ABSTRACT

Datla, Vasantha Madhuri. The Influence of Fiber properties and Processing conditions on the characteristics of Needled fabrics. (Under the direction of Dr. William Oxenham and Dr. Behnam Pourdeyhimi.)

In nonwovens, the inherent fiber crimp characteristics, along with finish determine the processing efficiency and the finished fabric properties like rapid wrinkle recovery, durability, bulk, loft, warmth and resistance to abrasion. Understanding the fiber crimp's influence on the processing properties of nonwoven fabrics has been hampered by the lack of appropriate techniques. Also the carding performance and other process parameters related to different aspects of web and fabric quality have always been a major concern in the manufacture of nonwoven fabric.

The purpose of this study is to investigate the role of fiber crimp and other processing conditions on nonwoven fabric properties. This will involve possible interactions between fiber crimp, carding parameters, crimp retention and relate these to fabric properties and processability in nonwoven equipment.

For this purpose, nonwoven needle-punched fabrics were produced from PET fibers with different crimp levels, using different card machine parameters during web formation. The webs were then cross-laid and bonded by needle punching using different needling densities and the influence all of these parameters were investigated with respect to "fabric" properties like basis weight, tensile strength, compressibility, air permeability, and directional distribution of the fibers (ODF's) using image analysis.

The basis weight measurements were statistically analyzed and investigated. It is concluded that the fiber crimp, carding and needling density significantly contribute to the differences in the basis weight measurement and so do the various fiber to card interactions.

The tensile strength of various needled fabrics were investigated. The results have shown that the mechanical response mainly depends on the fiber orientation distribution and processing conditions. Fiber crimp and finish also influence the mechanical performance. Higher carding speeds produced a dominant MD oriented structure and the ODF explains the cross-lapping effect and also the crimp pullout during carding.

The air permeability measurements were largely dependent on the weight per unit area and thickness of the final needled fabrics. So the fiber crimp, the various carding and the needling density parameters have a decisive effect on the rate of airflow through the fabric.

A power function can be used to describe the fabric behavior under compressive loads. This function, which is fit to experimental data, delivers two fitting parameters that characterize the shape of the experimental load-thickness curve. The extracted characteristic compression parameters are being evaluated with respect to inherent fiber crimp characteristics and the various carding and needling machine parameters during nonwoven production.

THE INFLUENCE OF FIBER PROPERTIES AND PROCESSING CONDITIONS ON THE CHARACTERISTICS OF NEEDLED FABRICS

by

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BIOGRAPHY

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1 INTRODUCTION

The definition of nonwoven fabrics has a long history. The term “nonwoven fabrics” was used to designate the whole group of textiles produced by unconventional methods [55]. In 1978, INDA [27], defined nonwoven fabrics as: “…. sheet or web structures made by bonding and interlocking fibers, yarns or filaments by mechanical, thermal, chemical or solvent means”. Although those associated with the manufacture of fibrous products have seen many examples of nonwoven materials, there remains no clearly defined or universally accepted definition of the limits of the range of materials, which might be called “nonwovens”. The term is generally considered to mean the fibrous webs processed by modifications on carding equipment and given body and substance through the application of bonding agents or by the fusion of self-contained thermoplastic fibers [11].

Petterson [53] has distinguished nonwovens from their woven counterparts on the basis of their structure. The properties of woven fabrics are determined by the properties and geometry of yarns, while nonwoven properties are determined directly by the properties of the individual fibers and binder material and the spatial geometry of the assembly.

Felts, the oldest type of nonwovens, from wool and camel hair were known to man for centuries. The early felts were produced manually by applying mechanical action to loose wool or hair fibers to interlock them to form usable structures. The geometry and surface characteristics of wool or hair were the key to the fiber interlocking [17].

In this present context, a more restricted definition of nonwoven fabrics has been used, namely as a fabric made directly from fiber webs or batts which have been interlocked by barbed needles. The needling action creates a three-dimensional structure held together by these mechanically interlocked fibers. The versatility of the needling process and the increasingly complex demands of the market have resulted in a large number of specialized fabrics like filtration, medical, marine, sports, aerospace, geotextiles, apparel,

paperfelts, industrial, home furnishing, insulation and automotive. Increasingly, needle punched nonwovens are thought of as “carriers of capabilities”[34].

In the present study, nonwoven fabrics from PET fibers with three different crimp levels were prepared. Eleven different card parameters using the most critical card settings such as clearance of flats to cylinder, cylinder speeds and feedplate-lickerin clearance were introduced during the web formation stage. All webs were cross-laid and bonded by needle punching using two different needling densities and the influence of these parameters were studied with respect to the following “fabric” properties:

1. Basis Weight.
2. Tensile Strength.
3. Compressive Strength.
4. Fiber Orientation (ODF) using image analysis
5. Air Permeability.

The purpose of this research is to determine the possible interactions between fiber crimp, crimp stability, carding performance during nonwoven fabric manufacture and relate them to fundamental fiber properties, nonwoven fabric properties and processability in nonwoven equipment.

Proceeding Chapter (2) explains the importance of fiber crimp, crimp stability, the carding and needle punching process in general for fiber processing performance and product quality as obtained from earlier research. Chapter 3 details the experimental plan to fulfill the objectives discussed above. In Chapter 4, the results of the experimental work are presented to reveal the effect of the processing parameters and the material parameter (fiber crimp) on the needled fabric properties. Chapter 5 concludes with the findings and recommendations for future work.

2 LITERATURE REVIEW

Different areas of study in the needle punching process may be summarized as in figure 2.1:

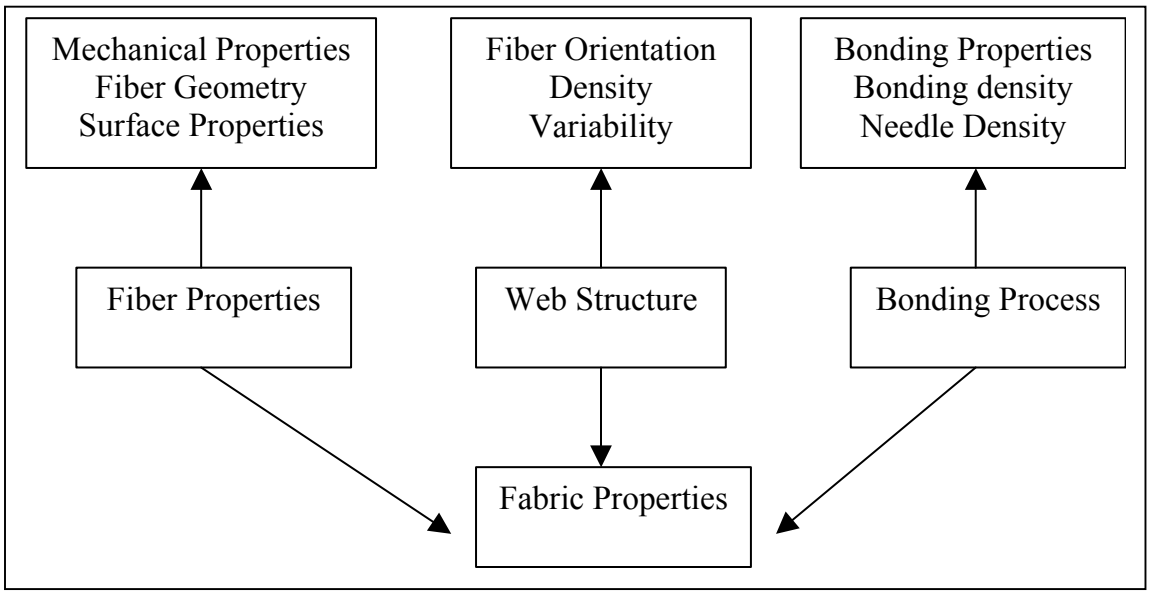


Figure 2.1: Parameters related to Needle punching Process.

2.1 CRIMP

Crimp in a textile strand is defined as "the undulations/succession of waves/curls in the strand induced either naturally (during fiber growth), mechanically, or chemically [57].

2.1.1 Fiber Crimp

Crimp in a fiber is thus considered as the degree of deviation from linearity of a non-straight fiber [1] [7]. Fiber crimp is the waviness of a fiber expressed as waves or crimps per unit length [56] or as the difference between the lengths of the straightened and crimped fiber expressed as a percentage of the straightened length [62] [7].

2.1.2 Yarn crimp

The yarn crimp in textile fabrics is the waviness or distortion of a yarn caused by interlacing in the fabric, and is defined as the difference in distance of a length of yarn

lying in a fabric and the same length of the straightened yarn [57,62]. Crimp in filament yarns is the bulk in textured yarns [57] and is almost directly a product of fiber crimp.

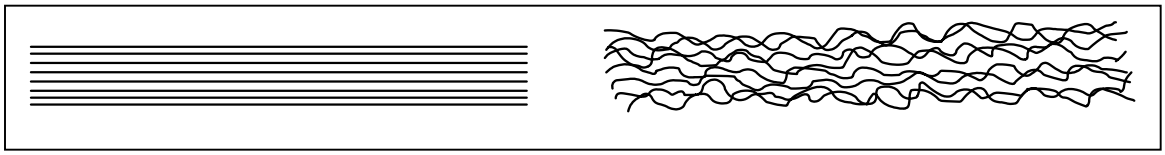


Figure 2.2: Uncrimped and Crimped Fibers

2.1.3 Importance of Crimp

Fiber crimp characteristics have a big influence on the processing performance of the fibers. Crimp also contributes substantially to the properties of intermediate fiber assemblies, yarns and finished fabrics [4,10,18,19,32,44,57,67]. For example, man-made fibers are processed into woven, knitted, and nonwoven fabrics. Fiber crimp imparted to synthetic fibers that are initially straight, makes it possible to process fibers with existing machinery designed originally for natural fibers. Straight synthetic fibers may not have sufficient cohesion for carding, combing, drawing, roving, and spinning [60]. The crimping of synthetic fibers also increases the bulkiness of the card web or sliver and changes the hand of the produced fabric [4]. In nonwoven production, crimp and crimp retention during processing are major contributors to processing efficiency, cohesion, fabric bulk and bulk stability [51]. Accurate knowledge about the quantitative effects of crimping on processing and products is still lacking [4] [7].

2.1.4 Impact of Crimp on Processing

Fiber crimp is necessary in processing to provide appropriate fiber-fiber cohesion for carding, drawing and spinning [26,43]. The card web itself needs sufficient strength through fiber cohesion not to fall apart [60,63]. The cohesion of the fibers also determines the amount of fly generated during processing [46]. However, the crimp is not only needed to hold fibers together, but also to keep them apart in order to make the card web bulky and lofty and to make drafting easier [60,43]. Too much fiber crimp however, may cause neps during processing and makes drafting difficult [26] [7].

Fiber crimp is as important as spin finish in its influence on processing. Finish affects crimp formation, since it determines the fiber-to-fiber friction in the tow and the fiber to metal friction during crimping. The static fiber-to-fiber friction depends only on the fiber surface and on the finish. However, the other fiber frictional properties such as dynamic friction between fiber and fiber, static friction between fiber and metal & dynamic friction between fiber and metal depend on fiber crimp as well, since the crimp determines the mean distance between adjacent fibers in the structure. Only if this distance is sufficiently small, these kinds of friction will be fully effective [19] [7].

During carding, crimp improves the fiber-to-fiber cohesion due to “locking” of the crimp bows, which facilitates the construction of a card web. Too high crimp however may cause fiber breaks and fiber sticking in the carding elements. Carding is the processing passage imposing the most strain to the fibers before drawing. Thus, card settings interact with inherent fiber crimp stability, determining the crimp pullout and the respective residual crimp for further processing such as drawing and spinning or web production in nonwovens [19] [7]

Because of the crimp pullout during processing, and the resulting increase in fiber to fiber contact, the processing properties at the last drafting passage or the flyer are largely influenced by the dynamic fiber to fiber friction due to finish, whereas in carding and the first drafting passage, fiber crimp has a major influence [19] [7].

2.1.5 Influence of Crimp on Final Product Properties

Crimp prevents the fibers from lying flat and tight in a yarn e.g. non-textured filament yarn. The fibers are kept at distance to each other, so that air pockets are created in the yarn or fabric. The effective crimp level in the final product depends more on the crimp permanence than on the initial crimp level, since crimp may be pulled out of the fiber differently during processing. Consequently, yarns and fabrics with quite different

properties such as bulk, elasticity and air content may be produced from fibers with the same original crimp level. Fiber crimp improves the following desirable properties of yarns and fabrics, such as knits, wovens, and nonwovens [4,18,32,35,44,45,46,56,57] [7]

- Wool – like aesthetics and visual appearance
- Warm, dry, soft handle without slickness
- Bulk, loft, hairiness, voluminosity, lightness, tuft
- Covering power of yarns and filling capacity of fibers in assemblies
- Greater extensibility, compressibility, recovery, elasticity and resilience
- Better wrinkle resistance and recovery
- Less flexural rigidity, better drape
- Good thermal insulation, air permeability, moisture absorption, higher wear comfort due to porosity

2.2 CARDING

2.2.1 The Technology

Carding as a dry laid terminology is adopted from the textile operation of the same name, where the staple fibers are combed between the rolls with a needle surface to produce a continuous fiber bundle called “sliver”, which is further spun into yarns. For nonwovens, however, carding uses wide, high-speed rolls to produce a staple fiber web rather than a sliver. The objective of carding is therefore to produce a uniform fibrous web of opened fibers having a degree of cohesive strength to carry them to the bonding operation**.** [48]

The webs to be used as raw material are produced either on conventional carding machines or on random cards – where web formation is based on the aerodynamic principles. When using carding machines, primary webs are produced as basic material and by using either single or double doffers or by connecting several card sets in-line. [20]

The selection of opening and blending equipment in carding is determined by the nature of fibers (dpf, fiber length, type) to be processed, and the manner in which the card is fed. In recent years, the manner in which the card is fed has gained a great deal of importance in case of products where uniformity of appearance and performance are critical determinants of its quality. This is particularly true for very lightweight fabrics. In general, nonwoven cards are chute fed. To improve uniformity of the carded web in both length and cross directions, chute feed systems have been designed which distribute fibers to the fiber column in the chute by a close loop aerodynamic system. [5] In order to obtain adequate stability of the textile fabric, these webs are either mechanically bonded by needling and/or chemical- or thermal-bonded. [20]

2.2.2 General Objectives of Carding

Carding is considered to be the culmination of those preparatory operations aimed at opening, blending, and cleaning the fiber stock [5]. The functions of a carding machine vary with the card design, raw material, and end product but these can be generalized [50] as:

- Opening, Blending & Cleaning
- Short fiber removal
- Nep reduction
- Alignment or parallelization
- Decrease in the linear density

The performance of a carding machine must not only include considerations of the productivity of the machine, but should also take into account the quality of the card web including all aspects of uniformity, neps and damaged fibers. [50]

2.2.3 Essentials of Carding

The carding process can be considered to consist of three key components, the feed of fibers into the card, the actual carding operation, and the removal of the carded fibers

from the card. The selection of these components is influenced by fiber type and the end product and they interact with what comes before (opening and blending), or after (cross lapping, bonding technique, etc) the card. [50]

There are two categories of cards, the conventional carding machine that centers around intensive combing action provided by large, high speed cylinders and peripheral rolls and, air laid cards which use centrifugal force and supporting air flow to emit fibers to a collecting surface. The major components of a carding machine include [48]:

1. Licker-in.
2. Main cylinder.
3. Workers
4. Strippers.
5. Doffers.
6. Take-off rolls or combs

Instead of worker and stripper rolls, a flat top is also used to work against the main cylinder for carding the fibermix (Figure 2.3 shows a traditional flat cotton card). Flat tops can either be a continuous belt with saw tooth clothing moving at a set clearance above the main cylinder, or stationary boards with saw tooth clothing. [48]

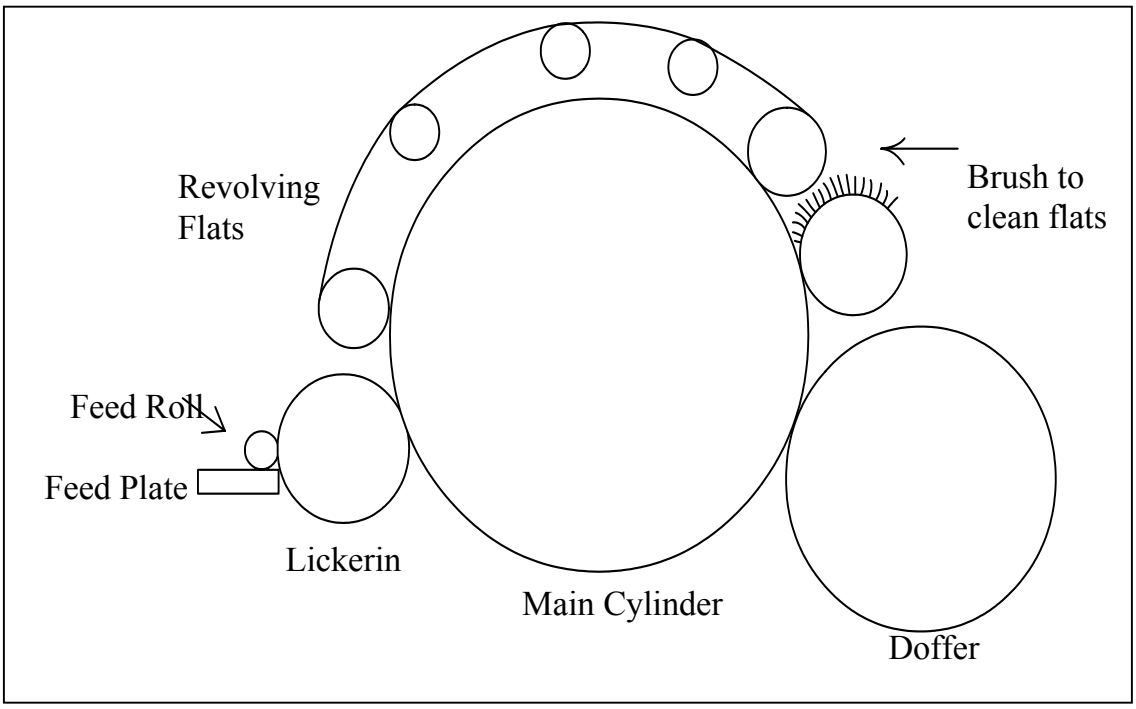


Figure 2.3: A Traditional Cotton Card

Based on the carding principles outlined above, the role of the main parts of the card has been discussed below to better understand the design process:

Cylinder: It is the principle element of a carding machine. Role of a cylinder is two fold:

(a) To carry the fibers from the feeding point over to the succession of carding fields.

(b) To act as one of the two interacting surfaces in the carding fields.

Workers/Flats: Role of the workers or flats is to provide the mating surface to the cylinder in the carding fields. Their motion is necessary to achieve subsequent stripping. This avoids overloading them with trapped with fibers (in depth of clothing). This motion also contributes to blending (particularly in roller-top carding).

Licker-In: The role of licker-in is two fold:

(a) To open the tufts in the feed-lap and to help remove any particulate.

(b) To transfer fibers from the feeding system to the cylinder.

Doffer: The role of doffer is to take-off fibers from the cylinder clothing and to deliver them to an output system. Therefore, the doffer must be incorporated in the machine in the carding mode, with respect to the cylinder, so as to lift-off some of the fiber mass from the cylinder surface. This necessary solution has two other beneficial effects:

(a) That of creating an additional carding field and

(b) That of further aid in achieving a good fiber blend. [5]

When a sequence of carding cylinders are used in tandem (see figure 2.4), transfer of fibers from one to the next is made by means of a stripper (also called carrier) roller which is in the stripping mode with respect to the doffer of the first cylinder, as well as with respect to the second cylinder. [5]

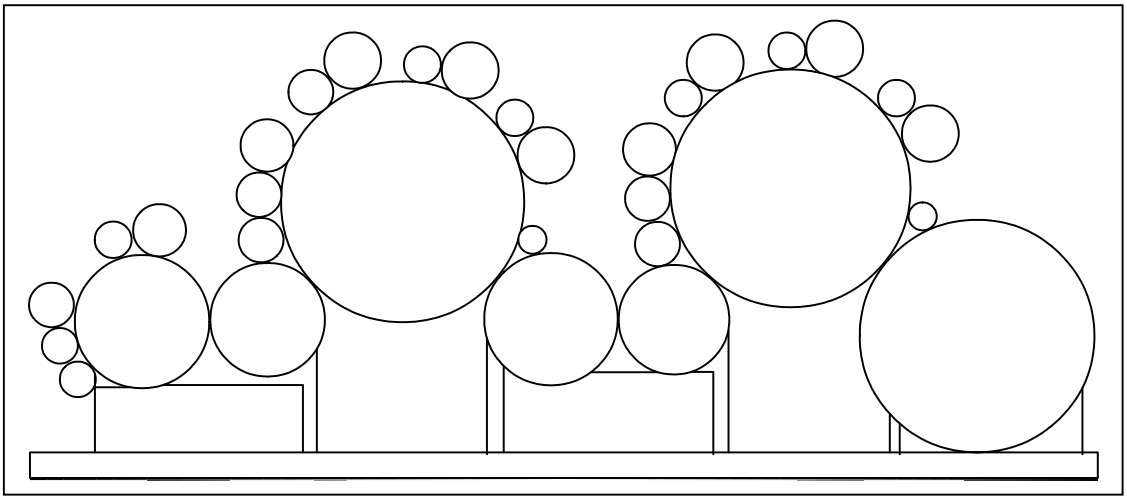


Figure 2.4: Nonwoven Card – Cylinders in Tandem

Conventional carding technology provides two basic mechanical actions on the incoming fibrous web (from the licker-in roll). (Figure 2.5)

Carding: Working or disentangling (point to point).

Stripping: Fiber removal and transfer (point to back). [48]

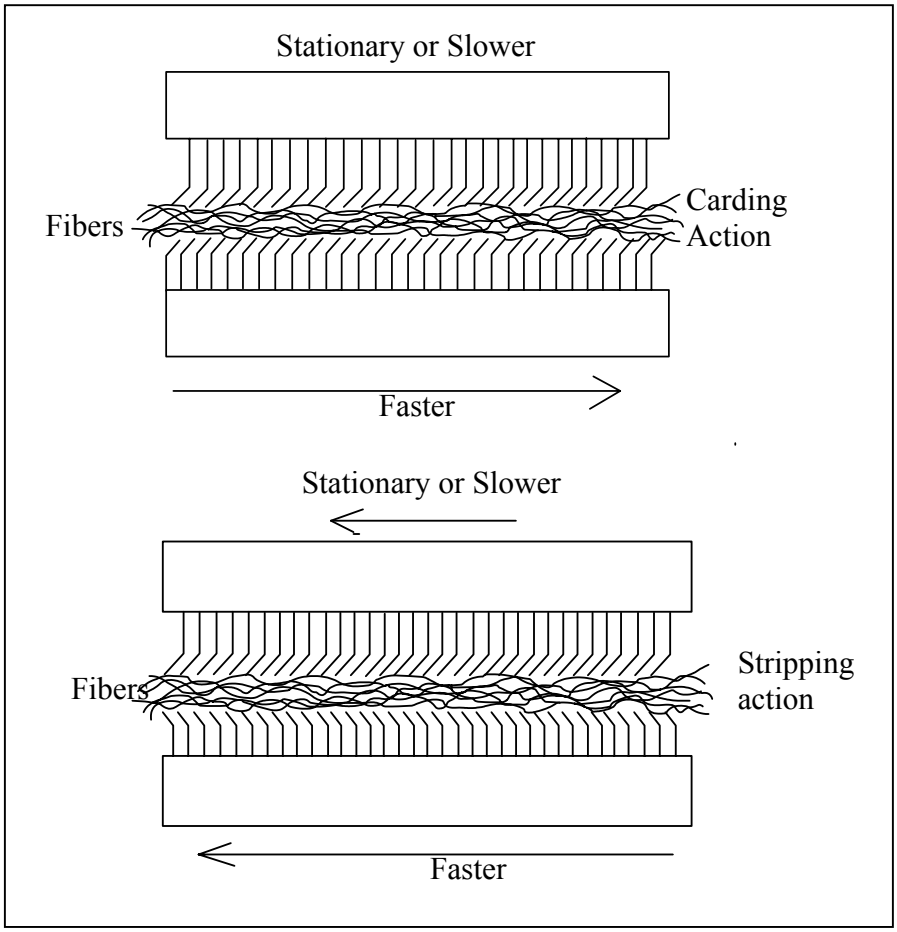


Figure 2.5: Primary Actions involved in Carding

2.2.4 Critical aspects affecting web quality

Factors that potentially affect the quality of the card web can be broadly classified into three groupings [48,50]:

(1) Input Parameters – these can be further subdivided into:

- Fiber properties and condition, including fiber crimp, fiber finish, moisture content, length and denier, as well as percent of recirculated fiber
- Uniformity of areal density

- Uniformity of openness

(2) Machinery Parameters – this includes the feed unit, the card and the system used to transfer the web from the doffer to the next component in the processing line. The features specific to the card are:

- Card Clothing – the type of wire or toothed clothing: size and angle of teeth, number of teeth/unit area, sharpness, etc
- Settings between various components, like position and clearance of worker/stripper rolls from the main cylinder. This is critical for optimizing opening/blending and output
- Relative speeds of different components

(3) Processing Parameters – this obviously includes fiber and machine specifications but additionally encompasses:

- Production speeds
- Input weight
- Web weight
- Fiber machine interactions
- Atmospheric conditions.

A well-carded web is characterized by [48]:

(1) Uniform web density across the width and machine direction

(2) Uniform distribution where two or more fibers are used in the fiber mix

(3) Absence or low occurrence of fiber neps-small fibrous entanglements caused by high production rate, low doffer collection efficiency, high fiber crimp, and low fiber finish etc

(4) Low fiber breakage- caused by high surface speeds which resulted in excessive fiber pulling, or incorrect settings of clearance between the rolls

(5) Absence of repeat patterns of creases of thick/thin sections of the fibrous web.

2.2.5 Significance of Carding in Nonwovens

The card has dominant importance in the processing of staple fibers for nonwovens production. Especially in recent times carding technology for nonwovens production has been considerably advanced.

Nonwovens produced by the dry laid technology do not always give satisfactory web uniformity or, more particularly, adequate strength in all directions. However, since the uniformity of a nonwoven has a substantial influence on its strength, among other things, the first point to be considered is how to achieve an ideal web and nonwoven fabric.[8] Especially with lightweight nonwovens, optimum strength values can be achieved only if the individual fibers can keep their natural form within the web and at the same time their random distribution is secured as far as possible. The result is a maximum number of 'fiber crossings', which can be chemically bonded, and as a consequence the fibers are well linked to each other within the web. In addition minimizing the use of fibers/bonding agent reduces the costs. This statement holds true for 'disposables' (uncrimped fibers) in the two-dimensional field, as well as for 'waddings' with three dimensional fiber structure (crimped fibers). [20]

The predominant influence of the web structure is on the strength and elongation properties of the nonwoven as the most important feature, as well as its volume, handle, and bending and forming properties. Since the web structure is in turn produced by the web former, the choice of card technology to be applied in the production of a specific nonwoven product is of defensive importance of knowledge of the fiber structure both in the bonded and in the unbonded web. [66]

Apart from the web forming machine, the following parameters, fiber origin, fiber type (crimp, finish), fiber mixture, web weight, rate of delivery of the web-former effect the ratio of the longitudinal to cross strength and longitudinal to diagonal strength to a certain degree. [66]. Fiber distribution in the finished web should result in [38]:

- Low cloudiness.
- Uniform distribution of the different component fibers.
- Low weight fluctuations in MD and CD within a square web sample.
- Low long-term web weight fluctuation.

2.2.6 Design considerations affecting web structure

It is important to know how the fibers are aligned in the unbonded-carded web and how the direction of the fibers can be influenced or, if necessary, changed. The task or the objective of ideal distribution should be to produce a web with strength values in all directions 1:1. This needs to be achieved not only with low web weights and maximum throughputs. The strength values are determined using tensile testing equipment, as this is the simplest way of ascertaining fiber alignment in the carded web. [8]

Some parallel webs are produced on conventional cards, some on Card masters and some on worker-and-stripper cards. By using carding segments, for instance, the fibers in the card clothing of the main roller are stretched, stressed and aligned in one direction only. The stationary elements force to remain in the card clothing, where they are stressed longitudinally. The doffer unit that follows can produce no more than a slight change in fiber alignment. This, however, depends on the adjusted distance between the rollers, the roller configuration (diameter of roller relative to one another) and the types of fiber employed. [8]

An important factor here is the relationship between the roller diameters. As already mentioned in the example of the carding segments, a large contact area leads to a very high degree of parallelism among the fibers and vice versa. But the alignment of the fiber is determined not by the contact area alone; another factor is the shape of the wedge formed by the narrowest point between the main roller (randomizing roller) and the doffer. The thinner the wedge, the better is the web formation (parallel alignment of the

fibers) on the doffer. The shape of the wedge also determines the processability of fiber length with certain roller configurations. [8]

Another factor of significant importance is the combing arc, i.e. the configuration of the rollers relative to one another. There is also the possibility of realignment by way of the stuffing device with the advantages and drawbacks of the absolute strength values in the preliminary product. [8]

Depending on the requirements and applications, different card types and technologies are used for web formation, which are appropriate to the required web structure, fiber material, and economy of production. Some of the most important characteristics regarding the concept of carding technology are: [65]

- Fiber type
- Staple length
- Fiber fineness
- Fiber blend
- Fiber orientation
- Card web laying
- Freedom from neps
- Throughput
- Web weight
- Web structure
- Type of web bonding
- Strength and elongation characteristics of the web and nonwoven product.
- Uniformity

2.3 LAPPING

Lapping is the stacking of fibrous web layers (from the carding machines) onto one another. Lapping can be carried out in parallel – carding machines positioned in series, or in cross lapping. [48]

The objectives of lapping are [48]:

1. Increase throughput rate and fabric weighs by using more than one card per production line and stacking layers of the web as in the case of cross lapping.

2. Improve the uniformity of the finished fabric by stacking layers of the fibrous web form the cards resulting in a statistically “averaging effect”.
3. Enable different types of fiber mixes to be used in different web layers to produce composite fabrics.
4. For cross lapping, improves cross directionality of the fibers and the resulting CD properties.

Obviously, cross and parallel lapping can be used together to produce the required fiber directionality for many nonwoven applications.

2.3.1 Cross Lapping

Employs a special cross lapper to lay down the carded web back and forth perpendicular to the direction of the production floor lattice. However, as the floor lattice is moving at a set speed, the laid down web becomes “tilted” at an angle ranging from 45° to 80° to the machine direction (see figure 2.6) [48]. For needle punching as a bonding technology to be meaningful, the webs need to be either parallel lapped or cross-lapped to the desired basis weight. The parallel lapped webs when bonded yield limited strength in the cross direction. To obtain optimal tensile characteristics, puncture strength, draping characteristics, permeability and compaction/densification in all directions, cross lapping is often practiced in conjunction with needle punching. The combination of cross and parallel lappers is a key factor in giving dry laid process a degree of versatility in weight, uniformity, fiber directionality, fiber mixes, layering capability and production rates. [6,48]

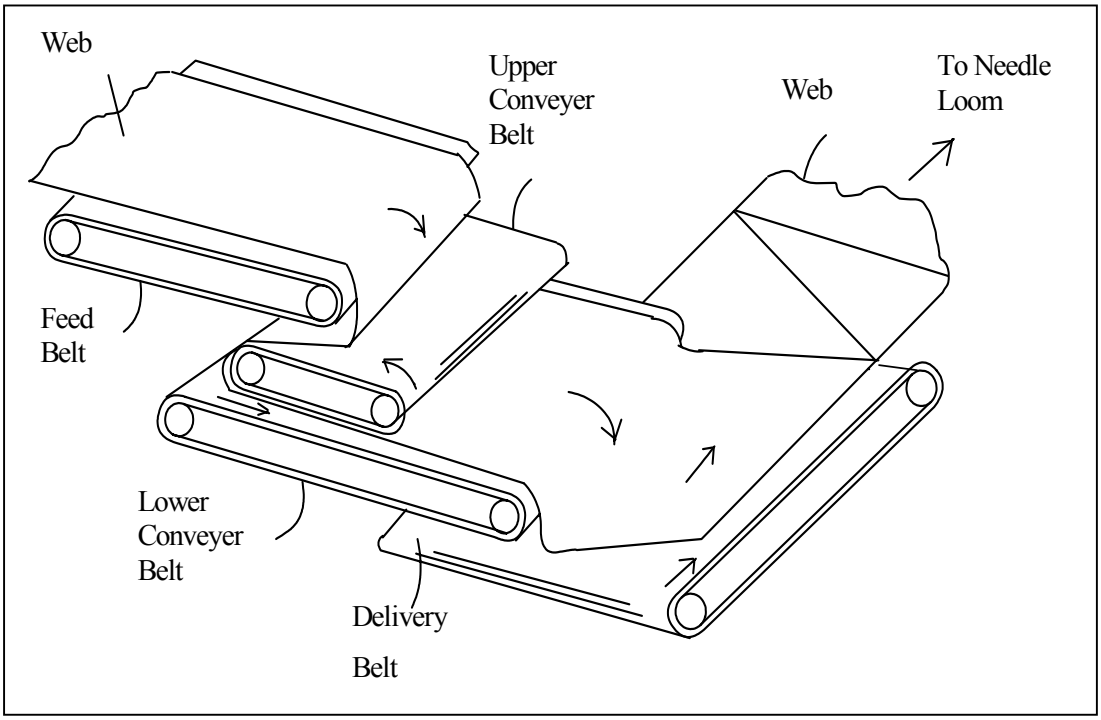


Figure 2.6: A Crosslapper

2.3.2 What does Cross-lapping do?

Higher number of layers will owing to the lower drawing-off speed – cause an increased orientation of the fibers in the cross direction. This is frequently not desirable, and in fact, it is generally attempted to achieve equal strength in the machine and cross directions and to eliminate any preferred fiber orientation. To reduce this orientation of the fibers in the cross direction, a drafting zone is introduced downstream from the card, which reorients the fibers but also stretches them. Since the drafting process acts mainly on the weak points already present in the web, such a process increases the variation coefficient of weight distributions. [9]

In summary, the following may be stated about cross-lapped webs:

1. High webs can be produced with greater uniformity than low weights.

2. An increase in longitudinal strength is achieved at the expense of quality in terms of weight uniformity and loft. [9]

It is certainly an advantage that with cross-lapper the width of the end product can be flexibly adjusted and high weights can also be produced without any problems. [9]

2.4 NEEDLE PUNCHING

2.4.1 The Technology

Needle punched nonwoven fabric is the oldest form of fully interlocked nonwovens known to man. Needle punching dates back to the late 1800's. William Bywater of Leeds, England produced the first needle loom. The first needle loom produced in the USA was by James Hunter around the year 1948 and needled non-woven fabrics were produced commercially in Germany in the 1940's and in the U.K. in the 1950's. [13,21]

The needle punching process is one of the oldest means for entangling or interlocking the fibers of a fibrous web structure into a strong fabric. The first needled fabrics were produced in 1870 when coarse fibers, such as jute, sisal and hair were used for primary production of padding materials. The first machine incidentally produced saddle pads and horse blankets from jute, wool or hair alone or from blends. [13]

It was through these efforts that the needle punch industry took a new direction from being the processor of waste and the producer of low-grade materials. Needle punching has grown into an industry that includes the medical field where blood is filtered, geotextiles used to stabilize road beds and prevent erosion, personal safety applications using bullet proof vests, and the automotive industry where needled fabrics provide insulation and a comfortable, aesthetically pleasing interior. [64]

2.4.2 The Process

There are three main regions of the loom, namely, the feed apron, needling zone and take-up rollers. The feed apron, an endless conveyor belt, feeds the fibrous webs into the needling zone, where the webs are punched in between the bed plate and stripper plate and finally the needled fabric is pulled through the pair of take-up rollers at the delivery side. The movement of the feed apron and take-up rollers are intermittent and the webs are needled during its stationary period. The needling density (punches per sq. inch) can be varied by changing the speed of the feed roller and correspondingly the delivery rollers by altering the settings of eccentrics, which drive both rollers. The relationship between the speeds of the rollers and the needling density has been established. The bedplate and stripper plate are mounted one above another and their gauge distance is varied according to the thickness of the web in such a way that the web can just pass smoothly. [13]

A complete account of the passage of the raw material through the needle loom is given below: (see figure 2.7)

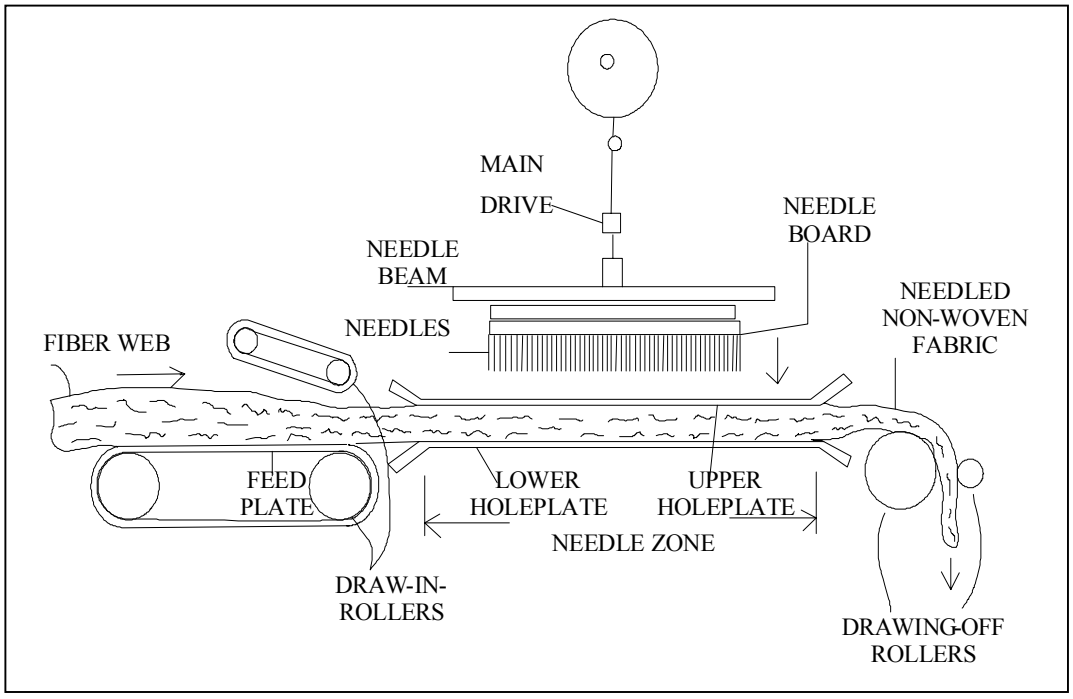


Figure 2.7: Needle Loom Machine

The cross lapped web is fed into the needle loom in a controlled manner. Drafting or stretching the web as it is needled again changes the fiber orientation and, therefore, strength and elongation properties are equally important. The amount of needling activity, the type or size of the needles, the depth of penetration of the needle, and the speed of needle penetration of the web influence the properties of the needled fabric.[13]

2.4.3 Classification of the Needling Process

Preneedling: Prior to entering the preneedler, the batt is very voluminous and has almost no strength or dimensional stability. Because the batt has such great loft, it must be compressed so that it can pass between the bed and stripper plate before entering the needling zone.

In applications where preneedling is a must, its importance cannot be down played. Needle punching is not a very forgiving process and, therefore, any imperfections formed here are very difficult, if not impossible to remove. For example in applications where surface quality is extremely important, it may be impossible to remove a pattern formed during preneedling. Another example is if too much preneedling is done, then attaining thickness properties during the finish needling could be very difficult. [47]

Finish Needling: After the batt has been preneedled, it becomes a fabric with sufficient strength and stability to be transported to the finish needler. The finish needling takes place on subsequent needle looms, which may be upstroke, down stroke, or both sides.

