

## **ABSTRACT**

NECMEDDIN BENER DOGUC, Influence of Fiber Types on Fiberweb Properties in High-Speed Carding. (Under the direction of Dr. William Oxenham and Dr. Abdelfattah M. Seyam)

Among all nonwoven manufacturing techniques, carding presents high flexibility in different aspects. Being regarded as the conventional way of web forming, this method is trying to meet today's high production needs. Therefore, the productivity of the nonwoven card is more critical than ever. The fact that some fibers cannot be processed at higher speeds as others in carding is one of the biggest drawbacks of the system that needs to be resolved.

It is the main objective of this research to investigate the role of fiber type on nonwoven carding productivity and quality. In order to realize this goal, a totally novel approach has been designed and implemented through the course of this research.

A set of fibers was designed to be used in the experiments. The most important feature of these fibers is their fixed diameters. Namely, all experimental fibers have the same diameter. The main idea behind fixing the fiber diameter is that it allows us to card different fiber types under unchanging conditions. In other words, it eliminates all the possible effects, but the fiber type, on the performance of the card. Another interesting aspect of the experimental fibers is the design of bicomponent fibers, which have a core/sheath structure with minimized sheath thickness. The intention was to create a fiber with the sheath as a skin over the core. PET and PP polymers were chosen.

To eliminate all the factors, the entire card processing parameters was fixed. In addition, all fiber parameters, i.e. crimp, length, finish was kept constant to leave the effect of fiber type alone. A set of experiments was designed with two carding speeds, 85 and 120 m/min. Each fiber was run through the card at both speeds and planned samples were taken for data collection. Samples have been tested to obtain data of an array of fiber parameters, such as strength, modulus, fineness, and crimp stability; web parameters, for instance uniformity, fiber orientation distribution function, thickness and basis weight and feed matt openness.

The collected data was statistically analyzed to reveal the similarities and/or differences among the measured parameters. ANOVA tests were utilized to compare the means of data sets. Comparisons have been made among all experimental fibers to observe the effect of fiber type on the output, fiber parameters and carding performance. Mutual comparisons have been carried out between the bicomponent and monopolymer fibers. The aim of these comparisons was to disclose the role of fiber surface properties on its carding performance. Finally, conclusions and recommendations for future application have been covered.

# Influence of Fiber Types on Fiberweb Properties in High-Speed Carding

by

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## **BIOGRAPHY**

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# **CHAPTER 1**

**“REVIEW of the LITERATURE”**

## 1. INTRODUCTION

It is essential to point out the importance of the carding process in the nonwovens manufacturing sector, where nowadays other methods are gaining a greater share. Because of the important role the carding process plays in the production as well as other technologies, some of which are faster than carding, rising as a rival to the process, more attention is given to increase the production rate of the system as well as the process quality.

Today, nonwoven production methods, such as melt blowing and spun bonding can achieve speeds around 600 m/min [20,24]. To answer this need for a high production level, the concept of high-speed carding was implemented.

Contemporary high-speed nonwoven cards can achieve production rate, which is several times higher than that of conventional cards owing to their wider widths and higher speeds.

Most of the fibers used in the nonwovens industry are man-made fibers; therefore it is more reasonable to choose a single-stage process than a multi-stage process like carding for these kinds of fibers [1]. However, there are some properties of carding that cannot be compensated with other production technologies, which give carding a competitive edge in the sharing war and help it survive.

One of the main advantages of carding is that it provides high flexibility by potentially using an array of materials and is able to manufacture products with different

features. One example of this will be the increment in the use of recycled and natural fibers in some nonwovens products, such as car interiors. In addition to this, some of the benefits of the carding process can be listed as follows:

- High web uniformity
- Excellent fiber mixture
- Defined MD/CD strength ratio
- High flexibility in changing the production rate and stopping the machine [1,2].

Although the principle of carding has not been changed significantly from the very first carding machine to the latest technology high-speed cards, a number of changes in several aspects of carding can be mentioned, which played role in increasing the production rate dramatically and improving the web quality.

Since carding is a very complicated process and involves significant number of parameters and variables, it is not an easy task to control the process completely. Therefore, there are still a huge amount of variables that remain a question mark and need to be identified.

One of these remaining questions, probably one of the most important and common one is, “Why do different fiber types have different maximum processing speeds in carding?” There is a fact suggested by the industry that PP can be carded faster than PET. To be more specific, it was suggested by the industry members in an NCRC carding focus group meeting [63] that PP can be carded at up to 500m/min, whereas with PET processing speed of 250 m/min cannot be exceeded. However, it should also be

stated that there are some arguments in the industry that PET can be carded faster than PP. It is the main goal of this research to investigate the reasons behind the fiber type effect on carding speed.

With the increasing production rates of different web forming techniques used in nonwovens industry, such as spun bonding or melt spinning, production rate of the carding process is becoming more and more important every day. Therefore, being able to process a variety of fibers at a faster speed in carding has an important effect on the survival possibility of the process among its high-tech, high-speed rivals.

Cardability at high speeds [2] is the key word for this research. Fibers today are being processed more than 10 times faster than they were in 30 years ago, when high speed carding began to take stage. This is partially due to some technological improvements experienced since then, and to some extent due to the developments in fiber process engineering. Fiber production is a very complicated process, involving number of parameters each of which finally will play a role in determining the properties and processability of the fiber. These parameters range from the chemical structure of polymers to the geometry of spinneret they are spun.

## **2. CARDING PRINCIPLE**

A thorough understanding of the carding principle is essential in order to study how different fibers behave in carding process. Card does not refer to a standard

machine; it rather indicates a wide range of designs determined by a number of possible configurations. These configurations, the carding elements and additional equipment used will influence the performance of fibers in carding and moreover the quality characteristics of the produced web [3].

## **2.1. Fiber Carding Zone**

Carding action can be described as the combing of fibers between two surfaces, which carry a set of angled wires (card clothing) oriented in the opposing directions, when their relative speed is greater than zero. [4]

What individualizes the fibers and gives parallelism to the fiber mass flow is the interaction between the wire-teeth clothing of cylinder, the flats/workers and the fiber mass [5].

There are several views on how the above-mentioned interaction occurs in the carding zone. Oxley [6] suggests that since the tooth angle has the same direction as the cylinder rotation, tuftlets are not strongly held on the cylinder clothing, causing them to be easily removed and more firmly held by the opposing teeth of the flats. Therefore, a flat becomes almost fully loaded with fibers as it enters the carding zone, and the fibers are stripped from the flat as it moves along the carding zone-the interaction zone between cylinder and flats- and carried towards the doffer by the cylinder. Here, the carding action occurs between the following areas of the cylinder clothing and the subsequent flats.

Combing causes the fibers to be hooked around the cylinder tooth points, thus preventing them from being picked up by following flats [5,6].

An alternative view to this comes from Varga [7], who reports that two types of actions occur at the cylinder-flats carding zone. First, a group of loosely opened fibers or a tuftlet is caught and held by the flats while the bottom of the tuftlet is sheared away by the fast moving surface of cylinder. Therefore, the top portion of the parted tuftlet contacts with the following part of the cylinder surface and the hooks of the cylinder clothing combs away a small group or a single fiber generating the combing action [5,7].

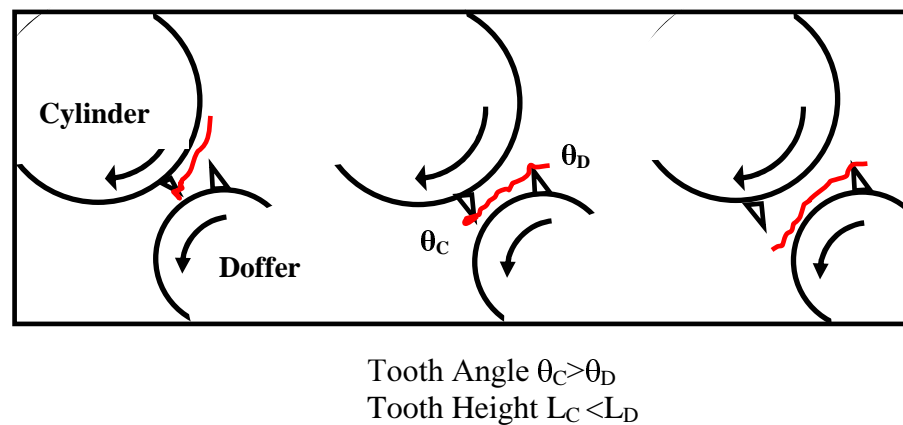
Another important aspect that needs to be addressed in the carding zone is that the fibers that are deeply embedded in the wire clothing of the flats/workers. Since these fibers cannot be reached by the cylinder wires, the setting between the cylinder and flats/workers becomes an important parameter. It may be assumed that closer cylinder-flats/workers settings and faster cylinder speeds can advance the carding efficiency thereby improve web quality [5].

The effectiveness of the carding and combing actions within the cylinder-flats/workers interaction zone is dependent on the quantity of the fiber mass on the cylinder, including the recycling layer [5].

A popular view is that a low fiber mass entering the cylinder-flats interaction zone- low fiber load on the cylinder- results in better carding quality. There are several ways to reduce the fiber load on cylinder and not all of them result in better carding [5].

## 2.2. Cylinder-Doffer Interaction

The transformation of fibers from a fiber flow into a web occurs at the doffer as seen in Fig. 1. Web formation is achieved by the stripping and accumulating actions of doffer [4]. One end (leading or trailing end) of fibers, which are held by the cylinder teeth, move towards outside because of the circumferential forces. This end then is picked up by a doffer tooth, which forms the mechanism of web formation.



**FIGURE 1:** Mechanism of Fiber Transfer for Trailing Hook Formation [5]

### 2.2.1. Advantage of Two-Doffer Configuration

A two-doffer configuration has a distinct advantage over one-doffer systems regarding the ability to transform more fiber to the doffer. Employing two doffers helps to improve the web quality as well as to increase the production speed [3]. With two doffers, there are two transfer points and therefore it is possible to load the card with more fiber.

It can be calculated by statistical equations that the variation factor is improved by approximately 40% when doubling two equal webs. In other words, the web quality is improved by the same amount [1].

The multiple transferring action and reintroduction of new groupings of fibers to the carding zones provides a doubling effect which enhances web uniformity [4].

### **3. HIGH SPEED CARDING**

The purpose of high speed carding is to increase the card productivity without reducing carding quality, or even improve it. It had been thought that increasing carding speed would increase fiber breakage, but there is no evidence why fiber breakage should increase as card speed increases [8]. It was necessary to increase the production rate of the carding machine, because new technologies with considerably higher production levels were started to be implemented.

#### **3.1. Increasing Carding Productivity**

Carding productivity has been improved dramatically since mid 20<sup>th</sup> century, which has mostly taken place after 1960s. Since carding is a complicated process - involves a number of parameters and variables- and embraces different technologies, improving the carding productivity has been made possible by the developments in

several sciences and fields, such as polymer and fiber science, machinery and material science and automation and control. These developments allow us several ways for increasing carding productivity.

One of these ways is to increase the feed rate to the card [8]. This method may be assumed to be the first option to increase the productivity since it is very simple and does not require any developments or modifications to the card. However, this method leads to worse carding quality, causing increase in nep formation and reduction in average fiber length as a result of more fiber breakage. Increasing the feed rate while keeping the cylinder speed constant causes thicker fiber layer on the card, which adversely affects the processing performance of card, causing the weaker quality parameters mentioned above.

Another way of increasing productivity is to increase the carding width. Higher production rates can be achieved with conventional cards, which can reach up to 4 meters or wider widths, comparing to the older type cards with 1meter width.

The best way of increasing productivity is regarded as increasing the surface speed of the cylinder, which allows higher production rates without increasing the thickness of the fiber layer. While cards are mechanically capable of reaching surface speeds over 2000 m/min, the belief in the industry that higher speeds would cause excessive fiber breakage limits these speeds [8].

Carding speeds has showed an increase with the technological advances. Cylinder speeds have remained constant from late 19<sup>th</sup> century until 1960s, around 165 revolutions per minute [9,10]. It can be said that two factors has lead to the increment in carding

speed: One of these factors is the developments in the carding technology, such as, better material use, better control equipment and invention of novel techniques. Another parameter is the improvements in the fiber production technology. By ever-increasing use of synthetic fibers it has been possible to exploit unique characteristics of these fibers in order to increase speed and productivity of carding machines.

### **3.1.1. Technological Developments in Carding**

The carding machine has remained basically unchanged after the introduction of the revolving flat card in the 1880s until the beginning of the 1960s. The production range was about 1.81 to 8.44 kg an hour. Most of the improvements in this field occurred beginning from the late 1950s and during the 1960s [9,10].

#### **3.1.1.1. Machinery Developments**

Development of high-speed cards represented some mechanical and technological problems that needed to be overcome. This section is aimed to address the difficulties that were experienced during the development phase of high-speed cards and solutions that were implemented to overcome these problems.

First of all, high-speed cards require some additional features to the classic card in order to operate properly. These additional features can be generally summarized as follows:

1. Antifriction bearings must replace the old types, because rotating parts run at higher speed.
2. A dynamically balanced cylinder is necessary for smooth running at higher speed.
3. Cast gears need to be replaced by cut steel ones for longer life and reduced maintenance.
4. Two-speed drive is needed at the doffer for piecing up at low speed.
5. Stop motions are necessary to reduce waste and to avoid possible chokes.
6. Continuous web removal systems are needed to replace the oscillating comb box.
7. Cards with metallic wire clothing and running at higher speeds create more dust and fly; therefore dust, fly and waste removal systems needed to be improved [10].

An adequate feeding system is very important in high speed carding. In order to obtain better opening and cleaning the de-coupling of the chute feed delivery to the card feed system can be implemented or it can be replaced with a single roll system. Introduction of increased licker roller speeds and therefore the possibility of lower fiber densities also result in better opening and cleaning [11,12].

Web removal was an important issue in high speed carding, because doffer combs operating at their maximum possible speed of 2500 rpm cannot reliably strip a doffer whose surface speed is much greater than 60m/min. It is strongly suggested by CSIRO researchers that cylinder to doffer surface speed ratio should not be allowed to exceed 15, in order to achieve satisfactory doffing performance. If the doffer speed were limited to 60m/min, this would limit the cylinder speed to around 900m/min. In order to overcome

this problem, take-off rollers were introduced which allows delivery speeds over 300m/min [11,13].

The “Ace” high-speed card, which was introduced to the market by “Gunter & Cooke Inc.”, was designed to develop a carding technology, which would improve the quality, increase the production rate and maintain efficiency [9]. The design criteria of this project were as follows:

- Fibers must be handled in a natural manner.
- A thorough study of the fibers would be conducted in order to determine the natural manner in which they behave.
- Full utilization of the natural movement properties of fibers would be considered in all designs.
- To design mechanisms that would not force the fibers to react in an unnatural manner.
- Machine design must be made as simple as possible.
- Problems were to be solved at their source. Equipment should not be designed to solve problems after they were created.
- Priority in event of design conflict: in the event of a design conflict, the quality of the sliver or web being produced should receive first consideration.

Some of the technological developments, which took place with the introduction of high-speed carding, can be summarized as what follows:

First was the magnetic crush and take-off rolls. Their function was to take the web off the doffer and to crush the foreign matter and trash at the same time. They consist of a small upper roller (2.5 cm in diameter) and a magnetized bottom roller (7.5 cm in

diameter), which attracts the upper roller evenly across the width creating a uniform pressure between the rollers.

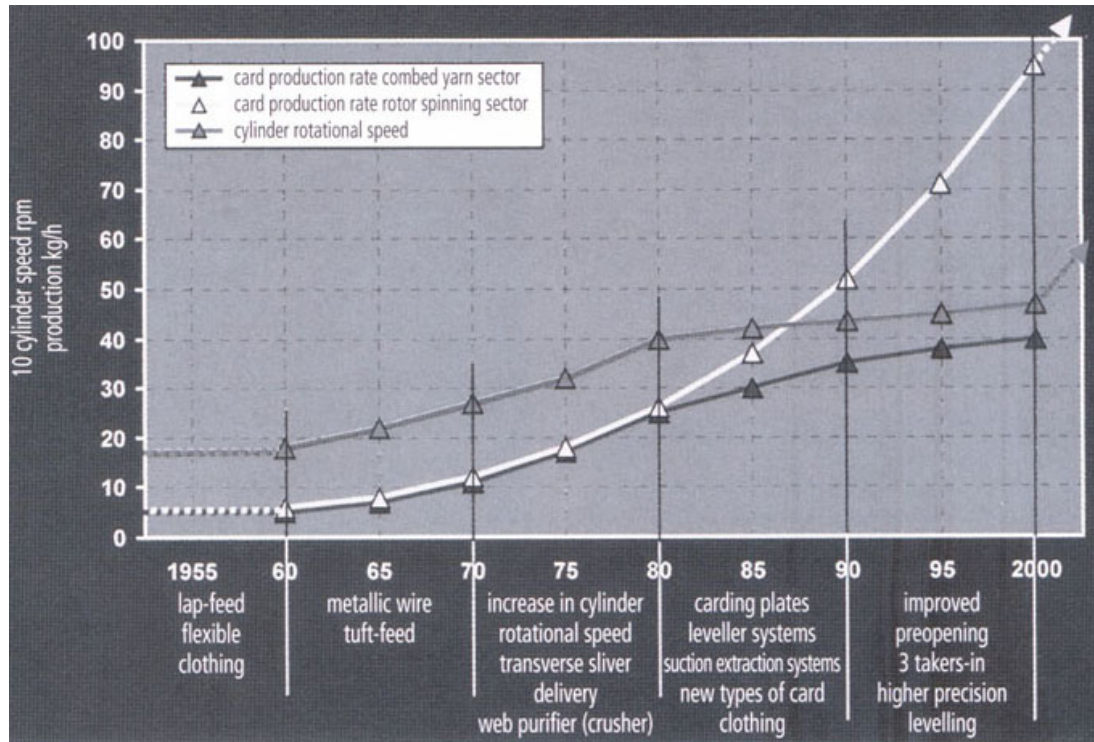
Another development was the 30cm. doffer, which is said to be one of the most significant changes in the card design [9]. These doffers were introduced in the 1960s. An important function of the doffer was to eliminate the unequal web stresses that had been present in all previous card designs. Another benefit of 30cm doffer was that it reduced nep formation. The possible contact area of fibers to cylinders was 7.62cm in 68cm doffer, while it was 2.54 in 30cm doffer. Because of the difference between the surface speeds of the cylinder and the doffer (cylinder surface speed is 15-25 times greater than that of doffer) a scrubbing or collapsing action takes place on fibers when they pass this zone. Low micronaire or immature fibers can easily form neps in this situation. The 30cm doffer reduces the contact area of the fiber with both the cylinder and the doffer, thus reduces the possibility of nep formation [9].

Uncontrolled air currents have been a problem for the carding process especially for the high processing speeds. The general problems generated by these currents are, chokes, blowout, cloudy webs, ragged selvages, inefficiency of operation and high amount of fly and dust liberated into the air. It was found that there were two high-pressure areas on the surface of the cylinder. The first high-pressure area is developed slightly above the transfer point with the doffer, which is responsible for approximately 70% of the air control problem. The other, which is responsible for 30% of such control problem, is located above the transfer point between the licker-in and the cylinder. This

problem has been solved by employing Air Control System, which does not allow these high-pressure areas to form by revealing the air stuck in the area [9].

One of the most important elements of the advancement of carding can be the use of metallic card clothing instead of flexible or fillet clothing. The introduction of the metallic clothing is as early as 1920s, occurring in the United States. Flexible clothing had a major drawback; it had to be periodically cleaned and stripped to maintain the quality level, causing frequent stops of the machine and reduction of the production rate. This handicap has been solved with the use of metallic clothing [9,14-17].

During the 1950's increased speeds and improved stability of card settings has been achieved with the adaptation of anti-friction bearings to the cards. These bearings prevented the contamination of the licker-in, cylinder and doffer wires, which is caused by excessive oiling of old type bearings, and allowed optimum synchronization of roller speeds [9,15].



**FIGURE 2:** Milestones in Card Development over the Past 40 Years [57]

Generally speaking, standard cylinder speed of a card in the 1960s was around 165 revolutions per minute (rpm) with a corresponding licker-in speed from 250-450 rpm. The use of anti-friction bearings and the stability of the cylinder provided by the base wire and metallic wire enabled to increase the speeds of these components. By 1960, some card cylinders were being operated at 250-300 rpm and licker-in at 800 rpm [9].

The oscillating doffer comb has become a limiting factor in the card production with increasing card speeds. The practical limit for an oscillating comb is approximately 2200 cycles per minute. Rotary take-offs were developed in order to overcome this

obstacle. These units uniformly remove the web from the doffer in a continuous rotary motion [9].

In order to improve the cleanliness of the carded web, crush rollers have been placed between the doffer and calender rollers. These rollers under the pressure crush the trash and foreign matter in the carded web. In addition to better cleaning, fewer neps and better evenness has been achieved with the crushing action [9,14].

### **3.1.1.2 Early Developments**

Following are some features of different cards, which are introduced to the market in early 1980s:

*Rieter C4:* Uniform feed, double combing segment for effective cleaning, new cylinder design to achieve 600 rpm, reliable doffing setting system with optional crush rollers, delivery speed of up to 300 m/min.

*Marzoli C41:* Larger licker-in diameter of 14 inch, new card clothing which eliminates micro-dust spreading, the detaching and condensing sliver unit overcomes the problem of condensing the web operating at high speeds.

*Supercard KU 12:* 120 kg/hr production rate, the forepart with three takers-in running at optimally synchronized speeds to achieve gentle fiber handling, carding segments placed close to the flat entry and exit, web doffing and transfer via cross-apron delivery system, high efficiency suction system for dust and waste removal [16,18].

Among these cards Rieter C4 card improved its production rate by increasing the delivery speed. Rieter's engineers thought that increasing the delivery speed was the best way to increase the production rate regarding carding quality. Rieter has taken 5 steps to develop this card:

1. More effective opening of the raw material before it reaches the flats area by:
  - a. Reversing the respective position of the feed roller and feed plate. With the feed plate on top, the material is fed to the licker-in in its same operating direction instead of against it providing more gentle and intensive opening.
  - b. Two combing plates under the licker-in.
  - c. Stationary carding plates on the cylinder prior to the flats.
2. Enlarged cylinder working area by raising the position of the cylinder, thus resulting in 16% more cylinder working surface.
3. Add a clean final-carding zone by reversing the direction of the flats and presenting clean flats to the departing zone.
4. Add stationary carding plates following the flats area for improved fiber parallelization.
5. Replacing the web with tangential take-off instead of duo coilers, allowing delivery speeds of up to 200 m/min [19].

Rieter suggests that cast iron provides the best material to construct a stable carding machine, and it will produce a cylinder, which will best hold its shape under high-speed conditions and centrifugal forces.

By implementing these ideas Rieter was able to increase the card production rate from 38kg/hr (C1/3 card) to 50 kg/hr (C4 card) through increasing the card speed by 30% [19].

#### **3.1.1.3. Latest Developments [1999]**

Trutzschler introduced Scanfeed FBK 5000 tuft feeder, which has a working width of 5 m and a production rate of 2000kg/h. This system provides better quality of web evenness both in machine and cross directions by avoiding false adjustments [20].

Thibeaudeau introduced their new cards CA10 and CA11 that brought new horizons to the levels of control and speed. Integration of LDS (Linear Doffing System) and WID (Web Introduction Device) allowed these cards to produce webs with higher performance characteristics, 4-4.5 m widths and industrial speeds over 300m/min. These developments helped carding sector gain some of the share it lost to spunbond technology- in the hygiene market- due to its higher production speeds [20-22].

#### **3.1.1.4. Latest Developments/Regulating/PRODYN [2000-2001]**

A regulating system, called PRODYN, which comprises of a Dynamic card, a Dynamic cross-lapper, an input auto-leveler (Servo-X) and an end-product profile measuring unit, has been developed and introduced to achieve better regulating in both directions. It is said that the system is able to decrease the weight variation range and thus

results in better CV values. In addition to this, a significant fiber saving (20 tons of fiber can be saved for every one million square meters produced) can be obtained with the system [23-25].

To attain a wide application, the system has been designed in a way so as to work regardless of the fiber type and specifications, line production, bonding system, product weight, width or density [23,24].

#### **3.1.1.5. Expected Developments until 2005 as of 1999**

- Working width up to 6000 mm (currently 4500-5000mm).
- Output up to 350kg/h/m
- 170-200 m/min web speeds on entering the crosslapper (currently max. 130m/min) [24].

#### **3.1.1.6. Developments in Card Clothing**

It is possible for tooth patterns to exist in the cross-machine direction, which cause some fibers to lie in the cross direction inducing greater cross-card variation. As a solution to this, new clothing that prevents patterning (with random tooth distribution) has been employed, which increases parallelization, provides better mixing and greater control of fibers, thus permitting higher speeds [26].

Hollingsworth Enhanced Point wire introduced to the industry in 1999 is said to increase the web uniformity more than ever before. The contours on the tips of the

clothing wires pick the fibers from the cylinder very efficiently, and the backside is formed in such a way that the fibers are released freely from the doffer [27].

Another innovation, which contributes to the high speed carding, is the Integrated Grinding System (IGS), which was introduced by Rieter with their Hi-Per-Card. This system performs the cylinder grinding automatically while the card is running. This guarantees constant web quality and longer clothing life, while it prevents any loss of production when grinding the cylinder. IGS is fitted under the cylinder and controlled by a computer, which determines when a grinding action is necessary and automatically actuates the system. With this system only a fraction of the wire is ground off. An additional advantage of the system is that in many cases it can prolong the service life of the wire clothing by 20% [11,28,29].

Besides the conversion from flexible clothing to the metallic wire, another important breakthrough in the course of achieving higher carding speeds, was conversion from over head shafts to individual (direct) drives- assigned to all working parts. These drives increased the power beyond the traditionally accepted levels [17,30].

### **3.1.2. Developments in the Fiber Production Field**

It should be recognized that the developments in the fiber production field have played an important role in increasing the carding productivity. Since fiber characteristics play important roles on the behavior of fibers during carding and these characteristics can be altered through changing micro and macro structure of fiber polymers, developments

in this field should not be overlooked when observing the differences in maximum carding speeds among different fiber types.

#### **3.1.2.1. Polymer Processing**

Polymers' mechanical, electrical, chemical and thermal properties are determined by their structural characteristics. Processing operations and conditions can alter these characteristics. An increase in the orientation during processing can affect many mechanical properties, such as ultimate strength, modulus of elasticity, resistance to creep or cold flow increase. Conversely, an increase in cross-linking ultimately decreases impact strength and elongation at break, while an increase in polymer chain flexibility decreases the polymer's modulus of elasticity [31].

Polymer molecular weights can be altered during processing. It can be decreased by a degradation reaction, which can be a result from oxidation or a hydrolytic mechanism. Polycondensation can increase the molecular weight.

#### **3.1.2.2. Metallocene Catalysts**

Metallocene catalyst is regarded as a breakthrough in polypropylene fiber production. It has been used since middle 1990s, and adds a lot to fiber properties and processability. The polypropylene produced by metallocene catalyst has a narrow molecular weight, slower crystallization kinetics, a more uniform chain length, and a

more custom made properties and rheological behavior. Narrower molecular weight distribution achieved by applying metallocene catalyst tends to increase the tensile strength of the polymer [32].

Metallocene type polypropylene may overcome some of the problems associated with conventional isotactic polypropylene, some of which are; difficulties to achieve maximum uniform strength, inadequate resilience and crush resistance, low sticking and softening temperature. These problems were solved through the ability of the metallocene catalyst that can change each property of polypropylene [33,34].

### **3.1.2.3. High Speed Fibers**

A cooperative study of FiberVisions and Thibeaumont NSC/Schlumberger Nonwoven Systems resulted in a high-tech fiber named “HY-Speed”. This fiber can be processed at a higher speed without making any changes to the current system [2]. This development gives an indication that the fiber type and specifications can directly affect the maximum processing speeds in carding.

### **3.1.2.4. Effect of Fiber Production on Fiber Processability**

Processability of a fiber is dependent not only its standard properties, but also its chemical structure, molecular structure, morphology and production parameters, as well as the finish applied to it [3,35-39].

Following are the important structural characteristics of polymers, which determine their end-use mechanical, electrical, thermal, chemical and optical properties:

1. Molecular weight
2. Molecular weight distribution
3. Degree of branching
4. Degree of cross-linking
5. Polarity of polymer chains
6. Flexibility of polymer chains
7. Macrocrystalline structure
8. Fine crystalline structure
9. Orientation of polymer chains [31].

These characteristics mainly influence the intermolecular forces in polymers, which give them their peculiar end-use properties. Since the processing of the polymer can change the structural characteristics, they constitute a means of tracking and controlling property development [31]. Molecular weight and its distribution are among the most important characteristics that influence the physical properties of man-made fibers.

## **4. KEY PARAMETERS OF HIGH-SPEED CARDING**

### **4.1. Fiber Parameters**

#### **4.1.1. Fiber Breakage**

Honold and Brown [40], using cotton fibers in their experiments, found no fiber damage occurred at licker-in speeds up to 600r/min. Krylov [41] reports the absence of fiber breakage at speeds up to 1,380 r/min, and Artzt [42] suggests taker-in speeds have a negligible effect on fiber shortening. High-production rates achieved by increased roller speed and closer setting of the batt fringe result in significant fiber breakage [5].

It can be said that the smaller the tuftlet entering the carding zone and the more parallel fibers in the tuftlets to the direction of mass flow, the lower the probability of the fiber breakage is [5]. Increase in the flat speed appears to have no effect on fiber breakage.

A study by Wang et al [43] confirmed that the carding process causes more damage to fibers than other processes. They stated that the carding process caused substantial fiber strength loss, nearly %19 for the wool they used in their study [38].

An experiment was conducted by CSIRO in order to understand the effect of the processing speed on the fiber breakage. The researchers have concluded that an increase in cylinder speed has no effect on the fiber breakage [8,13,44,45].

Most of the fiber breakage, which occurs when the processing speed is raised, takes place on the cylinder. That is, increased fiber density on the cylinder is far more

detrimental to fiber length and noil compared to increased fiber density on the forepart [13].

#### **4.1.2. Fiber Crimp**

Crimp characteristics of fibers have always been important for the textile manufacturing. Crimp affects the processing performance of fibers. With the increment in production speeds, developments in products and new processes, the importance of fiber crimp has been increased [39,46,47].

Crimp allows fiber bundles to be more easily grasped and separate into individual fibers and construct in a web, by increasing fiber-to-fiber cohesion due to the hooking of the crimp bows. Also, crimp geometry is essential for the cohesion or strength of in-process fiber assemblies and for the uniformity of fiber processing [39,47,48].

Nature of the crimp in the fibers can be established in three categories.

1. Macro crimp: It is characterized by high amplitude.
2. Micro crimp: It is characterized by low amplitude and high frequency.
3. Mixed macro-micro crimp: It is characterized by high amplitude and high frequency.

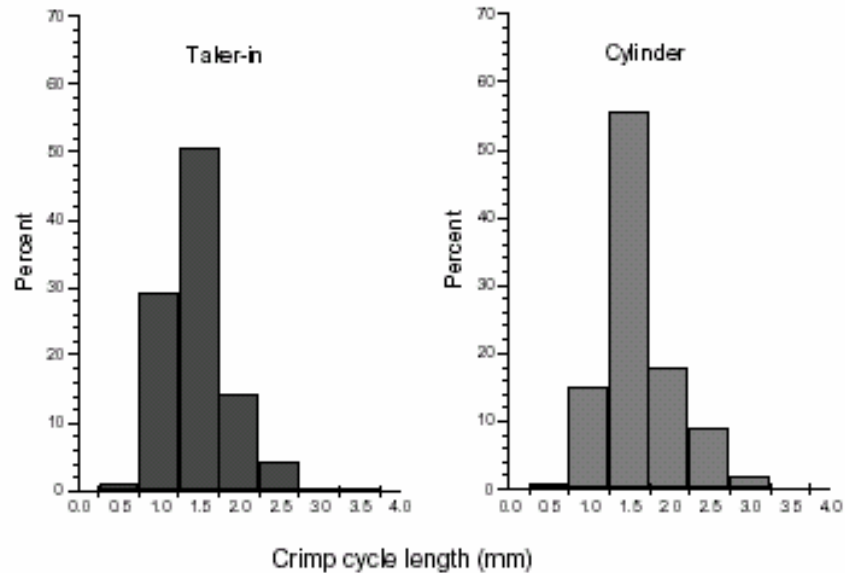
Macro crimp has 2-5 waves/cm, while micro crimp has 8-14. It is very possible that fibers having similar wavelengths but different amplitudes can behave very

differently. Fiber crimp has so important role in fiber processing that uncrimped staple fibers are processed only under some rare circumstances.

Dr. A. Naik [39] has observed in his experiments, using four different fibers with different crimps, that macro crimped fibers do not form a uniform web in carding. However, micro crimp fibers produced more uniform web. The best uniformity was achieved with the fiber having 8-waves/cm. When the crimp was 14 waves/cm in a different fiber, he observed that web consistency decreased. It can be deduced from these observations that crimp leads to a greater cohesion and resilience in card web structures. Higher resilience implies greater elastic recovery.

Crimp has also some influences on fiber properties. Crimped fibers show variation in breaking stress and strain and they generally have smaller elastic modulus [47].

The distributions of the crimp cycle length at these two positions are shown in Fig. 3. As the figure illustrates, both distributions are skewed and there is a clear difference between the skewness. Results show that the average crimp cycle length at the front of the cylinder is greater than that at the taker-in stage. This suggests that the individual fibers must be under a high tension at the front of cylinder [49].



**FIGURE 3:** Distributions of Fiber Crimp Cycle Length at Taker-in and Front of Cylinder [49]

#### 4.1.3. Fiber Finish

Finish is an important parameter for fiber processing. Frictional behavior of fibers is dependent on their surface characteristics. Since a finish applied fiber surface is coated by the finishing agent, the employed finish determines the fiber-to-fiber friction and fiber-to-metal friction during carding [36,47,48,50,51].

The function of the fiber finish in the carding process should be to reduce the fiber-to-metal friction in order to prevent fiber damage from the interaction of fibers with card clothing [52], and to optimize the fiber-to-fiber friction to obtain better web

cohesion. The finish should also control the static charge generation and wicking characteristics [50,51].

Experiments conducted by Velmurugan [48] have revealed that fiber finish levels influence fiber breakage, fiber web uniformity, fiber web cohesion, nep formation and static charge generation. According to the results of these experiments where polypropylene fibers were used, fiber breakage decreases with an increase in finish level while fiber web uniformity is affected only at very low levels of finish. Besides, fiber web cohesion decreases with increasing finish level, but at higher finish levels cohesion increases due to role of excessive finish as a binding agent, and finish can prevent static charge generation [50].

