	88.32200997
Standard Error	0.291168164	1.295180053	39.49880364
Confidence Interval (95%)	0.570689602	2.538552903	77.41765513

Sample 24CD	Peak Load (lbf)	Peak Load (N)	Strain to break (%)
Sample 24 (50% Cotton/50% PET belt speed 30 m/min)	3.91	17.3925402	294.792
	6.056	26.93842032	540.125
	4.777	21.24914694	470.792
	4.199	18.67807578	320.126
	4.919	21.88079418	497.459
Mean	4.7722	21.22779548	424.6588
Standard Deviation	0.827898363	3.682674058	110.1738134
Standard Error	0.370247404	1.646941906	49.27122721
Confidence Interval (95%)	0.725684911	3.228006137	96.57160534

Table 9.64: Tear strength in MD and CD for Sample 25: 100% Cotton, belt speed 45m/min (Experiment3)

Sample 25MD	Peak Load (lbf)	Peak Load (N)	Strain to break (%)
Sample 25 (100% Cotton belt speed 45 m/min)	1.53	6.8057766	367.459
	1.604	7.13494488	364.792
	1.661	7.38849342	371.459
	1.431	6.36540282	370.792
	1.683	7.48635426	363.459
Mean	1.5818	7.036194396	367.5922
Standard Deviation	0.102993689	0.458138588	3.540235402
Standard Error	0.046060178	0.204885805	1.583241403
Confidence Interval (95%)	0.090277949	0.401576178	3.10315315

Sample 25CD	Peak Load (lbf)	Peak Load (N)	Strain to break (%)
Sample 25 (100% Cotton belt speed 45 m/min)	1.83	8.1402426	279.458
	2.277	10.12859694	464.792
	2.465	10.9648623	517.459
	2.21	9.8305662	318.125
	2.321	10.32431862	433.459
Mean	2.2206	9.877717332	402.6586
Standard Deviation	0.237525367	1.056565088	100.3900807
Standard Error	0.106224573	0.472510272	44.89580896
Confidence Interval (95%)	0.208200164	0.926120133	87.99578556

Table 9.65: Tear strength in MD and CD for Sample 26: 100% PET, belt speed 45m/min (Experiment3)

Sample 26MD	Peak Load (lbf)	Peak Load (N)	Strain to break (%)
Sample 26 (100% PET belt speed 45 m/min)	8.171	36.34640562	485.458
	9.309	41.40847998	224.792
	8.088	35.97720336	296.792
	8.099	36.02613378	523.458
	8.26	36.7422972	289.458
Mean	8.3854	37.30010399	363.9916
Standard Deviation	0.520864954	2.316921904	131.938614
Standard Error	0.232937889	1.036158975	59.00474196
Confidence Interval (95%)	0.456558262	2.030871592	115.6492942

Sample 26CD	Peak Load (lbf)	Peak Load (N)	Strain to break (%)
Sample 26 (100% PET belt speed 45 m/min)	6.572	29.23370184	236.125
	7.213	32.08501086	538.125
	6.757	30.05662254	550.791
	7.348	32.68552056	533.458
	6.582	29.27818404	548.792
Mean	6.8944	30.66780797	481.4582
Standard Deviation	0.363205589	1.615618366	137.3356857
Standard Error	0.162430477	0.722526498	61.41838577
Confidence Interval (95%)	0.318363736	1.416151937	120.3800361

Table 9.66: Tear strength in MD and CD for Sample 27: Blend, belt speed 45m/min (Experiment3)

Sample 27MD	Peak Load (lbf)	Peak Load (N)	Strain to break (%)
Sample 27 (50% Cotton/50% PET belt speed 45 m/min)	5.749	25.57281678	204.125
	4.822	21.44931684	490.125
	5.09	22.6414398	165.459
	5.411	24.06931842	488.125
	6.339	28.19726658	486.125
Mean	5.4822	24.38603168	366.7918
Standard Deviation	0.591617021	2.631642667	166.7097931
Standard Error	0.264579175	1.176906379	74.55488597
Confidence Interval (95%)	0.518575184	2.306736503	146.1275765