Fiber that have been needled from both sides usually have better interlocking, higher abrasion resistance, and higher strengths. This is obviously the case with looms that needle from each side. Such a needle loom is used for high efficiency and high-density products, e.g. technical felts. [47]

Structuring: There are two types of needled felts: conventional and structured. Conventional felts have flat surfaces on the top and bottom. The basic system will have fiber opening, blending, feeding system, cards or garnets, a cross lapper, and winding. The basic system would consist of a preneedler and a finish needler. [47]

2.4.4 Critical features of the Needling Machine

The important aspect of needle punch is the needle. It is the action of the barbed needles that interlocks the fibers together to form the needled felt (see figure 2.8). The working parts of the needle are the blade and barbs for fiber transportation. The most common blades are triangular with rounded edges. The barbs are placed on the edges of the blade. Depending on the type of product required and fibers to be used, the needles are selected by gauge, barb style and size, and also barb spacing. Barb spacing is usually regular or close. Medium and frequent are also commonly used. It is evident that there are a lot of variables and interactions during the needling process. [47]

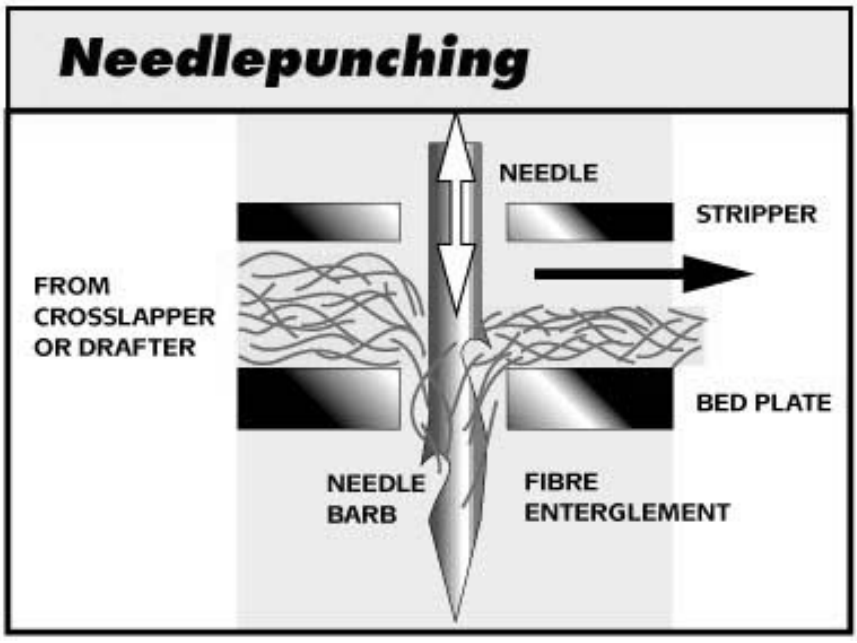


Figure 2.8: Nonwoven Fabric needle punched using barbed needle

During needle punching, a needle experiences forces due to inertia, vibration, and resistance from the fiber web. The forces due to vibration and inertia depend on the machine and needle construction and needling speed. The forces due to fiber web resistance are dependent on the needle loom variables, needle design parameters, and fiber web parameters. [59]

Needle punch density and depth of penetration are the two most important machine parameters that are known to influence the properties of needle-punched nonwovens. The effect of these two parameters and their order of importance on the density, tenacity, breaking elongation and air permeability of the nonwovens has been examined and interdependence of these properties and their relationship with needling parameters is brought out. Such an analysis is expected to help in optimization studies of parameters to engineer the needle-punched nonwovens to meet the specific property requirements. [16]

Apart from the needling density, the depth of penetration of the needle has also an important role in the improvement of the fabric tensile strength properties and this can be done by adjusting the height of the assembly of bedplate and stripper plate since the depth of displacement of the needle with its oscillating action remains constant. [16]

The many different end uses of mechanically bonded fabrics require a wide variety of physical properties; strength requirements in the CD or MD direction, good insulation (high thermal stability and acoustical absorption), filtration properties, surface quality, just to name a few. These, and many other features, are required for today's needled products. [64]

Today's needle punched fabrics are determined by the properties of the fiber, the fiber processing performance, the correct felting needle, and intensity of the needling operation. For all manufacturers, one requirement still remains; the control of uniformity and reproducibility of each finished product. [64]

Today, needle-punching industry is no longer considered a means of utilizing waste fibers and textile scraps. Today's products are sophisticated and technically oriented as any other textile product. [64]

Needle felts possess a structural geometry that is uniquely different from wovens, knits, and dry and wet laid nonwoven fabrics. In filtration applications or acoustical dampening end uses, needle felts have certain properties that other materials do not. Each material structure has advantages and disadvantages, pros and cons. [58]

Two needled products that make up the most needled volume in the US and abroad are automotive fabrics and Geotextiles. The vast majority of all needled fabrics can be classified into these twelve categories: [24]

1. Automotive
2. Geotextile/Agriculture
3. Filtration
4. Medical
5. Apparel
6. Paper Maker Felts
7. Marine
8. Industrial
9. Insulation Felts
10. Sport Felts
11. Home Furnishings
12. Other

Structural advantages of Needle felts [58]:

1. Low cost structure which requires weight and thickness
2. Good abrasion resistance both internal and external to the fabric structure
3. A custom design feature which allows easy selection of fibers, fiber sizes, finishes, and processing steps to get the unique design to do a job
4. Filtering efficiency of a very high rating
5. Generally, a very fibrous surface and internal structure for many end uses

2.4.5 Effects of Needle Design Parameters

In the needle punching process, needle geometry is one of the most influential parameters on needle punching process and resultant fabric properties. The effort to find proper needle geometry to obtain particular needled fabric properties was carried out by many researchers [22,23,37] [33]

Luenenschloss investigated the effects of the needling process and web weight on the properties of the needled fabric produced at high needling speed (from 800 up to 2800 strokes/min) [41]. The factors considered in the study were needling speed, needling density, penetration depth, needle type and web weight. He found that needling density and needle gauge significantly extended the web in machine direction, not in cross direction. Fabric weight, thickness and air permeability were significantly affected by web weight and needle gauge. [33]

2.4.6 Structure of Needled Fabrics

In the needle-punching process the fibers are invariably reoriented from one layer to another, irrespective of the machinery from different manufacturers, and interlocked fibrous structures are formed causing a crucial effect on the fabric tensile properties. The type of needle gauge, barb spacing, nature of needle barb and number of barbs differentiate felting needles. The nature of the needle has an important role on the reorientation of fibers causing a variation of tensile strength in the fabrics. [13]

Along with the investigations on the properties of needled fabrics, research efforts were directed toward understanding and characterizing the structure of needled fabrics. Previous investigations regarding structures of needle-punched fabric's usually relied on photography and microscopy. The pieces of fabric were set in resin and a section was cut from the resultant block for viewing under a microscope or a camera. Gardmark and Martensson [25] were the first to report such type of studies. They reported that fibers

were reoriented perpendicular to the needled fabric plane in distinct channels. It was also found that most of the fibers drawn through the fabric were from the top layer and formed a core around which a tube was formed. It is the structure that gives a fabric its strength. It was also found that the number of fibers in a vertical channel increased as the amount of needling increased. The fiber length in the fabric was measured before and after needling. It was found that as the amount of needling increased, the number of short fibers increased. And fiber length distribution shifted from normal distribution to exponential distribution. [33]

2.4.7 Physical and Mechanical Properties of Needled Fabrics

Hearle *et al* [28] considered the effects of fiber web parameters on the needled fabric properties were considered. The needle fabric weight, thickness and density increased as web weight increased. The tenacity of the needled fabric increased up to a certain limit of fabric weight and then decreased. When the fiber consolidation became too great, fiber breakage during needling resulted in a loss of strength. The breaking extension decreased, but modulus increased with fabric weight. This result is due to the increase in density and entanglement, causing more fibers in a unit fabric to withstand extension and greater frictional restraint. Compared to parallel-laid web, cross-laid webs showed more uniform properties in the different directions of the needled fabric. In the study, stress-strain curves of the needled fabric generally showed the S-shaped type. Due to the fiber slackness and curl and the disordered orientation in the unstretched fabric, the structure of the fabric provided low resistance to initial extension. At greater extensions, the curve steepened as the fibers were pulled into a closely packed, oriented structure. Near rupture, extension again became easier, perhaps due to the onset of fiber breakage. [33]

Table 2.1: Comparison of Strength of Rayon Web (2.5 in, 3 denier) Before and After Needling [29]

Fiber Density (g/cm^3)	Tenacity of unneedled fabric (g/tex)	Tenacity of Needled fabric (g/tex)
0.035	0.15	-
0.042	0.20	1.55
0.050	0.26	2.75

In further series of papers by Hearle *et al* [29], the origin of strength of needled fabric was investigated using unneedled and needled fabrics with the same fabric density. As the experimental results shown in Table 2.1, the strength of needled fabrics is considerably higher than that of unneedled fabrics. This result shows that the needled fabric strength comes more from the entanglement and interlocking of fibers than from increased density of the webs. The needling process reoriented the fibers in the depth wise direction, binded the different layers together and produced an integral coherent structure. [33]

In the study of Hearle *et al* [29], the effects of needling density and needle penetration depth on the needled fabric properties were also investigated. It was found that increased needling density decreased needled fabric weight. This is due to drafting and spreading of fibers during needling process. However, the fabric density increased with needling density, because the fibers in the fabric were more compactly packed. An increase in needling density increased the fabric modulus, strength, elastic recovery and bending rigidity. The more highly needled fabrics showed more coherence and strength. However, excessive needling tended to tear the fiber web and break the fibers, which reduced the fabric modulus and strength. The penetration depth showed similar results as needling density. When the penetration depth increased, the fabric showed an increase in breaking extension. But an excessive high penetration depth decreased the fabric modulus and strength due to fiber breakage. Luenenschloss *et al* [39, 40] confirmed these findings. As needling density or penetration depth increased, tear strength of the needled fabric generally increased. [33]

Hearle *et al* researched the influence of fiber type and fiber characteristics on needled fabric properties [30]. It was found, in general, that the longer and finer fibers produced stronger needled fabrics, but too fine fiber can be easily damaged during the needling process. As a result of the fiber damage, the needled fabric showed low fabric strength. [33]

In a similar study, Luenenschloss [39] reached the same conclusion. He also studied the effect of fiber dimension on air permeability of the needled fabric. The use of fine fibers produced low air permeability due to the greater surface area. Longer fibers decreased air permeability because the longer fiber produced denser fabrics. Additionally, he found that highly crimped fibers enhanced dimensional stability and breaking tensile strength of needled fabrics.[33]

The bulkiness of wool and Courtelle fibers tended to give more open structure in the needled fabrics. And the good elastic recovery of wool and Courtelle fibers led themselves to spring back when the needles are withdrawn. They concluded that high friction of fibers would lead to greater consolidation as more fibers are pulled down and, in addition, it will lead to greater resistance to slippage in the resulting needled fabric. The effect of fiber friction on the needled fabric properties was studied in detail by Hearle and Husain [31]. The experimental results indicate that an increase in fiber friction after the needling process, made the needled fabric stronger and more coherent. The differences were believed to be due to fiber damage, poor fiber rearrangement, or general irregularity. [33]

3 EXPERIMENTAL APPROACH

In a recently completed project on the measurement of crimp in synthetic fibers by Dr. Ina Bauer-Kurz, three polyester fibers with different crimp characteristics were carded under various conditions. Their mechanical fiber behavior was quantified during crimp removal and was related to fundamental fiber properties, nonwoven fabric properties, and processability in nonwoven equipment.

3.1 Fibers with Different Crimp Production Settings

The material available to explore the influence of differences in crimp production settings on fiber crimp behavior were three 3den PET fibers with different crimp levels supplied by Wellman. Table 3.1 shows the identification of the test material and the crimps per linear extended inch (CPLI). Even though the differences in numerical values of the CPLI's are relatively insignificant, processing temperatures and setting times during crimp production were very different for these three fibers and they were thus expected to behave very differently during crimp pullout and in terms of crimp stability behavior.

Table 3.1: 3den PET Test Material for Carding

Identification	Crimp Level	Type
Fiber 1 (**B1**)	9 CPLI	218
Fiber 2 (**B2**)	8.5 CPLI	216
Fiber 3 (**B3**)	9 CPLI	214

3.1.1 Data analysis of useful parameters to describe fiber crimp

Single fiber tensile tests in the crimp removal region have been performed on various fibers with the Textechno FAVIMAT and have also been monitored optically. Based on empirical evidence, a basic understanding of the physical crimp removal mechanism is obtained.

Some of the data analysis results from the dissertation of Ina Bauer Kurz [7] has been included here to afford a better understanding the fiber characteristics, which would further help in understanding the fabric property analysis explained in Chapter 4.

3.1.1.1 Load Extension curves for the three different 3-denier PET fibers

The data analysis by Ina Bauer-Kurz [7] was mainly focused on the extraction of meaningful and useful parameters to describe fiber crimp from the load-extension data of single fibers.

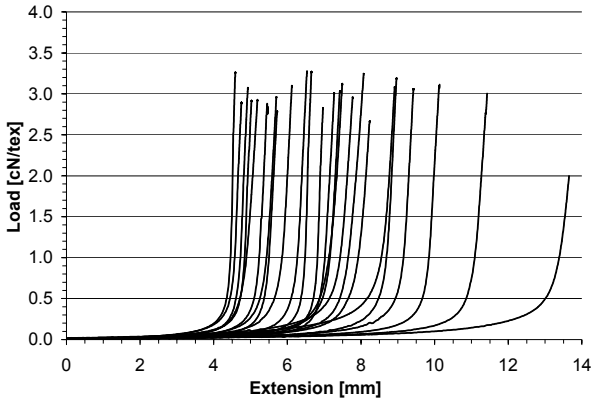


Figure 3.1: Stress-Strain Curves for 25 fibers of Bale 1.

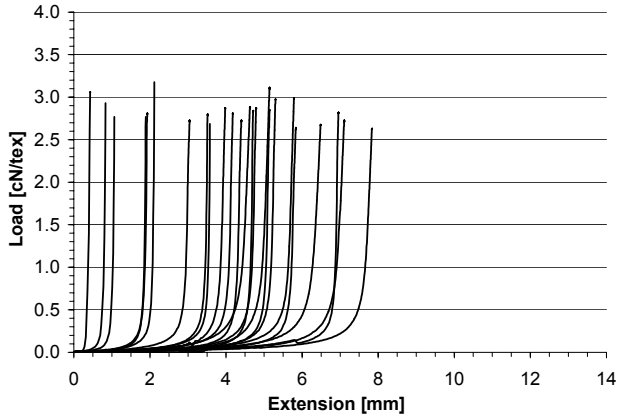


Figure 3.2: Stress-Strain Curves for 25 fibers of Bale 2

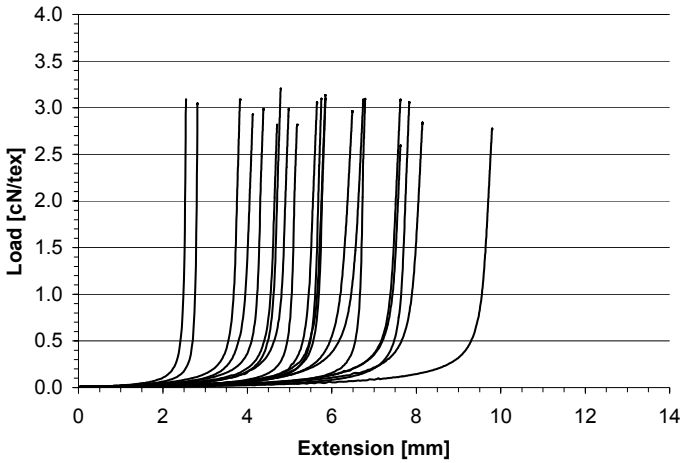


Figure 3.3: Stress-Strain Curves for 25 fibers of Bale 2

Figures 3.1 through 3.3 show the load extension curves for the 3 fibers in the crimp region during crimp removal. The extension % values for the 3 fibers were extracted at 0.7 g/tex assuming that this point lies in the crimp removal region are given in the table 3.2

Table 3.2: % Extension values of the 3-den PET fiber at 0.7 g/tex

Identification	**Extension at 0.7 g/tex**
Fiber 1 (**B1**)	35%
Fiber 2 (**B2**)	22.5%
Fiber 3 (**B3**)	27.5%

When comparing the load-extension curves in figures, it is apparent that fibers with different crimp characteristics have differently shaped load-extension curves in the crimp removal region.

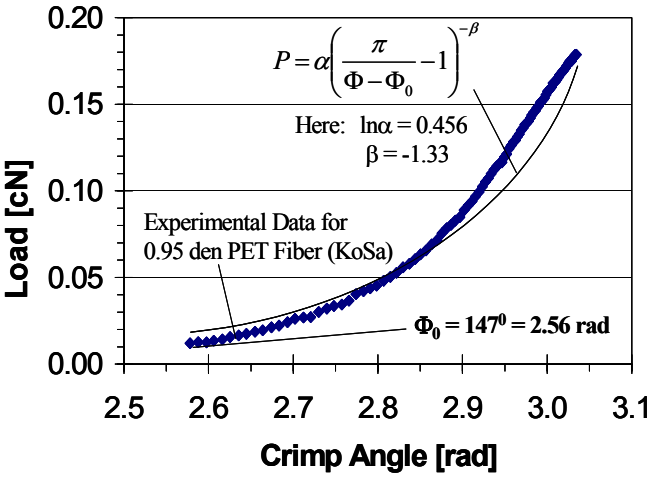
3.1.1.2 Characteristic Crimp parameters:

A mechanical model was developed to understand the nonlinear load-deflection behavior during crimp removal. According to this model, a logarithmic function was fit to experimental data, which delivered two fitting parameters that characterize the shape of the experimental load-extension curve in the crimp region.

The extracted characteristic crimp parameters were evaluated in terms of fiber material characteristics, such as fiber type, crimp processing settings and carding performance during nonwoven production.

These "characteristic parameters" were extracted by fitting a power law function suggested by Dent **[15]** , which has been used to describe the compressive behavior of fibrous structures, to the load-angle data in the crimp region.

Curve fitting parameters describing how the crimp is pulled out have been used as crimp parameters, which can ultimately be correlated to the fiber processing performance and product characteristics.



Where
Φ_0 = Initial crimp angle
α = Measure for load at crimp removal, where fiber approaches straightening
β = Shape factor characteristic for the mechanical crimp behavior

$$P = \alpha\left(\frac{\Phi_{straight}}{\Phi - \Phi_{initial}} - 1\right)^{-\beta} = \alpha\left(\frac{\pi}{\Phi - \Phi_0} - 1\right)^{-\beta}$$

$$\Leftrightarrow \underbrace{\ln P}_{y} = \underbrace{\ln\alpha}_{a} - \underbrace{\beta}_{b} \bullet \underbrace{\ln\left(\frac{\pi}{\Phi - \Phi_0} - 1\right)}_{x}$$

Figure 3.4: Power-Law Function to Fit Load-Angle Data in Crimp Region [7]

The fitting procedure is completed by transforming the equation P(ϕ) into a more suitable, linear equation between P and ϕ. For the relationship obtained between y and x, a linear regression is done which delivers the regression parameters a=lnα and –b= -β, as well as the R-square goodness of the fit.

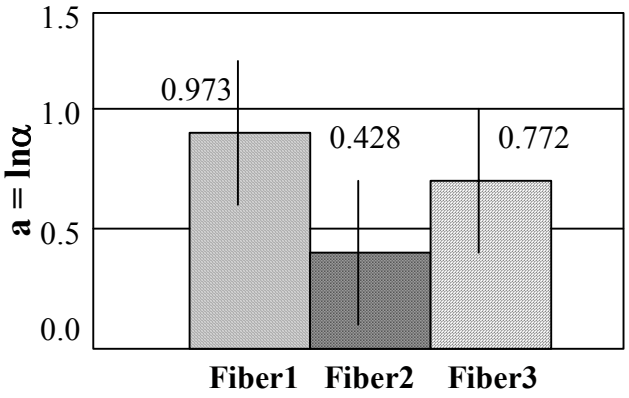


Figure 3.5: α Values for 3 Different 3 den PET Fibers [7]

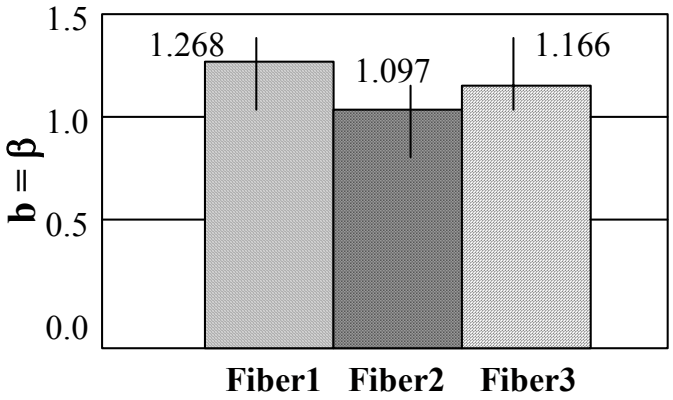


Figure 3.6: β Values for 3 Different 3 den PET Fibers [7]

The mean values and the standard deviations as error bars for the fitting parameters α and β are depicted in Figures 3.5 and 3.6 for the three different 3 den PET fibers.

The interpretation of the power law function fitting is used as a description of the whole crimp removal process and is better understood taking into consideration the mechanical structure of a crimp bow. Thus, the combination of α and β characteristics describe the

fiber behavior during crimp removal when subjected to load during processing. Combination of α and β make fiber 1 softer than fiber 3 at the very beginning of the crimp removal and gradually stiffer than fiber 3 during crimp removal.

With α and β, changes in softness of the fibers at the beginning of crimp removal, during the whole region, or at the end may be identified in dependence of different crimping conditions such as temperature and time settings.

For PET fibers in nonwovens production, it was seen from the values of α and β, that with progressive processing towards carding, the fibers got softer in response to load impacts in the magnitude of their crimp removal loads. This effect may be interpreted as hysteresis and loss of elasticity of the fibers after multiple subjections to loads during processing.

For carded PET fibers, an effect of the card settings, flat and feedroll- lickerin clearance on fiber crimp characteristics could not be established. This might be caused by the insufficient sample sizes of the fibers tested. An increase in cylinder speed clearly made the fibers softer towards the end of crimp removal, thus decreasing the elasticity of the fibers during crimp removal.

These complex differences in crimp removal behavior between fibers of the same polymeric material and denier can be attributed to differences in processing settings during crimping, such as time and temperature at crimping and during heat setting.

3.2 Carding Experiments

The experimental plan for processing PET fibers into nonwoven webs is depicted in Figure 3.7 The fibers were processed using a “typical” industrial production line at Hollingsworth Inc. Carding setting may be varied in processing step 5. Fiber samples through G and web samples H and J with two different needling settings were collected for data analysis with each processing setup.

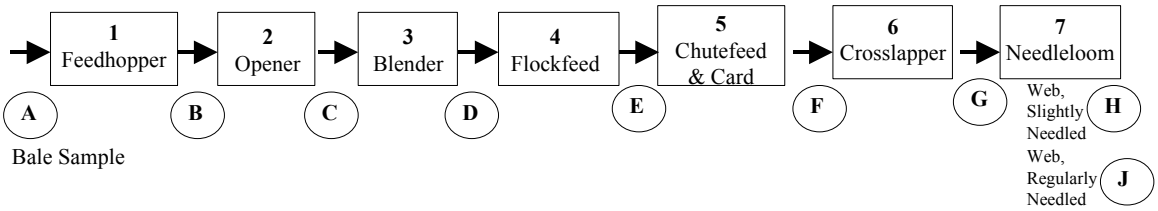


Figure 3.7: Flow Chart with Sample Schedule for 3 den PET Fibers

The material available is one bale each of the same fibers already tested for the influence of crimp settings during production, as presented in Table 3.1.

The card used in the experiments was the MASTERCARD® from Hollingsworth, which had two cylinders and flat top carding elements, as shown in Figure 3.8. The card settings most critical to the processing performance of the fibers and the web properties include

- Clearance of Flats to Cylinder
- Cylinder Speed.
- Feedplate-LickerIn Clearance

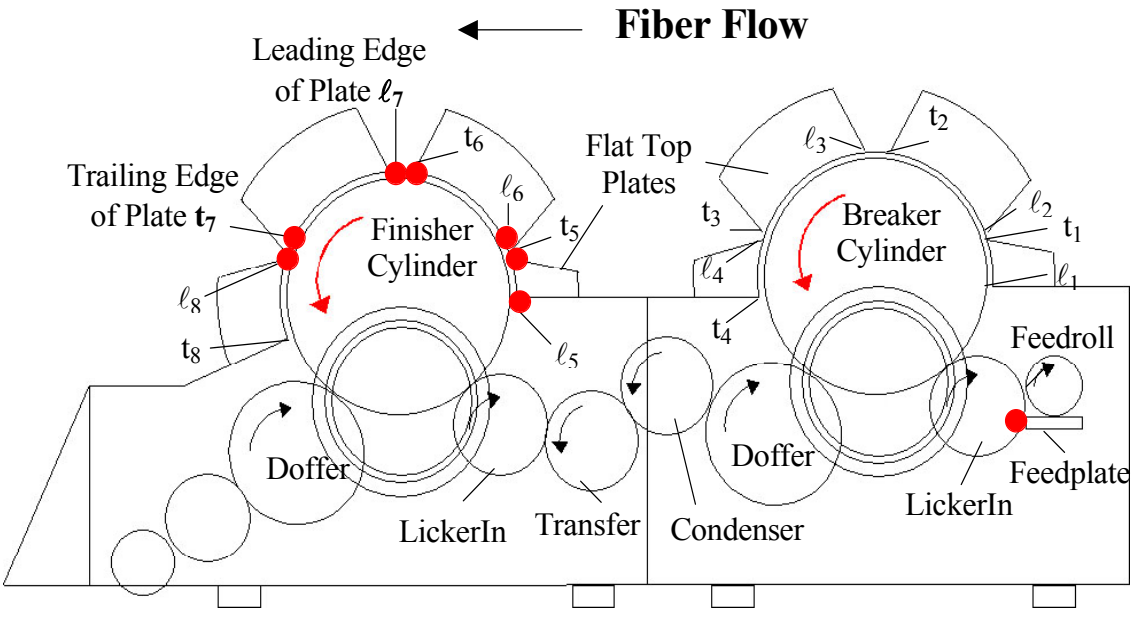


Figure 3.8: MASTERCARD®

Table 3.3: Experimental Plan for Carding of 3 den PET Fibers

Test #	Feedplate-LickerIn Clearance [inch]			Flat Clearances of Finisher Cylinder [inch]			Cylinder Speed [rpm]		
	0.017	0.029	0.034	ℓ5-0.017 t5-0.017 ℓ6-0.017 t6-0.017 ℓ7-0.017 t7-0.017 ℓ8-0.017 t8-0.012	ℓ5-0.022 t5-0.022 ℓ6-0.022 t6-0.022 ℓ7-0.022 t7-0.022 ℓ8-0.022 t8-0.012	ℓ5-0.034 t5-0.034 ℓ6-0.034 t6-0.034 ℓ7-0.034 t7-0.034 ℓ8-0.034 t8-0.012	500	800	1100
1			X			X		X	
2		X				X		X	
3	X					X		X	
4	X			X				X	
5		X		X				X	
6			X	X				X	
7			X		X			X	
8	X				X			X	
9		X			X			X	
10		X			X		X		
11		X			X				X

In order to explore the effect of these parameters, the carding experiments were performed according to the plan shown in Table 3.3. Other constant settings of card and needle loom are summarized in Table 3.4. For all tests, the material output of the card was kept constant at 15 grams/m^2, yielding a web weight of 50 grams/m^2 after the needle loom. For each of the three bales, fiber samples A, B, C, D and E were taken at random times. Furthermore, fiber samples F#1 through F#11 and G#1 through G#11 and web samples H#1 through H#11 and J#1 through J#11, Figure, were collected.

Table 3.4: Settings for Carding Experiments with 3den PET

Breaker Cylinder	Feed Roll Speed	2.7 rpm
	Feed Roll-to-Feed Plate Clearance	0.005”
	LickerIn Speed	535 rpm / 857 rpm / 1178 rpm
	LickerIn-to-Cylinder Clearance	0.010”
	CARDMASTER Flat Clearance	all Plates, Leading & Trailing Edges (l1-l4, t1-t4) 0.022”
	Doffer speed	335 rpm
	Doffer-to-Cylinder Clearance	0.010”
	Doffer-to-Condenser Clearance	0.012”
Transfer	Condenser Speed	24 rpm
	Condenser-to-Transfer Clearance	0.022”
	Transfer Speed	43 rpm
	Transfer-to-LickerIn Clearance	0.022”
Finisher Cylinder	LickerIn Speed of Finisher	278 rpm / 445 rpm / 612 rpm
	Doffer speed of Finisher	21 rpm
	Doffer-to-Cylinder Clearance	0.010”
Cross lapper		3.2 Double Layers
Needle Loom	Input Speed	5.48 m/min
	Output Speed	10.38 m/min
	Strokes Per Minute	200 for Slight Needling 760 for Regular Needling
	PPI	91 for Slight Needling 348 for Regular Needling
	Target Output Weight	50 grams/m^2

Needled fabrics were subsequently produced from these carded webs, but time precluded analysis by Dr. Ina Bauer-Kurz, which ultimately led to the initiation of this project, which is an investigation into the properties of those needled fabrics.

3.3 Test Procedures

The web samples H#1 through H#11 and J#1 through J11 from the carding experiments were tested for the following properties:

1. Basis weight
2. Tensile strength

3. Compressibility
4. Air permeability
5. ODF using image analysis.

3.3.1 Basis Weight

Basis Weight, in g/m^2, was determined by taking 10 random specimens of 0.1 X 0.1 m size out of every sample. The samples were then conditioned for 24 hrs at 65% RH and 70 F. The weights of the samples were then measured using a digital weighing machine and then converted to g/m^2.

3.3.2 Tensile Strength

Sintech Tensile Tester, Model 1/S fitted with a 5lb load cell was used to measure the tensile property and was carried out using the CRE principle and the test was conducted as detailed in ASTM D-5035-95.

The conditions used for carrying out the experiment, were as follows:

Atmospheric conditions	: 70° F, 65% RH
Specimen size	: 1" X 8"
Number of specimens	: 5 – MD, 5 – CD
Crosshead Speed	: 5cm/min
Gauge length	: 3"

For this test, five specimens per sample, 1" X 8" were cut out from each web with the aid of a template along both machine and cross direction. The sample weights were taken down after being conditioned for 24 hrs at 65& RH and 70° F.

Angular Tensile properties

The angular tensile properties were tested at 10° intervals starting with 18° till 180°. For this purpose a template was prepared representing 0°, 18°, 36°, 54°, 72°, and 90° on it and since it is symmetric the results for the other half range were replicated assuming uniform distribution of mass. Similar testing conditions were used.

3.3.3 Compressibility Tests

An Instron Tensile Tester, model 4400 R, fitted with a 50-kg compression load was used to measure the compression property.

In this experiment, the compression tests were done under the following conditions:

Atmospheric conditions	: 70° F, 65% RH
Specimen size	: 10 X 10 cm
Number of specimens	: 5
Crosshead speed	: 1mm/min
Platen separation	: 8mm
Strain Endpoint	: 30%
Data Acquisition rate	: 10 Hz

The sample weights were taken down before starting the testing after being conditioned for 24 hrs at 65% RH and 70° F.

3.3.4 Air Permeability Test

Air permeability was determined as detailed in ASTM D 737 – 96 using Frazier air permeability apparatus. Five specimens from each sample were taken for testing air permeability within in a 1" test area and rates of air flow were determined in Cubic Feet, per Square Foot of Fabric per Minute at 30" Mercury, 70° F, and 65% Relative Humidity.

3.3.5 Image Analysis (ODF measurement)

Distributions of fiber orientation angle were measured under a microscope. LED (Light Emitting Diode), a diffused light source was used for this purpose and the images were captured using a CCD (closed circuit display) camera placed directly above the light source, which were analyzed on a commercially available image analysis system (Figure 3.9).

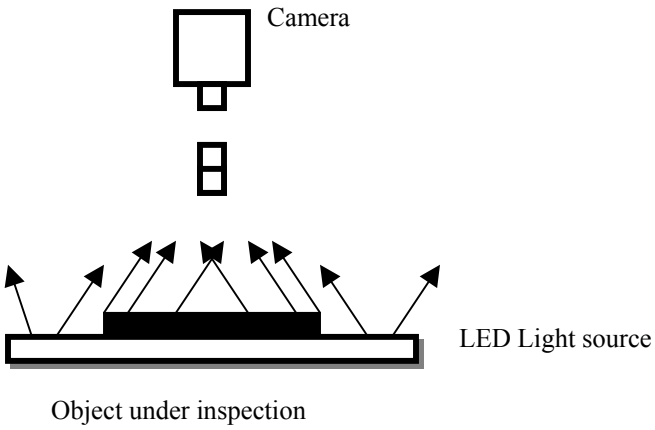


Figure 3.9: Image analysis system

For each fabric, three specimens were examined. Histograms of the number of fibers per 5° interval against the orientation angle with respect to the machine direction are shown in figure.

Specimens from each sample were taken for testing. The magnification of the camera lens was set at 1.0 and the zoom was around 200% i.e. twice the size of the initial size of the image. The images were captured using capture settings RS-170, 640 X 480, 8 bits, 12.5 MHz, analog. And the images were grabbed using a preset brightness and contrast levels and by properly adjusting the fine and coarse levels on the light source. The images were resized according to the dimensions given below in figure 3.10 due to the edge effects essentially to improve the visual appearance of an image to a form better suited to human or machine analysis and the Orientation Distribution Function determined using the settings shown in figure 3.11.

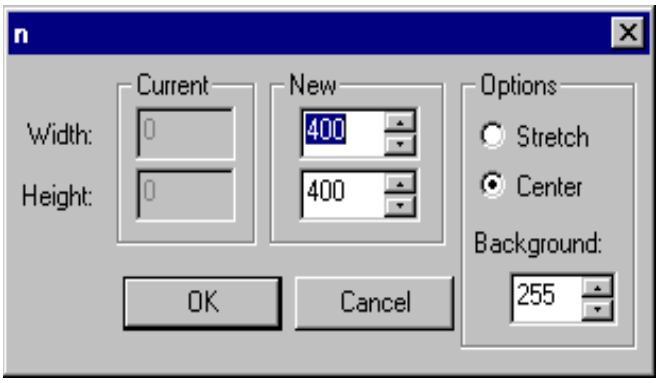


Figure 3.10: Settings used for resizing the image

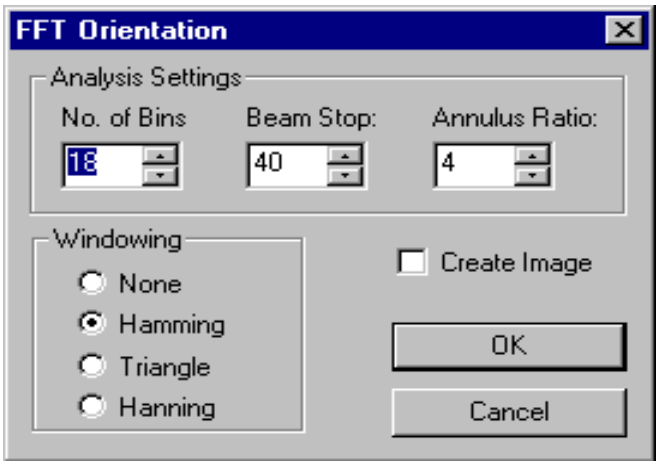


Figure 3.11: Settings used for determing fiber orientation function (ODF)

3.3.6 Thickness measurements

Thickness in mm was determined using a digimatic indicator from Spacenet. The sample was conditioned for 24 hrs at 65% RH and 70° F. Five measurements were taken randomly for each sample and the mean determined for each sample.

3.3.7 Z-Directional Test

This test was performed to determine the strength of entanglement or interlocking for the final needled fabrics, but the test didn't work out because of the improper tape attached to the sample being tested during the experimental run.

4 RESULTS AND DISCUSSION

The result of the experimental runs and explanation for the results are presented in this chapter. Experiments were conducted to analyze the influence of each of the following on the needled fabric properties:

- Effect of fiber type (fiber crimp and finish).
- Effect of Cylinder speeds.
- Effect of Feedplate-lickerin clearance.
- Effect of Flat clearances.
- Effect of Needling density.

4.1 Basis weight results:

The interpretation of basis weight data was done using statistical analysis and this was accomplished using SAS. In SAS, ANOVA procedure was used to determine which of the variables contributed statistically to the differences in the basis weight distribution. The final F-statistics, p-values, and the decision whether the variables involved contributed significantly to the group differences are summarized in Table: 4.1

Table: 4.1 summarizes the results of the General Linear Model (GLM) procedure for the basis weight.

Table 4.1: Summary of Statistics from the GLM procedure

Variable	F-Statistic	p-value	Interpretation
MT	12.51	0.0003	Significant
CS	4.68	0.0016	Significant
ND	18.87	0.0003	Significant
MT*CS	2.1	0.0525	Significant
MT*ND	0.01	0.9896	Insignificant
CS*ND	1.43	0.237	Insignificant

Where MT - Material type, CS - Card settings, ND - Needling density.

The ANOVA procedure sets each variable, in turn, equal to the material type variable, card settings type variable, and needling density type, and also setting the group interactions as variables. For each variable, the null hypothesis that the variable does not contribute to differences in basis weight versus the alternative hypothesis that the variable contributes to differences is tested. A general rule of thumb in using this analysis is to reject the null hypothesis if the F-statistic is greater than 2.00.And this was done at 95% confidence level.

Based on the results from the ANOVA analysis the contribution of the different variables involved was studied. In this analysis, fiber crimp, card settings and needling density individually as well as the fiber crimp-card settings interactions were found to contribute significantly to the differences in basis weight, while none of the fiber crimp-needling density and card settings-needling density interactions were significant.

The significant effects of each of the variable parameter on the differences in basis weight measurements were studied further in detail.

4.1.1 Effect of fiber type:

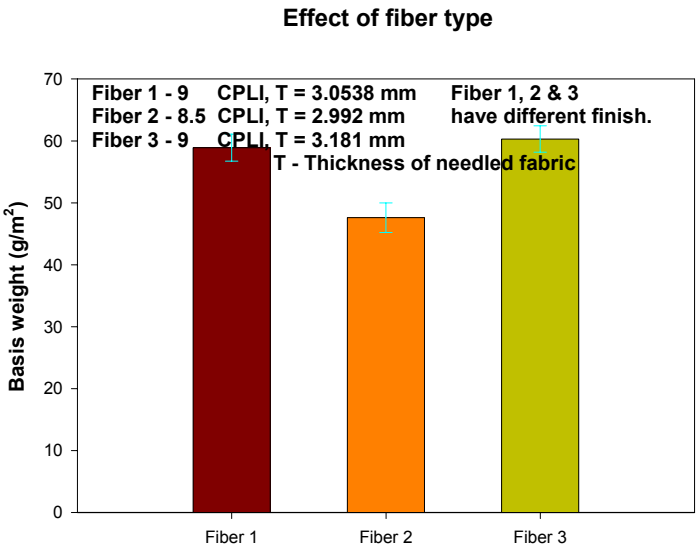


Figure 4.1: Basis weights of needled fabrics produced using three different 3 den PET fibers.

Figure 4.1 illustrates the effect of fiber type (fiber crimp and finish) alone on the basis weight of the final needled fabrics. (Feedplate-lickerin clearance – 0.029", Cylinder speed – 800 rpm, Flat clearance – 0.022").

The basis weight of the three fabrics produced from fibers of the same polymeric material having different crimp characteristics and finish level as seen from the figure are in the order of Fiber 3>Fiber 1>Fiber 2. There is no perceptible difference observed for fiber 1 and fiber 3, but a considerable difference in the basis weights is observed between fiber 1 and fiber 2 and also between fiber 3 and fiber 2. And also more compact structure is formed for fabrics with fiber 1 and fiber 3 than with fiber 2. This behavior is mostly due to their inherent fiber crimp characteristics and mechanical crimp removal behavior under the multiple subjection of loads during processing.

4.1.2 Effect of cylinder speeds:

Figures 4.2 through 4.4 shows the influence of cylinder speeds on the basis weights of the needled fabrics produced from each of the three fibers. (Feedplate-lickerin clearance – 0.029", Flat clearance – 0.022").

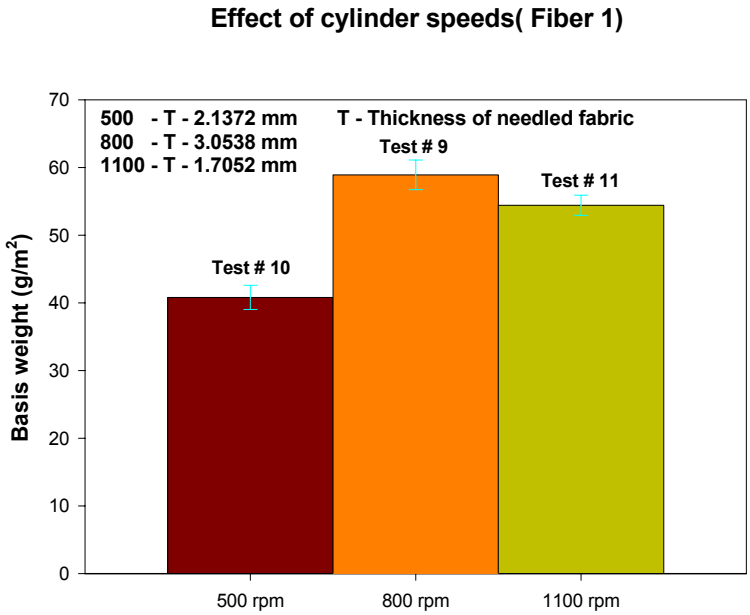


Figure 4.2: Basis weight of needled fabrics from fiber 1 produced using different cylinder speeds

In figure 4.2 (fiber 1), the basis weight increases with the cylinder speed, though this is not generally expected; because the increase in cylinder speeds causes more opening of the fibers (less entanglements), the fiber mass gets drafted, stretched and pulled apart which essentially causes reduction in the mass per unit area of the fabric. The trend observed between 800 rpm and 1100 rpm is adequate though there is not a perceptible difference.

