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An Exploratory Analysis of the Relationships between Cotton Fiber Properties and Needlepunched Nonwoven Characteristics

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An Exploratory Analysis of the Relationships between Cotton Fiber Properties and Needlepunched Nonwoven Characteristics

by

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Dedication

For my family and friends, who have provided me with their unconditional love and support throughout the course of my Master's degree.

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Abstract

An Exploratory Analysis of the Relationships between Cotton Fiber Properties and Needlepunched Nonwoven Characteristics

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Nonwovens represent one of the booming sectors in the textile industry today with a significant projected growth both domestically and globally. At present, cotton is supplanted by synthetic fibers in nonwovens, thereby limiting its utilization in an important market sector. One of the major challenges for cotton is the high variability and lack of uniformity associated with fiber properties. Currently, manufacturers do not take this variability into account while selecting cotton for nonwovens. Therefore, it is essential to understand the effect of fiber properties on the nonwoven fabric characteristics in order to address this problem of variability. Bridging this knowledge gap can help increase cotton's market share in the nonwoven sector and maintain its competitiveness in the fiber market.

This project was an exploratory study to investigate the effect of cotton fiber properties on nonwoven fabric properties. Twenty different samples of Upland cotton with various combinations of fiber length and maturity parameters were used for this research. The fabric mechanical properties – tensile and burst strength, pore structure characteristics and permeability were measured and investigated in this study. The relationships between various raw fiber properties and the measured fabric characteristics were analyzed.

The breaking strength of the fabric showed significant relations with fiber length and maturity. Using multiple regression analysis, an equation was derived to predict the specific breaking strength of the fabric from the mean fiber length and maturity ratio values of its constituent fibers. Though bursting strength and permeability showed significant single relations with several fiber properties, the multiple regression analysis returned a single significant predictor in each case – fiber length and fabric density respectively.

Results observed from this study show that the constituent fiber attributes have significant relationships with the nonwoven fabric characteristics. Taking these fiber properties into account during raw material selection for cotton nonwovens would be advantageous as manufacturers can optimize quality, and also predict final product characteristics. Future studies focusing on the inter-fiber interactions in cotton nonwovens, comparisons between 100% cotton and synthetic blended nonwovens etc. will help gain better understanding, and contribute towards improving cotton's marketability and utilization in the nonwoven industry.

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CHAPTER 1
Introduction

The widespread availability and excellent properties of cotton such as its easy dyeability, softness, and hygroscopic behavior makes it the most widely used natural fiber in the manufacture of apparel and other consumer goods. The world cotton consumption for the year of 2011/12 has been predicted to be more than 25 million metric tons [1]. This agricultural crop is a significant contributor to the US economy, and specifically to the Texas economy with more than 40% of the US cotton being produced in Texas according to a United States Department of Agriculture (USDA) report in January 2011 [2]. Thus, cotton is an important commodity and a major source of livelihood for the farmers in Texas. Despite its historic position as the leading fiber in the market, cotton has recently been facing major challenges and steep competition from synthetic fibers in traditional textile applications and particularly in technical utilization sectors such as nonwovens.

The cotton industry had spearheaded the industrial revolution in the 18^{th} and 19^{th} centuries and continued to aid industrial development but the fact that cotton is a natural fiber poses a multitude of challenges and has capped its possibilities for development in recent years. Since their introduction in the late 1950's, synthetic fibers have captured consumers' interest due to their easy care and durable nature and also their low prices. Manufacturers have also shown high interest in these fibers due to their ease of production, low cost and most importantly the high predictability or consistency exhibited by the fiber properties because of the 'made-to-order' nature of synthetic fibers. These relative advantages have helped synthetic fibers surge ahead of the traditional fibers and even 'the king' – cotton, to gain a major share in the textile market. New products are now being designed and developed to utilize the extraordinary properties that can be fulfilled by man-made fibers. Even with constant research and development, cotton has been unable to retain its market share in the textile industry. Barring the area of apparel and wearable textiles, the technical textiles industry comprising of automotive textiles, geo-textiles, smart clothing, protective textiles etc. favors synthetic fibers over cotton. A market report in 2002 by David Rigby Associates [3], confirms this with statistics showing that 66% of cotton staple fibers were utilized by the apparel industry, whereas only 7% was used in the technical textiles industry. This was in sharp contrast to the 28% of polyester staple fibers being consumed in the technical textiles industry. Therefore the technical textiles industry can be considered as an area with great potential for growth with respect to cotton utilization.

Early research and development to meet the challenge posed by synthetic fibers has contributed towards the improvement of the intrinsic fiber properties of cotton. Researchers have been able to successfully improve the crop yields of cotton and also properties such as strength, length etc. Though it is difficult for cotton to match the high production rates and exceptional levels of uniformity, predictability and adaptability offered by synthetic fibers, lately the advantageous characteristics of cotton such as its environment friendliness and biodegradability have emerged as its prominent marketable features. The increasing environmental concern among consumers and the trends to 'go green' have brought the focus back on natural fibers and cotton. Moreover, increasing synthetic fiber costs have moderated the price gap between natural and synthetic fibers. It is essential to utilize these characteristics of cotton and build on the increasing popularity to increase its market share and offer new products utilizing cotton.

Exploring new avenues for the utilization of cotton is an essential step for increasing cotton's market share in the textile industry. Cotton has always been the preferred material in the apparel and home textile sector but hasn't been utilized to its full potential in the field of industrial textiles. Nonwovens are the major materials used in industrial and technical textiles. The use of cotton in nonwovens is limited, and only in recent years have researchers started exploring the possibility of cotton in nonwovens. Though it has a potential for utilization in the nonwovens industry, cotton's growth is hampered due to its natural variability. The fact that each cotton fiber has a unique length, strength and fineness value, and these properties vary between fibers taken from the same plant, is a factor that plays against the selection of cotton as raw materials for nonwovens with high end applications. In the conventional textile industry, this issue of variability was resolved by a large number of research studies that investigated the effect of cotton variety, fiber properties, fiber-fiber interactions, and effect of manufacturing parameters on the final properties of cotton yarns and fabrics. These studies contributed to the existing knowledge about cotton manufacturing, and have been able to help manufacturers understand the factors affecting variability, and also successfully help them predict their yarn and fabric properties. While the issue of variability has been addressed with respect to cotton yarns and woven fabrics, the same needs to be done for the use of cotton in non-conventional textiles like nonwovens. Little knowledge exists about how different grades of cotton and their intrinsic fiber properties like length, strength etc. would affect the quality of the final nonwoven fabric. Thus, there exists a need in cotton nonwoven technology to understand the influence of fiber properties on the final product, in order to control the variability and increase the predictability of product properties. Therefore, extensive research in this area is essential for the successful adoption of cotton in the non-conventional textile industry. Previous studies by researchers and the Nonwovens Cooperative Research Center (NCRC) at North Carolina State University have focused extensively on the development of nonwovens. But none of these studies have looked into the effect of constituent fiber properties on the fabric characteristics in cotton nonwovens.

The aim of this research is to analyze the effect of individual cotton fiber properties like length, strength, and micronaire on the final fabric properties of nonwovens produced by needlepunching technology. Understanding these relations will help in predicting the properties of the produced nonwoven fabric at the time of raw material selection. Production of cotton nonwovens with desired properties using a simple and economical technology such as needlepunching will increase its popularity among manufacturers, specifically for disposable/hygiene applications and even for use in automobiles. This will work towards increasing cotton’s competitiveness and utilization in the textile industry.

CHAPTER 2

Background and Literature Review

2.1 COTTON

Cotton has been used in textiles since prehistoric times. The abundance of cotton and the relative ease to manufacture textiles from it combined with its excellent properties makes it the most popular fiber with consumers and manufacturers alike. Cotton is the most preferred material for home furnishings and apparel especially for children's wear and those worn close to the skin, and hence its consumption has always been on the rise. With increasing population, the world cotton consumption witnessed a fourfold growth from 5.35 million metric tons of cotton being consumed during 1945/46 to nearly 24.95 million metric tons in 2010/11 as shown below in Figure 1.1. This growth is expected to continue with cotton consumption predicted to reach 26.206 million metric tons by the year 2014/15. Thus, cotton is seen to be a major commodity for consumers all over the world.

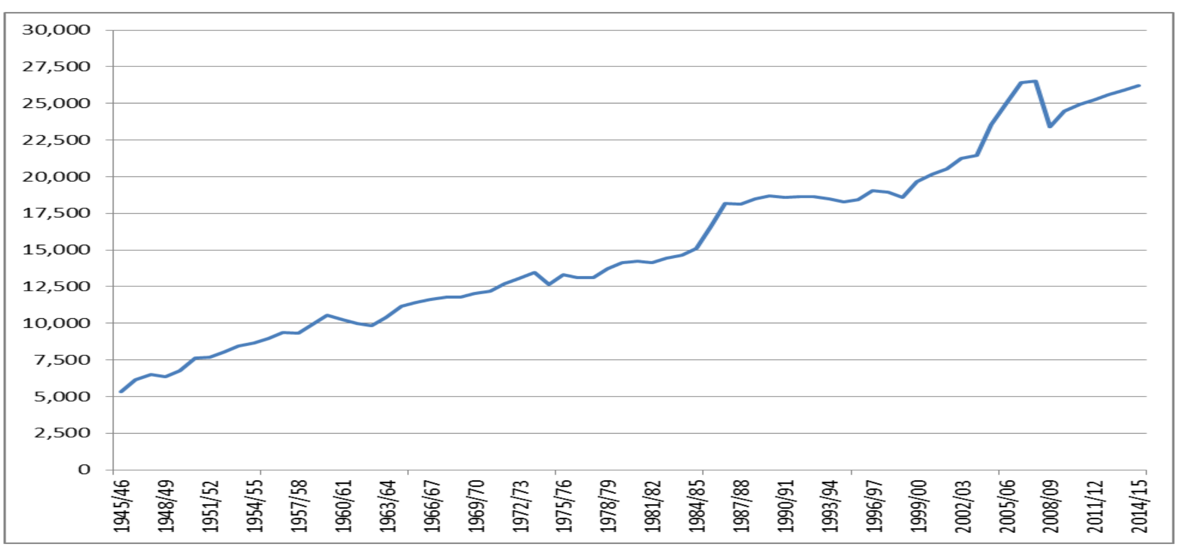

Figure 1.1 World cotton consumption over the years

The United States is currently the third largest producer of cotton in the world, after China and India according to the USDA reports for 2010/11 [4]. In Texas where 30% - 40% of the US cotton is produced, the gross value of cotton production, which is the direct economic output, was estimated at $2.07 billion in 2005 [5]. This $2.07 billion generated by the cotton industry supported more than 48,000 jobs in Texas of which 23,191 were directly related to cotton and farming; 17,901 were indirect jobs like input suppliers and 7,553 were jobs supported by household spending [5]. More recent data from the National Cotton Council of America for the 2008 crop year reveals that the cotton industry in Texas helped generate revenue of more than $5.5 billion and supported nearly 38,106 jobs and 7,688 businesses [6]. With more than 18 million bales of cotton produced in the US, the country is the leading exporter of cotton in the world. But on the other hand, the domestic consumption of US cotton by industries has been over the years from 60.39% being consumed in the year 1997/1998 to less than 24% consumed in 2007/2008 [1]. This is an issue of great concern for the US cotton and textile manufacturing industry.

2.2 Cotton Utilization and its Challenges

Cotton is the most widely used fiber in the manufacture of apparels and other consumer goods such as home furnishings, bath towels, bed sheets etc. It is also used in a diverse mixture of end-products including book-bindings, coffee filters, handbags, fishnets, diapers, tents, industrial hoses and wipes. According to a market report published in 2002, about 66% of the staple cotton produced in the world is utilized for manufacturing apparel, the home furnishing and household textiles sector together constitutes 27%, and the remaining 7% of cotton being produced is used in technical or industrial products [3].

The main challenges concerning the utilization of cotton in the industry are primarily due to its natural variability and secondly, due to the competition cotton faces from the synthetic/chemical fiber industry with respect to cost, uniformity and fiber properties.

2.2.1 Natural Variability

The issue of natural variability in cotton has been a major concern to the textile industry for a long time. Unlike chemical fibers manufactured under controlled conditions, natural fibers like cotton are dependent on a variety of factors including growing conditions like soil type, temperature, amount of precipitation, and also on the genetic variety of the plant. All these factors have an impact on the final properties of cotton fibers, resulting in each fiber being unique with respect to its individual properties. This natural variability in cotton fiber characteristics makes it difficult not only to decide the processing parameters for manufacturing, but also to predict the end product properties. Continuous research and genetic engineering have been able to improve cotton's intrinsic characteristics and uniformity. Also, textile researchers have been studying the effect of individual cotton fiber properties on the final yarn/fabric quality in the conventional textile industry. With the development and evolution of textile production technology, the industry continues to depend on the research of fiber-final product relations. Such research studies have added to the existing knowledge database of textile manufacturing industry. This knowledge helps in the prediction of final product properties and also during fiber selection for products with specific end uses. The lack of such research in the nascent cotton nonwoven industry is an issue that needs to be addressed in order to tackle the problem of natural variability for the development of the cotton nonwoven industry.

2.2.2 Inter-Fiber Competition

Since the late 1960's, cotton has been facing stiff competition from synthetic fibers. Cotton's inability to meet growing consumer demands has been one of the main reasons that spurned research and growth of chemical fibers in the market. The relatively higher processing costs for cotton when compared to synthetics until the late 1990's also played a role in depreciating cotton's competitiveness in the market. Cotton being a natural crop takes time to produce fibers and thus cannot compete with the high production rate of chemical fibers. Weather fluctuations and other natural disasters have always haunted cotton farmers and caused worry about their cotton crops. Recent natural calamities in major cotton suppliers China and Pakistan have resulted in a loss of crop and thereby a shortage of cotton to support the high demand levels in the industry. The high demand and low supply cycle has resulted in an increase in cotton prices over the last year, with prices of cotton reaching over $1.90 per pound confounding experts about price movements in the near future [7]. Besides cost and availability, uniformity and improved properties of synthetics are the other factors that helped champion the popularity of chemical fibers. Driven by profits, manufacturers turned to synthetic fibers which offer high uniformity, and were cheaper and easier to use during manufacturing apparel or other end products. Advancements in technology have helped the synthetic fiber industry in a twofold manner – first by developing advanced fibers and fostering new end uses/ applications for these fibers and second by increasing the capacity of synthetic fiber production. This has led to a decline in the use of cotton in the industry. As the world population increased over the years, it was observed that this disparity between natural fibers and synthetics/chemical fibers also increased. Synthetic fibers have gained significance as natural fibers are not able to meet the demands of the increasing population. This is evident from the graph shown below in Figure 1.2 which shows the decline in the market shares of cotton over the years.

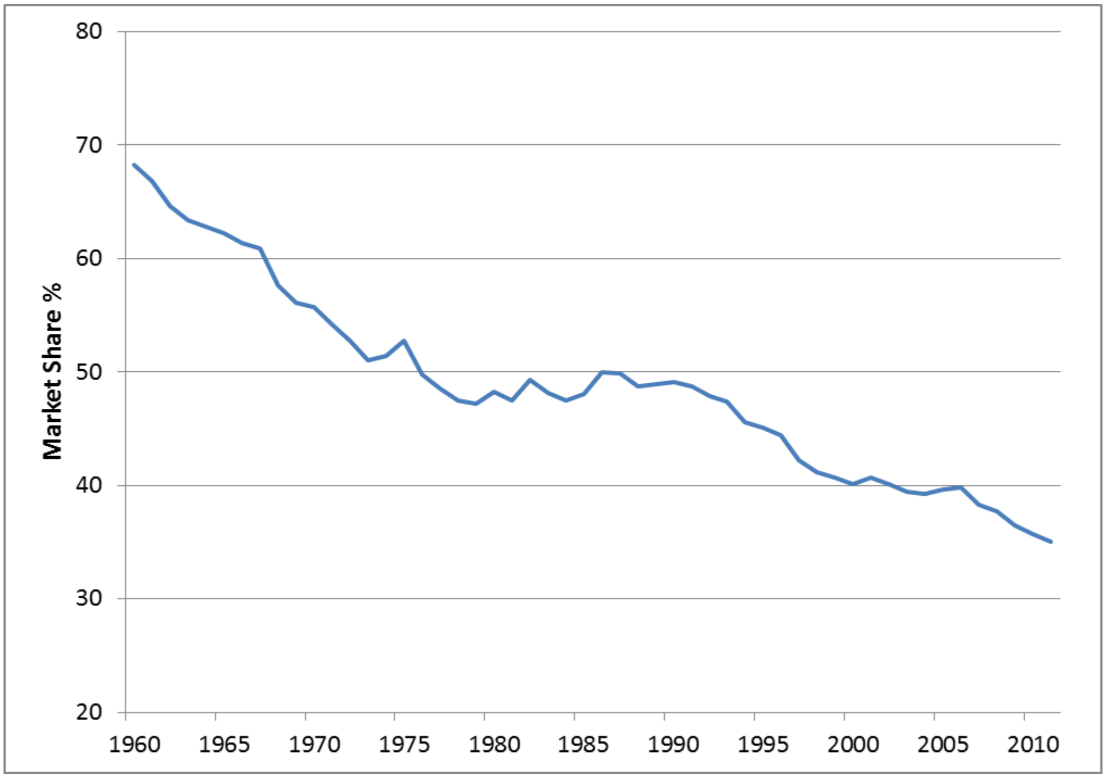

Figure 1.2 Cotton market share over the years

With current oil prices going above $110 per barrel, the price of synthetic fibers is also posed to increase. Increasing energy costs, overhead expenses and other production inputs will soon result in the removal of the 'low-cost fiber' status that synthetics enjoy [7]. But even with this increase in synthetic fiber prices in the last few years, cotton hasn't been able to regain its lost market share, and this trend is expected to continue unless new end uses and areas for cotton utilization are developed.

2.2.3 Opportunities for Cotton Utilization

The advantage cotton has over synthetic fibers is that it is environment friendly and renewable. Increasing awareness among consumers about pollution, disposal issues and concern for nature, as well as governmental policies regarding recycling advocates the use of natural fibers in all textile applications. Cotton is the most widely available natural fiber that has the potential to support this movement and satisfy the environment friendly demands.

Thus constant research and development on improving cotton properties and yield have helped improve cotton's marketability to textile manufacturers. But in order to regain and maintain cotton's market share, research must also focus on expanding its utilization. Cotton is seen as a material that can capitalize on the momentum from the eco-friendly movement to its benefit, and expand and grow its market base with new end uses by substituting and replacing chemical fibers. There exists potential for cotton in new applications besides apparels and home furnishings. The use of cotton in the technical textiles sector still has to be thoroughly investigated in order to fully exploit its potential.

2.3 NONWOVENS AND TECHNICAL TEXTILES

Traditionally cotton has been used as knits and woven materials to produce garments, bedspreads, sheets, window shades, towels etc. The apparel and home textile industries, together constitutes the conventional textile industry. With industrialization and advancements in technology, the use of textiles has spread to a variety of applications such as in construction materials, medical applications, industrial products, packaging materials etc., constituting a whole new sector of technical textiles in the industry. Sometimes referred to as para-textile materials or processes, this non-conventional textile sector has in recent years been growing at a fast pace. Market forecast reports by David Rigby Associates claim the technical textiles applications to "have a far more positive outlook than other fibre, textile and clothing markets" with an annual average volume growth between 4% - 5% in developing countries. The nonwovens sector is a major area in the technical textiles arena with "technical textiles and nonwovens accounting for over one-quarter of all textile consumption in weight terms" [8].

The nonwovens and composites categories were proclaimed to be the fastest growing sectors in the technical textiles field according to a 2002 report by Chang and Kilduff [9]. The volume growth rate for nonwoven materials was predicted to reach 5.4% by 2005 according to their report, which was higher than the predicted growth rate for traditional fabrics (1.7%) and other textiles (3.4%) consumed in the technical textiles industry [9]. A more recent study by IntertechPira in November 2010 reported that "the global nonwoven market is projected to reach $40.1 billion by 2015 with a CAGR(Compounded Annual Growth Rate) of 8.5% from a $26.7 billion 2010 base" [10]. Nonwoven materials are increasingly becoming a part of our day to day life, being used in applications varying from household and personal wipes to industrial and automotive materials. In 2008, the global nonwoven industry was valued at more than $14 billion at the roll goods level and growth of this sector is expected to continue [11]. Currently, the global sales of nonwovens according to the Association of the Nonwoven Fabrics Industry (INDA) is reported to be around $23 billion to $24 billion [12]. Slowly but steadily nonwovens have been increasing their marketshare and penetrating into the daily lives of consumers, becoming a necessary commodity.

2.3.1 What are Nonwovens?

Nonwovens, as indicated by their name are fabrics that are not woven or produced by other methods such as knitting. The formal definition of a nonwoven according to the International Standards Organization (ISO) describes it as "A manufactured sheet, web or batt of directionally or randomly oriented fibers, bonded by friction, and/or cohesion and/or adhesion, excluding paper and products which are woven, knitted, tufted, stitch-bonded incorporating building yarns or filaments, or felted by wet milling, whether or not additionally needled. The fibers may be of natural or man-made origin" [13].

More recently INDA and EDANA, organizations promoting the nonwoven industry, have proposed to amend the existing definition for nonwovens. A part of the proposed definition is as follows –

> "A nonwoven is a sheet of fibres, continuous filaments, or chopped yarns of any nature or origin, that have been formed into a web by any means, and bonded together by any means, with the exception of weaving or knitting. Felts obtained by wet milling are not nonwovens" [14].

As a result of the extensive marketing done by manufacturers and promotion organizations, today nonwoven fabrics are all around us and have become an integral part of our everyday lives [15]. Nonwoven fabrics were initially created to utilize the short fibers from spinning waste and other unspinnable fibers but with its low cost, high manufacturing speed and wide spectrum of properties, these fabrics have achieved success in plenty of applications [15, 16]. In particular, nonwovens have achieved widespread popularity in the disposables segment. They are widely used in the personal care and hygiene sector as baby diapers, feminine hygiene products, dry and wet pads etc.; in the healthcare sector like operation drapes, gown, face masks and wound dressings; in homes as wipes and dusters, home furnishing, curtain and drapes, fabric softeners and so on. The applications of nonwovens are not limited to disposables alone. They are used in durable products too and their applications include interlinings; industrial filters; construction materials as roofings, insulators; geotextiles; automotive components, and also floor covering applications [16].