Sample 27CD	Peak Load (lbf)	Peak Load (N)	Strain to break (%)
Sample 27 (50% Cotton/50% PET belt speed 45 m/min)	5.844	25.99539768	549.458
	5.625	25.0212375	560.059
	6.537	29.07801414	535.459
	5.761	25.62619542	495.459
	4.475	19.9057845	274.125
Mean	5.6484	25.12532585	482.912
Standard Deviation	0.74464139	3.312328725	119.2588105
Standard Error	0.333013753	1.481318438	53.33416143
Confidence Interval (95%)	0.652706957	2.903384139	104.5349564

Table 9.67: Tear strength in MD and CD for Sample 28: 100% Cotton, belt speed 60m/min (Experiment4)

Sample 28MD	Peak Load (lbf)	Peak Load (N)	Strain to break (%)
Sample 28 (100% Cotton belt speed 60 m/min)	1.081	4.80852582	324.792
	0.825	3.6697815	44.792
	0.977	4.34591094	325.459
	0.986	4.38594492	335.458
	0.898	3.99450156	333.458
Mean	0.9534	4.240932948	272.7918
Standard Deviation	0.096769313	0.430451195	127.5433299
Standard Error	0.043276553	0.192503627	57.03911114
Confidence Interval (95%)	0.084822043	0.377307108	111.7966578

Sample 28CD	Peak Load (lbf)	Peak Load (N)	Strain to break (%)
Sample 28 (100% Cotton belt speed 60 m/min)	1.654	7.35735588	310.125
	1.757	7.81552254	425.459
	1.693	7.53083646	414.792
	1.529	6.80132838	407.458
	1.822	8.10465684	297.459
Mean	1.691	7.52194002	371.0586
Standard Deviation	0.110830952	0.493000459	61.9005954
Standard Error	0.049565109	0.220476508	27.68278783
Confidence Interval (95%)	0.097147613	0.432133955	54.25826415

Table 9.68: Tear strength in MD and CD for Sample 29: 100% PET, belt speed 60m/min (Experiment4)

Sample 29MD	Peak Load (lbf)	Peak Load (N)	Strain to break (%)
Sample 29 (100% PET belt speed 60 m/min)	8.988	39.98060136	232.125
	7.391	32.87679402	302.792
	8.482	37.72980204	463.458
	9.211	40.97255442	462.791
	7.633	33.95326326	462.792
Mean	8.341	37.10260302	384.7916
Standard Deviation	0.806094597	3.58568611	109.9856768
Standard Error	0.360496463	1.603567578	49.18709
Confidence Interval (95%)	0.706573068	3.142992452	96.40669639

Sample 29CD	Peak Load (lbf)	Peak Load (N)	Strain to break (%)
Sample 29 (100% PET belt speed 60 m/min)	7.35	32.694417	492.792
	5.498	24.45631356	491.458
	6.183	27.50334426	484.792
	7.458	33.17482476	500.125
	6.932	30.83506104	498.792
Mean	6.6842	29.73279212	493.5918
Standard Deviation	0.830923101	3.696128757	6.171589034
Standard Error	0.371600108	1.652959031	2.760018522
Confidence Interval (95%)	0.728336211	3.2397997	5.409636302

Table 9.69: Tear strength in MD and CD for Sample 30: Blend, belt speed 60m/min (Experiment4)

Sample 30MD	Peak Load (lbf)	Peak Load (N)	Strain to break (%)
Sample 30 (50% Cotton/50% PET belt speed 60 m/min)	4.727	21.02673594	395.458
	4.809	21.39148998	384.792
	4.181	18.59800782	375.458
	5.465	24.3095223	392.792
	5.078	22.58806116	415.458
Mean	4.852	21.58276344	392.7916
Standard Deviation	0.47290591	2.103589528	14.87718612
Standard Error	0.211489952	0.940753836	6.653279895
Confidence Interval (95%)	0.414520307	1.843877519	13.04042859

Sample 30CD	Peak Load (lbf)	Peak Load (N)	Strain to break (%)
Sample 30 (50% Cotton/50% PET belt speed 60 m/min)	4.137	18.40228614	478.792
	4.432	19.71451104	315.458
	4.22	18.7714884	484.792
	4.511	20.06592042	460.125
	4.191	18.64249002	471.458
Mean	4.2982	19.1193392	442.125
Standard Deviation	0.163385128	0.726772993	71.40359857
Standard Error	0.07306805	0.325022763	31.93266005
Confidence Interval (95%)	0.143213379	0.637044616	62.5880137