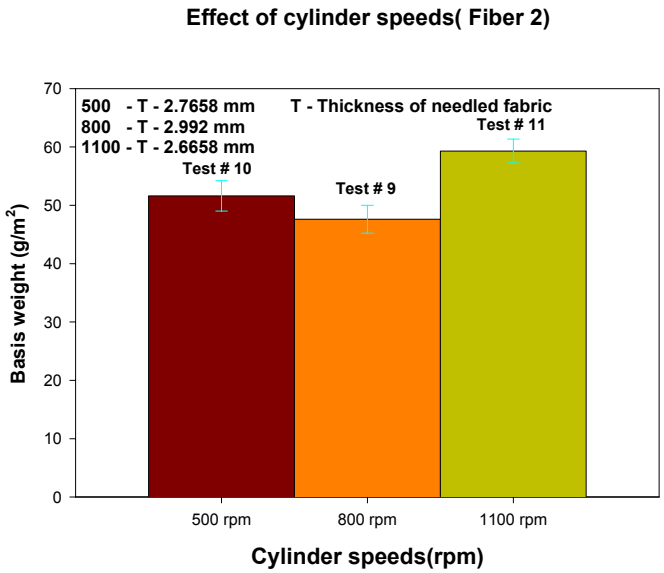


Figure 4.3: Basis weight of needled fabrics from fiber 2 produced using different cylinder speeds

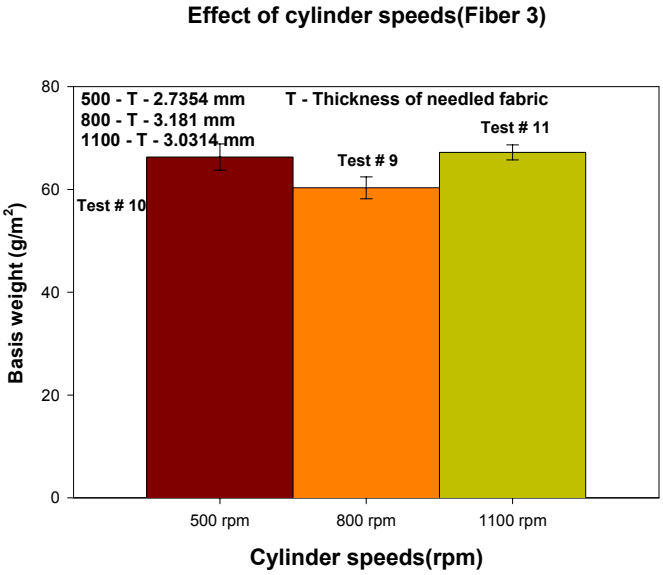


Figure 4.4: Basis weight of needled fabrics from fiber 3 produced using different cylinder speeds

In figure 4.3 (fiber 2) and figure 4.4 (fiber 3), the basis weight decreases with increase in cylinder speeds from 500 to 800 rpm, which is usually expected, but there is a slight increase in the basis weight with an increase in cylinder speed from 800 to 1100 rpm, though the difference is statistically insignificant.

The deviations from the expected results might be due to many factors coming into play during processing like throughput, cylinder to doffer setting and influence of fiber finish, which couldn't to established.

4.1.3 Effect of Feedplate-Lickerin clearances

Figures 4.5 through 4.13 shows the influence of feedplate-lickerin clearances on the basis weights of the final needled fabrics produced from each of the three fibers.

There are three graphs shown for each of the 3 fibers .The test #'s in the following graphs were the tests associated with the experimental plan carried out for carding 3 den PET fibers, which designates the production of a needled fabric using same cylinder speeds (800 rpm) and flat clearances but different feedplate-lickerin clearance settings. When comparing the measurements between the graphs obtained for the same fiber but using a different test sequence from the carding plan, the only variable observed between these graphs was the flat clearance setting.

Figures [4.5, 4.8 and 4.11] , [4.6, 4.9 and 4.12] and [4.7, 4.10, and 4.13] have the respective flat clearance settings 0.022", 0.034" and 0.017". So the slight discrepancy in the measurements/ trends observed between the graphs of the same fiber may be due to the different flat clearance settings.

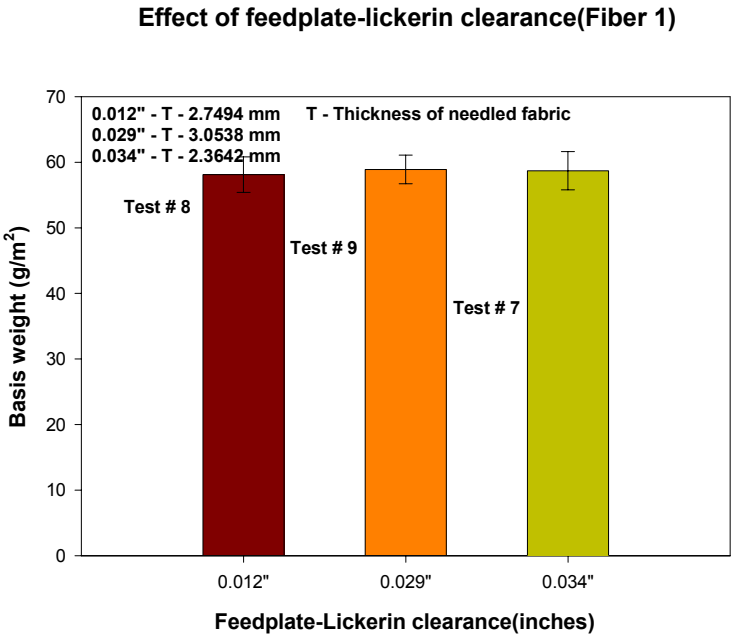


Figure 4.5: Basis weight of needled fabrics from fiber 1 produced using different feedplate-lickerin clearance.

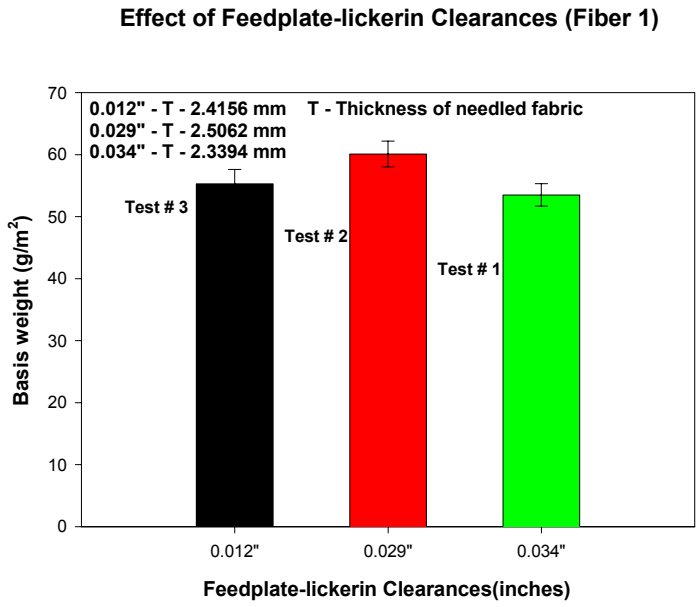


Figure 4.6: Basis weight of needled fabrics from fiber 1 produced using different feedplate-lickerin clearance.

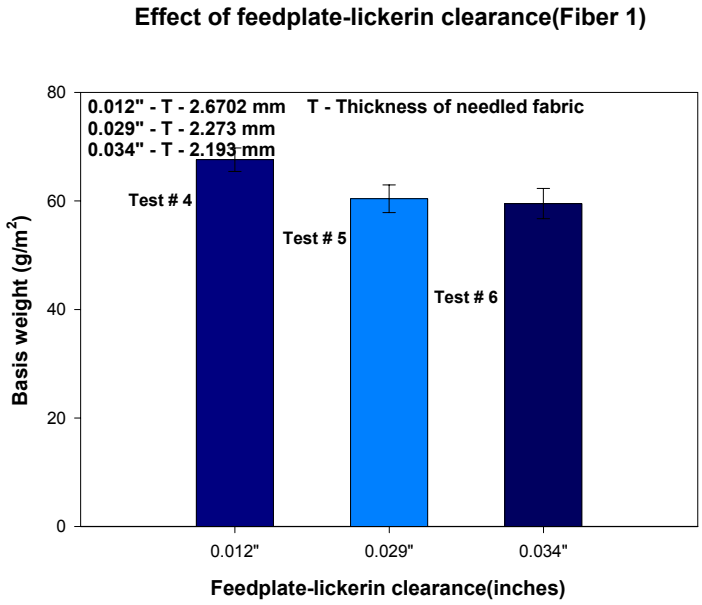


Figure 4.7: Basis weight of needled fabrics from fiber 1 produced using different feedplate-lickerin clearance.

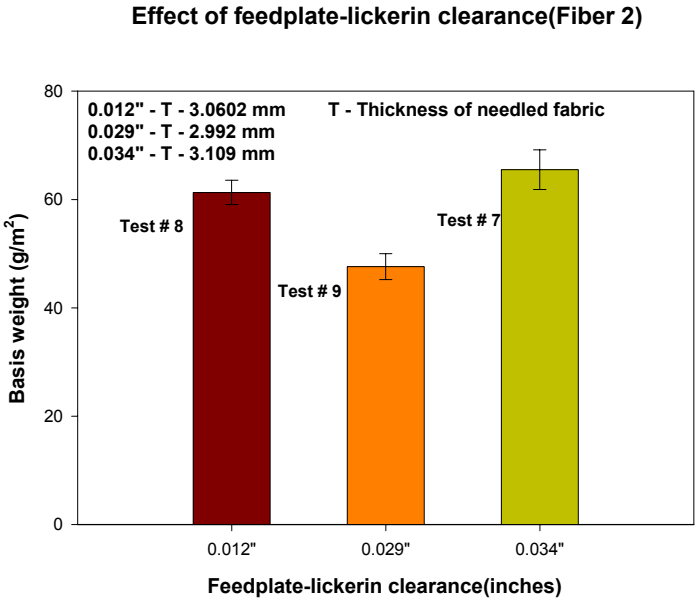


Figure 4.8: Basis weight of needled fabrics from fiber 2 produced using different feedplate-lickerin clearance.

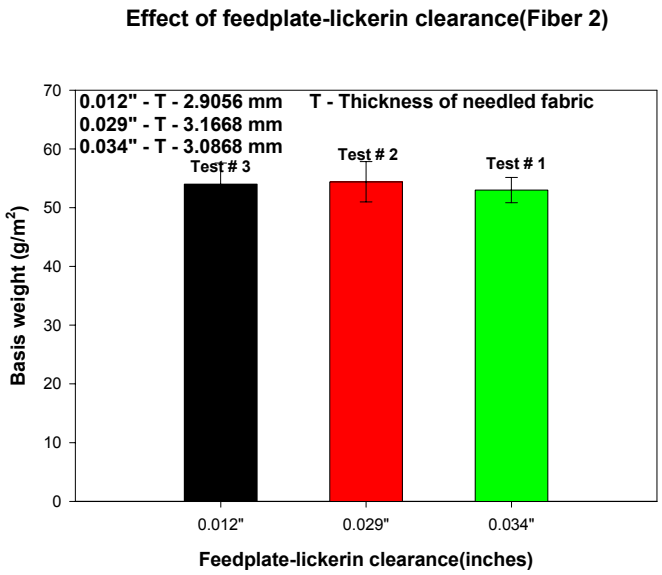


Figure 4.9: Basis weight of needled fabrics from fiber 2 produced using different feedplate-lickerin clearance.

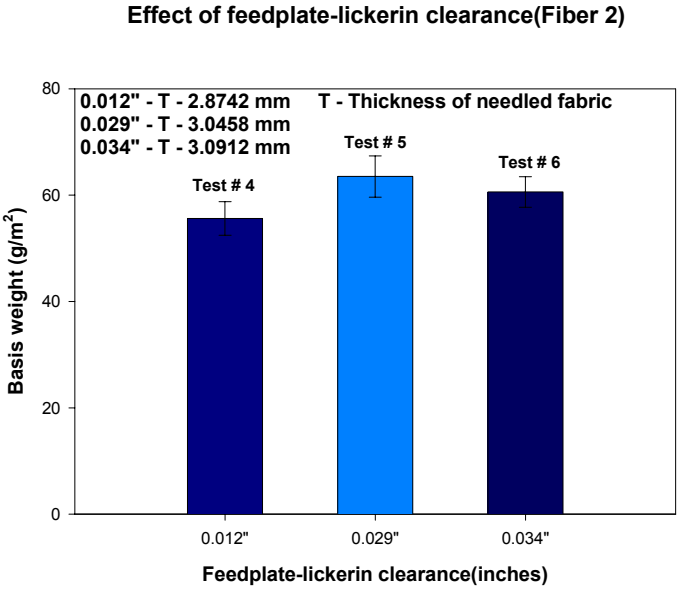


Figure 4.10: Basis weight of needled fabrics from fiber 2 produced using different feedplate-lickerin clearance.

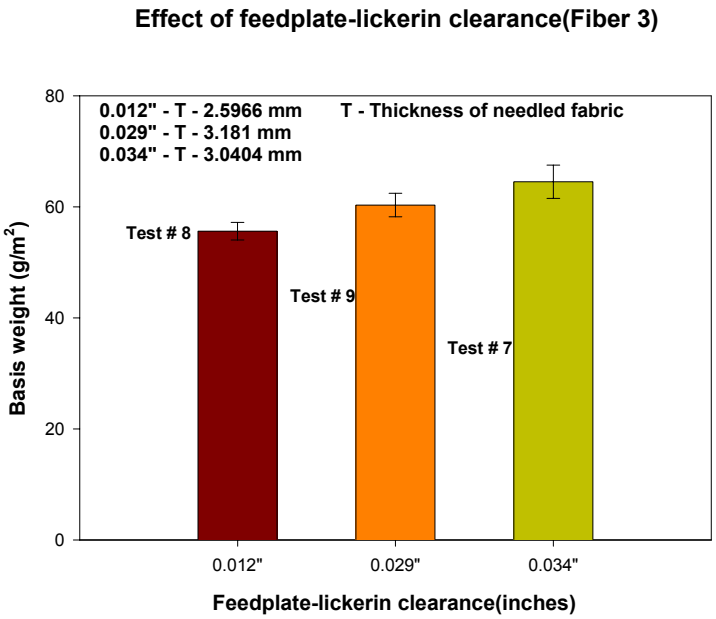


Figure 4.11: Basis weight of needled fabrics from fiber 3 produced using different feedplate-lickerin clearance.

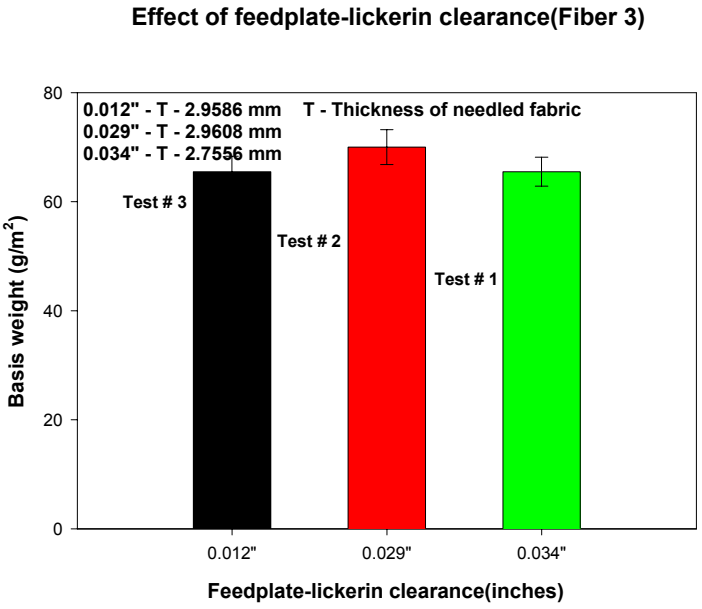


Figure 4.12: Basis weight of needled fabrics from fiber 3 produced using different feedplate-lickerin clearance.

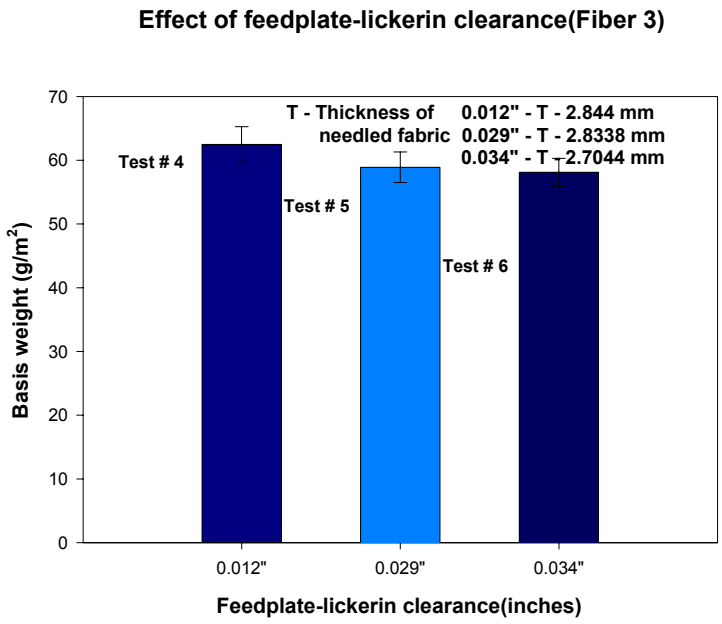


Figure 4.13: Basis weight of needled fabrics from fiber 3 produced using different feedplate-lickerin clearance.

The feedplate-lickerin clearance essentially controls the initial opening of the fiber mass and also critically effects the crimp removal. The fiber length to some extent and the feed weight dictates the clearance. And for all the graphs presented below no significant differences in the basis weights were observed. The influence of feedplate-lickerin clearance on basis weight could not be established. This might be due to the insufficient sample sizes of the fabrics tested and also due to large variation observed within the same fabric samples.

4.1.4 Effect of Flat clearances

Figures 4.14 through 4.22 depicts the influence of flat clearances on the basis weights of the final needled fabrics produced from each of the three fibers.

There are three graphs shown for each of the 3 fibers. The test #'s in the following graphs were the tests associated with the experimental plan carried out for carding 3 den PET fibers, which designate the production of a needled fabric using same cylinder speeds

(800 rpm) and feedplate-lickerin clearance but different flat clearance settings. When comparing the measurements between the graphs obtained for the same fiber but using a different test sequence from the carding plan, the only variable observed between these graphs was the feedplate-lickerin clearance setting.

Figures [4.14, 4.17, and 4.20] , [4.15, 4.18, and 4.21] and [4.16, 4.19, and 4.22] have the respective feedplate-lickerin clearance settings 0.029", 0.034" and 0.012". So the slight discrepancy in the measurements/ trends observed between the graphs of the same fiber may be due to the different feedplate-lickerin clearance settings.

The most critical setting in a carding machine is between cylinder and flat tops. The flat clearance essentially opens the flocks to individual fibers, removes short fibers, impurities and trash, reduces the formation of neps and aids in longitudinally orienting the fibers. So closer the setting, better the web quality in terms of uniformity, short fibers, neps and less variations in the desired properties.

And for all the graphs presented below no significant differences in the basis weight measurements were observed. The influence of flat clearance on basis weight could not be established. This might be due to the insufficient sample sizes of the fabrics tested.

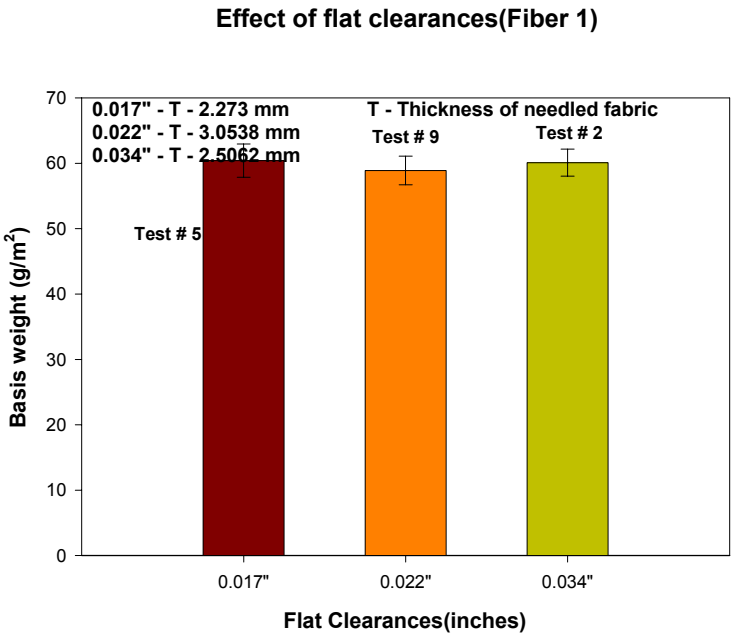


Figure 4.14: Basis weight of needled fabrics from fiber 1 produced using different flat clearances.

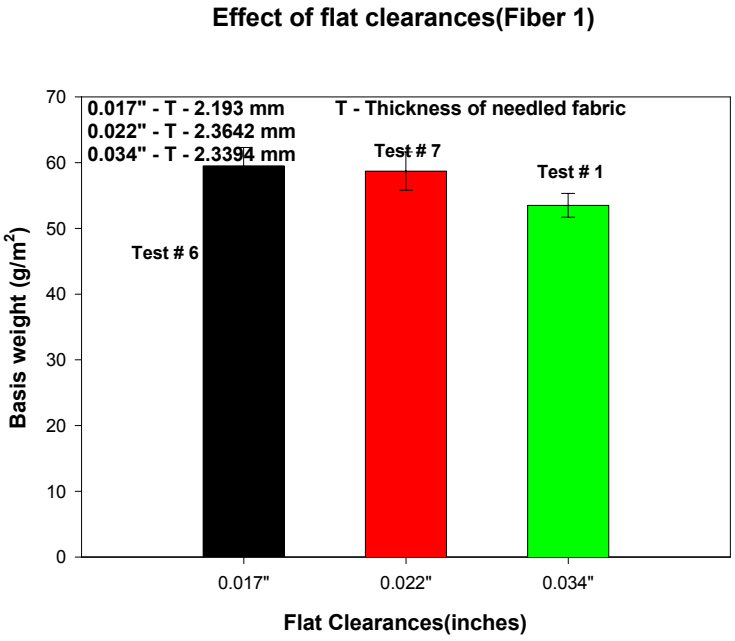


Figure 4.15: Basis weight of needled fabrics from fiber 1 produced using different flat clearances.

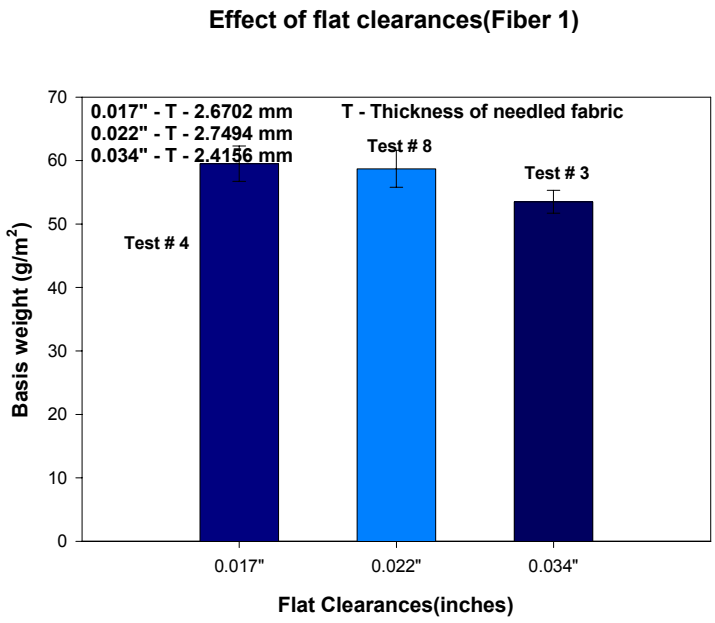


Figure 4.16: Basis weight of needled fabrics from fiber 1 produced using different flat clearances.

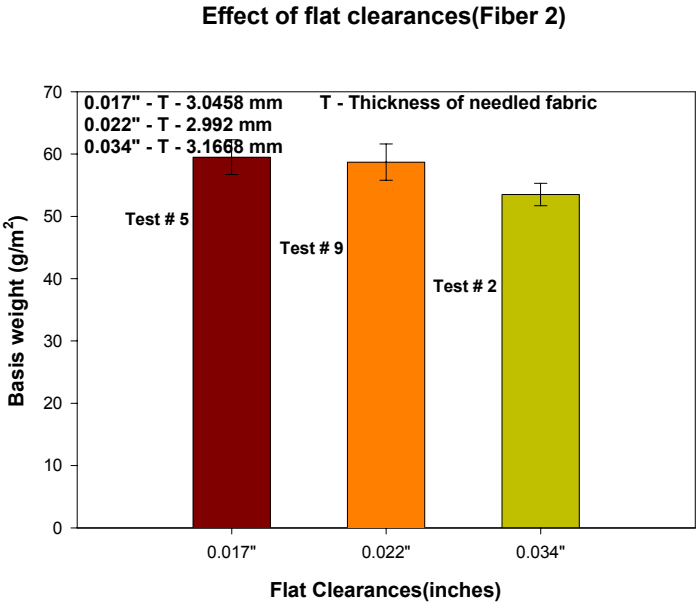


Figure 4.17: Basis weight of needled fabrics from fiber 2 produced using different flat clearances.

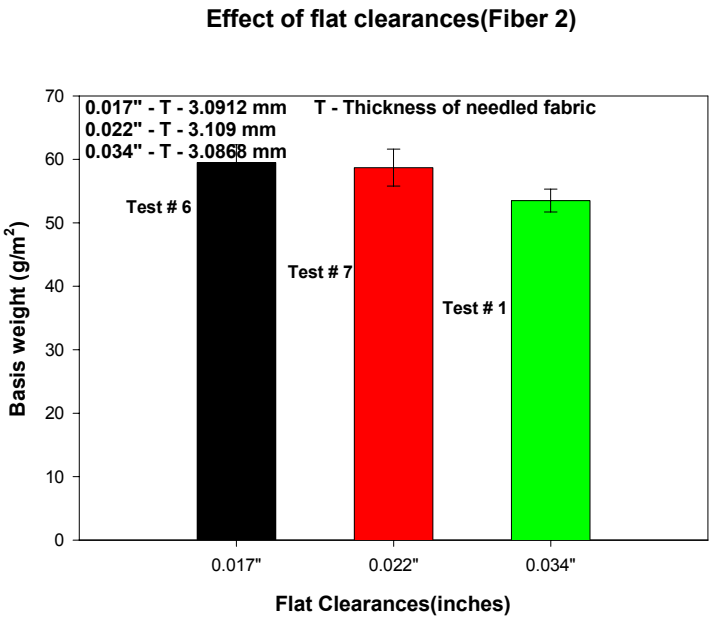


Figure 4.18: Basis weight of needled fabrics from fiber 2 produced using different flat clearances.

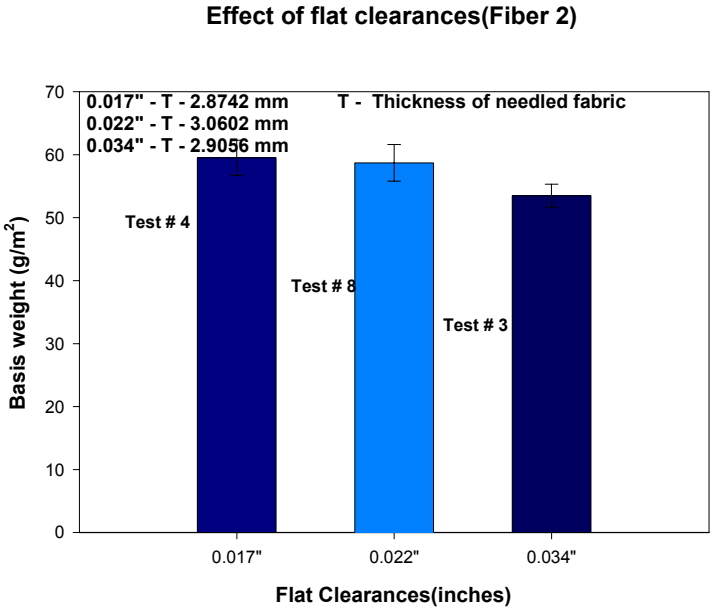


Figure 4.19: Basis weight of needled fabrics from fiber 2 produced using different flat clearances.

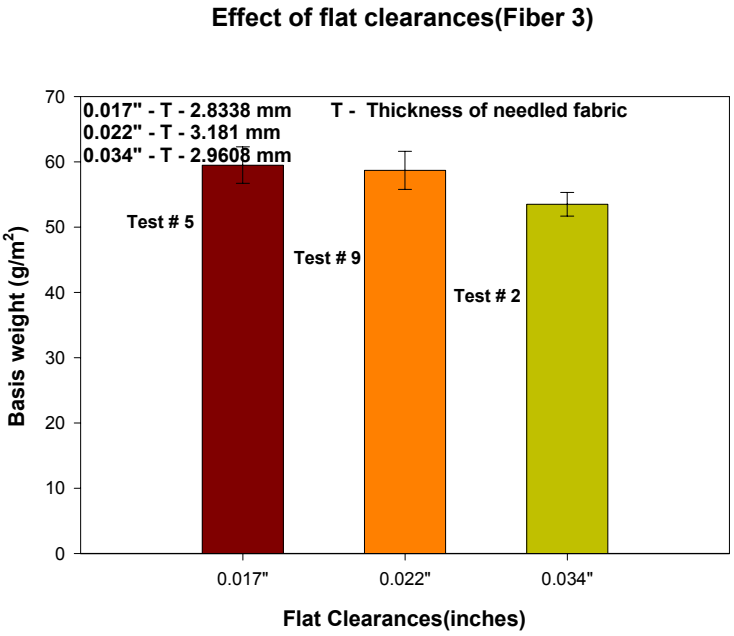


Figure 4.20: Basis weight of needled fabrics from fiber 3 produced using different flat clearances.

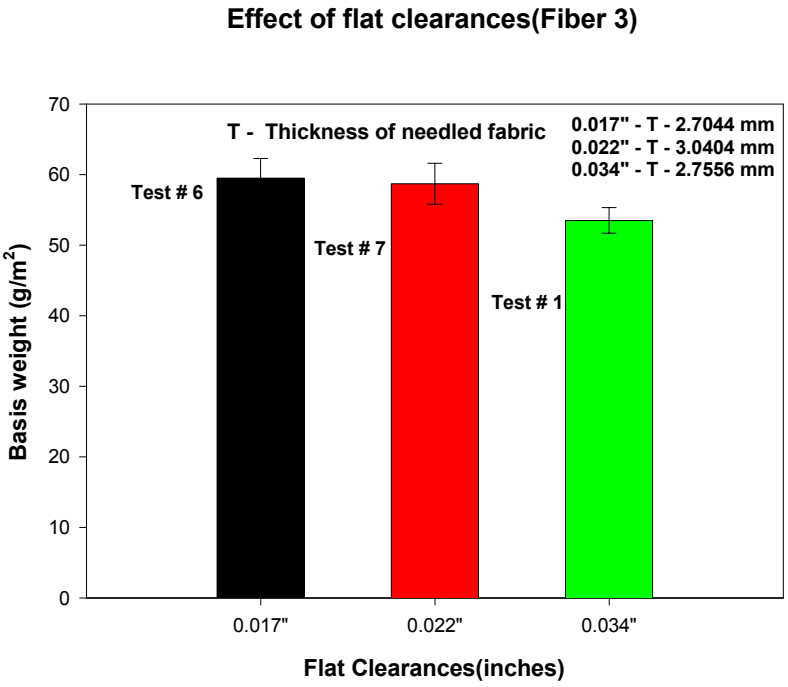


Figure 4.21: Basis weight of needled fabrics from fiber 3 produced using different flat clearances.

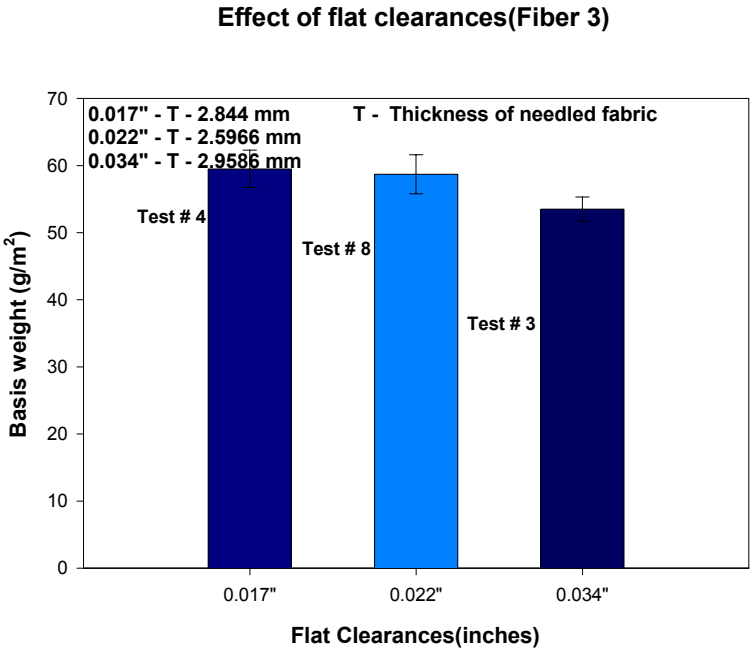


Figure 4.22: Basis weight of needled fabrics from fiber 3 produced using different flat clearances.

4.1.5 Effect of Needling densities

Figures 4.23 through 4.25 depicts the influence of needling density on the basis weights of the final needled fabrics from each of the 3 different PET fibers. (Feedplate-lickerin clearance – 0.029", Cylinder speed – 800 rpm, Flat clearance – 0.022").

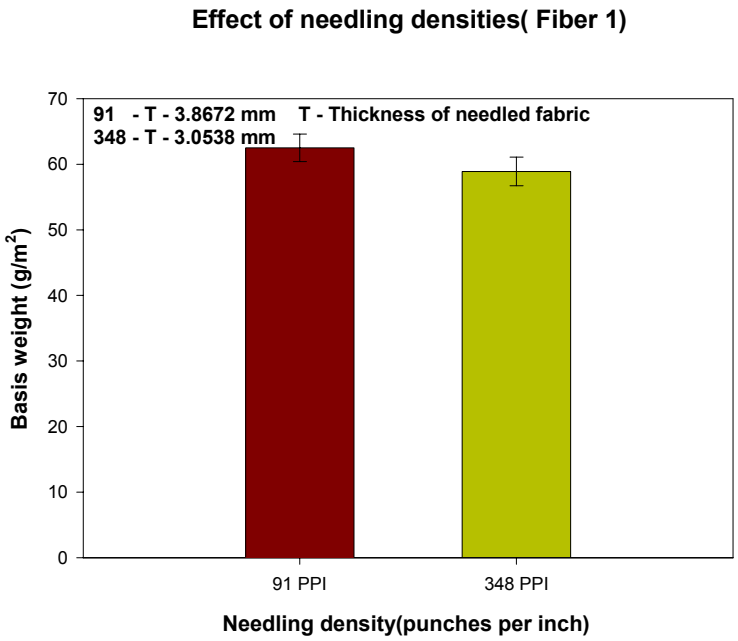


Figure 4.23: Basis weight of needled fabrics from fiber 1 produced using different needling densities.

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In figure 4.23 (fiber 1), the basis weight decreases with increase in needling density. This is because as needling density (punches per square inch) increases, this increases the needle forces acting on a unit area of a fabric pulling (drafting) the mass of fibers apart making it more uniform.

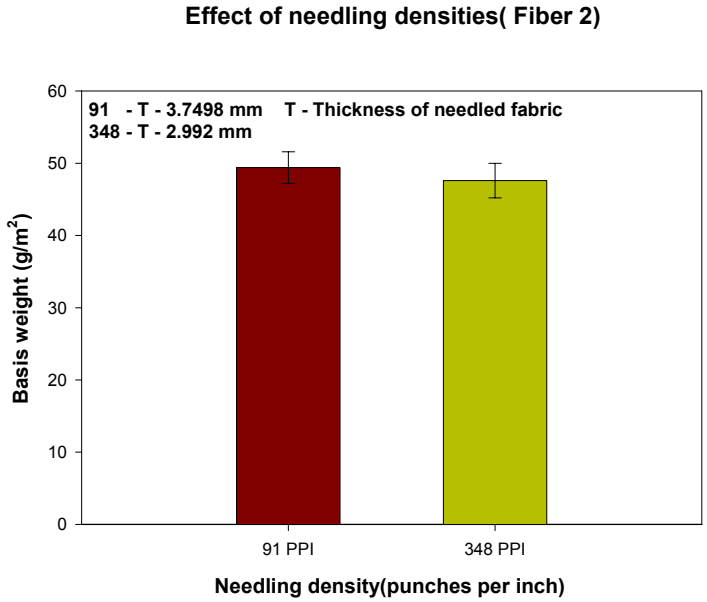


Figure 4.24: Basis weight of needled fabrics from fiber 2 produced using different needling densities.

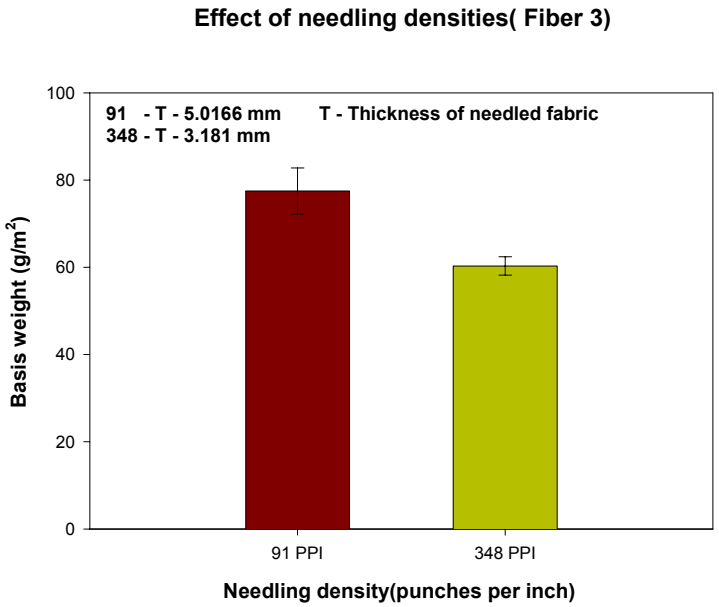


Figure 4.25: Basis weight of needled fabrics from fiber 3 produced using different needling densities.

Similar trends are observed for fiber 2 (figure 4.24) and fiber 3 (figure 4.25) as well. A significant change is observed between fiber 1 and fiber 3, this might be due to the inherent fiber crimp characteristics and their behavior to loads during processing.

4.2 Air permeability measurements:

Air permeability is defined as "the rate of air flow through a material under a differential pressure between the two fabric surfaces." [1] Porosity can be defined as the total volume of void space contained within the boundaries of a material. In discussing the relationship between porosity and permeability, Scheidegger [2] prefers the term "pore structure," claiming that there can be no general correlation between porosity and permeability because the permeability of a material is influenced by the capillary pressure curves and the internal surface area of the pores within the material, rather than the actual volume of the open space.

Several previous studies have addressed the relationship between air permeability and structural characteristics of nonwovens, including fabric weight, thickness, density and

fiber diameter. [5,6,7,8,9] Generally, these studies have shown that air permeability decreases nonlinearly as thickness, weight or fabric density increases. However, in a study of 80 nonwoven filters, air permeability declined linearly with increases in thickness. The same study also showed that fabric density had a more significant influence on air permeability than either thickness or fiber size. [5]

In a study designed to determine how the method of conversion of a fiber web into a nonwoven fabric influenced air permeability, Kothari and Newton [6] found that among the needle punched, stitch bonded and adhesive bonded fabrics that were evaluated, weight per unit area was a stronger determinant of air permeability than either thickness or fabric density. Evaluating the same data, Dent [7] maintained that the second most important factor was fabric density.

Atwal [8] studied 140 needle-punched fabrics constructed from 16 different fibers. A wind tunnel was used to determine fabric air resistance, the reciprocal of air permeability. Air resistance increased with fabric thickness and fabric weight per unit area, but decreased with fiber fineness.

Air permeability measurements are used to determine pore size distribution in the sample. Fiber-fiber cohesion within the fabric structure, which is determined by the inherent fiber crimp characteristics and fiber finish, affects the pore size and their distribution.

So the basis weights and the thickness of the all the fabric samples have been taken into consideration to understand the influence of each of the raw material and process related parameter on air permeability measurements.

4.2.1 Effect of fiber type

Figure 4.26 shows the influence of fiber type on the air permeability of the final needled produced from 3 different fibers of same polymeric material with different fiber crimp characteristics. (Feedplate-lickerin clearance – 0.029", Cylinder speed – 800 rpm, Flat clearance – 0.022").