At present, most nonwovens are manufactured as highly functional products for specific end uses. Like in the case of woven materials, the properties of nonwovens can be altered to make them conductive, flame-retardant, water-repellent, porous, antistatic, breathable, and absorbent and so on based on the requirements. Nonwoven materials can be made aesthetically appealing by finishing methods such as coating, printing, flocking or dyeing. They can also be combined with other materials to form complex laminates [17]. Thus nonwovens are seen to be versatile materials with ample scope for development and use in every possible field.

In comparison to the effect of fiber properties on woven fabric properties, constituent fiber properties may have a greater impact on the properties of nonwoven fabrics due to the high levels of fiber-fiber interaction in nonwovens resulting from their structure and method of manufacturing [18]. Hence it is important to study the fiber-fabric properties to build a knowledge base that can help in the development and manufacturing of nonwovens.

2.3.2 Fibrous Raw Materials for Nonwoven Manufacturing

Fibers are the building blocks of nonwovens and are determinants of the nonwovens' end uses. All natural and man-made fibers can be used in the manufacture of nonwoven fabrics. The selection of fiber depends on the required end product features and the cost effectiveness [18]. Krcma[18] discusses the effect of fiber properties on the properties of nonwoven fabrics and says that the constituent fiber properties are important since there is a strong similarity in the stress-strain curves of the bonded fabric and the corresponding fibers.

2.3.2.1 Natural Fibers

Natural fibers used in nonwoven production include vegetable and animal fibers. Wool and silk are animal fibers that have been used in making nonwovens. Traditionally wool was used to manufacture felts, which are similar to nonwovens. Due to their limited availability and high price, the use of these fibers is limited to certain specific high end specialty nonwovens [19].

Compared to animal fibers, the vegetable fibers find more use in nonwoven production due to the relative abundance of resources. Almost all fibers including jute, flax, hemp and coir can be used to manufacture nonwovens but have limited applications in the industry. With the exception of cotton, all the other natural fibers have restricted scope in the production of nonwovens due to the limited availability of the fiber, properties suited for specific end uses, and regional nature of the fiber. The king of fibers, cotton, with its good strength – dry and wet, structure and hygroscopic nature, met with a fair degree of success during its use in early nonwovens. Over the years this success declined due to the problems posed by the impurities in cotton, which affected the production as well as the final product quality [19]. The improvements in cotton processing over the years has tackled this issue and more and more bleached cotton fibers with excellent moisture absorption properties are being used in the manufacture of nonwovens. Nonwoven manufacturers have left behind their inhibitions concerning difficulties in processing cotton and have opened up to using cotton in the production of hydroentangled and needlepunched nonwovens [20].

2.3.2.2 Chemical Fibers

The evolution of chemical fibers over the years has strongly influenced their use in nonwoven bonded fabrics and has increased rapidly since the end of the 1950s [19]. Increased knowledge about the properties of chemical fibers and their interaction effects on the fabric quality have led to more careful selection of the commercially available fibers for different end uses in nonwovens. Chemical fibers provide manufacturers with the advantage of being able to alter the fiber properties, by changing the fiber length, diameter settings during production, in order to meet the specific requirements of the fabric end use [18]. Compared to synthetics, cellulose based chemical fibers are less popular and are mainly used in nonwovens requiring high absorbency [19].

Synthetic chemical fibers are the most widely used type of fibers in nonwoven production. Amongst all the fibers, polypropylene, polyester and rayon are the major fibers consumed by the nonwoven industry according to Moreau [21]. The major reason for this being the low cost, uniformity, ease of processing of synthetic fibers and also the wide range of properties associated with synthetic fibers like deniers, lengths and degree of crimp. All this coupled with the worldwide production and widespread availability of these fibers in large quantities have championed the use of these fibers in nonwovens [21]. This category of fibers is constantly evolving, trying to overcome its drawbacks such as low moisture absorbency and offer new properties to the end product.

2.3.2.3 Other Fibers

The other fibers used in the nonwovens industry as described by Guobiao [22] include glass, silicate, carbon, boron and metal fibers. They have unique properties and most of them exhibit high values of tenacity and modulus. These fibers are used on small scale and only in limited applications [22].

2.3.3 Nonwoven Fabric Production

While traditional nonwovens consisted of needlepunched felts, advancements in technology have led to the development of various methods for the fast and efficient preparation of high quality nonwovens. Each of these methods employs different sets of raw materials in order to produce specialty nonwovens for specific end uses. The steps in the production process and some of the main technologies used for the production of nonwoven fabrics are as discussed below.

2.3.3.1 Web Forming

The first step in the manufacturing of a nonwoven fabric is the preparation of the fiber web or batt. “The creation of a loosely held together sheet structure, usually by the laying down of fibers, is called web forming” [15]. The fiber webs or batts can be prepared from short staple fibers or long filament fibers in three ways – wet laying method, dry laying method or by the direct laying method.

The manufacture of nonwovens by wet laid process, derived from the paper making process typically comprises of dispersion of fibers in water, followed by continuous web formation on a wire cloth through filtration and finally consolidation, drying and batching up of the web. Wet laid fabrics are highly isotropic due to uniform blending and random orientation of constituent fibers. Though it has a high production rate, in most commercial processes, the wet laid process is generally restricted to manufacturing webs with very short fibers [15, 23].

The dry laid process for the manufacture of fiber webs for nonwoven manufacturing can be done by either of the two processes – air laying and carding. Similar to the wet laid process, air laying suspends the fibers in air and collects them as a sheet on a screen producing web with randomly oriented fibers. The fiber deposition is achieved with free-fall or with the aid of compressed air and/or suction. Carding on the other hand “uses rotating drums covered with fine wires and teeth that comb fibers into parallel arrays” [15]. The webs produced by carding have anisotropic properties with increased web strength in fabrics produced in the direction of the machine. It is possible to increase the weight and thickness of carded webs by overlapping layers of webs or by pleating a single web. The carding method for web preparation is commonly used for cotton nonwovens [24].

“Direct laid processes make webs directly from fibers as they are being spun from molten plastic” [15]. Spunbond and meltblown are two useful direct laid processes that produce nonwoven fabrics by web forming and bonding. In both processes, molten plastic is extruded through a spinneret, and is blown out and spread on a moving belt to form a web. The hot molten fibers/filaments adhere to each other at their crossing points thus bonding the fabric. Compared to webs produced by other methods, both spunbond and meltblown webs have sufficient web strength after formation due to the bonding between its constituent fibers.

2.3.3.2 Web Bonding

Web bonding is a vital part of the nonwoven manufacturing process. As mentioned earlier, webs made from processes other than spunbonding and meltblowing have little strength and it is necessary to consolidate the web in order to impart strength to the fabric. The choice of method for web bonding is dependent upon the constituent fibers in the web and the properties required from the final fabric. The methods of web bonding can be broadly classified into mechanical, chemical and thermal bonding as discussed below.

Mechanical bonding by needling is the oldest technique employed for web consolidation. Needling bonds and imparts strength to the fabric by entangling the fibers in the web. Needlepunched fabrics are produced from bulky and dense carded, air laid or spunbond webs [15]. “The principle of the production of needled fabrics consists in an inter-binding of the basic fibrous layer (web) with fibre strands which are either perpendicular or inclined to the web plane the web being considered a three-dimensional system with mostly surface oriented fibres” [18]. The main functional element during this process is a set of barbed needles, which are punched through the web and can hook and seize tufts of fiber through the web thereby bonding it. Sawhney et al. [24] state that though needlepunching “is not as efficient as other mechanical or chemical bonding technologies, it still is at least 20 times faster than the traditional weaving and at least 5 times more productive than knitting”. Needlepunching is the preferred process to manufacture heavy fabrics for use as geotextiles and for heat and sound insulation materials.

Another popular mechanical bonding technique employed in the industry is the process of hydroentanglement also known as spunlacing which employs fine, high speed jets or currents of water to impact on the surface of a fibrous web causing the fibers to get entangled, intertwined or even knotted with other fiber elements in the web. This method is used for the commercial production of lightweight nonwovens used in disposable hospital and hygiene products and home furnishings [15, 25].

Besides mechanical bonding, binding of the matrix fibers in the nonwoven can be achieved by the application of adhesive chemicals on the fabric by padding, spraying, or in the foam form [26]. Also processes such as hot-air treatment, calendaring and welding of nonwovens are widely used in the industry to produce thermally bonded nonwoven fabrics [27].

2.4 COTTON IN NONWOVENS

Currently the nonwoven industry is dominated by the synthetic fibers such as polypropylene and polyester [21]. Cotton, though used in this industry, has been relegated to the second spot in comparison with synthetic fibers and is used mostly in blends for nonwoven manufacturing. Though synthetic fibers have been successful in the nonwovens industry till date and have been able to meet market demands, the non-renewable nature of the raw materials for synthetic fibers urges to look into alternate raw material sources. Increase in synthetic fiber costs owing to the slow depletion of fossil fuel resources, is a matter of acute concern for the synthetic fiber industry. As discussed by Negulescu *et al*. [28] with increasing crude oil prices, touching up to $100 for a barrel of oil, synthetic fiber costs as raw materials is not promising. Another issue that emphasizes the need for alternate raw materials is the non-biodegradability of synthetic fibers.

Lately, increasing consumer awareness regarding the disposal of synthetic nonwovens and shortage of landfill space, have become pressing issues that has urged the industry to look into alternate biodegradable fibers that can be used for nonwovens [29]. This increasing consumer knowledge and awareness about product biodegradability demands a shift from the use of petroleum based synthetic fibers to natural fibers in all products. This shift towards natural fibers is also seen in the automotive industry, which uses nonwoven materials for boot liners, shelf trim, oil and cabin air filters, molded bonnet liners, heat shields, airbags etc. [16]. Schmidt[30] states that the worldwide consumption of nonwoven fabrics in the car industry amounted to approximately 420 million m^2 in 1996. With the rise in population and subsequent boost in number of cars manufactured, the consumption of nonwovens by the automotive industry is only bound to increase. In order to promote the use of environmentally safe products in vehicles, legislations in the U.S and Europe have issued special directives to incorporate recyclable and biodegradable fibers in nonwovens used in automotive components like hoods, mats, liners, etc. The directive, which came into effect at the turn of the century, predetermined the deposition fraction of a vehicle to be 15% for the year 2005, and gradually to be reduced to 5% for the year 2015 [31]. All these factors have substantiated the need for extensive research and development of natural fibers as substitutes for synthetics in nonwovens. Cotton with its wide range of properties as well as worldwide availability in large quantities serves as the best contender from natural fibers to take synthetic fibers place in the nonwoven industry and satisfy the increasing demand for eco-friendly nonwovens.

100% cotton nonwoven fabrics still find very little takers in the industry due to the perception that it cannot measure up to the properties of synthetic nonwovens. Sawhney *et al*. [32] state that "single fiber characteristics, such as the tensile strength, modulus, dirt and mildew resistance, etc., of cotton generally are not comparable with those of equivalent manufactured fibers, such as polypropylene (PP), polyethylene (PE) and polyethylene terephthalate (PET), that are widely used in industrial durable nonwovens". Nonwovens with made-to-order synthetic fibers are easier to manufacture and have more predictable properties than nonwoven fabrics made with natural fibers that have a high degree of variation in their fiber properties, and are therefore the more preferred raw materials in the industry. But it is still too early to rule out the possibility of cotton as a substitute as very little work has been done on studying the effect of cotton fiber properties in nonwovens. Keeping in mind the limitations of cotton being a natural fiber, it would be unreasonable to expect features of cotton nonwovens to be at par with those of synthetic nonwovens, though a marginal improvement in the properties of the cotton nonwovens will still be a significant achievement.

2.4.1 Previous Studies on Cotton Nonwovens

With over 38% of the nonwoven products being disposable, natural fibers are being increasingly used in nonwovens. Cotton tops the list of natural fibers being used in nonwovens, by constituting nearly 20% of the raw materials used in the nonwovens industry [33]. The following literature reviews previous studies which have investigated the use of cotton in nonwovens.

Researchers at the University of Tennessee have been conducting studies on cotton-based nonwovens since 1987, using different kinds of binder fibers in combination with cotton to produce nonwoven fabrics. Nonwovens for this study were produced by carding cotton and the binder fiber followed by thermal bonding of the carded webs by calendaring. Suh *et al.* [34] state that cellulose acetate had been found to be a good binder for producing nonwovens with cotton, and the blended nonwoven fabric was found to be good except for its low tensile strength. To overcome this, researchers have used acetone vapors as solvent in a pre-treatment process to decrease the softening temperature of the cellulose acetate fiber and impart relatively higher strength to the webs [34]. But the use of acetone has not been accepted by industries due to practical complications posed by its flammable nature. Bhat [35] states that recent research in this field has led to the use of Easter *Bio* GP copolyester unicomponent (Eastar) fiber, which has a relatively low softening temperature (~ 80°C) and is completely degradable into carbon dioxide, water and biomass; and PLA fiber as binders to successfully produce cotton based nonwovens.

As discussed earlier, mounting petroleum prices, environmental concern and competitiveness in the industry, are pushing automotive manufacturers to look at natural fiber composites with the final goal of weight and cost reduction. Studies conducted by Mueller, Bhat, Parikh and Kamath [31, 36] have evaluated the performance of cotton-based nonwoven composites for automotive and other similar purposes. They have used blends of natural fibers, mainly cotton with binder fibers to produce hot pressed nonwovens used in moldable composites for automobile components. Their studies have shown that cotton and other natural fibers (kenaf and flax) have good ability to bond with binder fibers. It was seen that blending kenaf or flax enhanced the tensile strength and modulus of the cotton composite. The results of the study suggest that employing web production methods such as air-laying or carding produces more uniform webs that can help improve the tensile properties of the composites [31, 36].

Presenting the latest developments in natural fiber composites, their processing technologies and fields of applications, Mueller and Krobjilowski [37] have stated cotton based composites to have remarkably good acoustical properties. The authors also emphasize that though desired acoustic properties can be achieved, it was at the expense of mechanical strength and stiffness of the composite [37]. In another study conducted to evaluate the acoustical properties of nonwovens, Jiang, Chen and Parikh [38] tested three nonwoven composites produced with a base layer of raw cotton nonwoven and a surface layer of glass fiber nonwoven, cotton nonwoven, and carbonized and activated cotton (ACF cotton) nonwoven respectively. The results of the study showed that "the nonwoven composites with cotton as a surface layer had significantly higher sound absorption coefficients than the glass fiber surfaced composite in the frequency range from 100 to 6400 Hz". The sound absorption ability was significantly increased by the carbonization and activation of the cotton nonwoven. The authors conclude ACF cotton nonwoven as a low cost option for high performance acoustical materials [38].

Another area utilizing cotton in the nonwoven industry is that of medical textiles and hygiene applications. Materials used in these industries are mainly for short term use and disposable in nature. Parikh et al. [39] have reported the sales and production of hydroentangled nonwovens to challenge that of traditional woven gauze for medical applications. They state that this is due to the better aesthetic and physical characteristics, and cost competitiveness offered by nonwovens; and cotton is one of the most frequently used fibers for the production of spunlaced nonwovens for medical applications [39]. A study by Hong, Kim, Kang and Oh [40] looked into the mechanical and surface properties of different nonwoven fabrics, cotton spunlace, tencel spunlace, poplypropylene (PP) thermal bonded and PP thru-air bonded carded web (TABCW), used as top sheets in feminine and infant hygiene products. The results of the study show that synthetic nonwoven top sheets had higher coefficient of friction, and relatively superior water transport abilities and abrasion strengths compared to cotton and tencel fabrics. On the other hand, in the wet condition, the cellulose spunlaces had higher frictional coefficients. Moreover, the study also found that consumers preferred cellulose spunlaces over treated PP nonwoven fabrics [40].

Wadsworth, Suh and Allen. Jr. [41] reported the successful production of a stretchable cotton-containing nonwoven at the Textiles and Nonwovens Development Center (TANDEC) at the University of Tennessee. The composite laminate used for their study was produced by feeding a thermally bonded cotton/polypropylene (60/40) nonwoven fabric at the end of a spunbond line, resulting in bonding by entrapping the cotton fibers between the spunbond filaments. The resultant cotton-spunbond laminate's stretchability was improved by subjecting it to a heating and stretching 'consolidation' process. According to the authors, the laminate fabrics so produced demonstrate excellent wetting, wicking rates, water adsorption, flexibility, extensibility and are suitable for short-wear-cycle apparel and products such as medical isolation gowns, head covers, bed sheets and consumer products such as disposable underwear, towels, wipes etc. [41]. Bhat, Gulgunje et al. [42] explored the utilization of nanomaterials for the development of functional cotton-based nonwovens. They successfully developed cotton-based nonwovens incorporated with nanophase manganese (VII) oxide (NM7O) with high anti-bacterial properties with potential for use in healthcare and hygiene products [42].

Investigating the improvement in copper ion absorption for flax and/or cotton fiber nonwoven mats treated with citric acid, Marshall et al. [43] have found that fiber mats composed of 100% flax and 75%/25% flax/cotton blends had better copper ion absorption than 100% cotton or 50%/50% cotton/flax blended mats. However the authors have reported that while all the different composition samples suffered significant strength loss during citric-acid treatment, the 100% cotton nonwoven mats were not affected and had no loss of strength [43]. Another similar study conducted by Sekine et al. [44] developed a metal adsorbent by graft polymerization onto a cotton nonwoven fabric. The resulting product was able to rapidly adsorb mercury (Hg) and was found to be biodegradable as well. Such developments can help improve cotton's functionality and its use in industrial/technical textiles.

Parikh, Calamari et al. [45, 46] discuss the use of cotton in highloft nonwovens instead of the traditionally used synthetic fibers. Their research which used cotton blends for producing highlofts and compared perpendicular laid (p-laid) and cross laid (c-laid) nonwovens, conclude that p-laid nonwovens are superior to c-laid both in compressional and recovery behavior. The p-laid nonwoven fabrics with low levels of cotton exhibited compressional behavior similar to that of synthetic fiber fabrics. These cotton blended fabrics also have an added advantage of being more biodegradable compared to the synthetic nonwovens [45, 46].

Looking at the potential of greige cotton in hydroentangled nonwovens compared to the traditionally used bleached cotton, Sawhney et al. [47] conclude from their study that the absorbency of greige nonwoven fabrics can be controlled by optimizing the processing parameters like water pressure etc. and that greige cotton is a promising candidate with huge scope for use in the nonwovens sector.

Biodegradability is a major factor that advocates and promotes cotton's use in nonwovens. Goynes et al. [29] tested the biodeterioration of hydroentangled nonwovens with various blends of cotton. The results of the study showed that 100% cotton nonwoven fabric was completely biodegradable, while the chemically bonded cotton nonwoven exhibited controlled degradation and the 100% polypropylene nonwoven did not undergo biodegradation at all. They concluded cotton to be an ideal biodegradable material due to its excellent properties and the possibility of protection from degradation that can be provided by coating the fabric. The authors suggest that the use of cotton in disposable products should be encouraged [29].

2.4.2 Cotton in Needlepunched Nonwovens

One of the earliest studies researching the potential of cotton needlepunched nonwovens was done by Choi, Kwon and Moreau [48]. The authors investigated the effectiveness of cotton nonwovens from gray cotton as oil spill cleanup. Four needlepunched fabrics were made with different compositions of cotton (100% cotton, 80% cotton/20% polypropylene, 65% cotton/35% polypropylene and 50% cotton/50% polypropylene) and one with 100% polypropylene. It was found that while there was an increase in strength of the nonwovens, the oil sorption capacity decreased with the increase in the number of passages through the needlepunching equipment, and increase in polypropylene percentage. The cotton containing nonwovens were also able to retain more than 60% of their initial oil sorption capacity for five repeated applications. Thus the authors conclude that "partial or complete replacement of synthetic sorbent with cotton is possible as an oil spill cleanup application" [48].

A lot of work has also been done by researchers at the USDA, ARS Southern Regional Research Center, New Orleans on developing needlepunched nonwoven fabrics from naturally colored cottons. The work by Kimmel et al. [49] compared 'brown' nonwovens from naturally pigmented cotton and 'white' nonwoven from normal cotton. It was found that brown nonwoven were weaker than white nonwovens, but their strength and other performance parameters could be enhanced with the help of suitable reinforcements like aramid or nylon scrim. But the brown nonwovens were found to exhibit better insulation and flame-resistant properties when compared to the white nonwovens [49]. To study this advantageous property of colored cottons, Yachmenev, Kimmel and Delhom [50] developed nonwoven composites from brown, white and green cottons and compared their insulation properties. It was seen that nonwovens from brown and white cottons had higher thermal conductivity compared to the nonwoven from green cotton. Also reinforcing the nonwoven composites with cotton scrim resulted in a significant higher thermal conductivity value [50]. Research and development in this area could open up a new arena for colored cotton utilization in insulation and building materials.

Looking into needlepunched cotton nonwovens for use in absorbent products, Kiekens and Zamfir [33] conclude that needlpunching parameters specifically the feed rate, can influence the nonwoven characteristics, such as the average weight and the liquid absorption speed. They state that the liquid absorption speed of their tested cotton nonwoven was similar to that of commercially available absorbent products. The authors also suggest that the liquid absorption speed, if not satisfactory, can be improved by alkaline cleaning of the needlepunched nonwoven by the elimination of natural impurities and waxes [33].

A more recent study by Parikh, Chen and Sun [51] compared cotton and polyurethane needlepunched underpads used along with natural fiber composites of jute, kenaf, or cotton with PET and PP to achieve significant noise reduction properties. Though the use of polyurethane underpads gave better results for absorption coefficient, the use of cotton underpads suit the requirements of environment friendliness and renewability as well [51].

Most of the research so far in the field of cotton needlepuched nonwovens has dealt with developing new end uses or evaluating the impact of process parameters, such as feed rate, intensity of needling and other needlepunching parameters, on the properties of the final nonwoven fabric. Not much importance has been given to selection of cotton used for the production of these nonwovens. Researchers have used commercially available cotton or cotton supplied by supporting organizations for their study, irrespective of its properties. Hence not much is known about the effect of the constituent cotton on the fabric. The influence of fiber properties on the final cotton nonwoven fabric properties, is an area that is yet to be explored. Understanding the fiber-final fabric interactional effects will help in predicting fabric properties and performance, and also in the selection of fibers during nonwoven production. This will help in the production of cotton nonwovens with required properties for use in the disposable/hygiene industry and even in the automobile industry. Such work can help in increase the utilization of cotton in the nonwovens and technical/industrial textiles field.