Table 9.70: Tear strength in MD and CD for Sample 31: 100%Cotton, belt speed 30m/min, Manifolds 1,2,5 (Experiment5)

Sample 31MD	Peak Load (lbf)	Peak Load (N)	Strain to break (%)
Sample 31 (100% Cotton belt speed 30 m/min Manifolds 1, 2, 5)	1.102	4.90193844	336.792
	0.932	4.14574104	321.459
	1.083	4.81742226	341.458
	1.194	5.31117468	336.125
	1.296	5.76489312	342.791
Mean	1.1214	4.988233908	335.725
Standard Deviation	0.135535235	0.602890544	8.479576788
Standard Error	0.0606132	0.269620848	3.792182024
Confidence Interval (95%)	0.118801872	0.528456862	7.432676766

Sample 31CD	Peak Load (lbf)	Peak Load (N)	Strain to break (%)
Sample 31 (100% Cotton belt speed 30 m/min Manifolds 1, 2, 5)	2.205	9.8083251	437.458
	1.981	8.81192382	289.458
	2.26	10.0529772	433.458
	1.991	8.85640602	434.792
	2.131	9.47915682	438.126
Mean	2.1136	9.401757792	406.6584
Standard Deviation	0.125203035	0.556930645	65.54478808
Standard Error	0.055992499	0.249066956	29.31252034
Confidence Interval (95%)	0.109745299	0.488171234	57.45253988

Table 9.71: Tear strength in MD and CD for Sample 32: 100%PET, belt speed 30m/min, Manifolds 1,2,5 (Experiment5)

Sample 32MD	Peak Load (lbf)	Peak Load (N)	Strain to break (%)
Sample 32 (100% PET belt speed 30 m/min Manifolds 1, 2, 5)	8.134	36.18182148	440.792
	8.064	35.87044608	458.792
	6.486	28.85115492	350.792
	6.48	28.8244656	432.792
	5.811	25.84860642	419.458
Mean	6.995	31.1152989	420.5252
Standard Deviation	1.044777967	4.647402248	41.50127602
Standard Error	0.467238911	2.078381469	18.55993487
Confidence Interval (95%)	0.915788266	4.073627679	36.37747234

Sample 32CD	Peak Load (lbf)	Peak Load (N)	Strain to break (%)
Sample 32 (100% PET belt speed 30 m/min Manifolds 1, 2, 5)	7.316	32.54317752	496.792
	6.957	30.94626654	494.126
	5.683	25.27923426	482.125
	6.016	26.76049152	475.458
	6.825	30.3591015	482.125
Mean	6.5594	29.17765427	486.1252
Standard Deviation	0.682721246	3.036894302	8.994245088
Standard Error	0.305322223	1.35814042	4.022348685
Confidence Interval (95%)	0.598431558	2.661955223	7.883803422

Table 9.72: Tear strength in MD and CD for Sample 33: Blend, belt speed 30m/min, Manifolds 1,2,5 (Experiment5)

Sample 33MD	Peak Load (lbf)	Peak Load (N)	Strain to break (%)
Sample 33 (50% Cotton/50% PET belt speed 30 m/min Manifolds 1, 2, 5)	4.096	18.21990912	381.459
	4.881	21.71176182	392.792
	4.42	19.6611324	401.459
	4.618	20.54187996	384.125
	4.887	21.73845114	392.792
Mean	4.5804	20.37462689	390.5254
Standard Deviation	0.333972005	1.485580951	7.952724206
Standard Error	0.149356821	0.664371999	3.556566386
Confidence Interval (95%)	0.292739369	1.302169117	6.970870117

Sample 33CD	Peak Load (lbf)	Peak Load (N)	Strain to break (%)
Sample 33 (50% Cotton/50% PET belt speed 30 m/min Manifolds 1, 2, 5)	4.177	18.58021494	451.459
	4.286	19.06507092	444.126
	4.463	19.85240586	436.792
	3.739	16.63189458	457.459
	4.166	18.53128452	447.459
Mean	4.1662	18.53217416	447.459
Standard Deviation	0.266954491	1.187472304	7.760376569
Standard Error	0.119385678	0.531053759	3.470545908
Confidence Interval (95%)	0.233995928	1.040865367	6.80226998