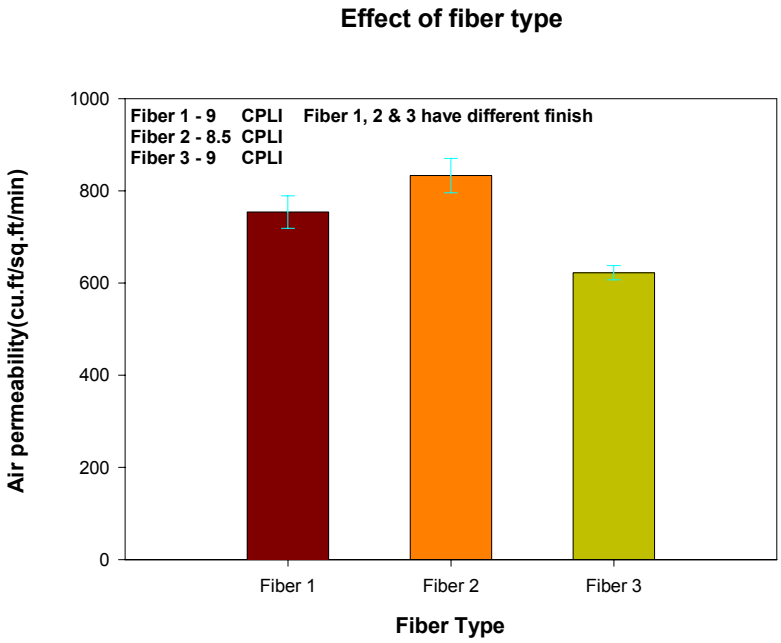


Figure 4.26: Air permeability of needled fabrics produced using three different 3-den PET fibers.

The increasing order of airflow rates of the needled fabrics were Fiber 2>Fiber 1>Fiber 3. This can very well be explained by their basis weights which arranged in the increasing order are Fiber 3>Fiber 1>Fiber 2. Therefore, the air resistance increased with the fabric weight per unit area.

4.2.2 Effect of cylinder speeds

Figures 4.27 through 4.29 depict the influence the cylinder speeds on the air permeability's of the needled fabrics produced from each of the 3 different PET fibers. (Feedplate-lickerin clearance – 0.029", Flat clearance – 0.022")

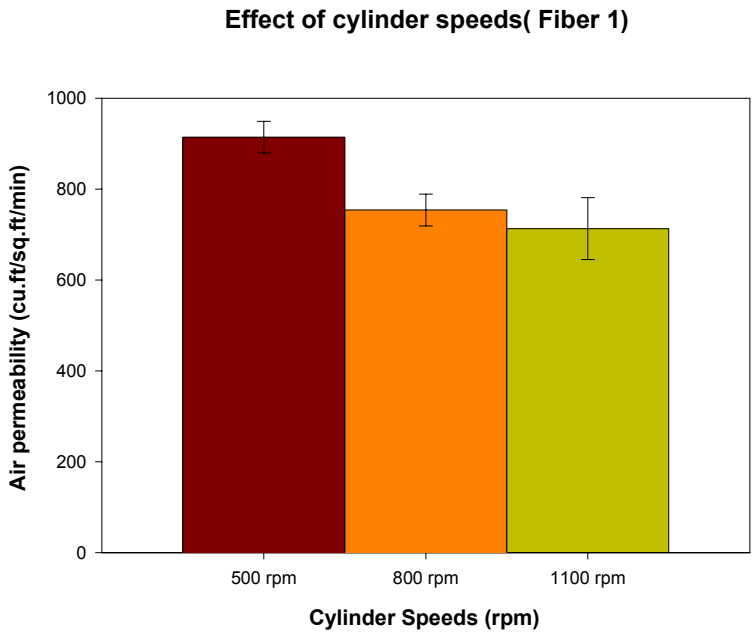


Figure 4.27: Air permeability of needled fabrics from fiber 1 produced using different cylinder speeds.

In figure 4.27 (Fiber 1), the air permeability decreased with the cylinder speed which is in good agreement with the basis weight measurements, 800>1100>500. Generally speaking, the basis weight should decrease with the cylinder speed, which is not the case here, which might be due to several other factors coming into play during processing.

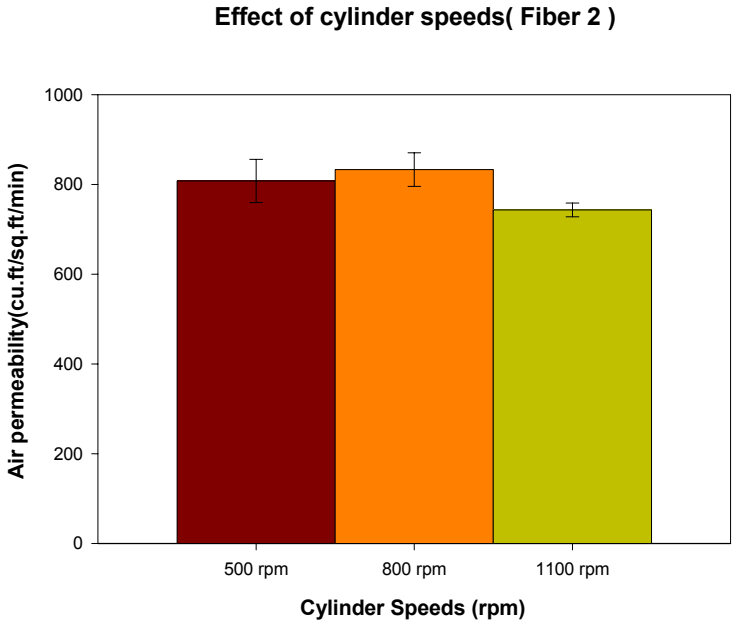


Figure 4.28: Air permeability of needled fabrics from fiber 2 produced using cylinder speeds.

In figure 4.28 (Fiber 2), there has been no significant change in the air permeability values with the cylinder speeds but were in direct proportion their respective basis weights 1100>500>800 rpm.

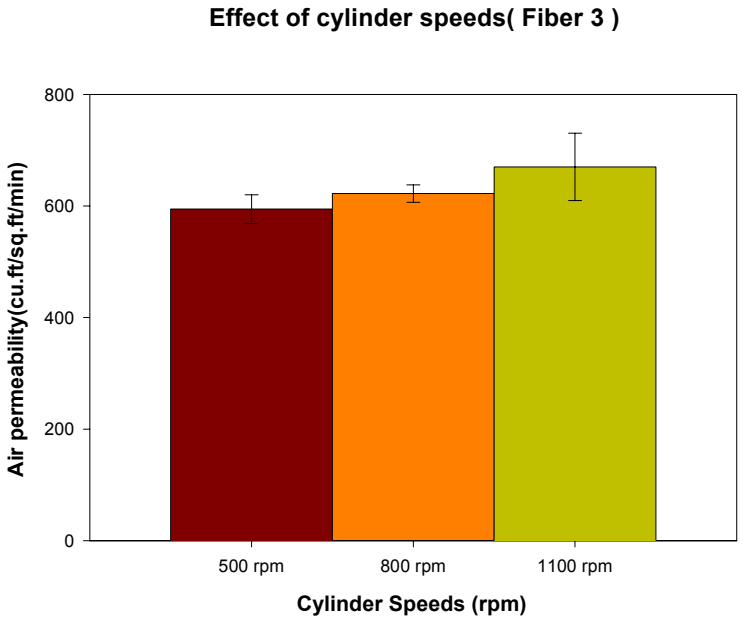


Figure 4.29: Air permeability of needled fabrics from fiber 3 produced using different cylinder speeds.

In figure 4.29 (Fiber 3), the air permeability values increased with the cylinder speeds, which is what is generally expected though there has not been a significant change. The values were not in proportion to the basis weights 1100>500>800 rpm but were in proportion to the thickness of the needled fabrics.

4.2.3 Effect of Needling density

Figures 4.30 through 4.32 shows the effect of needling density on the air permeability of the needled fabrics produced from each of the 3 different PET fibers. (Feedplate-lickerin clearance – 0.029", Cylinder speeds – 800 rpm, Flat clearance – 0.022")

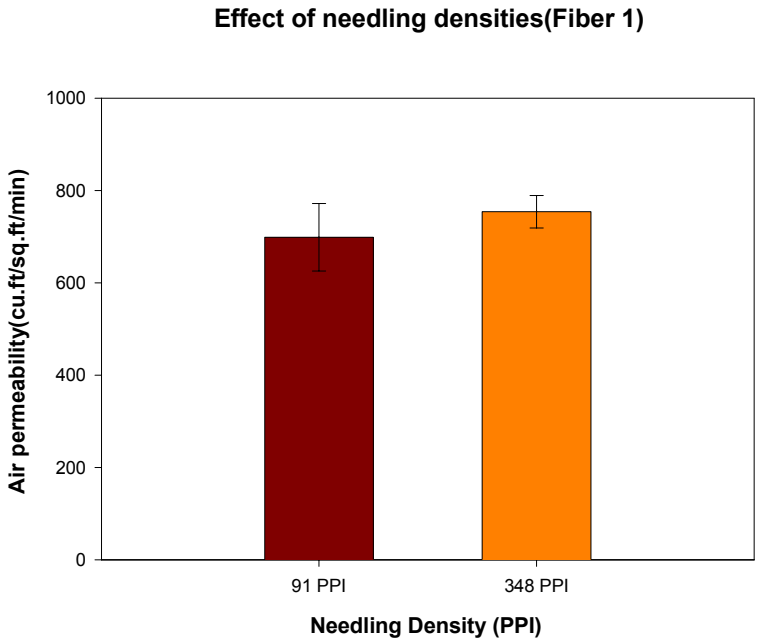


Figure 4.30: Air permeability of needled fabrics from fiber 1 produced using different needling densities.

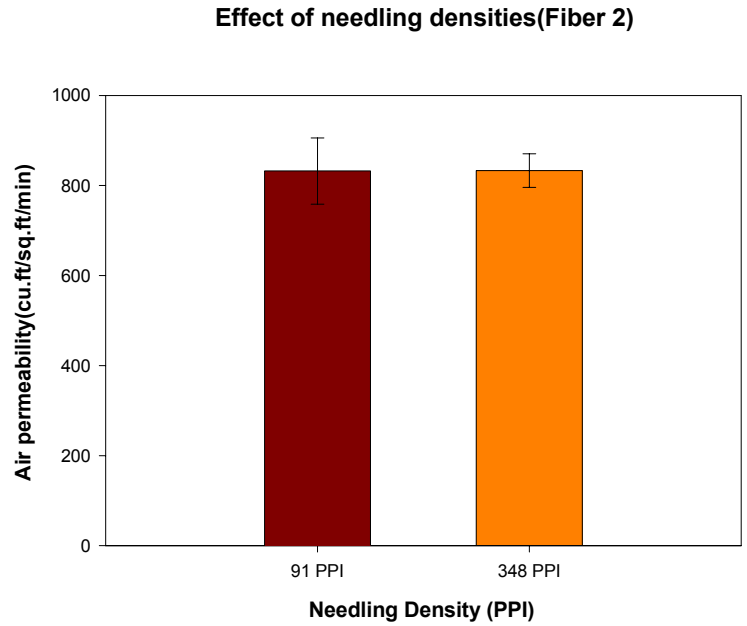


Figure 4.31: Air permeability of needled fabrics from fiber 2 produced using different needling densities.

In figure 4.30 (Fiber 1), the air permeability increased with needling density though the difference is negligible. Increase in needling density essentially decreases the basis weights 91>348 PPI, therefore the air permeability measurements are in direct proportion to the basis weights of the needled fabrics. In figure 4.31 (fiber 2), no considerable difference has been observed, but were in agreement to the basis weights of the needled fabrics. In figure 4.32 (Fiber 3), similar behavior was observed as with fiber 1.

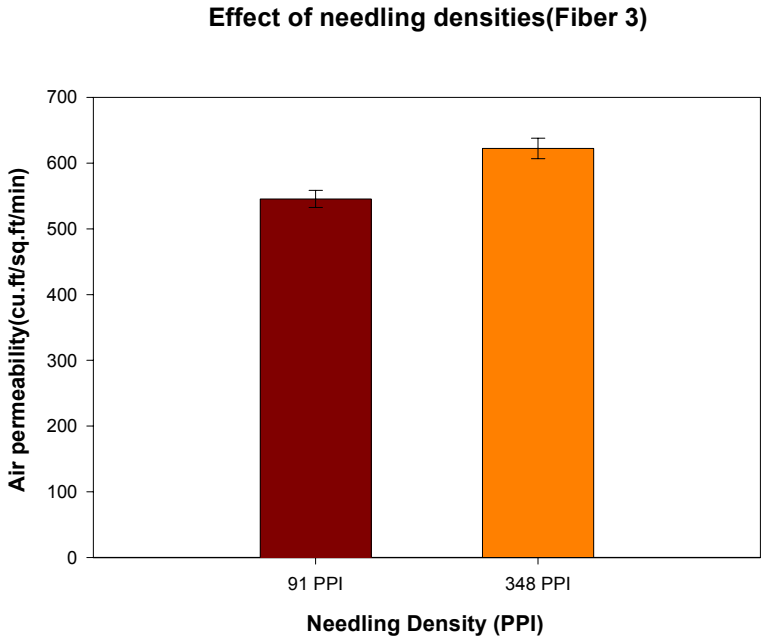


Figure 4.32: Air permeability of needled fabrics from fiber 3 produced using different needling densities.

4.2.4 Effect of Feedplate-Lickerin clearance

Figures 4.33 through 4.41 shows the influence of feedplate-lickerin clearances on the air permeability measurements of the final needled fabrics produced from each of the three fibers.

There are three graphs shown for each of the 3 fibers. The test #'s in the following graphs were the tests associated with the experimental plan carried out for carding 3 den PET fibers, which designate the production of a needled fabric using same cylinder speeds

(800 rpm) and flat clearances but different feedplate-lickerin clearance settings. When comparing the measurements between the graphs obtained for the same fiber but using a different test sequence from the carding plan, the only variable observed between these graphs was the flat clearance setting.

Figures [4.33, 4.36, and 4.39] , [4.34, 4.37, and 4.40] and [4.35, 4.38, and 4.41] have the respective flat clearance settings 0.022", 0.034" and 0.017". So the slight discrepancy in the measurements/ trends observed between the graphs of the same fiber may be due to the different flat clearance settings.

From the discussion of the basis weight results we studied that the effect of feedplate-lickerin clearance on the basis weight of the needled fabrics was negligible. Since weight per unit area was a stronger determinant of air permeability, therefore, there has not been a considerable change in the air permeability measurements observed for needled fabrics produced from each of the 3 different PET fibers, but most of the measurements were in good agreement with either the basis weight or their respective thickness.

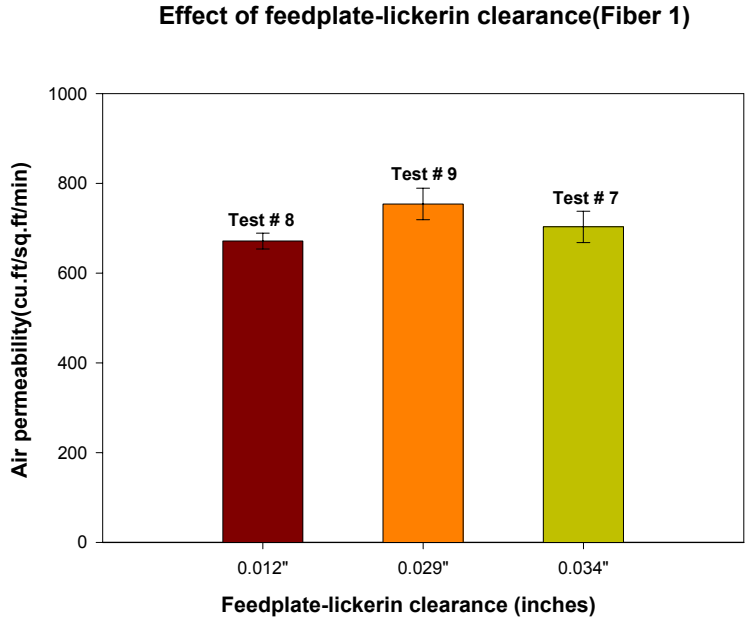


Figure 4.33: Air permeability of needled fabrics from fiber 1 produced using different feedplate-lickerin clearances.

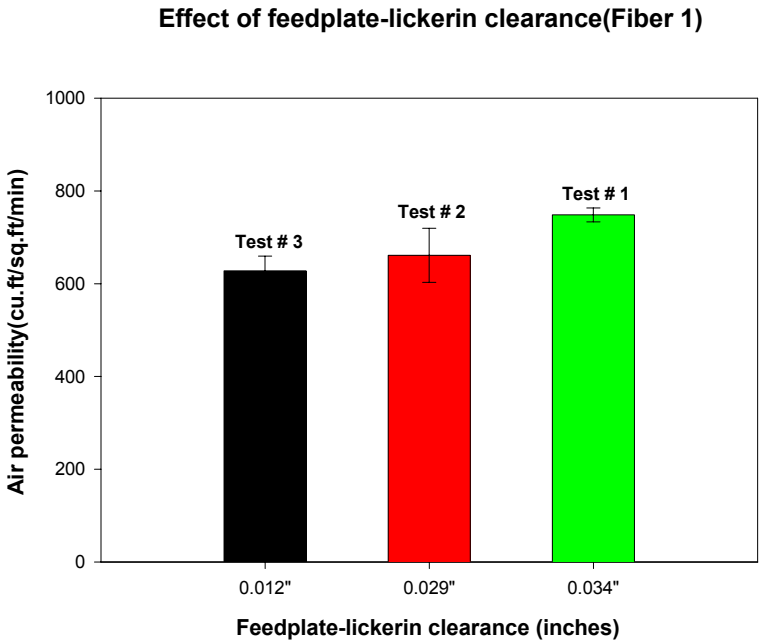


Figure 4.34: Air permeability of needled fabrics from fiber 1 produced using different feedplate-lickerin clearances.

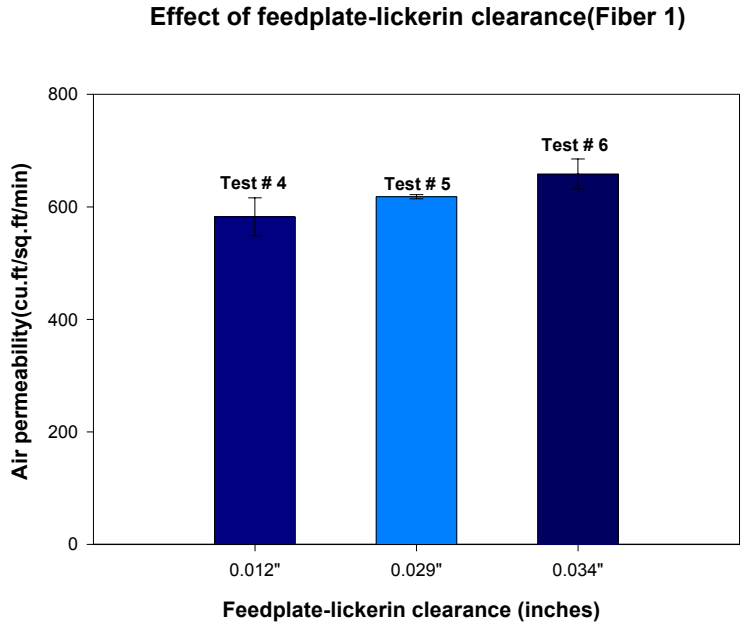


Figure 4.35: Air permeability of needled fabrics from fiber 1 produced using different feedplate-lickerin clearances.

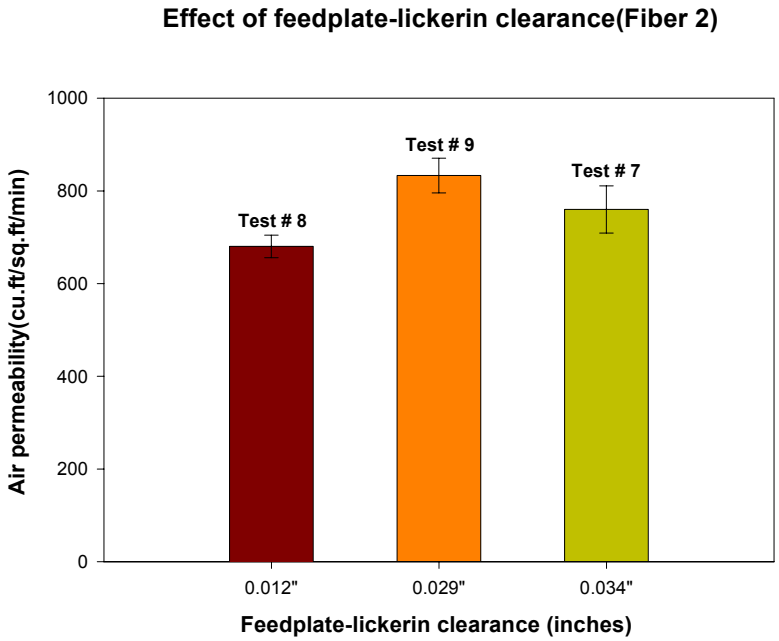


Figure 4.36: Air permeability of needled fabrics from fiber 2 produced using different feedplate-lickerin clearances.

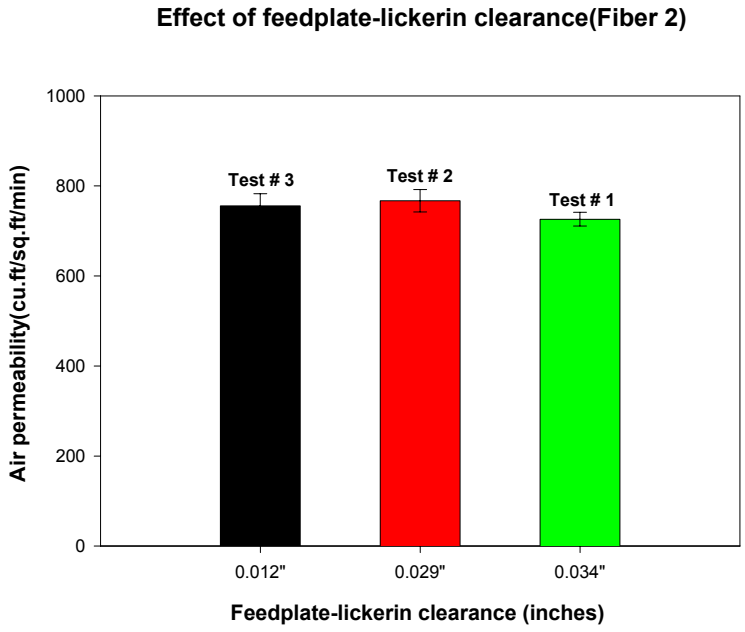


Figure 4.37: Air permeability of needled fabrics from fiber 2 produced using different feedplate-lickerin clearances.

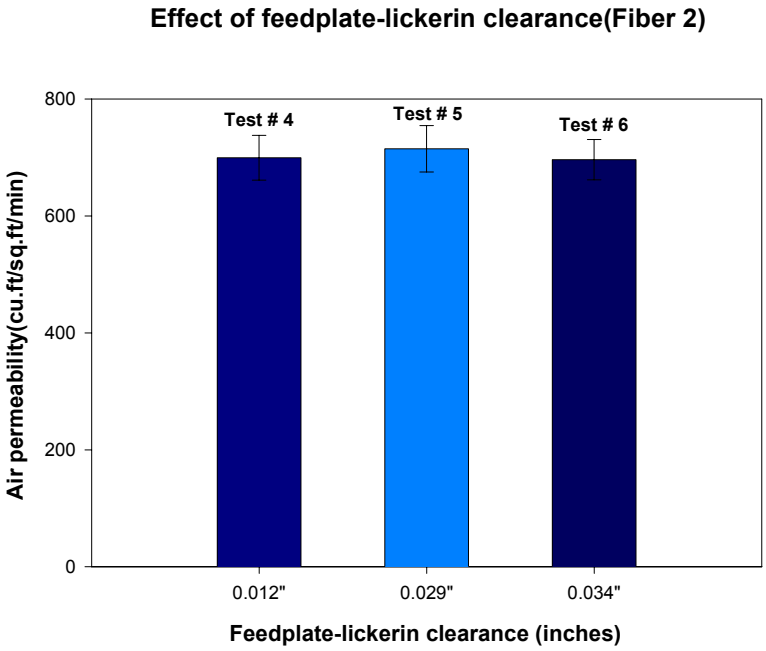


Figure 4.38: Air permeability of needled fabrics from fiber 2 produced using different feedplate-lickerin clearances.

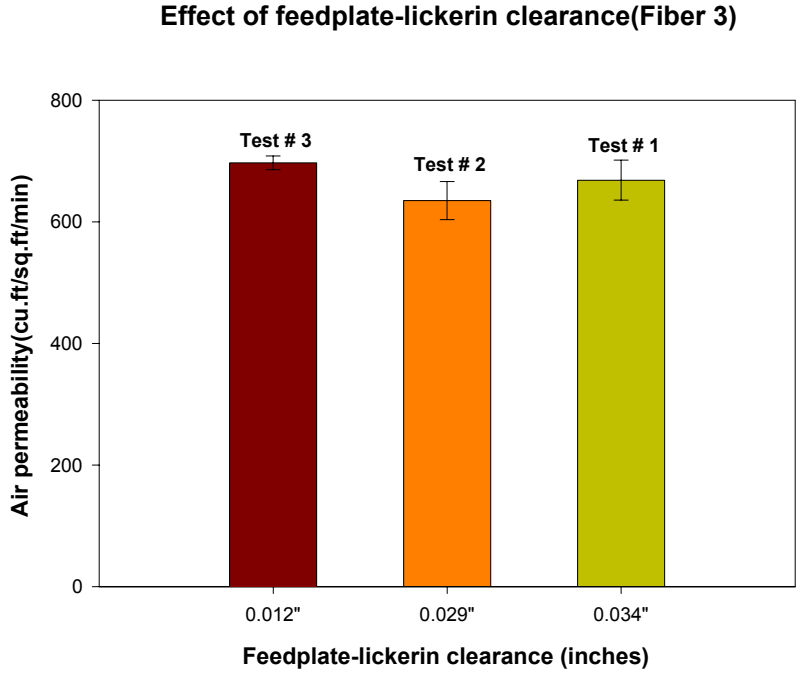


Figure 4.39: Air permeability of needled fabrics from fiber 3 produced using different feedplate-lickerin clearances.

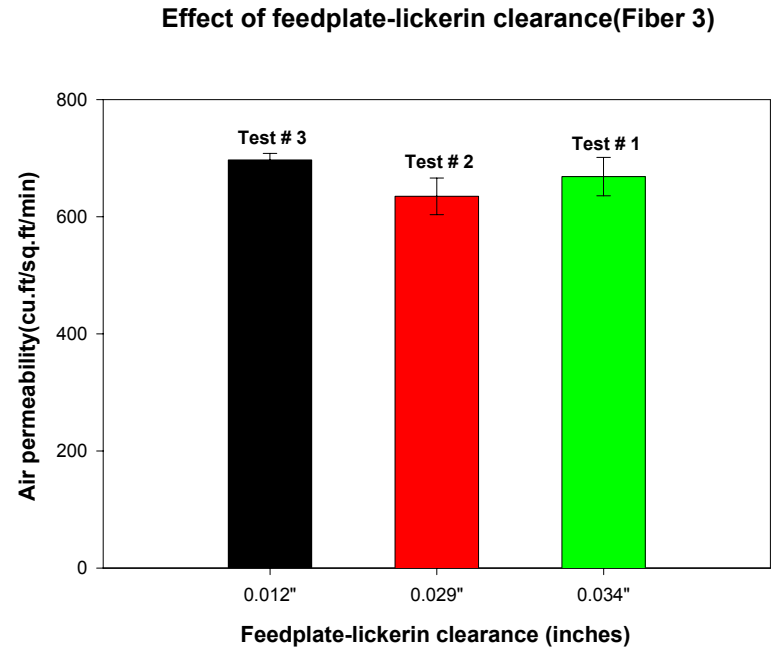


Figure 4.40: Air permeability of needled fabrics from fiber 3 produced using different feedplate-lickerin clearances.

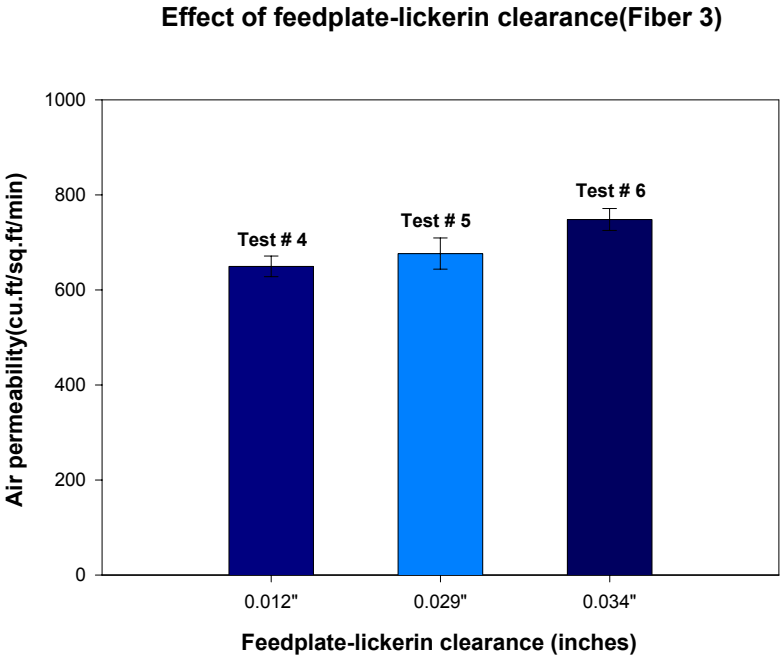


Figure 4.41: Air permeability of needled fabrics from fiber 3 produced using different feedplate-lickerin clearances.

4.2.5 Effect of Flat clearances

Figures 4.42 through 4.50 shows the influence of flat clearances on the air permeability measurements of the final needled fabrics produced from each of the 3 different PET fibers.

There are three graphs shown for each of the 3 fibers. The test #'s in the following graphs were the tests associated with the experimental plan carried out for carding 3 den PET fibers, which indicate the production of a needled fabric using same cylinder speeds (800 rpm) and feedplate-lickerin clearance but different flat clearance settings. When comparing the measurements between the graphs obtained for the same fiber but using a different test sequence from the carding plan, the only variable observed between these graphs was the feedplate-lickerin clearance setting.

Figures [4.42, 4.45, and 4.48], [4.43, 4.46, and 4.49] and [4.44, 4.47, and 4.50] have the respective feedplate-lickerin clearance settings 0.029", 0.034" and 0.012". So the slight discrepancy in the measurements/ trends observed between the graphs of the same fiber may be due to the different feedplate-lickerin clearance settings.

From the discussion of the basis weight results we studied that the effect of flat clearance on the basis weight of the needled fabrics was negligible. Since weight per unit area was a stronger determinant of air permeability, therefore, there has not been a considerable change in the air permeability measurements observed for needled fabrics produced from each of the 3 different PET fibers, but most of the measurements were in good agreement with either the basis weight or their respective thicknesses.

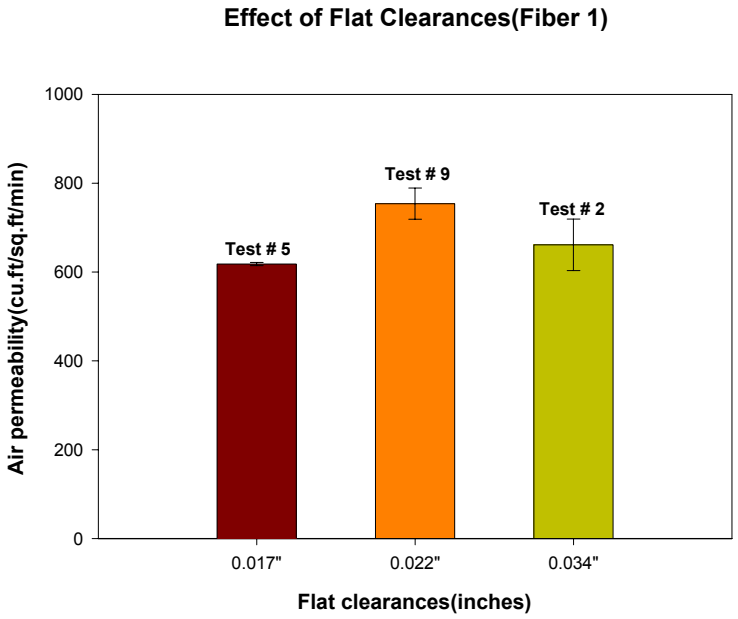


Figure 4.42: Air permeability of needled fabrics from fiber 1 produced using different flat clearances.

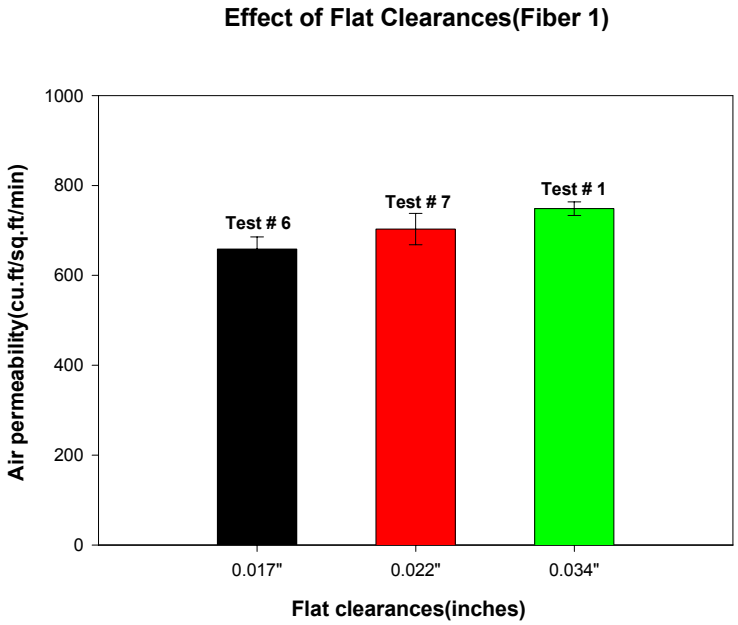


Figure 4.43: Air permeability of needled fabrics from fiber 1 produced using different flat clearances.

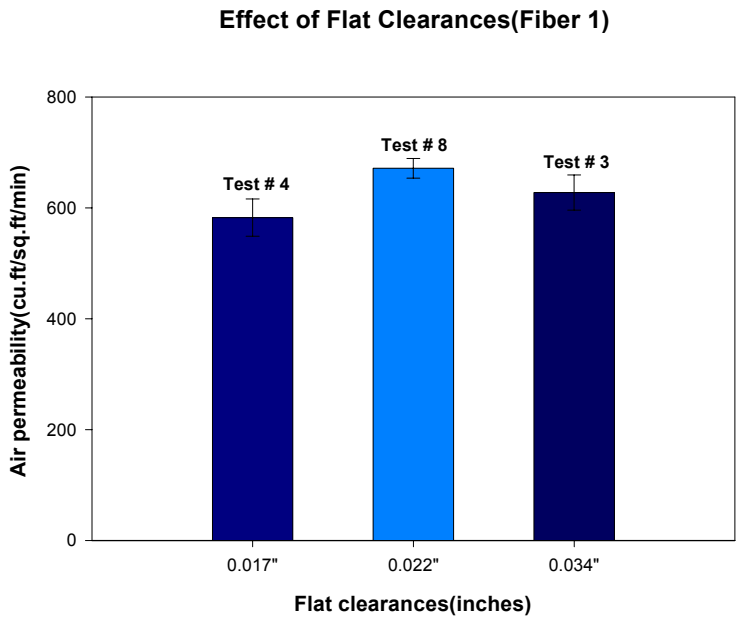


Figure 4.44: Air permeability of needled fabrics from fiber 1 produced using different flat clearances.

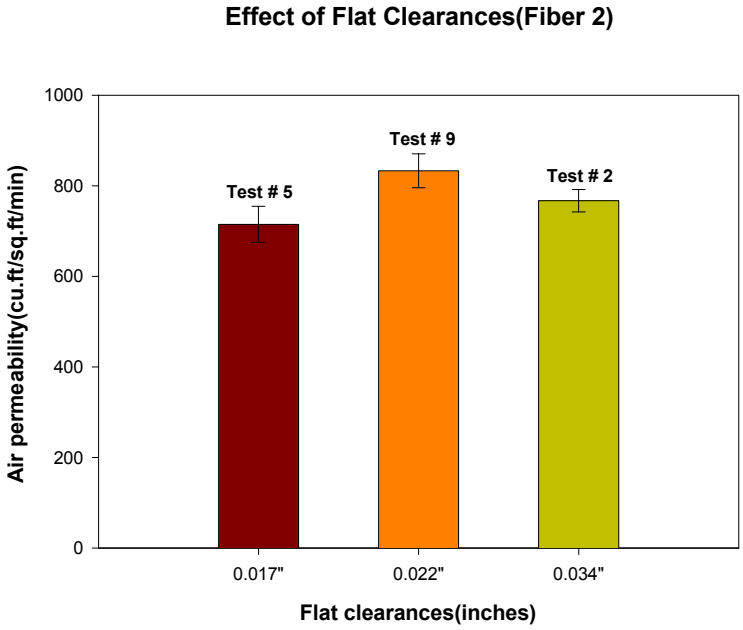


Figure 4.45: Air permeability of needled fabrics from fiber 2 produced using different flat clearances.

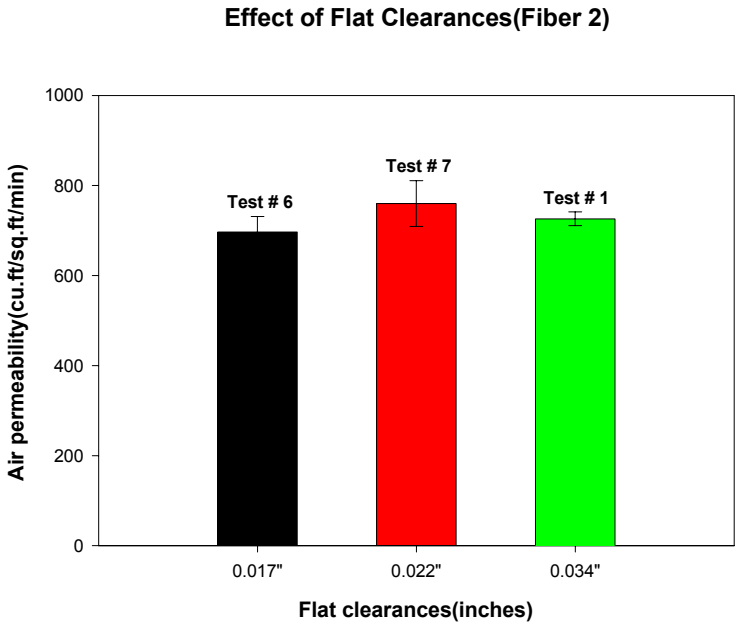


Figure 4.46: Air permeability of needled fabrics from fiber 2 produced using different flat clearances.

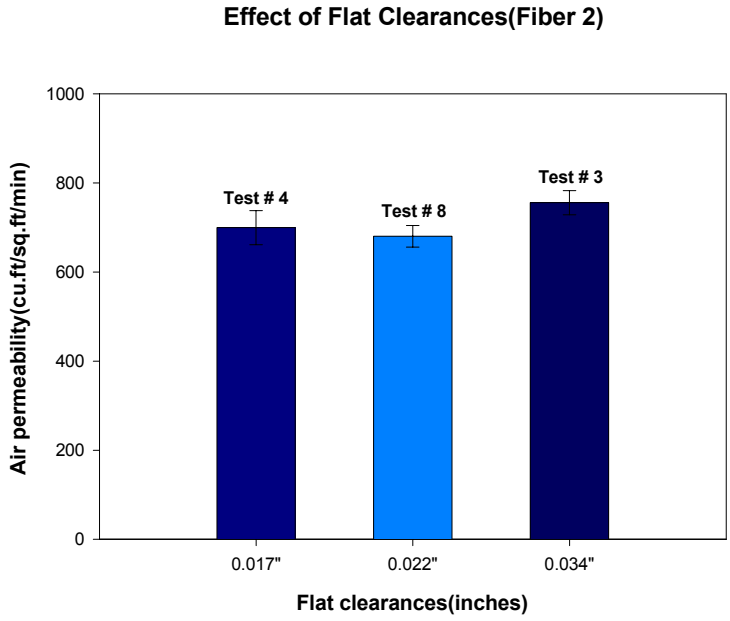


Figure 4.47: Air permeability of needled fabrics from fiber 2 produced using different flat clearances.