In the case of polyester, fiber breakage changes differently with finish level, fiber web uniformity is not affected by finish level and nep formation seems to be influenced the same way as polypropylene does. However, fiber web cohesion decreases with an increase in finish level for polyester fibers. It should be noted that finish levels for polyester are much lower than those for polypropylene. It was reported that finish uniformity has no effect on any parameters mentioned above for both polypropylene and polyester [50].

A new finish application technology called ESC (Enhanced Surface Coverage), which improves the degree of surface coverage of the spin finish on fiber surfaces, has been used for polypropylene fibers. Since the performance of a finish is determined by its ability to maintain even after the water diluents evaporate from the finish, better finish

performance can be achieved with this technology. The ESC spin finish provides a fully covered fiber surface even at the lower finish loading levels. Hereby, better lubrication and antistatic performance can be achieved by using the same amount of finish or the same effect can be achieved with using lower amount of finish [51]. This will eliminate the problems associated with excessive finish, such as contamination and loading of card clothing.

The increase in carding and other processing speeds has led to the development of high performance spin finishes. During late 80s and early 90s, Henkel has conducted investigations that lead us to the high performance spin finishes. Henkel's principle was that "for optimal performance; spin finish properties, fiber structural characteristics and processing machine parameters need to be harmonized" [53].

#### **4.1.4. Role of Additives**

Additives give the fibers their final properties. Synthetic fibers without additives can be regarded as naked; they are relatively useless if not stabilized [35]. Certain additives, depending on the process and use of fiber, should be added to obtain the required fiber properties [54].

The main reasons for the use of additives can be summarized as follows:

- Guaranteeing process stability.
- Color adjustments.

- Altering stiffness: Stiffness can be adjusted by adding plasticizers, fillers, or nucleators.
- Altering molecular weight and molecular weight distribution: Additives can be used to lower the molecular weight and narrow the molecular weight distribution.
- Antistatic purposes: Antistats are used to decrease or prevent static charge generation during processing.
- Control surface properties: Frictional and adhesion properties can be altered by applying different additives.

Titanium dioxide has an important role in the processability and quality of man-made fibers. Their first function is to give a matting effect and to deluster. In addition, titanium dioxide particles create a “hill” structure below the upper-most polymer layer, improving frictional behavior of the fiber. This function is very important for high speed processing [55].

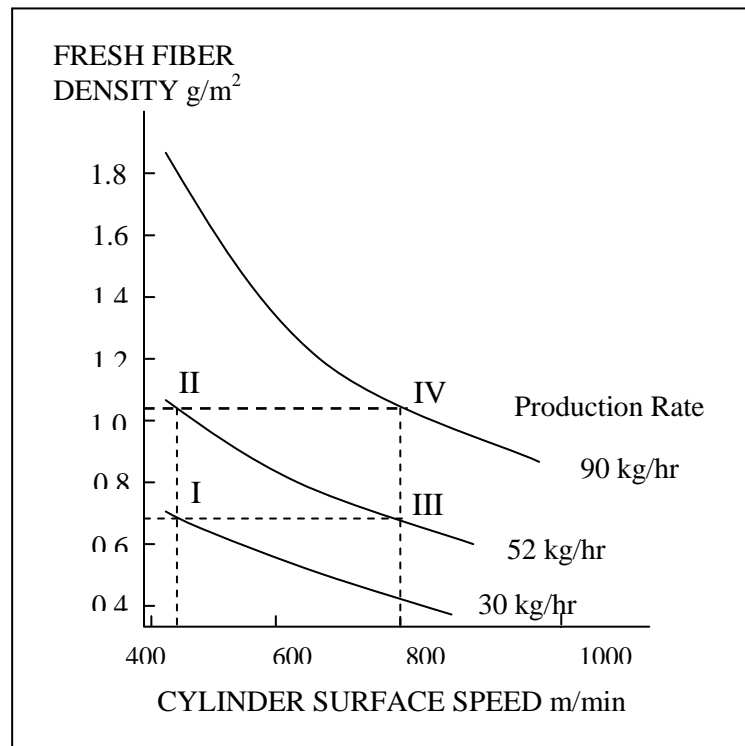
## **4.2. Machinery Parameters**

### **4.2.1. Fiber Loading**

Fiber loading is an important factor for card productivity and quality. It is a well-known fact that increasing the amount of fiber on the cylinder for a given time decreases the quality of the process and output.

Fig. 4 shows the change in fresh-fiber density with the change in cylinder surface speed. The figure shows how higher card speeds can be used in two ways. One way is

increasing the card speed at constant production rate, which results in better product quality and waste removal. The other way is to increase the card speed with increasing production rate, which results in a large gain in production rate without any sacrifice in the carding quality [8].

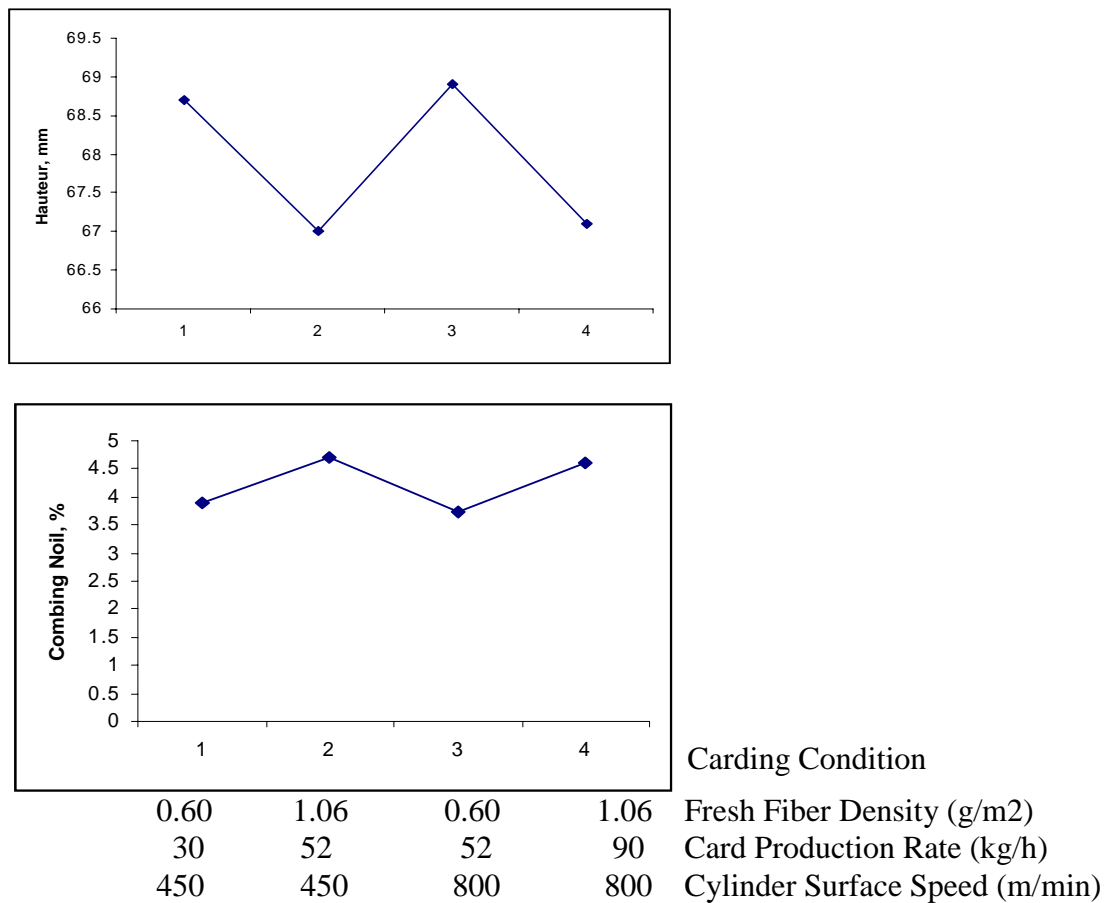


**FIGURE 4:** The Dependence of Fresh Fiber Density on Cylinder Surface Speed [44]

Fresh fiber density can be defined as the layer of fiber that is newly introduced to the cylinder. Fig. 4.2 displays four carding conditions and three production rates. In moving from condition I to III and II to IV, the cylinder speed is increased by 70%, resulting an increase in the production rate by the same amount. Therefore, the fiber

density within each move remains constant. It can be concluded that card production can be increased without any detriment to carding quality, by simply increasing cylinder speed. Moving from condition II to III will result in a reduction of the fresh fiber density of over 40% while the production rate remains constant. In this case, improvements in carding quality should be expected [8,13,44].

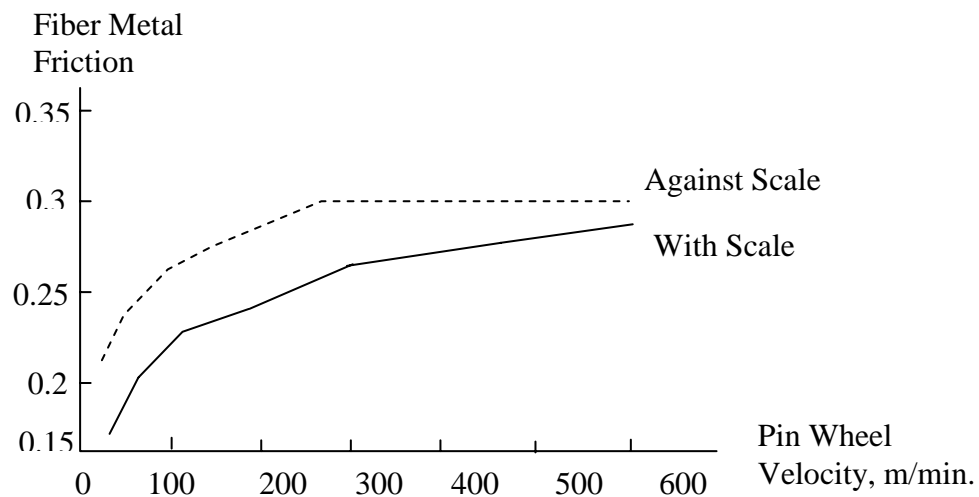
Fig. 5 shows the effects of fresh fiber density and speed on Hauteur and noil [44].



**FIGURE 5:** Effects of Fresh-Fiber Density and Speed on Hauteur and Combing Noil [44]

#### 4.2.2. Frictional Forces

It may be considered that increasing card speed would increase frictional forces, and it is known that fiber breakage in carding depends on the fiber-metal coefficient of friction. Experiments done by Gary Robinson on high speed carding of wool has revealed that fiber-metal friction remains substantially constant at higher speeds as seen in Fig.6, and the greatest sensitivity to speed changes occurs at levels considerably lower than those encountered in carding applications. [44].



**FIGURE 6:** The Variation of the Fiber-To-Metal Friction of Wool Fibers as a Function of Pin Wheel Velocity [44]

In their experiments CSIRO researchers have tried carding wool on a modified cotton card at cylinder speeds of up to 1440 m/min. Results of this study again indicate

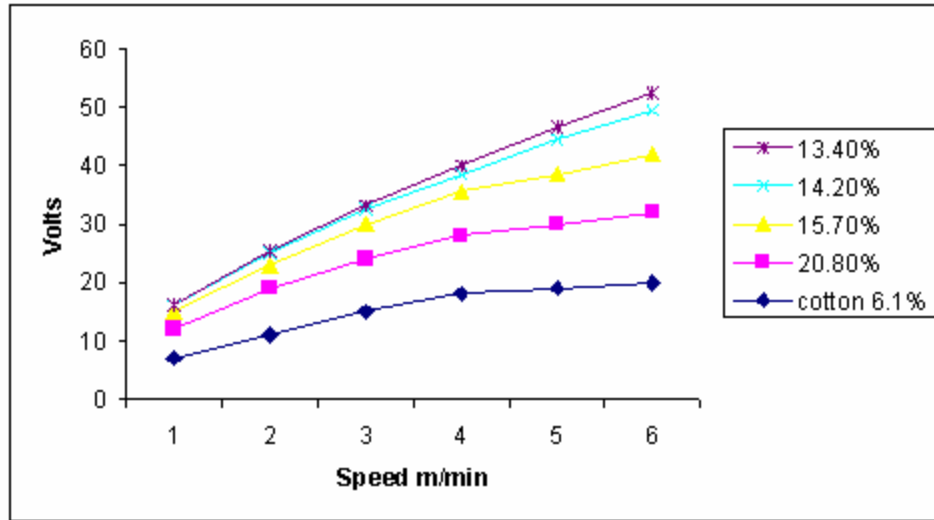
that for any particular fiber density, increasing the speed of the card has no effect on top length and noilage [44].

For high speed carding, fibers must satisfy two criteria: first, they must pass through the carding process without any problems (with the aid of additives to prevent ejection by centrifugal forces), and they must allow the draft between card and calender rolls that is necessary at these speeds, without giving up cohesion [30]. The main problem of high speed carding is that web cohesion weakens as the delivery speed increases, thus limiting the maximum processing speed [19].

#### **4.2.3. Static Charge**

Static charge may cause problems in carding process if its generation is not prevented or controlled. The static charge generation may cause fibers to stick to certain rollers or machine surfaces and repel from each other. Static charge generation is affected by humidity, regain, processing speed and additives [50,55].

CSIRO researchers have investigated the effect of speed on static charge generation in wool during carding. Their findings are illustrated in Fig. 7. These results suggest that static charge generation increases with an increase in processing speed [55].

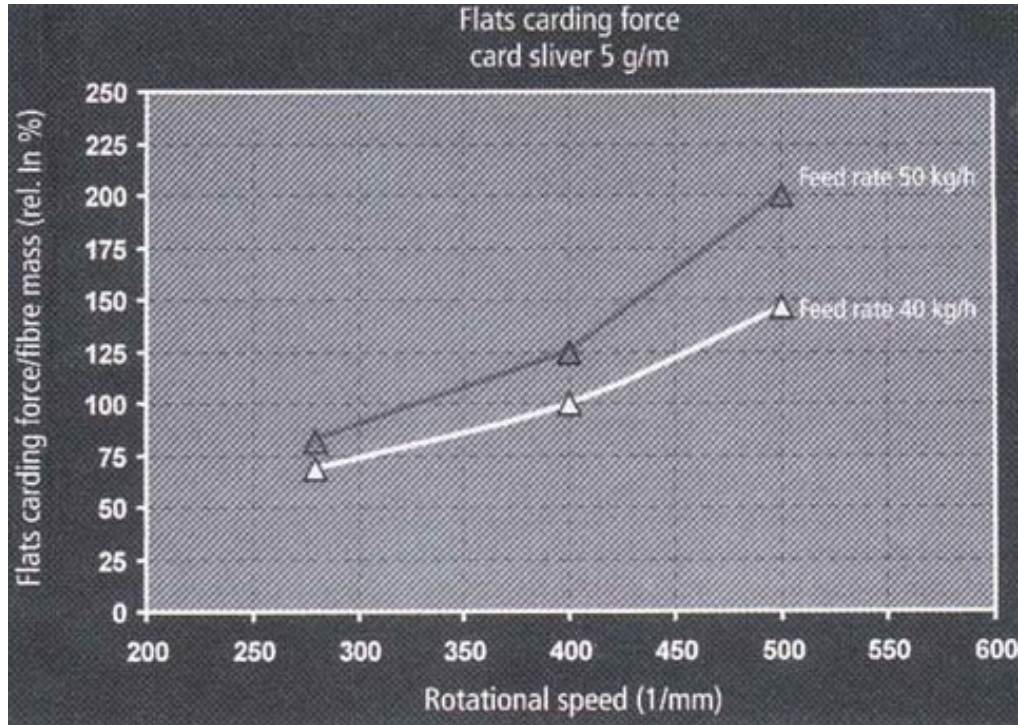


**FIGURE 7:** The Influence of Roller Speed and Regain on the Charge Level of Wool and Cotton Slivers [55]

#### 4.2.4. Carding Forces

A study conducted by Artzt and Jehle [57] revealed the changes in carding forces with the cylinder speed. They stated that an increase in cylinder speed from 300 to 500 rpm as seen in Fig. 8 has no dramatic effect on the carding forces. They reported an increase of about 10-20% due to this change. However, one thing that should be taken into account is the decrease in fiber density on the cylinder with the increasing speed. Therefore, it can be said that the force that an individual fiber is exposed to may not be proportional to the cylinder speed. They observed that at 40kg/h production rate and 400-rpm cylinder speed (result at this point was indexed as 100%) an individual fiber is subjected to 50% greater stress when the cylinder speed is increased to 500-rpm.

They also pointed out that increasing the throughput by 25% (from 40 to 50 kg/h) caused twice as high stress on a fiber [57].



**FIGURE 8:** Dependence of Force/Fiber Mass on Rotational Speed [57]

#### 4.2.5. Importance of Settings

“For great carding the decisive setting is the flats-to-cylinder distance” [26]. As an inherent result of heat and centrifugal forces, any cylinder will expand while the card is running. Depending on the cylinder speed and size, the effective clearance in running condition is reduced about 1-2/1000” compared to the setting at rest due to centrifugal

forces. Adding the effect of heat to this will result in a total of 3/1000” of difference between the rest and running conditions. When the possible eccentricity is taken into account this phenomenon becomes more important [57].

#### **4.2.6. Card Clothing**

It is a very well known fact that processing different fibers in carding requires different wire clothing with different characteristics [3].

Metallic card clothing has two essential functions: pulling fiber and discharging fiber. Both of these actions take place on every single wire tooth. The front or the tip of the tooth pulls the fiber, and the back of the tooth discharges it. If the tooth cannot release the fiber, it will load up and will not be able to take any more fibers, which will cause inefficiency in carding. When the roll speed increases, more teeth are presented thus more fibers are pulled and thus the capacity increases [58].

One of the main constraints in increasing carding speeds was stripping and grinding of the card, which had to be done quite frequently when flexible clothing was used. Therefore, metallic clothing was one of the most important developments in achieving high speed carding.

Since metallic wire does not require regular stripping, it could save 2 to 3 percent of good fibers and increase the production rates of 15-18%.

One of the main features of the metallic wire clothing is its ability to keep fibers on the surface of the clothing more than flexible wires. With fillet clothing, fibers tend to slide down to the knee of the wire, thus causing loading up the clothing. The loading capacity of the metallic wire is 20-25% less than the fillet clothing. As a result, the fiber is transferred to the doffer after 10-15 revolutions of the cylinder whereas this takes 14-20 revolutions in case of flexible fillet wire. Some type of metallic clothing with high capacity doffer requires only 4-6 turns of cylinder to transfer the fiber to the doffer, decreasing the loading of the cylinder by 40%. Increased transfer efficiency reduces the fiber loading on the cylinder providing better carding action [10].

Design of the metallic wire clothing is an issue, which should be considered when operating cards at high speeds. Number of teeth or their density should be large enough to ideally carry individual fibers forward, holding them against the opposing force of flats' teeth. If the number of teeth is not sufficient, a single tooth will have to carry more fibers, which will result in insufficient combing and bad carding [15].

Design of the wire teeth should be in such a way that they could hold the fibers against opposite force, namely, they could stand the tremendous strain put on them. Wire angles should be adjusted for different raw materials [15].

## **CHAPTER 2**

### **“EXPERIMENTAL DESIGN and SETUP”**

## 1. INTRODUCTION

The main goal of the research is to understand the reasons behind the phenomenon that some fibers cannot be carded as fast as others in carding process. To investigate the reason(s), a totally new approach was developed and implemented.

The experimental plan was to card different fiber types in the same card and under constant operating conditions and then to compare the results gathered from these experiments. However, unlike the previous researchers the present study uses the novel concept of fixing the fiber diameters.

It was decided to use the two most widely used fibers in nonwovens carding industry, i.e. polyester and polypropylene. In addition to these, two bicomponent fibers were designed using polyester and polypropylene polymers. The distinctive feature of these bicomponent fibers was that they had a very thin sheath over the core. For example, PET/PP fiber was desired to be a PET fiber with a PP surface. The main idea behind this was to see the effects of fiber surface characteristics on fiber's carding performance and quality. 3-denier polyester was chosen as the base fiber and the denier number of other fibers was calculated to achieve constant diameter among all experimental fibers.

To realize these objectives, a set of experiments was carried out using the experimental fibers. Each fiber was run in the card at two different speeds to observe the effect of production speed on carding performance and quality. Samples were taken from

the predetermined areas for each run and planned tests were performed to acquire data from those samples.

The analysis of the collected data was based on comparison among the different fiber types. Data collected from different speeds and different locations of the card were compared to recognize the existence of possible similarities or differences. The main aim of this comparison was to observe if the fibers were behaving differently under fixed conditions. Since all the parameters were kept constant and the diameter of each fiber was the same, any difference detected among the fibers was because of the inherent difference in fibers.

## **2. RESEARCH OBJECTIVES**

The objectives of the proposed research are to provide a better understanding of:

- The effects of fiber types on carding process.
- The reasons behind the dependency of maximum processing speed on fiber type.
- Carded web uniformity, as related to fiber type and processing speed.

It was aimed to realize these objectives through the planned experiments and testing. Responses of interests were identified and the corresponding data collected via various tests. The main goal was to explore the effects of fiber type on high-speed

carding quality and performance. Comparison methods have been utilized to observe the differences among the data group means. The effect of the carding process on fiber properties was another area of interest to be investigated. Data analysis has been made in a way to disclose the effects of the changes in fiber parameters to the output quality.

### **3. DESIGN OF EXPERIMENTS**

A totally new approach has been employed in order to study the effects of fiber types on fiber processability. Most important key points are the design of the experiment fibers and the setup of the experiments.

Previous researchers conducted cardability investigations utilizing commercial fibers and attempted to explain their results in terms of differences in fiber diameters and number of fibers per unit time processed through the card. Our approach is to study the cardability of different fibers with the same diameter and process these at constant number of fibers per unit time for a given speed. This method will allow the elimination of such two significant parameters and may reveal the reasons behind the behavior of different fibers in carding.

Experiments were designed in a way to allow us the elimination of many parameters, which affect the processability of the fibers, and leave the effect of fiber type alone in order to observe the different behaviors of different fiber types under fixed

carding conditions as seen in Table 1. In addition, the effects of production speed on fiber processability were investigated by using an appropriate experimental design.

**TABLE 1:** Variable and Constant Parameters

<b>PARAMETERS</b>	<b>Constant</b>	<b>Variable</b>
Settings	X	
Production Speeds		- 85 m/min, - 120 m/min
Relative Speeds	X	
Number of Fibers	X	
Fiber Type		- PET - PP - Bicomponent 1 (PET/PP) - Bicomponent 2 (PP/PET)
Fiber Diameter	X	
Fiber Finish	X	
Fiber Crimp	X	
Fiber Length	X	
Card Clothing	X	

**TABLE 2:** Responses of Interest

<b>RESPONSES</b>	<b>Input</b>	<b>Output</b>
<b>Fiber Parameters</b>		
Fineness	X	X
Crimp	X	X
Strength	X	X
Stress-Strain Behavior	X	X
<b>Web Parameters</b>		
Uniformity		X
Thickness		X
Fiber Orientation		X
Openness of Feed Matt	X	

Since all the physical fiber parameters, such as diameter, crimp, finish, and length are the same; carding the same number of fibers will eliminate all factors but the fiber type. By this way, we will achieve an understanding of the effects of fiber types on the carding performance.

Table 2 shows the responses of interest for the proposed research. Throughout these measurements we expect to find out the effects of the carding process on the fiber parameters (crimp, strength, etc.), and the effect of the characteristics of the input feed batt on the characteristics of the carded web and finally understand the reasons behind different maximum processing speeds for different fiber types. Table 3 illustrates the configuration of the designed trial runs.

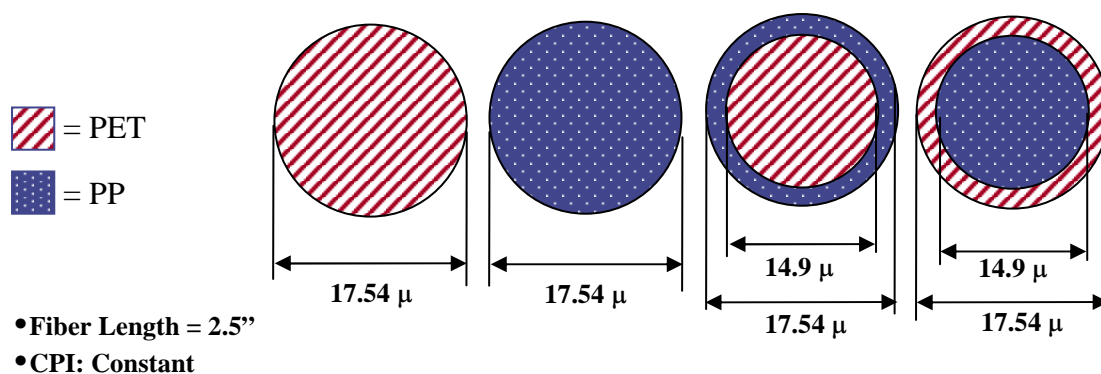
**TABLE 3:** Configuration of Experimental Runs

Run	Fiber Type (PET/PP)				Production Speed	
	100/0	0/100	80/20	37/63	85 m/min	120 m/min
1	X				X	
2	X					X
3		X			X	
4		X				X
5			X		X	
6			X			X
7				X	X	
8				X		X

### 3.1. Design of Experimental Fibers

The design of the experimental fibers is very crucial to the current research. The main inspiration when designing the fibers was to create a carding condition which would leave the effect of fiber type alone when carding under fixed operating conditions. The specifications of the experimental fibers can be seen in Table 4.

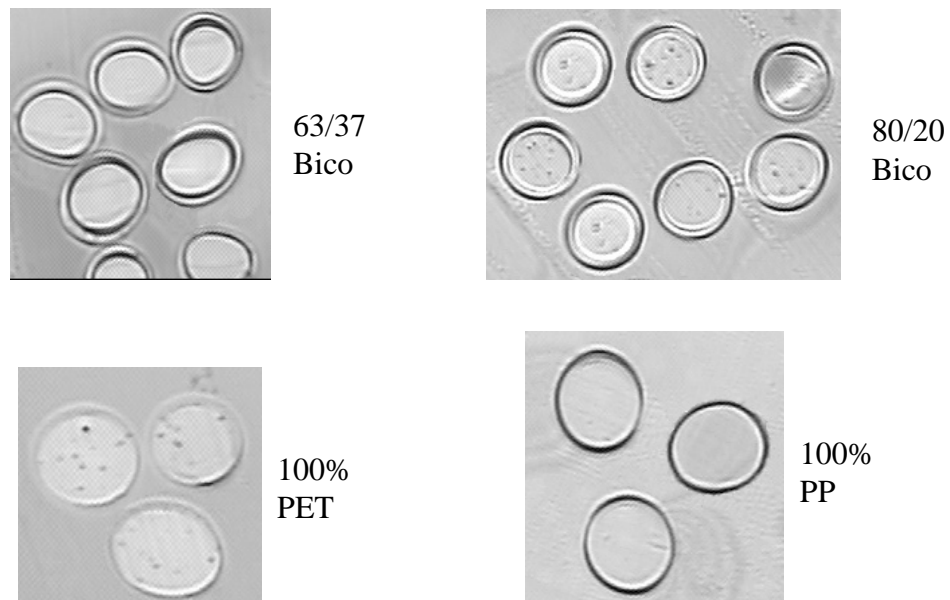
**TABLE 4:** Specifications of Experimental Fibers



Fiber Type	PET	PP	Bicomponent	Bicomponent
Denier	3.00	1.96	2.70	2.25
Outer Diameter, $\mu$	17.54	17.54	17.54	17.54
Inner Diameter, $\mu$	-	-	14.9	14.9
% Weight core/sheath	100/0	100/0	80/20	63/37
Web basis weight $g/m^2$	30.0	19.6	27.0	22.5

One of the most important features of the experimental fibers is their fixed diameter. The main idea behind fixing the diameter is to be able to card constant number of fibers per tooth for a given time for each fiber type. Therefore, it is aimed to eliminate the possible effects of fiber loading. To achieve this, output web weight was adjusted for each fiber type according to its denier number (see Table 4). This adjustment also makes the webs of each fiber type have same number of fibers per unit area, which enables them to be comparable.

Since all the physical fiber parameters, such as diameter, crimp, finish, and length are the same; carding the same number of fibers will eliminate all factors but the fiber type. By this, we will obtain an understanding of the effects of fiber types on carding performance.



**FIGURE 1:** Fiber Cross-Sections

Another very interesting aspect of the research is the use of bicomponent fibers. These fibers have a very thin sheet. This kind of structure allows us to observe how a fiber's behavior in carding is affected by its physical structure, i.e. surface properties or as a whole. In other words, it will reveal for example 80/20 bicomponent fibers behave whether more like 100% PET or 100% PP or neither.

### **3.2. Calculations of Fiber Deniers for Different Fiber Types at Constant Diameter**

It has been planned to use 4 different fibers. It was also determined that the fiber diameter should be fixed for all fiber types, which will provide the ability of carding a constant number of fibers per unit area for each fiber type. This will also fix the interrelation between fiber physics and wire clothing geometry. These facts will help in understanding the effects of fiber types in carding. The following are the calculations for the above-mentioned fibers. 3-denier standard PET fiber was chosen as the base fiber and the diameter of this fiber was calculated. Furthermore, corresponding deniers are calculated based on this diameter.

#### **3.2.1. PET = 3 denier $\rightarrow \varnothing = 17.54 \mu$**

The following calculations give the diameter of 3-denier PET fiber:

$d$  = Fiber Diameter (cm)

$N$  = Fiber Count (denier)

$\rho$  = Fiber Specific Gravity ( $\text{g}/\text{cm}^3$ ),  $\rho_{\text{PET}} = 1.38$

$$D = \frac{1}{280.2} \sqrt{\frac{N_{\text{PET}}}{9 \times \rho}}$$

$$d_{\text{PET}} = \frac{1}{280.2} \sqrt{\frac{3}{9 \times 1.38}} = 0.001754 \text{ cm}$$

$$0.001754 \text{ cm} = 0.01754 \text{ mm} = 17.54 \mu$$

### 3.2.2. PP = 1.96 denier

The following calculations give the denier number for PP for the same diameter calculated above. Using the allocations stated above:

$$d = \frac{1}{280.2} \sqrt{\frac{N_{\text{PP}}}{9 \times \rho}}, \quad \rho_{\text{PP}} = 0.9$$

$$0.001754 \text{ cm} = \frac{1}{280.2} \sqrt{\frac{N_{\text{PP}}}{9 \times 0.9}} \rightarrow N_{\text{PP}} = 1.9565 \text{ denier}$$

### 3.2.3. PET/PP (80/20) = 2.7 denier

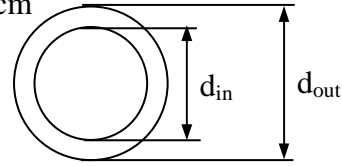
In order to calculate the inner diameter and the thickness of the cover sheet of this bicomponent fiber, we can use the known ratio of masses of two polymers.

$m$  = Mass (g)

$L$  = Length (cm)

$d_{out}$  = Outer diameter of fiber (cm) = 0.001754 cm

$d_{in}$  = Inner diameter of fiber (cm)



$m$  = Area x Length x Specific Gravity

$$m_{PET} = \pi d_{in}^2 (\text{cm}^2) \times L (\text{cm}) \times 1.38 (\text{g/cm}^3)$$

$$m_{PP} = \pi (d_{out}^2 - d_{in}^2) (\text{cm}^2) \times L (\text{cm}) \times 0.9 (\text{g/cm}^3)$$

$$m_{PET}/m_{PP} = 80/20 = 4 = \frac{\pi d_{in}^2 (\text{cm}^2) \times L (\text{cm}) \times 1.38 (\text{g/cm}^3)}{\pi (d_{out}^2 - d_{in}^2) (\text{cm}^2) \times L (\text{cm}) \times 0.9 (\text{g/cm}^3)}$$

$$4 = \frac{d_{in}^2 \times 1.38}{(d_{out}^2 - d_{in}^2) \times 0.9}$$

$$3.6 \times d_{out}^2 - 3.6 \times d_{in}^2 = 1.38 \times d_{in}^2$$

$$4.98 \times d_{in}^2 = 3.6 \times d_{out}^2$$

$$d_{in}^2 = 2.224 \times 10^{-6}$$

$$d_{in} = 0.00149 \text{ cm} = 0.0149 \text{ mm} = 14.9 \mu$$

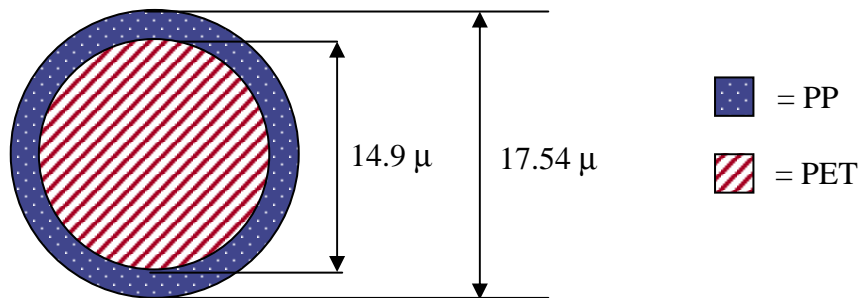
In order to calculate the denier for this bicomponent fiber we can use the principle of denier, which is;

$$\text{Denier (g)} = \text{Fiber cross-section area (cm}^2) \times \text{Specific Gravity (g/cm}^3) \times 9 \times 10^5 \text{ cm}$$

For this bicomponent fiber, we should consider the fiber consisting of two parts. One is the core and the other is the cover sheet. To calculate the denier of the fiber we

need to calculate the mass of the 9000 m of PET as the core, and the mass of the 9000 m of PP as the cover sheet and then add them up. The following shows these calculations:

$$\begin{aligned} \text{Denier} &= \underbrace{\frac{\pi \times d_{in}^2}{4} \times \rho_{PET} \times 9 \times 10^5}_{m_{PET} \text{ (g)}} + \underbrace{\frac{\pi (d_{out}^2 - d_{in}^2)}{4} \times \rho_{PP} \times 9 \times 10^5}_{m_{PP} \text{ (g)}} \\ &= \frac{\pi}{4} \times 9 \times 10^5 (d_{in}^2 \times \rho_{PET} + (d_{out}^2 - d_{in}^2) \times \rho_{PP}) \\ &= \frac{\pi}{4} \times 9 \times 10^5 (0.00149^2 \times 1.38 + (0.001754^2 - 0.00149^2) \times 0.9) \\ &= 2.702628 \text{ denier} \end{aligned}$$



### 3.2.4. PP/PET (63/37) = 2.25 denier

In order to calculate the denier amount of this bicomponent fiber, using the above-calculated outer and inner diameters, we can use the denier principle again. Since this is a bicomponent fiber, we should consider the effect of different fiber types into the denier of this fiber. The denier of this fiber can be calculated by calculating the mass of the 9000 m

of PP as the core and calculating the mass of 9000 m of PET as the cover sheet then adding them up.