CHAPTER 3

Research Objectives and Approach

3.1 PURPOSE OF THE RESEARCH

For cotton to recapture its lost market share and continue competing with advanced man-made fibers, it is necessary to expand its utilization to areas beyond traditional textiles such as apparels and furnishings. The technical textiles sector is a relatively new and advanced segment of the textile industry. It comprises of textile materials used in products other than garments and includes materials used for construction sound insulators etc., in automobile manufacturing, geo-textiles, for filtration purposes etc. As discussed in the earlier chapters, the nonwovens industry constitutes the major sector in the technical textiles industry and has a high potential for growth. In order to improve cotton's market share and its utilization, it is necessary to harness this boom in the nonwoven industry to cotton's advantage. Capitalizing on the current trend of environmental friendly product, cotton nonwovens can find a niche for itself in the market. Hence it is essential to investigate the potential of cotton in nonwovens in order to develop new areas for its utilization.

At present, cotton nonwovens are primarily used for medical textiles and other disposable products in the industry and are produced mainly by spunlace technology. In nonwoven production techniques such as needlepunching where the forming materials in the final fabric are only the fibers used, the properties of the fabric produced will be largely dependent on the constituent fiber properties. Due to the natural variability of cotton fibers and lack of knowledge regarding fiber-final product properties in cotton nonwovens, there exists a challenge to predict the final fabric properties without actual testing of the fabric. Hence it is necessary to study the fiber-fabric relationship and understand the effect of individual fiber properties on the final fabric properties for the successful creation of a product. Thus adding the element of predictability may help in overcoming the barriers against cotton's use in nonwovens. Correspondence with cotton nonwoven manufacturers have revealed that the cotton used in nonwovens is purchased purely based on its availability and regardless of its fiber properties. No previous research has investigated the interactional effects of cotton fiber properties in nonwoven fabrics. It is hence essential to understand the effect of cotton fiber properties on the final nonwoven fabric properties and its performance.

The broad objective of this study is to investigate new areas of utilization for cotton fibers in non-apparel textile and thereby increase its competitiveness in the industry. The purpose of this research is to study the effect of cotton fiber properties on the final nonwoven fabric properties produced by needlepunching technology. This research will investigate the effect of cotton fiber characteristics such as fiber maturity and length on the final cotton needlepunched fabric properties. Knowledge about this will help nonwoven industries in evaluating the suitability of cotton for nonwoven fabrics targeting specific end uses, aid in fiber selection and prediction of final product properties. This will eventually help in promoting the use of cotton in nonwoven fabrics and thereby increase cotton's market share in the textile industry.

3.2 MATERIAL – UPLAND COTTON

Upland cotton sourced from Lubbock, Texas was used for the preparation of samples for this study. Cotton from three micronaire levels (high, medium and low micronaire) was selected for this study. In each of these three micronaire levels, cotton samples with different lengths were selected. Combination of different micronaires and lengths resulted in different levels of strength in the cotton fiber samples. Thus a total of 20 different samples with various levels of micronaire, length and strength were selected to study the effect of these parameters on the final needlepunched nonwoven fabric properties. Table 1.1 below gives the HVI[1] fiber data of the samples used in this study.

[1] HVI: High Volume Instrument used to determine bulk cotton characteristics for classing

Table 1.1 HVI Data of Selected Samples

Bale#	Micronaire	Length [in]	Uniformity	Strength	Elongation	Whiteness "Rd"	Yellowness "+B"	Leaf
3619	3.0	1.12	82.6	29.4	8.5	78.4	9.2	6
3614	2.9	1.15	80.3	28.4	7.8	81.8	7.8	4
3617	3.0	1.17	81.3	30.1	7.7	82.4	7.9	4
3615	3.3	1.19	82.8	30.7	6.6	81.3	7.9	4
3620	3.4	1.20	82.7	31.2	7.0	80.2	9.0	4
3560	3.6	1.22	82.0	30.1	8.8	82.1	8.7	3
3555	3.3	1.23	82.7	32.4	8.8	81.5	8.6	4
3556	3.7	1.13	82.4	28.2	11.8	72.7	13.3	2
3563	3.9	1.14	82.4	32.9	9.0	79.3	10.7	2
3553	3.8	1.15	82.4	28.6	11.0	73.2	12.7	3
3565	3.8	1.16	81.8	29.7	9.5	84.4	8.2	2
3561	3.8	1.18	82.0	30.5	8.4	79.7	9.4	3
3541	4.6	1.11	80.3	28.1	5.3	77.9	8.0	1
3542	4.6	1.13	81.2	27.2	7.7	73.0	9.3	3
3572	4.4	1.15	83.0	35.9	8.6	81.0	9.2	2
3543	4.5	1.16	82.2	30.7	5.5	72.9	7.5	2
3544	4.6	1.18	81.4	29.2	5.6	74.2	8.7	4
3576	4.4	1.19	84.0	35.6	9.1	79.5	8.7	3
3466	4.5	1.21	84.0	31.5	6.5	76.3	8.4	2
3570	4.4	1.25	84.6	35.7	9.4	79.7	8.5	2

3.3 NONWOVEN SAMPLE PREPARATION

3.3.1 Processing Equipment

The equipment used in the preparation of the nonwoven samples include: (1) Laboratory Carding Machine (Figure 1.3), and (2) Morrison Berkshire laboratory needlepunching loom (Figure 1.4).

Carding is done in order to open the tufts of fibers and create a homogeneous mix of parallelized fibers. The preparation of a card web is the first step in the production of a nonwoven fabric. The carding equipment employed for this purpose was a F105D Universal Carding Machine as shown below in Figure 1.3.

Figure 1.3 Laboratory Carding Machine

The equipment used for the bonding and production of the nonwoven fabric was a Morrison Berkshire Laboratory Needle Punching Loom as shown in Figure 1.4. The loom employed a needleboard of density 130 needles per linear inch. The needles used were fine needles of 40 gauge - Foster 5240795 CON. These fine needles are the best suited for the production of needlepunched cotton nonwovens. The high density needleboard along with the fine gauge needle helped in producing compact and strong cotton needlepunched fabric samples. The loom was operated on intermittent feed mode, working at a speed of 230 strokes/min.

Figure 1.4 Morrison Berkshire Laboratory Needle Punching Loom

3.3.2 Procedure

The nonwoven samples for the study were produced after the preparation and testing of many trial samples. Cotton needlepunched fabrics of approximately 140 GSM and 195 GSM were prepared as trial samples. The trial samples were processed for different number of passages – 2, 4, 6, 8 and 10 on the needle loom to check for the effect of number of passages on the strength of the fabric. This test was used to decide the density of the nonwoven fabric to be used for the study and also to get an idea about how many passages would be required for the production of a nonwoven fabric with maximum strength. The plots in Figure 1.5, shows the average maximum load (in N) of the 140 GSM and 195 GSM nonwoven samples that were needlepunched for 2, 4, 6, 8 and 10 times. It was seen that the average maximum load of the 195 GSM nonwoven kept increasing with the number of times it was passed through the needlepunching loom. Whereas for the 140 GSM nonwoven, the maximum load increased with an increase in number of passages up to 8 passages. The average maximum load observed for the 8 and 10 passages nonwoven fabric are almost the same, and the curve starts to flatten out forming a plateau. As the 140 GSM sample displayed a maximum load that was stable and didn't increase with number of passages after the eighth passage, it was decided to be fixed as fabric density for the preparation of samples for the study.

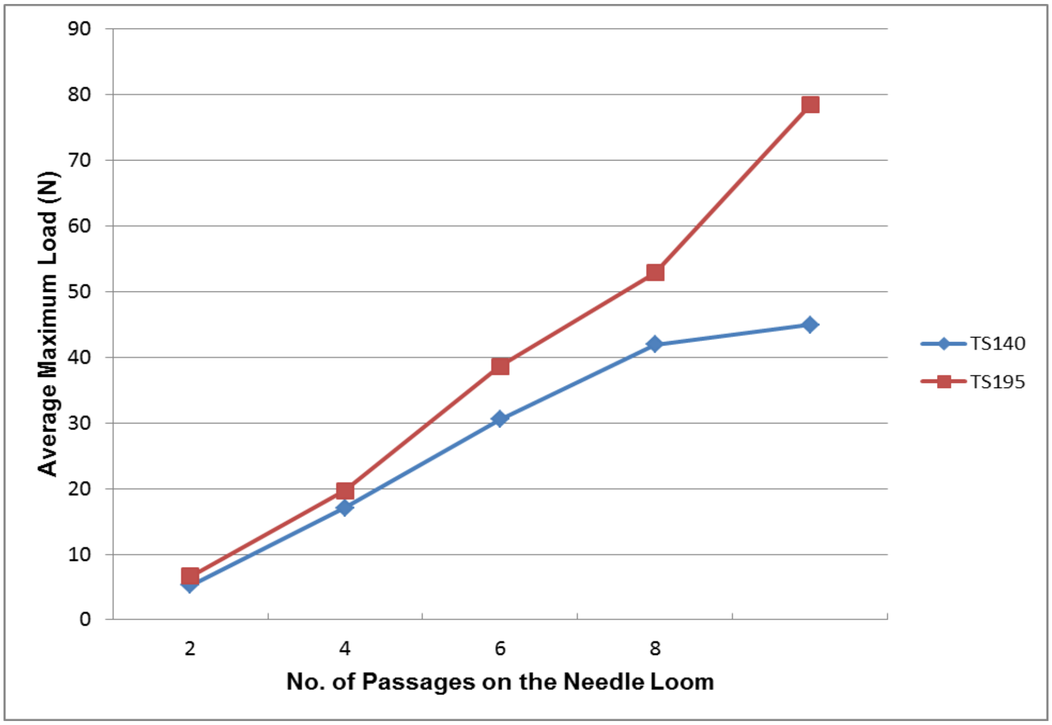

Figure 1.5 Average maximum load plot for 140 GSM (TS140) and 195 GSM (TS195) needlepunched nonwoven samples

In order to ensure that all the samples follow the same trend with respect to their maximum load strength, samples with four extreme combinations – low micronaire short fibers (3619), low micronaire long fibers (3555), high micronaire short fibers (3541), and high micronaire long fibers (3570) were taken. Sample fabrics needlepunched 8 and 10 times were prepared using these fibers. Specimens from all the sample fabrics were tested on the INSTRON for tensile strength as per WSP 110.4 (05) [52] standard test.

The results of the test as seen in the graph in Figure 1.6 shows that except for sample 3570 which had long fibers with high micronaire value, the remaining samples exhibited low variation in strength between the 8 and 10 times needlepunched fabrics. Since the influence of the number of passages on the strength of sample 3570 is significantly high, it cannot be ignored. Hence it was decided that needlepunched nonwoven fabric of approximately 140 GSM, processed for 10 passages on the needlepunching loom will be used for this research.

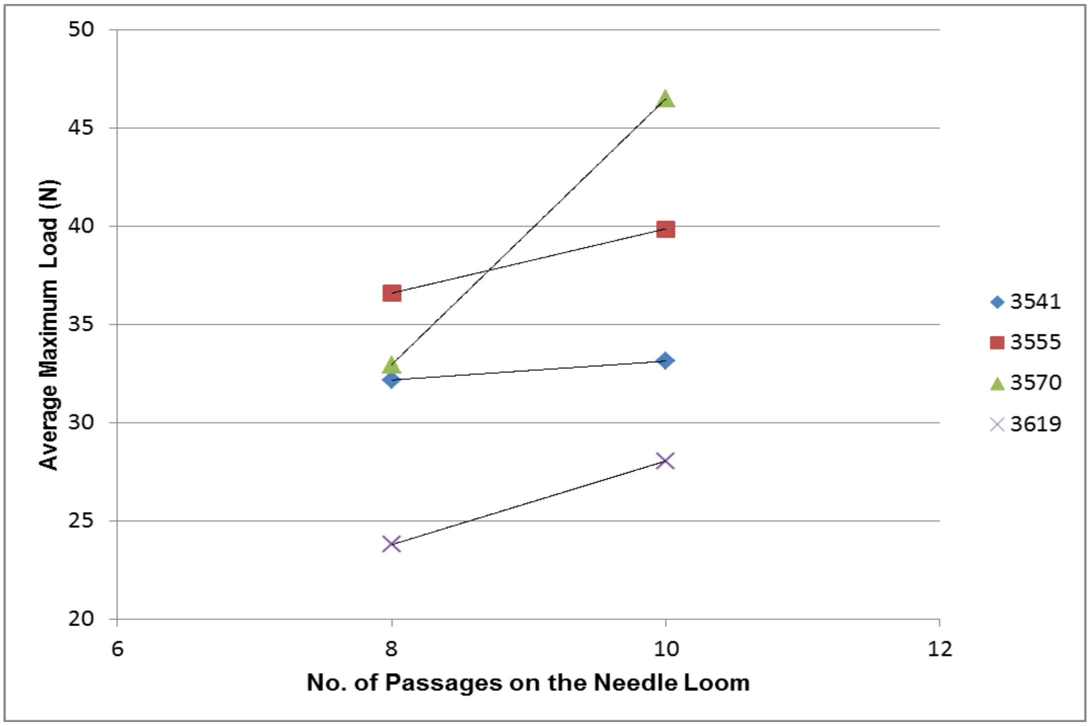

Figure 1.6 Average maximum load values for different cotton samples needlepunched 8 and 10 times

3.3.3 Experimental Protocol

In order to produce a fabric that was representative of all the fibers in the cotton sample, a total of 500g of fibers was taken from different parts of the 5 lb. cotton sample and spread out on a table after manual opening. The opened layer of fibers was then doubled, and from this doubled layer two replications of 150g was selected for all the samples. These replications were named as “Sample No.”- 1, and “Sample No.”- 2. In order to obtain adequate number of specimens required for testing of fabric properties, it was decided to produce two 60”x7” (approx.) nonwoven fabrics of 140 GSM from each of the sample replications.

The stepwise procedure adopted for the preparation of the samples was as given below:

1. The 150g of fibers from each replication were spread out as a uniform layer on a table.

2. 5g of fibers was selected from different parts of the spread layer of fibers and taken for AFIS[2] testing of raw fiber properties.

3. Two sets of fibers, each weighing 35g, were selected from different sections of the spread fiber layer to obtain a random mix from each sample for the preparation of the two nonwoven fabrics required for testing.

3. Both sets of 35g of fibers were carded once and 2.5g of fibers were collected from both the carded webs to get a total of 5g required for the AFIS testing of fiber properties after one card passage.

4. Both the remaining webs were passed through the card for a second time, and again 2.5g of fibers were collected from each of the carded webs to get the 5g required for the AFIS testing of fiber properties after two card passages.

5. Each web, after removal of fibers for AFIS testing, was folded in half along its length and needlepunched 10 times on the Morrison Berkshire loom, alternating between sides to ensure uniform needling.

Thus from the 20 selected fiber samples, a total of 80 nonwoven fabric samples, and 120 AFIS samples, were prepared for the study.

3.4 FIBER TESTING

The fiber samples were sent to Cotton Inc. in North Carolina for testing on the Advanced Fiber Information System (AFIS). The USTER Advanced Fiber Information System (AFIS) is an instrument used to measure the properties of single fibers of cotton. The fiber individualizer in the AFIS individualizes each fiber by separating the lint from the trash and dust present in the cotton sample as shown in Figure 1.7. Figure 1.8 shows

[2] AFIS: Advance Fiber Information System (Described in Section 3.4)

the optical system used to measurement of fiber properties in the USTER AFIS. Each fiber, trash particle and impurity has its own distinct electrical waveform. When a fiber passes through the opto-electronic sensor, it creates an impulse which is converted to an electric signal and analyzed by the computer software of the instrument. This helps in accurately determining the fiber properties of the cotton used in the preparation of the nonwoven fabric. The AFIS measures various useful fiber characteristics such as fiber length, maturity and trash.

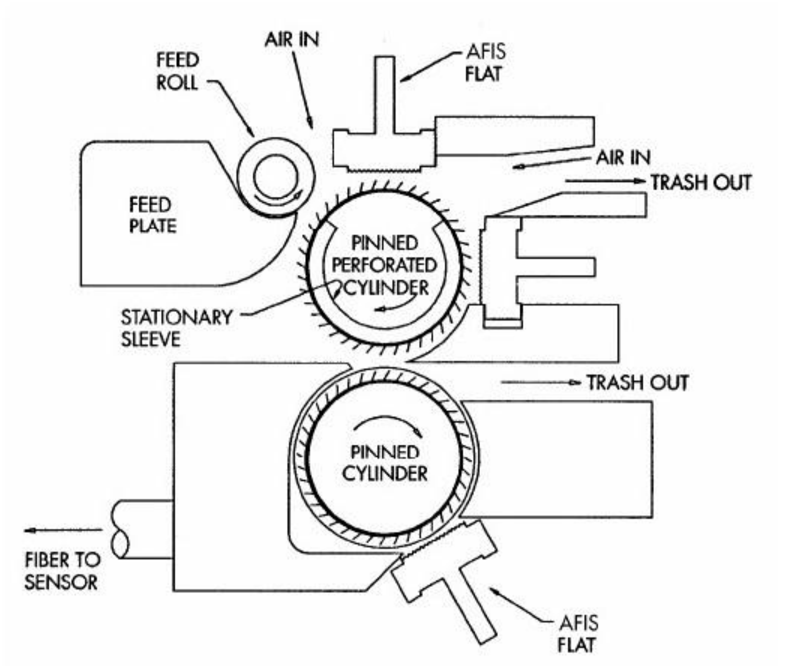

Figure 1.7 USTER AFIS Fiber Individualizer Principle (Source: www.uster.com)

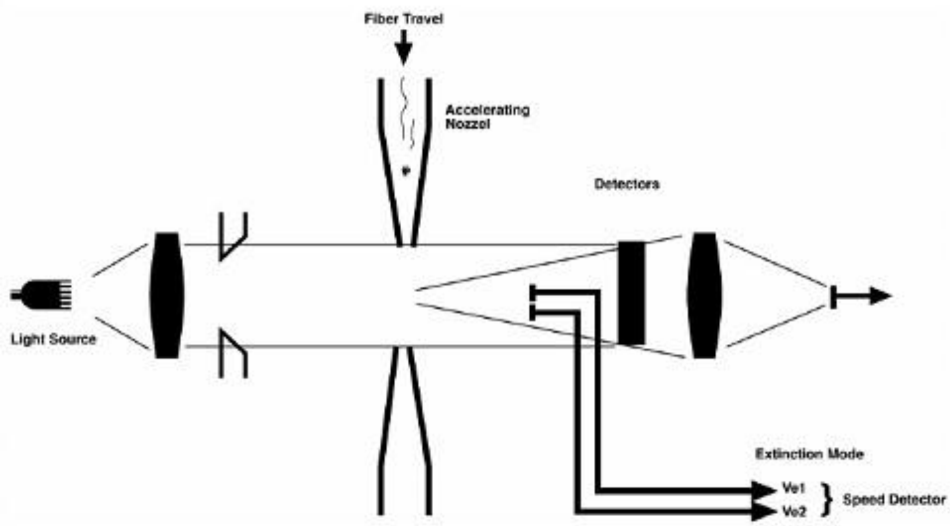

Figure 1.8 USTER AFIS Optical Measurement Principle (Source: www.uster.com)

A total of 120 samples were taken for AFIS testing, which included the 3 samples - raw fibers, fibers after one card passage, and fibers after two card passages, from each of the 40 samples. In addition to the AFIS fiber data, we also have all the HVI data (Table 1.1) used to select the cotton samples. The fiber characteristics measured by these two instruments will be useful in determining relationships between cotton fiber traits and fabric quality parameters.

3.5 NONWOVEN FABRIC TESTING

3.5.1 Tensile Test

The tensile strength of the produced nonwoven fabric samples were tested using a universal tensile tester. The tester used was an Instron 5966, a dual column tabletop system. This tester utilizes pneumatic grips for the setting up of specimens for tensile testing, and Instron Bluehill software for test control, data acquisition, and reporting results with a high level of accuracy. The instrument conforms to the ASTM and ISO standards.

The testing of samples was carried out as per the WSP 110.4 (05) [52] standard for the tensile test of nonwoven fabrics (strip method). Ten specimens of dimension 6” x 1” as shown in Figure 1.9 were taken from the two webs of each of the 40 samples. The specimens were all taken along the machine direction as the fibers were aligned parallel to each other during needlepunching, and not randomly aligned. The distance between the clamps, known as gauge length, was set at 75 ± 1 mm as per the standard, and the rate of loading was set as 300 ± 10 mm/min (12 ± 0.5 inch/min). Figure 1.10 below shows the tensile testing of the nonwoven specimen. The values for breaking load (maximum load), and apparent elongation (extension at maximum load) were recorded for all samples as specified in the test method. The area under the load-elongation curve was calculated to give the work done in breaking the sample. Data for load at break and elongation at break were also captured by the software. Figure 1.11 shows a set of specimens after the tensile test.