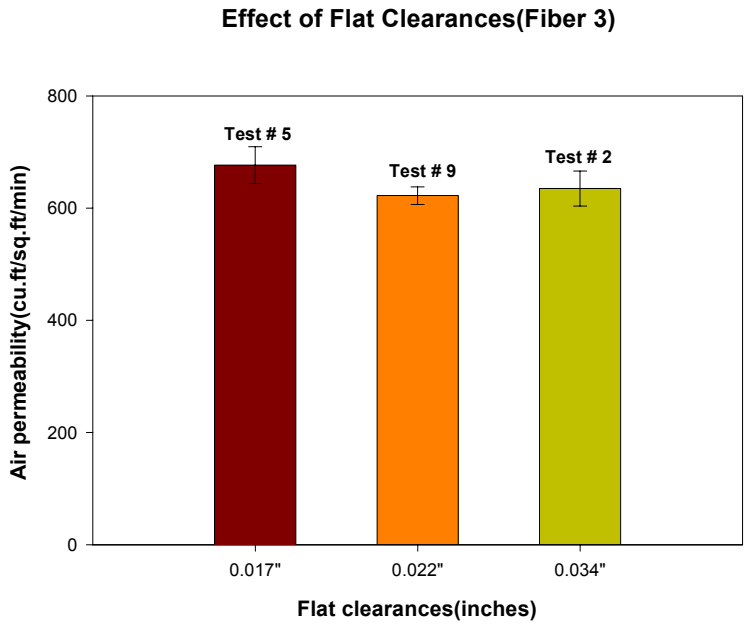


Figure 4.48: Air permeability of needled fabrics from fiber 3 produced using different flat clearances.

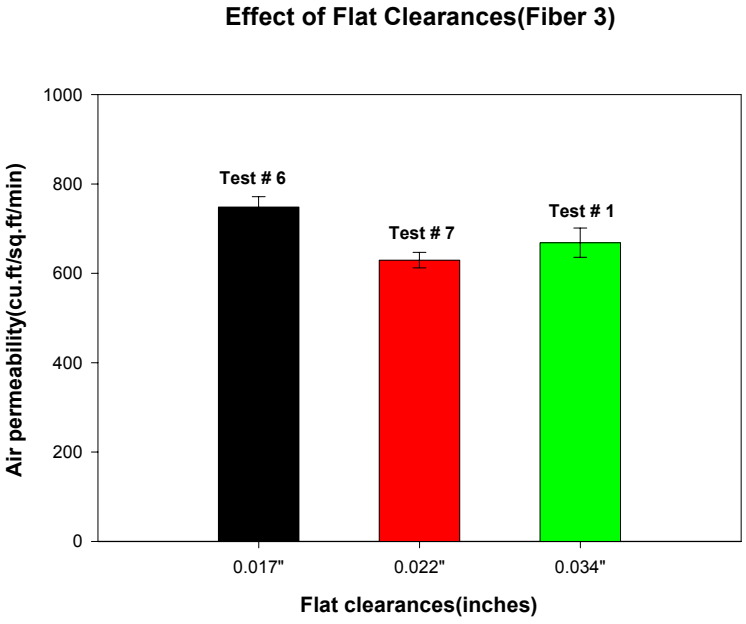


Figure 4.49: Air permeability of needled fabrics from fiber 3 produced using different flat clearances.

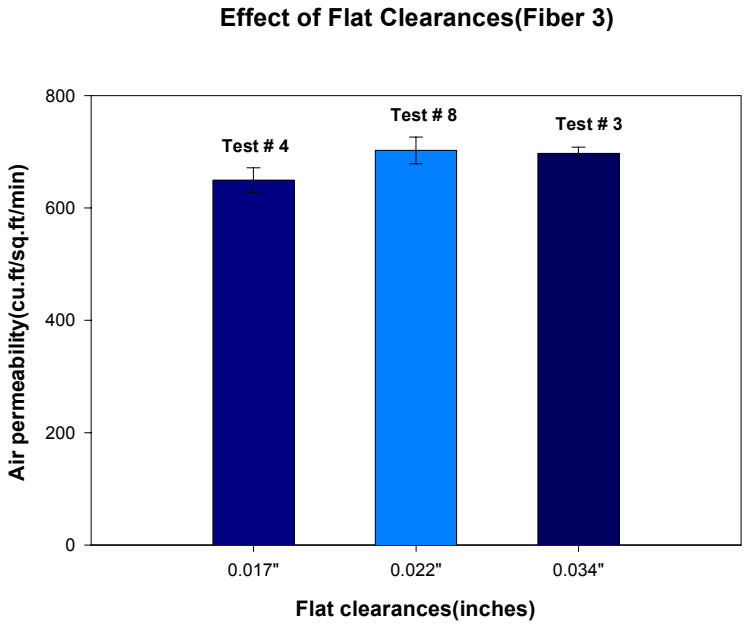


Figure 4.50: Air permeability of needled fabrics from fiber 3 produced using different flat clearances.

4.3 Tensile strength and ODF measurements:

The mechanical properties of nonwoven fabrics are determined by the properties of fiber constituents and the structural arrangement of these components. Among the important aspects of fiber morphology are fiber orientation, fiber curl, and thickness. Their changes can affect the mechanical behavior and failure mechanisms. These parameters can also be varied and controlled more easily during manufacture to improve fabric design and performance.

The mechanical properties of needled fabrics, stress (machine and across the machine directions), strain at break (machine and across the machine directions) when subjected to loads has been studied with respect to the fabric tensile properties and web structure. Fabric tensile strength (tenacity of the fabric) was calculated by normalizing the peak loads obtained from tensile testing raw data on the basis weight (g/m^2) of the nonwovens and width of the specimen by using the formula given below:

$$\text{Normalized fabric strength (g/tex)} = \frac{\text{Load (gm)}}{\text{Basis weight (g/m}^2\text{)} \times \text{Width of the specimen (mm)}}$$

And anisotropy ratio was calculated from the measured fiber orientation distribution functions to correlate with the tensile properties.

4.3.1 Effect of fiber type:

Figure 4.51 depicts the influence of fiber type on the fabric tensile strength of the final needled fabrics produced from each of the three fibers along cross and machine directions and figure 4.52 shows the fiber orientation distribution function (ODF) measured from a series of images captured at regular intervals at each test direction. (Feedplate –lickerin clearance – 0.029", Cylinder speed – 800 rpm, Flat clearance – 0.022").

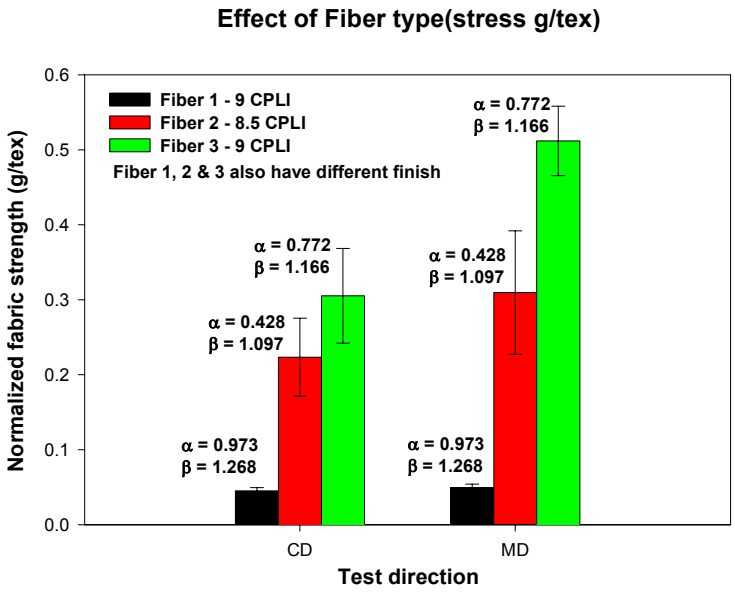


Figure 4.51: Fabric tensile strength of needled fabrics produced from three different 3-den PET fibers

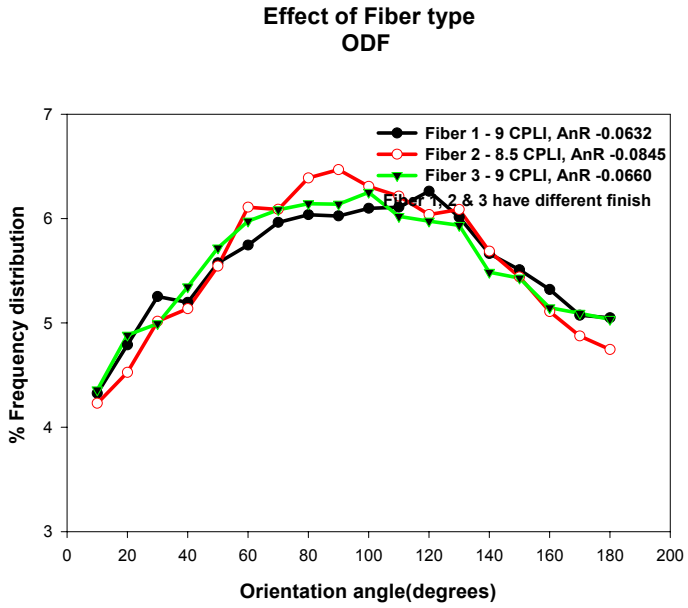


Figure 4.52: Fiber Orientation distribution of needled fabrics produced from three different 3-den PET fibers

The mean values and standard deviations as error bars of the fabrics tensile strength is depicted in Figure 4.51 for the three fabrics produced from different fibers. We can see that fabrics are stronger in the MD direction than in the CD direction, this is caused by more fibers being oriented along MD than CD. And also fabrics produced from fiber 3 fibers appear to be the strongest then followed by fiber 2 and fiber 1. This can be explained by the inherent fiber crimp characteristics during tensile loading. The different extension% values from the load-extension curves and also the characteristic crimp parameters α and β demonstrate their mechanical behavior and is well supported by their ODF"s and the anisotropy ratios calculated from the respective ODF's (refer figure 4.52).

4.3.2 Effect of cylinder speeds:

Fiber 1

Figure 4.53 depicts the influence of cylinder speeds on the fabric tensile strength produced using fiber 1 under different loading or testing directions and figure 4.54 shows

their respective ODF's and anisotropy ratios. (Feedplate-lickerin clearance –0.029", Flat clearance – 0.022")

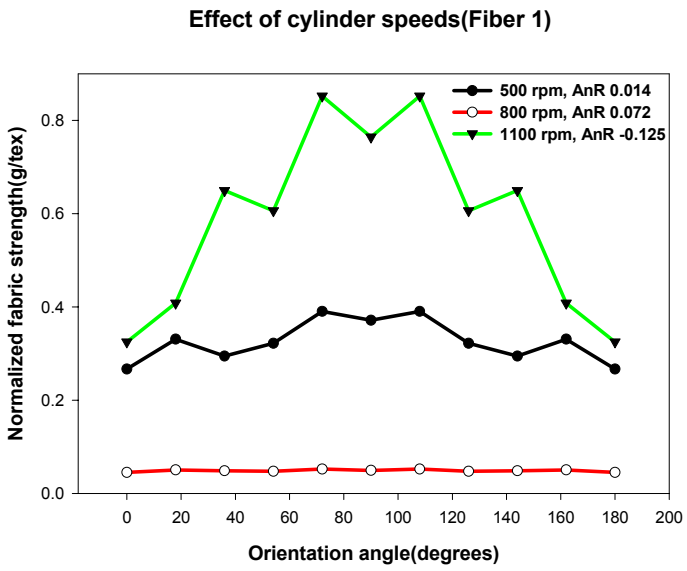


Figure 4.53: Fabric tensile strength of needled fabrics from fiber 1 produced using different cylinder speeds

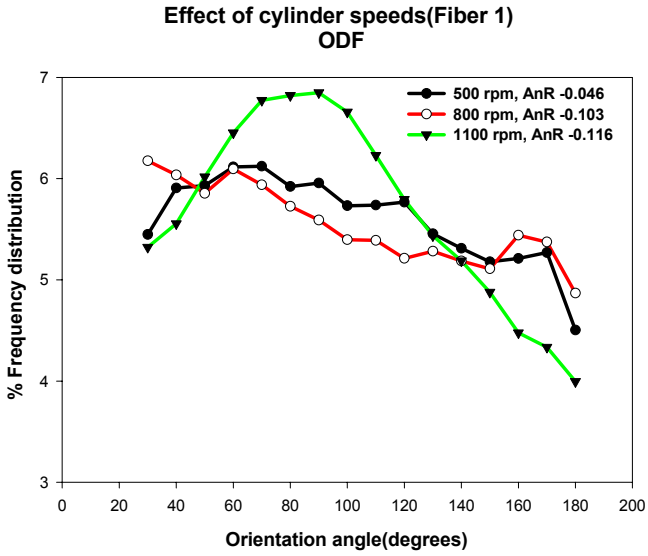


Figure 4.54: Fiber orientation distribution of needled fabrics from fiber 1 produced using different cylinder speeds

In figure 4.53 , the fabric produced using 800 rpm is a perfectly random web with high uniformity and as the cylinder speed is increased to 1100 rpm it getting highly oriented. The higher peak loads observed for the one produced with 500 rpm is due to the incomplete removal of crimp (which can also be explained by its bimodal distribution) and the fiber still holds some elasticity, before actually breaking up, and for the one produced with 1100 rpm even though we expect more crimp being pulled out, because the load acting on a fiber is higher during carding, the fibers becomes stiff, the sample breaks more due to breakage than slippage of fibers which is also the case with the fabrics produced using 800 rpm. This remarkable difference is greatly supported by the ODF's of the fabrics depicted in Figure 4.54 , and their anisotropy ratios indicating a change in their orientations from random orientation to fiber getting perpendicularly aligned as speed increases from 500 – 1100 rpm.

Fiber 2

Figure 4.55 depicts the influence of cylinder speeds on the fabric tensile strength produced using fiber 2 under different loading or testing directions and figure 4.56 shows their respective ODF's and anisotropy ratios. (Feedplate-lickerin clearance –0.029", Flat clearance – 0.022")

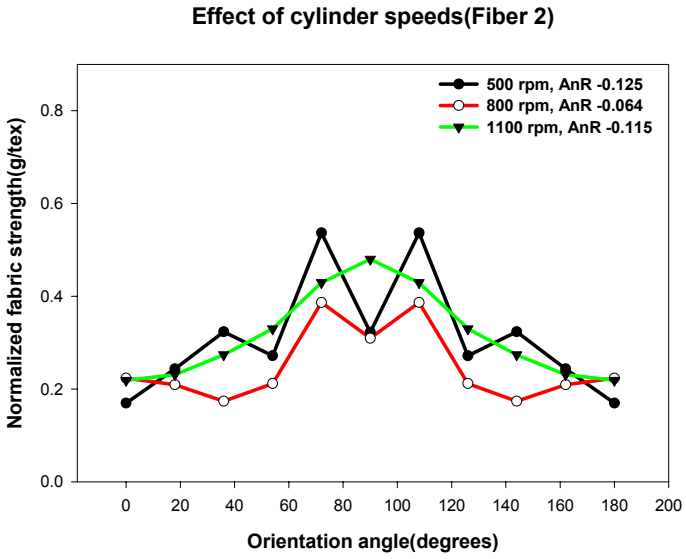


Figure 4.55: Fabric tensile strength of needled fabrics from fiber 2 produced using different cylinder speeds

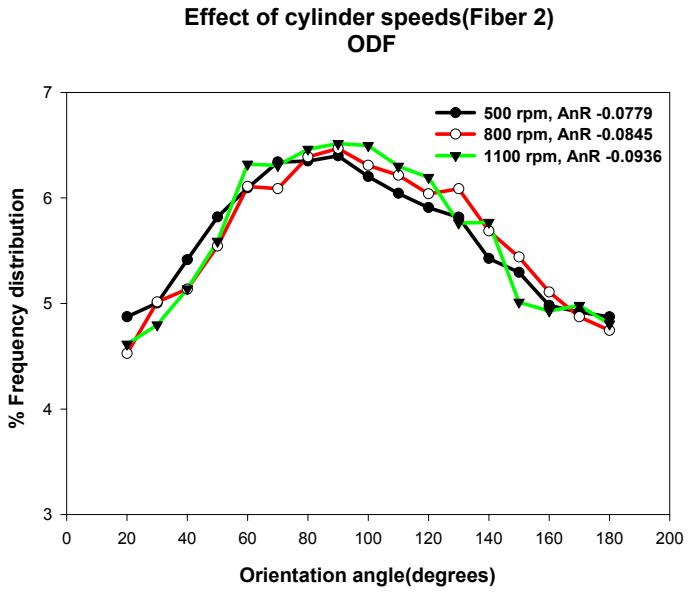


Figure 4.56: Fiber orientation distribution of needled fabrics from fiber 2 produced using different cylinder speeds

In Figure 4.55, the fabric produced using 500 rpm bears a higher load than the ones produced using 800 and 1100 rpm, this can be explained by the fact that crimp is not removed because of the lower load acting on the fibers during carding, so the fiber still holds some elasticity (extensibility) before actually breaking up. It can also be seen that the fibers are getting oriented along the MD direction as the cylinder speed is increased. The anisotropy ratios and their respective ODF's (figure 4.56) indicate a similar and random fiber orientations for the all the three fabrics produced under different cylinder speeds.

Fiber 3

Figure 4.57 depicts the influence of cylinder speeds on the fabric tensile strength produced using fiber 3 under different loading or testing directions and figure 4.58 shows their respective ODF's and anisotropy ratios. (Feedplate-lickerin clearance –0.029", Flat clearance – 0.022")

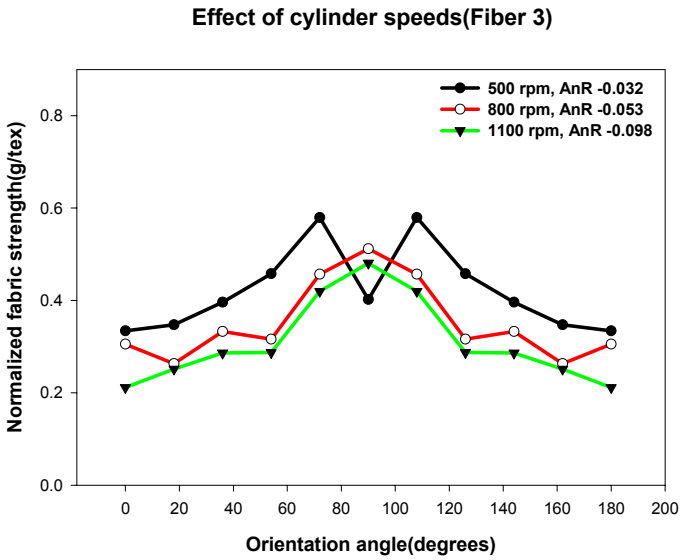


Figure 4.57: Fabric tensile strength of needled fabrics from fiber 3 produced using different cylinder speeds

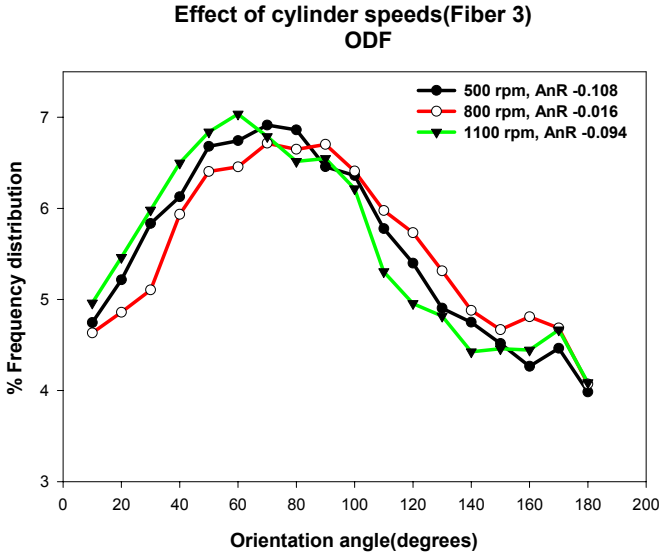


Figure 4.58: Fiber orientation distribution of needled fabrics from fiber 3 produced using different cylinder speeds

In Figure 4.57, the fabric produced using 500 rpm bears a higher load than the ones produced using 800 and 1100 rpm, this can be explained by the fact that crimp is not removed because of the lower load acting on the fibers during carding, so the fiber still holds some elasticity (extensibility) before actually breaking up. And the fabric produced

using 1100 rpm is seems to be more uniform and almost similar to the one produced using 800 rpm.

It can also be seen that the fibers are getting oriented along the MD direction as the cylinder speed is increased from 500 to 1100 rpm. The anisotropy ratios and their respective ODF's (figure 4.58) indicate a similar and random fiber orientations for all the three fabrics produce under different cylinder speeds.

From all the figures (figure 4.53 through 4.58) above it was seen that the tensile behavior mainly depended upon the fiber orientation distribution and also on the processing conditions and the amount of crimp removed during processing. Fabrics produced using fiber 3 were stronger, then fiber 2 followed by fiber 1 produced under the same cylinder speeds, except for the one produced using 1100 rpm, in which case fabric produced using fiber 1 was found to be the strongest. This was attributed to the different fiber crimp characteristics and the amount of crimp being removed during processing and finish factor involved.

And as the cylinder speed was increased, the fibers were oriented highly in the machine direction, this behavior was observed for all the three different 3 den PET fibers each of which were produced using different cylinder speeds, due to higher loads acting on the fibers where they were stretched, stressed and caused to align more in the machine direction.

4.3.2 Effect of Needling density:

Figure 4.59 depicts the influence of needling density (punches per square inch) on the fabric tensile strength produced using fiber 1 under different loading or testing directions and figure 4.60 shows their respective ODF's and anisotropy ratios. (Feedplate-lickerin clearance – 0.029", Cylinder speed – 800 rpm, Flat clearance - 0.022")

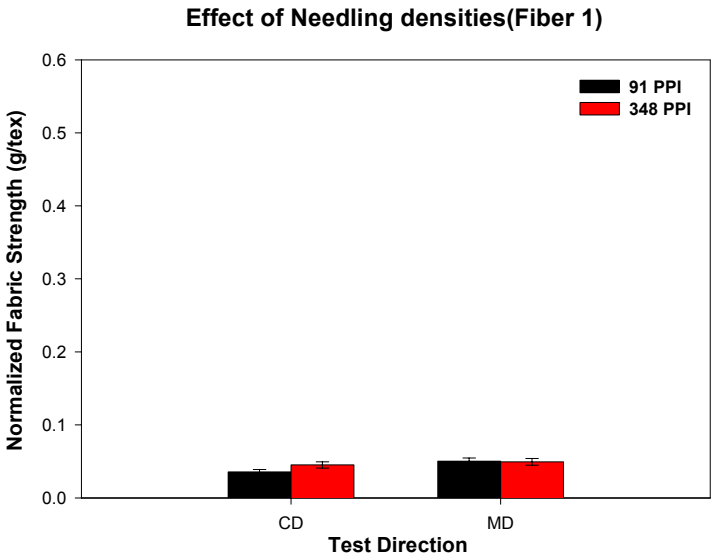


Figure 4.59: Fabric tensile strength of needled fabrics from fiber 1 produced using different needling densities

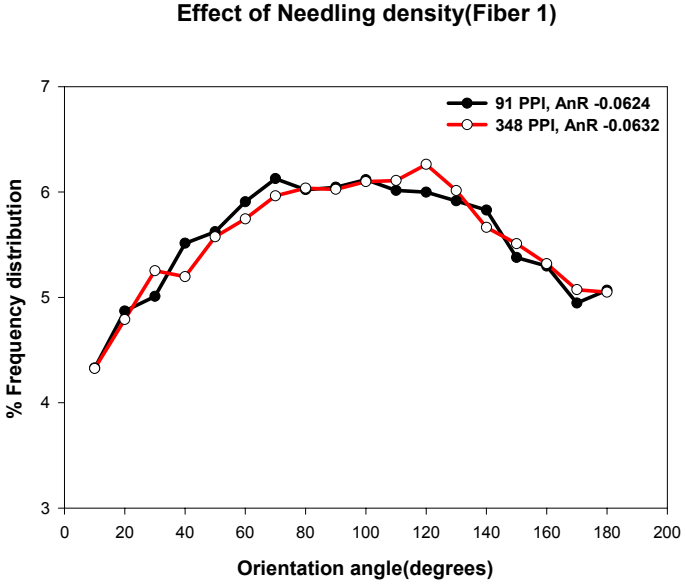


Figure 4.60: Fiber orientation distribution of needled fabrics from fiber 1 produced using different cylinder speeds

From figure 4.59 it can be seen that fabric produced with higher (348 PPI) needling density is stronger than the one produced using 91 PPI. This resultant strength is due to the better interlocking or entanglement produced within a unit area of a fabric. Also the fabrics tested along the MD direction are stronger than the ones tested along the CD direction. The anisotropy ratios and their respective ODF's (figure 4.60) indicate a

similar and random fiber orientations for the two fabrics produced using different needling densities.

Figure 4.61 depicts the influence of needling density (punches per square inch) on the fabric tensile strength produced using fiber 2 under different loading or testing directions and figure 4.62 shows their respective ODF's and anisotropy ratios.

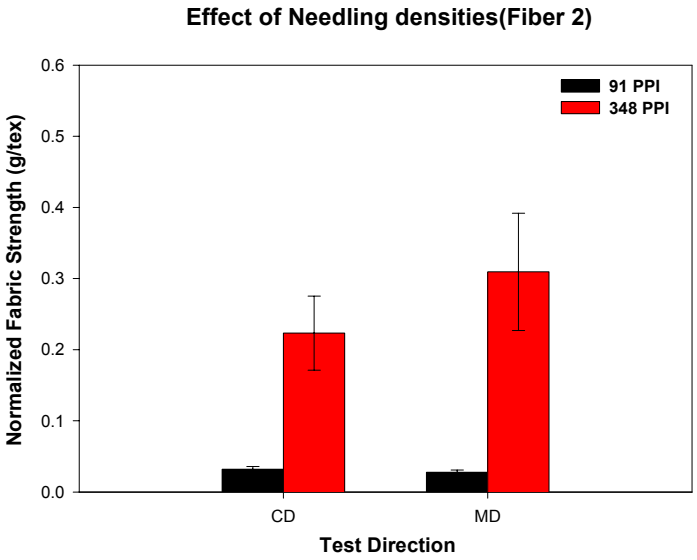


Figure 4.61: Fabric tensile strength of needled fabrics from fiber 2 produced using different needling densities

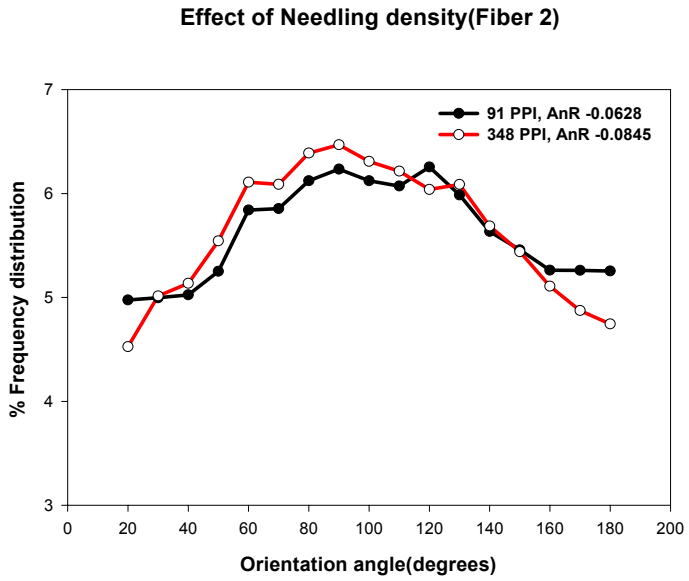


Figure 4.62: Fiber orientation distribution of needled fabrics from fiber 2 produced using different needling densities

From figure 4.61 it can be seen that fabric produced with higher (348 PPI) needling density is stronger than the one produced using 91 PPI. This resultant strength is due to the better interlocking or entanglement produced within a unit area of a fabric. Also the fabrics tested along the MD direction are stronger than the ones tested along the CD direction. The anisotropy ratios and their respective ODF's (figure 4.62) indicate a slight variation in the fiber orientations (though the difference is not very perceptible) for the two fabrics produced using different needling densities.

Figure 4.63 depicts the influence of needling density (punches per square inch) on the fabric tensile strength produced using fiber 3 under different loading or testing directions and figure 4.64 shows their respective ODF's and anisotropy ratios.

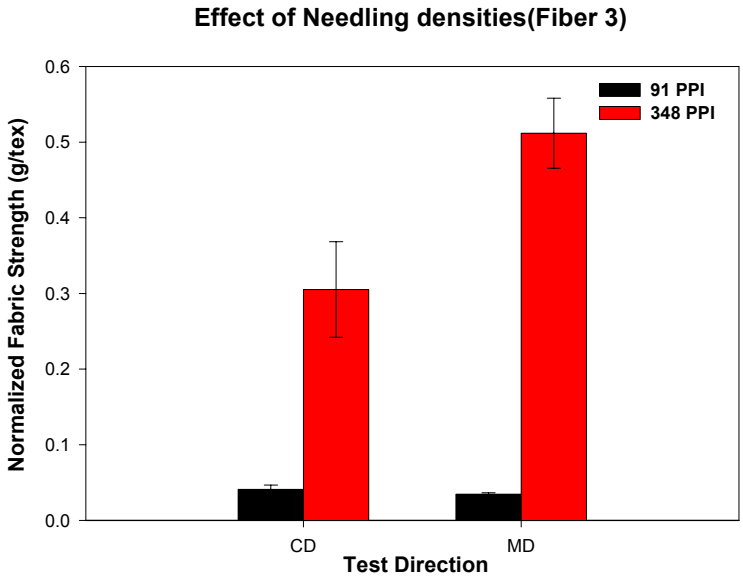


Figure 4.63: Fabric tensile strength of needled fabrics from fiber 3 produced using different needling densities

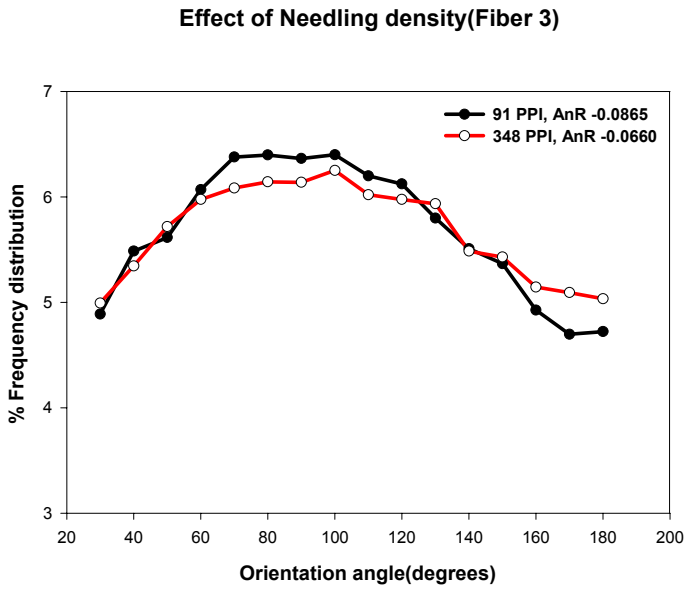


Figure 4.64: Fiber orientation distribution of needled fabrics from fiber 3 produced using different needling densities

From figure 4.63 it can be seen that fabric produced with higher (348 PPI) needling density is stronger than the one produced using 91 PPI. This resultant strength is due to the better interlocking or entanglement produced within a unit area of a fabric. Also the fabrics tested along the MD direction are stronger than the ones tested along the CD direction. The anisotropy ratios and their respective ODF's (figure 4.64) indicate a slight difference in the fiber orientations (though the difference is not perceptible) for the two fabrics produced using different needling densities.

4.3.4 Effect of feedplate-lickerin clearance:

Figure 4.65 through 4.82 depicts the effect of feedplate-lickerin clearance on the fabric tensile strength as well as on their respective fiber orientation distribution produced using each of the three fibers subjected to different loading or testing directions.

There are three graphs shown for each of the 3 fibers. The test #'s in the following graphs were the tests associated with the experimental plan carried out for carding 3 den PET fibers, which indicates the production of a needled fabric using same cylinder speeds

(800 rpm) and flat clearances but different feedplate-lickerin clearance settings. When comparing the measurements between the graphs obtained for the same fiber but using a different test sequence from the carding plan, the only variable observed between these graphs was the flat clearance setting.

Figures [4.65, 4.66, 4.71, 4.72, 4.77, and 4.78] , [4.67, 4.68, 4.73, 4.74, 4.79, and 4.80] and [4.69, 4.70, 4.75, 4.76, 4.81, and 4.82] have the respective flat clearance settings 0.022", 0.034" and 0.017". So the slight discrepancy in the measurements/trends observed among the graphs of the same fiber may be due to the different flat clearance settings.

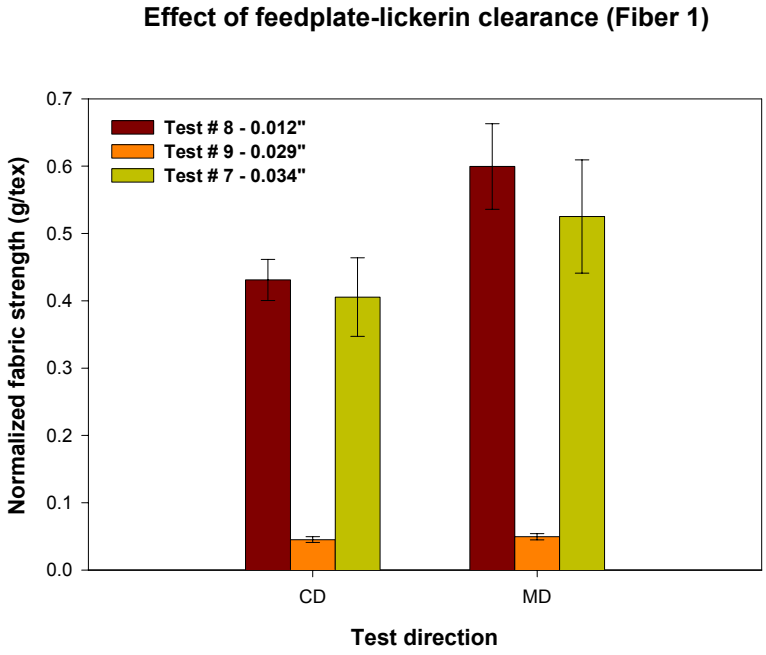


Figure 4.65: Fabric tensile strength of needled fabrics from fiber 1 producedusing different feedplate-lickerin clearances.

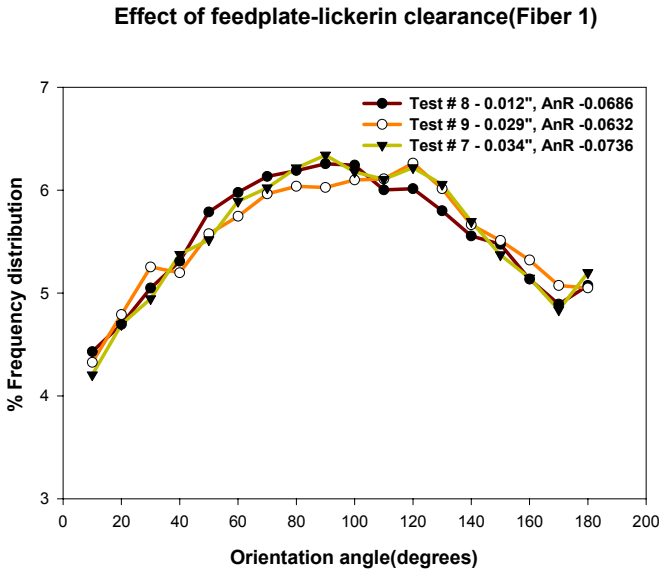


Figure 4.66: Fiber orientation distribution of needled fabrics from fiber 1 produced using different feedplate-lickerin clearances.

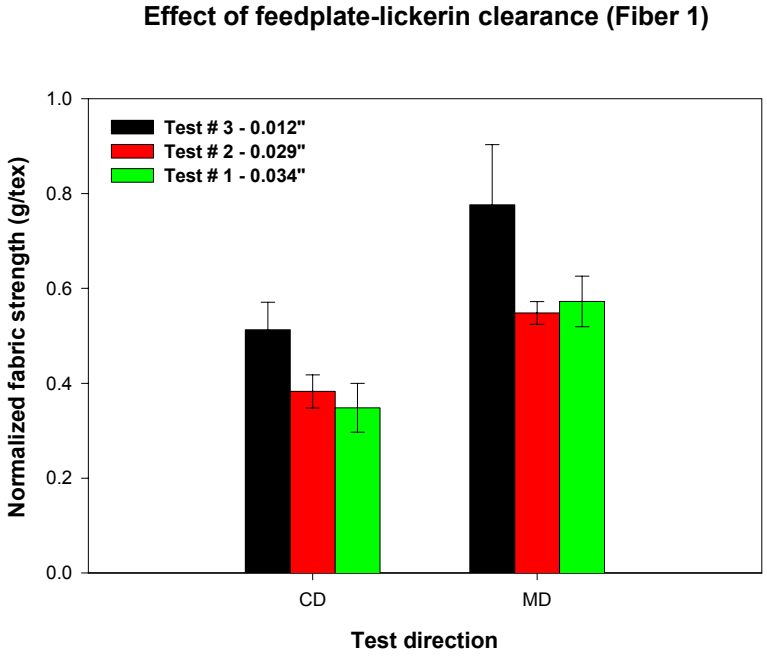


Figure 4.67: Fabric tensile strength of needled fabrics from fiber 1 produced using different feedplate-lickerin clearances.

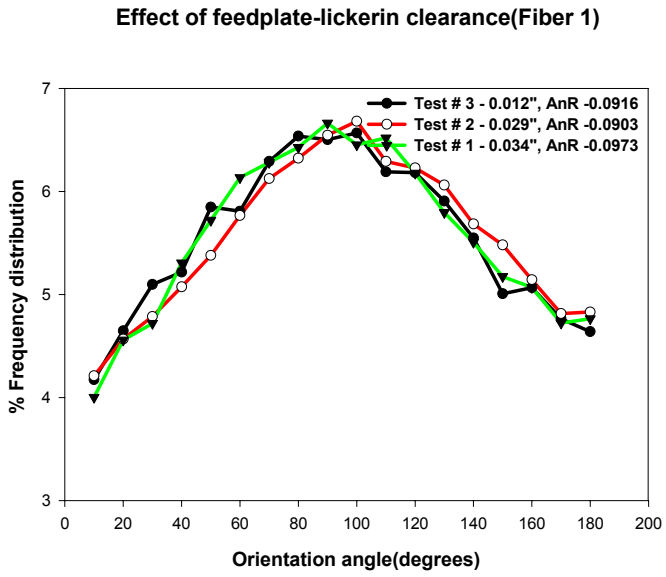


Figure 4.68: Fiber orientation distribution of needled fabrics from fiber 1 produced using different feedplate-lickerin clearances.

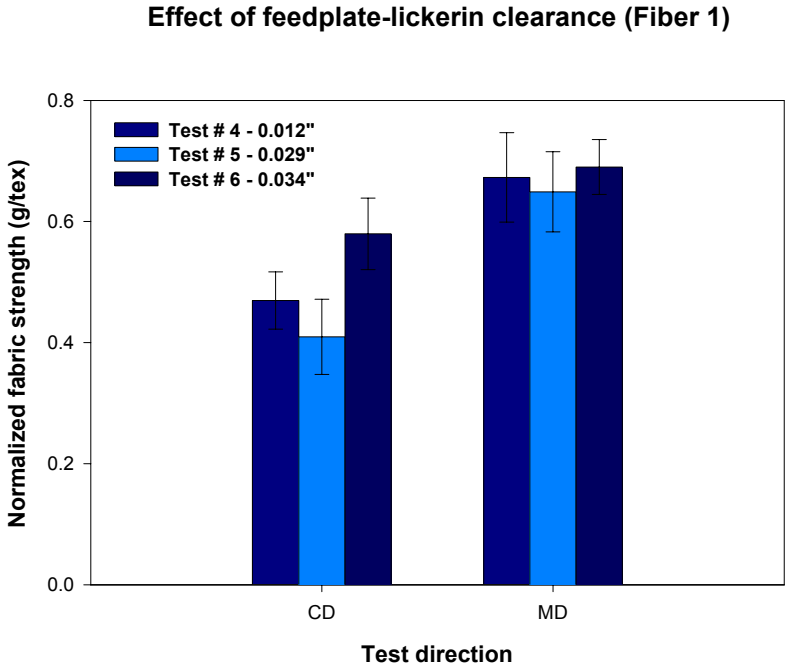


Figure 4.69: Fabric tensile strength of needled fabrics from fiber 1 produced using different feedplate-lickerin clearances.