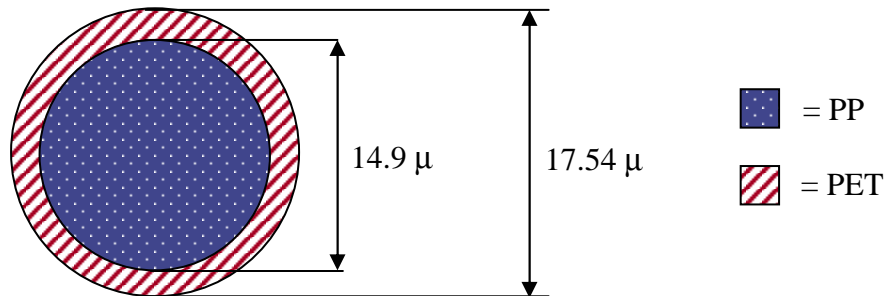
$$\text{Denier (g)} = \text{Area (cm}^2\text{)} \times \text{Specific Gravity (g/cm}^3\text{)} \times 9 \times 10^5 \text{ cm}$$

$$\text{Denier} = \left( \frac{\pi \times d_{in}^2}{4} \times \rho_{PP} \times 9 \times 10^5 \right) + \left( \frac{\pi \times (d_{out}^2 - d_{in}^2)}{4} \times \rho_{PET} \times 9 \times 10^5 \right)$$

$$\text{Denier} = \underbrace{\frac{\pi(0.00149^2)}{4} \times 0.9 \times 9 \times 10^5}_{1.4123 \text{ g (PP)}} + \underbrace{\frac{\pi((0.001754^2) - (0.00149^2))}{4} \times 1.38 \times 9 \times 10^5}_{0.8355 \text{ g (PET)}}$$

$$= 2.25 \text{ denier}$$

$$\%PP = \frac{m_{PP}}{m_{fiber}} = \frac{1.4123}{2.25} \cong \%63 \quad \%PET = \frac{m_{PET}}{m_{fiber}} = \frac{0.8355}{2.25} \cong \%37$$



### 3.3. Calculation of Web Weights

Carded web basis weight for PET fiber can be calculated using the following equation:

$$\text{Web Weight (g/m}^2\text{)} = k \times \sqrt{\text{fiber denier}},$$

$$k = 17 \text{ (constant for double doffer cards).}$$

$$\text{Basis Weight}_{\text{PET}} = 17 \times \sqrt{3} = 30 \text{ g/m}^2$$

Since the number of fibers per unit area will be same for every fiber type, we can calculate the basis weight for the PP fiber web by calculating the total length of fibers per  $\text{m}^2$  and find the corresponding weight for the PP fiber.

$$\text{Total length of fibers/m}^2 = \frac{30 \text{ g} \times 9000 \text{ m}}{3 \text{ denier(g)}} = 9 \times 10^4 \text{ m.}$$

$$N_d = \frac{\text{Weight(g)}}{\text{Length(m)}} \times 9000 \text{ m.}$$

$$\text{Weight(g)} = \frac{N_d \times \text{Length(m)}}{9000 \text{ m.}}$$

$$\text{Basis Weight}_{\text{PP}} = \frac{(1.96 \text{ denier(g)}) \times 9 \times 10^4}{9000} = 19.6 \text{ g/m}^2$$

$$\text{Basis Weight}_{\text{PET/PP}} = \frac{(2.7 \text{ denier(g)}) \times 9 \times 10^4}{9000} = 27 \text{ g/m}^2$$

$$\text{Basis Weight}_{\text{PP/PET}} = \frac{(2.25 \text{ denier(g)}) \times 9 \times 10^4}{9000} = 22.5 \text{ g/m}^2$$

## **4. CARDING TRIALS**

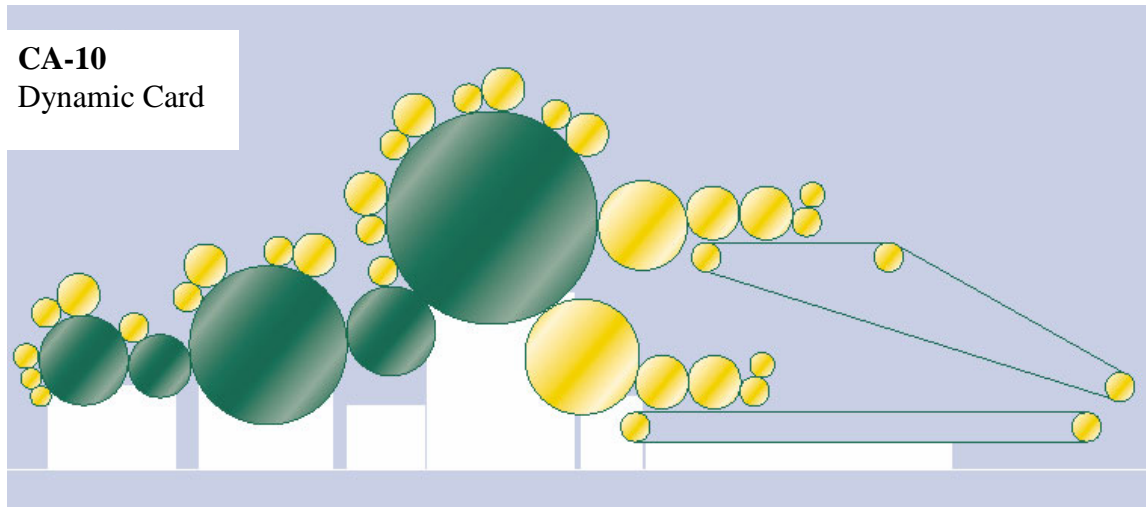
### **4.1. Card Specifications**

Experiments were conducted at NSC-USA's Nonwoven Systems Showroom located at Fort Mill, SC. Details and specifications about the card used in the experiments are given below:

The card used in the experiments was a CA-10 (2255PP) dynamic roller-top card and was manufactured by Thibeu as can be seen in Fig.2 and Fig.3. The card has a two-doffer configuration, which allows superior quality. It was equipped with latest technology systems such as, Servo-X input auto-leveler, LDS and WID.

Servo-X is composed of an X-Ray emitter and a collector on the other side of the feed matt. The amount of X-Ray received by the collector is used as a measure of the mass density of the input. The system is used to control the machine directional uniformity of the card input.

LDS is a web doffing system, which allows the transfer of the web with minimized or zero draft. One advantage of the system is that it can work regardless of web type and production speed.



**FIGURE 2:** Schematic of a Thibeu CA-10 Dynamic Nonwoven Card [59]



**FIGURE 3:** Experimental Card (Thibeu CA 10)

WID (Web Introduction Device) is a system used to transfer the web without applying any draft to it. It can be also used irrespective of the speeds and types of webs. At the same time it minimizes the air disturbance to the web.

Since the card was designed as a trial card, the card clothing used was special type universal clothing, which gives an edge on eliminating or at least minimizing the affect of card clothing for using different fiber types. Maximum speed of the card is 120 m/min and the working width is 2.5 meters (100 inches).

The specifications of the experimental card can be seen in Table 5.

**TABLE 5: Card Processing Specifications**

	<b>Max</b>	<b>120m/min</b>	<b>85m/min</b>
<b>Main Cylinder:</b>		1400	1400
<b>Stripper:</b>		250	250
<b>Worker:</b>		125	125
<b>Load</b>		100%	71%
<b>Upper Doffer Speed:</b>	120	120	85.2
<b>Upper Take-Off:</b>	120	120	85.2
<b>Upper Apron:</b>	120	120	85.2
<b>Bottom Doffer Speed:</b>	120	120	85.2
<b>Bottom Take-Off:</b>	120	120	85.2
<b>Bottom Apron:</b>	120	120	85.2

#### **4.2.Execution of Experiments**

The fibers used for experimentation were conditioned for at least 24 hours prior to the trial for optimum results. Since, there was only one bale of each fiber type, a cleaning fiber was used to fill the card elements and clothing with the same finish as the experimental fibers. 2 denier 100% PP fibers were used as the cleaning fiber. Before each trial run, a bale of cleaning fiber was run through the card. After the card was ready for the trial, experiment fiber was fed to the card through the fiber opening system and chute feeder.

To reach a steady state, the card was run for around 15 minutes prior to taking any samples. After the card reached a steady state, it was stopped using emergency brakes to eliminate any detriment to the web that may be caused by the slowing of the card. With the emergency brakes, the card stops very quickly causing negligible harm to the web, however on the other hand, with regular stopping procedure, it will take couple of minutes for the card to reach a full-stop, which means that the useful web will be gone in to the crosslapper by the time the card stops.

After stopping the card, samples were taken according to the sampling plan given above. This plan is different from the initial plan owing to the conditions of the area that the samples were taken. When the samples were taken, they were brought to the College of Textiles for testing.

### 4.3. Sampling Plans

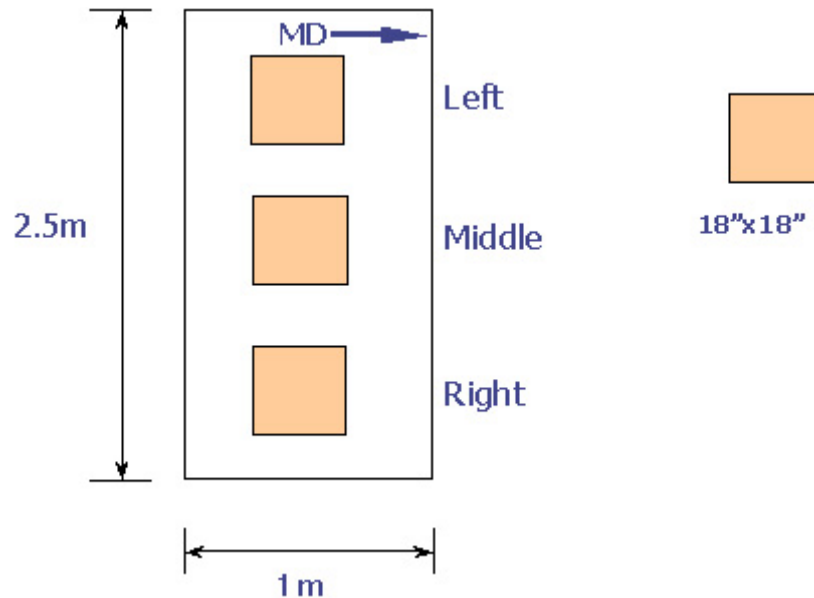
Sampling is another important step of the experimental procedure. Conditions of the taken samples are important to obtain proper results through testing. Since, carded web and feed matt are quite delicate, extreme care was taken when handling samples in order to preserve the original condition of the samples.

#### 4.3.1 Sampling For The Feed Matt

3 number of samples sized 18x18 inches were taken from the feed matt area for both of the test speeds. The sampling plan can be seen in Fig. 5. An 18x18" cardboard was slided under the matt and the sample was disentangled out of the whole web by hand. Each sample was put in a cardboard box to protect from any damage as seen in Fig. 4.



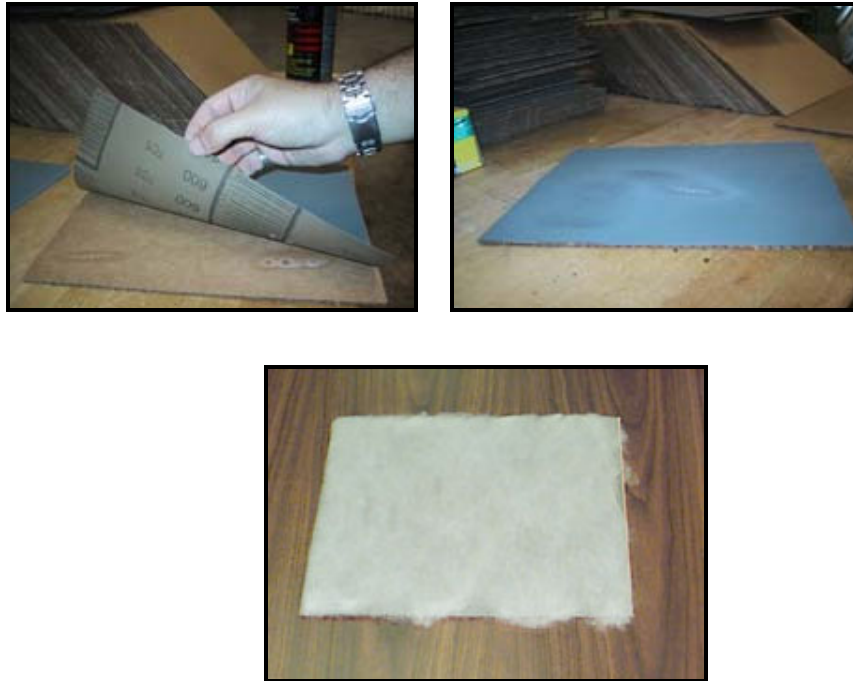
**FIGURE 4:** Actual Picture of a Feed Matt Sample in a 18x18" Cardboard Box



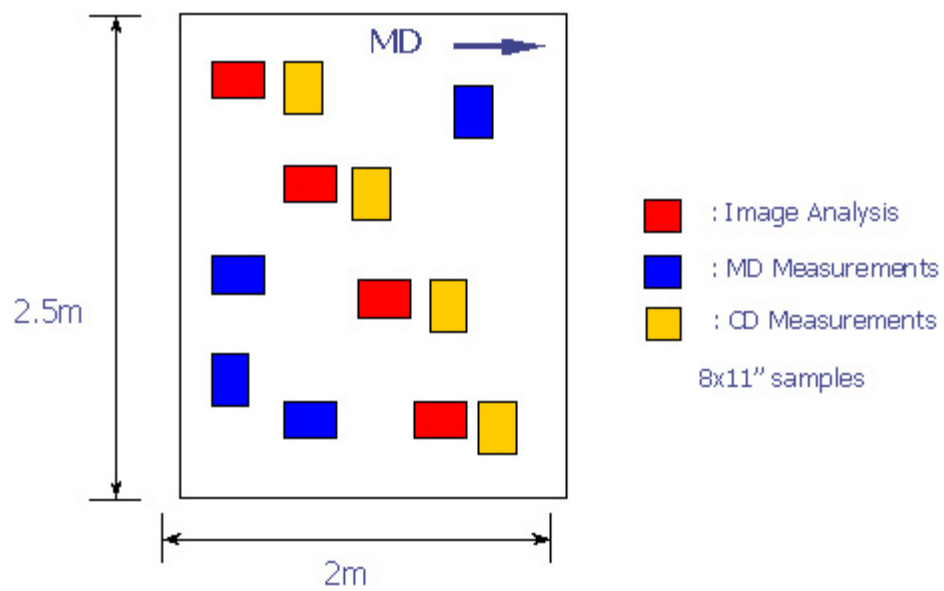
**FIGURE 5:** Sampling Plan for the Feed Matt

#### 4.3.2. Sampling For The Carded Web

Total of 12 8x11" sized samples were taken from the carded web for each speed and were selected in a way to represent the whole web. Since the web is very delicate it cannot be handled by hand, a cardboard, a very fine sandpaper and spray glue were used for sample taking as seen in Fig.6. A sheet of sandpaper was stuck on to the cardboard and the surface of the sandpaper was sprayed with glue so as to create a surface where the web could attach. The sandpaper was put on the web and the sample was disentangled from the entire web by hand. Afterwards, each sample was put in a plastic bag and 4 number of samples together were put in a cardboard box so that they keep their original forms. The sampling plan for the carded web can be seen in Fig. 7.



**FIGURE 6:** Preparation and Actual Picture of a Carded Web Sample

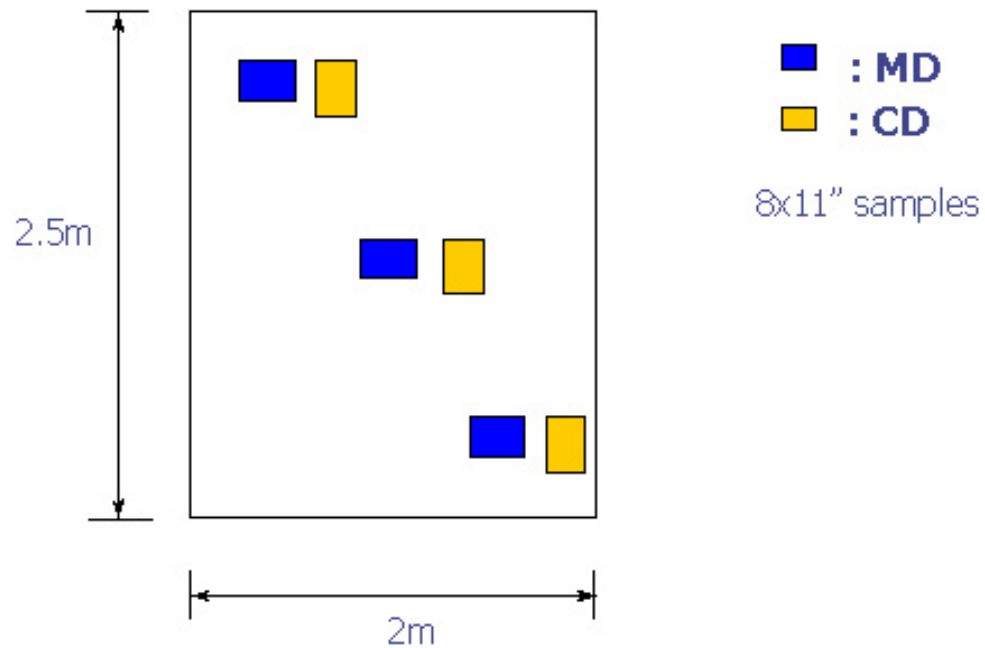


**FIGURE 7:** Sampling Plan for the Carded Web

### 4.3.3. Sampling For The Cross-Lapped Web

3 number of 8x11 inches sized samples for the cross direction measurements were gathered from the cross-lapper. The plan for sampling is given in Fig 8.

In addition to these, samples from each bale of fiber were taken before the processing of fibers in order to measure the fiber parameters before the carding process. Also, single fibers were taken out from the carded web in order to measure the fiber parameters after the carding process and observe the differences in these parameters caused by the carding process.



**Error!**

**FIGURE 8:** Sampling Plan for the Cross-Lapped Web



**Feed Matt Area**



**Carded Web Area**

**FIGURE 9: Pictures of Actual Sampling Areas**

## **CHAPTER 3**

**“TESTING and INSTRUMENTATION”**

## 1. INTRODUCTION

Several tests were executed to measure different characteristics of the collected samples. A number of fiber, feed matt and web parameters were measured and compared in order to see the potential effects of the fiber type on carding performance and quality.

Numerous testing techniques and equipment were employed to complete the testing phase of the research. State of the art fiber measurement devices, latest image analysis techniques and a variety of analytical testing instruments were utilized.

Since most of the tests done did not have established standards, the number of samples was determined by statistical means. Before each test, a preliminary test was carried out and the number of samples needed was calculated using the following formula:

$$n = \left( \frac{z_{\alpha/2} \times \sigma_e}{E} \right)^2$$

Where;

$n$  = Sample size

$z_{\alpha/2} = 1.96$  (for 95% CI)

$\sigma_e$  = Estimated standard deviation

$E$  = Error term (10% was used for all experiments)

Most of the testing was conducted using NCRC's equipment located at College of Textiles, NCSU, whereas some fiber tests (fiber friction) were performed by industrial partners at their facilities.

## **2. TESTING OF FIBER PARAMETERS**

### **2.1. Testing with FAVIMAT Tester**

Most of the fiber parameters such as fiber strength, fiber fineness, and fiber crimp stability and stress-strain properties were measured using FAVIMAT Tester, which can be seen in Fig.1 and Fig.2.

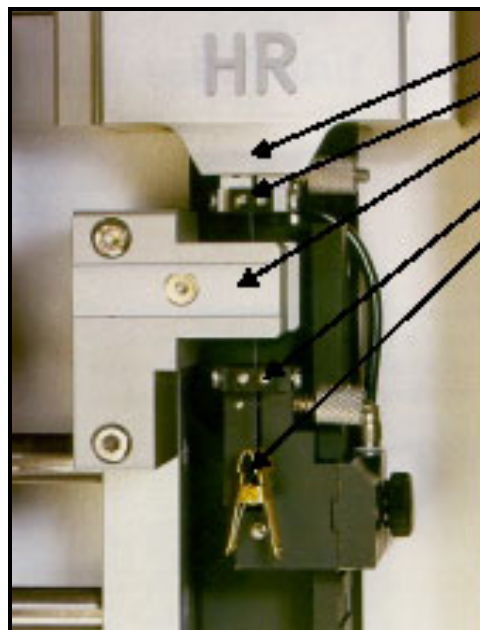
The sequence of a standard tensile and crimp stability test with count measurement with the FAVIMAT is as follows:

1. Fiber is pre-tensioned with paper weight (approx. 0.01 cN/tex)
2. Load sensor at upper clamp is calibrated to zero
3. Fiber is clamped (initial gage length e.g. 20 mm)
4. Position of lower clamp is adjusted, so that fiber is exactly pre-tensioned with 0.01 cN/tex referred to nominal count
6. Actual crimp test starts:
  - Lower clamp moves downwards at constant rate of extension (e.g. 20 mm/min)
  - Until preset "crimp force" (e.g. 1 cN/tex) is reached
  - Lower clamp moves upwards
  - Until preset gage length is reached
7. Count test is done:

- Fiber is loaded at a predefined rate
  - Fiber is excited acoustically & resonance frequency is detected
8. Fiber is loaded until it breaks
  9. Lower and upper clamp open, fiber drops
  10. Lower clamp moves upwards to initial position



**FIGURE 1:** Textechno FAVIMAT Single Fiber Tester [47]



- **Force Measuring Head**
- **Upper Clamp**
- **Optical Fiber Count Measuring Head**
- **Lower Clamp**
- **Fiber Clamp for Handling Purposes**  
(For Crimp Tests, Much Lighter Paper Tabs Are Being Used)
- **Gage Length:** Continuously Variable: 5 - 80mm
- **Maximum Force:** 200cN  
 $\pm 0.0001\text{cN}$
- **Force Sensitivity:** 0.001 cN
- **Extension Resolution:**  $\pm 0.1 \text{ }\mu\text{m}$
- **Testing Speeds:** 0.1 - 100 mm/min

**FIGURE 2:** Measuring Unit of Textechno FAVIMAT [47]

### 2.1.1. Count Measurement

Fiber fineness measurement on FAVIMAT is done according to the ASTM D 1577 standard using a built in automatic measuring head. Vibroscopic method is used, where the fiber is loaded to a predetermined specific tension at a predefined speed. Then the fiber is excited with an electro acoustic sinusoidal vibration and the resonance frequency is detected with an optoelectronic sensor. For the simplicity of the calculation, uniform mass distribution and circular cross section of the fiber is assumed and bending rigidity is disregarded. The following formula is used to calculate the fiber count:

$$T_t = \frac{F_v \times 10^{11}}{4 \times f^2 \times L^2}$$

$T_t$  = Fineness in dtex

$F_v$  = Pre-tensioning force in cN

$f$  = Resonance frequency in Hz

$L$  = Testing length in mm.

### 2.1.2. Fiber Strength Measurement

Fiber strength value obtained from the FAVIMAT tester is simply the peak load of the fiber. For this test, the fiber, which is mounted between the two clamps of the tester, is loaded until it breaks.

If the test is done with the crimp measurement, the fiber is loaded until its crimp is removed then released to its original position and loaded again until its breaking point.

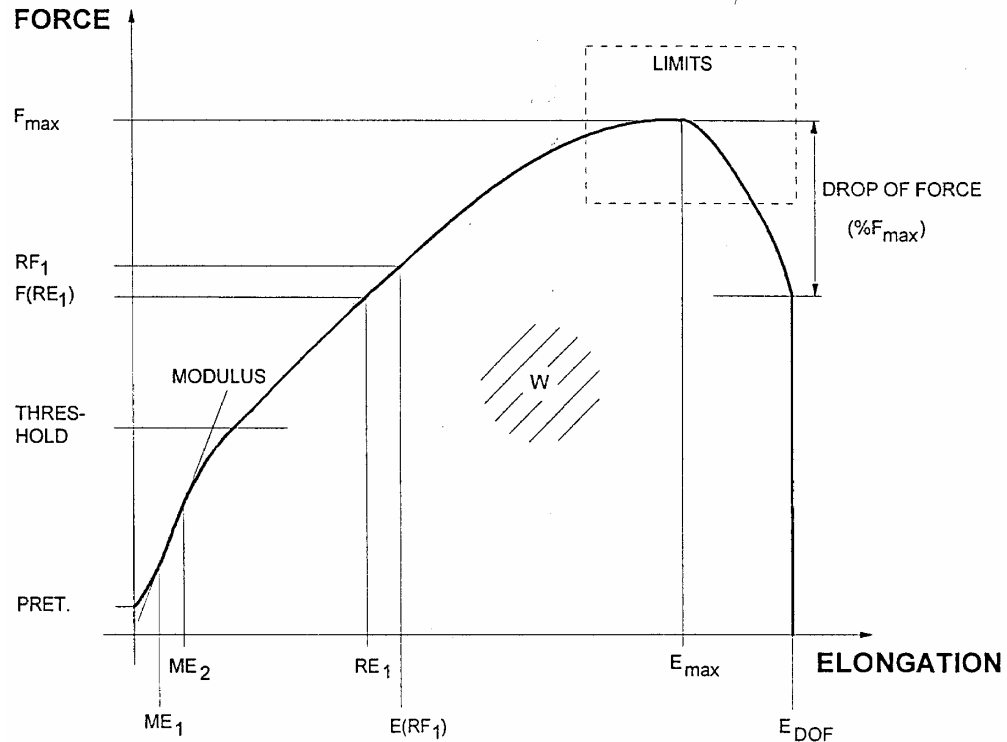
### **2.1.3. Fiber Modulus Measurement**

Fiber modulus measurement is made using certain points on the stress-strain diagram of the fiber. Modulus here is defined as follows:

$$E = \left( \frac{F_2 - F_1}{E_2 - E_1} \right) \times 100\%$$

$F_1$  and  $F_2$  are the force values and are taken from the stress-strain curve (see Fig. 3) of the fiber, whereas  $E_1$  and  $E_2$  are the elongation coordinates of the two force values. Depending on the distance between the two points on the curve 2 moduli can be determined: a straight line between the two points forms a tangent (close distance) or a secant (larger distance) to the curve.  $E_1$  is set to 0 in order to find out the initial modulus

[60]. Stress-strain diagrams of all fiber types for all carding conditions are given in the appendix.



**FIGURE 3:** Standard Force-Elongation Curve of a Fiber [60]

#### 2.1.4. Crimp Stability Measurement

Fiber crimp stability is calculated using the following formula:

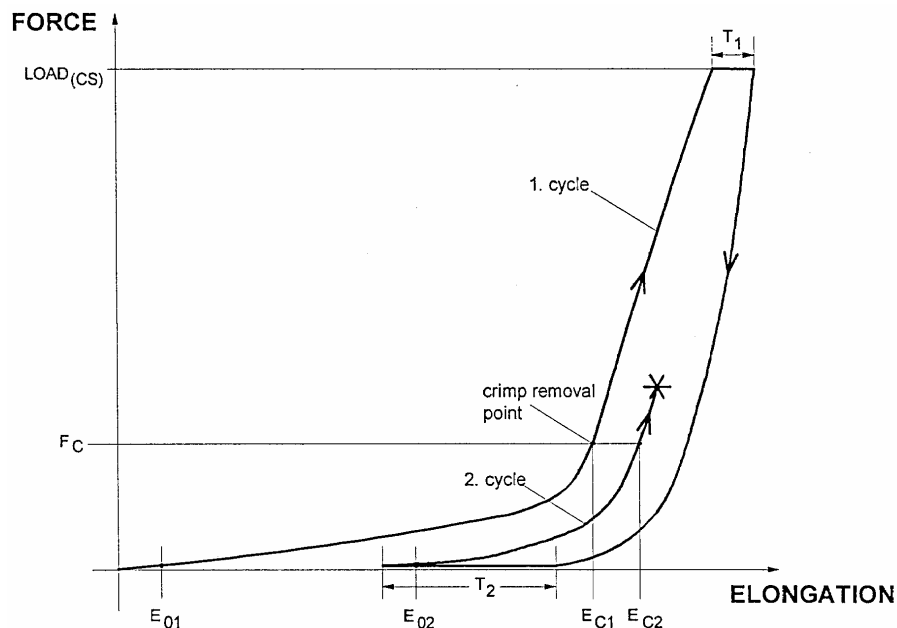
$$\text{Crimp Stability} = \frac{\text{Remaining Crimp}}{\text{Crimp Extension}} \times 100 (\%)$$

Here, crimp extension is measured using the initial section of the force-elongation curve, where the fiber is loaded to a preset tension (until its crimp is removed) and

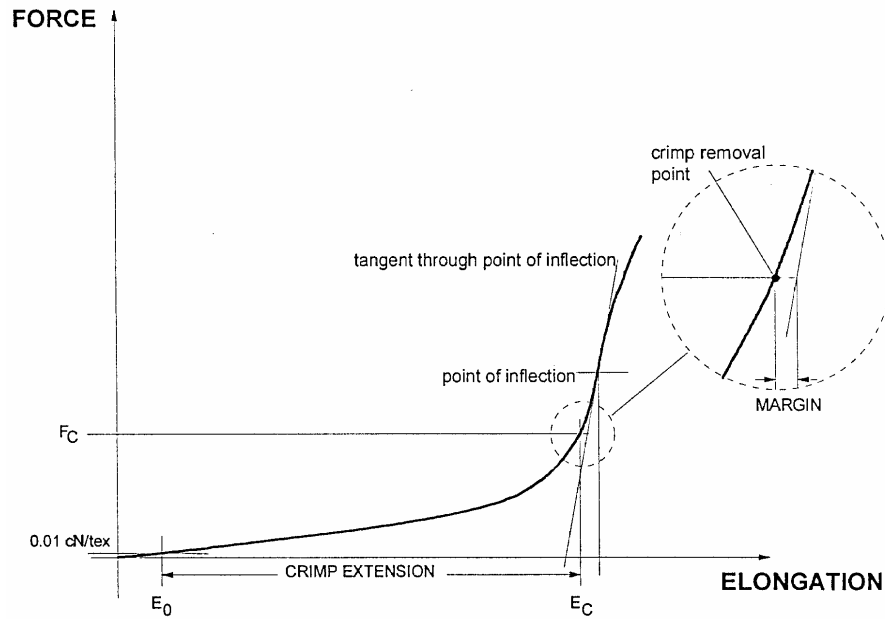
maintained in that position for a predefined time, then relieved to its initial position. This first cycle can be seen in Fig.4. However, Fig.5 illustrates this section more closely. As can be seen in Fig.5, the crimp removal point determines the upper end of this section, with the coordinates  $F_c$  and  $E_c$ . The lower end (fully crimped condition), is defined by the coordinates  $F=0.01\text{cN/tex}$  and  $E_0$ . Using these coordinates, crimp extension is calculated using the following formula:

$$\text{Crimp Extension} = E_C - E_0$$

After the fiber reached to the low level it is held for another preset period, then extended again until the tension has reached  $F_c$ . From this second cycle (see Fig.4) remaining crimp is obtained.



**FIGURE 4:** Loading Cycles of the Test Illustrated on a Force-Elongation Curve [60]

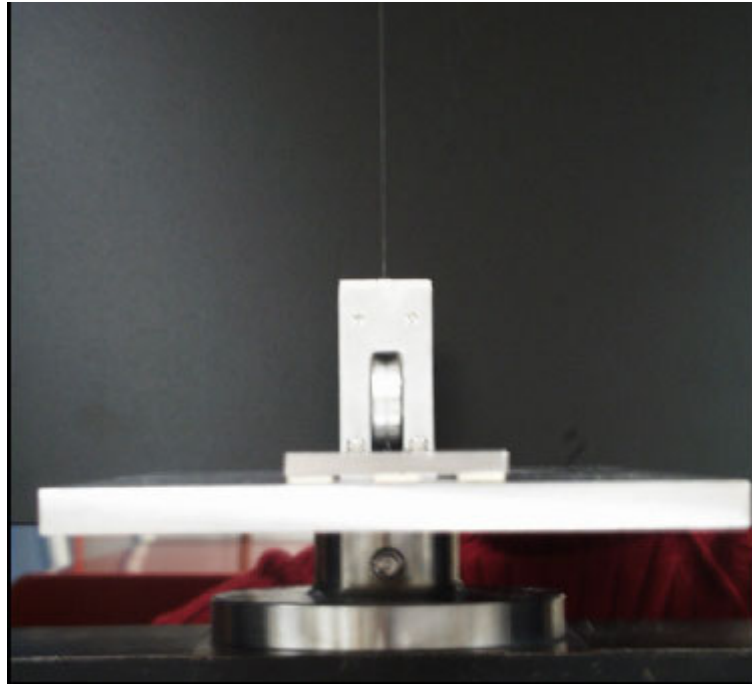


**FIGURE 5:** Crimp Removal Section of the Force-Elongation Curve [60]

## 2.2. Fiber Friction Measurements

Fiber friction tests were conducted at Goulston Technologies' facilities by their technicians using their state of the art equipment. Two types of fiber frictional characteristics, which are fiber-fiber and fiber-metal friction and percent finish on fibers, were measured for each experimental fiber. Both of these parameters are important in

carding, where fibers are exposed to significant frictional forces. It is a very well known fact that the frictional behavior of fibers is important to their performance in carding.



**FIGURE 6:** Staple Pad Friction Test Apparatus on Instron

The test method employed to measure both fiber-fiber and fiber-metal friction test was staple pad friction test. The staple pad friction apparatus can be seen in Fig.6. It is mounted on an Instron Tester and driven by its clamps.

As can be seen in Fig.6, the apparatus consists of a metal plate, a dead weight and a piece of rope (Kevlar was used to obtain minimum elongation). One end of the rope is tied to the upper clamp of Instron and the other end is tied to the dead weight, which sits

on the fiber sample. The metal plate is mounted on top of the lower clamp. By the use of rope, the vertical displacement of clamps is transformed to a horizontal movement.

For the fiber-fiber friction test a piece of sandpaper was stuck on the plate, a fiber sample was put on the sandpaper, which sits on top of the metal plate. Then the dead weight (which is driven by the rope) was located on top of the sample. The test was carried out by dragging the dead weight for a certain amount of time. The frictional characteristics were obtained from the load vs time curve.

A metal piece, whose surface was polished, was used instead of a piece of sandpaper for the fiber-metal friction test. The rest of the test was conducted the same as the fiber-fiber friction test was carried out.

Table 1 shows the results of fiber-fiber friction results for all fibers, whereas Table 2 illustrates fiber-metal friction test results. Data in Table 3 shows the percent finish on fiber, in other words how much finish a given fiber takes.