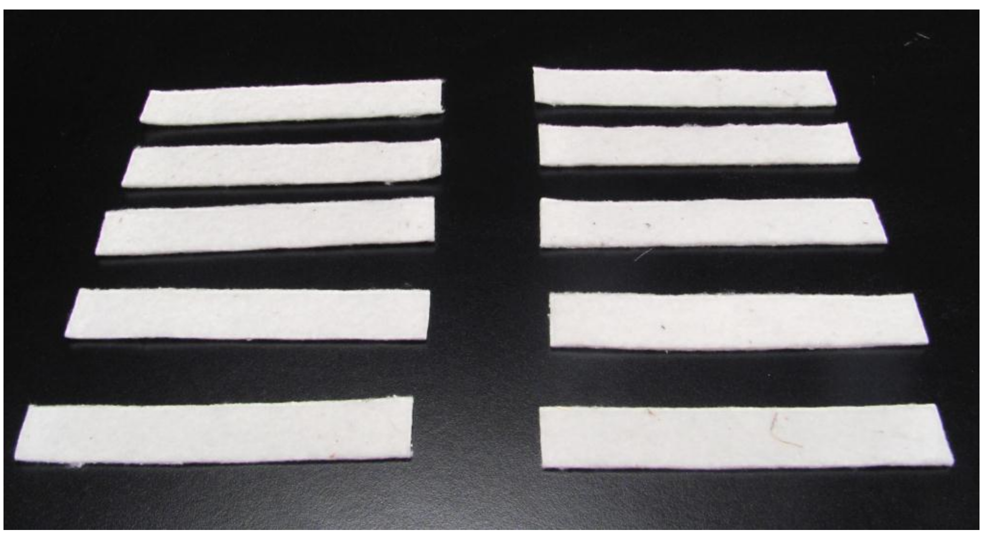

Figure 1.9 Specimens for Tensile Test

Figure 1.10 Tensile Testing of Nonwoven Specimen

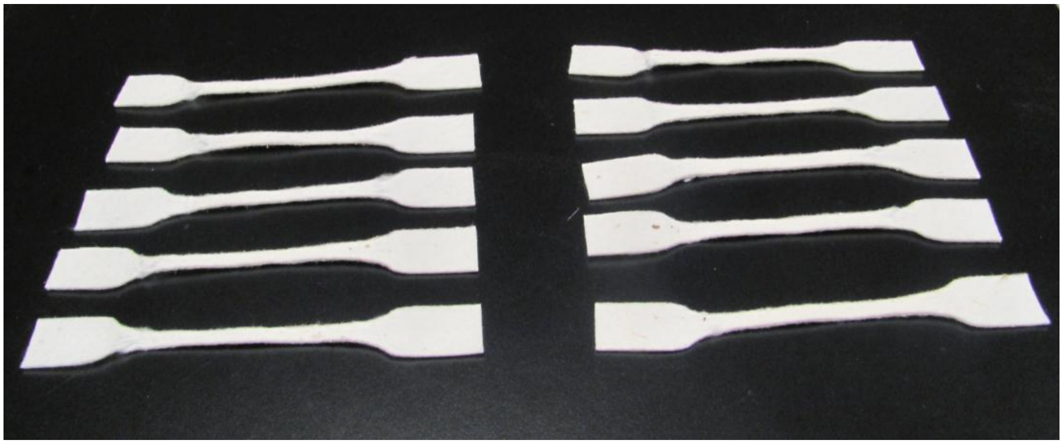

Figure 1.11 Specimens after Tensile Testing

The weight of each specimen was also recorded after testing, in order to calculate the density of the nonwoven fabrics produced.

3.5.2 Burst Test

The same Instron tester described in Section 3.5.1 is used for testing the burst strength of nonwoven fabrics. The pneumatic grips used for the tensile test were replaced with the ball burst attachment for this test. Figure 1.12 shows the INSTRON tester with the ball burst attachment fixed.

Figure 1.12 INSTRON 5966 with Ball Burst Attachment

The test was carried out in accordance with the standard test method for resistance to mechanical penetration of nonwoven fabrics - WSP 110.5 (05) [53]. Five specimens of dimension 5” x 5” were tested from each sample. The loading rate was set as 12 ± 0.5 in/min and testing was carried out as shown in Figure 1.13. The bursting strength (maximum load) and elongation (compressive extension) at peak load were recorded as specified in the test standard and the work done in bursting the sample was computed by the software. The test also gave data for load at break, compressive extension at break and compressive strain at break.

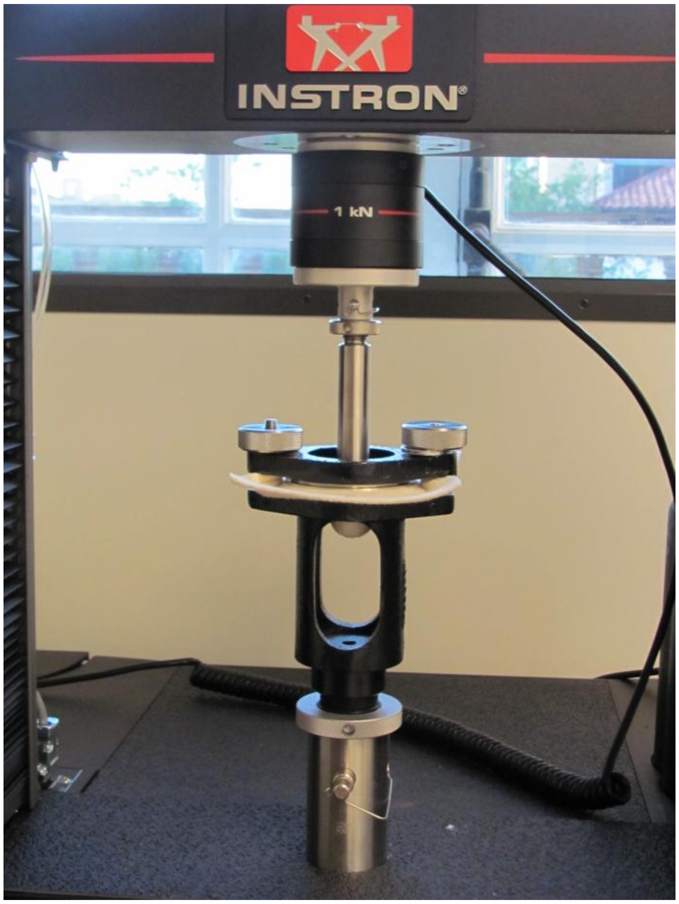

Figure 1.13 Ball Burst Testing of Nonwoven Specimen

3.5.3 Permeability Test

Tests for gas permeability, pore distribution and bubble point (largest pore) were conducted by Porous Materials, Inc in New York using their capillary flow porometer equipment. Fabric samples of dimension 1.5 inch x 1.5 inch were sent to their testing labs for this purpose. The test results gave values for specific flow ($cc/s/cm^2$) which is a measure of permeability, mean flow pore pressure (PSI), mean flow pore diameter (μm), bubble point pressure (PSI) and bubble point pore diameter (μm) of the tested sample.

The Capillary Flow Porometer measures the rate of flow of a liquid or gas through a porous material. This instrument is capable of testing bubble point, mean pore size, pore size distribution, integrity, Frazier permeability etc. The working principle of the capillary flow porometer is shown in detail in Figure 1.14 given below. The displacement of the wetting liquid from the pores by the gas under pressure is measured to give the pore characteristics of the fabric. The capillary flow porometer has been used in various studies to measure pore characteristics and permeability in nanofibrous membranes, battery separator materials, protective textile materials, and nonwovens.

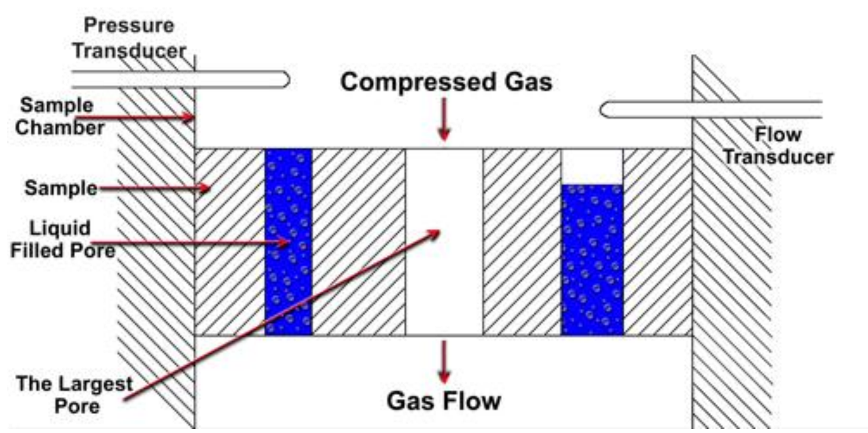

Figure 1.14 Working Principle of Capillary Flow Porometer (Source: Jena, A. and K. Gupta, Pore Structure of Advance Textiles, Porous Materilas, Inc., http://www.pmiapp.com/publications/index.html)

3.6 SUMMARY

All the materials and equipments used in the study, specimen preparation method and the testing methods have been discussed in this chapter. The results from these tests will help in determining significant relationships between fiber properties and fabric properties.

CHAPTER 4

Results and Discussions

4.1 INTRODUCTION

This chapter discusses the results of the tests conducted during this study. The purpose of this research is to investigate the effect of fiber properties on the fabric mechanical properties such as tensile and burst strength, permeability, and fabric structure characteristics. This research also aims to establish relationships between fiber and fabric properties, and propose empirical equations based on the observed significant relations. A total of 20 different cottons were used as samples for this study. Sample preparation and testing were carried out according to the methods specified in the previous chapter. This section describes in detail the different properties that were tested, the results of the tests and the significance of the obtained results.

Important Terms and Abbreviations [54, 55]:

Nep – Nep is a small knot or cluster of entangled fibers.

Mean Length – This gives the average length of the cotton fibers in the sample. It can be measured from the weight distribution (L_w) and from the number distribution (L_n). The number distribution gives the true distribution of the sample by including measurements of every individual fiber. On the other hand the weight distribution is more biased towards longer fibers as they weigh more than shorter fibers.

Length Coefficient of Variation – L_n CV (%) and L_w CV (%) are the coefficient of variation of fiber length by number and by weight respectively.

UQL – Upper Quartile Length (UQL) of the sample is a measure taken by weight which gives the length exceeded by 25% fibers in the cotton sample.

SFC – It is the Short Fiber Content (SFC) in a sample and can be measured by weight (SFC_w) and by number (SFC_n). It gives the percentage of fibers in the whole tested cotton sample that are shorter than 0.5 inches or 12.7 mm.

L5% – This is the length exceeded by 5% of the fibers (by number) in the tested cotton sample.

VFM – Visible Foreign Matter (VFM) gives a percent measure of both dust and trash present in the cotton sample.

SCN – Seed Coat Neps (SCN) are fragments of the cottonseed that still have some fibers attached.

Fineness – The AFIS provides a measure of the gravimetric fineness or fiber linear density, expressed in millitex [mTex] or mg/km.

IFC – The Immature Fiber Content (IFC) is the percent of all fibers within a cotton sample that have a cell wall thickness covering less than 25% of the full area.

Maturity Ratio – Maturity Ratio is the measure of cell wall thickening of a cotton fiber.

4.2 COTTON NONWOVEN SAMPLES

The cotton nonwoven samples for this study were prepared by needlepunching twice-carded webs in a laboratory scale loom as described in the previous chapter. Each web was needled ten times, alternating between sides during processing. The input fiber weight was controlled in order to maintain comparable densities between samples. The density as estimated by the total weight and area ranged from 95 - 125 GSM as shown in Figure 4.1. The variation in density seen in Figure 4.1 is probably caused by differences in area of the fabric given that the fiber weight was strictly controlled to the 0.5g. From the correlation matrix between fabric and fiber properties (Table B.1 in Appendix B), significant relationships were observed between the fabric density, weight, and area, and the fiber maturity and fineness measurements. The fabric density is seen to have a positive relation with micronaire (R=0.79), fineness (R=0.80) and maturity ratio (R=0.59). Figure 4.2 shows the relationship between fineness and fabric density.

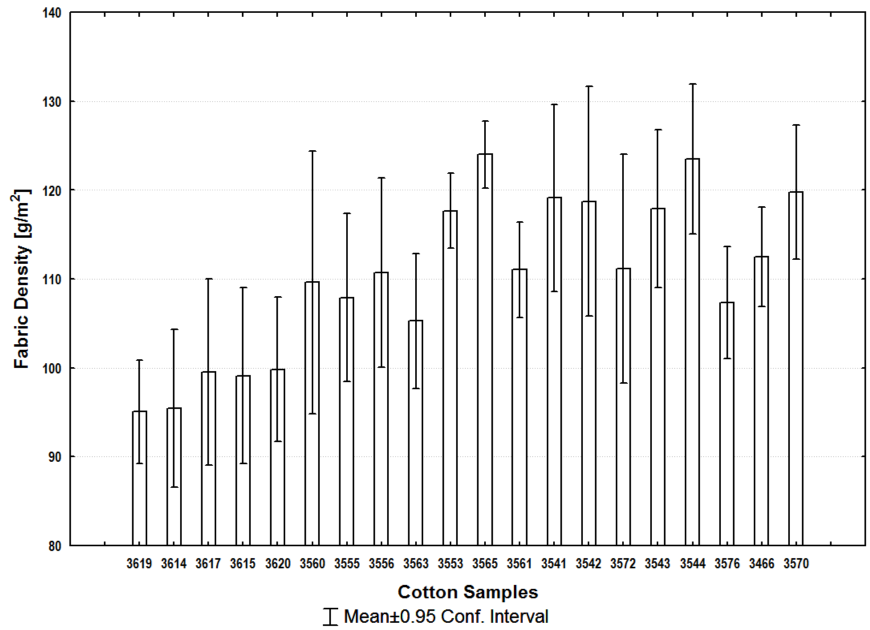

Figure 4.1 Fabric Density for all Cotton Samples with 95% CI

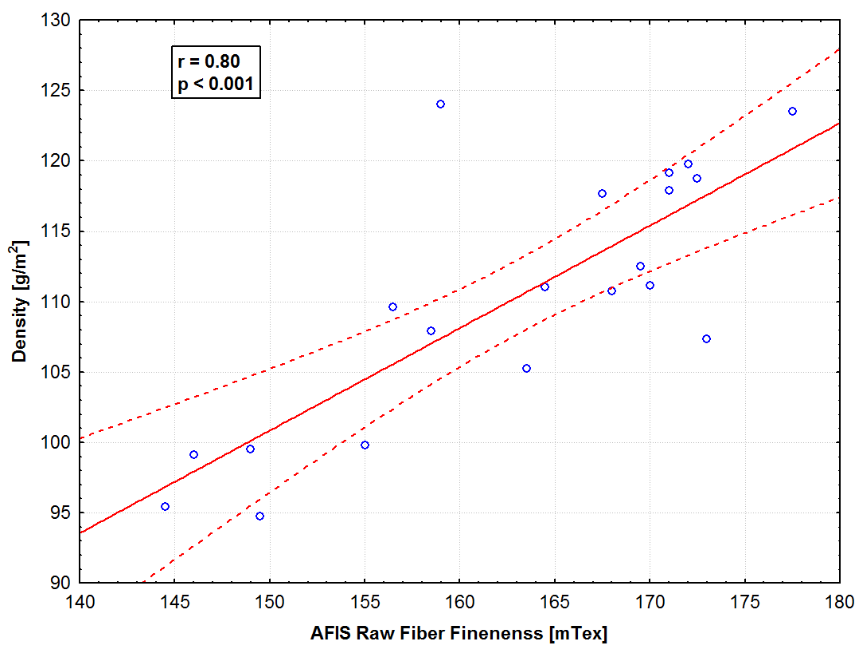

Figure 4.2 Nonwoven Density vs. AFIS Raw Fiber Fineness

A significant relationship is also observed between fabric area and fiber fineness. Figure 4.3 shows that the area of the nonwoven fabric decreases with an increase in constituent fiber linear density.

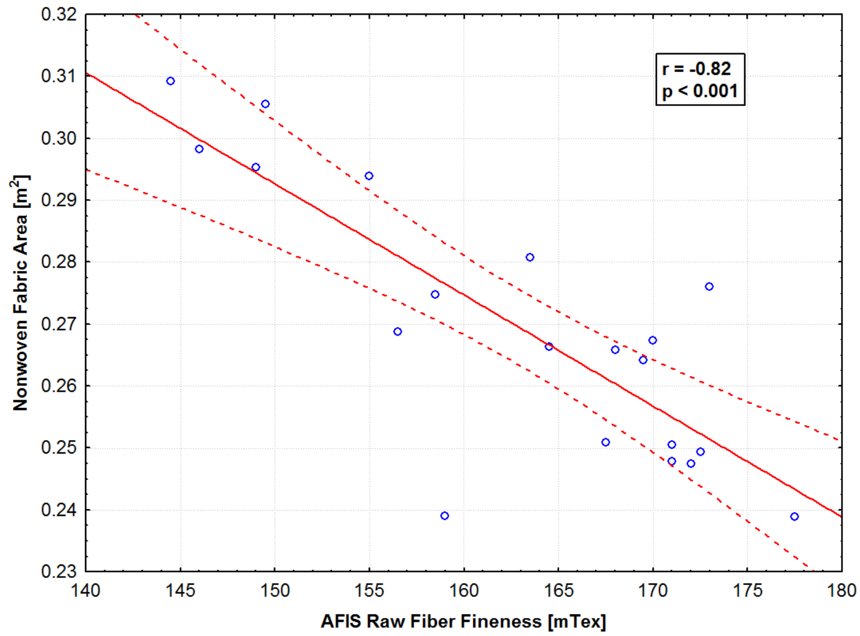

Figure 4.3 Nonwoven Fabric Area vs. AFIS Raw Fiber Fineness

From these results it may be concluded that a significant variation is present between the fabric densities made with different cottons. This may be due to variation in area which is affected by changes in fineness between the cottons. The fabric density appears related to fineness and micronaire of the cotton used. Fiber fineness may have an effect the on compacting and spreading of cotton fibers during needlepunching. According to the observed relations, finer fibers spread out more during needling thereby increasing the fabric area. The fibers with higher density appear to have better packing density. Therefore, fineness may have an impact upon the loftiness and packing density of the fibers which results in density variations. This is an important effect that needs to be taken into consideration while evaluating the fabric mechanical properties. Hence a parameter for fabric specific strength will be considered for the comparison of mechanical properties and analysis of fiber-fabric interactional effects.

Given this sizeable variation in density, despite the strict control of weight during processing, we included the estimate of fabric density (g/m^2) taken while measuring mechanical properties. The density of each specimen was determined based on its weights as specified in Section 3.5.1 in Chapter 3. As ten specimens were taken from each replication of the sample, a true representation of the density of the sample is obtained. The densities of the cotton nonwovens measured by this method varied from 120 – 210 GSM as shown in the graph in Figure 4.4.

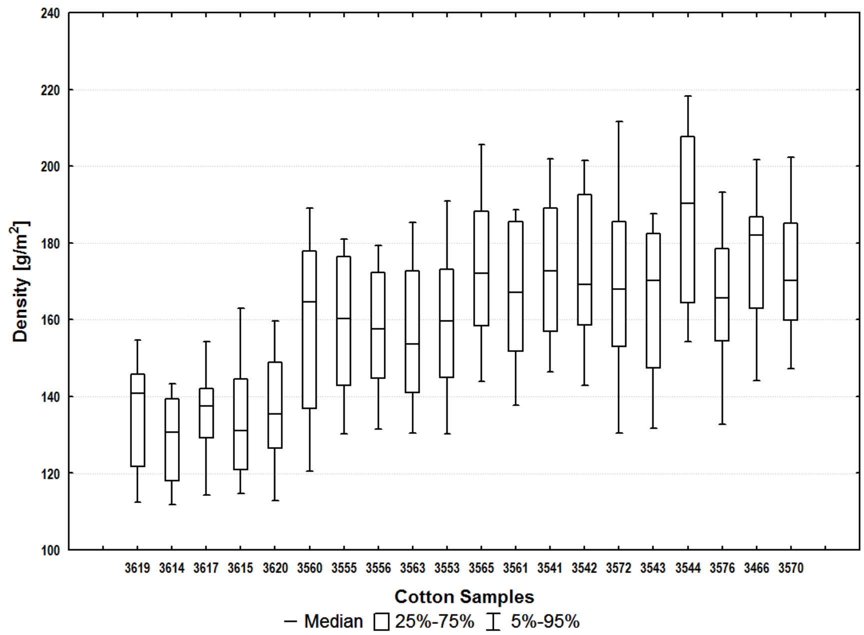

Figure 4.4 Density of Cotton Samples (Measured from specimens for mechanical test)

4.3 AFIS TEST RESULTS

AFIS testing was carried out on fiber samples taken from each of the cottons before carding, after one card passage, and after two card passages. The data obtained from this test gives the single fiber properties of the cottons used for this study. These fiber characteristics measured by the AFIS are the primary independent variables which will be used to explain and predict the variation in the nonwoven fabric properties. The AFIS test results include nep content, fiber length, trash content, fiber fineness and maturity data. The measured AFIS properties of raw fibers, fibers taken after one card passage and fibers taken after two card passages were checked for significant variation between replications by plotting scatterplots. The results showed highly significant correlations between the two replications, with some expected experimental error but no outliers that affected the ranking of the cottons. The results of the two replications were therefore averaged to derive the one characteristic value for each of the measured fiber properties for each of the cottons used in this study. The resultant average fiber properties for all the cottons are given in Table A.1 in Appendix A. A summary table of the observed fiber properties is given below in Table 4.1.

Table 4.1 Measured AFIS Properties Summary Range

	Raw Fiber			Card 1			Card 2		
	Min	**Max**	**Median**	**Min**	**Max**	**Median**	**Min**	**Max**	**Median**
Nep size [um]	693	760	725.3	680	764	723	664	759	719.5
Neps per Gm	354	1055	553.8	359	1246	604.5	374	1296	627.3
L(w) [in]	0.92	1.08	1.00	0.88	1.07	0.98	0.89	1.08	0.98
L(w) CV [%]	31.9	41.4	36.2	31.6	43.5	35.8	32.7	42.3	36.3
UQL (w) [in]	1.16	1.3	1.2	1.13	1.3	1.2	1.13	1.3	1.2
SFC (w) [%]	5.6	14.9	9.4	5.5	17.4	9.5	5.5	15.6	10.1
L(n) [in]	0.67	0.88	0.78	0.63	0.89	0.77	0.65	0.9	0.75
L(n) CV [%]	45.5	64.1	53.1	43.8	65.7	51.9	44.9	63.8	52.3
SFC (n) [%]	18.7	39.2	28.7	17.8	43	27.0	17.8	39.6	28.2
L5% (n) [in]	1.32	1.49	1.39	1.3	1.49	1.37	1.3	1.49	1.37
Total Cnt/g	84	550	163	72	481	142	50	346	107
Trash Size [um]	291	434	358	312	537	425	358	583	438.5
Dust Cnt/g	64	435	133.3	56	370	106	36	252	75
Trash Cnt/g	13	114	30	16	110	33	14	100	28.5
VFM [%]	0.22	2.06	0.8	0.31	1.97	0.8	0.26	1.7	0.7
SCN Size [um]	1039	1385	1209	916	1359	1169	923	1336	1174.5
SCN [Cnt/g]	11	43	24.5	10	48	26	10	50	24.5
Fineness [mTex]	142	178	166	142	179	166	142	180	165
IFC [%]	2.9	7.8	4.9	2.8	9.9	5.3	2.9	8	5.1
Maturity Ratio	0.86	1.02	0.94	0.83	1.02	0.93	0.85	1.01	0.94

The average fiber properties at the raw fiber level and after two card passages were also compared to see if any significant variation occurred during the carding of the fibers. Figure 4.5 below depicts the relationship between nep counts obtained on the raw fibers and the nep counts in the fiber samples after two card passages. Nep counts are discrete, non-normal and typically show a variance that depends on the mean; in the best case scenario this is equivalent to a Poisson distribution, where the variance is equal to the mean. This dependence violates the assumption of homogeneity of variances in the linear model and hence the square root transformation is often used in those cases to stabilize the variance [56, 57].