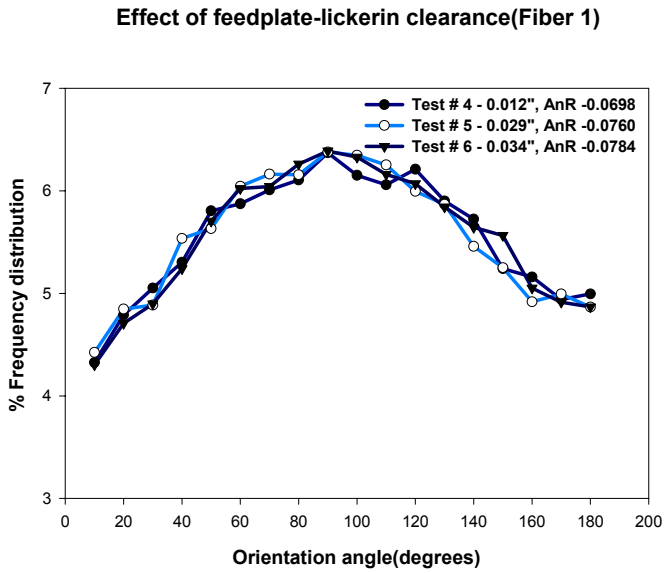


Figure 4.70: Fiber orientation distribution of needled fabrics from fiber 1 produced using different feedplate-lickerin clearances.

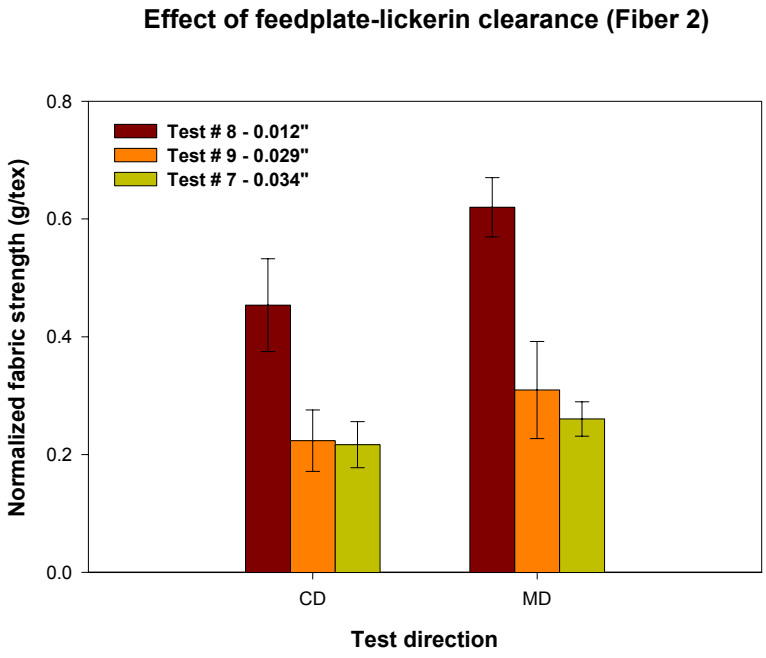


Figure 4.71: Fabric tensile strength of needled fabrics from fiber 2 produced using different feedplate-lickerin clearances.

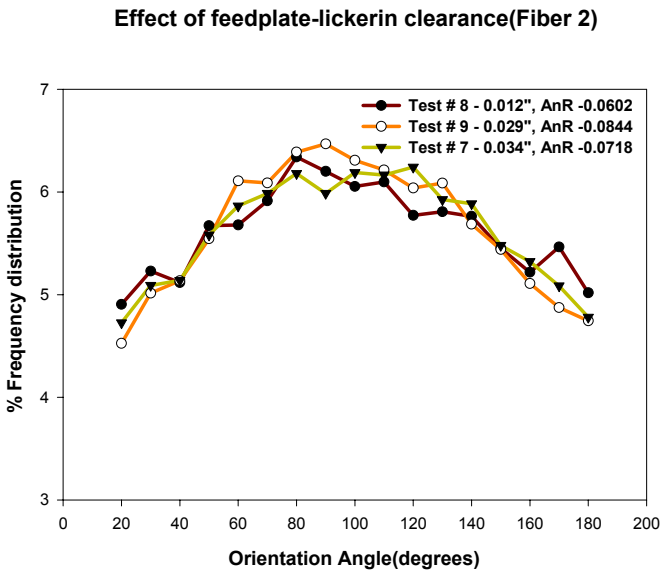


Figure 4.72: Fiber orientation distribution of needled fabrics from fiber 2 produced using different feedplate-lickerin clearances.

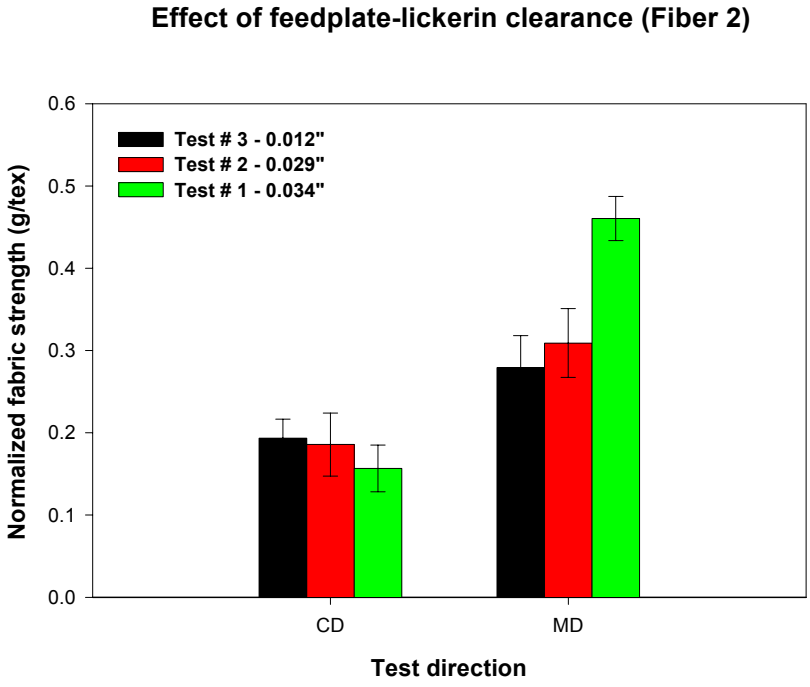


Figure 4.73: Fabric tensile strength of needled fabrics from fiber 2 produced using different feedplate-lickerin clearances.

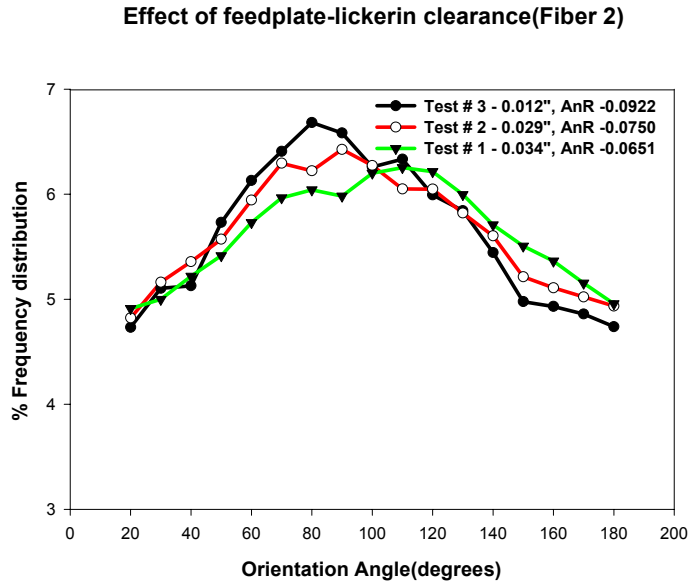


Figure 4.74: Fiber orientation distribution of needled fabrics from fiber 2 produced using different feedplate-lickerin clearances.

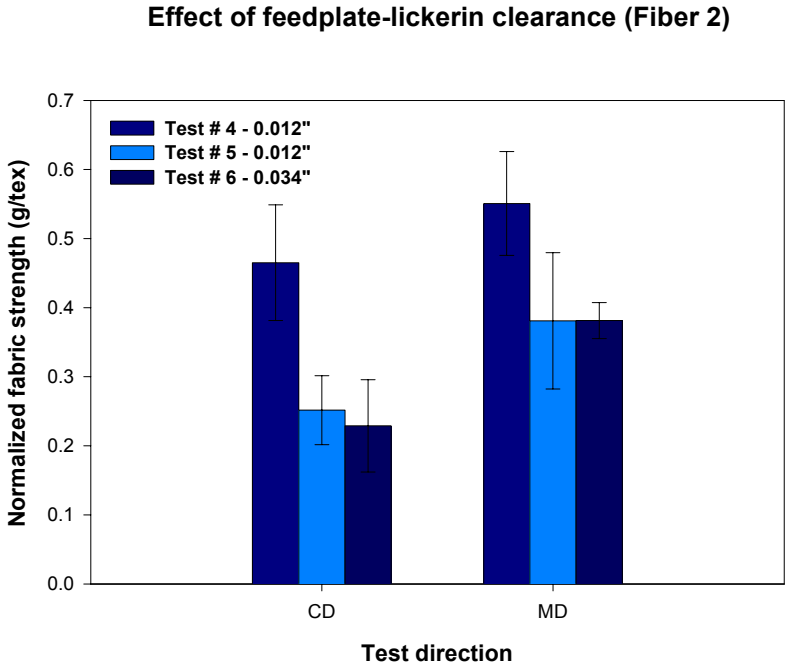


Figure 4.75: Fabric tensile strength of needled fabrics from fiber 2 produced using different feedplate-lickerin clearances.

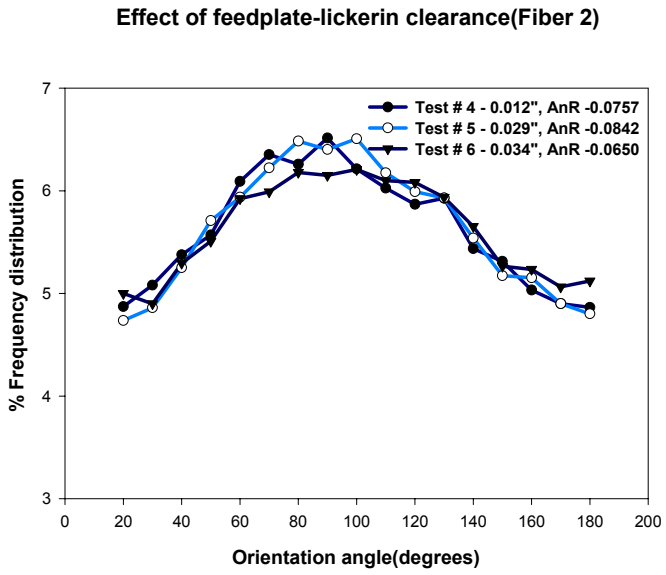


Figure 4.76: Fiber orientation distribution of needled fabrics from fiber 2 produced using different feedplate-lickerin clearances.

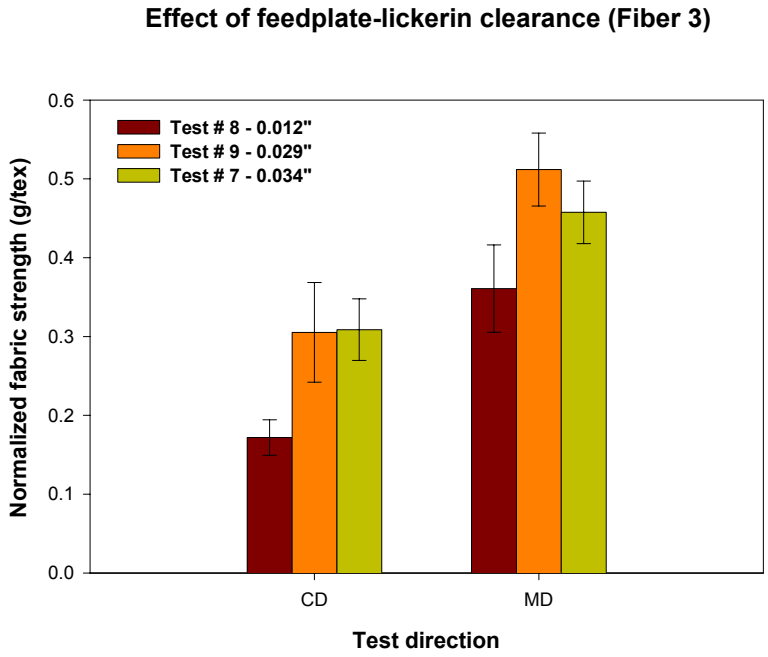


Figure 4.77: Fabric tensile strength of needled fabrics from fiber 3 produced using different feedplate-lickerin clearances.

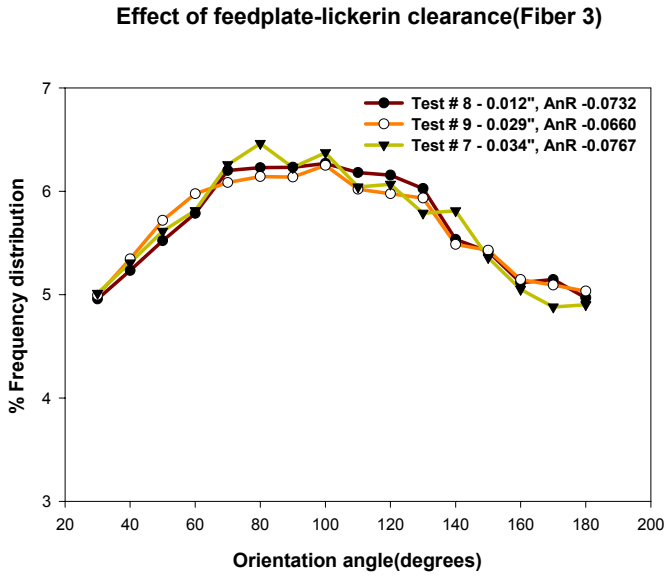


Figure 4.78: Fiber orientation distribution of needled fabrics from fiber 3 produced using different feedplate-lickerin clearances.

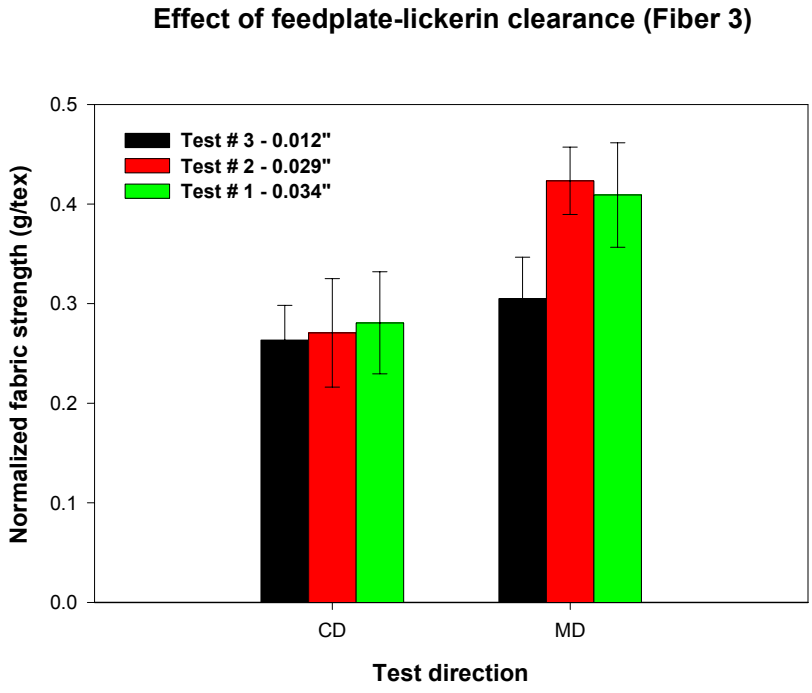


Figure 4.79: Fabric tensile strength of needled fabrics from fiber 3 produced using different feedplate-lickerin clearances.

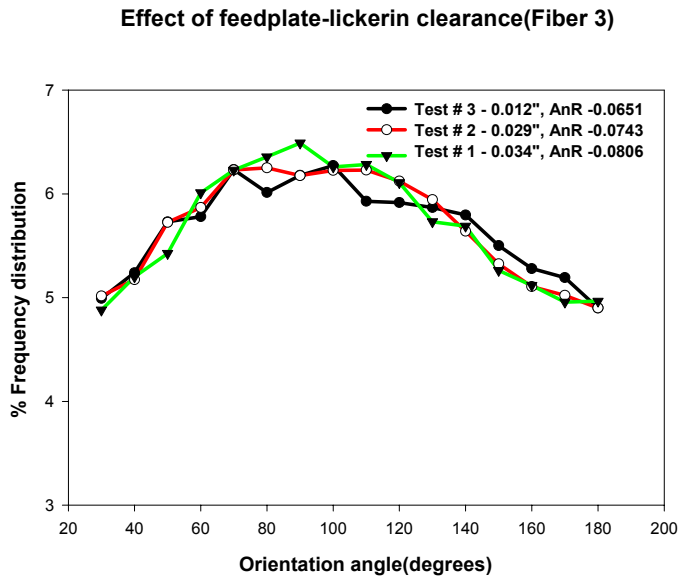


Figure 4.80: Fiber orientation distribution of needled fabrics from fiber 3 produced using different feedplate-lickerin clearances.

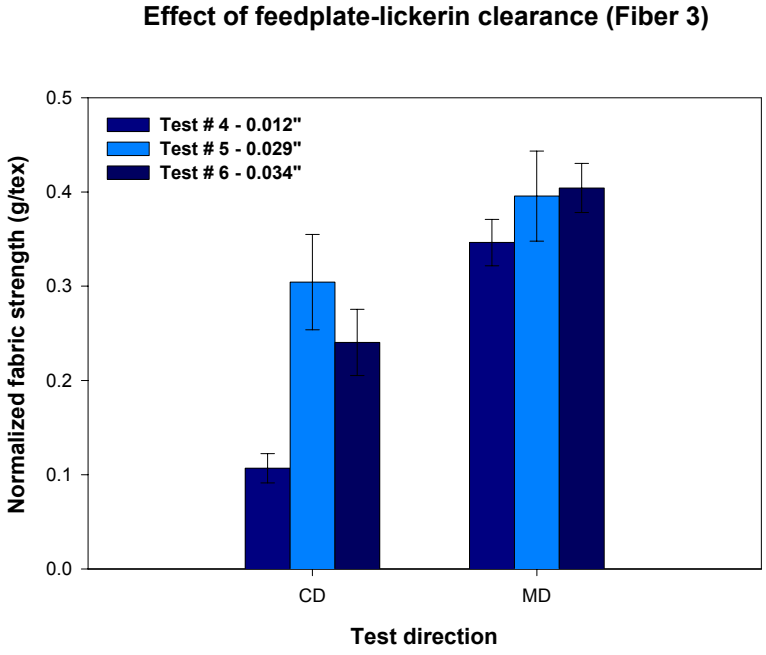


Figure 4.81: Fabric tensile strength of needled fabrics from fiber 3 produced using different feedplate-lickerin clearances.

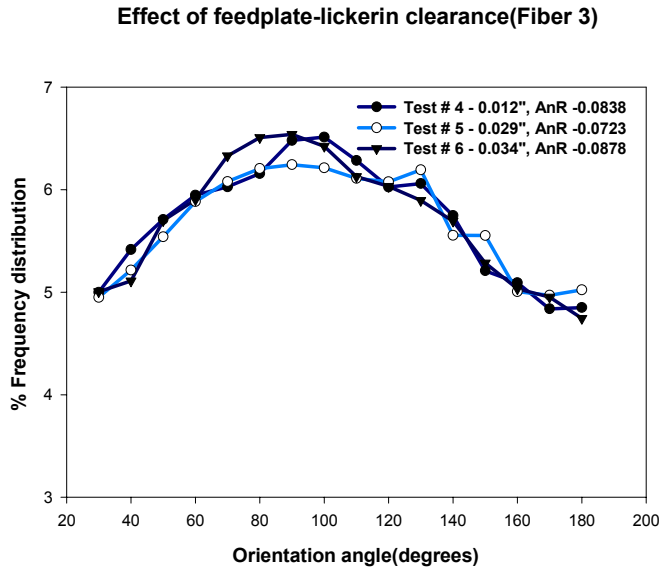


Figure 4.82: Fiber orientation distribution of needled fabrics from fiber 3 produced using different feedplate-lickerin clearances.

From all of the figures above it can be seen that the needled fabrics were stronger along MD were than CD, this is because more fibers were oriented along MD which make it possible to take on higher loads when subjected to stress. The trend observed with the fabric tensile strengths were supported by their respective fiber orientation distributions (ODF's) often. For the ones produced using different fibers this particular trend couldn't established, which may be due to the presence of crimped fibers that couldn't be taken into account when developing the algorithm while taking the ODF measurement.

There is no noticeable change observed in the fiber orientations between the fabrics produced with different feedplate-lickerin clearance, which is often the case with all the figures. Also the anisotropy ratios and the ODF's together indicate a random and a unimodal distribution of fibers.

The feedplate-lickerin clearance essentially controls the initial opening of the fiber mass and considerably effects the crimp removal, which influences the load bearing capacity of the fiber. An appropriate trend for the fabric's tensile strength between fabrics produced

from the same fiber and also between the ones produced using different fibers couldn't be established. This might be due to the large variation associated with the samples.

4.3.5 Effect of Flat clearance:

Figure 4.83 through 4.100 depicts the effect of flat clearance on the fabric tensile strength as well as on their respective fiber orientation distribution produced using each of the three fibers when subjected to different loading or testing directions

There are three graphs shown for each of the 3 fibers here .The test #'s in the following graphs were the tests associated with the experimental plan carried out for carding 3 den PET fibers which details the production of a needled fabric using same cylinder speeds (800 rpm) and feedplate-lickerin clearances but different flat clearance settings. When comparing the measurements between the graphs obtained for the same fiber but using a different test sequence from the carding plan, the only variable observed between these graphs was the flat clearance setting.

Figures [4.83, 4.84, 4.89, 4.90, 4.95, and 4.96] , [4.85, 4.86, 4.91, 4.92, 4.97, and 4.98] and [4.87, 4.88, 4.93, 4.94, 4.99 and 4.100] have the respective flat clearance settings 0.029", 0.034" and 0.012". So the slight discrepancy in the measurements/ trends observed between the graphs of the same fiber may be due to the different feedplate-lickerin clearance settings.

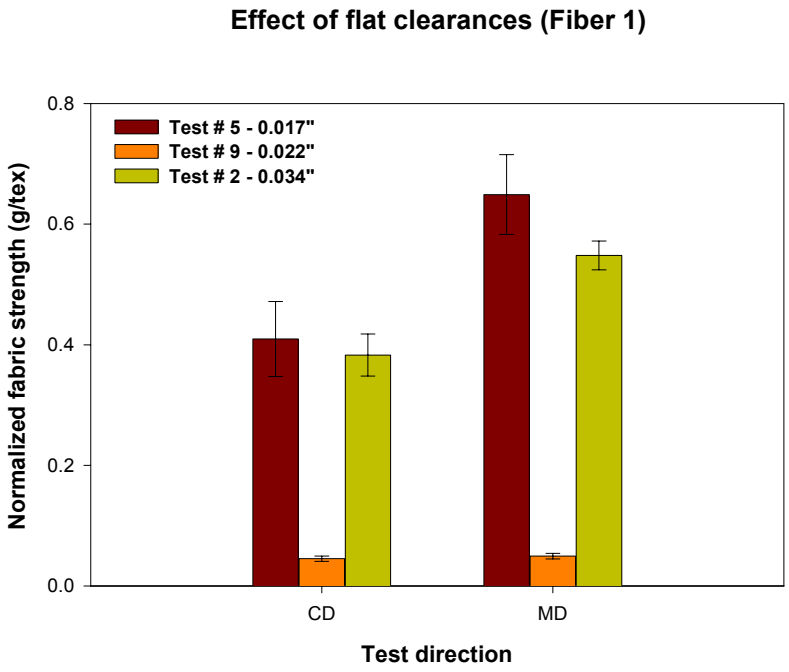


Figure 4.83: Fabric tensile strength of needled fabrics from fiber 1 producedusing different flat clearances.

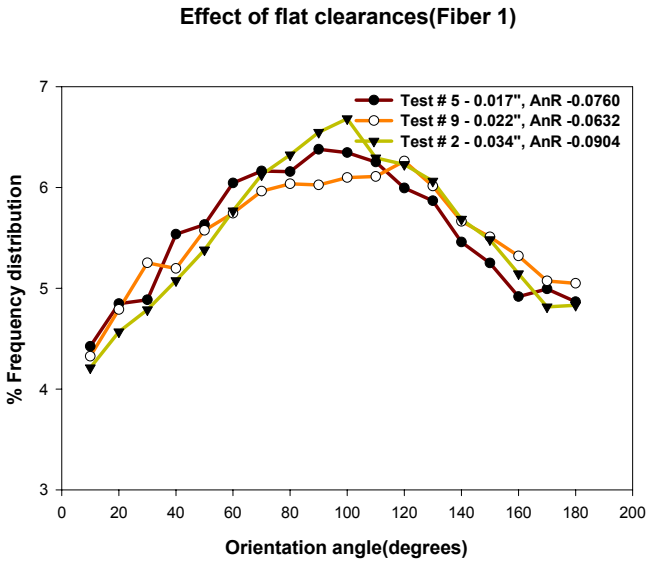


Figure 4.84: Fiber orientation distribution of needled fabrics from fiber 3 produced using different flat clearances.

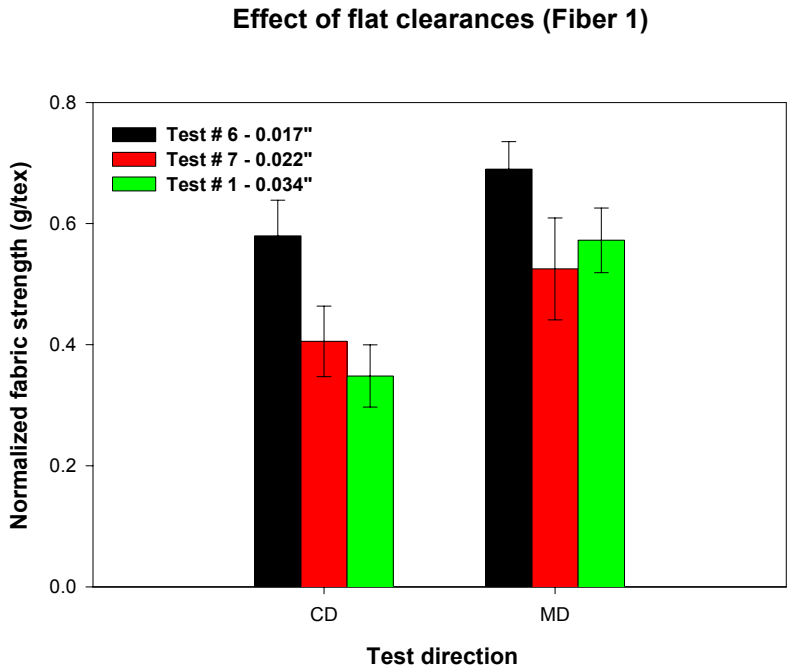


Figure 4.85: Fabric tensile strength of needled fabrics from fiber 1 produced using different flat clearances.

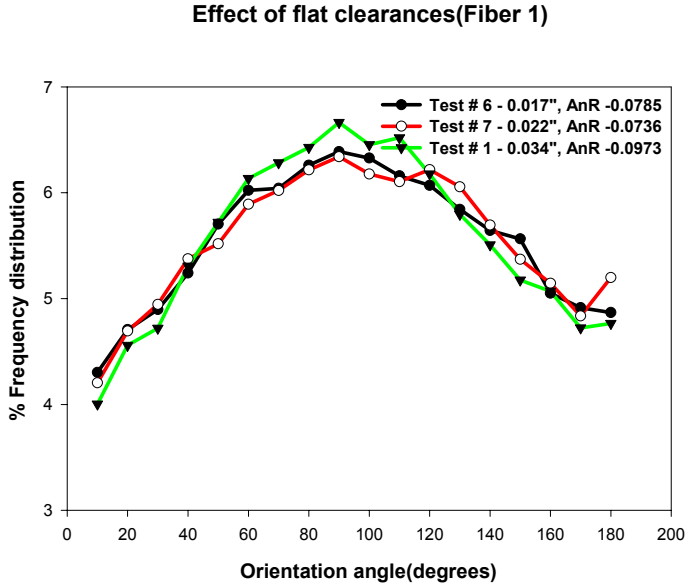


Figure 4.86: Fiber orientation distribution of needled fabrics from fiber 1 produced using different flat clearances.

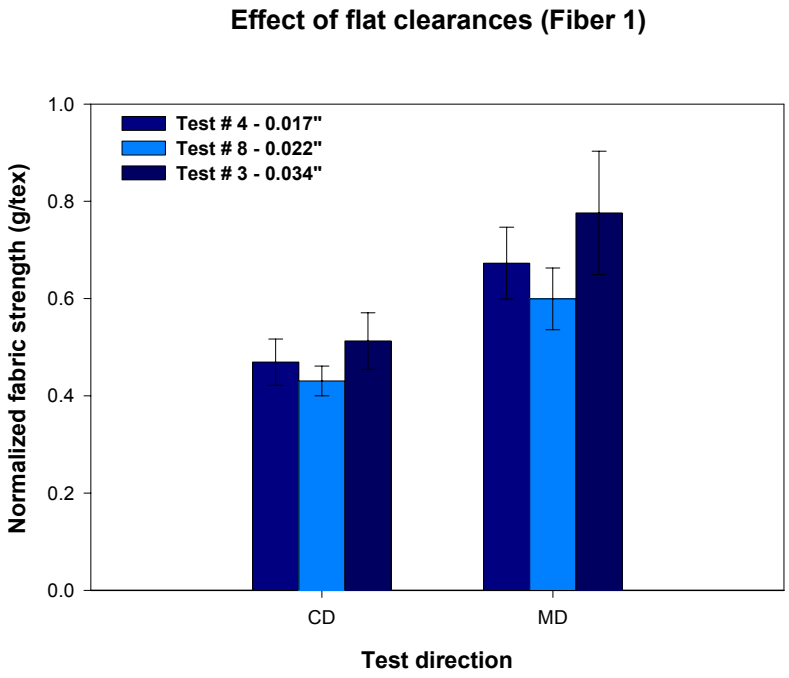


Figure 4.87: Fabric tensile strength of needled fabrics from fiber 1 produced using different flat clearances.

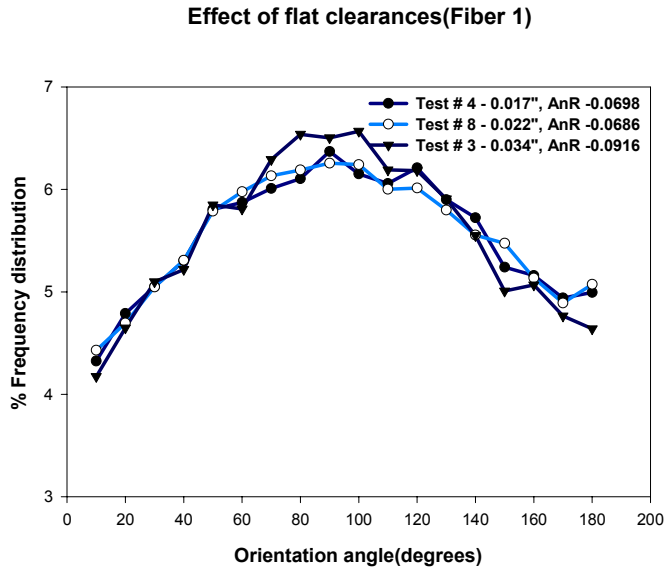


Figure 4.88: Fiber orientation distribution of needled fabrics from fiber 1 produced using different flat clearances.

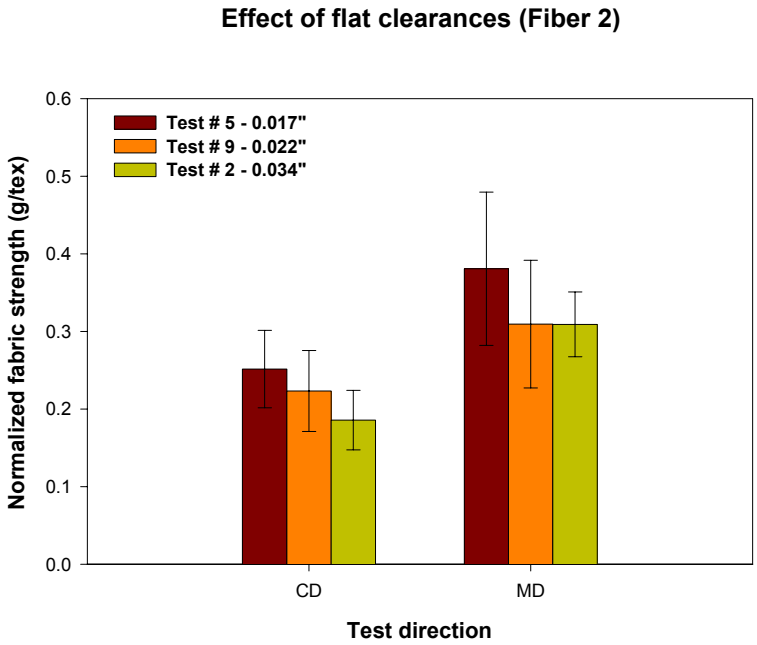


Figure 4.89: Fabric tensile strength of needled fabrics from fiber 2 produced using different flat clearances.

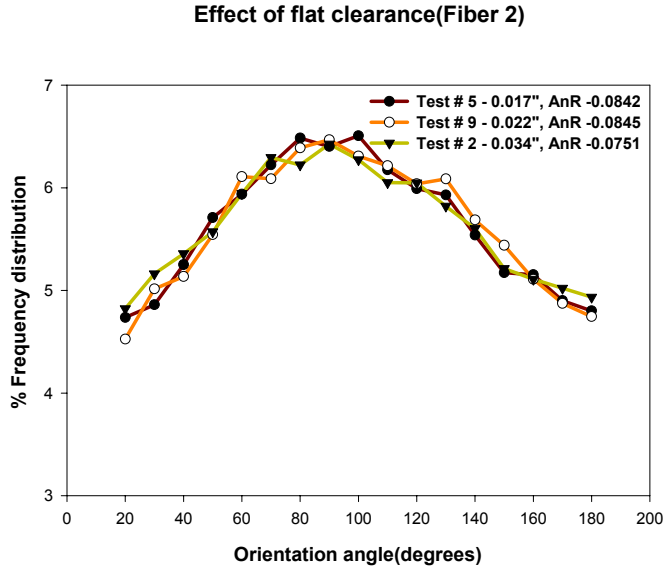


Figure 4.90: Fiber orientation distribution of needled fabrics from fiber 2 produced using different flat clearances.

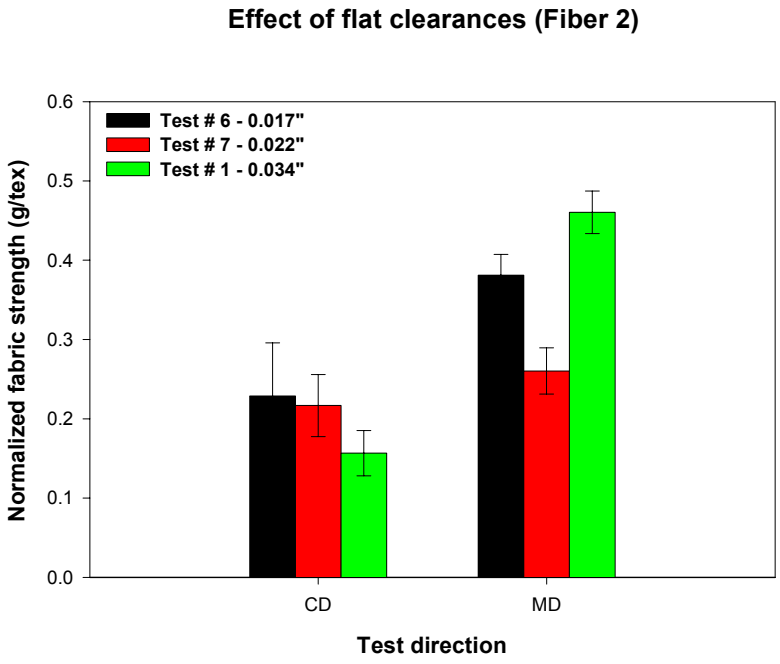


Figure 4.91: Fabric tensile strength of needled fabrics from fiber 2 produced using different flat clearances.

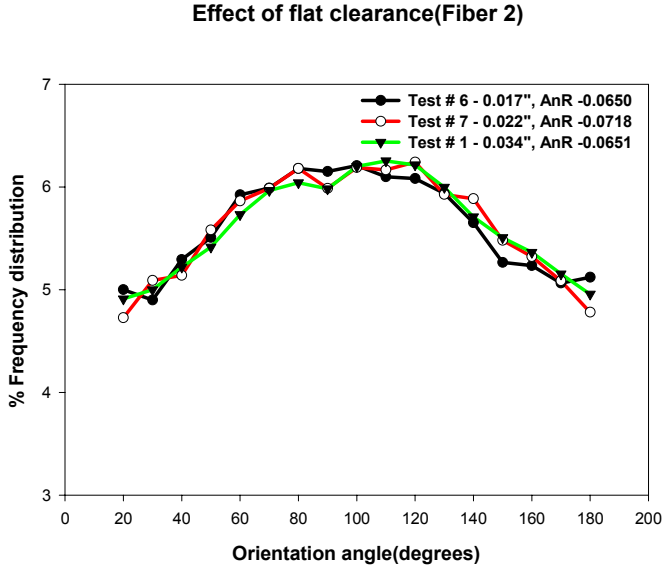


Figure 4.92: Fiber orientation distribution of needled fabrics from fiber 2 produced using different flat clearances.

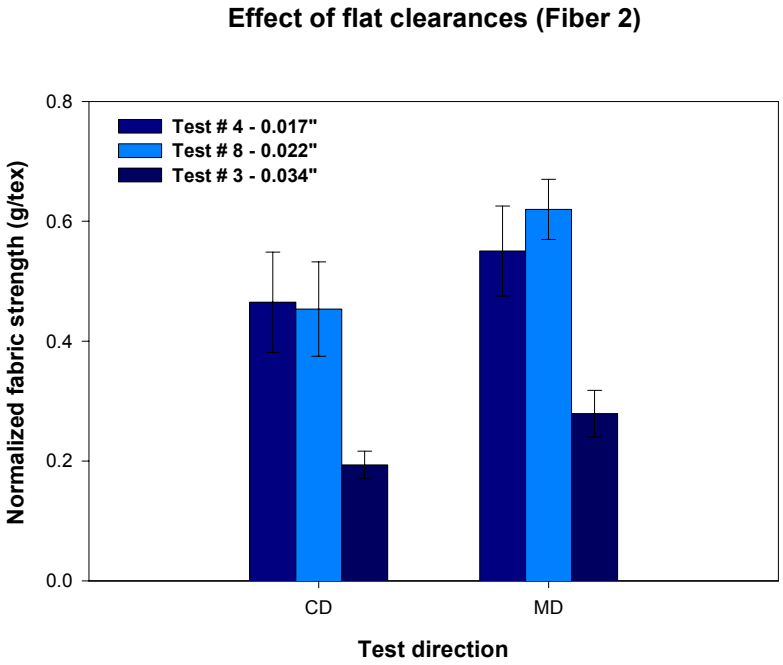


Figure 4.93: Fabric tensile strength of needled fabrics from fiber 2 produced using different flat clearances.

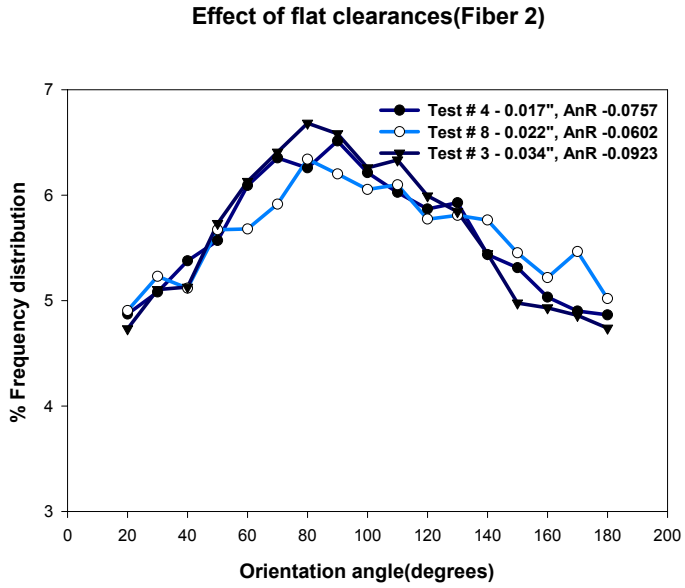


Figure 4.94: Fiber orientation distribution of needled fabrics from fiber 2 produced using different flat clearances.