**TABLE 1:** Fiber/Fiber Staple Pad Friction

Sample ID	Static Friction, g	Dynamic Friction, g	Scroop, g	Average Friction, g	SPF, $\mu$
100% PET	775	540	234	667	0.480
80/20 PET/PP	672	470	203	583	0.419
63/37 PP/PET	721	493	228	617	0.444
100% PP	703	498	205	615	0.442

**TABLE 2:** Fiber/Metal Staple Pad Friction

Sample ID	Average Friction, g	SPF, $\mu$
100% PET	262	0.188
80/20 PET/PP	291	0.209
63/37 PP/PET	275	0.198
100% PP	283	0.203

**TABLE 3:** Percent Finish on Yarn

Sample ID	%FOY
100% PET	0.32
80/20 PET/PP	0.39
63/37 PP/PET	0.33
100% PP	0.48

### 3. FEED MATT PARAMETERS

#### 3.1. Openness

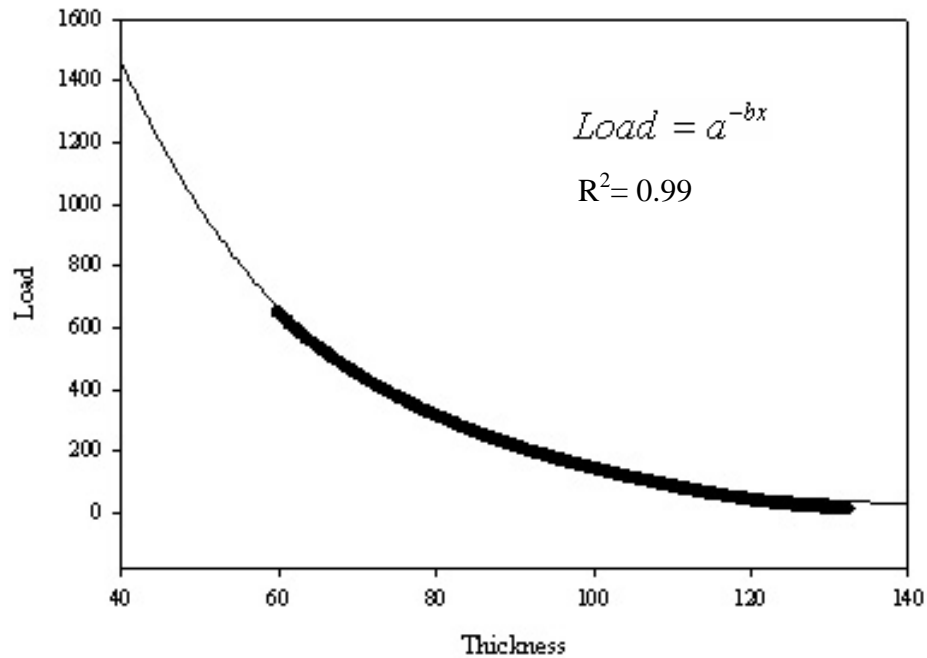
It is believed that the openness of the feed matt has a significant impact in determining the overall quality of the carded web. Oumera [61], in his thesis, explained a method to quantify the openness. According to this procedure, a compression test was performed on the feed matt and the corresponding data was fitted with an exponential curve.

Instron 4450 was used to perform the compression tests. A 50 kg load cell was used. Since the material was very fluffy and extremely hard to handle larger pieces were used for testing instead of cutting smaller samples. A metal board was used to handle the large feed matt samples.



**FIGURE 7:** Compression Tester on Instron

Fig. 7 shows an actual picture of the compression tester that was to perform the tests. A circular head with a 6" diameter was performed the compression test on the samples. For each test, displacement of the crossheads was set at 50 mm/min and the compression test was performed until a final sample thickness of 60 mm. The initial separation between the crossheads was 150 mm, so the sample was compressed 90 mm. Data collection rate was 10 Hz.



**FIGURE 8:** Compression Test Result and Fitted Exponential Curve

Fig.8 shows the actual compression curve obtained along with the fitted exponential curve for a sample. Sample curves for each fiber type and speed are given in the appendix. The equation of the fitted exponential curve is displayed on the graph. It is

believed that the value of the exponent term in the displayed equation is a measure of the openness of the sample. Fit is true only for the range of the experimental data.

## 4. WEB PARAMETERS

### 4.1. Uniformity

Web uniformity tests were performed using image analysis techniques. A flatbed scanner (up to 2400 dpi resolution) and image analysis software were utilized to quantify the mass uniformity of the carded webs. Images of 8x11” carded web samples were taken using the scanner; afterwards the images were prepared for the analysis and analyzed by using the software.

The main idea here is to measure the mass variation of the web using the image of it. The principle of the process is to relate the variations in the local density of an image to the mass uniformity of the sample. Namely, the uniformity index is calculated by relating the local density variations of the image, which are caused by the variation of the web’s mass distribution. The smallest area that the software measures is 1cm<sup>2</sup>. Therefore, depending on the sample size the data population will consist of a certain number of measurements. To determine an index describing the data, it is normalized as follows:

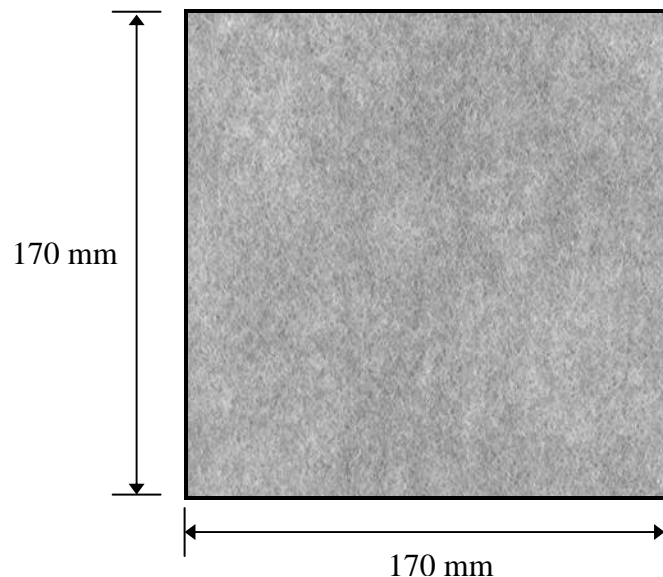
$$\text{Uniformity Index} = \left( 1 - \frac{\sum_{i=2}^{i=n} \chi_i^2}{\sum_{i=2}^{i=n} (N_i - 1) \chi_{\max}} \right) \times 100$$

Where  $\chi_{\max} = 1$

Studies conducted by Pourdeyhimi et al. [62] revealed that a sample size of at least  $10 \times 10 \text{ cm}^2$  is sufficient to represent the whole web, thus determine the uniformity of it. 150 dpi, which is the minimum level of resolution needed to capture the required detail of the sample, was used for the image capturing. The images were resized and centered to eliminate the irregularities of sample edges and equalized to optimize for the uniformity measurement.

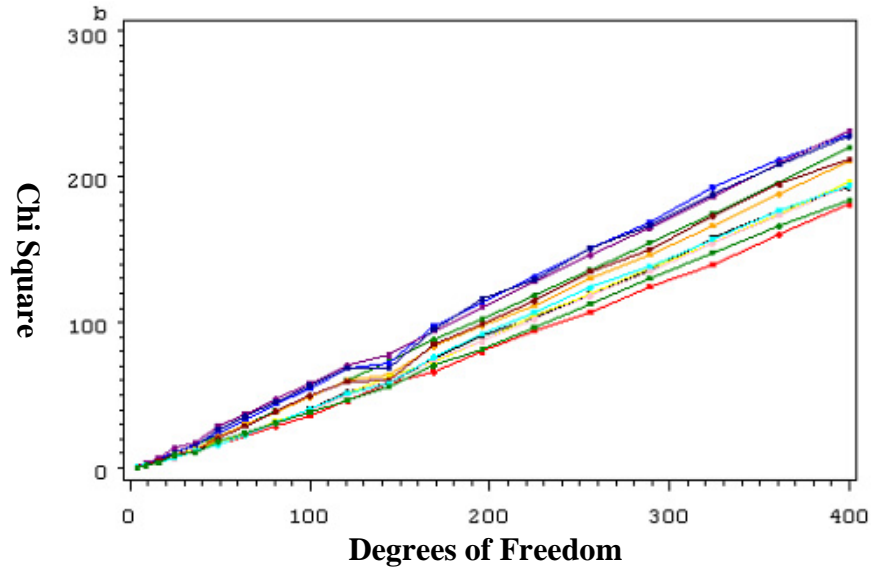
Twelve samples were collected from each run. Therefore, a total of 12 images were captured and analyzed for every run. A sample image is given in Fig.9.

The software gives two types of results; first form is the uniformity index (explained above with the formula), which is essentially a number between 0-100 (100 being most uniform) indicating the degree of uniformity. Second form is the quadrant analysis, which gives a chart that indicates the level of uniformity of the sample. The results can fall into three levels of uniformity, which are defined as clustered, random and uniform.



**FIGURE 9:** Sample Image Used for Uniformity Measurements

An example of a quadrant analysis graph mentioned above can be seen in Fig.10.

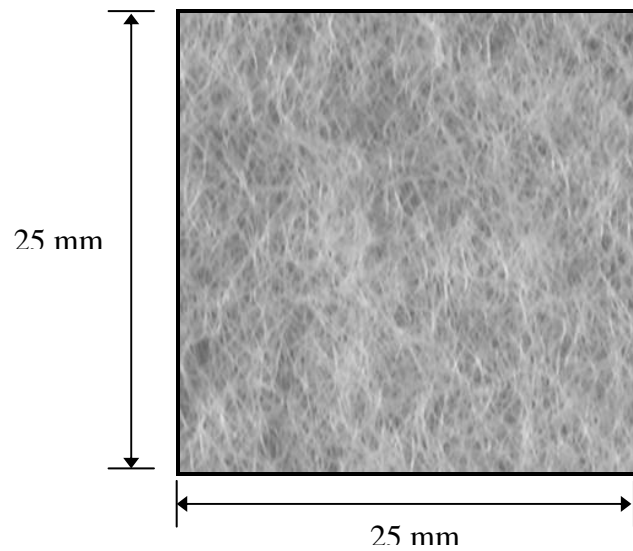


**FIGURE 10:** An Example of a Quadrant Analysis Graph

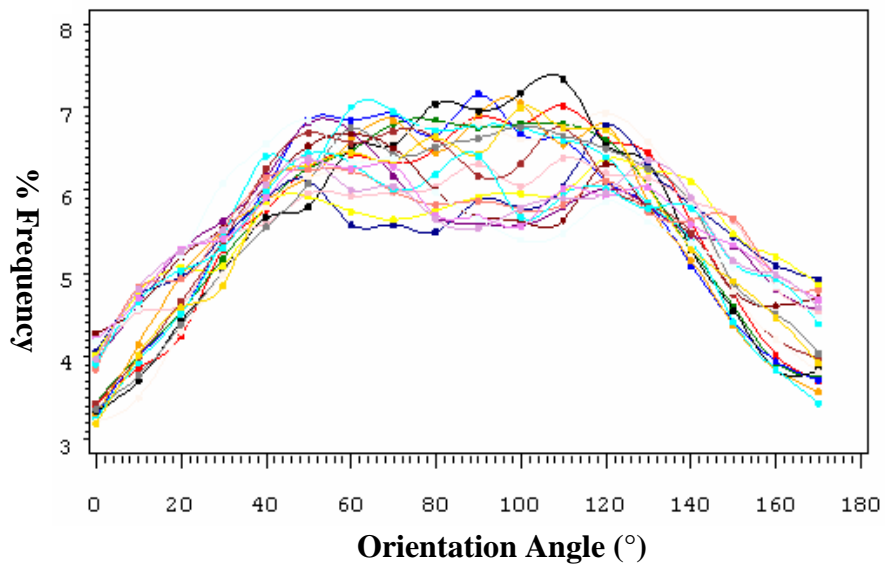
#### 4.2. Fiber Orientation Distribution Function

Fiber orientation distribution measurements were also made using image analysis. The same flatbed scanner and software used for the web uniformity measurements were used for these tests. One important difference is that a much higher resolution is required to be able to measure the fiber orientation, because individual fibers should be seen in the image. For this specific test, 1200 dpi images were used. 5x5" image samples (see in Fig.11) were taken from the web samples and 5 1x1" (1200x1200 dpi) images were taken randomly from each sample by the software to make measurements. The software

performs a Fast Fourier Transform to measure the orientation distribution. Results are illustrated as mean dominant angle of orientation and frequencies of orientation angles as can be seen in Fig.12.



**FIGURE 11:** Sample Image for Fiber Orientation Distribution Function Measurements



**FIGURE 12:** An Example of an ODF Graph

### **4.3. Web Thickness**

Carded web thickness tests were performed using a Nonwoven Thickness Measurement Device, which basically applies a defined amount of pressure on the sample and measures the thickness under that specified force. Since the web samples were stuck on sandpaper, it was necessary to measure the thickness of the sandpaper also. 50 measurements were made for sandpaper and the results showed that it has almost perfect thickness distribution with a mean of 0.2507 mm and 1.61 %CV value. Therefore the effect of sandpaper is neglected. For each run 50 measurements were made.

### **4.4. Web Basis Weight**

Web basis weight has an impact on the output of some of the tests, especially web uniformity test. To compare the uniformity and web thickness, number of fibers per unit area should be the same for all the webs produced using different fiber types. A web with more fiber per unit area should have a higher uniformity level because there are more fibers to cover non-uniform areas. In the same sense, if there are more fibers at a given area the thickness will be higher.

Web basis weights were planned in a way to produce webs, which all have constant number of fibers per unit area. Therefore, it was necessary for this experiment to achieve the desired web basis weights.

Measurements for this purpose were done using a high sensitive (4 decimal points) laboratory scale. 1”x1” samples were cut out of the webs using a die cut to obtain unvarying sample size.

Since the webs were stuck on a piece of sandpaper through a layer of sprayed glue and the uniformity of the sprayed glue was not evenly distributed among the samples, the glue had to be removed from the samples. This procedure also loosens the fibers (web) from the sandpaper and allows them to be collected.

Acetone was used to dissolve the glue from the samples. Individual samples were impregnated in acetone for 10-15 seconds, until the glue was liquefied. Then the loosen fiber were collected. Afterwards samples were left in an open area for 30 minutes to allow the evaporation of the acetone.

Once the acetone was completely vanished, the fiber bundles were weighed. Total of 20 samples were measured for each run. The planned web weights and the actual results are given in Table 4. Data in the table suggest that the actual weights are similar to the planned weights.

**TABLE 4:** Comparison of Planned and Measured Carded Web Basis Weights

	<b>Planned Web Weight (g/m<sup>2</sup>)</b>	<b>Measured Web Weight (g/m<sup>2</sup>)</b>
<b>100%PET-85m/min</b>	30.0	29.4
<b>100%PET-120m/min</b>	30.0	29.5
<b>100%PP-85m/min</b>	19.6	20.9
<b>100%PP-120m/min</b>	19.6	20.8
<b>80/20 PET/PP- 85m/min</b>	27.0	27.6
<b>80/20 PET/PP- 120m/min</b>	27.0	28.3
<b>63/37-85m/min</b>	22.5	21.1
<b>63/37-120m/min</b>	22.5	21.3

## **CHAPTER 4**

**“DATA ANALYSIS”**

**&**

**“RESULTS & DISCUSSION”**

## **1.INTRODUCTION**

Statistical data analyses were carried out using SAS statistical analysis software. Required codes were written to run the analyses. The codes for different applications are given in the appendix. ANOVA was the main analysis technique to be used to compare the means of the data sets, because the main idea was to see any statistically significant similarities or differences among the fiber types and between the two production speeds.

In order to establish an understanding of the inherent variation among the behaviors of different fiber types in the carding process, analyses were conducted to deduce a conclusion from the acquired data.

The main intention of the statistical analyses was to make a comparison among the characteristics of the samples from different fiber types and production speeds. To realize this, the differences in the tested characteristics, which may have been caused by the different fiber behaviors in the carding process, were examined.

## **2. RESULTS and DISCUSSION**

Table 1 shows the results for the experimental speed of 85 m/min. As can be seen from the F test values (p-values from the ANOVA table) web uniformity and ODF do not differ significantly among the experimental fibers. However, as can be seen from Table 2,

when the speed is increased to 120 m/min there is a significant difference in all of the parameters measured.

These results suggest that fiber type has an impact on the processing performance of the fibers. However, the effect of production speed cannot be underestimated. It can be said that a speed fiber interaction effect exists.

**TABLE 1:** Fiber Type Comparison at 85 m/min

85 m/min	100% PET		100% PP		80/20 PET/PP		63/37 PP/PET		F test
	Mean	%CV	Mean	%CV	Mean	%CV	Mean	%CV	
<b>Web Uniformity (index)</b>	50.53	11.14	53.99	9.56	51.05	10.18	53.38	10.47	0.322
<b>ODF (Dominant Angle)</b>	93.51	7.95	92.39	6.26	93.58	3.73	95.06	9.84	0.351
<b>Web Thickness (mm)</b>	3.12	7.67	2.72	8.44	3.47	7.16	2.43	3.52	<. 0001
<b>Feed Matt Openness</b>	2.98	2.54	3.202	5.91	3.696	5.94	3.646	9.73	<. 0001

**TABLE 2:** Fiber Type Comparison at 120 m/min

120 m/min	100% PET		100% PP		80/20 PET/PP		63/37 PP/PET		F test
	Mean	%CV	Mean	%CV	Mean	%CV	Mean	%CV	
<b>Web Uniformity (index)</b>	50.30	9.76	51.76	12.28	42.89	18.48	50.36	8.09	<b>0.0031</b>
<b>ODF (Dominant Angle)</b>	89.06	7.51	97.96	9.20	94.29	3.35	96.93	8.40	<b>0.0003</b>
<b>Web Thickness (mm)</b>	3.41	10.32	2.43	9.16	3.54	11.89	2.34	12.22	<. 0001
<b>Feed Matt Openness</b>	3.188	3.45	3.328	3.36	3.857	11.48	3.637	4.19	<b>0.0006</b>

Table 3 shows the comparison of the data between the two speeds and the p-values of the ANOVA test for all experimental fibers. The aim here is to observe the effect of the speed on measured characteristics. As can be seen from the table, each fiber

type is affected differently by the speed. As a general conclusion, it can be stated that speed itself does not necessarily has an impact on the output characteristics.

**TABLE 3:** Effect of Card Speed on Fiber and Web Parameters

	100% PET			100% PP			80/20 PET/PP			63/37 PP/PET		
	85	120	F test	85	120	F test	85	120	F test	85	120	F test
<b>Web Uniformity</b> (index)	50.53	50.30	0.91	53.99	51.76	0.34	51.05	42.89	<b>0.0007</b>	53.38	50.36	0.19
<b>ODF</b> (Dominant Angle)	93.51	89.06	0.31	92.39	97.96	<b>0.04</b>	93.58	94.29	0.78	95.06	96.93	0.65
<b>Web Thickness</b> (mm)	3.12	3.41	<b>&lt;0.001</b>	2.72	2.43	<b>&lt;0.001</b>	3.47	3.54	0.22	2.43	2.34	0.09
<b>Fiber Modulus</b> (g/den)	93.4	91.2	0.4635	72.72	74.9	0.4200	98.39	99.94	0.5393	58.5	61.2	0.2256
<b>Fiber Strength</b> (g/den)	4.13	4.07	0.5596	5.52	5.49	0.7806	5.06	4.96	0.1166	2.54	2.54	0.9936
<b>Crimp Stability</b> (%)	45.98	47.92	0.3065	56.72	58.20	0.4428	57.31	55.00	0.2904	44.90	33.38	<b>0.0003</b>
<b>Fiber Fineness</b> (denier)	3.04	3.12	0.2124	1.97	1.95	0.4730	2.72	2.74	0.7061	2.52	2.31	0.1475
<b>Remaining Crimp (%)</b>	12.6	13.10	0.4272	11.14	10.03	<b>0.0341</b>	11.46	11.09	0.5955	8.57	5.79	<b>0.0077</b>

Tables 4 and 5 demonstrate a comparison between two fiber types. Namely, two fibers with the same polymer on the surface (100% PET and 63/37 PP/PET Bico both has the same polyester surface) characteristics are compared to see if there is a similarity in the carding performance between the two.

As can be seen from Table 4, 100% PET and 63/37 PP/PET Bico have some similarities at 85 m/min and fewer similarities at 120 m/min. The results suggest that these two fibers do not show a parallel trend and do not necessarily behave similarly in the card.

**TABLE 4:** Comparison Between 100% PET and 63/37 PP/PET Bicomponent

	85 m/min				F test	120 m/min				F test
	100% PET		63/37 PP/PET			100% PET		63/37 PP/PET		
	Mean	%CV	Mean	%CV		Mean	%CV	Mean	%CV	
<b>Web Uniformity (index)</b>	50.53	11.14	53.38	10.47	<b>0.22</b>	50.3	9.76	50.36	8.09	<b>0.98</b>
<b>ODF (Dominant Angle)</b>	92.76	6.67	95.06	9.84	<b>0.12</b>	90.57	7.94	96.93	8.4	0.0046
<b>Web Thickness (mm)</b>	3.12	7.67	2.43	3.52	<.0001	3.41	10.32	2.341	12.22	<.0001
<b>Feed Matt Openness</b>	2.98	2.54	3.646	9.73	<.0001	3.188	3.45	3.637	4.19	0.0024

**TABLE 5:** Comparison Between 100% PP and 80/20 PET/PP Bicomponent

	85 m/min				F test	120 m/min				F test
	100% PP		80/20 PET/PP			100% PP		80/20 PET/PP		
	Mean	%CV	Mean	%CV		Mean	%CV	Mean	%CV	
<b>Web Uniformity (index)</b>	53.99	9.56	51.05	10.18	<b>0.21</b>	51.76	12.28	42.89	18.48	0.0003
<b>ODF (Dominant Angle)</b>	92.39	6.26	93.65	5.69	<b>0.32</b>	97.96	9.2	94.35	3.67	0.0055
<b>Web Thickness (mm)</b>	2.72	8.44	3.46	7.16	<.0001	2.433	9.16	3.54	11.88	<.0001
<b>Feed Matt Openness</b>	3.202	5.91	3.696	5.94	0.0009	3.328	3.36	3.857	11.48	0.0005

**TABLE 6:** ANOVA Results of General Model

Pr > F	General Model	speed	fiber	speed*fiber
Web Uniformity	<b>0.0005</b>	<b>0.0043</b>	<b>0.0034</b>	0.1063
ODF	<b>0.0015</b>	0.3269	<b>0.0004</b>	0.2230
Web Thickness	< <b>0.0001</b>	0.8634	< <b>0.0001</b>	< <b>0.0001</b>

Table 5 illustrates the comparison of 100% PP and 80/20 PET/PP, both of which have polypropylene surfaces. These results also show fewer similarities at the higher

speed. It can be concluded from the both tables that surface characteristics solely do not determine the behavior of the fiber in carding process.

Table 6 is intended to present an overall analysis of the whole data (four fiber types and two production speeds) for web parameters. p-values from the ANOVA test are given in the table. It can be seen from the table that web uniformity is affected by both speed and fiber type. There is a significant fiber type effect on ODF and web thickness. It should also be noted that speed\*fiber type effect exist for web uniformity.

Tables 7, 8, 9, 10 and 11 are intended to show the effects of the carding process on fiber parameters. Therefore, to reveal if such effects exist, the fibers taken from raw material, input matt and output web (at both speeds) are statistically compared.

The results do not prove a clear trend to substantiate the effects of the process on fibers. It is apparent that each fiber type is affected by the carding process and production speed in a different way.

**TABLE 7: Effect of Carding Process on Fiber Strength**

<b>Speed (m/min)</b>	<b>100% PP</b>	<b>63/37 PP/PET</b>	<b>80/20 PET/PP</b>	<b>100% PET</b>
<b>Raw Material</b>	5.66	2.89	5.04	4.54
<b>Card Input</b>	5.62	2.85	5.08	4.45
<b>85</b>	5.52	2.69	5.06	4.13
<b>120</b>	5.49	2.54	4.96	4.07
<b>General Model</b>	0.0818	0.2821	0.2399	<b>&lt;.0001</b>
<b>raw vs. input</b>	0.5687	0.8443	0.5249	0.4021
<b>raw vs. 85</b>	0.0542	0.3282	0.7765	<b>0.0001</b>
<b>raw vs. 120</b>	<b>0.0281</b>	0.0816	0.1974	<b>&lt;.0001</b>
<b>input vs. 85</b>	0.1723	0.4342	0.7247	<b>0.0025</b>
<b>input vs. 120</b>	0.1011	0.1218	0.0555	<b>0.0004</b>
<b>85 vs. 120</b>	0.7806	0.4420	0.1166	0.5596

**TABLE 8:** Effect of Carding Process on Fiber Modulus

Speed (m/min)	100% PP	63/37 PP/PET	80/20 PET/PP	100% PET
<b>Raw Material</b>	75.45	54.60	99.77	95.14
<b>Card Input</b>	74.48	59.80	99.98	92.12
<b>85</b>	72.72	58.04	98.39	93.41
<b>120</b>	74.91	60.34	99.85	91.22
<b>General Model</b>	0.7664	<b>0.0065</b>	0.8977	0.5843
<b>raw vs. input</b>	0.7227	<b>0.0040</b>	0.9276	0.3183
<b>raw vs. 85</b>	0.3152	0.0558	0.5609	0.5607
<b>raw vs. 120</b>	0.8422	<b>0.0015</b>	0.9741	0.1898
<b>input vs. 85</b>	0.5149	0.3223	0.5015	0.6761
<b>input vs. 120</b>	0.8762	0.7688	0.9534	0.7521
<b>85 vs. 120</b>	0.4200	0.1997	0.5393	0.4635

**TABLE 9:** Effect of Carding Process on Remaining Crimp

Speed (m/min)	100% PP	63/37 PP/PET	80/20 PET/PP	100% PET
<b>Raw Material</b>	10.69	8.81	11.27	11.74
<b>Card Input</b>	9.06	7.04	11.38	12.48
<b>85</b>	11.14	8.02	11.46	12.60
<b>120</b>	10.03	6.38	11.09	13.10
<b>General Model</b>	<b>0.0007</b>	<b>0.0087</b>	0.9562	0.1793
<b>raw vs. input</b>	<b>0.0022</b>	<b>0.0202</b>	0.8729	0.2296
<b>raw vs. 85</b>	0.3904	0.2991	0.7830	0.1620
<b>raw vs. 120</b>	0.2025	<b>0.0016</b>	0.7981	<b>0.0295</b>
<b>input vs. 85</b>	<b>0.0001</b>	0.1951	0.9081	0.8420
<b>input vs. 120</b>	0.0666	0.3887	0.6777	0.3210
<b>85 vs. 120</b>	<b>0.0341</b>	<b>0.0317</b>	0.5955	0.4272

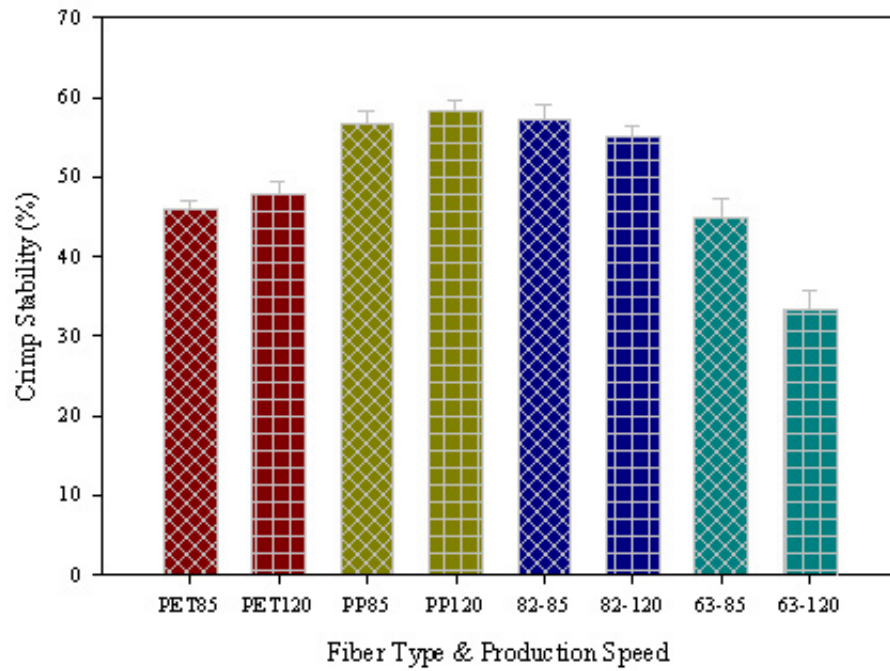
**TABLE 10:** Effect of Carding Process on Crimp Stability

Speed (m/min)	100% PP	63/37 PP/PET	80/20 PET/PP	100% PET
<b>Raw Material</b>	57.04	40.99	59.05	44.73
<b>Card Input</b>	55.77	38.67	58.54	49.76
<b>85</b>	56.72	40.78	57.31	45.98
<b>120</b>	58.20	34.52	55.00	47.92
<b>General Model</b>	0.6567	<b>0.0260</b>	0.2554	<b>0.0465</b>
<b>raw vs. input</b>	0.5138	0.3329	0.8150	<b>0.0087</b>
<b>raw vs. 85</b>	0.8674	0.9304	0.4275	0.5099
<b>raw vs. 120</b>	0.5479	<b>0.0074</b>	0.0657	0.0941
<b>input vs. 85</b>	0.6268	0.3782	0.5755	<b>0.0472</b>
<b>input vs. 120</b>	0.2111	0.0844	0.1072	0.3296
<b>85 vs. 120</b>	0.4428	<b>0.0095</b>	0.2904	0.3065

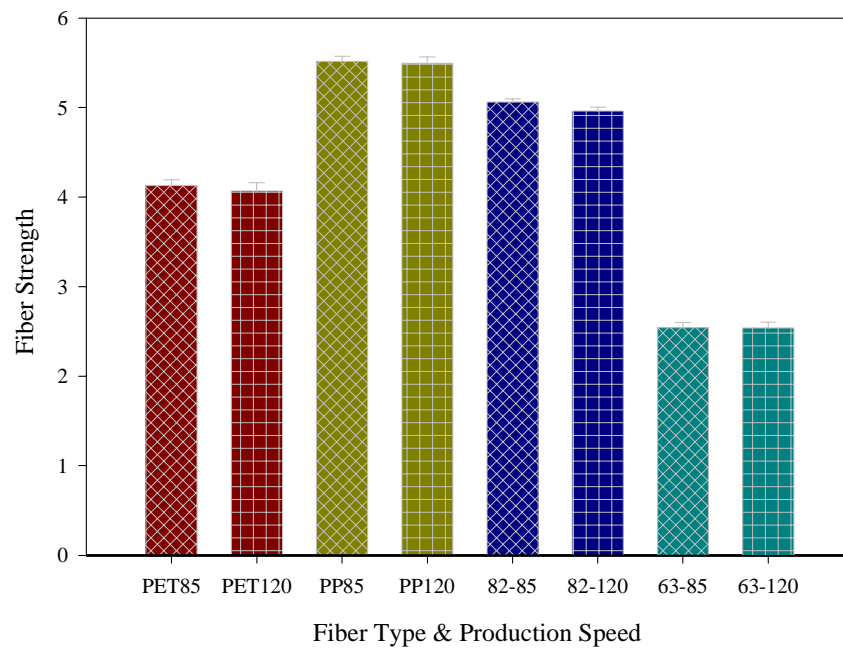
**TABLE 11:** Effect of Carding Process on Fiber Fineness

Speed (m/min)	100% PP	63/37 PP/PET	80/20 PET/PP	100% PET
<b>Raw Material</b>	1.95	2.40	2.70	2.99
<b>Card Input</b>	1.89	2.27	2.78	3.12
<b>85</b>	1.95	2.40	2.72	3.04
<b>120</b>	1.97	2.34	2.74	3.12
<b>General Model</b>	0.0680	0.5920	0.4116	0.1272
<b>raw vs. input</b>	0.0551	0.2313	0.1017	<b>0.0486</b>
<b>raw vs. 85</b>	0.9242	0.9789	0.6120	0.4615
<b>raw vs. 120</b>	0.5334	0.5828	0.3771	<b>0.0486</b>
<b>input vs. 85</b>	0.0680	0.2417	0.2562	0.2124
<b>input vs. 120</b>	<b>0.0117</b>	0.5160	0.4470	1.0000
<b>85 vs. 120</b>	0.4730	0.6011	0.7061	0.2124

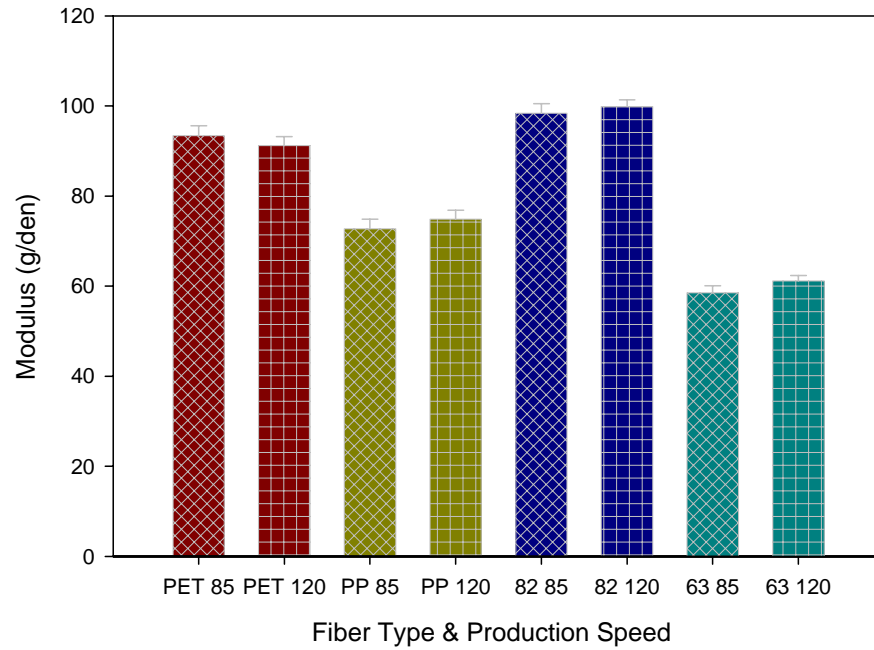
The following error bar graphs are intended to show the mean of the data group and the error within the data group. For each tested parameter a graph is given for four fiber types and two production speeds. Red color represents 100% PET, yellow stands for, 100% PP, blue corresponds to 80/20 (PET/PP) and green represents 63/37 (PP/PET) fiber. Diamond filling is used for 85 m/min and grid filling is used for 120 m/min.