Looking at the correlation between neps counts before and after carding, Figure 4.5 shows a highly significant positive correlation between the measured values with an R^2=0.96 and a slope > 1. All the data points are above the identity line and appear to stray further away from it in the range of high nep counts. This increase in the number of neps observed can be attributed to the entanglements caused during carding.

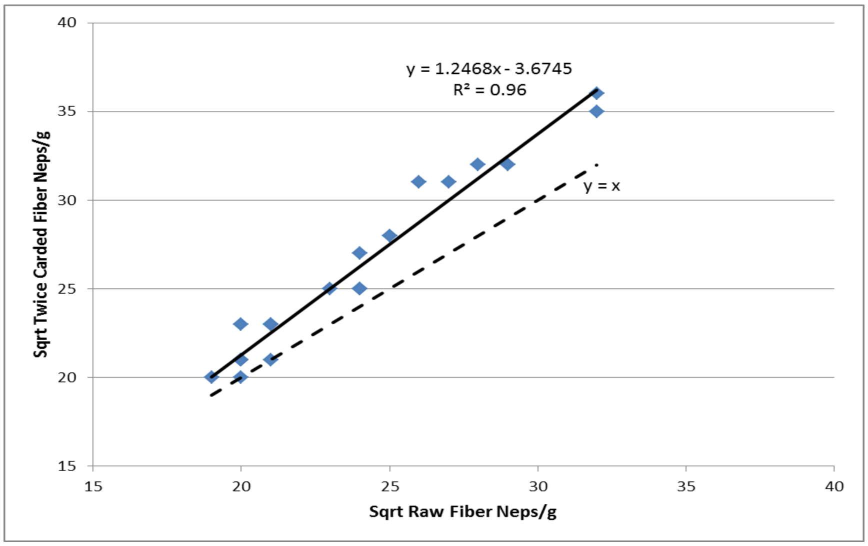

Figure 4.5 Sqrt Raw Fiber Neps/g vs. Sqrt Twice Carded Fiber Neps/g

Because neps are known to depend on maturity [58], we examined the relationship between the two variables (Figure 4.6). It is seen from the graph in Figure 4.6 that there is an increase in the nep count of twice carded fibers with low maturity ratio values. This confirms that less mature fibers have a greater tendency to form entanglements and this effect increases with carding.

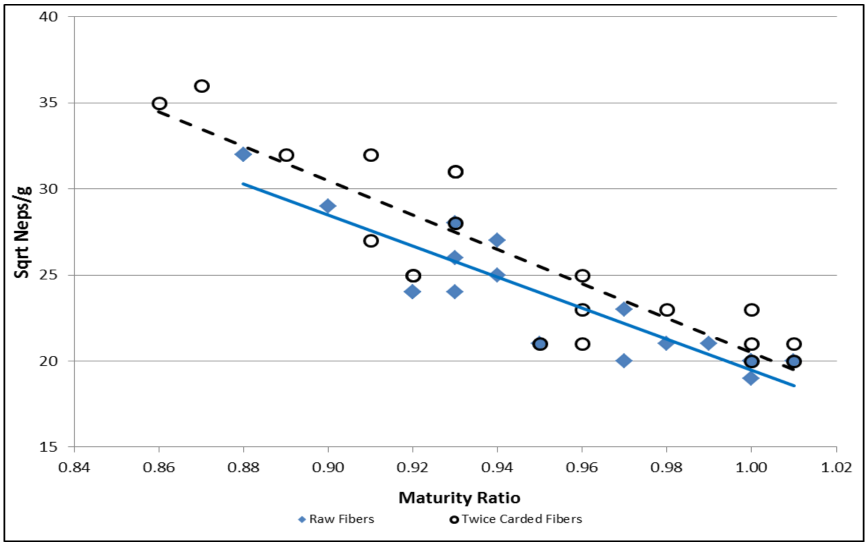

Figure 4.6 Square root of Neps/g vs. Maturity Ratio for Twice Carded and Raw Fibers

The graphs in the figures below (Figure 4.7, Figure 4.8, Figure 4.9) show the relationships observed between the length parameters of the raw fibers and fibers after two card passages. Figure 4.7 shows there is a highly significant relationship with R^2=0.93, between the upper quartile length (UQL) measured before and after carding. Like in the case of neps, a shift in the regression line with respect to the identity line is also observed. However, in the case of UQL, the shift appears uniform over the experimental range and the slope of the regression line is equal to 1.

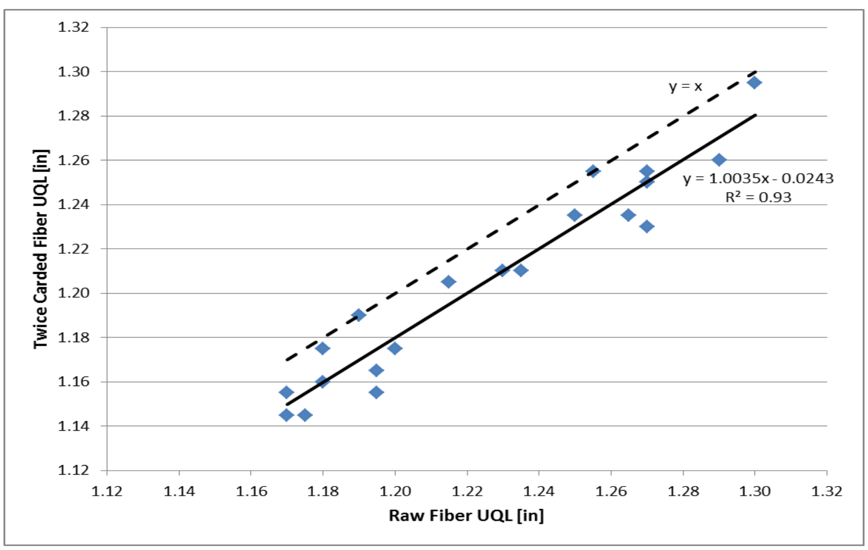

Figure 4.7 Raw Fiber UQL vs. Twice Carded Fiber UQL

Figure 4.8 and Figure 4.9 show a relationship similar to that observed for UQL. There is a highly significant relationship with R^2=0.89 between the measured mean lengths of fibers before and after carding in Figure 4.8. Figure 4.9 shows a significant relationship with R^2=0.92 for the L5%. There is a slight shift in the regression with respect to the identity line in both these graphs.

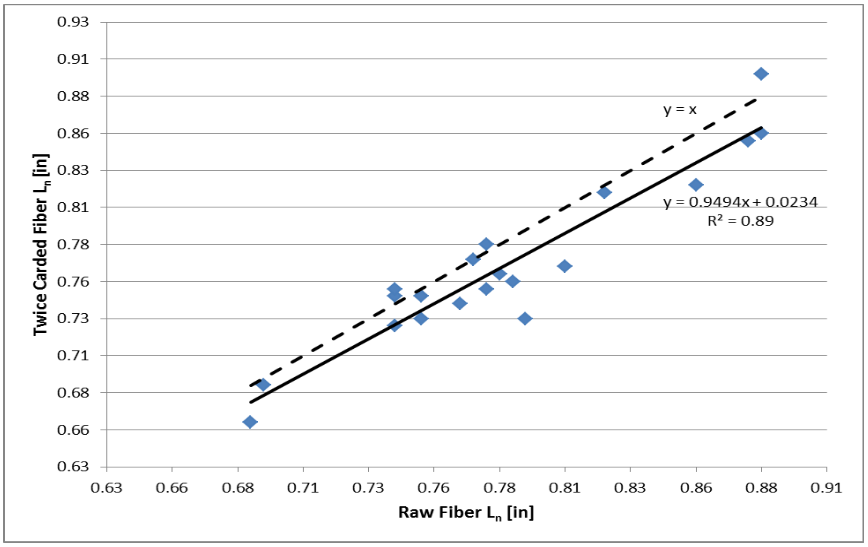

Figure 4.8 Raw Fiber L_n vs. Twice Carded Fiber L_n

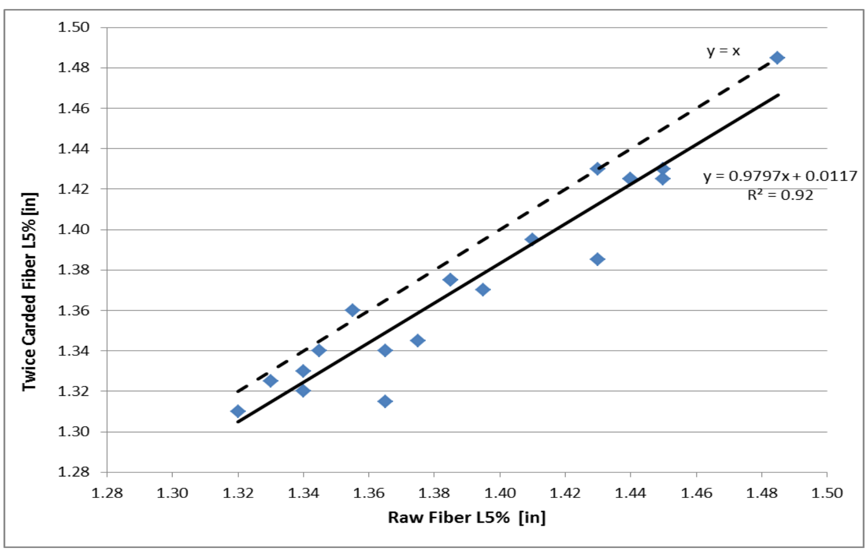

Figure 4.9 Raw Fiber L5% vs. Twice Carded Fiber L5%

The reason for the shift seen in Figure 4.7, Figure 4.8 and Figure 4.9 would be due to the fiber breakage from the aggressive mechanical action during carding. Reduction in fiber length due to breakage will cause a decrease in the measured values of UQL, L_n and L5%. The decrease appears to be relatively more substantial for the parameters that measure the length of the longest fibers i.e., UQL and L5%. This is an indicator that the longer fibers may have a higher breakage probability.

The short fiber content by number, (SFC_n) before and after carding is highly correlated as seen in Figure 4.10 below. The relation is highly significant with R^2=0.91, and no significant shift is observed in the regression line with respect to the identity line.

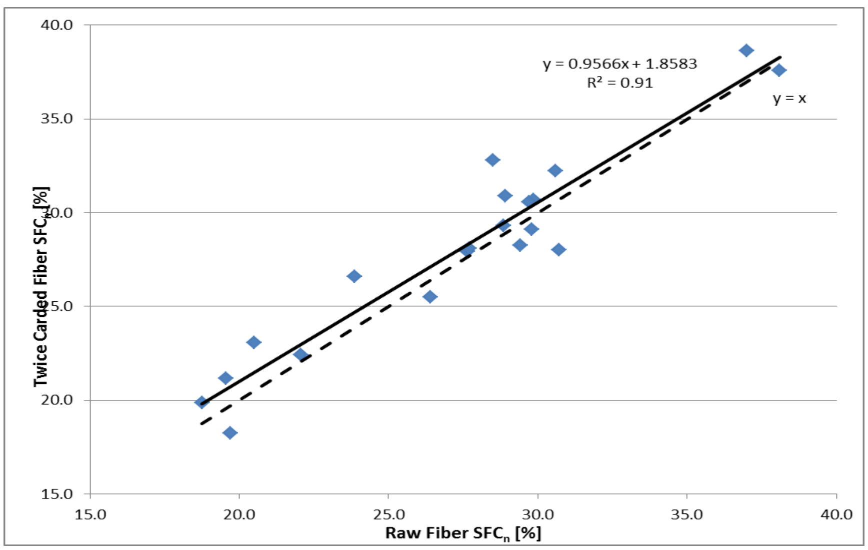

Figure 4.10 Raw Fiber SFC_n vs. Twice Carded Fiber SFC_n

Finally, Figure 4.11 and Figure 4.12 show the relationships between fiber fineness and maturity ratio, measured before and after two passages in the card. Both exhibited high correlations with the regression line for fineness almost falling on the identity line with R^2=0.99 as shown in Figure 4.11.

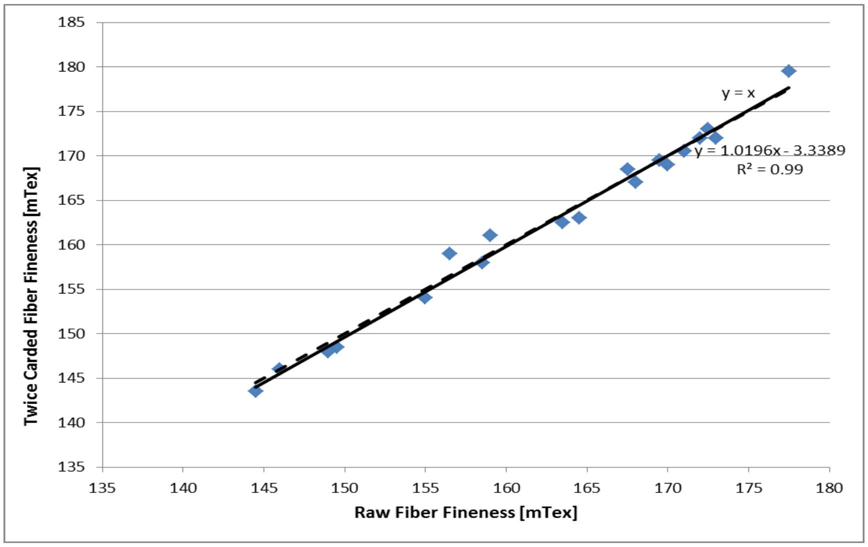

Figure 4.11 Raw Fiber Fineness vs. Twice Carded Fiber Fineness

Figure 4.12 also shows a high correlation (R^2=0.98) between the measured maturity ratio of fibers taken before and after carding. Though some shifts have been observed in the values after carding, the overall ranking of the cotton is not affected.

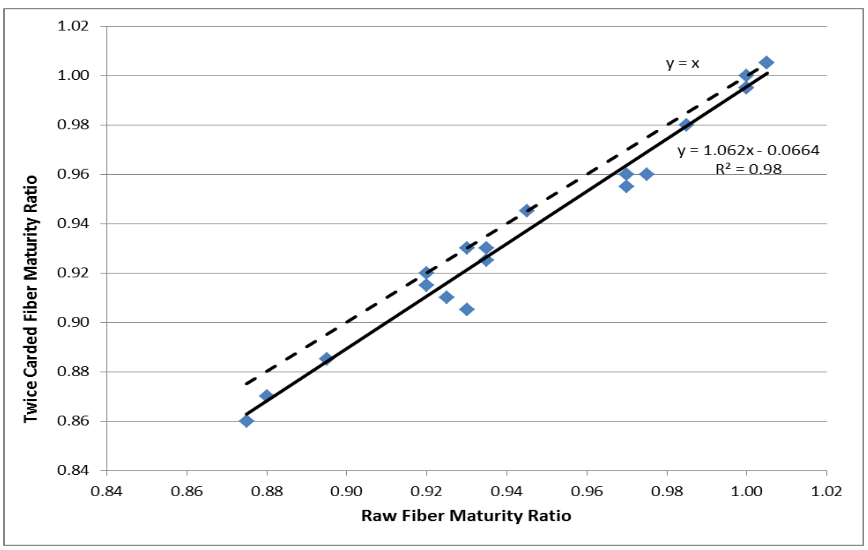

Figure 4.12 Raw Fiber Maturity Ratio vs. Twice Carded Fiber Maturity Ratio

To evaluate if these observed shifts in all the properties after carding are significant, paired t-test was performed on the data to evaluate the effect of the carding process on the fiber properties. The results of the t-test are as given below in Table 4.2.

Table 4.2 Paired t-test Results

Variable	Mean	Std. Dv.	Diff.	Std. Dv. Diff.	N	T	df	p	Confidence -95.0000%	Confidence +95.0000%
Raw Fiber Neps/g	580	203								
Twice Carded Fiber Neps/g	703	286	-123	96	20	-5.73	19	<0.001	-168	-78
Raw Fiber UQL	1.22	0.04								
Twice Carded Fiber UQL	1.20	0.04	0.02	0.01	20	7.37	19	<0.001	0.01	0.03
Raw Fiber L_n	0.78	0.06								
Twice Carded Fiber L_n	0.77	0.06	0.02	0.02	20	3.80	19	0.001	0.01	0.03
Raw Fiber SFC_n	27.4	5.3								
Twice Carded Fiber SFC_n	28.1	5.4	-0.7	1.6	20	-1.85	19	0.080	-1.4	0.1
Raw Fiber L5%	1.39	0.05								
Twice Carded Fiber L5%	1.38	0.05	0.02	0.02	20	4.57	19	<0.001	0.01	0.03
Raw Fiber Fineness	162.9	10.0								
Twice Carded Fiber Fineness	162.8	10.3	0.2	1.2	20	0.6	19	0.573	-0.4	0.7
Raw Fiber Maturity Ratio	0.95	0.04								
Twice Carded Fiber Maturity Ratio	0.94	0.04	0.01	0.01	20	3.91	19	<0.001	0.00	0.01

The results of the paired t-test shows that there is a significant effect of carding on the fiber properties like nep count, UQL, L_n, L5% and maturity ratio measured after two card passages. The variations in these parameters are expected due to the tendency of fibers to break and also form entanglements during mechanical processing.

The variation observed in the maturity ratio of the cottons is very low but still significant. This is a minor difference but as it is observed across all cottons, it is significant. Increase in immature fiber breakage during processing, results in higher immature fiber count and biases the mean maturity value of the sample towards immature fibers. This is the reason for the decrease in maturity ratio values of twice carded fibers when compared to that of raw fibers.

Thus, though a significant difference is observed in most of the properties, it is uniform for all cottons and the overall ranking of the cottons is not affected. Therefore, though some variation is observed, the AFIS properties of the raw fibers can be used to predict the fabric properties as they are highly correlated to the properties of the fiber used for the production of the nonwoven fabric.

The AFIS properties selected to check for significant relationships in this study include-

- the measurement of average length by number L_n
- the Upper Quartile Length (UQL), which gives the length exceeded by 25% of the fibers in the cotton sample
- the percentage variation in the length of all the fibers in the sample (L_n CV)
- the short fiber content by number (SFC_n) which is the percentage of fibers in the whole tested cotton sample that are shorter than 0.5 inches or 12.7 mm
- the 5% length by number (L5%), which gives the length exceeded by 5% of fibers in the tested cotton sample
- the fiber fineness measured in mTex
- Immature Fiber Content (IFC), which gives the percentage of all fibers within the sample that have a cell wall thickness covering less than 25% of the full area
- And the maturity ratio of the fiber.

4.4 NONWOVEN FABRIC CHARACTERISTICS

4.4.1 Tensile Breaking Strength

The tensile breaking force measured by the testing equipment is the maximum load the material can withstand before breaking. The various cottons exhibited different values of breaking force in the range 35 – 110N. Density is an important factor affecting the mechanical properties of a fabric. Hence, the variation in fabric densities over the different cottons was taken into consideration and to determine the specific strength of the nonwoven fabrics. Figure 4.13 shows the average specific strength and average breaking force for all the cottons with a 95% confidence interval.

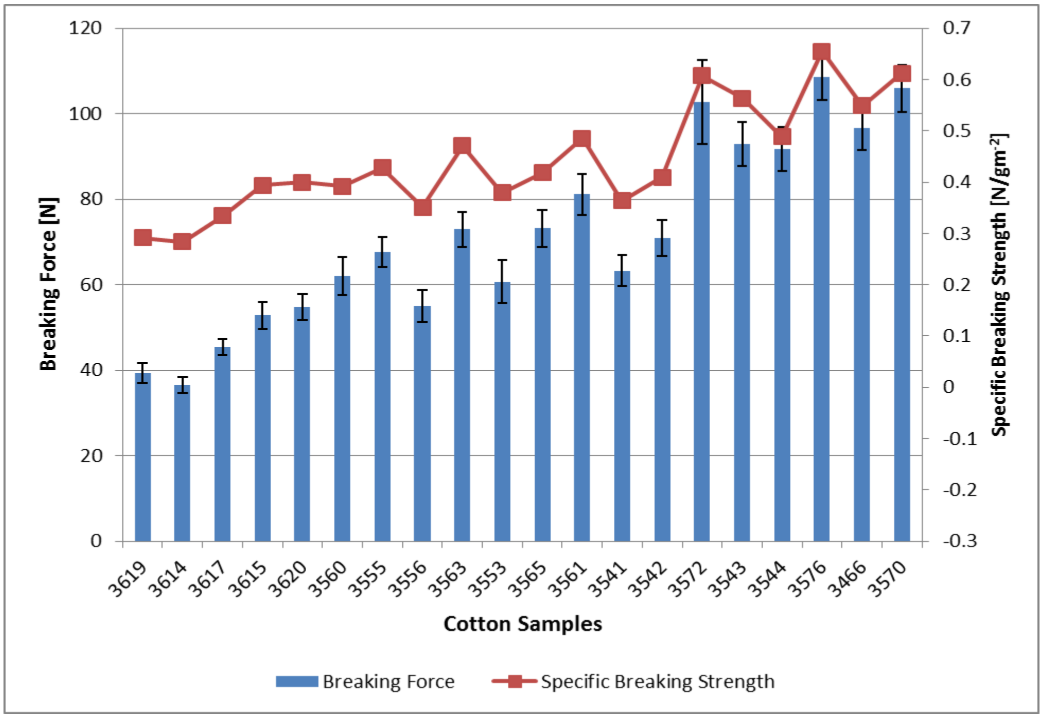

Figure 4.13 Average Specific Strength & Breaking Force of all Cottons at 95% CI

The correlation matrix between the AFIS fiber parameters and measured fabric properties (Table B.2 in Appendix B) showed all the AFIS measurements to have a significant correlation with the specific breaking strength of the samples at confidence level of 95%. Focusing on the raw fiber AFIS measurements and its relation with the specific breaking force, it was seen that almost all the parameters showed highly significant correlations. To look at the relations in detail, the regression plots between each AFIS measurement and specific breaking strength were plotted.