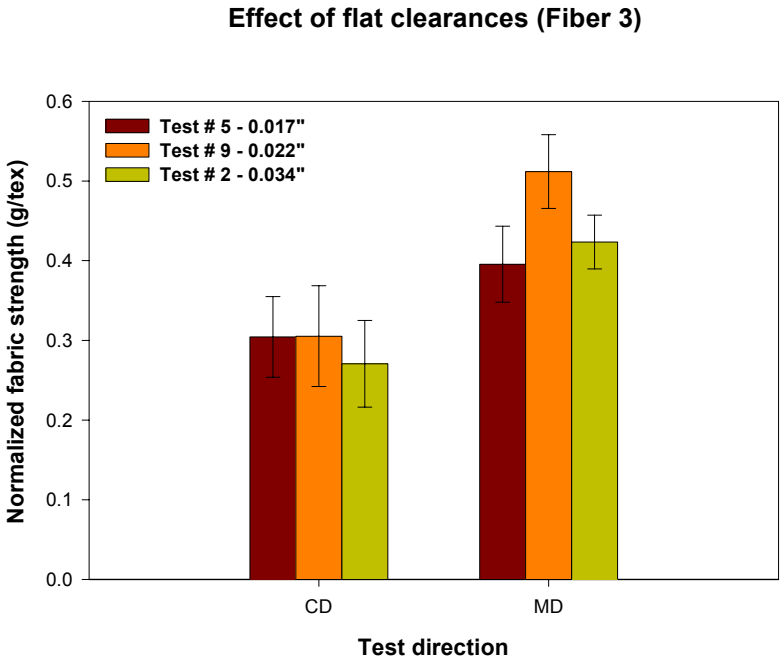


Figure 4.95: Fabric tensile strength of needled fabrics from fiber 3 produced using different flat clearances.

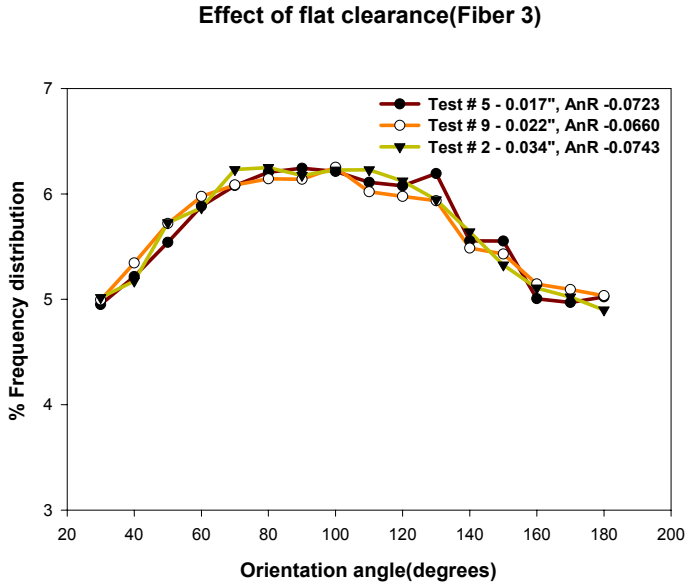


Figure 4.96: Fiber orientation distribution of needled fabrics from fiber 3 produced using different flat clearances.

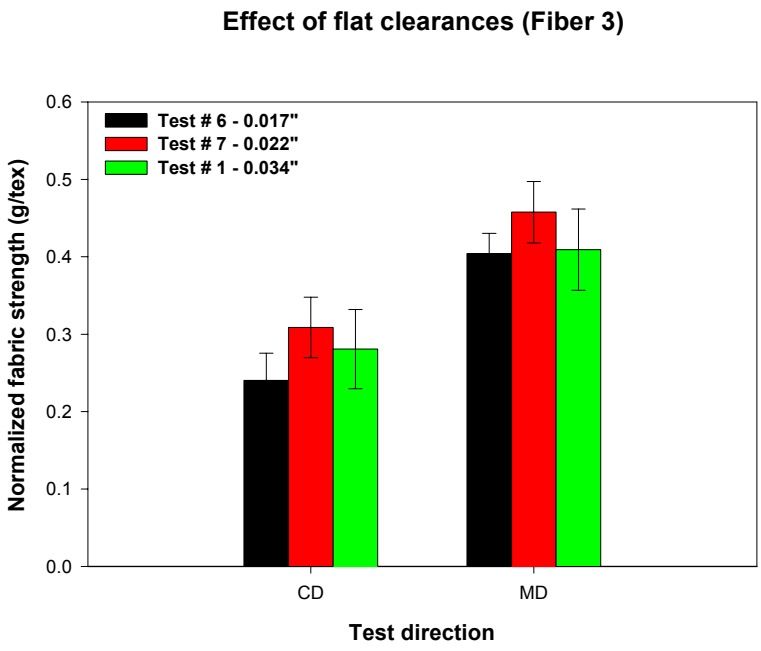


Figure 4.97: Fabric tensile strength of needled fabrics from fiber 3 produced using different flat clearances.

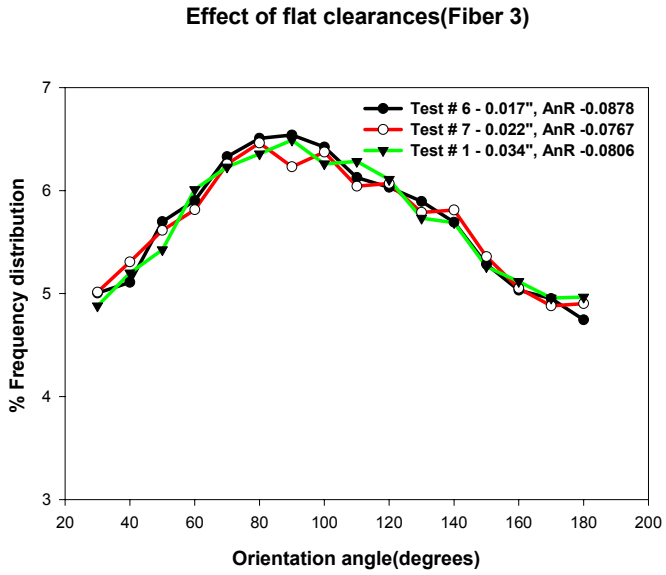


Figure 4.98: Fiber orientation distribution of needled fabrics from fiber 3 produced using different flat clearances.

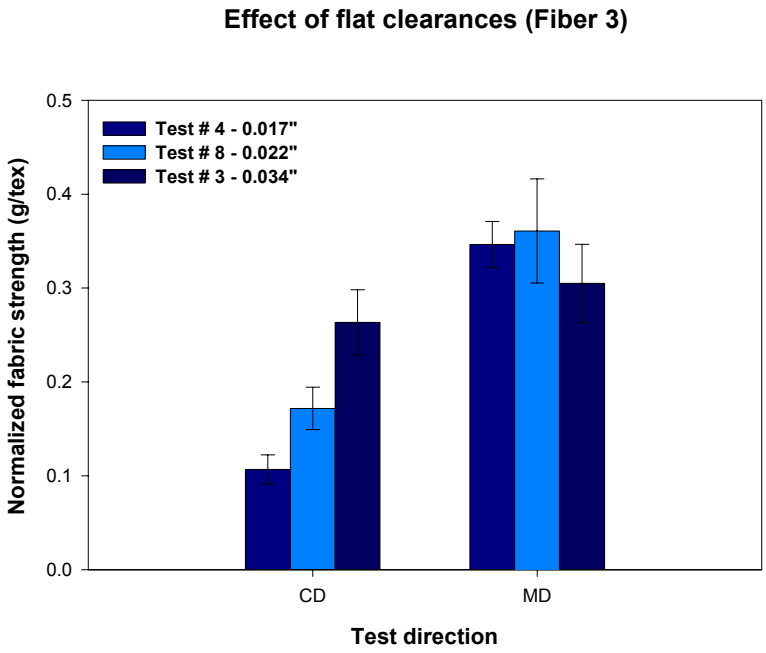


Figure 4.99: Fabric tensile strength of needled fabrics from fiber 3 produced using different flat clearances.

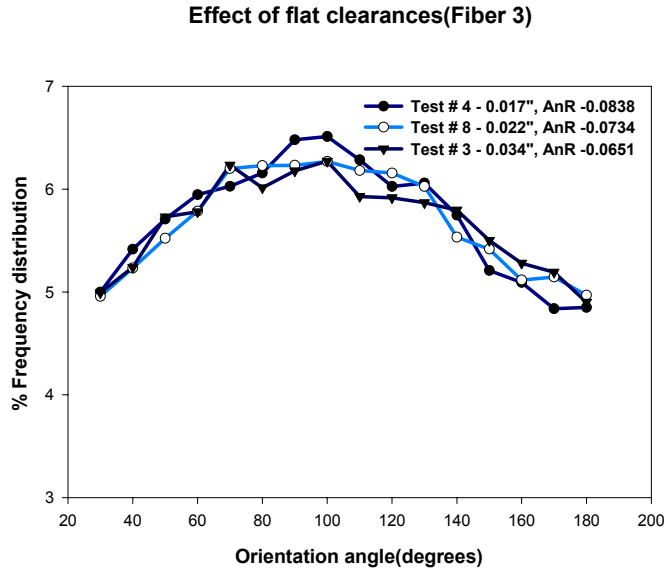


Figure 4.100: Fiber orientation distribution of needled fabrics from fiber 3 produced using different flat clearances.

In the all the figures displayed above it could be seen that the needled fabrics tested along the MD were stronger than the fabrics tested along the CD, this is because more fibers were oriented along MD which make it possible to take on higher loads when subjected to stress. The trend observed with the fabric tensile strengths were supported by their respective fiber orientation distributions (ODF's) often. For the ones this particular trend couldn't established, this may be due to the presence of crimped fibers that couldn't be taken into account when developing the algorithm while taking the ODF measurement.

There is no noticeable change observed in the fiber orientations between the fabrics produced with different feedplate-lickerin clearance, which is often the case with all the figures. Also the anisotropy ratios and the ODF's together indicate a random and a unimodal distribution of fibers.

The most critical setting in a carding machine is between cylinder and flat tops. The flat clearance essentially opens the flocks to individual fibers, removes short fibers, impurities and trash, and reduces the formation of neps and aids in longitudinally orienting the fibers. So closer the setting, better the web quality in terms of uniformity, short fibers, neps and less variations in the desired properties. Very close setting imposes too much stress on the fibers not giving much space for fiber alignment and doesn't aid in crimp removal. Wider setting allows more fibers to accumulate between the cylinder and the flats with less force acting on the fiber mass resulting in more nep formation and poor fiber alignment and crimp removal. Thus optimum setting between the cylinder and the flats essentially aids in proper fiber alignment and crimp removal. An appropriate trend for the fabric's tensile strength between fabrics produced from the same fiber and also between the ones produced using different fibers couldn't be established. This might be due to the large variation associated with the samples.

4.4 Compression Property Measurements:

Fabric properties are fundamentally based on its structure and its fiber (and yarn) properties. An important attribute of a fibrous mass is its behavior under compression. The compression property of a fabric is one of the most important of the fabric's basic mechanical properties, and is closely related to fabric handle. That is, the compression property is concerned with the softness and fullness of the fabric and also with the fabric's surface smoothness. Furthermore, the compression property is also related to the fabric structure, the surface property of fibers and/or yarns, and the lateral compression property of fibers and/or yarns. There have been many studies on the thickness and bulk density of nonwoven fabrics. But only a few experimental literatures can be found related with compression property of nonwoven fabrics. [42]

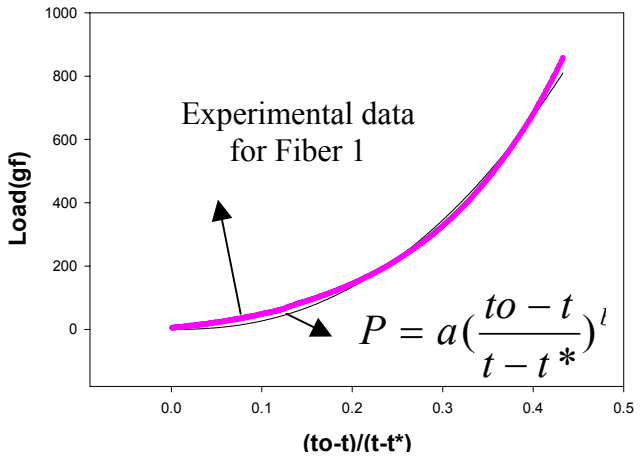
The mechanical behavior of needled fabrics when subjected to compressive loads has been investigated and studied. The "load-extension" curve of a fibrous mass during compression and recovery characterizes this behavior. With the resulting availability of almost continuous data of the whole compression process, it could be possible to quantify how the shape of the load-extension curve of the fabric influences the mechanical behavior during processing and thus the processing performance. For an optimization of the fabric production process and the fiber processing performance, quantitative, meaningful parameters need to be established characterizing the compression behavior as response to applied loads. Curve fitting parameters describing compression behavior may then be used as compression parameters and ultimately be correlated to fiber processing performance and product characteristics.

One basic problem for the evaluation of "the typical compression behavior of a certain type of fabric" is the appropriate reduction of a large number of single-fabric curves to one averaged curve. The data handling and manipulation is complicated by the fact that (load/displacement)-data pairs for specimens of the same sample are not collected at constant platen displacement intervals with the tester such as the INSTRON. It is

therefore important to find fitting parameters that converge against a steady value for the parameters obtained for the specimens of the same sample.

There are no standards or guidelines published on how to interpret load-compression data and how to describe the fabric compression mechanical behavior. So the load-extension curve is approached with a linear regression line. The loading and the unloading set of each of the specimens data points of the compression curve were separated by determining the end point of loading part and at the same time the beginning point of the unloading part of the compression curve.

Searching for a theoretical function that would generally fit the course of experimental single fiber data in the crimp removal region, the power law suggested by Dent [15], which has been used to describe the compressive behavior of fibrous structures comes to mind. Experimental load-thickness data of the final needled fabrics obey the boundary conditions of this function, as depicted in Figure 4.101.



$y = ax^{b}$

Where
α = Stiffness or modulus (gf)
β = Shape factor characteristic for the compressional behaviour
t_0 = Platen separation (cm)
t = Variable thickness (in cm) from the experiment
t* = Thickness at zero void volume /Initial thickness (in cm)

Figure 4.101: Power law function to fit the loading part of the compression data

The fitting of the above described power law of the load as function of the intrinsic thickness delivered the curve in Figure 4.101 at an R-square value of 0.996. The linear

regression of y and x is demonstrated for the example of a needled fabric produced from fiber 1.

Because of the great amount of data, the fit of a theoretical function to experimental data and the extraction of the characteristic parameters α and β needs to be automated completely. Commercial software like SAS was useful to test and check the fit of experimental data curves, and NLIN procedure was necessary for a complete analysis.

4.4.1 Analysis of the Fitting Parameters

On the basis of this interpretation of the power law as description of the compression of fiber assemblies, a numerical analysis of the fitting parameters α and β is introduced below. Regression constant 'a' is related to deformation (thickness change), and is considered to be more important than b. Figures 4.102 and 4.103 demonstrates the general influence of the magnitude of 'a' and 'b' respectively. As can be seen from the curves for a=700, 300 and a=80, an increase in 'a' results in subtle changes, meaning resistance to compression increases rapidly for the same amount of compression. As shown with the curves for b=3, 5, 7 and b=9, an increase in b causes an increase in curve steepness, meaning the resistance to compression increases slower with compression. Thus, high 'a' values and low 'b' values relates to a fiber assembly that is stiff, bulkier and less resilient in compression.

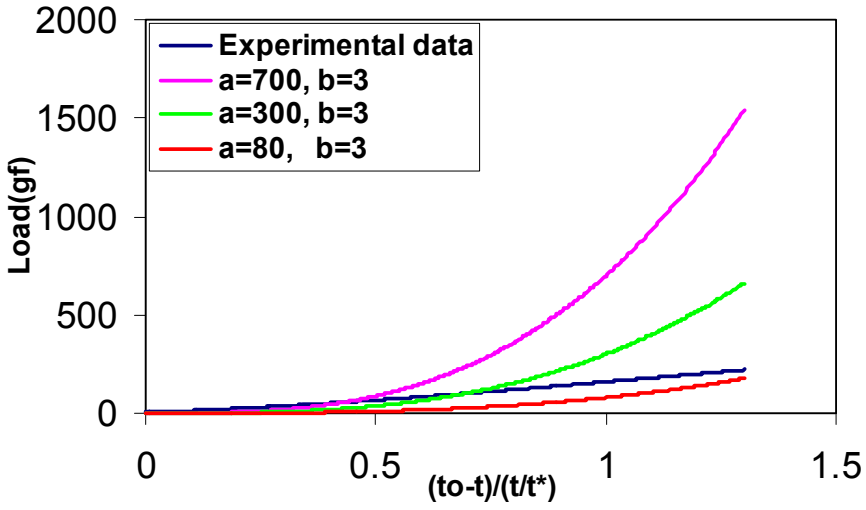


Figure 4.102: Shape of Power-Law Function in Dependence of Fitting Parameter 'a'

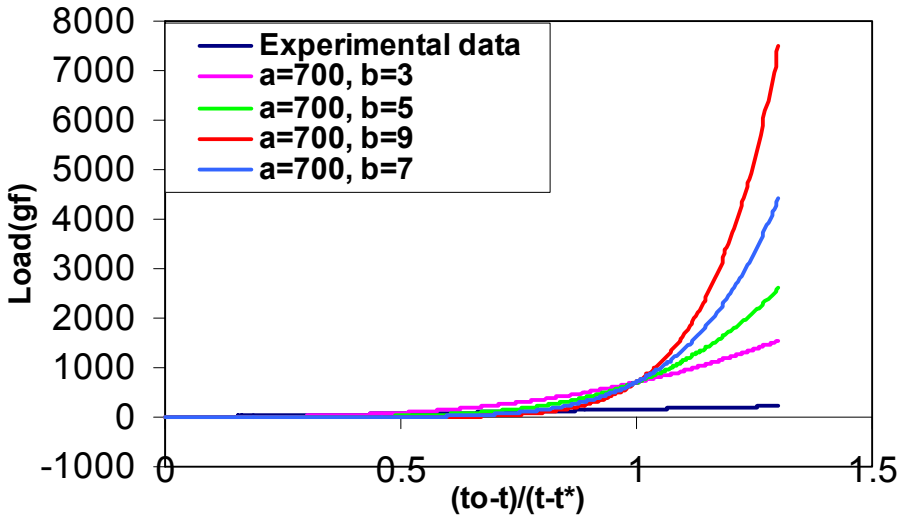


Figure 4.103: Shape of Power-Law Function in Dependence of Fitting Parameter 'b'

Note: The fitting parameters 'a' and 'b' one for the loading (L) and the other for the unloading execution (UL) are represented on the each of following load-compression curves and also the thickness(T in mm) is indicated.

4.4.2 Influence of Fiber Type on Compression Parameters:

Figure 4.104 depicts the influence of fiber type on the compression behavior of final needled fabrics produced from 3 different fibers of same polymeric material with different fiber crimp characteristics under same processing conditions. (Feedplate-lickerin clearance – 0.029", Cylinder speeds – 800 rpm, Flat clearance – 0.022")

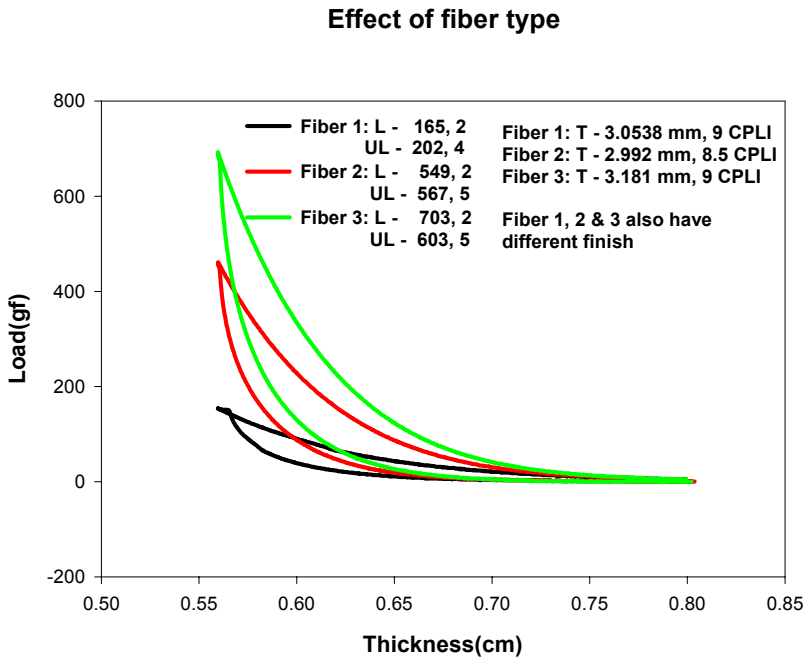


Figure 4.104: Load-thickness curves of needled fabrics produced from three different 3-den PET fibers

Referring to the numerical values of the stiffness parameters 'a' for both the loading and the unloading part of the execution in the above figure, it can seen that the fabric produced using fiber 3 is stiffer than the ones produced using fiber 2 and fiber 1. The load-thickness curves also elucidates their behavior under compressive forces. It is apparent from the curves that the resistance to compression increases rapidly for the fabric produced with fiber 3 and then followed by the fabric produced with fiber 2 compared to the more continuous and gradual change when a soft fabric like the one produced with fiber 1 is compressed. It would be difficult to discriminate between the fabrics at low pressures, but at higher pressures the relative change could be perceived. This can be explained by the inherent fiber crimp characteristics and finish level. Studies associated with crimp and compression properties showed that the thickness and compressibility of the fiber assembly are strongly related to the amount of crimp in the fibers. The fabrics produced using fiber 3 would be judged as hard & stiff because of barely perceptible deformation compared to the other 2 fabrics. And fabric produced

from fiber 2 would be judged as stiff compared to the fabric produced from fiber 1 which would be judged as soft because of the amount of compression.

4.4.3 Influence of Cylinder Speeds on Compression Parameters:

Figures 4.105 through 4.107 shows the influence of cylinder speeds on the compression behavior of the needled fabrics produced from each of the three fibers. (Feedplate-lickerin clearance – 0.029", Flat clearance - 0.022').

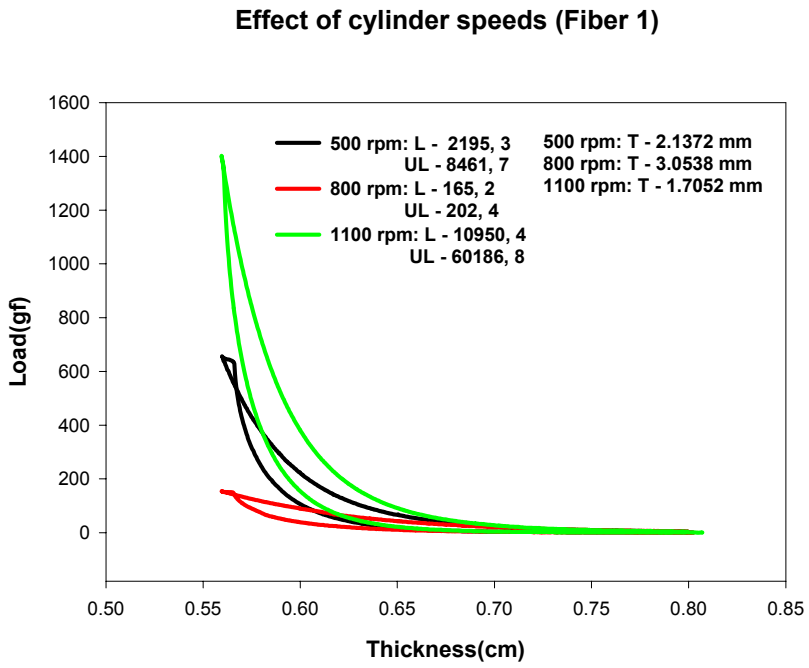


Figure 4.105: Load-thickness curves of needled fabrics produced from fiber 1 using different cylinder speeds

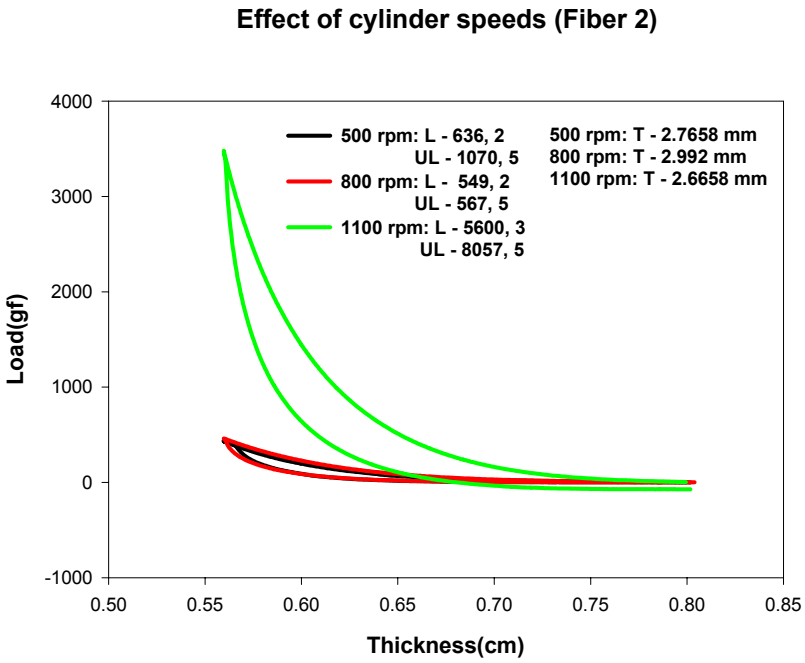


Figure 4.106: Load-thickness curves of needled fabrics produced from fiber 2 using different cylinder speeds

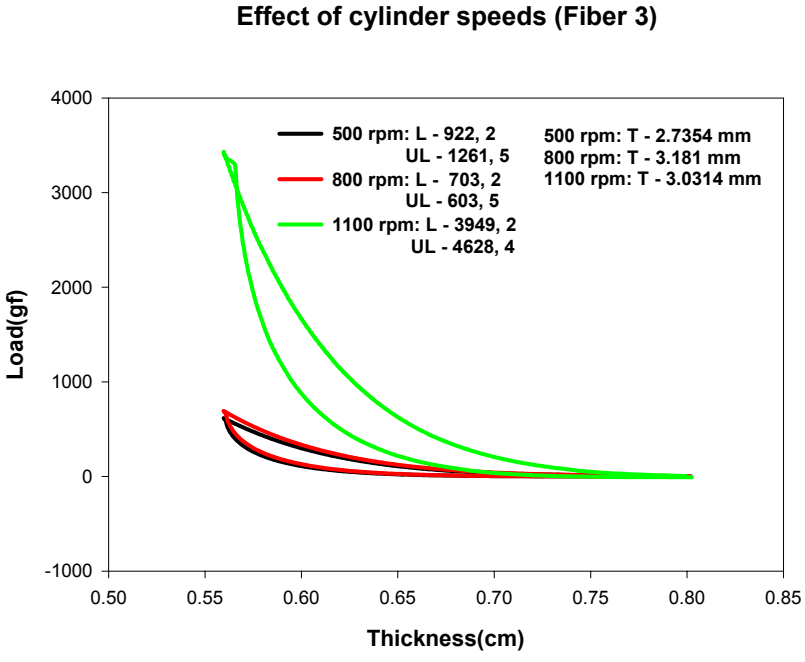


Figure 4.107: Load-thickness curves of needled fabrics produced from fiber 3 using different cylinder speeds

From the numerical value of the stiffness parameters 'a' for both the loading and the unloading part of the execution in the figure 4.105 through 4.107, it can seen that the fabric produced using 1100 rpm is stiffer than the ones produced using 500 rpm and then followed by the one produced using 800 rpm. The fabric compression behavior observed from their respective load thickness curves substantiates the stiffness values. It is apparent from the curves that the resistance to compression increases rapidly for the fabric produced with 1100 rpm and then followed by the fabric produced with 500 rpm compared to the more continuous and gradual change when a soft fabric like the one produced with 800 rpm is compressed. It would be difficult to discriminate between the fabrics at low pressures, but at higher pressures the relative change could be perceived. A similar behavior was observed with their fabric tensile strength measurements as well. The results demonstrated that fiber crimp persists throughout the carding operation, although the amount of crimp reduced as fibers react to the strains imposed during processing varied. Thus the fabrics produced using 1100 rpm would be judged as hard, stiff, having a harsher handle and less resilient because of barely perceptible deformation compared to the other 2 fabrics produced using 500 rpm and 800 rpm. A similar trend is observed for fabrics produced using fiber 2 and fiber 3 as well.

4.4.4 Influence of Needling Densities on Compression Parameters:

Figures 4.108 through 4.110 depicts the influence of needling densities on the compression behavior of the needled fabrics produced from each of the three fibers. (Feedplate-lickerin clearance – 0.029", Cylinder speeds – 800 rpm, Flat clearance – 0.022")

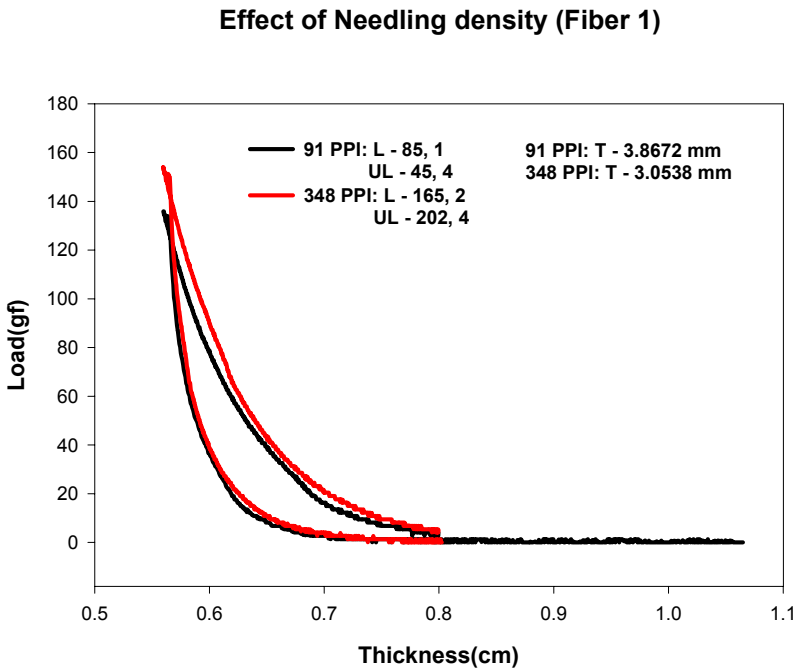


Figure 4.108: Load-thickness curves of needled fabrics produced from fiber 1 using different needling densities

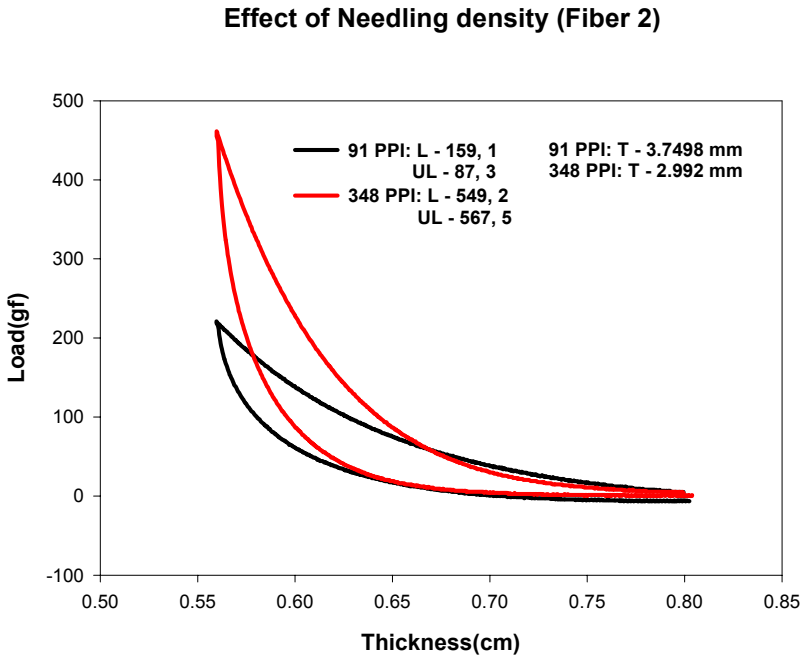


Figure 4.109: Load-thickness curves of needled fabrics produced from fiber 2 using different needling densities

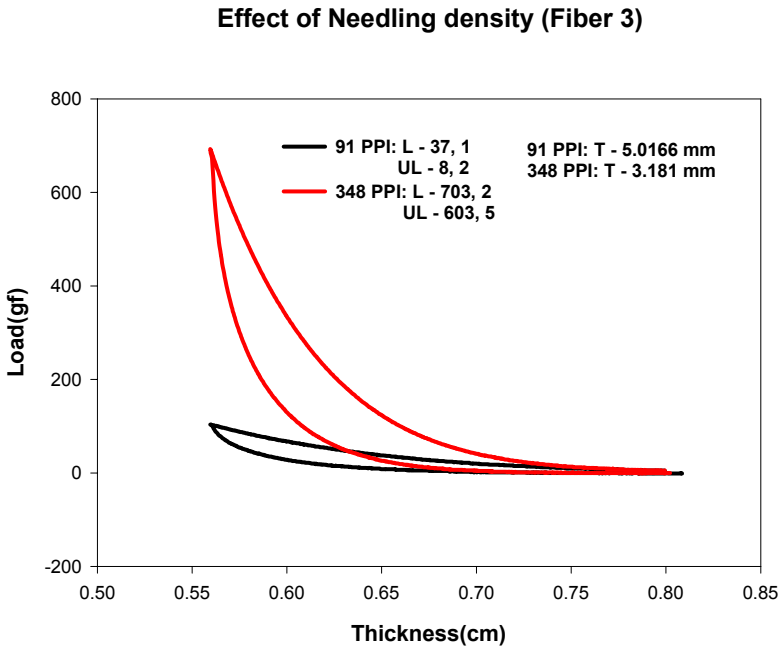


Figure 4.110: Load-thickness curves of needled fabrics produced from fiber 3 using different needling densities

From the numerical value of the stiffness parameters 'a' for both the loading and the unloading part of the execution in the figure 4.108 through 4.110, it can seen that the fabric produced using 348 PPI is stiffer than the ones produced using 91 PPI. The fabric compression behavior observed from their respective load-thickness curves substantiates the stiffness values. It is apparent from the curves that the resistance to compression increases rapidly for the fabric produced with 348 PPI compared to the more continuous and gradual change when a soft fabric like the one produced with 91 PPI is compressed. This may be due to the fact that increasing the needling density increases the forces acting per unit area of a fabric forming fiber network between the several layers of the assembly making it more compact and bulkier. Thus the fabrics produced using 348 PPI rpm would be judged as relatively hard, stiff, having a harsher handle, comparatively thinner and less resilient because of barely perceptible deformation. And fabric produced using 91 PPI would be judged as relatively soft because of the amount of compression. A significant change is observed between fiber 1 and fiber 3, this might be due to the inherent fiber crimp characteristics and their behavior to loads during processing.

4.4.5 Influence of Feedplate-Lickerin Clearance on Compression Parameters

Figure 4.111 through 4.119 depicts the influence of feedplate-lickerin clearance on the fabric compression behavior produced using each of the three fibers.

There are three graphs shown for each of the 3 fibers. The test #'s in the following graphs were the tests associated with the experimental plan carried out for carding 3 den PET fibers, which indicate the production of a needled fabric using same cylinder speeds (800 rpm) and flat clearances but different feedplate-lickerin clearance settings. When comparing the measurements between the graphs obtained for the same fiber but using a different test sequence from the carding plan, the only variable observed between these graphs was the flat clearance setting.

Figures [4.111, 4.114 and 4.117] , [4.112, 4.115, and 4.118] and [4.113, 4.116, and 4.119] have the respective flat clearance settings 0.022", 0.034" and 0.017". So the slight discrepancy in the measurements/ trends observed between the graphs of the same fiber may be due to the different flat clearance settings.

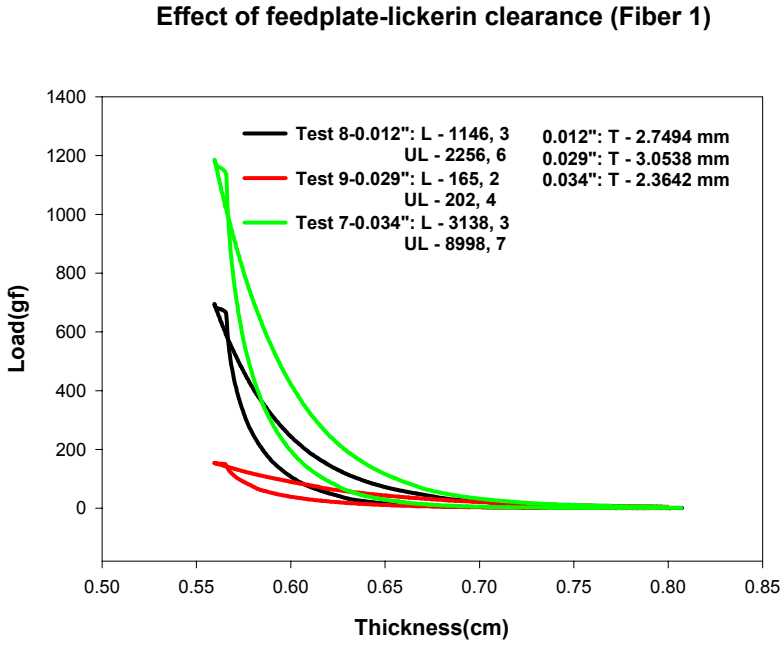


Figure 4.111: Load-thickness curves of needled fabrics produced from fiber 1 using different feedplate-lickerin clearance.

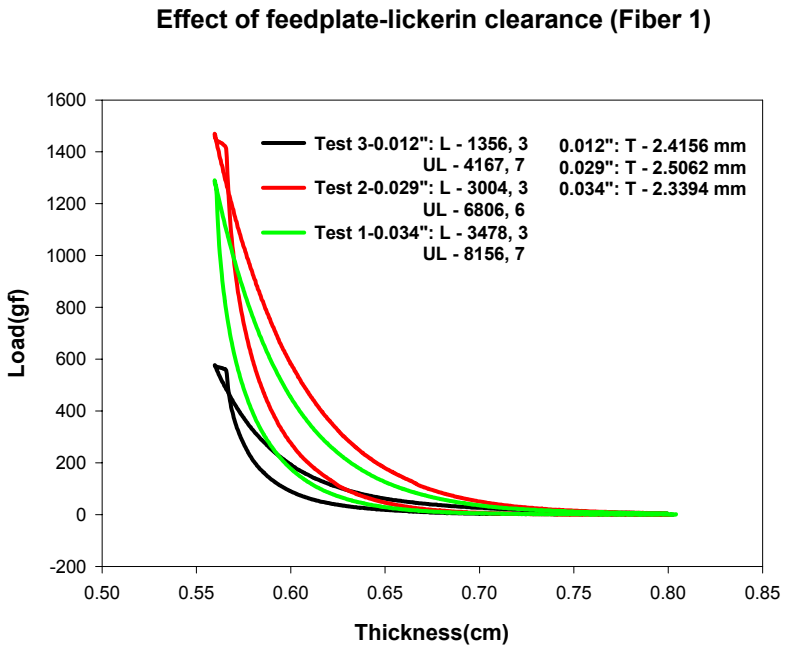


Figure 4.112: Load-thickness curves of needled fabrics produced from fiber 1 using different feedplate-lickerin clearance.

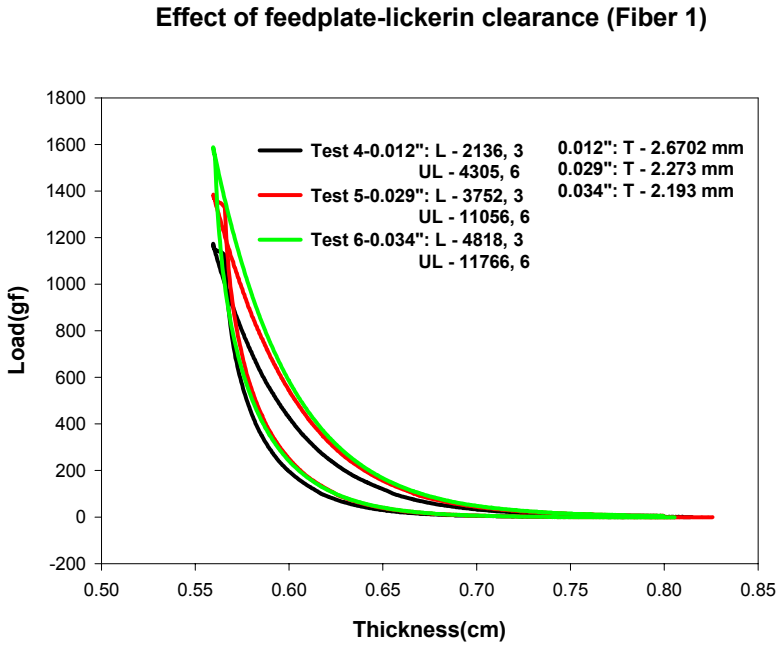


Figure 4.113: Load-thickness curves of needled fabrics produced from fiber 1 using different feedplate-lickerin clearance.