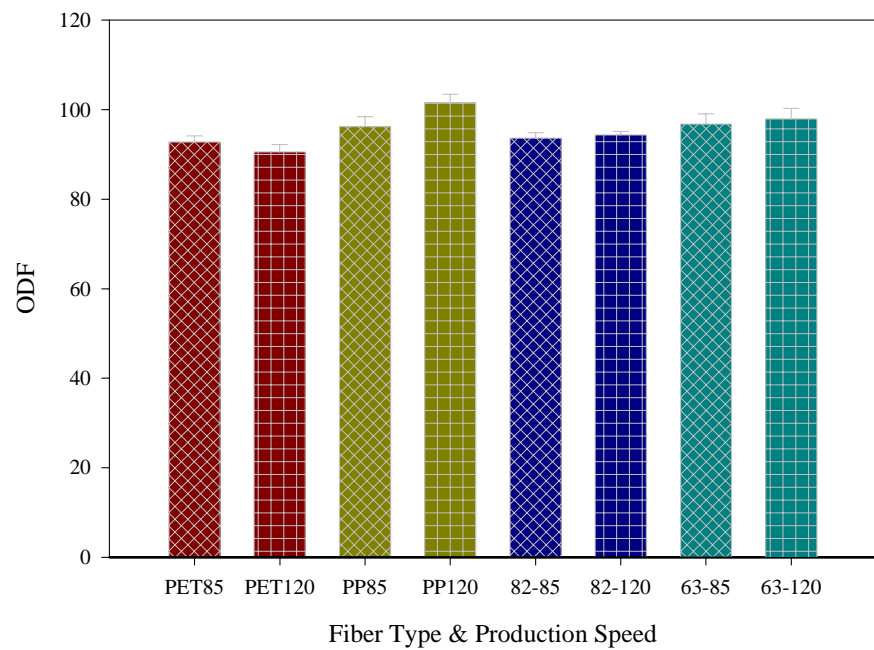
**FIGURE 1:** Error Bar Graph for Crimp Stability Data



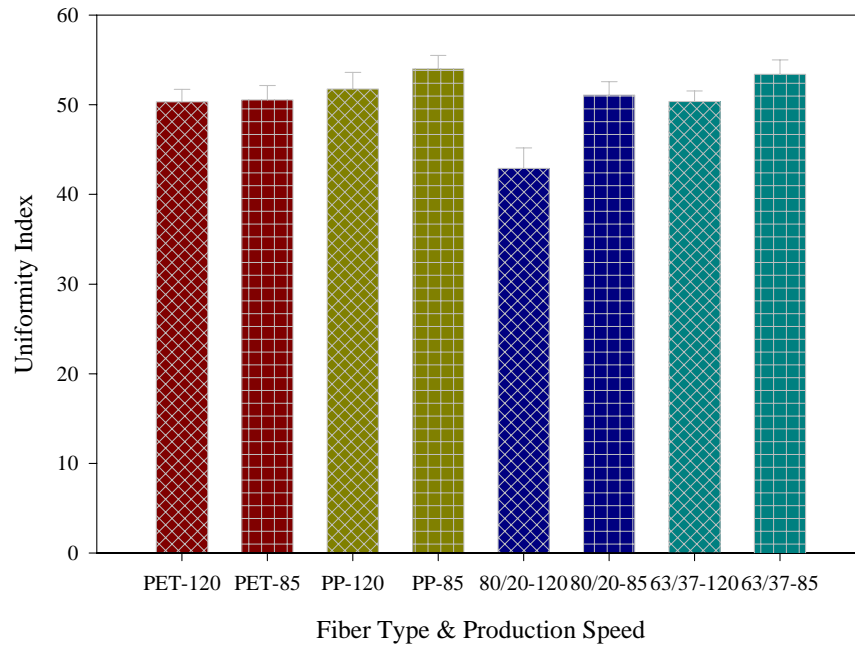
**FIGURE 2:** Error Bar Graph for Fiber Strength Data



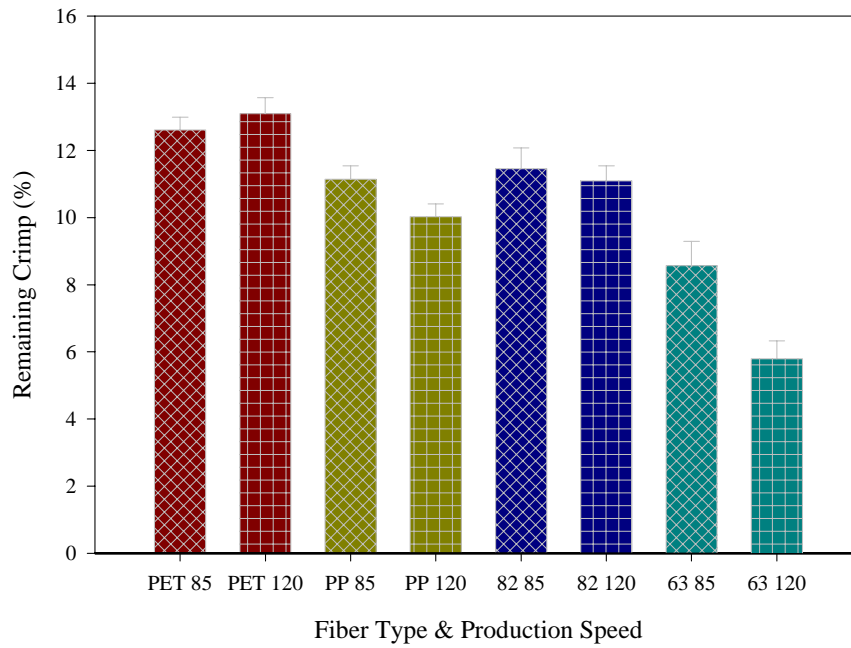
**FIGURE 3:** Error Bar Graph for Fiber Modulus Data



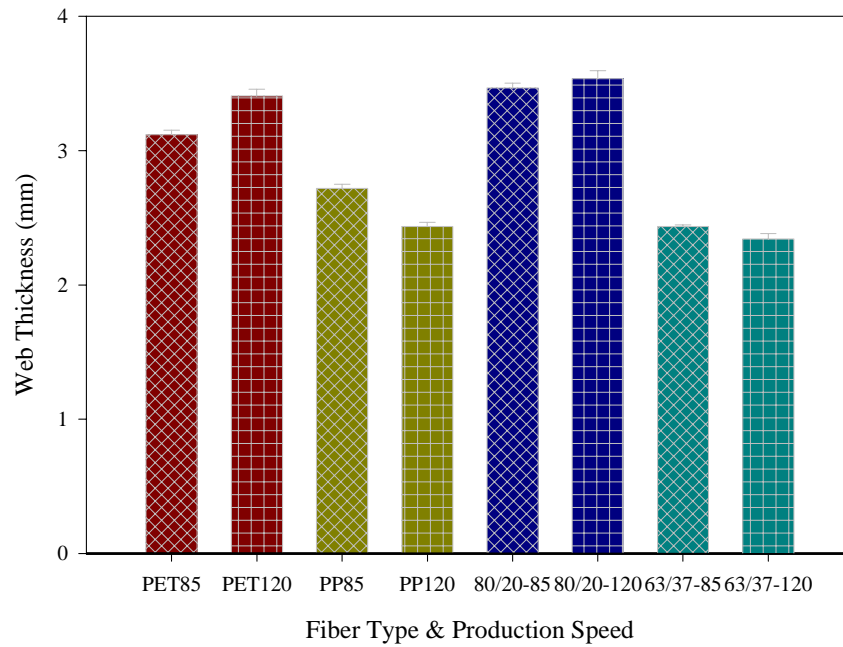
**FIGURE 4:** Error Bar Graph for Orientation Distribution Function Data



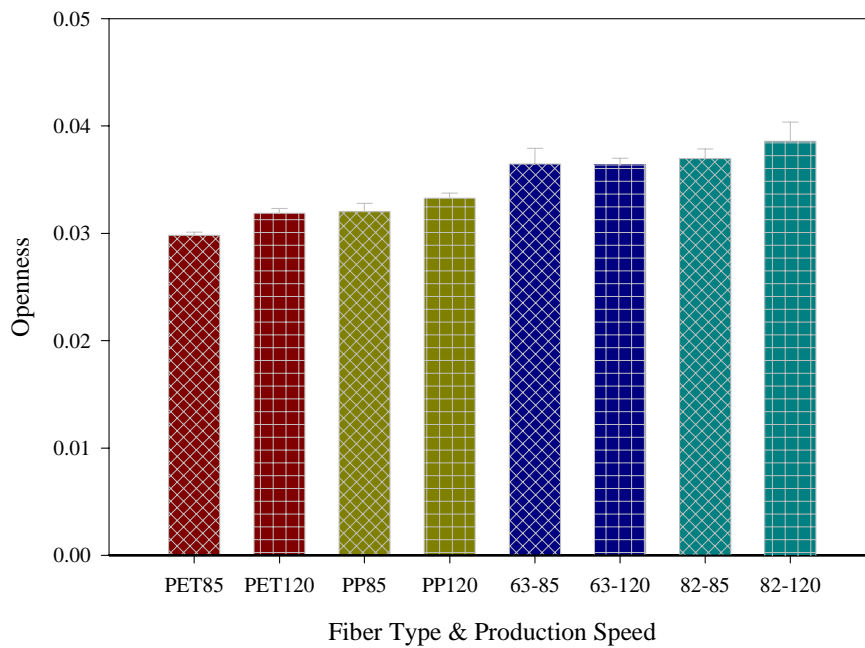
**FIGURE 5:** Error Bar Graph for Web Uniformity Index Data



**FIGURE 6:** Error Bar Graph for Remaining Crimp Data



**FIGURE 7:** Error Bar Graph for Web Thickness Data



**FIGURE 8:** Error Bar Graph for Feed Matt Openness Data

Fig. 1 shows error bar chart for the crimp stability data. As can be seen from the chart, 100% PP has the highest crimp stability values for both test speeds. It should be noted that the mean crimp stability value is higher at the higher speed for fibers: 100% PET and 100% PP. A dramatic decline is seen for the 63/37 PP/PET fiber as the production speed increased.

Fiber strength data is illustrated in Fig.2. Here, it can be clearly seen that 100% PP has the highest strength value amongst all. Another thing that stands out in the chart is the very low strength level of the 63/37 PP/PET Bico fibers. None of the fibers show a change in their strength between the two speeds. Therefore, it can be said that increasing the card speed from 85 m/min to 120 m/min did not significantly affect fiber strength.

Fig. 3 shows the fiber modulus data for both experimental speeds for all fibers. It can be concluded from the graph that there is no speed effect on fibers. In other words, increasing the production speed from 85m/min to 120 m/min did not significantly affect the modulus of fibers. Data also suggest that 100% PP and 63/37 PP/PET fibers have lower modulus values at both speeds.

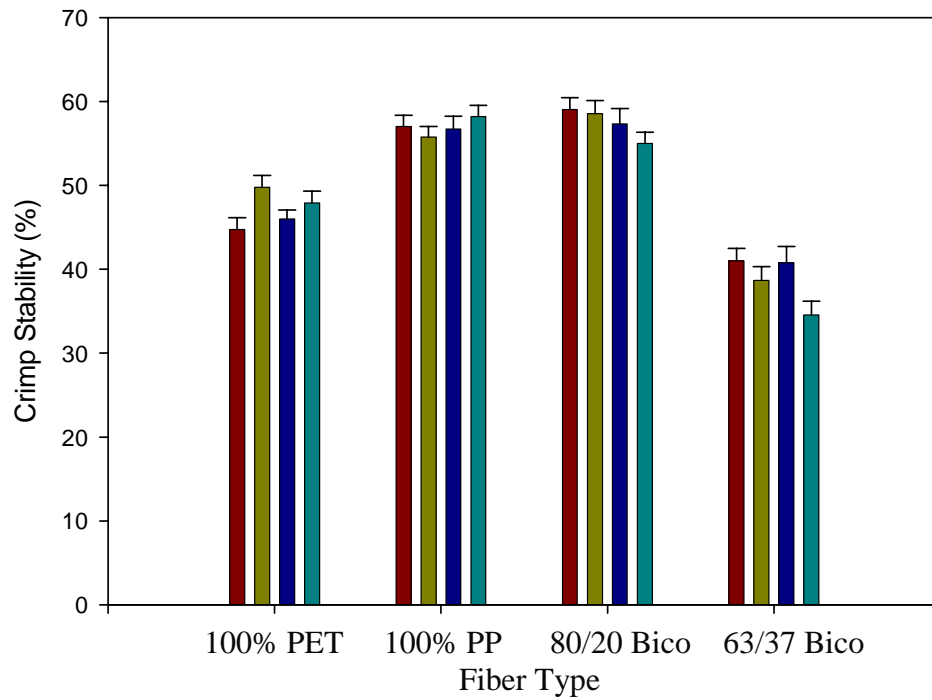
Mean values for the fiber orientation distribution function data are given as a chart in Fig.4. All of the experimental fibers seem to have significantly close mean values. It can be realized from the graph that values for 85 m/min are much closer than those for 120 m/min. Means for 120 m/min seem to have more variation among them. This might be an indication of the effect of carding speed on fiber orientation distribution.

Fig.5 gives the web uniformity results. One of the interpretations of the data can be that bicomponent fibers show a change in the uniformity level when the speed is increased. The interesting thing however is that the uniformity index values are higher at the higher speed. Uniformity values for 100% PET and 100% PP do not seem to change significantly with the change in the card speed.

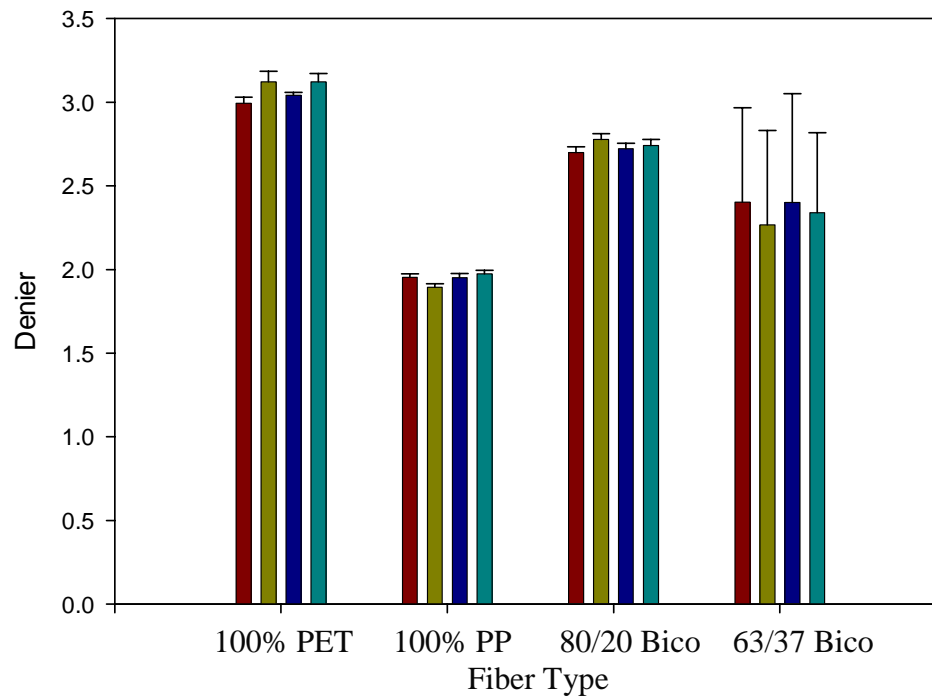
Average remaining crimp values are given in Fig.6. 100% PET seems to have the highest remaining crimp value. In addition 80/20 PET/PP Bico seems to have a higher mean than that of 100% PP. Significant drop in the 63/37 PP/PET data with the increase in the speed should be noticed.

Web thickness data, which is plotted in Fig.7, draw an interesting profile for the experimental fibers. 80/20 PET/PP Bico has the highest thickness value. 100% PET and 80/20 PET/PP Bico shows almost identical profiles. For these two fibers, thickness seems to increase when the speed increases. However, 100% PP and 63/37 PP/PET show a decrease in the thickness with a decrease in the speed. These two fibers also seem to behave almost identical regarding the web thickness values.

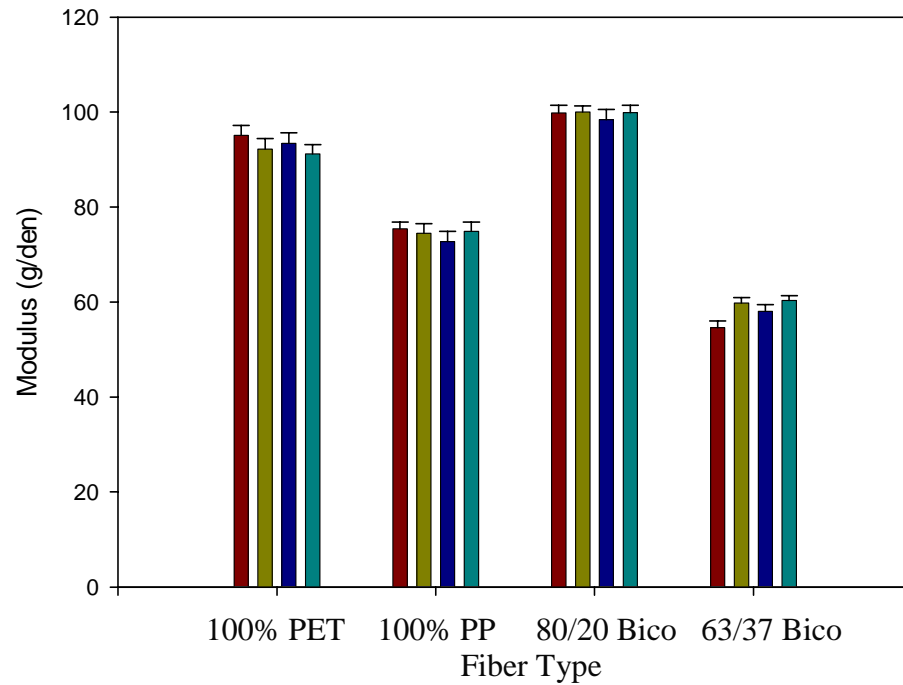
Fig.8 shows the error bars for feed matt openness data. 80/20 PET/PP Bico at 120 m/min seems to have the highest openness value. It is apparent from the chart that bicomponent fibers have higher openness values than the monopolymer fibers. Values seem to increase slightly when the card production speed increases.



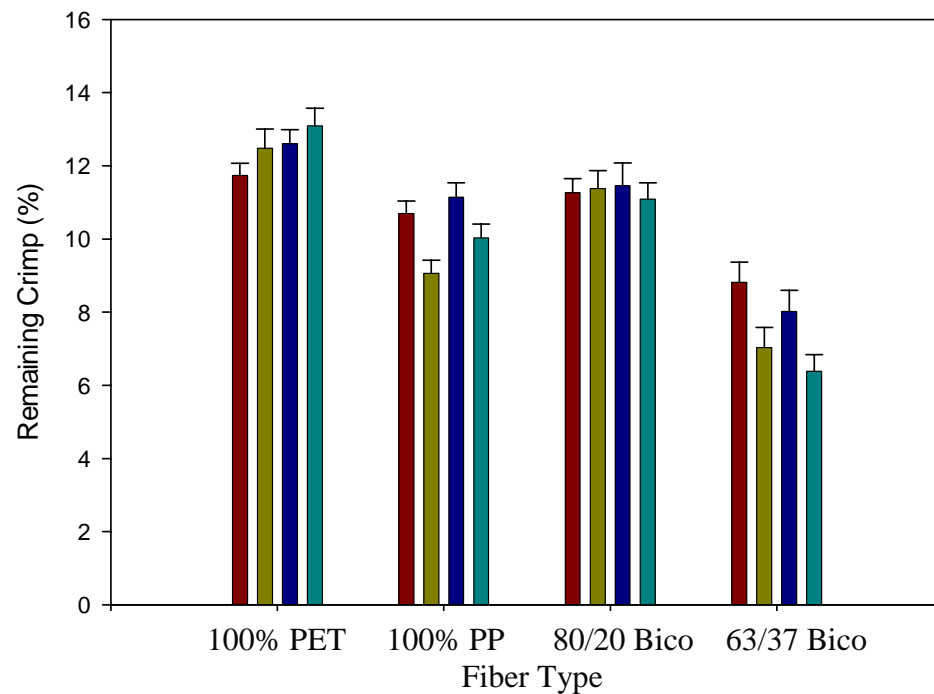
**FIGURE 9:** Error Bar Graph Grouped by Fiber Type for Crimp Stability



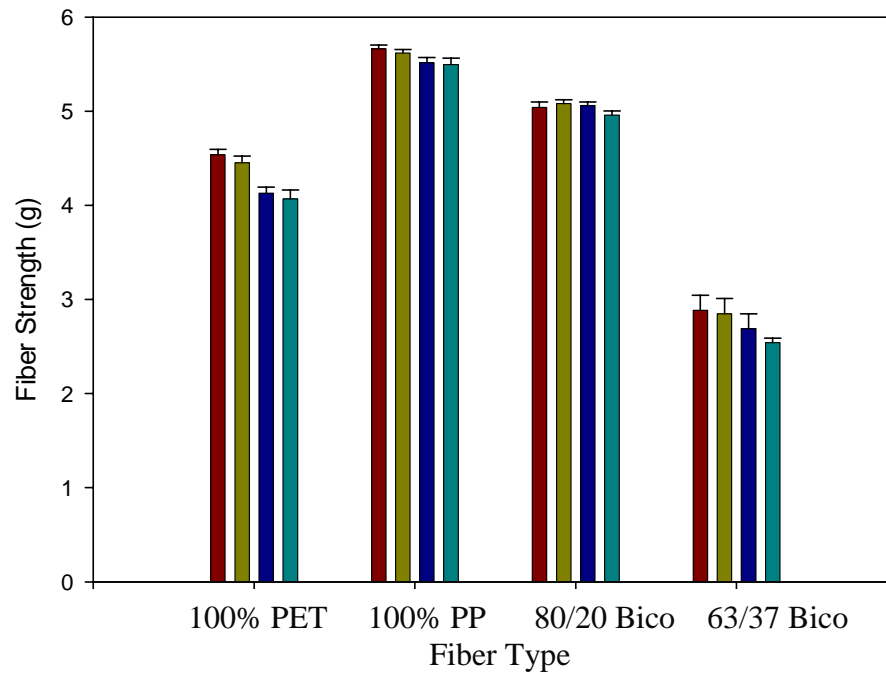
**FIGURE 10:** Error Bar Graph Grouped by Fiber Type for Fiber Fineness



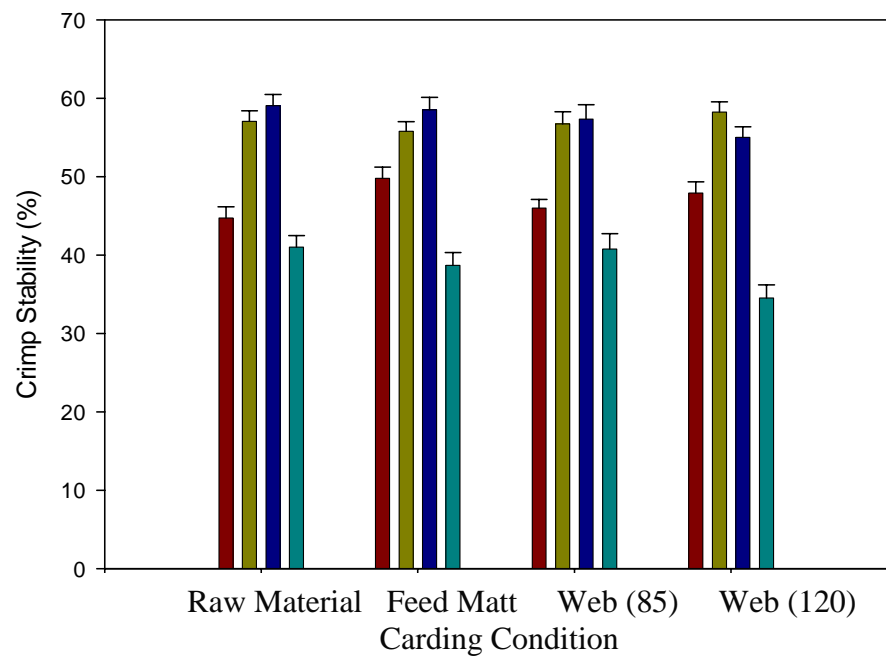
**FIGURE 11:** Error Bar Graph Grouped by Fiber Type for Fiber Modulus



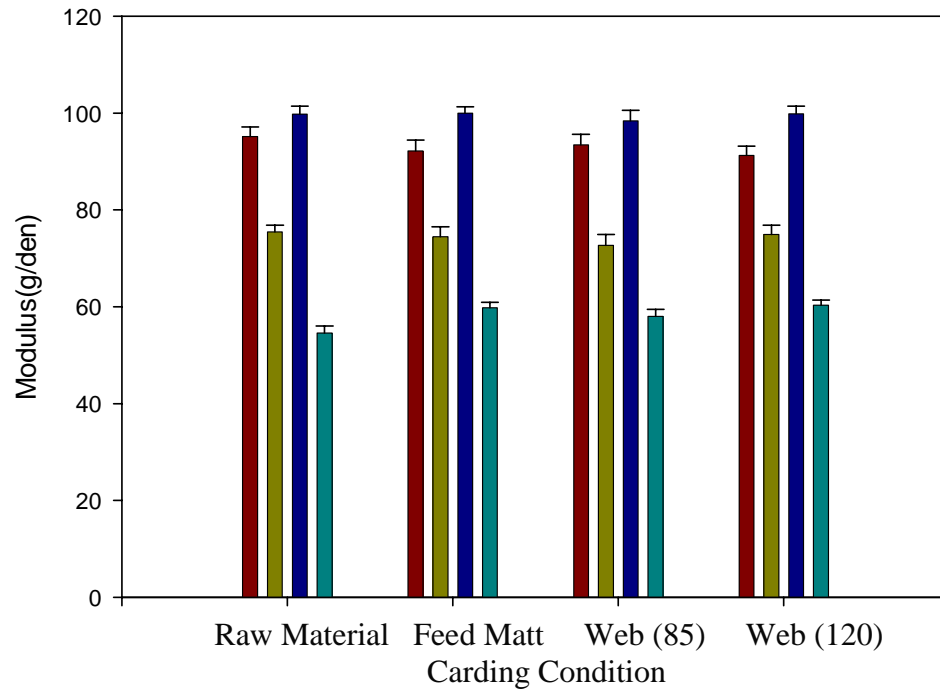
**FIGURE 12:** Error Bar Graph Grouped by Fiber Type for Remaining Crimp



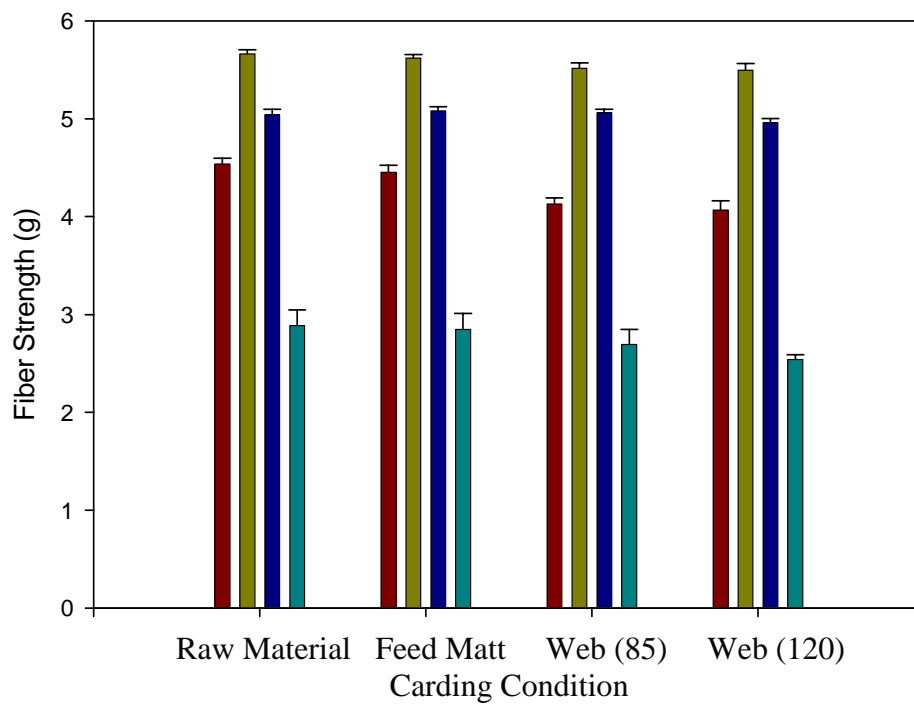
**FIGURE 13:** Error Bar Graph Grouped by Fiber Type for Fiber Strength



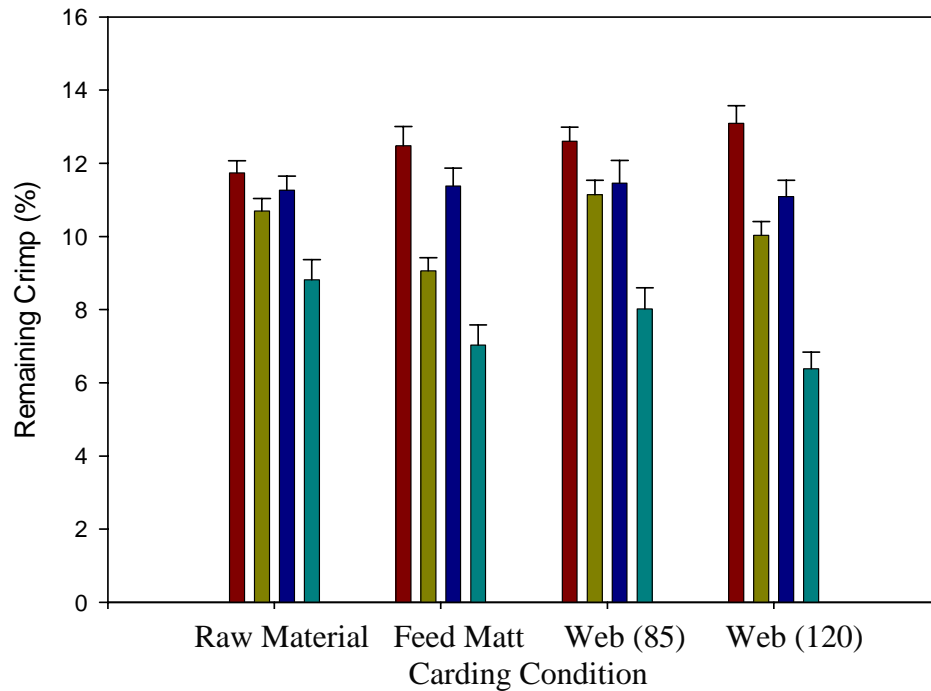
**FIGURE 14:** Error Bar Graph Grouped by Carding Condition for Crimp Stability



**FIGURE 15:** Error Bar Graph Grouped by Carding Condition for Fiber Modulus



**FIGURE 16:** Error Bar Graph Grouped by Carding Condition for Fiber Strength



**FIGURE 17:** Error Bar Graph Grouped by Carding Condition for Remaining Crimp

Figures 9-17 show grouped error bar graphs for measured fiber parameters. Grouping has been done in two ways to reveal the effect of fiber type and the carding process on the measured parameters. For figures 9-13 each designated color shows a carding condition, i.e.: *red*: raw material, *yellow*: feed matt, *blue*: carded web at production speed of 85 m/min, *green*: carded web at production speed of 120 m/min. For figures 14-17 each color illustrates a fiber type, where: *red*: 100% PET, *yellow*: 100% PP, *blue*: 80/20 PET/PP bicomponent, *green*: 63/37 PP/PET bicomponent.

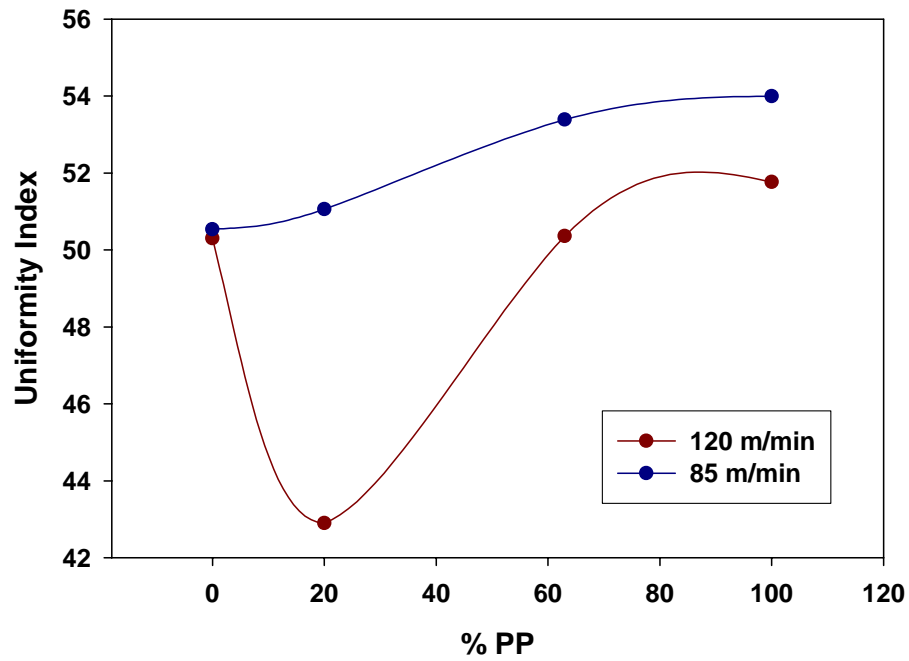
It can be seen from Fig. 9 and Fig. 14 that 100% PP and 80/20 PET/PP bicomponent fibers have higher crimp stability values. It should be noted that 63/37 PP/PET bicomponent fiber seems to be affected by the carding process.

Fig. 10 shows the fiber fineness data. The high variation for the 63/37 PP/PET bicomponent is apparent. However, fineness does not seem to be affected by the carding process for all fibers.

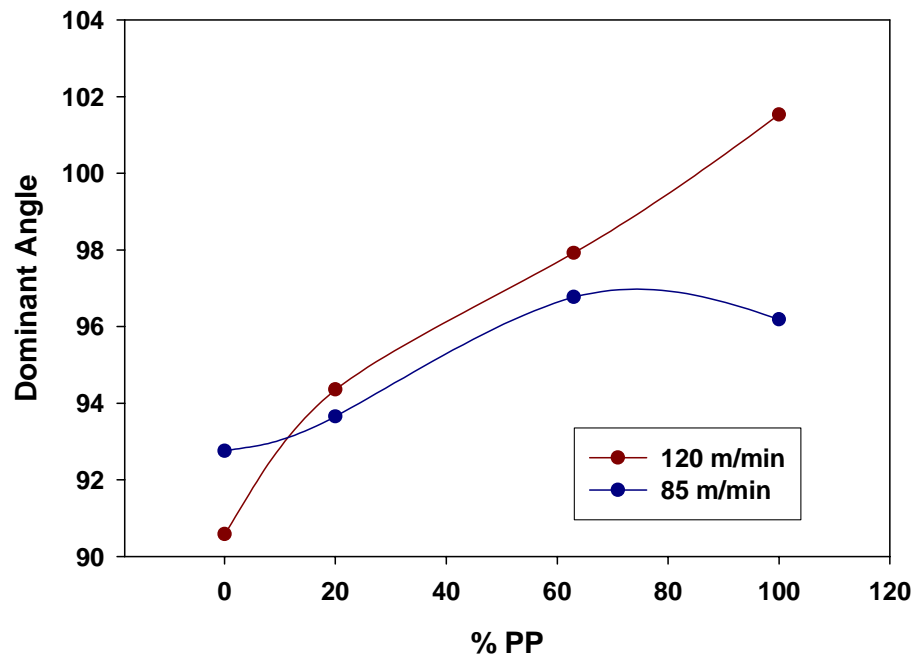
Fiber modulus data is given in Fig. 11 and Fig. 15. It can be deduced from the graph that 80/20 PET/PP bicomponent and 100% PET has higher modulus values. 63/37 PP/PET bicomponent has the lowest modulus among the fibers. It can also be said that the carding process does not affect the modulus of fibers.