Table 9.73: Tear strength in MD and CD for Sample 34: 100% Cotton, belt speed 30m/min, Manifolds 1,2,4,5 (EXPERIMENT5)

Sample 34MD	Peak Load (lbf)	Peak Load (N)	Strain to break (%)
Sample 34 (100% Cotton belt speed 30 m/min Manifolds 1, 2, 4, 5)	0.936	4.16353392	164.126
	0.809	3.59860998	35.459
	0.696	3.09596112	317.459
	0.78	3.4696116	338.125
	0.91	4.0478802	348.125
Mean	0.8262	3.675119364	240.6588
Standard Deviation	0.098057126	0.43617967	136.8494998
Standard Error	0.04385248	0.195065478	61.20095686
Confidence Interval (95%)	0.085950861	0.382328338	119.9538754

Sample 34CD	Peak Load (lbf)	Peak Load (N)	Strain to break (%)
Sample 34 (100% Cotton belt speed 30 m/min Manifolds 1, 2, 4, 5)	1.899	8.44716978	428.792
	1.51	6.7168122	317.459
	1.426	6.34316172	416.792
	1.44	6.4054368	145.459
	1.704	7.57976688	401.459
Mean	1.5958	7.098469476	341.9922
Standard Deviation	0.202549253	0.900983639	118.2081768
Standard Error	0.09058278	0.402932133	52.86430377
Confidence Interval (95%)	0.177542248	0.78974698	103.6140354

Table 9.74: Tear strength in MD and CD for Sample 35: 100% PET, belt speed 30m/min, Manifolds 1,2,4,5 (Experiment5)

Sample 35MD	Peak Load (lbf)	Peak Load (N)	Strain to break (%)
Sample 35 (100% PET belt speed 30 m/min Manifolds 1, 2, 4, 5)	6.071	27.00514362	450.792
	5.103	22.69926666	429.459
	6.956	30.94181832	458.792
	6.566	29.20701252	442.792
	5.295	23.5533249	408.792
Mean	5.9982	26.6813132	438.1254
Standard Deviation	0.797018005	3.545311429	19.65250055
Standard Error	0.356437288	1.585511472	8.788865431
Confidence Interval (95%)	0.698617084	3.107602484	17.22617624

Sample 35CD	Peak Load (lbf)	Peak Load (N)	Strain to break (%)
Sample 35 (100% PET belt speed 30 m/min Manifolds 1, 2, 4, 5)	5.752	25.58616144	452.125
	6.323	28.12609506	460.126
	5.316	23.64673752	457.465
	5.292	23.53998024	449.459
	5.159	22.94836698	457.458
Mean	5.5684	24.76946825	455.3266
Standard Deviation	0.477190004	2.12264612	4.382602914
Standard Error	0.213405857	0.949276203	1.959959607
Confidence Interval (95%)	0.418275481	1.860581358	3.841520829

Table 9.75: Tear strength in MD and CD for Sample 36: Blend, belt speed 30m/min, Manifolds 1,2,4,5 (Experiment5)

Sample 36MD	Peak Load (lbf)	Peak Load (N)	Strain to break (%)
Sample 36 (50% Cotton/50% PET belt speed 30 m/min Manifolds 1, 2, 4, 5)	3.928	17.47260816	390.125
	4.011	17.84181042	408.972
	4.201	18.68697222	427.792
	4.238	18.85155636	502.479
	4.159	18.50014698	342.792
Mean	4.1074	18.27061883	414.432
Standard Deviation	0.132247117	0.588264272	58.48866398
Standard Error	0.059142709	0.26307978	26.15692572
Confidence Interval (95%)	0.115919709	0.515636369	51.2675744

Sample 36CD	Peak Load (lbf)	Peak Load (N)	Strain to break (%)
Sample 36 (50% Cotton/50% PET belt speed 30 m/min Manifolds 1, 2, 4, 5)	3.647	16.22265834	421.459
	3.873	17.22795606	424.792
	3.856	17.15233632	478.126
	3.762	16.73420364	532.125
	3.9005	17.35028211	438.962
Mean	3.8077	16.93748729	459.0928
Standard Deviation	0.103828946	0.461853994	46.62097658
Standard Error	0.046433716	0.206547385	20.84953456
Confidence Interval (95%)	0.091010084	0.404832875	40.86508775