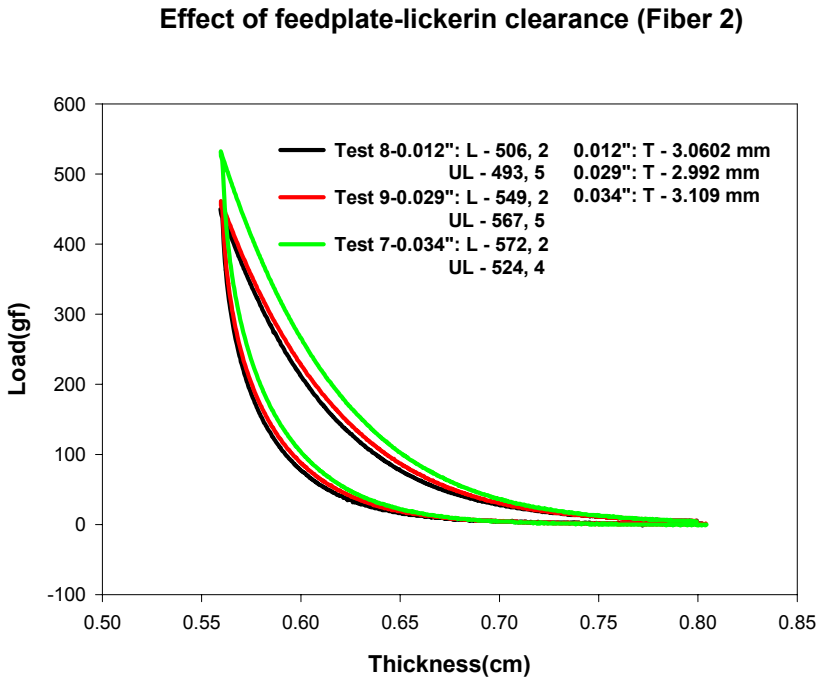


Figure 4.114: Load-thickness curves of needled fabrics produced from fiber 2 using different feedplate-lickerin clearance.

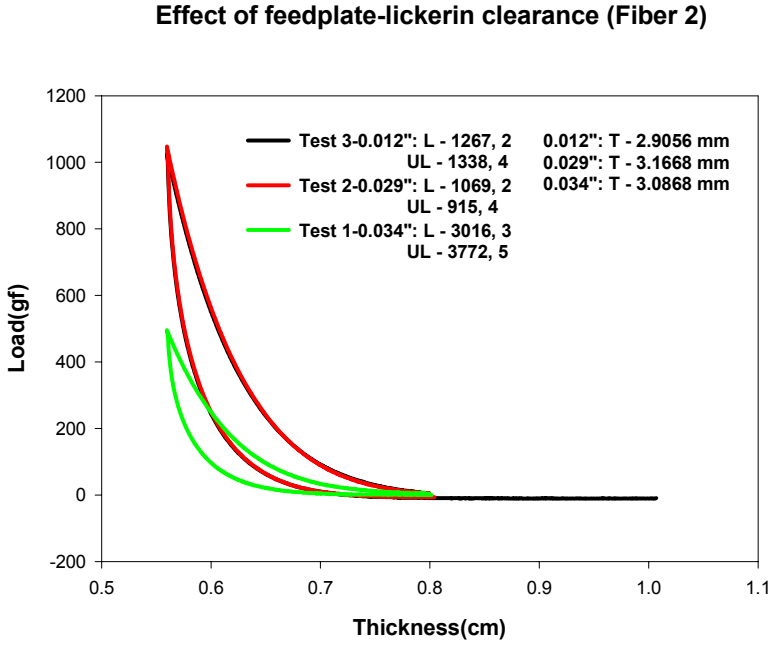


Figure 4.115: Load-thickness curves of needled fabrics produced from fiber 2 using different feedplate-lickerin clearance.

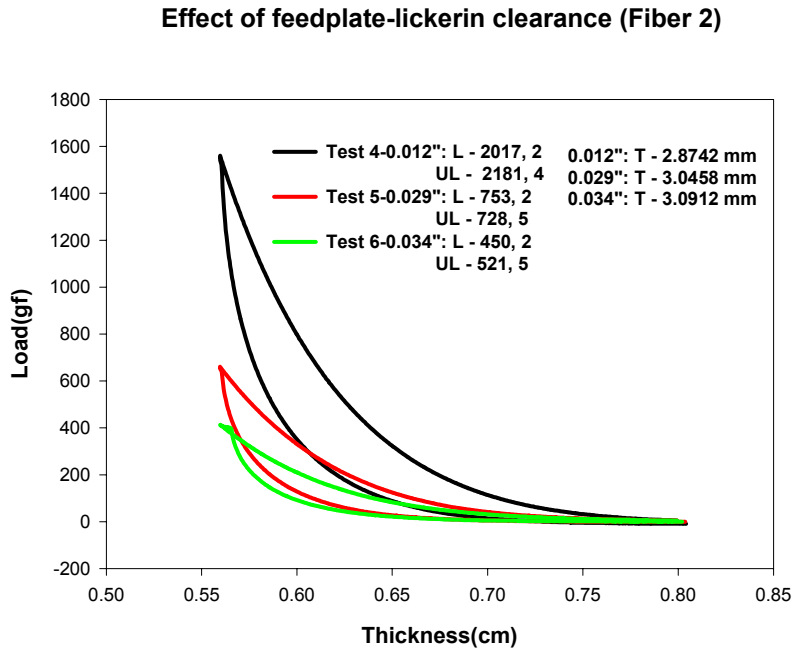


Figure 4.116: Load-thickness curves of needled fabrics produced from fiber 2 using different feedplate-lickerin clearance.

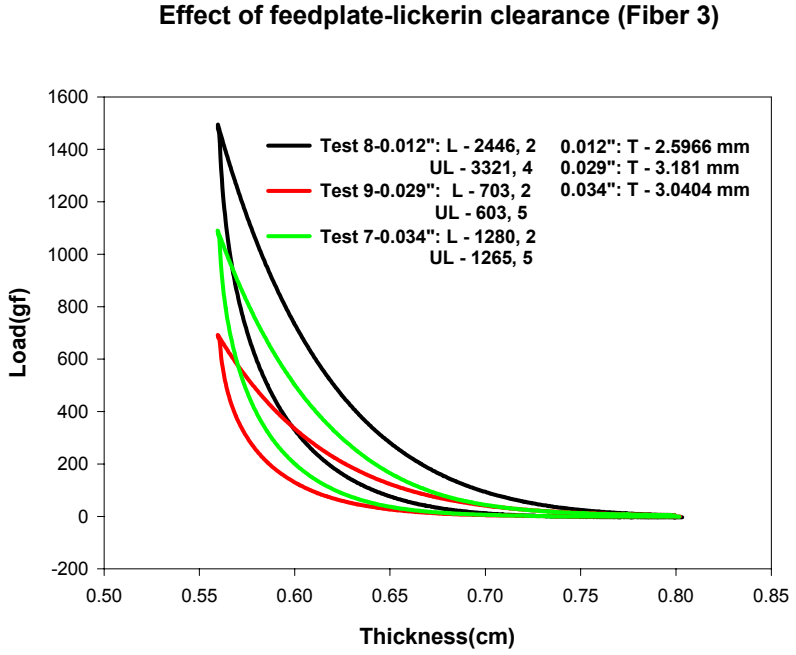


Figure 4.117: Load-thickness curves of needled fabrics produced from fiber 3 using different feedplate-lickerin clearance.

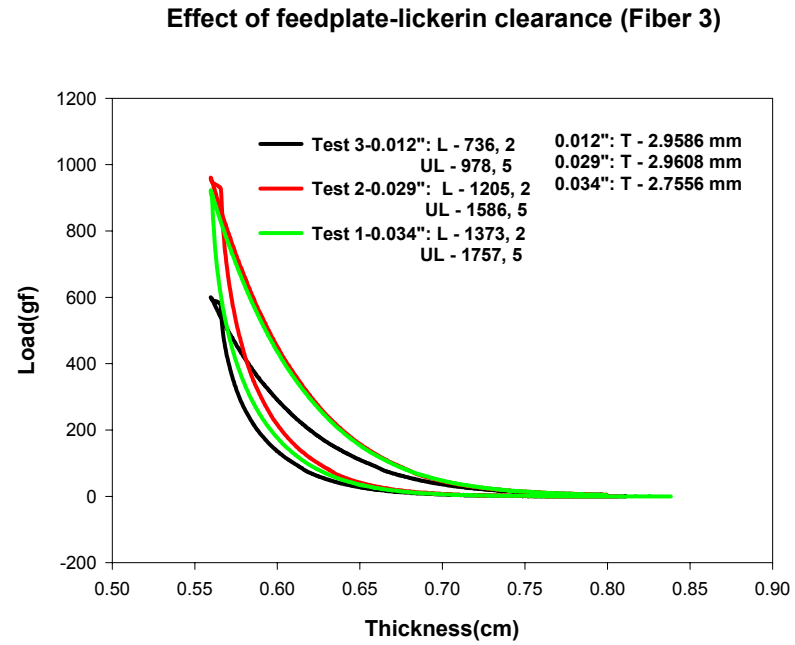


Figure 4.118: Load-thickness curves of needled fabrics produced from fiber 3 using different feedplate-lickerin clearance.

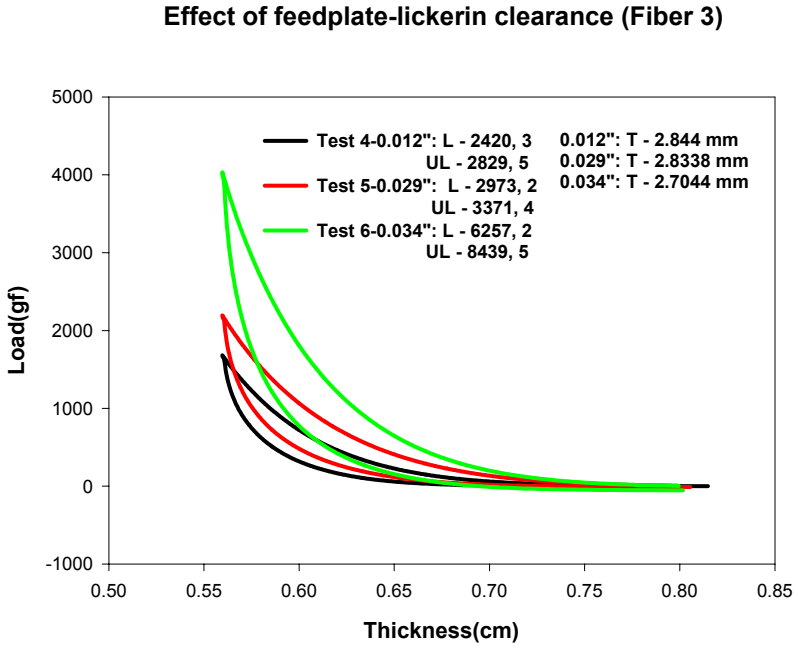


Figure 4.119: Load-thickness curves of needled fabrics produced from fiber 3 using different feedplate-lickerin clearance.

The feedplate-lickerin clearance essentially controls the initially opening of the fiber mass and considerably effects the crimp removal, which affects the load bearing capacity of the fiber. A relative change is observed in the fabric compression behavior with respect to the compression curves among fabrics produced using the same fiber and also among the fabrics produced using different fibers relating to feedplate-lickerin clearance. The reasons for these subtle differences observed with their compressive behavior may be associated to their inherent fiber crimp characteristics and also due to the variable amounts of strains imposed on the fibers during processing, the measurements of which seem to be unfeasible.

4.4.6 Influence of Flat Clearance on Compression Parameters:

Figure 4.120 through 4.128 depicts the effect of flat clearance on the fabric compression produced using each of the three fibers.

There are three graphs shown for each of the 3 fibers here .The test #'s in the following graphs were the tests associated with the experimental plan carried out for carding 3 den PET fibers which designates the production of a needled fabric using same cylinder speeds (800 rpm) and feedplate-lickerin clearances but different flat clearance settings. When comparing the measurements between the graphs obtained for the same fiber but using a different test sequence from the carding plan, the only variable observed between these graphs was the flat clearance setting.

Figures [4.120, 4.123 and 4.126] , [4.121, 4.124, and 4.127] and [4.122, 4.125, and 4.128] have the respective flat clearance settings 0.029", 0.034" and 0.012". So the slight discrepancy in the measurements/trends observed between the graphs of the same fiber may be due to the different feedplate-lickerin clearance settings.

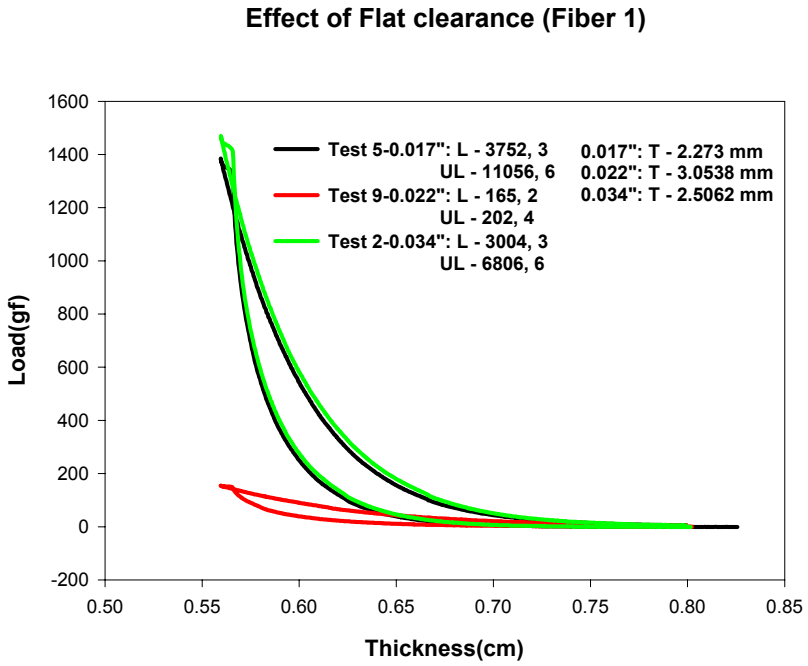


Figure 4.120: Load-thickness curves of needled fabrics produced from fiber 1 using different flat clearance.

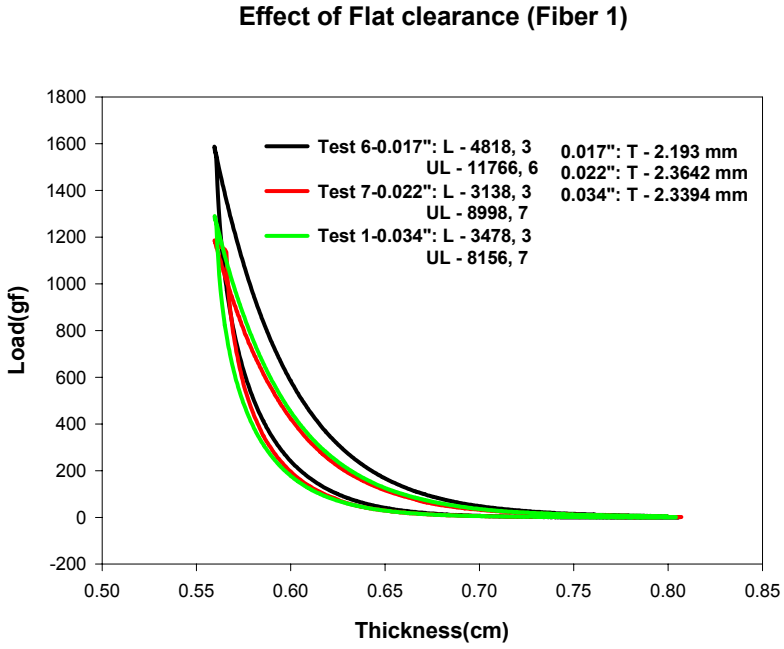


Figure 4.121: Load-thickness curves of needled fabrics produced from fiber 1 using different flat clearance.

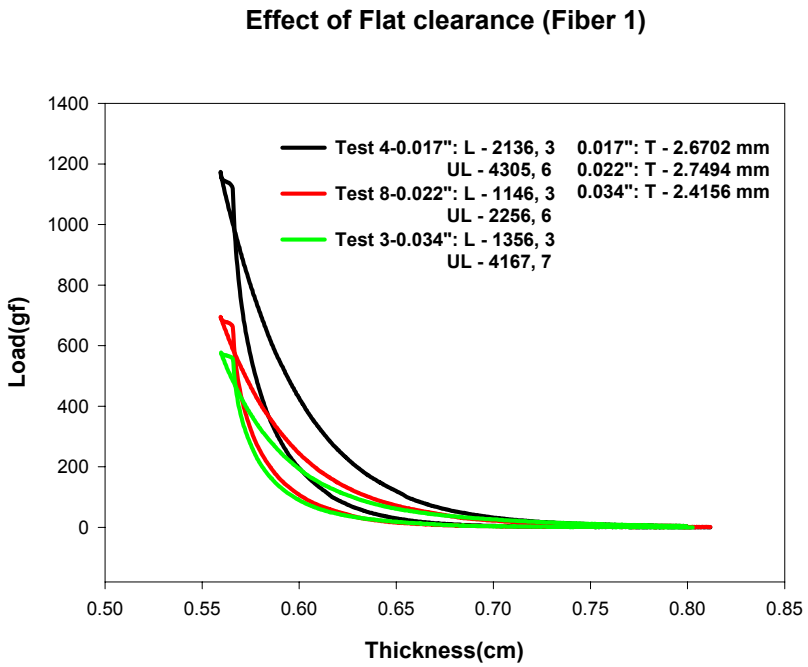


Figure 4.122: Load-thickness curves of needled fabrics produced from fiber 1 using different flat clearance.

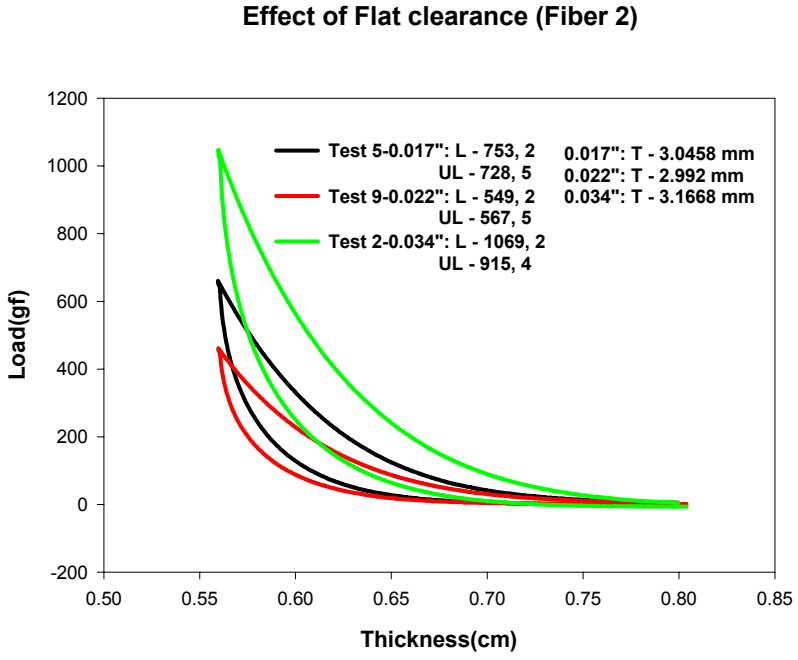


Figure 4.123: Load-thickness curves of needled fabrics produced from fiber 2 using different flat clearance.

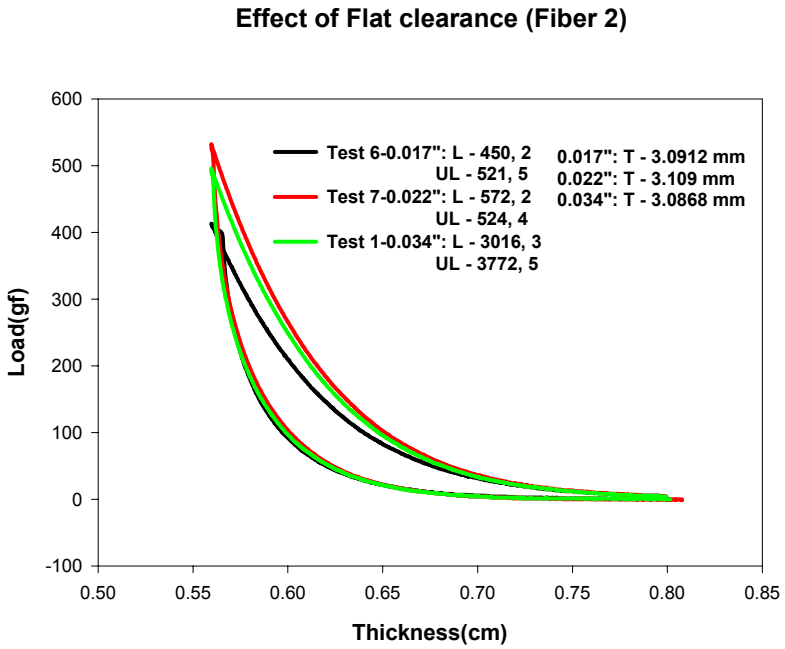


Figure 4.124: Load-thickness curves of needled fabrics produced from fiber 2 using different flat clearance.

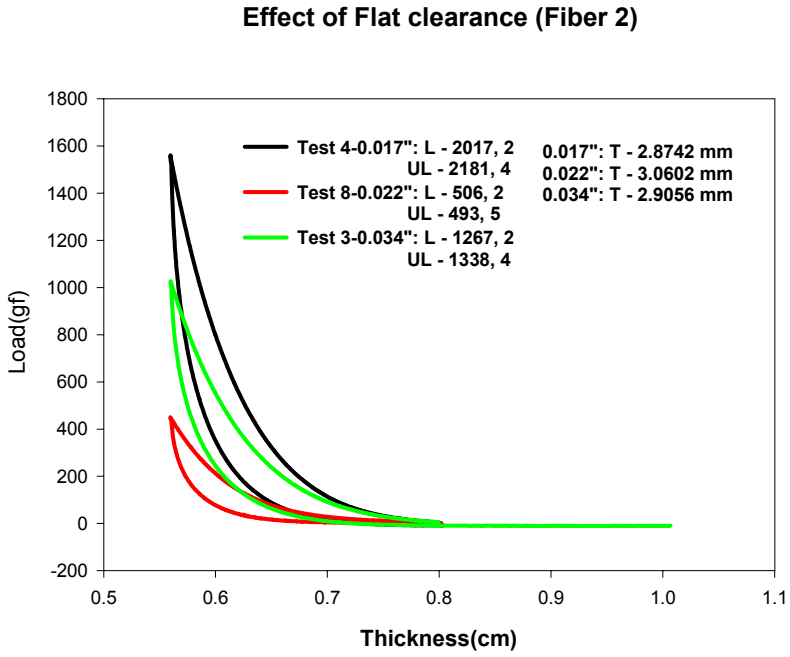


Figure 4.125: Load-thickness curves of needled fabrics produced from fiber 2 using different flat clearance.

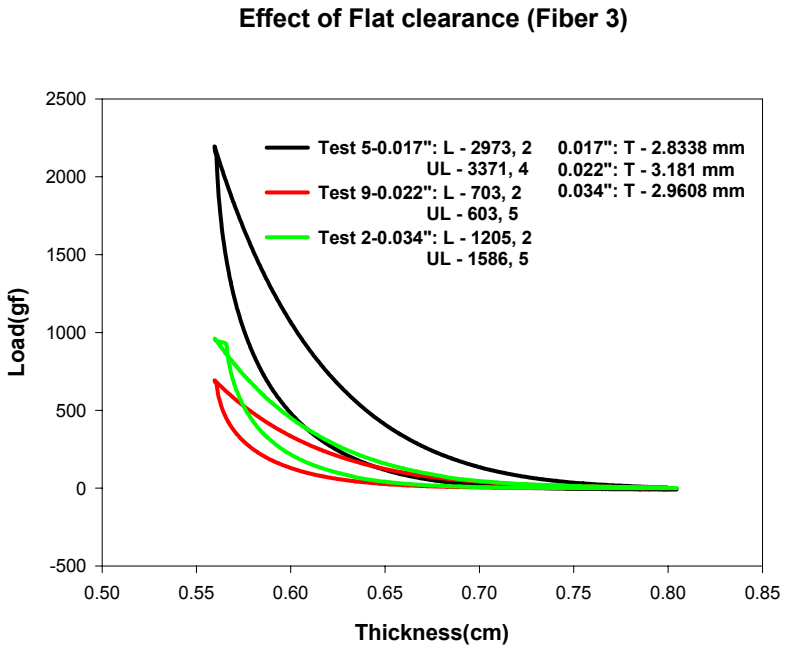


Figure 4.126: Load-thickness curves of needled fabrics produced from fiber 3 using different flat clearance.

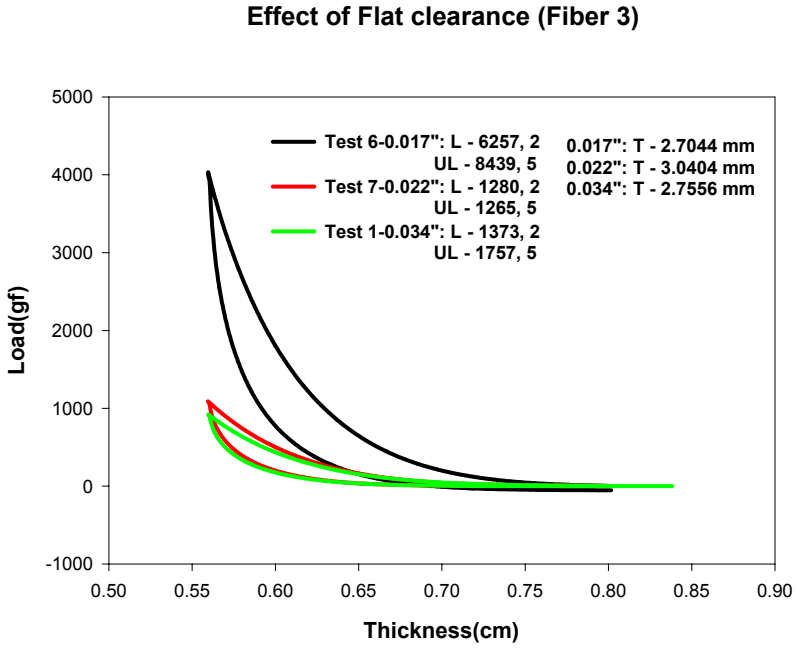


Figure 4.127: Load-thickness curves of needled fabrics produced from fiber 3 using different flat clearance.

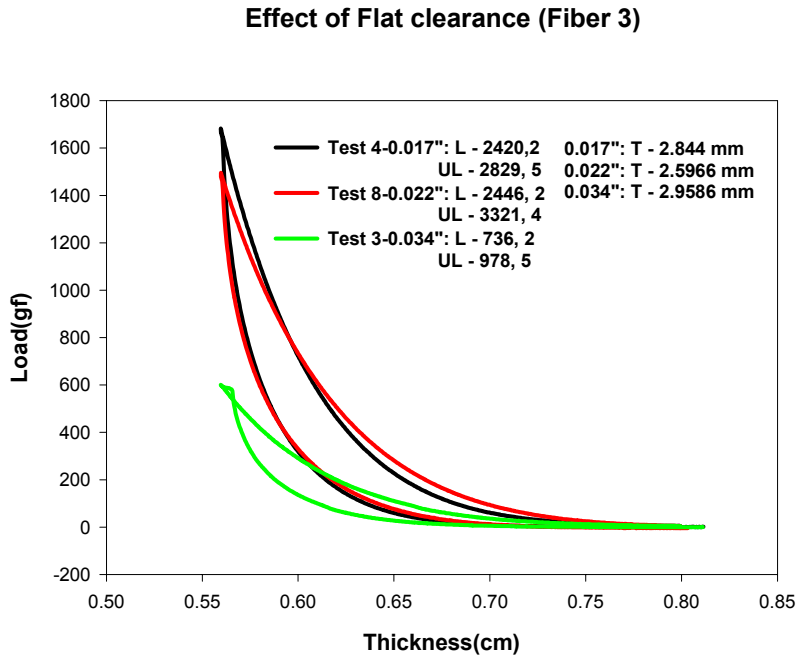


Figure 4.128: Load-thickness curves of needled fabrics produced from fiber 3 using different flat clearance.

The most critical setting in a carding machine is between cylinder and flat tops. The flat clearance essentially opens the flocks to individual fibers, removes short fibers, impurities and trash, and reduces the formation of neps and aids in longitudinally orienting the fibers. So closer the setting, better the web quality in terms of uniformity, short fibers, neps and less variations in the desired properties. Very close setting imposes too much stress on the fibers not giving much space for fiber alignment and doesn't aid in crimp removal, due to which the fiber assembly might be stiff, hard and less resilient during compression which is dependent on the residual crimp present in the fibers. Wider setting allows more fibers to accumulate between the cylinder and the flats with less force acting on the fiber mass resulting in more nep formation and poor fiber alignment and less crimp removal, due to which the fiber assembly might be stiff and hard during compression. Thus optimum setting between the cylinder and the flats essentially aids in proper fiber alignment and crimp removal, so the fiber mass might be relatively soft when subjected to compressive forces.

An appropriate trend for the fabric's compressive behavior between fabrics produced from the same fiber and also between the ones produced using different fibers couldn't be established. This can be due to many factors, which come into play during processing, which is beyond our comprehension.

5 CONCLUSIONS

The experimental results are explained in terms of influence of each of the following on the needled fabric properties:

- Effect of fiber type (fiber crimp and finish.
- Effect of cylinder speeds.
- Effect of feedplate-lickerin clearance.
- Effect of flat clearance.
- Effect of needling density.

The fiber, machine and process parameters showed significant effect on the needled fabric properties. More specifically, the following conclusions were drawn from the experimental results:

1. The fiber crimp showed significant effect on the basis weight of the needled fabrics.
    - Generally, fibers with higher crimp level produced a more compact and higher basis weight than fiber with lower crimp level due to their inherent fiber crimp characteristics and finish.
    - The basis weights for fabrics produced with fiber 1 increased as the cylinder speeds but decreased as the cylinder speeds. Generally the basis weight should decrease with cylinder speeds because the fibrous mass gets drafted, stretched and pulled apart resulting in a lower weight per unit area of the fabric. The deviation from the expected results might be due to several factors, which couldn't be established.
    - The basis weight decreased as the needling density increased because this increases the needle forces acting on a unit area of a fabric pulling (drafting) the mass of fibers apart making it more uniform.
    - However, the basis weight was not significantly affected by feedplate-lickerin clearance and flat clearance.

2. The rate of airflow largely depended on the basis weight and the thickness of the needled fabrics.

- The air resistance increased with increase in fabric weight per unit area due to more number of fibers per unit area and decreased with higher crimp level fibers due to increase in the internal surface area of the pores within the material.
- The air permeability was not significantly affected by cylinder speeds, thought the results were in direct proportion to their respective basis weight and the thickness of the final needled fabrics.
- The rate of airflow increased with needling density though the difference was not perceptible, the measurements were in direct proportion to their respective basis weights of the needled fabric.
- However, the air permeability was not significantly affected by feedplate-lickerin clearance and flat clearance.

3. The influence of fiber, machine and process related parameters were significant on the mechanical properties of the needled fabrics. The tensile response mainly depended on the fiber orientation and on the processing conditions.

- In all the cases, the needled fabrics were stronger along the machine direction due to the alignment of more number of fibers along machine direction compared to the cross direction. The trend observed with the fabric tensile fabric strengths is well supported by their fiber orientation distribution and the anisotropy ratios.
- The fabric tensile strength produced from fiber 3 was higher followed by the fabrics produced from fiber 2 and fiber 1. This is explained by their intrinsic fiber crimp characteristics during tensile loading and also by their characteristic crimp parameters, which demonstrate their mechanical behavior.
- The fabric structure was highly oriented as the card cylinder speeds was increased. Higher peak loads were observed for fabrics produced using 500 rpm than 800 rpm due to the variable amount of crimp reduced during processing.

- The resultant fabric strength increased with the needling density due to improved fiber entanglement.
- However, the variation of long-term nature in the fabric tensile strengths did not show any clear trends relating to feedplate-lickerin and flat clearances.

4. The load P acting on the fibrous material and the change in the thickness(t) are related to each other with a power-law function, containing two parameters 'a' and 'b'. 'a' is a measure for the stiffness or modulus of the material and 'b' is a shape factor of the curve. 'a' and 'b' are characteristic for the fabric compression behavior. The analysis of the obtained values for a and b shows that:
    - Fabrics produced with fiber 3 was found to be stiffer in compression than the fabrics produced with fiber 2 and fiber 1 which was comparatively soft in compression than the other two. This was due to their inherent fiber crimp characteristics. Fibers with higher crimp level are stiffer, rougher, thicker, less extensible and less resilient than lower crimp fibers.
    - The cylinder speed has a decisive effect on the fabric compressive behavior. The fabric produced using 1100 rpm was stiffer in compression than the fabric produced using 500 rpm, then followed by fabric produced using 800 rpm, which was relatively soft in compression. This is due to the varying amounts of crimp removed during processing.
    - Increase in needling density made the fabrics stiffer in compression due to the formation of a more compact structure.
    - Subtle changes were observed in the fabric compression behavior among fabrics produced from same fiber and also among the ones produced using different fibers relating to different feedplate-lickerin and flat clearances but a clear trend couldn't be established.

Knowledge of these effects can be used by textile manufacturers to design and engineer fabrics with particular handle characteristics and mechanical properties.

6 SUGGESTED FUTURE STUDY

From the understanding of the presented work, following work may be suggested for future:

1. To investigate the influence of polymeric material, a much more controlled experiment should be carried out where fibers of different materials need to have similar geometric properties such as fiber denier, crimp amplitude and frequency, to reduce the complexity of correlation.

2. Resolve to quantitatively measure the fiber crimp parameters at various stages of processing which could be used to predict the amount of strain imposed on the fibers during processing. This analysis may ultimately lead to a characterization of process and product performance as function of fiber crimp properties.

3. A similar experimental design should be carried out to investigate the structure-property relations of nonwoven materials produced by various processing technologies such as carded, air-laid, thermally bonded and wet laid nonwovens.

4. A study should be devoted to other needled design parameters such as barb depth, shape of needle cross-section in terms of needled force parameters and needled fabric performance.

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APPENDIX

Program 1: SAS Program (ANOVA Procedure) to determine the significance of the variables involved to the differences in the basis weight distribution.

```
data one;
input MT$ CS$ ND$ basweigh@;
cards;
 B1 c1  H 65 64 64 68 63 70 63 59 73 64
 B1 c1  J 53 48 55 56 55 57 49 53 55 54
 B1 c2  H 67 60 58 62 72 63 59 59 63 73
 B1 c2  J 58 59 58 62 58 59 63 57 68 59
 B1 c3  H 67 57 67 56 65 65 58 60 59 67
 B1 c3  J 51 55 60 56 52 63 56 54 53 53
 B1 c4  H 69 69 60 62 61 64 74 62 74 62
 B1 c4  J 70 64 65 64 74 69 66 67 65 72
 B1 c5  H 74 63 63 75 61 66 62 58 73 62
 B1 c5  J 66 56 58 64 57 67 62 58 60 56
 B1 c6  H 75 64 59 67 75 75 63 67 64 71
 B1 c6  J 63 55 56 54 66 67 57 60 59 58
 B1 c7  H 58 59 59 61 67 66 62 63 61 63
 B1 c7  J 59 55 54 63 57 63 55 54 68 59
 B1 c8  H 58 66 52 64 55 58 57 55 66 55
 B1 c8  J 60 63 55 58 53 56 65 54 63 54
 B1 c9  H 59 61 64 59 69 60 65 64 59 65
 B1 c9  J 56 55 60 61 66 57 60 57 62 55
 B1 c10 H 47 48 55 49 55 48 49 56 47 55
 B1 c10 J 41 37 41 40 40 42 47 43 40 37
 B1 c11 H 63 59 55 62 67 59 58 59 59 71
 B1 c11 J 59 54 52 52 56 56 52 56 52 55
 B2 c1  H 72 57 56 64 66 62 53 55 68 65
 B2 c1  J 51 51 57 48 58 55 56 54 49 51
 B2 c2  H 50 60 48 59 49 47 60 55 61 52
 B2 c2  J 54 59 53 47 61 60 54 46 50 60
 B2 c3  H 58 61 61 66 54 51 58 64 67 60
 B2 c3 J  45 54 61 62 49 49 59 55 57 49
 B2 c4 H  73 59 69 60 70 66 57 67 61 73
 B2 c4 J  51 66 53 50 58 53 55 52 56 62
 B2 c5 H  58 60 64 59 64 59 64 63 57 67
 B2 c5 J  56 67 68 70 55 61 72 68 61 57
 B2 c6 H  65 60 67 45 58 59 73 58 73 62
 B2 c6 J  64 63 56 55 59 68 60 54 65 62
 B2 c7 H  73 59 69 60 70 66 57 67 61 73
 B2 c7 J  73 59 69 60 70 66 57 67 61 73
 B2 c8 H  62 75 56 72 58 62 62 57 70 55
 B2 c8 J  57 63 69 58 61 61 64 63 59 58
```

```
B2 c9 H  51 46 46 53 54 51 46 54 46 47
B2 c9 J  50 46 44 45 56 49 46 45 44 51
B2 c10 H 54 50 50 48 62 52 50 58 44 50
B2 c10 J 47 56 50 57 54 43 51 54 52 52
B2 c11 H 59 57 56 56 53 59 54 54 56 60
B2 c11 J 60 63 58 56 59 54 64 56 62 61
B3 c1  H 77 86 73 86 76 69 81 78 83 77
B3 c1  J 63 71 68 67 58 59 67 69 68 65
B3 c2  H 71 72 77 67 82 77 71 82 75 79
B3 c2  J 70 65 72 79 63 64 74 75 68 70
B3 c3  H 66 79 79 72 82 77 71 85 80 71
B3 c3  J 63 59 67 70 65 65 66 59 74 67
B3 c4  H 76 68 74 65 80 79 67 75 68 78
B3 c4  J 61 66 71 57 56 61 65 64 64 60
B3 c5  H 65 63 70 71 67 63 66 67 70 76
B3 c5  J 62 61 53 57 58 61 62 55 55 65
B3 c6  H 65 63 79 77 67 73 63 68 77 67
B3 c6  J 63 58 59 54 63 62 56 55 54 57
B3 c7  H 71 61 74 75 65 63 75 66 66 75
B3 c7  J 71 65 59 61 63 73 66 60 67 60
B3 c8  H 54 52 51 46 61 56 51 52 49 58
B3 c8  J 58 53 56 56 55 57 50 59 56 56
B3 c9  H 83 70 90 75 69 88 68 81 83 68
B3 c9  J 56 59 60 66 59 62 58 60 57 66
B3 c10 H 55 49 63 48 61 60 47 66 48 52
B3 c10 J 62 68 67 71 67 63 71 68 68 58
B3 c11 H 79 84 91 79 73 70 77 94 95 82
B3 c11 J 71 67 66 66 71 69 64 66 66 66
;

 proc glm;
 class MT CS ND;
 model basweigh=MT CS ND MT*CS MT*ND CS*ND;
 run;
```

Program 2: SAS Program (NLIN Procedure) to fit the power law function to the experimental data and extract the necessary compression parameters.

```
**test.sas;
options ls=132 ps=76;
 title '3b9h.csv';
data a;
infile '3b9h.csv' dsd missover firstobs=2 end=eof;
input ratio load rep type $;

ods listing close;
```

```
ods trace off;
ods output parameterestimates=parms anova=anova;
proc sort; by rep type;
proc nlin data=a; by rep type;
parms a=1 to 100  b= 1 to 10;

model load= a*(ratio**b);
output out=m1 pred=phat;
run;

ods listing;
proc print data=parms width=min round;
title2 'Parms';
proc print data=anova width=min round;
title2 'Anova';
run;

data rsquare; set anova; by rep type;
keep rep type resid corrtot r2;
retain resid corrtot;
if first.rep or first.type then do; resid=.; corrtot=.; r2=.; end;
if source='Residual' then resid=ss;
if source='Corrected Total' then corrtot=ss;
if last.rep or last.type the do; r2=1-(resid/corrtot); output; end;

proc print data=rsquare;
title2 'Rsquare';
run;


/**
axis1 label=(h=2 a=90 'Load')
     value=(h=2)
     minor=(n=2)
     offset=(3);
axis2 label=(h=2 'Ratio')
     value=(h=1)
     minor=none
     offset=(3);

symbol1 c=black   v=dot i=;
symbol2 c=black   v=circle i= ;
symbol3 c=black   font=marker v=U i=;
symbol4 c=black   v=square;
symbol5 c=black i=join  font=marker v=P;
symbol6 c=black i=join  v=diamond;
symbol7 c=black i=join  font=marker v=C;
```

```
***use this to send to printer; *goptions dev=psl ftext=zapf rotate=landscape;
***use this to see in window;   goptions dev=win ftext=zapf rotate=landscape;
proc gplot data=m1 uniform;
plot load*ratio=type  phat*ratio=type / vaxis=axis1 haxis=axis2;
run;
quit;
**/
```