It can be inferred from the remaining crimp data given in Fig. 12 and Fig. 17 that 63/37 PP/PET bicomponent fiber has lower value than the rest of the fibers. 100% PP seems to be affected by the carding process.

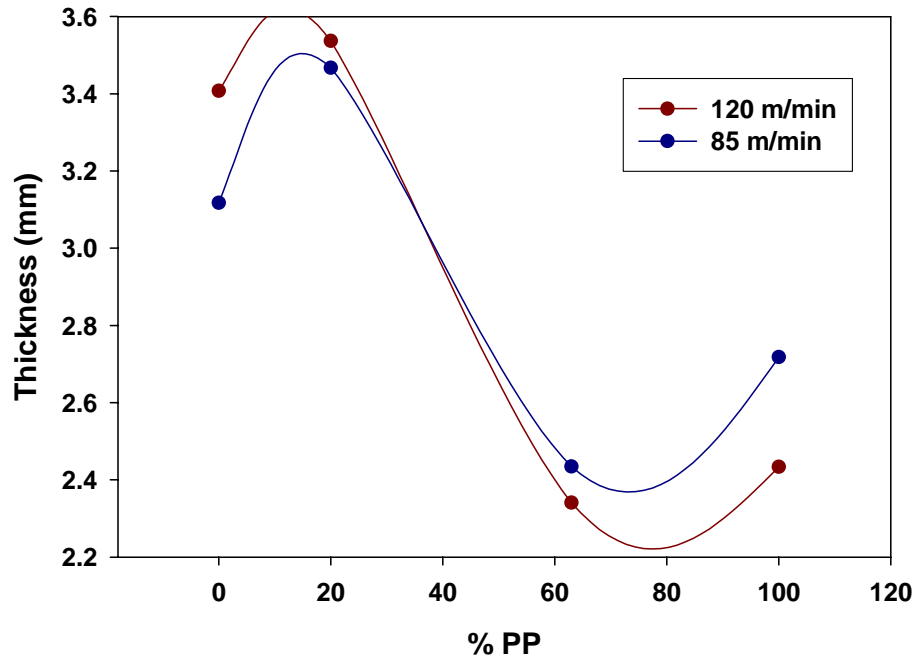
Fiber strength data illustrated in Fig. 13 and Fig. 16 suggest that all experimental fibers have significantly different strength. 100% PP has the highest value among all. Carding process seems to affect the strength of 100% PET and 100% PP.



**FIGURE 18:** Scatter Plot of Web Uniformity Data for All Fibers at Two Speeds



**FIGURE 19:** Scatter Plot of ODF Data for All Fibers at Two Speeds



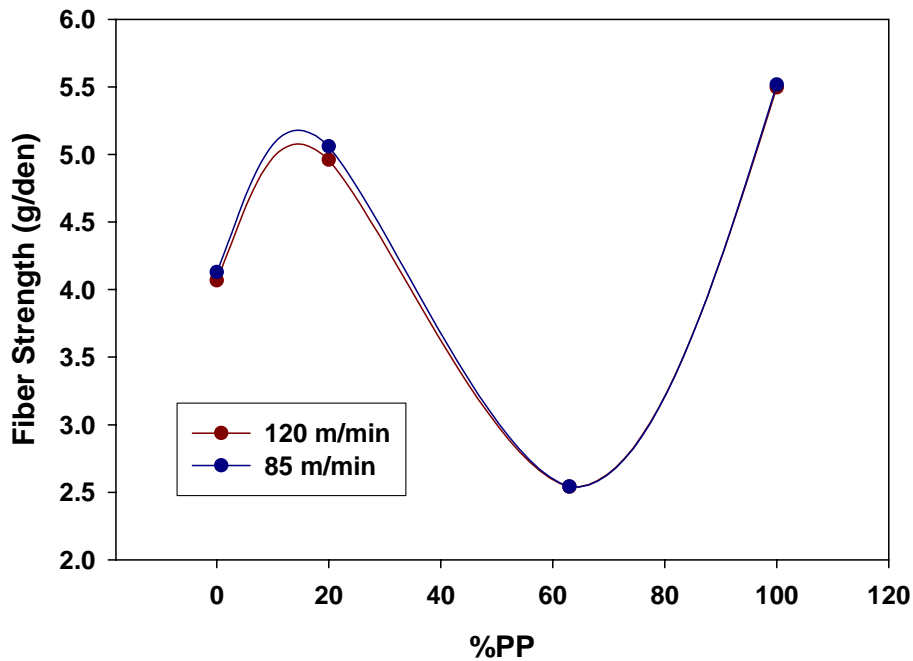
**FIGURE 20:** Scatter Plot of Web Thickness Data for All Fibers at Two Speeds

Scatter plots shown in figures 18-20 are given to illustrate both the effect of fiber type and processing speed on carded web parameters. The x-axis of the graphs shows fiber type. It should be noted that polypropylene content is decreasing from left to right.

As can be seen in fig. 18, web uniformity at 85 m/min does not reveal significant differences among the fiber types; however at production speed of 120 m/min a significant drop in uniformity level for fiber type 80/20 PET/PP is apparent. Another point is to be underlined is the effect of speed on web uniformity. It should be expected to see more significant differences in uniformity with further increment in the speed.

In fig. 19, the distribution of the ODF data suggests that difference in ODF at higher speed is more. In addition, as the ANOVA results support, there is a fiber type effect on fiber orientation distribution.

Fig. 20 shows the distribution of the web thickness data. An interesting point is that the curves for both speeds are almost identical. This can be inferred as an indication of the absence of speed effect on web thickness. However, significant differences are observed among different fiber types. It can be briefly concluded that there is no speed effect on web uniformity, whereas there is fiber type and speed\*fiber type interaction effect.



**FIGURE 21:** Scatter Plot of Fiber Strength Data for All Fibers at Two Speeds

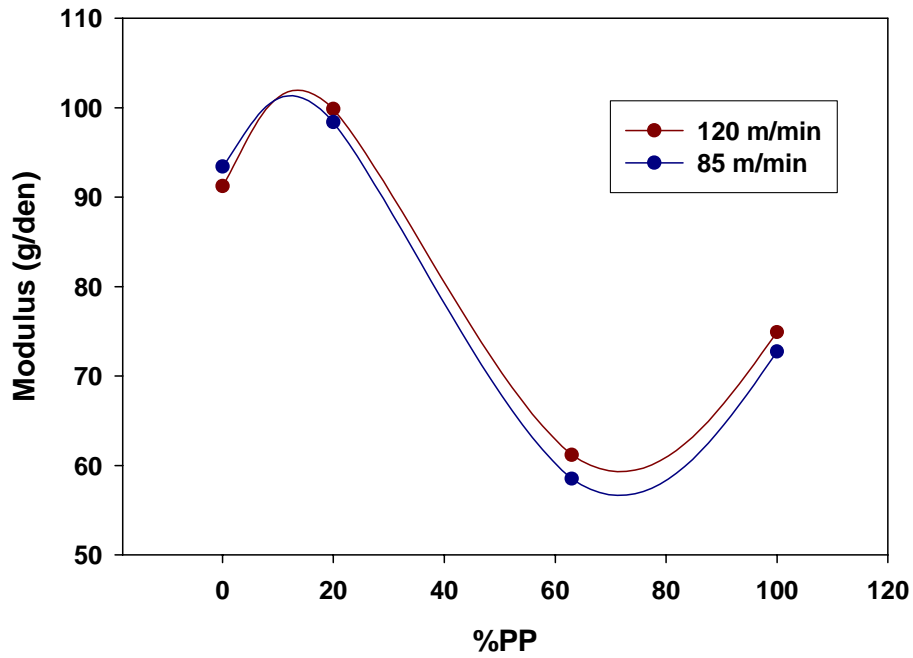


FIGURE 22: Scatter Plot of Fiber Modulus Data for All Fibers at Two Speeds

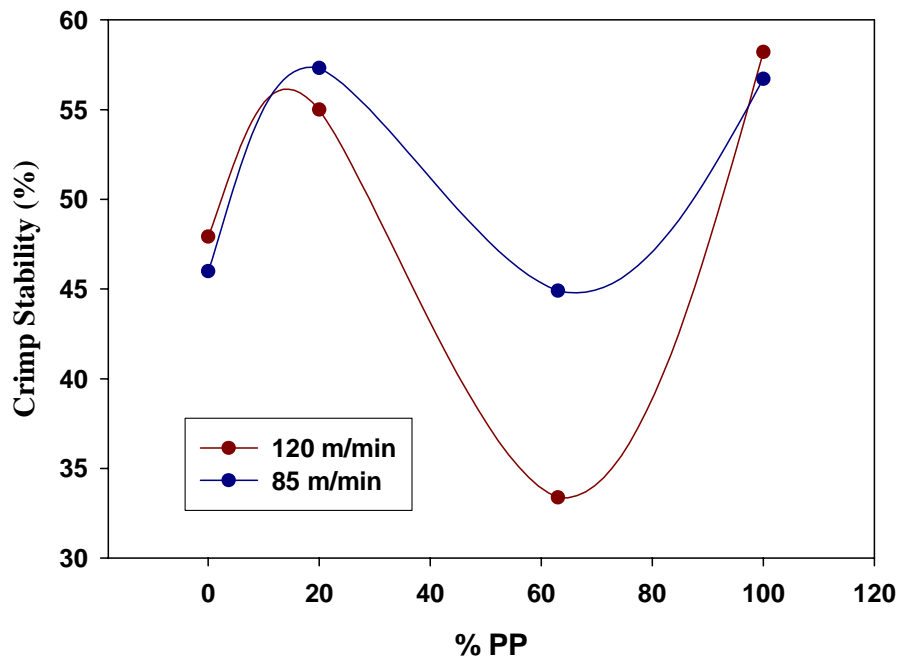
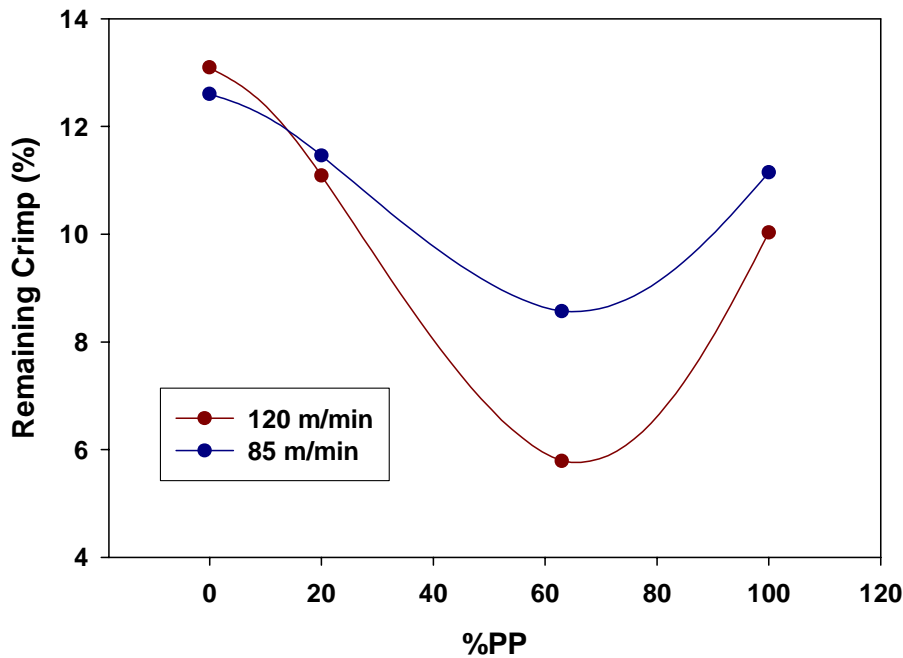


FIGURE 23: Scatter Plot of Crimp Stability Data for All Fibers at Two Speeds



**FIGURE 24:** Scatter Plot of Remaining Crimp Data for All Fibers at Two Speeds

Figures 21-24 illustrate the change in fiber properties with change in the %PP content in a fiber for all experimental fibers at both speeds. Overall, it can be said that a similar trend is observed for all measured parameters. In other words, the %PP content in a fiber seems to affect its properties in a parallel way. This observation reveals the importance of blend ratio of different polymers in a fiber. It can be seen from the graphs that 80/20 PET/PP showed a better performance than 63/37 PP/PET in terms of fiber properties.

Another point to be mentioned is that except for the remaining crimp and crimp stability, there is no speed effect on fiber parameters. For these two parameters only

63/37 PP/PET shows a drop in remaining crimp and crimp stability at 120 m/min. Other than this significant change, the curves for both speeds are almost identical.

If we compare the trends for changes in fiber characteristics and web characteristics, we may be able to explain the differences in web characteristics in terms of fiber parameters.

It can be deduced from the graphs that web thickness and fiber parameters show a similar trend among experimental fibers. Therefore, it can be stated that change in the fibers parameters has a direct effect on web thickness.

However, when we look at the uniformity and ODF graphs, we do not see similar trends. That is to say there must be other reasons behind the differences in these parameters.

**TABLE 12:** Tukey (HSD) Ranking for Web Uniformity at Production Speed of 85 m/min

Web Uniformity at 85 m/min				
	100% PP	63/37 PP/PET	80/20 PET/PP	100% PET
Web Uniformity	A	A	A	A
Fiber Strength	A	D	B	C
Fiber Modulus	B	C	A	A
Crimp Stability	A	B	A	B
Remaining Crimp	A	B	A	A
Web Thickness	C	D	A	B
Feed Matt Openness	B	A	A	B

**TABLE 13:** Tukey (HSD) Ranking for Web Uniformity at Production Speed of 120 m/min

Web Uniformity at 120 m/min				
	100% PP	63/37 PP/PET	80/20 PET/PP	100% PET
Web Uniformity	A	A	B	A
Fiber Strength	A	D	B	C
Fiber Modulus	C	D	A	B
Crimp Stability	A	C	A	B
Remaining Crimp	B	C	B	A
Web Thickness	B	B	A	A
Feed Matt Openness	B/C	A/B	A	C

**TABLE 14:** Tukey (HSD) Ranking for Fiber Orientation Distribution at Production Speed of 85 m/min

Fiber Orientation Distribution at 85 m/min				
	100% PP	63/37 PP/PET	80/20 PET/PP	100% PET
ODF	A	A	A	A
Fiber Strength	A	D	B	C
Fiber Modulus	B	C	A	B
Crimp Stability	A	B	A	B
Remaining Crimp	A	B	B	A
Web Thickness	C	D	A	A
Feed Matt Openness	B	A	A	C

**TABLE 15:** Tukey (HSD) Ranking for Fiber Orientation Distribution at Production Speed of 120 m/min

Fiber Orientation Distribution at 120 m/min				
	100% PP	63/37 PP/PET	80/20 PET/PP	100% PET
ODF	A	A/B	B/C	C
Fiber Strength	A	D	B	C
Fiber Modulus	C	D	A	B
Crimp Stability	A	C	A	B
Remaining Crimp	B	C	B	A
Web Thickness	B	B	A	A
Feed Matt Openness	B/C	A/B	A	C

Tables 12 and 13 show results of Tukey honest significant difference (HSD) test, where web uniformity is regarded as the main parameter to be examined. Table 12 shows the parameters ranking listed against web uniformity at 85 m/min. The intention here is to observe effects of fiber parameters on the level of web uniformity. It is desired to note any trends that show similarities with the web uniformity trend.

Tables 14 and 15 illustrate the Tukey (HSD) test results for ODF as the main parameter. Table 14 is prepared for data from 85m/min and table 15 shows data for 120m/min.

**TABLE 16:** % Values Of Fiber Characteristics Compared To Raw Material and Listed Against Ranked Web Uniformity At 85 m/min

Web Uniformity at 85m/ min				
	100%PP	63/37 PP/PET	80/20 PET/PP	100%PET
Web Uniformity	53.99	53.38	51.05	50.53
Fiber Strength	%97.42	%93.27	%100.36	%90.98
Fiber Modulus	%96.39	%106.30	%98.61	%98.18
Crimp Stability	%99.43	%99.49	%97.06	%102.79
Remaining Crimp	%104.20	%91.04	%101.70	%107.41

**TABLE 17:** % Values Of Fiber Characteristics Compared To Raw Material and Listed Against Ranked Web Uniformity At 120 m/min

Web Uniformity at 120m/min				
	100%PP	63/37 PP/PET	80/20 PET/PP	100%PET
Web Uniformity	51.76	50.36	42.89	50.30
Fiber Strength	%97.04	%87.97	%98.37	%89.64
Fiber Modulus	%99.29	%110.51	%100.08	%95.88
Crimp Stability	%102.04	%84.22	%93.14	%107.12
Remaining Crimp	%93.75	%72.41	%98.42	%111.60

**TABLE 18:** % Values Of Fiber Characteristics Compared To Raw Material and Listed Against Ranked ODF At 85 m/min

ODF at 85 m/min				
	100%PP	63/37 PP/PET	80/20 PET/PP	100%PET
ODF	96.19	96.77	93.65	92.76
Fiber Strength	%97.42	%93.27	%100.36	%90.98
Fiber Modulus	%96.39	%106.30	%98.61	%98.18
Crimp Stability	%99.43	%99.49	%97.06	%102.79
Remaining Crimp	%104.20	%91.04	%101.70	%107.41

**TABLE 19:** % Values Of Fiber Characteristics Compared To Raw Material and Listed Against Ranked ODF At 120 m/min

ODF at 120m/min				
	100%PP	63/37 PP/PET	80/20 PET/PP	100%PET
ODF	101.53	97.92	94.35	90.58
Fiber Strength	%97.04	%87.97	%98.37	%89.64
Fiber Modulus	%99.29	%110.51	%100.08	%95.88
Crimp Stability	%102.04	%84.22	%93.14	%107.12
Remaining Crimp	%93.75	%72.41	%98.42	%111.60

Tables 16 and 17 give the percent values of the measured fiber parameters compared to the raw material characteristics. In other words, these data show how much the carding process affected the fiber properties. These data also listed against web uniformity for both speeds to reveal any relation between the change in the fiber parameters and degree of web uniformity.

Tables 18 and 19 are prepared to illustrate the effect of change in the fiber parameters to the degree of fiber orientation distribution for both experimental speeds.

## **CHAPTER 5**

### **“CONCLUSIONS & FUTURE WORK”**

## 1. CONCLUSIONS

Data resulted from the testing part of the research are given in the previous chapter. Data analysis was based on the comparison of the data group means. Main intention when conducting the data analysis was to observe the effect of fiber type on the output quality. Web uniformity was the main parameter that was to be investigated. Fiber orientation distribution function is another important output characteristic that was observed. For each experimental speed, the measured responses for all fiber types were ranked by means of Tukey (HSD) test.

A general model, which includes all data from all fiber types and both speeds, was run for each output parameter to observe the overall picture. As can be seen in table 6 in chapter 4, general model suggest significant differences for all measured web parameters. The results suggest speed and fiber type effect on web uniformity, fiber type effect on ODF and fiber type and speed\*fiber type effect on web thickness.

Further and more specific analyses of the data revealed detailed information on the effect of fiber type at different speeds and the effect of speed for each fiber type.

Web uniformity measurements revealed that, at 85 m/min there was no statistically significant difference in web uniformity among the fibers. However at 120 m/min, 80/20 PET/PP fiber type produced significantly less uniform web.

However there were no statistically significant differences for web uniformity among the fiber types, it can be seen from the tables that for both production speeds, 100% PP produced more uniform webs.

It should be emphasized that the following statements in the paragraph are not statistically valid. It can be said that fiber types with lower modulus values have higher uniformity levels. It can also be stated that the fibers, which have the two highest uniformity levels have significantly lower web thickness values than the other two experimental fibers. For production speed of 120m/min, with a decrease in the uniformity level, fiber orientation distribution values are also declines. It can be seen from the results that, fibers that have the highest and the lowest fiber/fiber and fiber/metal coefficient of friction values, which are 100% PET and 80/20 PET/PP bicomponent, resulted in less uniform webs. It may be an indication that extreme frictional characteristics have a detrimental effect on carded web uniformity. 100% PP and 63/37 PP/PET bicomponent fibers have very similar frictional characteristics; especially for fiber/fiber friction and they produced a more uniform web.

Tables 14 and 15 in the previous chapter show the ranking for the fiber orientation distribution function. It can be deduced from the tables that ODF did not differ significantly among the experimental fibers at production speed of 85 m/min. On the other hand, it should be noted that, there are significant differences at 120 m/min.

However not being statistically valid, the trend with the low modulus and web thickness values can also be observed for the fiber orientation distribution. In explanation, fiber orientation distribution seems to be higher for fiber types with lower fiber modulus and web thickness values.

Another factor that was investigated was the effect of carding process on the fiber properties. As the results, which are given in the previous chapter in tables 7, 8, 9, 10 and 11 suggest the carding process affects some of the fiber parameters. However, an interesting note is that the differences in the responses for the bicomponent fibers are fewer.

The effect of production speed on the measured responses was another factor that was studied. Table 3 in the previous chapter shows the results of ANOVA test that was run in order to reveal the differences in the measured parameters between the two experimental speeds. It can be realized from the table that some parameters have been affected by an increment in the speed. There is no clear evidence to conclude that an increase in the production speed affects the output and fiber parameters.

Tables 4 and 5 in chapter 4 illustrate the p-values of the ANOVA tests that were conducted to understand the similarities between the experimental fibers with the same surface structure. In other words, two fibers with the same polymer on the surface were compared. As can be seen in table 4, web uniformity does not significantly differ between 100% PET and 63/37 PP/PET PP at both speeds. Table 5 shows that crimp stability and remaining crimp does not differ significantly at both speeds between 100% PP and 80/20 PET/PP bicomponent fibers. In addition, web uniformity and ODF values are not significantly different for these fibers at 85 m/min.

When we look at the scatter plots, we can see a similar trend between the fiber parameters and web thickness, suggesting that a change in web thickness may be due to

change in the fiber parameters. However, the same resemblance cannot be seen in web uniformity and ODF. Therefore, it can be concluded that output web quality does not necessarily determined by fiber properties. Frictional properties of fibers have more significant effects on web quality.

## **2. FUTURE WORK**

This study was meant to be a starting point for the future studies. Further investigations are needed to achieve concrete results about the effects of fiber type on carding performance. Some of the recommendations for future studies can be summarized and listed as follows:

- ◆ Include study of micro and macro fiber structure.
- ◆ Use a high-speed card for the experiments.
- ◆ Measure temperature at various parts of the card.
- ◆ High-speed photography of the cylinder-doffer transfer point.

Since the main question that has been tried to be answered through this study addresses high-speed carding conditions around 500 m/min, utilization of a card, which can be run at such speeds, would be very beneficial and logical. The idea of fixing the diameter should be preserved, because of the fact that it allows to create fixed carding conditions for different fiber types.

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## APPENDIX

TABLE 1: Sample SAS Code and ANOVA Table for Factorial Analysis

```

Data webthickness;
Input speed $ fiber $ @;
Title '1';
Do rep=1 to 50;
Input yield @;
X=85*(speed='s85')+ 120*(speed='s120');
Y1=(fiber='fpet'); y2=(fiber='fpp'); y3=(fiber='82bc'); y4=(fiber='63bc');
Output; end;
Cards;
S85 fpet 3.625 3.185 3.052 3.970 3.539 3.610 2.985 3.142 3.456 2.974
      2.929 3.117 3.072 2.929 3.117 3.072 3.097 3.104 3.064 3.179 3.004
      3.188 3.146 3.052 3.169 3.139 3.406 2.756 2.693 2.858 3.091 2.694
      3.151 2.908 2.970 3.160 3.168 3.336 2.976 3.136 2.839 3.192 3.068
      3.012 3.084 2.952 2.878 3.484 2.964 3.203
S85 fpp 2.572 2.905 2.611 2.784 2.729 2.840 2.879 2.685 2.840 2.699
      2.769 2.702 2.571 2.785 2.891 3.003 2.983 3.023 3.300 3.233 3.182
      3.110 2.462 2.424 2.386 2.563 2.813 2.928 2.823 2.775 2.510 2.602
      2.462 2.567 2.486 2.439 2.402 2.367 2.480 2.522 2.462 2.609 2.539
      2.612 2.862 2.736 2.719 2.648 2.613 2.980
S85 82bc 3.190 3.163 3.465 3.430 3.502 3.480 3.153 3.216 3.658 3.446
      3.718 3.539 3.486 3.230 3.678 3.477 3.510 3.360 3.268 3.626 3.136
      3.212 3.054 3.109 3.142 3.033 3.011 3.153 3.646 3.722 3.561 3.816
      3.729 3.735 3.733 3.740 3.724 3.524 3.632 3.776 3.597 3.704 3.712
      3.709 3.479 3.420 2.930 3.736 3.651 3.647
S85 63bc 2.431 2.409 2.463 2.460 2.333 2.548 2.529 2.362 2.567 2.524
      2.594 2.470 2.545 2.388 2.508 2.579 2.351 2.348 2.450 2.446 2.357
      2.434 2.426 2.428 2.447 2.439 2.418 2.560 2.418 2.397 2.462 2.448
      2.556 2.435 2.321 2.350 2.380 2.225 2.364 2.364 2.377 2.374 2.265
      2.287 2.452 2.378 2.452 2.600 2.485 2.501
S120 fpet 3.424 2.848 3.137 3.524 3.518 3.558 3.535 3.512 3.428 3.489
      2.808 2.804 3.591 3.947 3.900 3.936 3.797 3.504 3.766 3.696 3.652
      3.804 3.359 3.518 3.109 2.847 2.910 3.558 3.447 3.102 2.790 3.202
      3.688 2.782 3.057 3.730 3.205 2.902 2.980 3.126 3.098 3.450 3.539
      3.668 3.329 3.458 3.818 3.848 3.985 3.692
S120 fpp 2.358 2.378 2.381 2.441 2.486 2.450 2.479 2.464 2.446 2.352
      2.482 2.468 1.986 2.164 1.823 2.055 2.425 2.569 2.544 2.672 2.787
      2.851 2.830 2.905 2.173 2.378 2.568 2.536 2.582 2.457 2.652 2.676
      2.500 2.481 2.501 2.576 2.464 2.512 2.190 2.129 2.155 1.982 2.120
      2.293 2.552 2.481 2.516 2.519 2.446 2.442
S120 82bc 4.042 3.860 3.853 3.974 3.961 4.001 2.785 3.849 3.808 3.735
      3.833 3.748 3.725 3.801 3.859 3.723 3.816 3.752 3.700 3.711 3.666
      3.532 3.747 3.774 3.716 3.737 3.789 3.784 3.569 3.556 2.690 2.555
      2.568 2.963 3.481 3.580 3.549 3.799 2.856 3.795 3.536 3.798 3.692
      3.689 2.579 3.032 3.120 2.661 3.190 3.284
S120 63bc 2.382 2.423 2.431 2.500 2.512 2.587 2.613 2.537 2.494 2.477
      2.538 2.432 2.523 2.603 2.550 2.570 2.539 2.547 2.446 2.531 2.524
      2.460 2.409 2.342 2.303 2.223 2.330 2.537 2.568 2.521 2.489 2.362
      2.466 2.224 1.654 2.212 1.693 1.735 1.624 1.792 2.397 2.458 2.322
      2.354 2.429 2.422 2.204 2.439 1.686 1.615
;
Proc means data=webthickness noprint nway; var yield; class speed fiber;
Output out=out1 mean=meanyield; proc print;
Proc gplot; plot meanyield*fiber=speed/haxis=axis1;
Axis1 offset=(4,4);
Symbol1 v=dot c=red i=needle;

```

```

Symbol2 v=dot c=green i=none; run;
Proc glm data=webthickness;
Class speed fiber; model yield=speed fiber speed*fiber;
Lsmeans speed*fiber/slice=speed;
Lsmeans speed*fiber/slice=fiber;
Contrast 'fpet vs 82bc in s85' fiber 0 -1 1 0 speed*fiber 0 0 0 0 0 -1 1 0;
Contrast 'fpet vs 63bc in s85' fiber -1 0 1 0 speed*fiber 0 0 0 0 -1 0 1 0;
Contrast 'fpet vs 82bc in s120' fiber 0 -1 1 0 speed*fiber 0 -1 1 0 0 0 0 0;
Contrast 'fpet vs 63bc in s120' fiber -1 0 1 0 speed*fiber -1 0 1 0 0 0 0 0;
Contrast 'fpp vs 82bc in s85' fiber 0 -1 0 1 speed*fiber 0 0 0 0 0 -1 0 1;
Contrast 'fpp vs 63bc in s85' fiber -1 0 0 1 speed*fiber 0 0 0 0 -1 0 0 1;
Contrast 'fpp vs 82bc in s120' fiber 0 -1 0 1 speed*fiber 0 -1 0 1 0 0 0 0;
Contrast 'fpp vs 63bc in s120' fiber -1 0 0 1 speed*fiber -1 0 0 1 0 0 0 0;
Contrast 'fpet vs fpp in s85' fiber 0 0 1 -1 speed*fiber 0 0 0 0 0 0 1 -1;
Contrast 'fpet vs fpp in s120' fiber 0 0 -1 1 speed*fiber 0 0 -1 1 0 0 0 0;
Contrast 's85 vs s120 in 63bc' speed -1 1 speed*fiber -1 0 0 0 1 0 0 0;
Contrast 's85 vs s120 in 82bc' speed -1 1 speed*fiber 0 -1 0 0 0 1 0 0;
Contrast 's85 vs s120 in fpet' speed -1 1 speed*fiber 0 0 -1 0 0 0 1 0;
Contrast 's85 vs s120 in fpp' speed -1 1 speed*fiber 0 0 0 -1 0 0 0 1;
Run;

```

Obs	speed	fiber	_TYPE_	_FREQ_	Meanyield
1	s120	63bc	3	50	2.34058
2	s120	82bc	3	50	3.53646
3	s120	fpet	3	50	3.40750
4	s120	fpp	3	50	2.43354
5	s85	63bc	3	50	2.43410
6	s85	82bc	3	50	3.46736
7	s85	fpet	3	50	3.11790
8	s85	fpp	3	50	2.71774

**The GLM Procedure**  
**Class Level Information**

Class	Levels	Values
Speed	2	s120 s85
Fiber	4	63bc 82bc fpet fpp

Number of observations      400

**The GLM Procedure**  
**Dependent Variable: yield**

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	7	90.2346471	12.8906639	168.88	<. 0001
Error	392	29.9223037	0.0763324		
Corrected Total	399	120.1569508			

R-Square	Coeff Var	Root MSE	Yield Mean
0.750973	9.423358	0.276283	2.931898

Source	DF	Type I SS	Mean Square	F Value	Pr > F
Speed	1	0.00226100	0.00226100	0.03	0.8634
Fiber	3	85.78068213	28.59356071	374.59	<. 0001
Speed*fiber	3	4.45170401	1.48390134	19.44	<. 0001

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Speed	1	0.00226100	0.00226100	0.03	0.8634
Fiber	3	85.78068213	28.59356071	374.59	<. 0001
Speed*fiber	3	4.45170401	1.48390134	19.44	<. 0001

The GLM Procedure  
Least Squares Means

Speed	fiber	yield LSMEAN
S120	63bc	2.34058000
S120	82bc	3.53646000
S120	fpet	3.40750000
S120	fpp	2.43354000
S85	63bc	2.43410000
S85	82bc	3.46736000
S85	fpet	3.11790000
S85	fpp	2.71774000

The GLM Procedure  
Least Squares Means

Speed\*fiber Effect Sliced by speed for yield

Speed	DF	Sum of Squares	Mean Square	F Value	Pr > F
S120	3	59.484376	19.828125	259.76	<. 0001
S85	3	30.748010	10.249337	134.27	<. 0001

The GLM Procedure  
Least Squares Means

Speed	fiber	yield LSMEAN
S120	63bc	2.34058000
S120	82bc	3.53646000
S120	fpet	3.40750000
S120	fpp	2.43354000
S85	63bc	2.43410000
S85	82bc	3.46736000
S85	fpet	3.11790000
S85	fpp	2.71774000

**The GLM Procedure**  
**Least Squares Means**  
**Speed\*fiber Effect Sliced by fiber for yield**

Fiber	DF	Sum of Squares	Mean Square	F Value	Pr > F
63bc	1	0.218650	0.218650	2.86	0.0914
82bc	1	0.119370	0.119370	1.56	0.2119
Fpet	1	2.096704	2.096704	27.47	<. 0001
Fpp	1	2.019241	2.019241	26.45	<. 0001

**The GLM Procedure**  
**Dependent Variable: yield**

Contrast	DF	Contrast SS	Mean Square	F Value	Pr > F
Fpet vs 82bc in s85	1	3.05305729	3.05305729	40.00	<. 0001
Fpet vs 63bc in s85	1	11.68956100	11.68956100	153.14	<. 0001
Fpet vs 82bc in s120	1	0.41576704	0.41576704	5.45	0.0201
Fpet vs 63bc in s120	1	28.45795716	28.45795716	372.82	<. 0001
Fpp vs 82bc in s85	1	14.04825361	14.04825361	184.04	<. 0001
Fpp vs 63bc in s85	1	2.01129124	2.01129124	26.35	<. 0001
Fpp vs 82bc in s120	1	30.41081316	30.41081316	398.40	<. 0001
Fpp vs 63bc in s120	1	0.21603904	0.21603904	2.83	0.0933
Fpet vs fpp in s85	1	4.00320064	4.00320064	52.44	<. 0001
Fpet vs fpp in s120	1	23.71495204	23.71495204	310.68	<. 0001
S85 vs s120 in 63bc	1	0.21864976	0.21864976	2.86	0.0914
S85 vs s120 in 82bc	1	0.11937025	0.11937025	1.56	0.2119
S85 vs s120 in fpet	1	2.09670400	2.09670400	27.47	<. 0001
S85 vs s120 in fpp	1	2.01924100	2.01924100	26.45	<. 0001