4.4.1.1 Impact of Fiber Length on Specific Breaking Strength

Mean fiber length by number (L_n) is the average length of all the individual fibers in a tested cotton sample. It is a true representation of the mean length of the sample as it does not leave out any fiber. Figure 4.14 shows the relation between specific strength and the mean length for all the different samples. It is seen that there is a highly significant relation with R=0.90. The specific strength of the fabric is seen to increase with increase in the mean length value of the constituent cotton fibers.

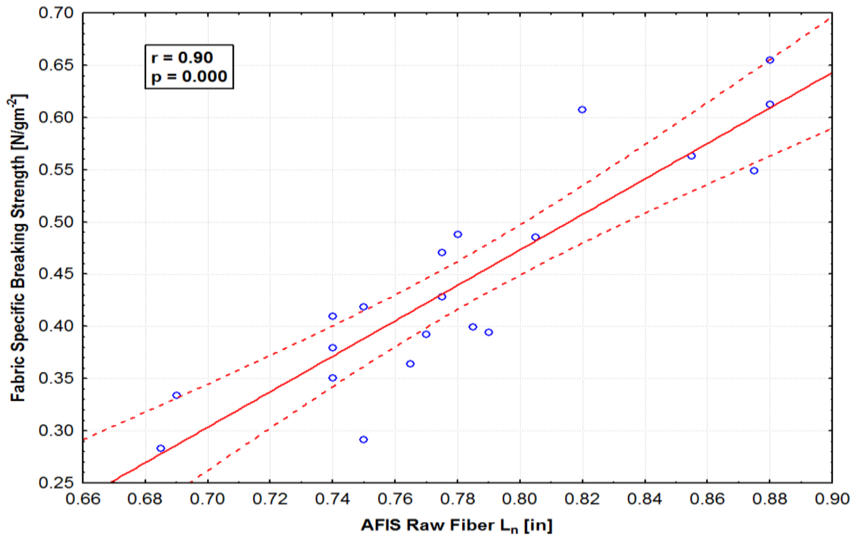

Figure 4.14 Fabric Specific Breaking Strength vs. AFIS Raw Fiber L_n

Looking at the effect of length variability (L_n CV%) on the breaking strength, we can see that there is a strong negative relation between the two with R=-0.81 at p <0.001 (Figure 4.15). This indicates that a higher dispersion of the fiber length distribution is associated with a decrease in the needlepunched fabric strength. This is an important result given the fact that the variability of fiber length is an inherent characteristic of cotton and is dependent upon complex interactions between genetic, plant growth, and process related factors [54, 59].

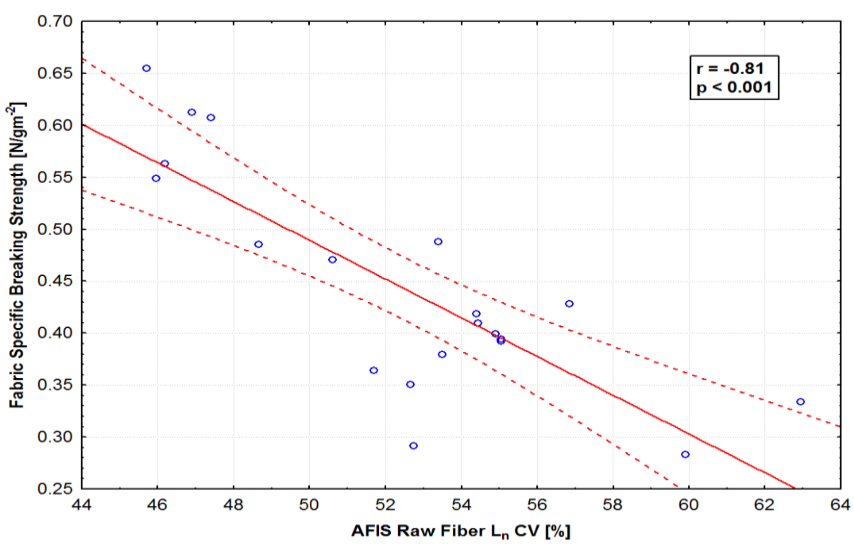

Figure 4.15 Fabric Specific Breaking Strength vs. AFIS Raw Fiber L_n CV

A similar relation is seen with the short fiber content as shown in Figure 4.16. The specific strength has a highly significant negative correlation with SFC_n with R=-0.89. Therefore, excessive amounts of short fibers in the cotton due to fiber damage are associated with lower fabric breaking strength.

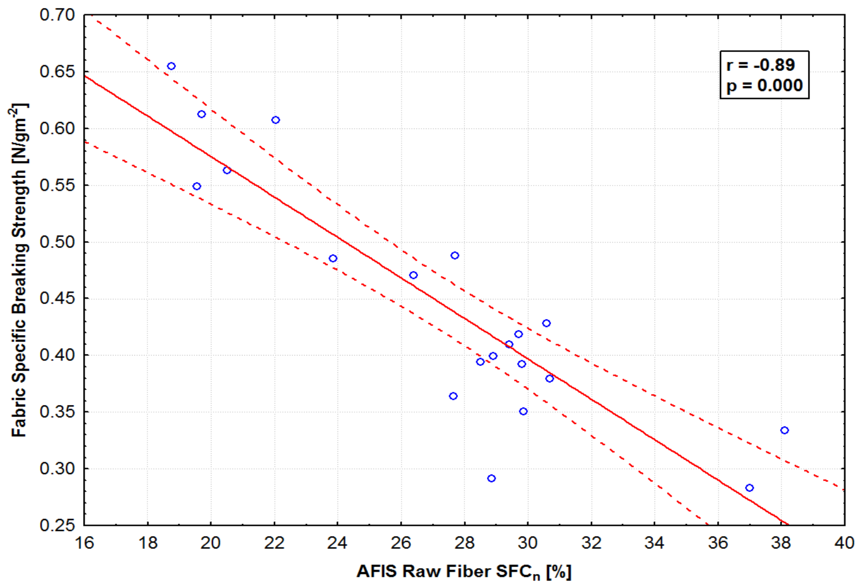

Figure 4.16 Fabric Specific Breaking Strength vs. AFIS Raw Fiber $\boldsymbol{SFC_n}$

From all these relations between length parameters and specific strength it is seen that fabric strength increases with fiber length. Variation in fiber length and increase in short fibers results in a decrease in the specific strength of the nonwoven fabric. Longer fibers may impart greater strength to the fabric due to more inter-fiber cohesion. Increase in short fiber content would mean that there is less inter-fiber friction due to smaller contact area which results in a decrease in fabric strength.

4.4.1.2 Impact of Maturity and Fineness on Specific Breaking Strength

Graphs in Figure 4.17, Figure 4.18 and Figure 4.19 below show the relations between fineness, and fiber maturity parameters with the specific breaking strength. From Figure 4.17 we see that fineness has a highly significant positive relation with breaking strength (R=0.67).

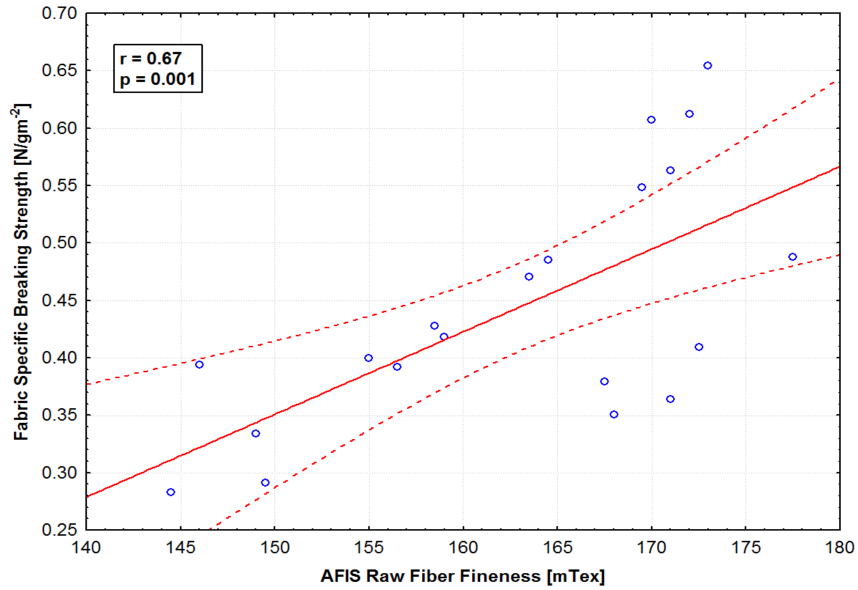

Figure 4.17 Fabric Specific Breaking Strength vs. AFIS Raw Fiber Fineness

Some of the data points showed significant scatter in the graph in Figure 4.17. It is seen that though all these cottons had high fineness values, they show significant difference in breaking strength. This may be due to the effect of length on the fabric strength as discussed in Section 4.4.1.1. The cottons showing higher values of breaking strength were longer than the ones with lower breaking strength, although they had almost the same fineness value. Hence the relationship explained by the regression is not completely independent and is affected by the length parameter.

Immature fiber content (IFC) shows a strong negative correlation with specific breaking strength (R=-0.88) as shown in Figure 4.18. Maturity ratio shows a highly significant relation with specific strength as seen in Figure 4.19. It is a positive relation with R=0.91. The specific strength of the fabric increases with increase in the fiber maturity ratio value.

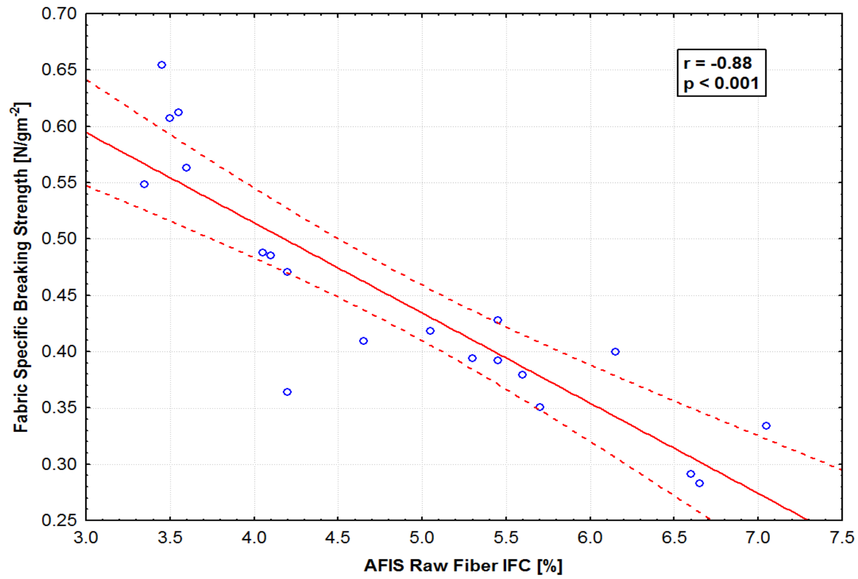

Figure 4.18 Fabric Specific Breaking Strength vs. AFIS Raw Fiber IFC

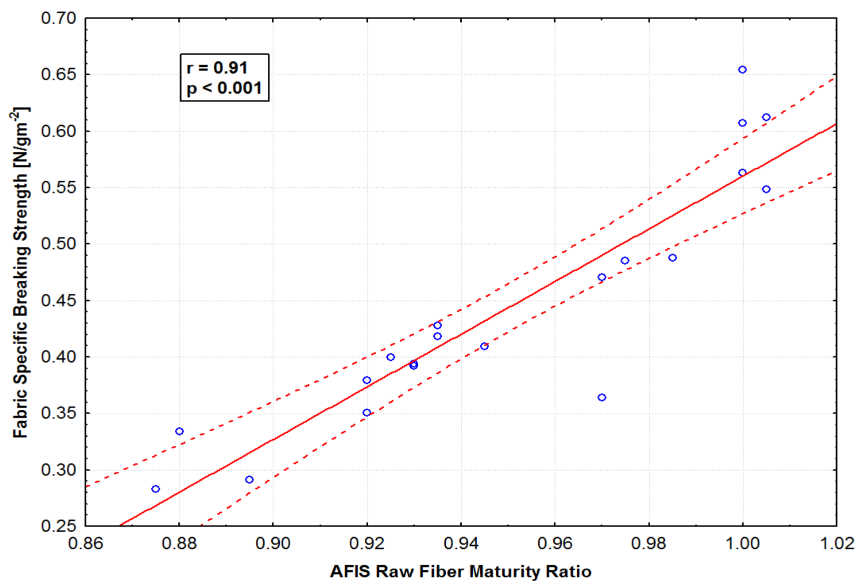

Figure 4.19 Fabric Specific Breaking Strength vs. AFIS Raw Fiber Maturity Ratio

As shown by the graphs in Figure 4.17, Figure 4.18 and Figure 4.19, the breaking force of the nonwoven fabric specimen increases with increase in fiber linear density and maturity of the cottons.

Based on the results above, it is seen that specimens with longer fibers and with higher fiber maturity and fineness (linear density) value are able to withstand higher levels of loads compared to the needlepunched nonwoven specimens made with short finer fibers. The tensile strengths of the specimens thus varied based on their constituent cotton fiber attributes.

In the case of fineness, the observed result is in contradiction to results seen from other studies where the researchers have concluded that nonwovens with finer fibers (smaller denier) were stronger than those with coarser fibers [60]. The authors explained the result by the fact that the former has more fibers per unit weight in the structure. An increase in fibers per unit weight would mean that there is more inter-fiber contact and greater cohesion between fibers therefore giving better strength to the fabric. As the previous studies dealt with nonwovens from synthetic fibers this may not be entirely relevant in the case of cotton nonwovens.

Cotton has a complex fiber structure and its linear density (gravimetric fineness) is affected by the deposition of cellulose (maturity). Hence, increase in gravimetrically finer fibers may result in more immature fibers in the sample which would decrease the strength of the fabric, which confirms to the results observed in this study. Also, the variation in nonwoven fabric densities for the different cottons, and its relationship with fiber fineness (Figure 4.2) may have an impact on the strength of the fabric. Though the specific breaking strength was taken for the analysis to overcome this, a significant relationship is still seen between specific breaking strength and fabric density as shown in Figure 4.20 below. Thus, multiple factors are seen to influence the breaking strength of the fabric. Therefore, a multiple regression analysis will be conducted later to see the effect of all the important fiber parameters on the fabric strength.

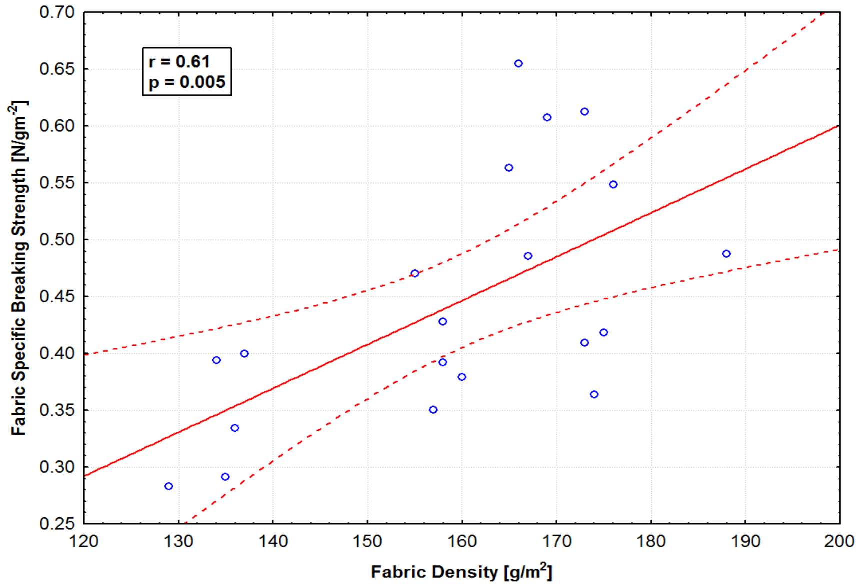

Figure 4.20 Fabric Specific Breaking Strength vs. Fabric Density

4.4.2 Tensile Apparent Elongation

The apparent elongation measured during tensile testing of the specimen is the extension undergone by the specimen till it reaches maximum load. The average elongation is seen to vary between 64 - 87% as shown in Figure 4.21 below.

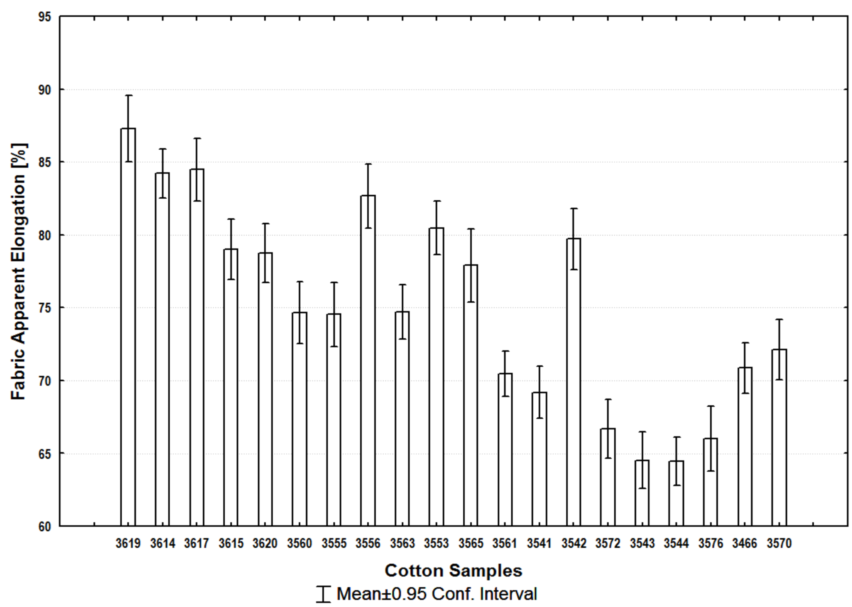

Figure 4.21 Average Apparent Elongation of all Cottons at 95% CI

All the AFIS parameters have significant correlations with the apparent elongation measured during tensile testing. As in the case of specific strength, fiber length and maturity parameters are seen to be significant for elongation as well.

4.4.2.1 Impact of Fiber Length on Apparent Elongation

AFIS raw fiber mean length (L_n) showed a highly significant negative relation with apparent elongation with R= -0.74 ($p < 0.001$), although a few data points showed substantial scatter as seen in Figure 4.22. The reason for this negative correlation may be that fabrics with longer fibers had greater friction between fibers and hence lesser fiber slippage and fabric elongation was observed on loading.

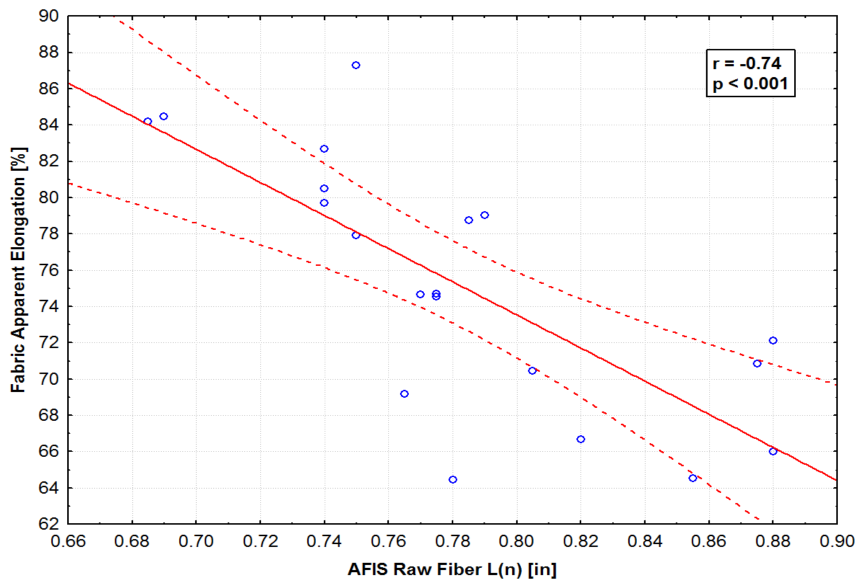

Figure 4.22 Fabric Apparent Elongation vs. AFIS Raw Fiber L_n

The other AFIS length parameters such as L_n CV and SFC_n shows highly significant positive relationships with the measured apparent elongation for all the cottons as shown in Figure 4.23 and Figure 4.24 below.