Table 9.76: Tear strength in MD and CD for Sample 37: 100% Cotton, belt speed 30m/min, Manifolds 1,3,5 (Experiment5)

Sample 37MD	Peak Load (lbf)	Peak Load (N)	Strain to break (%)
Sample 37 (100% Cotton belt speed 30 m/min Manifolds 1, 3, 5)	1.362	6.05847564	350.126
	0.923	4.10570706	342.125
	1.006	4.47490932	343.458
	1.001	4.45266822	341.458
	1.154	5.13324588	348.792
Mean	1.0892	4.845001224	345.1918
Standard Deviation	0.173884157	0.773474984	3.989372031
Standard Error	0.077763359	0.345908529	1.78410141
Confidence Interval (95%)	0.152416184	0.677980716	3.496838763

Sample 37CD	Peak Load (lbf)	Peak Load (N)	Strain to break (%)
Sample 37 (100% Cotton belt speed 30 m/min Manifolds 1, 3, 5)	2.004	8.91423288	336.126
	1.922	8.54947884	464.125
	1.597	7.10380734	231.459
	2.069	9.20336718	456.792
	1.861	8.27813742	457.459
Mean	1.8906	8.409804732	389.1922
Standard Deviation	0.182173818	0.810349221	103.1271029
Standard Error	0.081470608	0.362399189	46.11984249
Confidence Interval (95%)	0.159682392	0.71030241	90.39489128

Table 9.77: Tear strength in MD and CD for Sample 38: 100% PET, belt speed 30m/min, Manifolds 1,3,5 (Experiment5)

Sample 38MD	Peak Load (lbf)	Peak Load (N)	Strain to break (%)
Sample 38 (100% PET belt speed 30 m/min Manifolds 1, 3, 5)	6.678	29.70521316	426.792
	4.859	21.61390098	403.459
	6.173	27.45886206	419.459
	4.746	21.11125212	403.458
	6.469	28.77553518	412.792
Mean	5.785	25.7329527	413.192
Standard Deviation	0.915538912	4.072518501	10.17198769
Standard Error	0.409441449	1.821285641	4.549051187
Confidence Interval (95%)	0.80250524	3.569719857	8.916140326

Sample 38CD	Peak Load (lbf)	Peak Load (N)	Strain to break (%)
Sample 38 (100% PET belt speed 30 m/min Manifolds 1, 3, 5)	4.527	20.13709194	451.459
	4.649	20.67977478	442.125
	4.933	21.94306926	427.458
	4.579	20.36839938	452.792
	4.661	20.73315342	446.125
Mean	4.6698	20.77229776	443.9918
Standard Deviation	0.156860448	0.69774978	10.18092116
Standard Error	0.070150125	0.312043188	4.553046358
Confidence Interval (95%)	0.137494244	0.611604648	8.923970862

Table 9.78: Tear strength in MD and CD for Sample 39: Blend, belt speed 30m/min, Manifolds 1,3,5 (Experiment5)

Sample 39MD	Peak Load (lbf)	Peak Load (N)	Strain to break (%)
Sample 39 (50% PET/50% Cotton belt speed 30 m/min Manifolds 1, 3, 5)	3.185	14.1675807	374.126
	3.515	15.6354933	368.792
	3.937	17.51264214	384.792
	4.077	18.13539294	378.792
	3.616	16.08476352	378.792
Mean	3.666	16.30717452	377.0588
Standard Deviation	0.353208154	1.571147574	5.973935989
Standard Error	0.157959488	0.702638556	2.671625393
Confidence Interval (95%)	0.309600597	1.377171569	5.23638577

Sample 39CD	Peak Load (lbf)	Peak Load (N)	Strain to break (%)
Sample 39 (50% PET/50% Cotton belt speed 30 m/min Manifolds 1, 3, 5)	3.991	17.75284602	430.792
	3.767	16.75644474	414.792
	3.412	15.17732664	410.125
	3.842	17.09006124	440.126
	4.118	18.31776996	418.792
Mean	3.826	17.01888972	422.9254
Standard Deviation	0.268152009	1.19279913	12.2966608
Standard Error	0.119921224	0.533435988	5.499233888
Confidence Interval (95%)	0.235045599	1.045534536	10.77849842