**TABLE 2:** Sample SAS Code and ANOVA Table for Fiber Type Analysis

```

Data tenacity;
Input fiber $ @;
Title '1';
Do rep=1 to 30;
Input yield @;
X1=(fiber='fpet'); x2=(fiber='fpp'); x3=(fiber='82bc'); x4=(fiber='63bc');
Output; end;
Cards;
Fpet  3.53  4.63  3.52  4.07  3.42  4.29  4.14  4.24  4.36  3.94  4.64
      3.78  4.16  4.03  4.27  4.16  4.56  3.85  3.56  4.00  4.40  4.08
      4.35  4.61  4.06  3.94  4.27  4.10  4.10  4.80
Fpp   4.73  5.52  4.86  5.22  5.87  5.31  5.71  5.18  5.76  5.47
      5.44  6.13  5.92  5.45  5.34  5.69  5.45  5.95  5.73  5.60  5.49
      5.82  5.55  5.45  5.54  5.61  5.74  5.29  5.57  5.08
82bc  4.71  4.80  5.18  4.98  4.52  5.10  5.08  4.86  5.21  5.22  5.00
      5.07  5.00  5.16  5.18  5.10  4.79  4.89  4.76  5.39  5.04  5.27
      5.00  5.00  5.08  5.36  5.33  5.07  5.35  5.29
63bc  1.99  2.78  2.33  2.41  2.75  2.67  2.33  2.52  2.77  2.44  2.95
      2.75  2.96  2.84  2.07  2.60  2.23  2.04  2.78  2.44  3.34  2.40
      2.50  2.25  2.50  2.64  2.52  2.92  2.58  1.92
;
Proc glm data=tenacity;
Class fiber; model yield=fiber;
Run;

```

**The GLM Procedure**  
**Class Level Information**

Class	Levels	Values
Fiber	4	63bc 82bc fpet fpp
Number of observations		120

**The GLM Procedure**  
**Dependent Variable: yield**

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	3	155.3714700	51.7904900	569.51	<. 0001
Error	116	10.5489667	0.0909394		
Corrected Total	119	165.9204367			

R-Square	Coeff Var	Root MSE	yield Mean
0.936422	6.994894	0.301562	4.311167

Source	DF	Type I SS	Mean Square	F Value	Pr > F
Fiber	3	155.3714700	51.7904900	569.51	<. 0001

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Fiber	3	155.3714700	51.7904900	569.51	<.0001

**TABLE 3: Sample SAS Code and ANOVA Table for Fiber Type Comparison**

```

Data crstb;
Input fiber $ step $ @;
Title '4';
Do rep=1 to 20;
Input yield @;
X1=(fiber='63'); x2=(fiber='pet');
Y1=(step='raw'); y2=(step='feed'); y3=(step='85'); y4=(step='120');
Output; end;
Cards;
63 raw 51.54 48.18 33.52 15.76 44.59 15.52 53.16 26.21 54.25 39.65 55.50
      45.33 44.86 48.39 43.04 39.13 39.91 38.55 32.86 57.71
63 feed 38.00 66.43 23.68 53.04 41.14 22.26 39.11 42.81 27.58 40.09 27.95
      44.19 26.45 30.16 38.64 15.12 20.16 45.10 13.41 39.51
63 85 23.82 30.68 40.08 56.27 50.96 62.69 57.16 28.35 23.65 45.21 34.10
      48.36 52.22 52.81 64.89 33.95 34.39 45.00 21.09 60.02
63 120 32.25 41.17 38.68 25.32 46.09 12.21 18.31 51.39 43.85 40.20 33.79
      39.01 48.15 43.51 46.05 46.38 41.03 40.54 48.67 38.97
Pet raw 49.57 61.62 43.35 45.12 58.36 45.83 35.05 62.33 37.20 38.03 45.37
      37.76 43.31 34.77 47.72 43.98 42.23 39.21 47.32 35.14
Pet feed 30.48 50.44 48.30 62.35 38.67 44.15 43.89 53.56 39.64 54.00
      61.18 49.70 66.21 52.02 50.70 54.00 47.26 39.91 59.74 45.32
Pet 85 54.67 52.06 52.86 49.76 38.45 35.17 43.40 50.21 57.32 37.86 45.26
      52.19 41.58 42.55 44.67 40.17 50.52 42.60 43.48 39.29
Pet 120 53.94 50.31 56.11 60.72 51.44 57.35 41.51 60.99 40.60 47.24 36.71
      68.16 41.19 43.44 46.35 51.71 47.05 44.99 40.15 42.57
;
Proc glm data=crstb;
Class fiber step; model yield=fiber step fiber*step;
Contrast '63 vs pet in raw' fiber -1 1 step*fiber 0 0 0 -1 0 0 0 1;
Contrast '63 vs pet in feed' fiber -1 1 step*fiber 0 0 -1 0 0 0 1 0;
Contrast '63 vs pet in 85' fiber -1 1 step*fiber 0 -1 0 0 0 1 0 0;
Contrast '63 vs pet in 120' fiber -1 1 step*fiber -1 0 0 0 1 0 0 0;
Run;

```

**The GLM Procedure**  
**Class Level Information**

Class	Levels	Values
Fiber	2	63 pet
Step	4	120 85 feed raw

Number of observations 160

**The GLM Procedure**  
**Dependent Variable: yield**

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	7	3564.94616	509.27802	4.71	<. 0001
Error	152	16448.27508	108.21234		
Corrected Total	159	20013.22123			

R-Square	Coeff Var	Root MSE	yield Mean
0.178130	23.96496	10.40252	43.40719

Source	DF	Type I SS	Mean Square	F Value	Pr > F
Fiber	1	2384.167606	2384.167606	22.03	<. 0001
Step	3	127.402992	42.467664	0.39	0.7586

Fiber*step	3	1053.375562	351.125187	3.24	0.0237
<b>Source</b>	<b>DF</b>	<b>Type III SS</b>	<b>Mean Square</b>	<b>F Value</b>	<b>Pr &gt; F</b>
Fiber	1	2384.167606	2384.167606	22.03	<. 0001
Step	3	127.402992	42.467664	0.39	0.7586
Fiber*step	3	1053.375562	351.125187	3.24	0.0237
<b>Contrast</b>	<b>DF</b>	<b>Contrast SS</b>	<b>Mean Square</b>	<b>F Value</b>	<b>Pr &gt; F</b>
63 vs pet in raw	1	107.616803	107.616803	0.99	0.3202
63 vs pet in feed	1	2200.623903	2200.623903	20.34	<. 0001
63 vs pet in 85	1	58.491422	58.491422	0.54	0.4633
63 vs pet in 120	1	1070.811040	1070.811040	9.90	0.0020

**TABLE 4:** Sample SAS Code and ANOVA Table for Processing Step Comparison

```

Data modulus;
Input step $ @;
Title '4';
Do rep=1 to 30;
Input yield @;
X1=(step='raw'); x2=(step='feed'); x3=(step='85'); x4=(step='120');
Output; end;
Cards;
Raw 80.62 101.46 92.44 107.5 97.68 102.7 98.36 118.88 94.14 83.98 99.96
106.78 96.02 104.68 109.8 107.02 94.46 101.22 101.86 86.78 94.92 104.7
102 97.72 99.56 87.92 109.92 103.52 116.96 89.64
Feed 102.38 103.36 106.9 112.46 105.3 99.78 102.06 92.68 97.42 114.12 95.32
103.14 88.72 106.3 89 93.1 100.74 102.22 101.52 84.9 103.62 87.04
100.56 106.34 94.4 98.64 103.82 95 102.88 105.98
85 97.18 107 106.96 90.24 57.22 106.1 81.1 95.9 115.14 107.82 90.84
103.76 84.34 93.68 104.12 98.54 94.74 92.7 106.98 113.3 91.74 116.38
93.28 100.54 110.62 91.38 100.46 99.76 93.72 106.04
120 115.3 99.52 107.46 102.68 102.4 104.04 105.38 98.32 88.1 99.08 104.92
88.54 111.38 95.78 100.92 98.3 92.1 99.56 92.02 94.26 104.98 120.06
97.12 104.16 105.04 91.82 102.96 77.84 91.08 100.4
;
Proc glm data=modulus;
Class step; model yield=step;
Contrast 'raw vs. feed' step 0 0 -1 1;
Contrast 'raw vs. 120' step -1 0 0 1;
Contrast 'raw vs. 85' step 0 -1 0 1;
Contrast 'feed vs. 120' step -1 0 1 0;
Contrast 'feed vs. 85' step 0 -1 1 0;
Contrast '85 vs. 120' step -1 1 0 0;
Run;

```

**The GLM Procedure**  
**Class Level Information**

Class	Levels	Values
Step	4	120 85 feed raw
Number of observations		120

**The GLM Procedure**  
**Dependent Variable: yield**

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	3	12.590807	4.196936	0.20	0.8977
Error	116	2461.450793	21.219403		
Corrected Total	119	2474.041600			
<b>R-Square</b>		<b>Coeff Var</b>	<b>Root MSE</b>	<b>yield Mean</b>	
0.005089		9.259201	4.606452	49.75000	

<b>Source</b>	<b>DF</b>	<b>Type I SS</b>	<b>Mean Square</b>	<b>F Value</b>	<b>Pr &gt; F</b>
Step	3	12.59080667	4.19693556	0.20	0.8977

<b>Source</b>	<b>DF</b>	<b>Type III SS</b>	<b>Mean Square</b>	<b>F Value</b>	<b>Pr &gt; F</b>
Step	3	12.59080667	4.19693556	0.20	0.8977

<b>Contrast</b>	<b>DF</b>	<b>Contrast SS</b>	<b>Mean Square</b>	<b>F Value</b>	<b>Pr &gt; F</b>
Raw vs. feed	1	0.17604167	0.17604167	0.01	0.9276
Raw vs. 120	1	0.02242667	0.02242667	0.00	0.9741
Raw vs. 85	1	7.21760167	7.21760167	0.34	0.5609
Feed vs. 120	1	0.07280167	0.07280167	0.00	0.9534
Feed vs. 85	1	9.64806000	9.64806000	0.45	0.5015
85 vs. 120	1	8.04468167	8.04468167	0.38	0.5393

**TABLE 5:** An Example of a Nonlinear Regression Analysis for Exponential Fit for Feed Matt Openness Data

Nonlinear Regression

[Variables]

x = col(4)

y = col(3)

Reciprocal\_y=1/abs (y)

Reciprocal\_ysquare=1/y^2

'Automatic Initial Parameter Estimate Functions

Xnear0 (q)=max (abs (q))-abs (q)

Yatxnear0 (q, r)=xatymax (q, xnear0(r))

[Parameters]

A = yatxnear0 (y, x) "Auto {{previous: 7018.14}}

B = -ln (.5)/(x50 (x, y)-min (x)) "Auto {{previous: 0.0393359}}

[Equation]

F=a\*exp (-b\*x)

Fit f to y

“Fit f to y with weight reciprocal\_y

“Fit f to y with weight reciprocal\_ysquare

[Constraints]

B>0

[Options]

Tolerance=0.0001

Stepsize=100

Iterations=100

R = 0.99673545 Rsqr = 0.99348157 Adj Rsqr = 0.99346662

Standard Error of Estimate = 14.2986

	<b>Coefficient</b>	<b>Std. Error</b>	<b>t</b>	<b>P</b>
A	7018.1379	104.6220	67.0809	<0.0001
B	0.0393	0.0002	193.1416	<0.0001

**Analysis of Variance:**

	<b>DF</b>	<b>SS</b>	<b>MS</b>	<b>F</b>	<b>P</b>
Regression	1	13585961.5906	13585961.5906	66451.2331	<0.0001
Residual	436	89140.2458	204.4501		
Total	437	13675101.8363	31293.1392		

PRESS = 89757.0032

Durbin-Watson Statistic = 0.0071

Normality Test: Failed (P = <0.0001)

Constant Variance Test: Failed (P = <0.0001)

Power of performed test with alpha = 0.0500: 1.0000

**Regression Diagnostics:**

Row	Predicted	Residual	Std. Res.	Stud. Res.	Stud. Del. Res.
1	38.0984	-27.9880	-1.9574	-1.9585	-1.9649
2	38.3482	-28.2193	-1.9736	-1.9747	-1.9813
3	38.6104	-27.8025	-1.9444	-1.9455	-1.9518
4	38.8666	-27.8171	-1.9454	-1.9466	-1.9528
5	39.1222	-26.8851	-1.8803	-1.8813	-1.8869
6	39.3653	-27.8187	-1.9456	-1.9467	-1.9530
7	39.6281	-27.1977	-1.9021	-1.9032	-1.9090
8	39.8979	-27.4674	-1.9210	-1.9221	-1.9281
9	40.1506	-29.1011	-2.0352	-2.0365	-2.0439
10	40.4227	-29.3732	-2.0543	-2.0555	-2.0632
.	.	.	.	.	.
.	.	.	.	.	.
.	.	.	.	.	.
428	625.8003	-15.3032	-1.0703	-1.0815	-1.0817
429	629.9406	-14.7203	-1.0295	-1.0406	-1.0407
430	634.0577	-12.7872	-0.8943	-0.9042	-0.9040
431	638.2207	-17.5027	-1.2241	-1.2380	-1.2387
432	642.4111	-15.8922	-1.1114	-1.1244	-1.1248
433	646.7260	-14.8317	-1.0373	-1.0497	-1.0499
434	650.8812	-17.9537	-1.2556	-1.2711	-1.2720
435	655.1547	-18.7462	-1.3111	-1.3277	-1.3288
436	659.5618	-18.7476	-1.3112	-1.3282	-1.3294
437	663.5872	-19.4996	-1.3637	-1.3820	-1.3834
438	665.9451	-17.1611	-1.2002	-1.2165	-1.2172

**Influence Diagnostics:**

Row	Cook'sDist	Leverage	DFFITS
1	0.0021	0.0011	-0.0657
2	0.0022	0.0011	-0.0665
3	0.0021	0.0011	-0.0658
4	0.0022	0.0011	-0.0661
5	0.0020	0.0012	-0.0641
6	0.0022	0.0012	-0.0666
7	0.0021	0.0012	-0.0653
8	0.0022	0.0012	-0.0662
9	0.0025	0.0012	-0.0705
10	0.0025	0.0012	-0.0714
.	.	.	.
.	.	.	.
.	.	.	.
428	0.0123	0.0206	-0.1569
429	0.0117	0.0212	-0.1530
430	0.0091	0.0217	-0.1348
431	0.0175	0.0223	-0.1872
432	0.0148	0.0229	-0.1723
433	0.0133	0.0236	-0.1632
434	0.0200	0.0242	-0.2004
435	0.0225	0.0249	-0.2122
436	0.0231	0.0256	-0.2153
437	0.0257	0.0262	-0.2270

438            0.0202            0.0266            -0.2012

**95% Confidence:**

<b>Row</b>	<b>Predicted</b>	<b>Regr. 5%</b>	<b>Regr. 95%</b>	<b>Pop. 5%</b>	<b>Pop. 95%</b>
1	38.0984	37.1595	39.0374	9.9800	66.2169
2	38.3482	37.4056	39.2908	10.2296	66.4667
3	38.6104	37.6639	39.5568	10.4917	66.7291
4	38.8666	37.9165	39.8168	10.7478	66.9854
5	39.1222	38.1683	40.0760	11.0032	67.2411
6	39.3653	38.4079	40.3226	11.2462	67.4843
7	39.6281	38.6670	40.5892	11.5089	67.7473
8	39.8979	38.9329	40.8628	11.7785	68.0172
9	40.1506	39.1821	41.1191	12.0311	68.2700
10	40.4227	39.4503	41.3951	12.3031	68.5423
.	.	.	.	.	.
.	.	.	.	.	.
.	.	.	.	.	.
428	625.8003	621.7669	629.8336	597.4096	654.1910
429	629.9406	625.8523	634.0289	601.5420	658.3392
430	634.0577	629.9142	638.2011	605.6511	662.4642
431	638.2207	634.0212	642.4203	609.8059	666.6355
432	642.4111	638.1547	646.6676	613.9879	670.8344
433	646.7260	642.4105	651.0414	618.2938	675.1582
434	650.8812	646.5085	655.2539	622.4403	679.3221
435	655.1547	650.7227	659.5867	626.7046	683.6048
436	659.5618	655.0682	664.0553	631.1020	688.0215
437	663.5872	659.0370	668.1375	635.1185	692.0560
438	665.9451	661.3616	670.5287	637.4710	694.4192

**TABLE 6:ANOVA with Tukey (HSD) Comparison of Means**

```

Data tenacity;
Input speed $ fiber $ @;
Title '1';
Do rep=1 to 30;
Input yield @;
x=85*(speed='s85')+ 120*(speed='s120');
Y1=(fiber='fpet'); y2=(fiber='fpp'); y3=(fiber='82bc'); y4=(fiber='63bc');
Output; end;
Cards;
S85 fpet      3.53   4.63   3.52   4.07   3.42   4.29   4.14   4.24   4.36   3.94
              4.64   3.78   4.16   4.03   4.27   4.16   4.56   3.85   3.56   4.00   4.40
              4.08   4.35   4.61   4.06   3.94   4.27   4.10   4.10   4.80
S85 fpp       4.73   5.52   4.86   5.22   5.87   5.31   5.71   5.18   5.76   5.47
              5.44   6.13   5.92   5.45   5.34   5.69   5.45   5.95   5.73   5.60   5.49
              5.82   5.55   5.45   5.54   5.61   5.74   5.29   5.57   5.08
S85 82bc      4.71   4.80   5.18   4.98   4.52   5.10   5.08   4.86   5.21   5.22
              5.00   5.07   5.00   5.16   5.18   5.10   4.79   4.89   4.76   5.39   5.04
              5.27   5.00   5.00   5.08   5.36   5.33   5.07   5.35   5.29
S85 63bc      1.99   2.78   2.33   2.41   2.75   2.67   2.33   2.52   2.77   2.44
              2.95   2.75   2.96   2.84   2.07   2.60   2.23   2.04   2.78   2.44   3.34
              2.40   2.50   2.25   2.50   2.64   2.52   2.92   2.58   1.92
S120 fpet     4.18   4.73   3.83   4.10   4.61   4.14   4.38   2.23   3.95   3.43
              4.71   3.82   4.24   3.73   4.30   4.30   3.98   3.69   4.26   4.29   3.36
              3.73   4.51   4.18   4.35   3.75   3.55   4.70   4.42   4.58
S120 fpp      5.81   5.89   5.74   5.45   5.05   5.91   5.84   5.58   5.97   5.42
              5.88   4.17   4.94   5.01   5.60   5.39   5.49   5.63   5.30   5.19   5.83
              5.54   5.21   5.48   5.41   5.44   5.68   5.88   5.21   5.90
S120 82bc     5.11   4.84   5.36   4.81   4.89   5.32   4.69   4.92   4.94   5.13
              5.15   4.99   4.87   4.76   4.73   4.92   4.90   4.53   5.19   5.20   5.33
              5.05   4.84   4.46   4.93   5.34   5.18   4.58   4.83   5.00
S120 63bc     2.79   2.66   2.15   2.35   2.06   2.35   2.42   2.03   2.40   2.89
              3.18   3.04   2.74   2.37   2.48   3.17   2.97   2.39   2.00   2.40   2.54
              2.40   2.49   3.03   2.12   2.07   2.81   2.45   2.91   2.51
;
Proc glm data=tenacity;
Class speed fiber; model yield=speed fiber speed*fiber;
Means fiber/Tukey;
Means speed/Tukey;
Run;

```

**The GLM Procedure**  
**Class Level Information**

Class	Levels	Values
Speed	2	s120 s85
Fiber	4	63bc 82bc fpet fpp
Number of observations		240

**The GLM Procedure**

**Dependent Variable: yield**

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	7	305.8777129	43.6968161	365.90	<. 0001
Error	232	27.7062167	0.1194233		
Corrected Total	239	333.5839296			

R-Square	Coeff Var	Root MSE	yield Mean
0.916944	8.058770	0.345577	4.288208

Source	DF	Type I SS	Mean Square	F Value	Pr > F
speed	1	0.1265004	0.1265004	1.06	0.3045
fiber	3	305.6652413	101.8884138	853.17	<. 0001
speed*fiber	3	0.0859713	0.0286571	0.24	0.8684

Source	DF	Type III SS	Mean Square	F Value	Pr > F
speed	1	0.1265004	0.1265004	1.06	0.3045
fiber	3	305.6652413	101.8884138	853.17	<.0001
speed*fiber	3	0.0859713	0.0286571	0.24	0.8684

#### The GLM Procedure

#### Tukey's Studentized Range (HSD) Test for yield

**NOTE:** This test controls the Type I experimentwise error rate, but it generally has a higher Type II Error rate than REGWQ.

Alpha	0.05
Error Degrees of Freedom	232
Error Mean Square	0.119423
Critical Value of Studentized Range	3.65966
Minimum Significant Difference	0.1633

Means with the same letter are not significantly different.

Tukey Grouping	Mean	N	fiber
A	5.50517	60	fpp
B	5.00967	60	82bc
C	4.09817	60	fpet
D	2.53983	60	63bc

**The GLM Procedure**

**Tukey's Studentized Range (HSD) Test for yield**

**NOTE:** This test controls the Type I experimentwise error rate, but it generally has a higher Type II error rate than REGWQ.

Alpha	0.05
Error Degrees of Freedom	232
Error Mean Square	0.119423
Critical Value of Studentized Range	2.78634
Minimum Significant Difference	0.0879

**Means with the same letter are not significantly different.**

Tukey Grouping	Mean	N	speed
A	4.31117	120	s85
A			
A	4.26525	120	s120

**TABLE 7: ANOVA with Tukey (HSD) Comparison of Means by Speed**

```

Data crstb;
Input fiber $ @;
Title '1';
Do rep=1 to 30;
Input yield @;
X1=(fiber='fpet'); x2=(fiber='fpp'); x3=(fiber='82bc'); x4=(fiber='63bc');
Output; end;
Cards;
Fpet 38.53 42.80 50.94 45.64 47.25 48.25 57.13 41.04 50.62 43.14 54.67
     52.06 52.86 49.76 38.45 35.17 43.40 50.21 57.32 37.86 45.26 52.19
     41.58 42.55 44.67 40.17 50.52 42.60 43.48 39.29
Fpp 51.04 65.29 49.00 56.69 49.97 65.16 57.18 60.27 45.36 45.15 51.70
     62.50 68.29 70.22 60.42 64.95 60.38 64.89 48.78 48.43 60.50 64.93
     51.41 45.00 47.51 57.15 65.07 47.34 71.00 45.88
82bc 55.25 65.83 68.69 61.32 47.68 48.99 49.28 58.14 57.55 50.93 58.56
     65.06 60.90 52.66 50.87 48.90 55.73 50.53 69.49 53.50 77.52 65.28
     56.88 75.14 69.41 67.79 40.31 32.74 56.48 48.02
63bc 57.08 48.54 46.27 29.89 56.41 38.70 55.66 59.55 37.32 51.96 23.82
     30.68 40.08 56.27 50.96 62.69 57.16 28.35 23.65 45.21 34.10 48.36
     52.22 52.81 64.89 33.95 34.39 45.00 21.09 60.02
;
Proc glm data=crstb;
Class fiber; model yield=fiber;
Means fiber/Tukey;
Run;

```

**The GLM Procedure**  
**Class Level Information**

Class	Levels	Values
Fiber	4	63bc 82bc fpet fpp
Number of observations		120

**The GLM Procedure**  
**Dependent Variable: yield**

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	3	4041.06383	1347.02128	14.60	<. 0001
Error	116	10699.94037	92.24087		
Corrected Total	119	14741.00420			

R-Square	Coeff Var	Root MSE	yield Mean
0.274138	18.74791	9.604211	51.22817

Source	DF	Type I SS	Mean Square	F Value	Pr > F
Fiber	3	4041.063830	1347.021277	14.60	<. 0001

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Fiber	3	4041.063830	1347.021277	14.60	<. 0001

**The GLM Procedure****Tukey's Studentized Range (HSD) Test for yield**

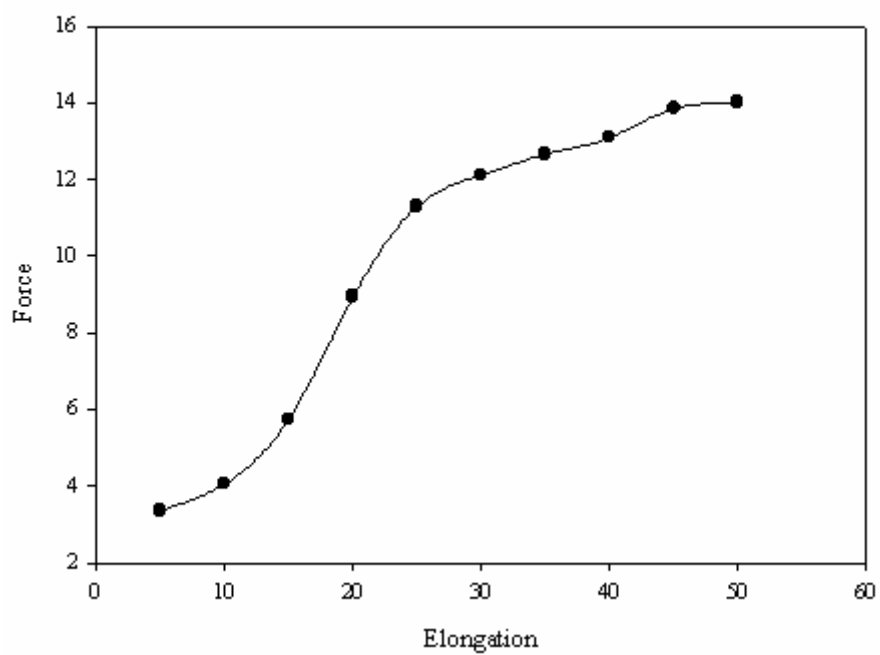
**NOTE:** This test controls the Type I experimentwise error rate, but it generally has a higher Type II error rate than REGWQ.

Alpha	0.05
Error Degrees of Freedom	116
Error Mean Square	92.24087
Critical Value of Studentized Range	3.68639
Minimum Significant Difference	6.464

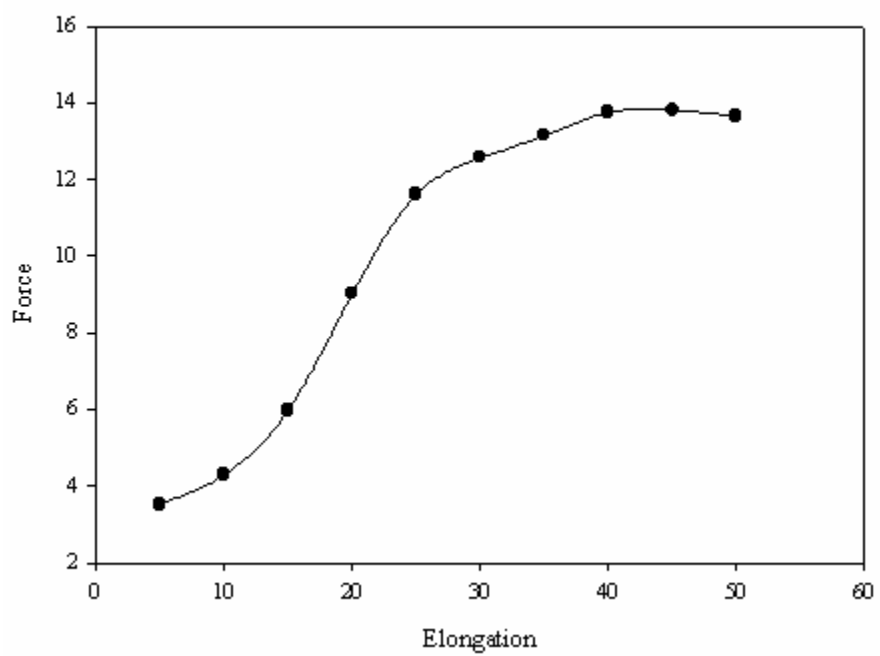
Means with the same letter are not significantly different.

Tukey Grouping	Mean	N	fiber
A	57.314	30	82bc
A	56.715	30	fpp
B	45.980	30	fpet
B	44.903	30	63bc