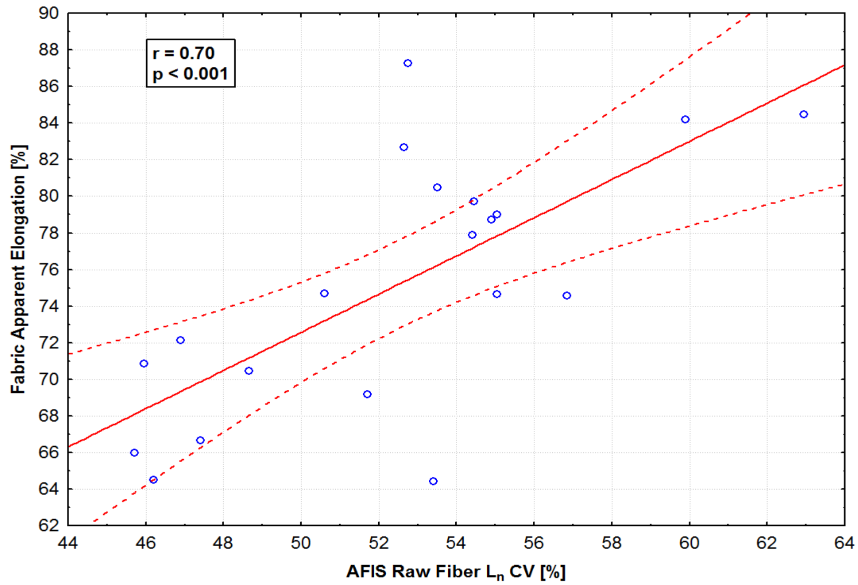

Figure 4.23 Fabric Apparent Elongation vs. AFIS Raw Fiber L_n CV

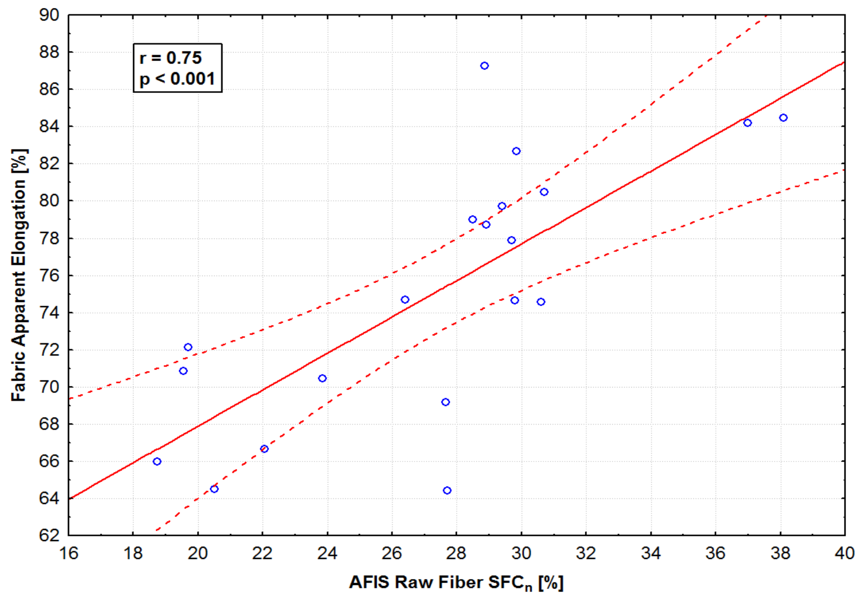

Figure 4.24 Fabric Apparent Elongation vs. AFIS Raw Fiber SFC_n

Increase in the amount of short fibers in the sample results in less fiber-fiber friction in the nonwoven fabric. This decrease in inter-fiber friction in the fabric causes an increase in fiber slippage and thereby elongation in the fabric specimen when subjected to loading. This may be the reason for the increase in elongation with increase in short fibers and length variations.

4.4.2.2 Impact of Fiber Fineness and Maturity on Apparent Elongation

Fiber fineness is seen to have a negative relation with apparent elongation in the fabric. A significantly high negative relation with R=-0.72 can be seen between fineness and elongation in Figure 4.25.

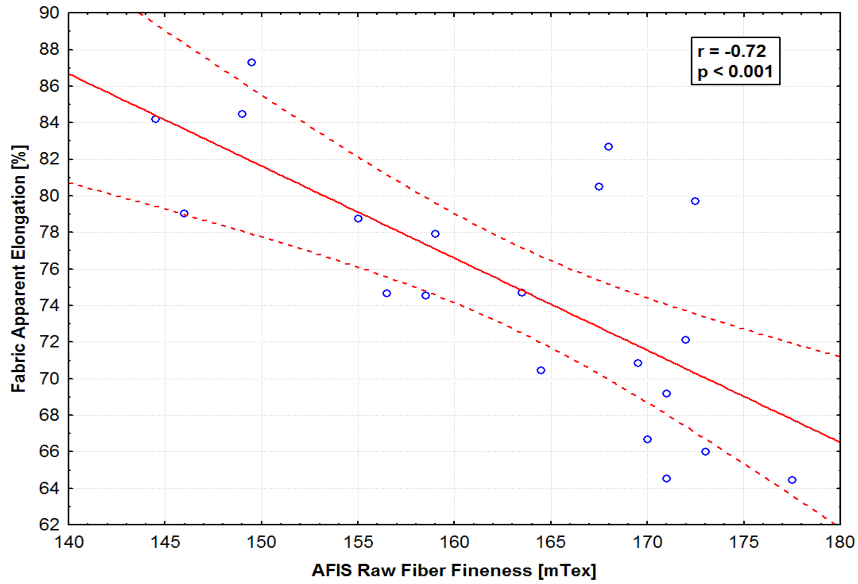

Figure 4.25 Fabric Apparent Elongation vs. AFIS Raw Fiber Fineness

Whereas, IFC and apparent elongation have a significant positive relation (R=0.88) as seen in Figure 4.26, which shows that an increase in presence of immature fibers in the sample results in greater elongation in the fabric. Fiber maturity ratio shows a highly significant relation with apparent elongation with R=-0.90 in Figure 4.27.

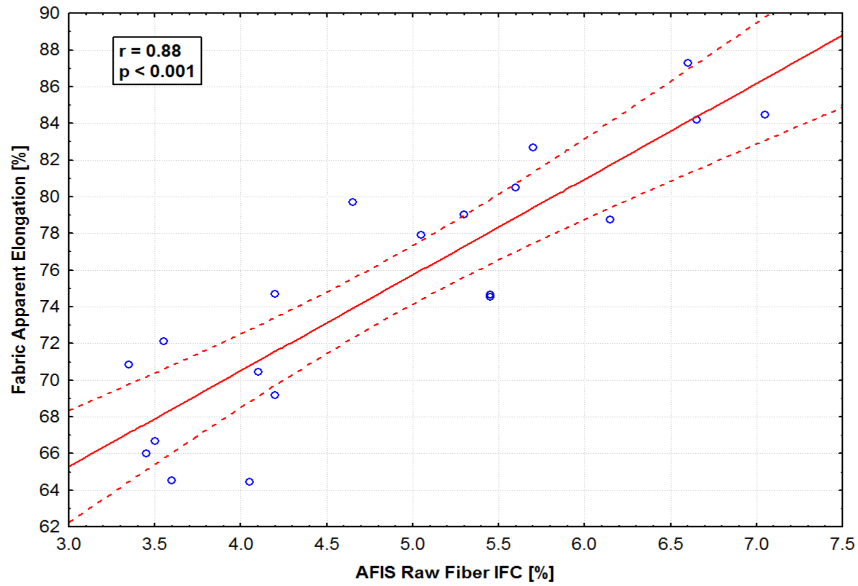

Figure 4.26 Fabric Apparent Elongation vs. AFIS Raw Fiber IFC

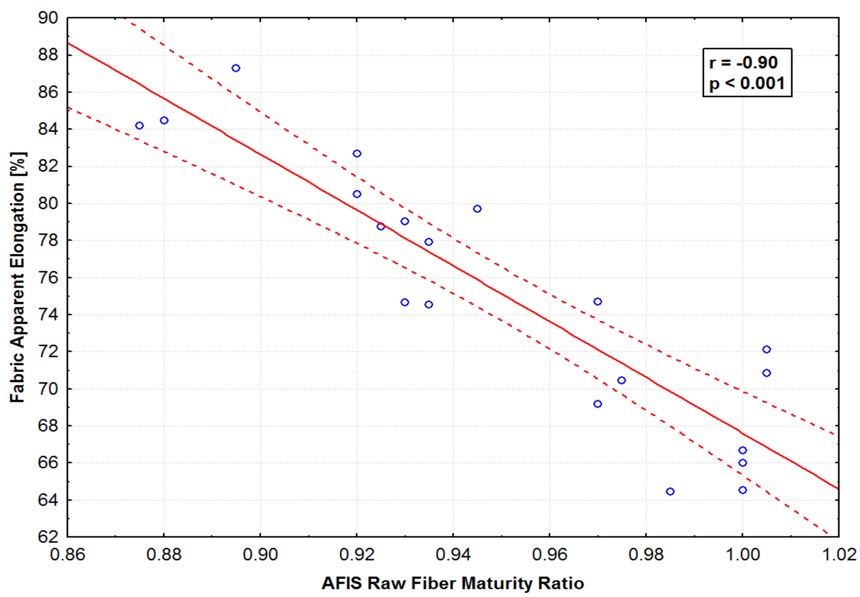

Figure 4.27 Fabric Apparent Elongation vs. AFIS Raw Fiber Maturity Ratio

The reason for this negative relation between maturity and elongation may be due to the fact that mature fibers were able to withstand higher loads better than immature fibers, and hence did not undergo much elongation or deformation at maximum load.

In order to explain the effect of fiber length and maturity on apparent elongation, let us look at Figure 4.28 below showing the load-extension curves for two different cottons – 3614 (with low L_n= 0.69 in, and low maturity ratio=0.88) and 3570 (with high L_n= 0.88 in, and high maturity ratio=1.00).

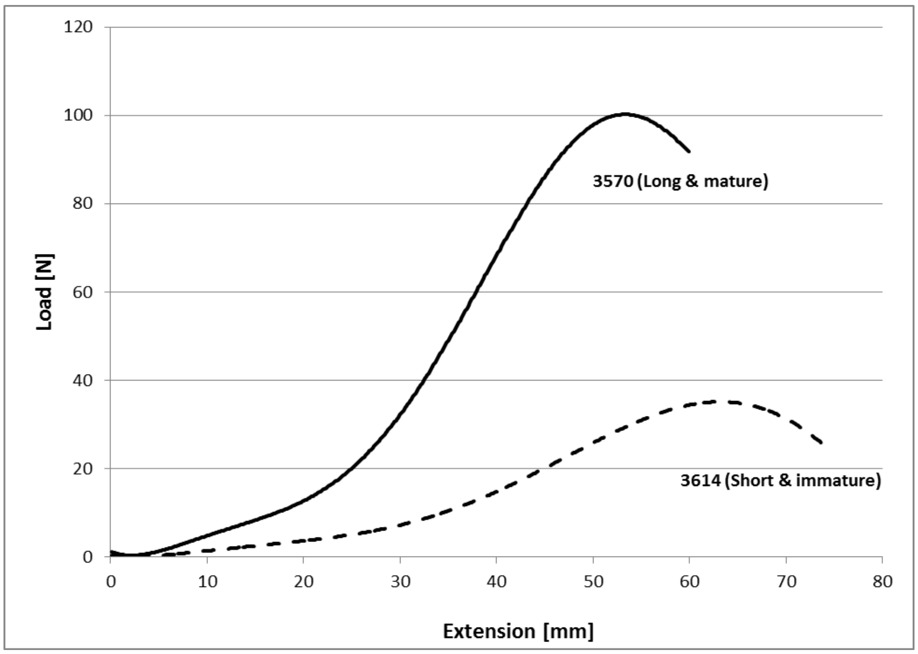

Figure 4.28 Load vs. Extension curves for cottons 3614(short, immature) and 3570(long, mature)

On comparing the two cottons in Figure 4.28, we can see cotton 3570 reaches the peak load after an extension of about 50mm, whereas cotton 3614 attained peak load at an extension of 62mm. Also significant differences can be seen in the maximum loads tolerated by the cottons before failure. This confirms that the presence of short and less mature fibers increase the apparent elongation in a nonwoven fabric during loading.

Thus, from the results observed it is seen that as the fiber length and maturity increased, the elongation in the samples decreased. Increase in short immature fibers in the sample may lead to slippage of the fibers during loading and this will result in a high degree of elongation in the specimen at low loads.

4.4.3 Bursting Strength

The bursting strength of the nonwoven fabric recorded here is the maximum load that the specimen can withstand before complete failure during testing according to the specified standard – WSP 110.5 (05). The bursting strength was measured for five specimens from each of the two replications per sample and was averaged to get the value for each sample. Figure 4.29 shows that the average measured bursting strengths of all the samples ranged between 112 – 290N. The specific bursting strength was also plotted on the same graph to show the variation.

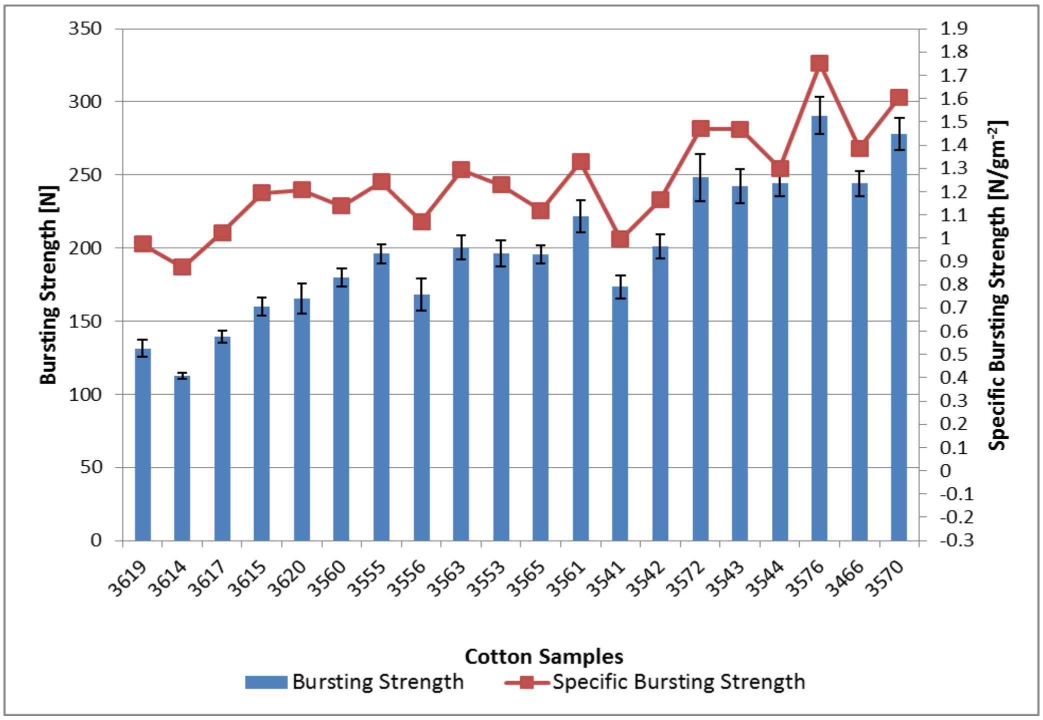

Figure 4.29 Average Specific Strength & Bursting Strength of all Cottons at 95% CI

Since the fabric density varies for the different cottons, the 'specific bursting strength' and its relationship with each of the fiber properties was used for the analysis.

4.4.3.1 Impact of Fiber Length on Specific Bursting Strength

Amongst the length measurements, L_n shows a highly significant positive correlation with specific bursting strength with R=0.89 as seen in Figure 4.30.

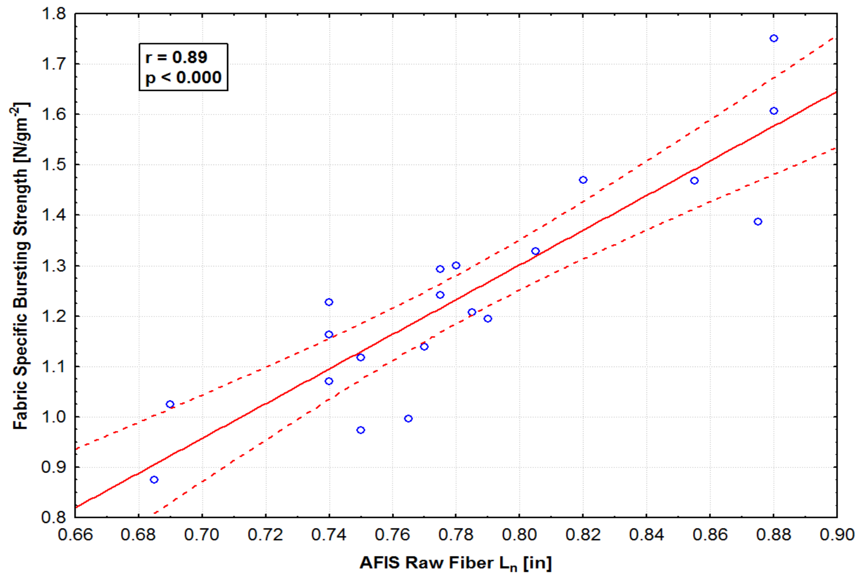

Figure 4.30 Fabric Specific Bursting Strength vs. AFIS Raw Fiber L(n)

The other parameters such as length variation (L_n CV) and SFC_n showed strong negative relation with the specific bursting strength. Figure 4.31 below shows a significant negative relation between L_n CV and specific bursting strength (R=-0.78). A highly significant correlation between SFC_n and specific bursting strength with R=-0.86 is seen in Figure 4.32.

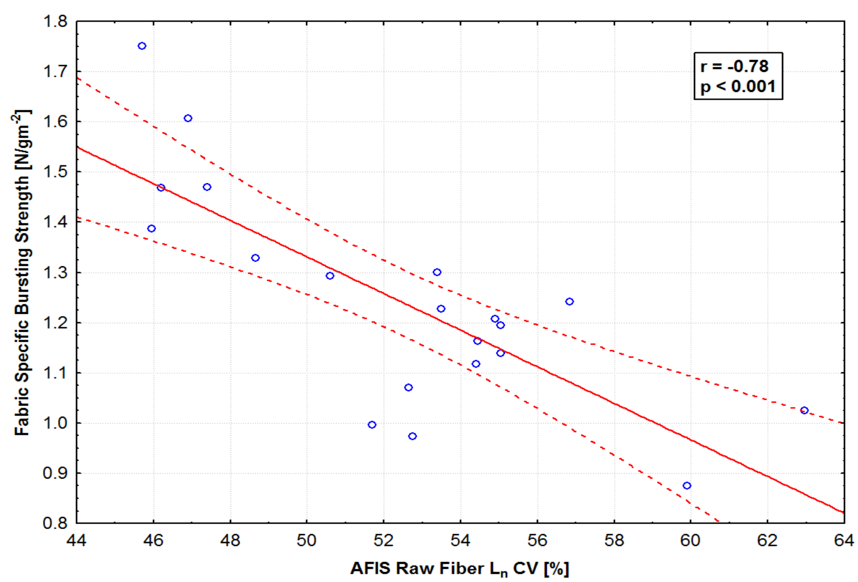

Figure 4.31 Fabric Specific Bursting Strength vs. AFIS Raw Fiber L_n CV

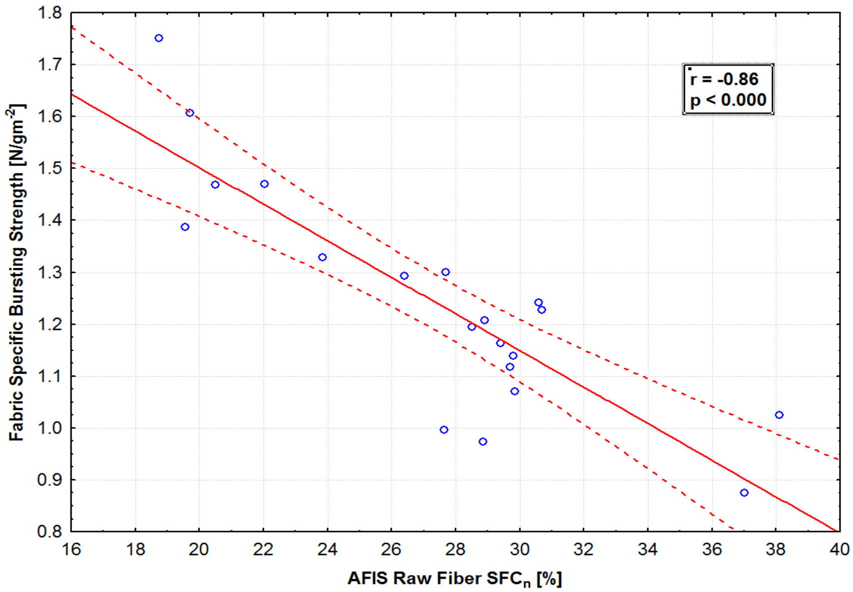

Figure 4.32 Fabric Specific Bursting Strength vs. AFIS Raw Fiber SFC_n

Increase in fiber length variation may be due to increased number of short fibers in the sample which may lead to loss in inter-fiber cohesion and therefore decrease the load bearing capacity of the nonwoven fabric.

4.4.3.2 Effect of Fiber Fineness and Maturity on Specific Bursting Strength

Fineness and maturity ratio showed significant correlations with bursting strength. Figure 4.33 shows a positive relation between fiber fineness and specific bursting strength with R=0.62 and $p < 0.01$.

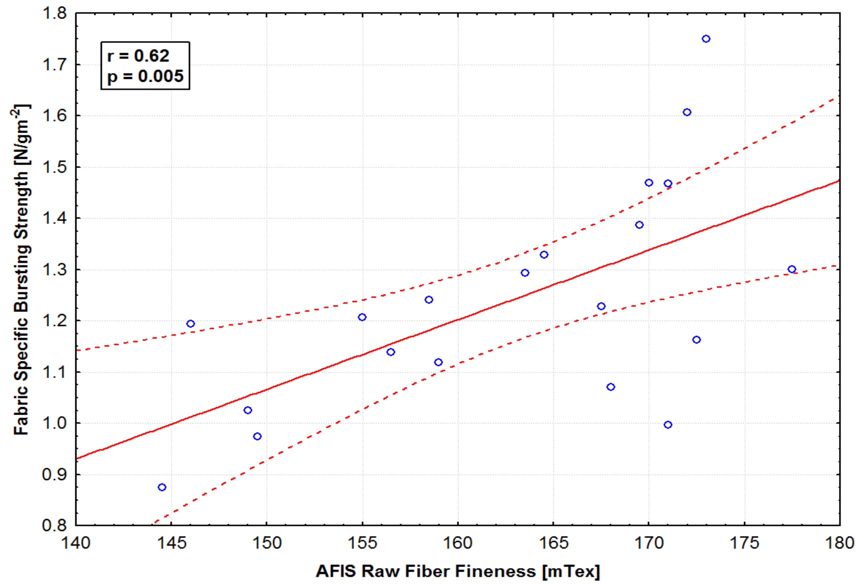

Figure 4.33 Fabric Specific Bursting Strength vs. AFIS Raw Fiber Fineness

A negative relation is seen between specific bursting strength and IFC (R=-0.79) in Figure 4.34. Whereas, a significantly high correlation is seen between specific bursting strength and maturity ratio with R=0.84 in Figure 4.35. A positive relation is seen between maturity ratio and specific bursting strength with cottons with higher maturity exhibiting high specific bursting strength values in Figure 4.35.