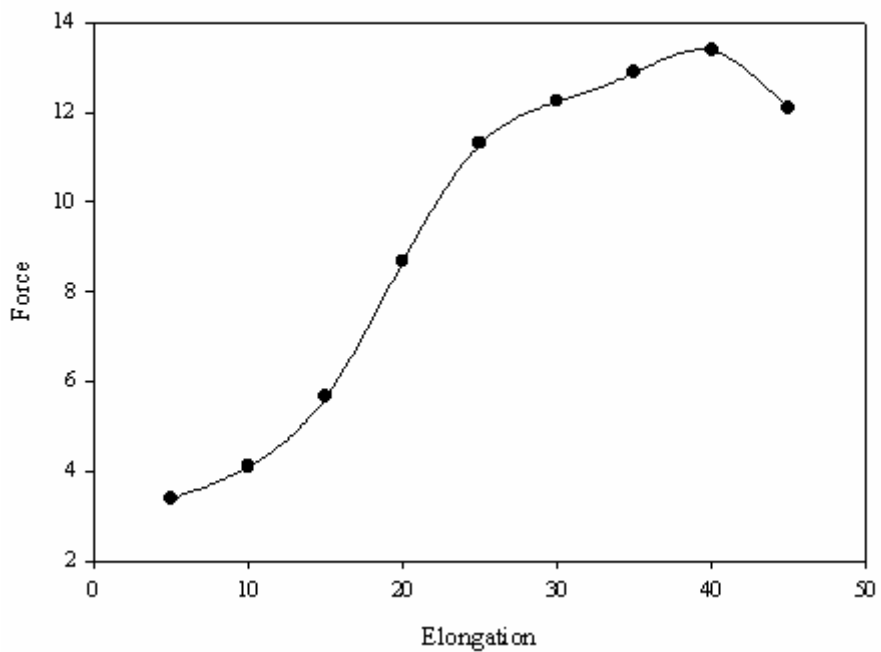
PET Raw



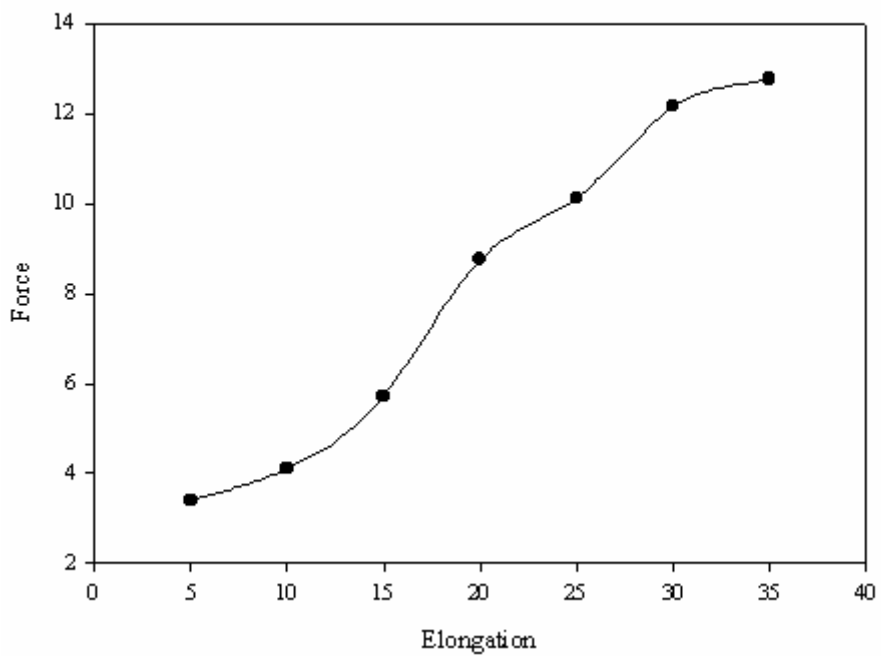
PET Feed



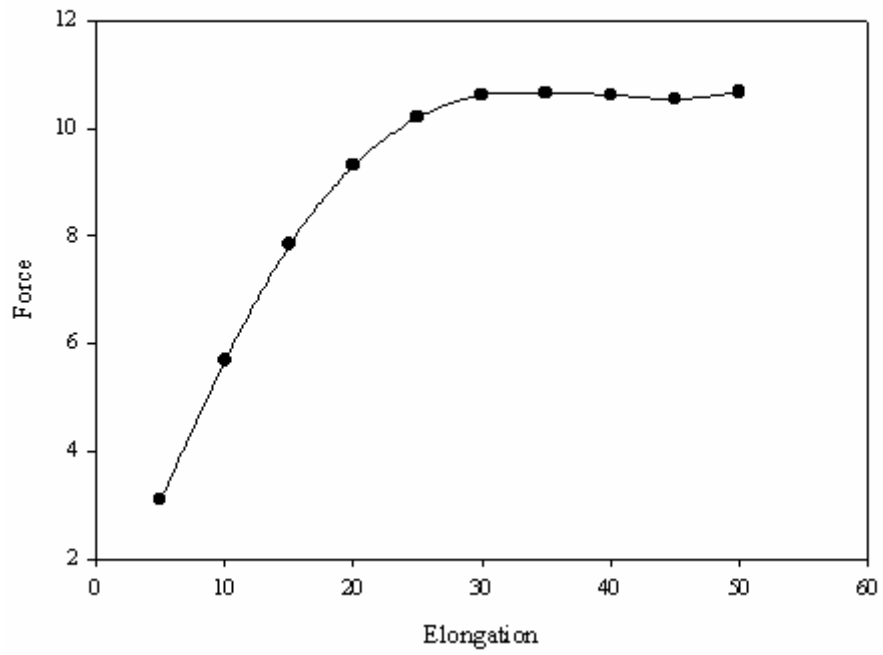
PET 120



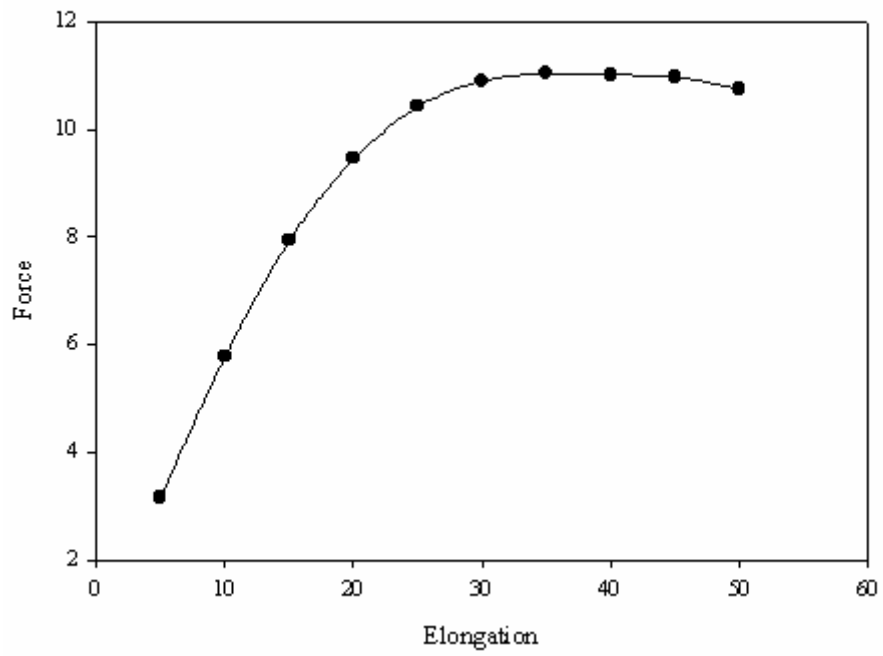
PET 85



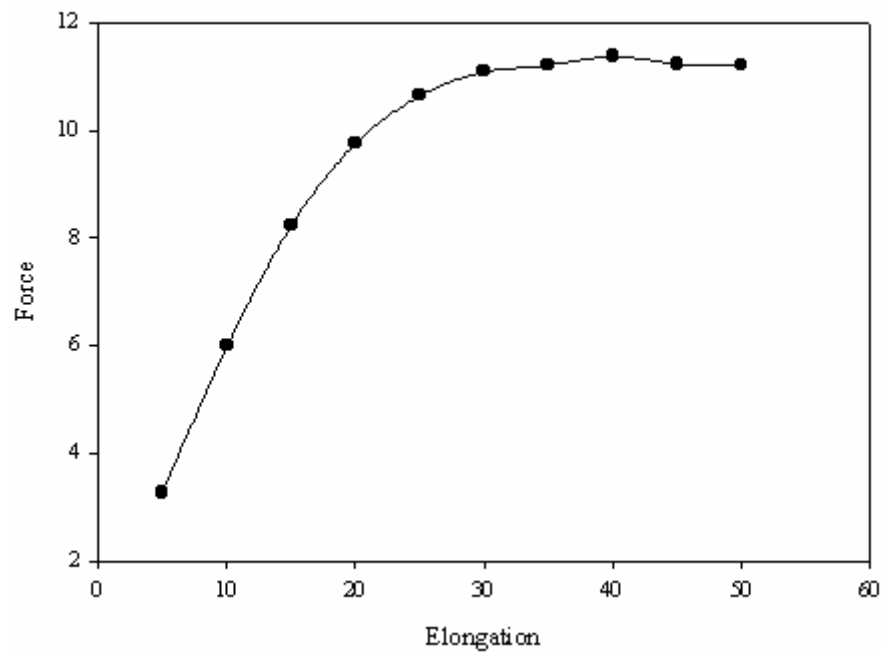
PP Feed



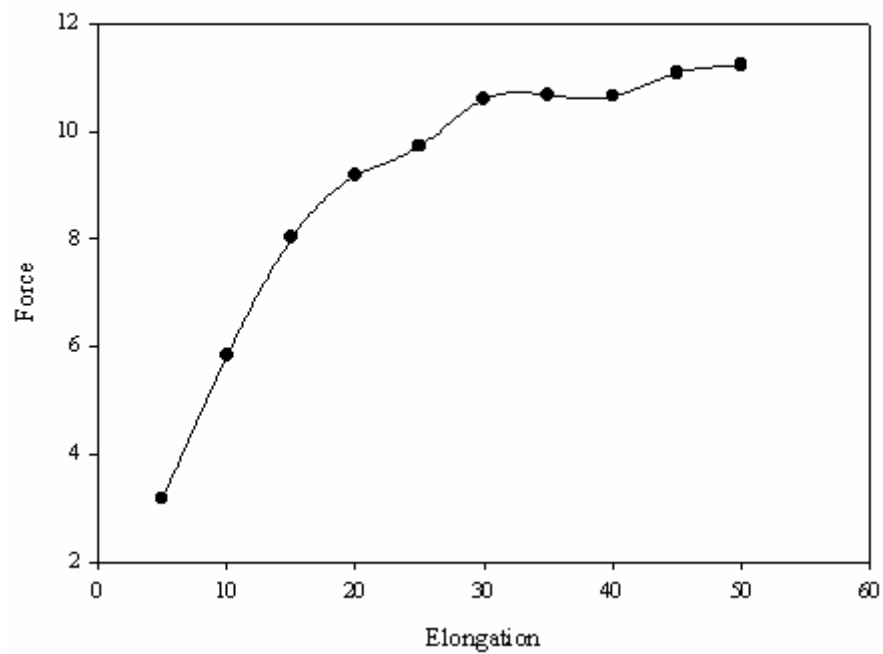
PP Raw



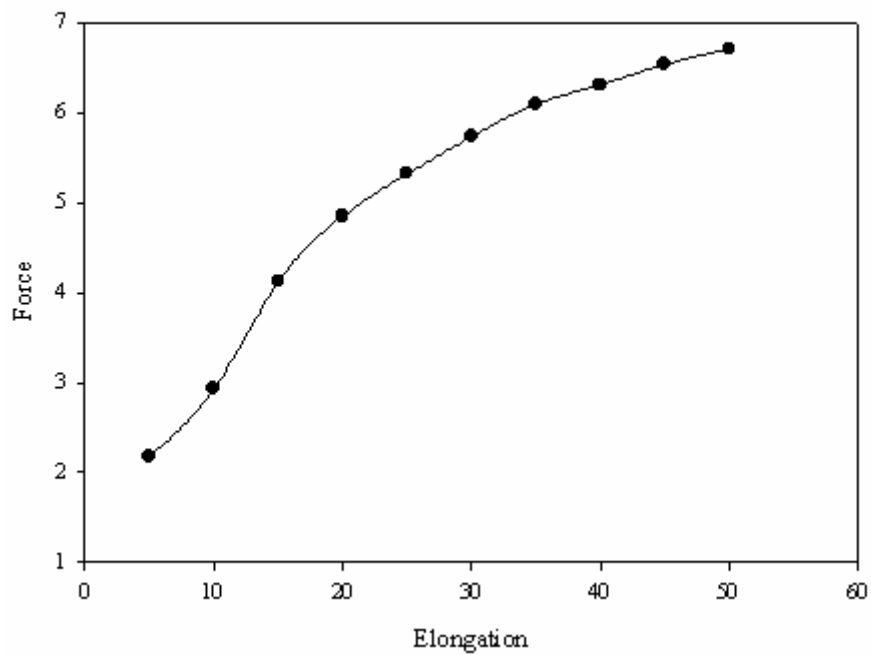
PP 120



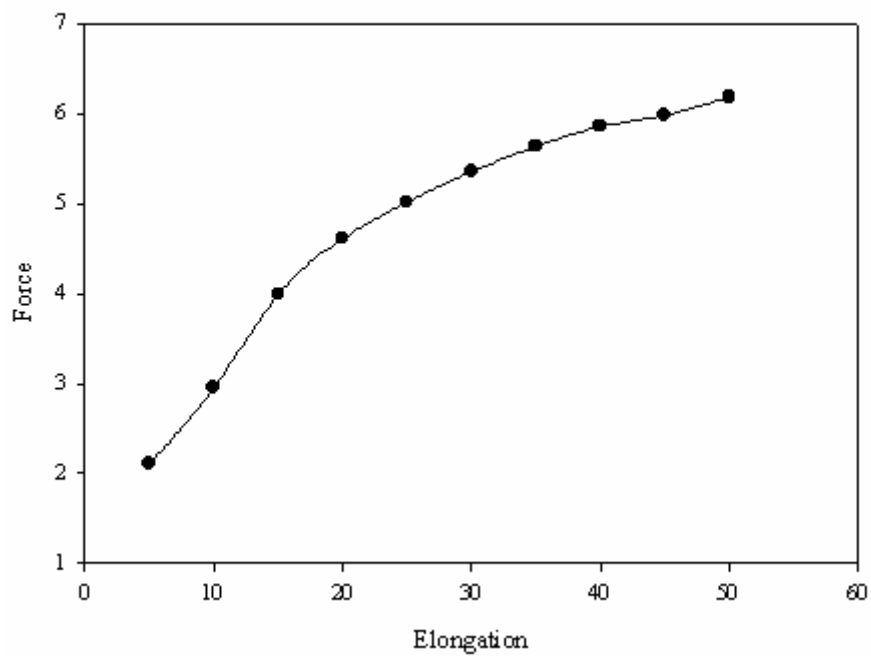
PP 85



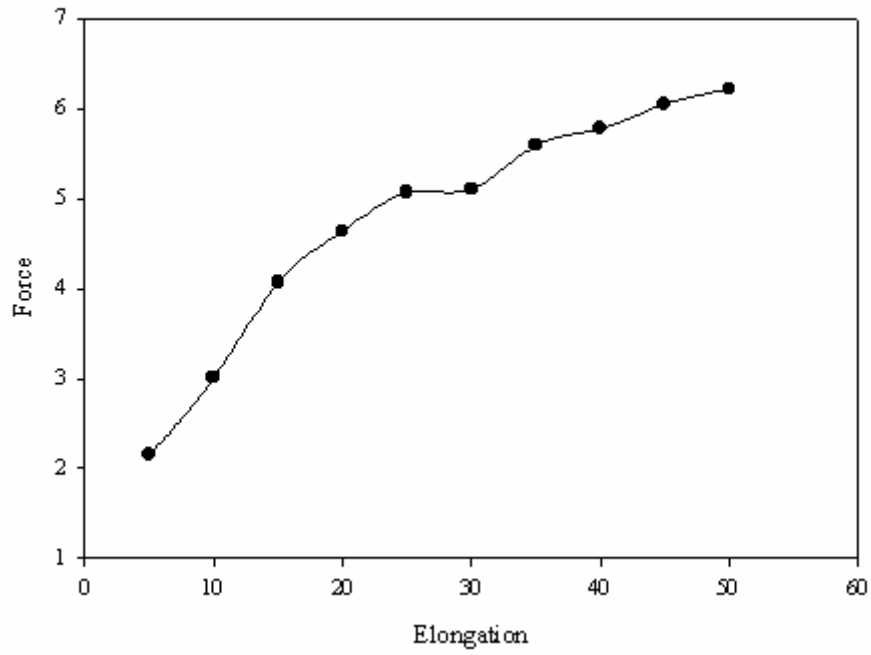
63/37 Raw



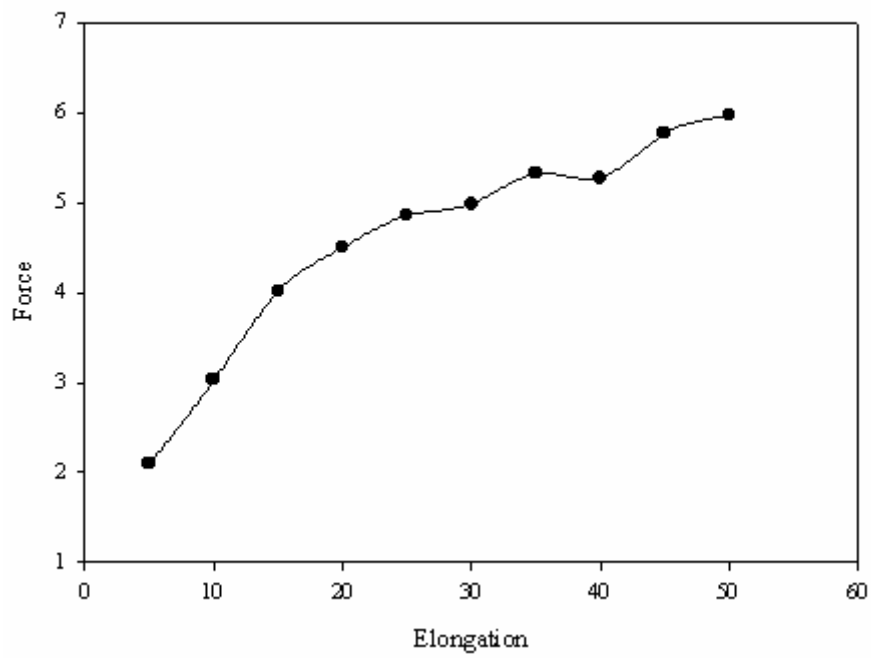
63/37 Feed



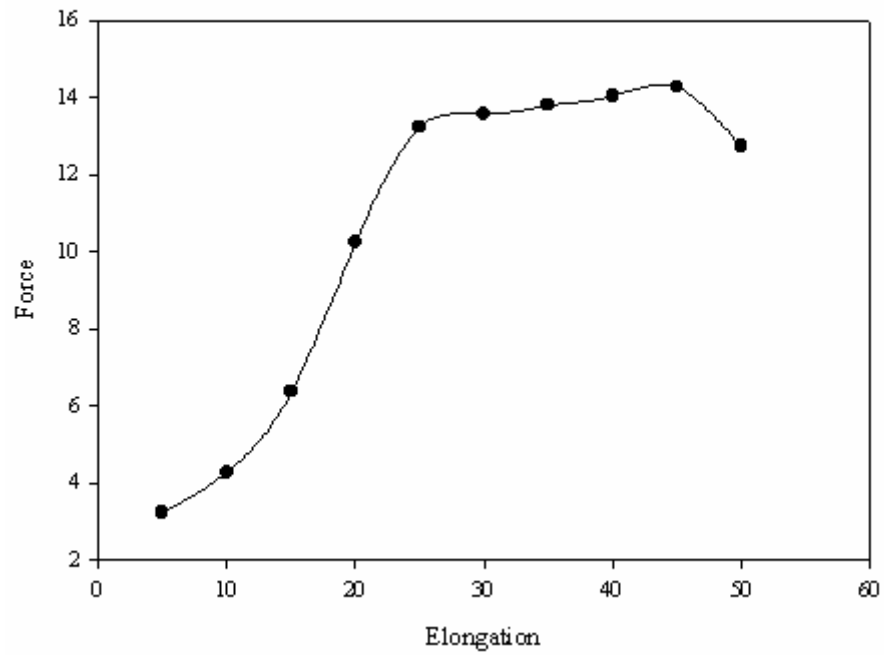
63/37 85



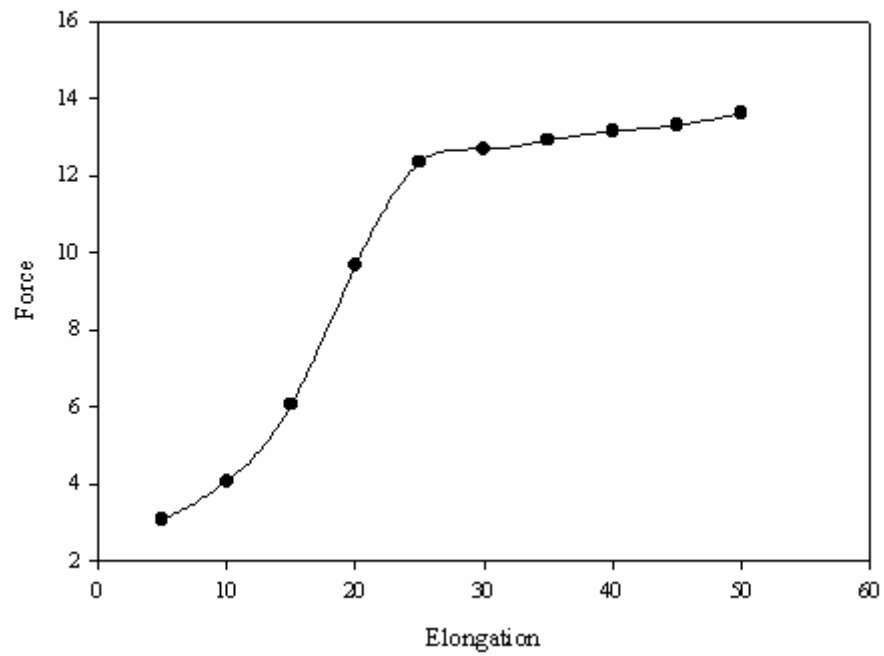
63/37 120

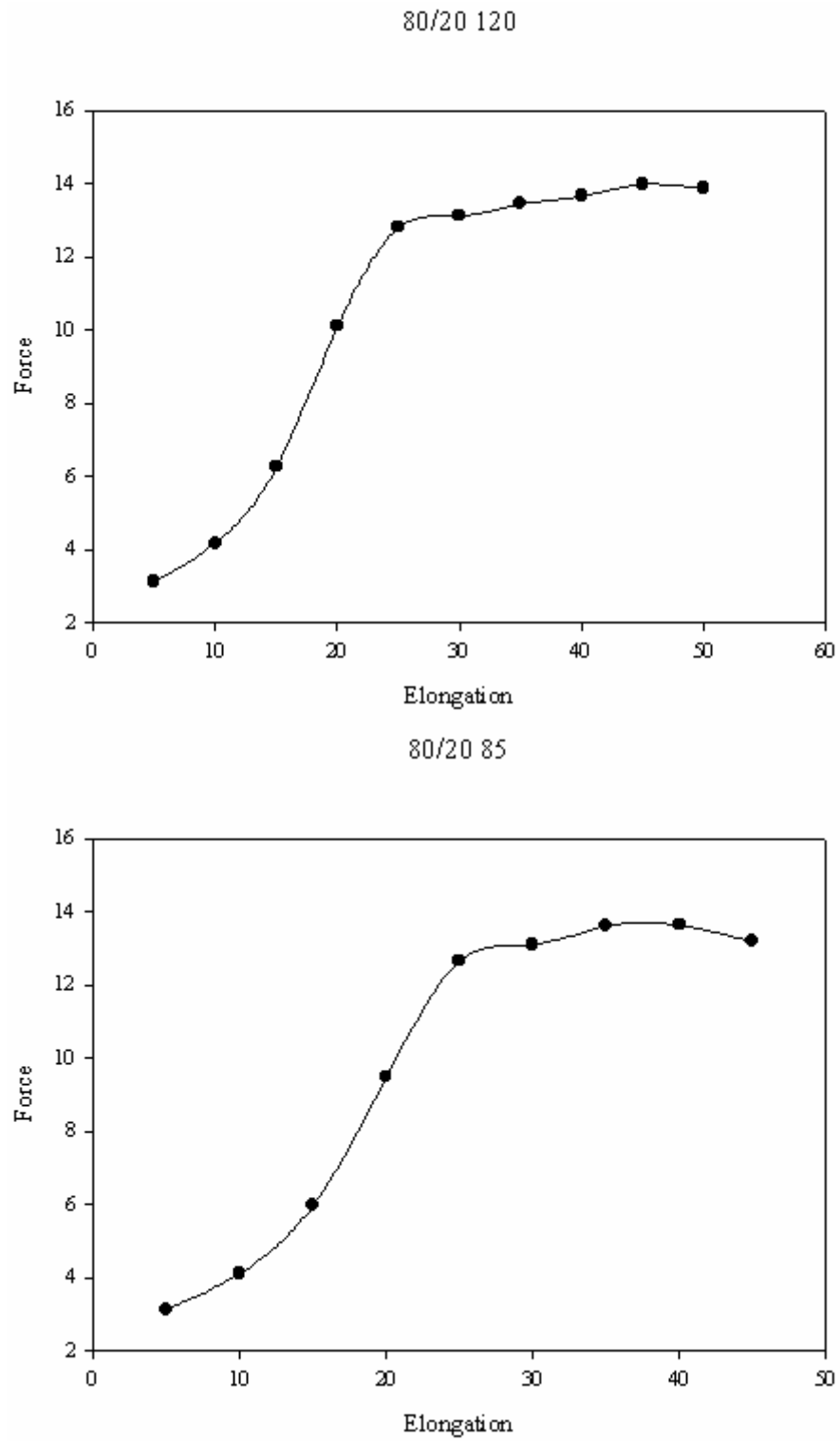


80/20 Feed



80/20 Raw





**FIGURE 1:** Force-Elongation Diagrams For Experimental Fibers

The above figures illustrate the force-elongation diagrams of all experimental fibers for all carding conditions: raw material, feed matt, carded web at 85m/min production speed and carded web at 120 m/min production speed. The following annotations were used when labeling the graphs:

80/20: Fiber type of 80/20 PET/PP bicomponent.

63/37: Fiber type of 63/37 PP/PET bicomponent

PET: Fiber type of 100% PET

PP: Fiber type of 100% PP

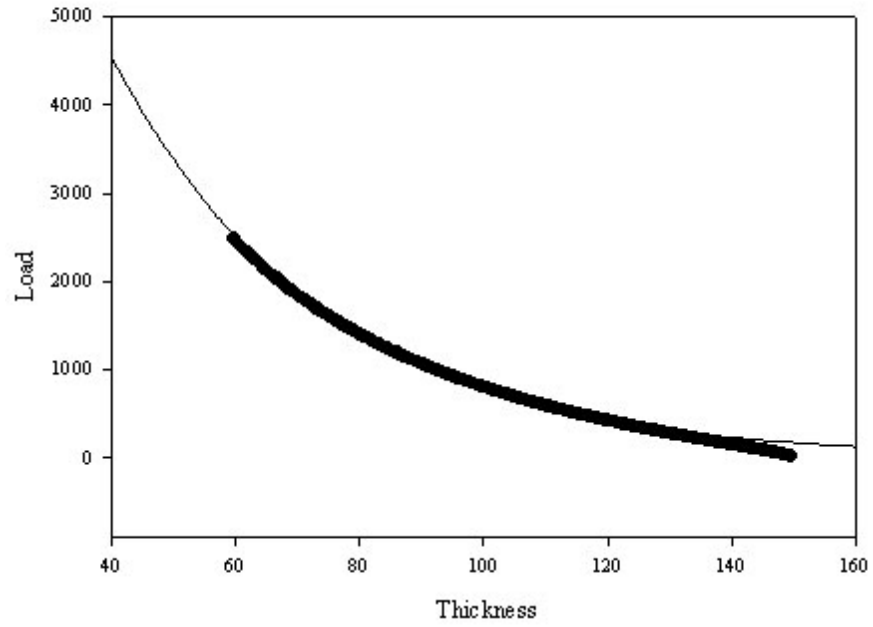
Raw: Carding condition of raw material

Feed: Carding condition of feed matt

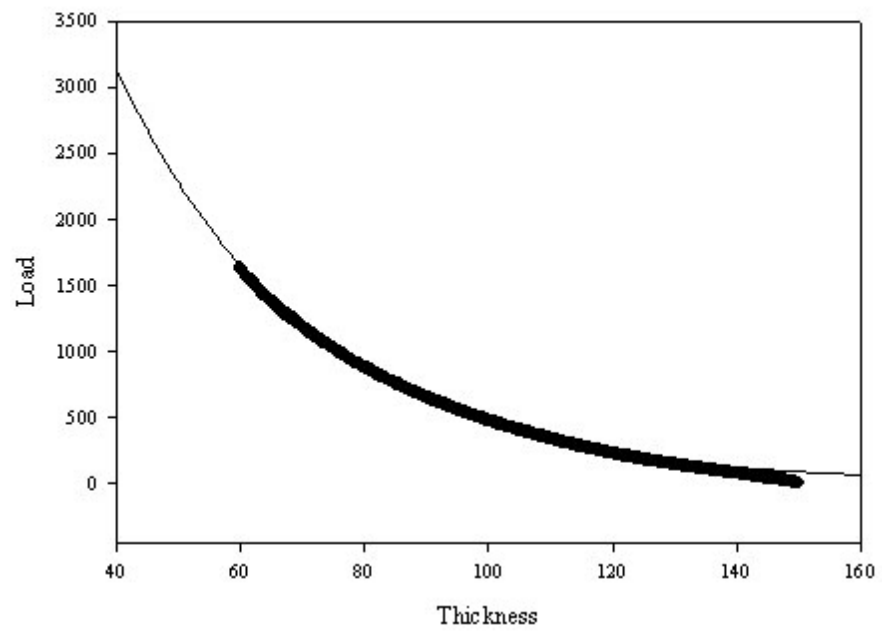
85: Carding condition of carded web at 85m/min production speed

120: Carding condition of carded web at 120-m/min-production speed

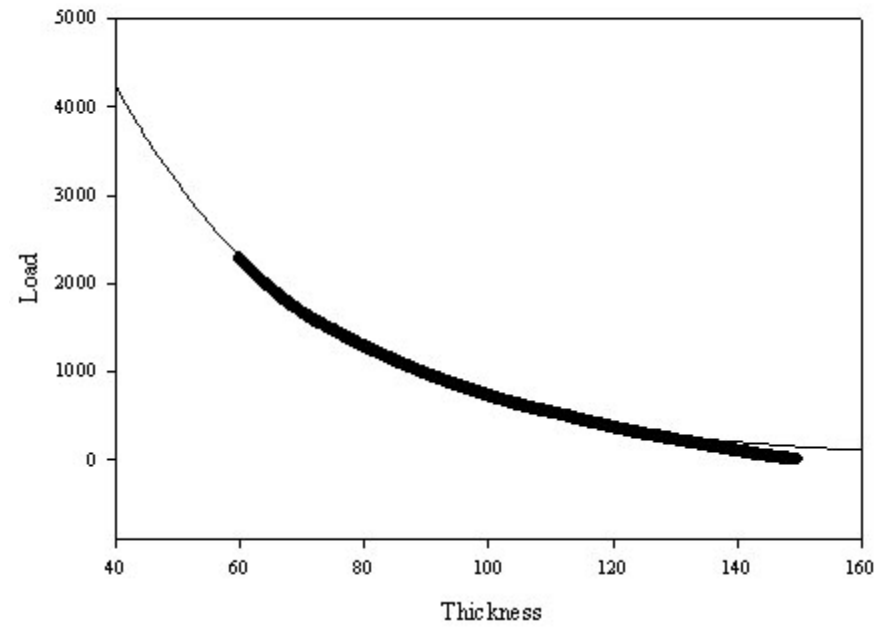
PET-85-1



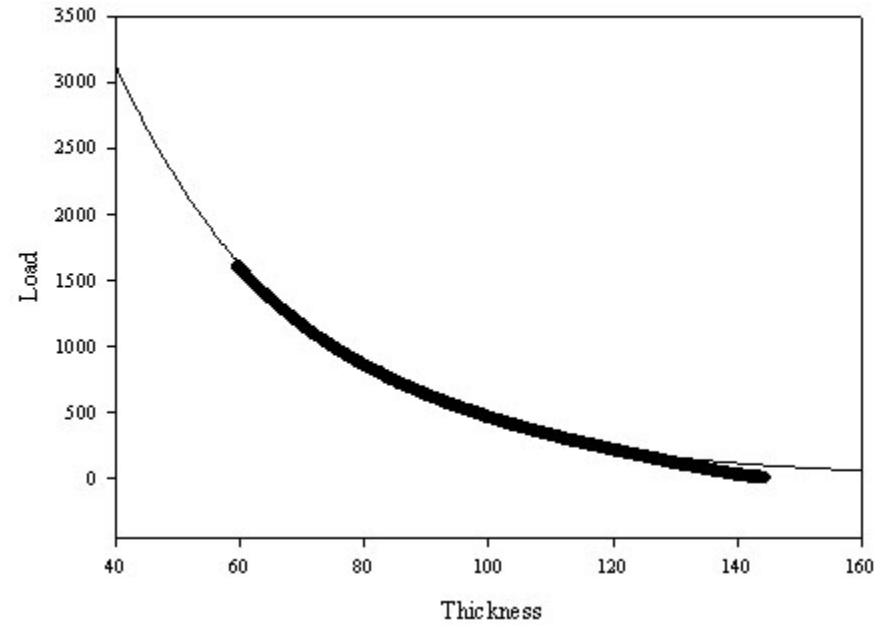
PET 120-3



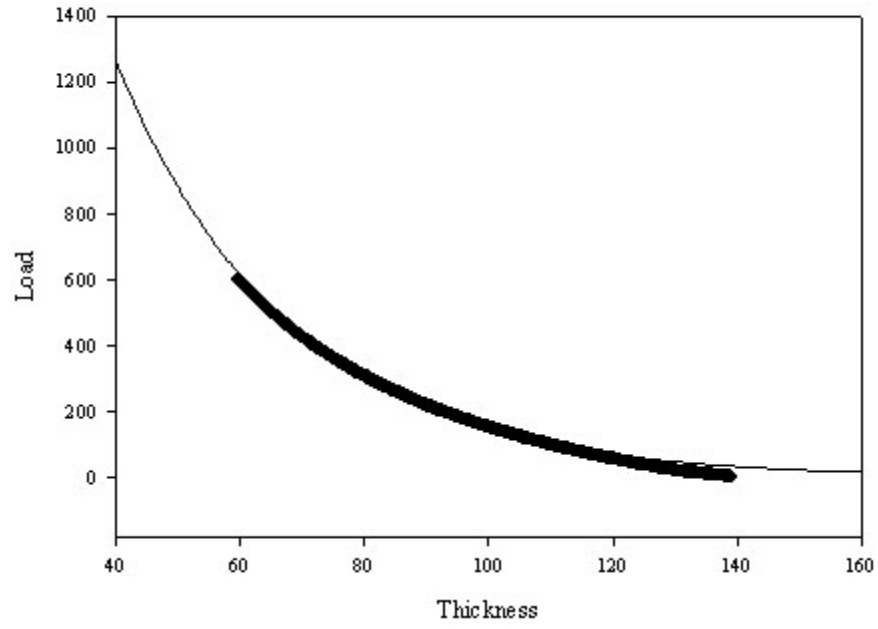
PP-85-1



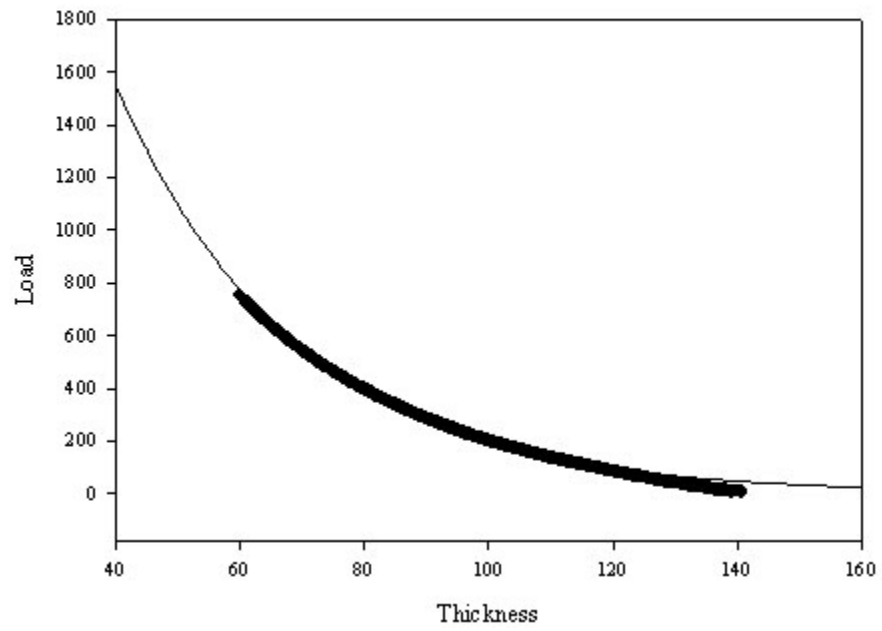
PP-120-1



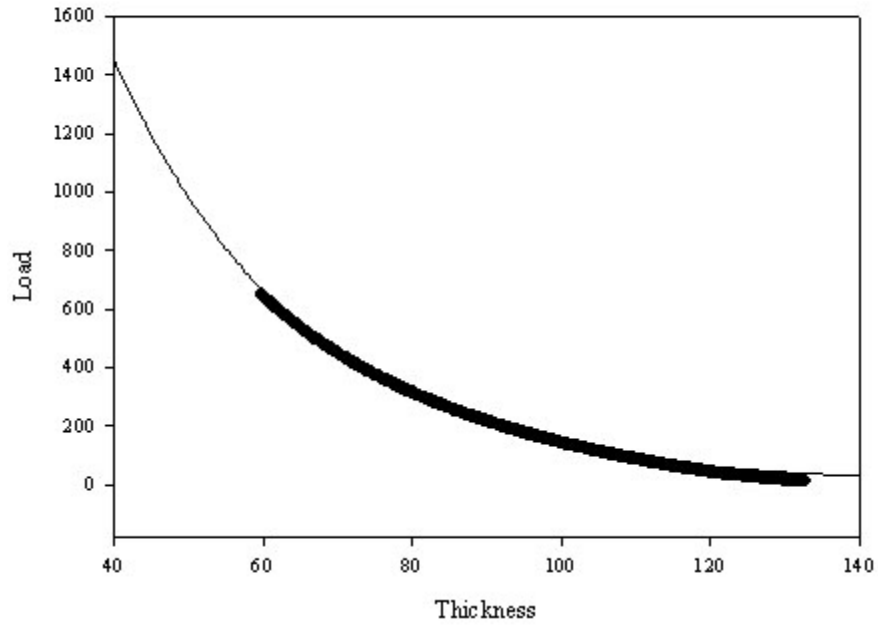
82-85-1



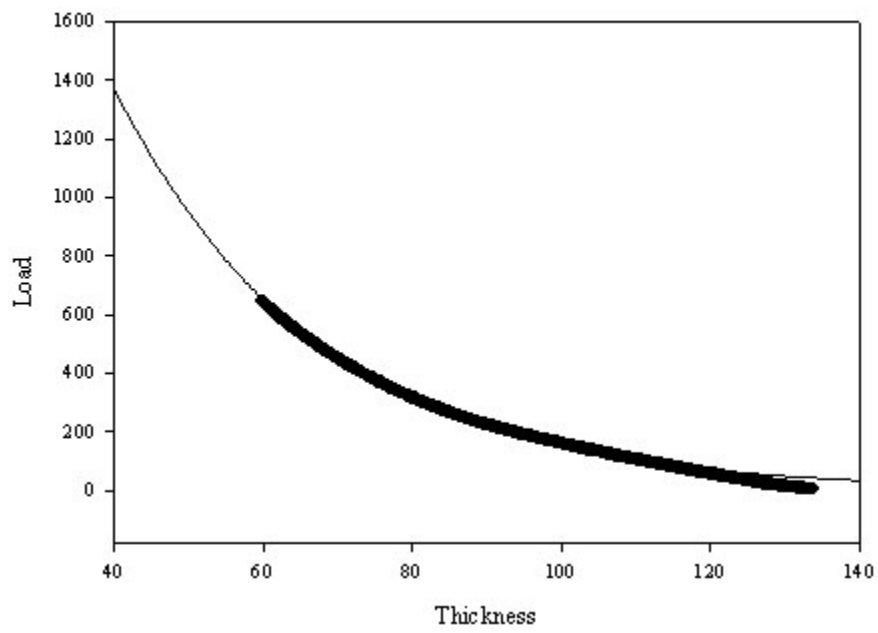
82-120-1



63-85-2



63-120-1



**FIGURE 2:** Examples of Openness Exponential Fit Curves

Graphs given in figure 2 illustrate samples of exponential fit of openness data of all experimental fibers for both experimental production speeds. The following annotations were used when labeling the graphs:

82: Fiber type of 80/20 PET/PP bicomponent.

63: Fiber type of 63/37 PP/PET bicomponent

PET: Fiber type of 100% PET.

PP: Fiber type of 100% PP

85: Carding condition of carded web at 85m/min production speed.

120: Carding condition of carded web at 120-m/min-production speed.