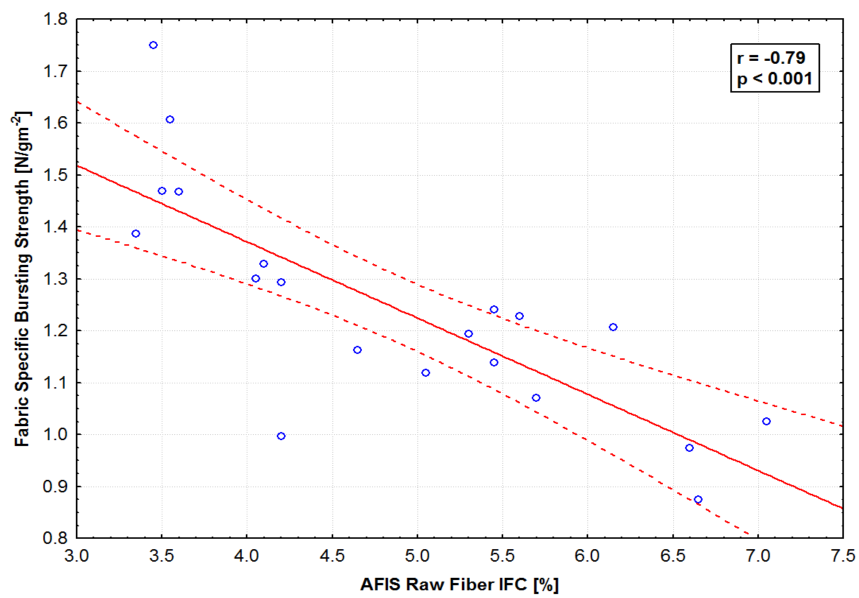

Figure 4.34 Fabric Specific Bursting Strength vs. AFIS Raw Fiber IFC

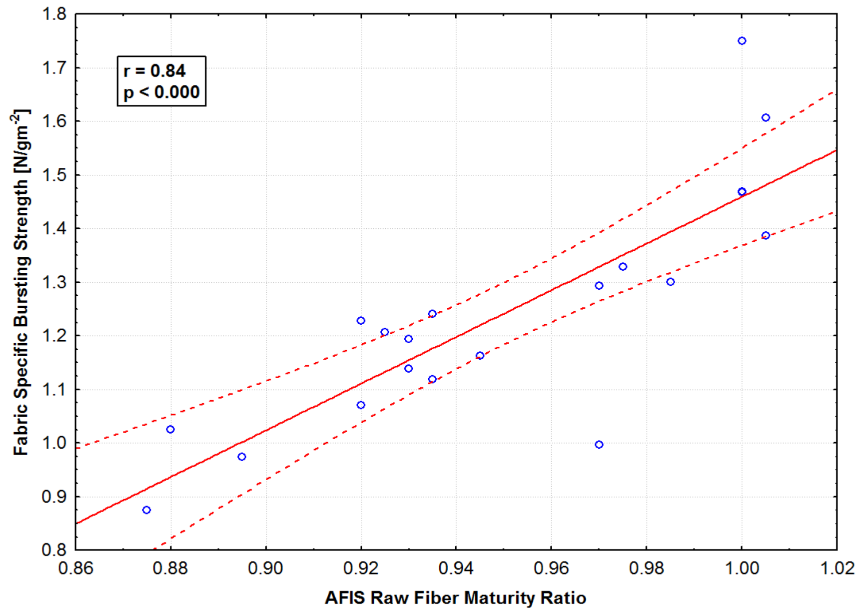

Figure 4.35 Fabric Specific Bursting Strength vs. AFIS Raw Fiber Maturity Ratio

Similar to the specific breaking strength, increase in fiber length and maturity improved the specific bursting strength of the samples. Variation in fiber length and increase in fiber fineness led to a decrease in strength. While finer fibers are believed to have better packing density and better strength, the same might not be the case with cotton. The convoluted fiber structure and the dependence of fiber fineness on maturity in the case of cotton, needs to be taken into consideration while analyzing the effect of fiber parameters on fabric strength. Finer fibers in cotton may be immature, and even with better packing density they will not contribute much to fabric strength. This explains why fineness and maturity show a positive relation with fabric burst strength in cotton nonwovens.

4.4.4 Elongation at Peak Load

The elongation at peak load is the value of compressive extension at the maximum load that the nonwoven specimen undergoes during burst strength testing. The observed elongations varied between 21mm -27mm as shown in the plot in Figure 4.36.

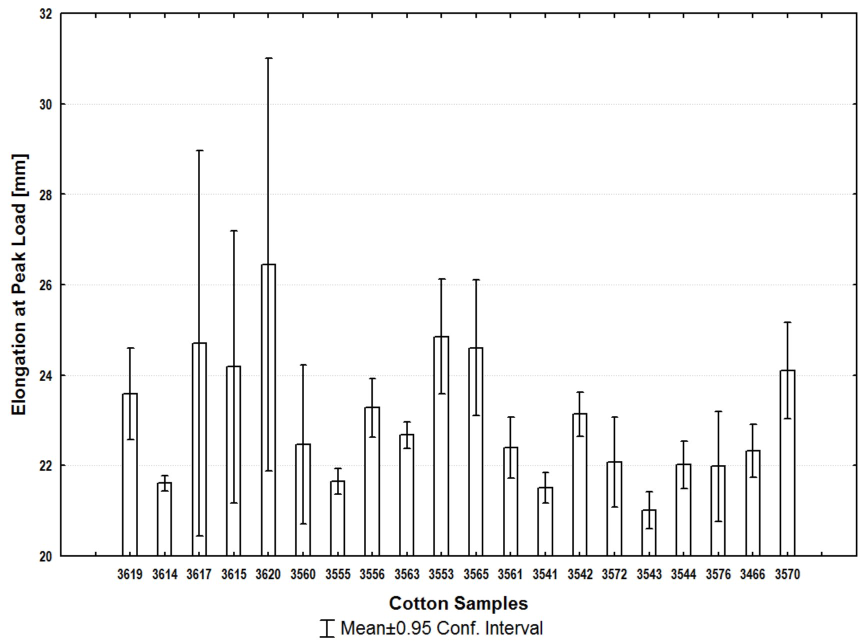

Figure 4.36 Average Elongation at Peak Load of all Cotton Samples at 95% CI

Only IFC showed a significant correlation (R=0.48) with elongation at peak at 95% confidence level as shown in Figure 4.37.

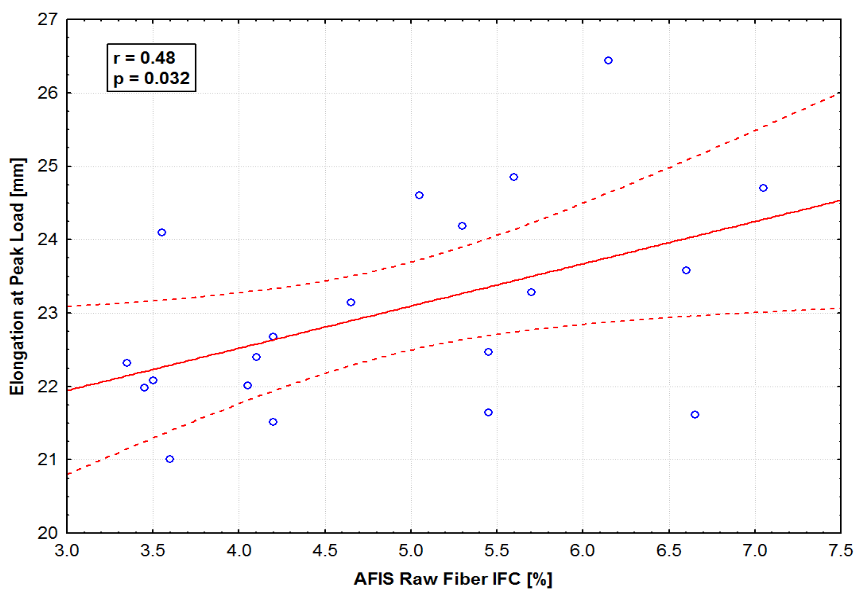

Figure 4.37 Elongation at Peak Load vs. AFIS Raw Fiber IFC

As seen from the graph in Figure 4.37 there is a slight increase in fabric elongation at peak load with an increase in presence of immature fibers. But it is not a strong effect and some variations are observed in the results. The elongation at peak load does not vary much based on the fiber length, fineness or maturity ratio.

4.4.5 Pore Structure Characteristics and Permeability

The pore structure characteristics were measured using a Capillary Flow Porometer. The data was collected from one specimen from both replications and averaged to get the characteristics for each of the cotton samples. The pore structure distributions of the two replications for all the samples were checked for similarity. Figure 4.38 shows pore size distribution for one of the tested sample cotton (3619). It is seen that the specimens from both replications had similar pore size distributions.

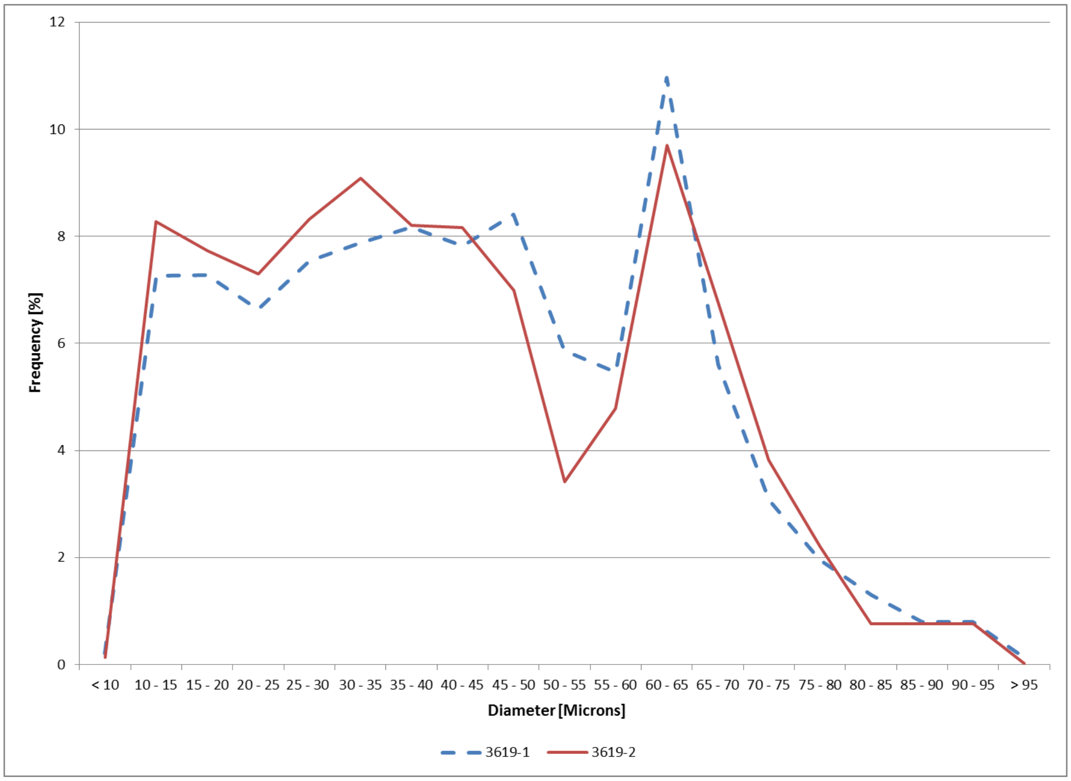

Figure 4.38 Pore Size Distribution for the Two Replications of Selected Cotton 3619

Some samples showed slight variations between the two replications. Figure 4.39 given below shows the pore size distribution of sample 3615 which showed variations in the distributions between its two replications.

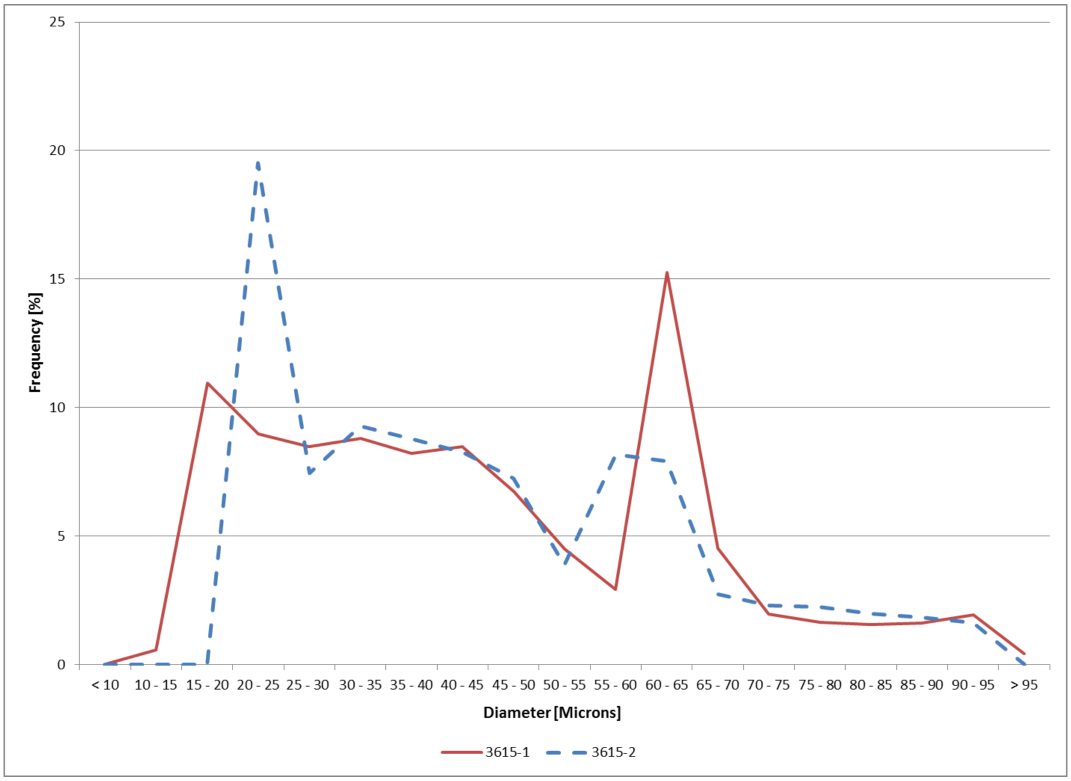

Figure 4.39 Pore Size Distribution for the Two Replications of Selected Cotton 3615

As seen in Figure 4.39, the very fine pores have not been detected in one replication during measurement. But this is not a very significant variation as the first measurement of pore distribution for that replication is cumulative and includes the missed pores as well. Hence there is not much variation in the pore distribution between replications in a sample.

Taking the average from the two replications, a plot with the pore size distributions for cottons with different combinations of length and micronaire were plotted to check for variations as shown in Figure 4.40. The samples used are 3619(low micronaire, short fiber), 3555(low micronaire, long fiber), 3541(high micronaire, short fiber) and 3570(high micronaire, long fiber).

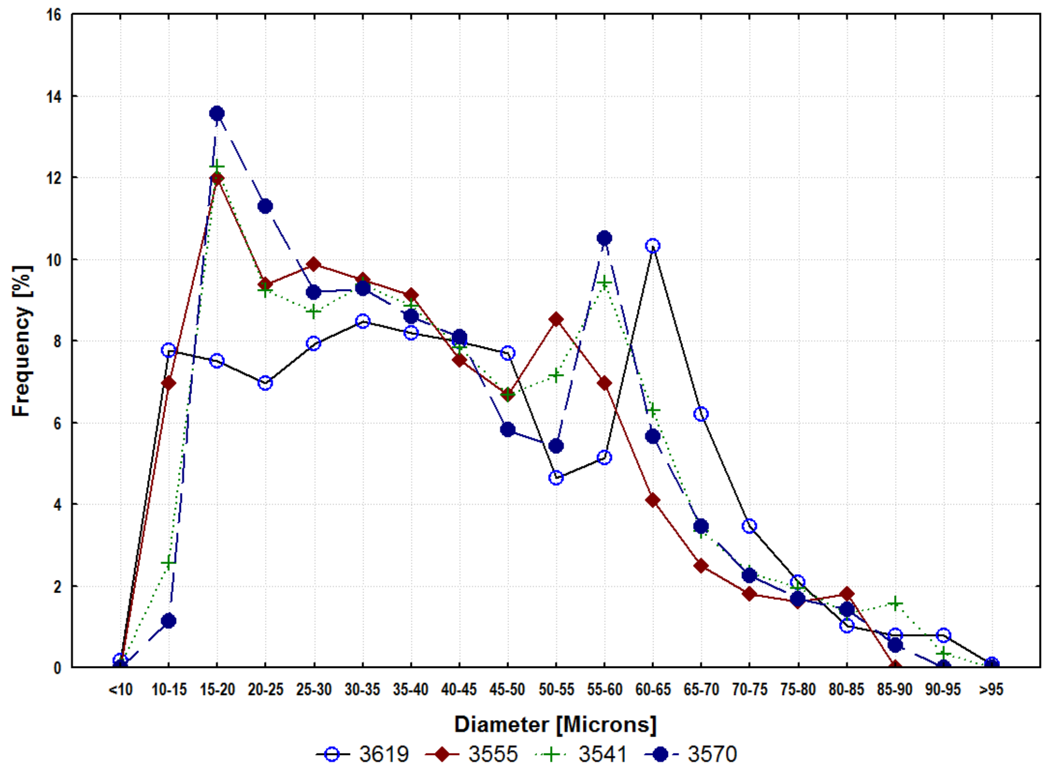

Figure 4.40 Pore Size Distribution for Selected Cottons

The graph in Figure 4.40 shows that the pore size distributions of the selected cottons exhibit some common features. It is notable that the pore size distributions observed in this study show similar patterns to the results seen by Anandjiwala and Boguslavsky during the pore structure analysis of needlpunched flax fabrics [61]. The distributions were seen to be bimodal with the first peak occurring between diameters of 10-30 microns and the second peak in a diameter range of 50-70 microns. Both high micronaire (3570) and low micronaire (3619) cottons showed similar frequency of pores for the second peak. Hence it is seen that in the case of cotton nonwovens, the shape of the pore size distributions did not vary much due to differences in micronaire or length.

This observation was confirmed on all 20 cottons. The measured pore size distribution for the different fabric samples is shown in Figure 4.41 with multiple line plots. It is seen that almost all cottons had distributions with the same shape, showing that there is very little variation between the pore size distributions of different cottons. Most of the distributions in the graph are bimodal with increased frequencies observed at a low pore size diameter of 10 – 30 microns, and at a pore size diameter of 50 – 70 microns.

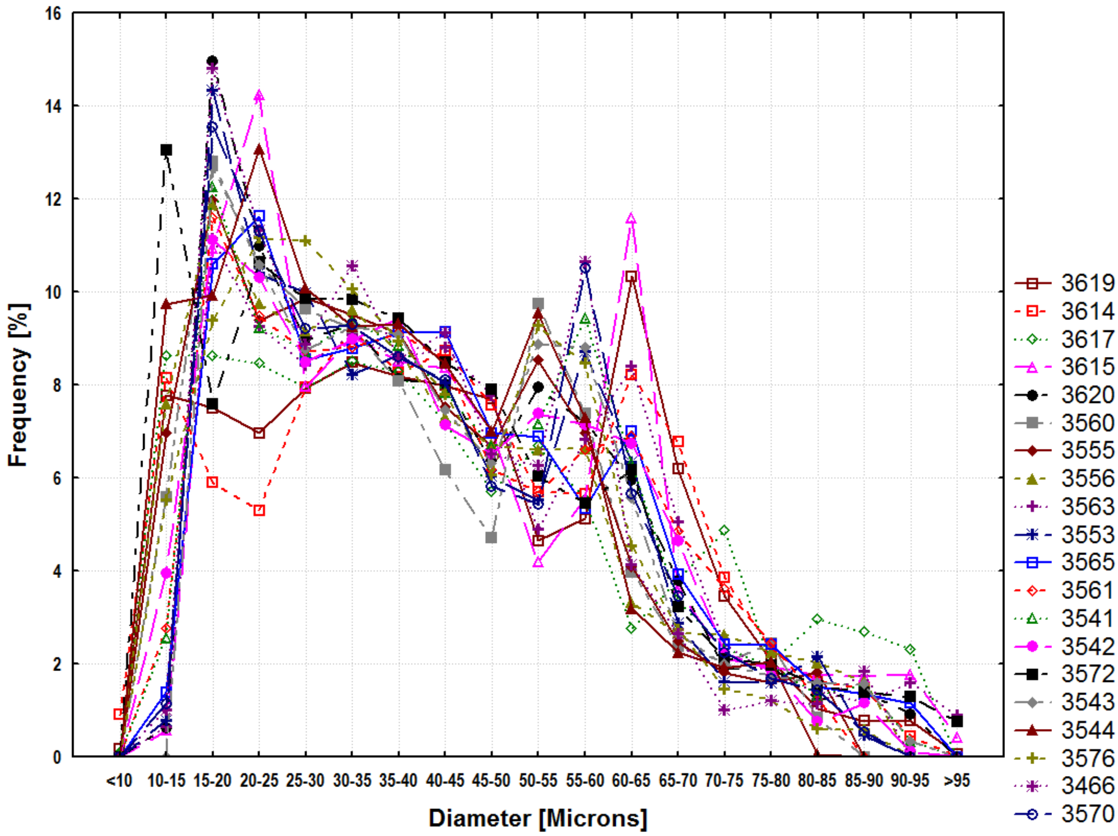

Figure 4.41 Pore Size Distribution for All Cottons

4.4.5.1 Pore Diameter Characteristics

Measurement of the nonwoven specimens on the capillary flow porometer gave the pore structure characteristics like the mean flow pore pressure (PSI), mean pore diameter (µm), and the characteristics of the largest pore in the fabric structure with measurements of bubble point pore pressure (PSI) and bubble point pore diameter (µm). The measured mean flow pore diameter varied between 33-42 µm, and bubble point pore diameter varied between 74-96 µm as shown by the line plots in Figure 4.42.

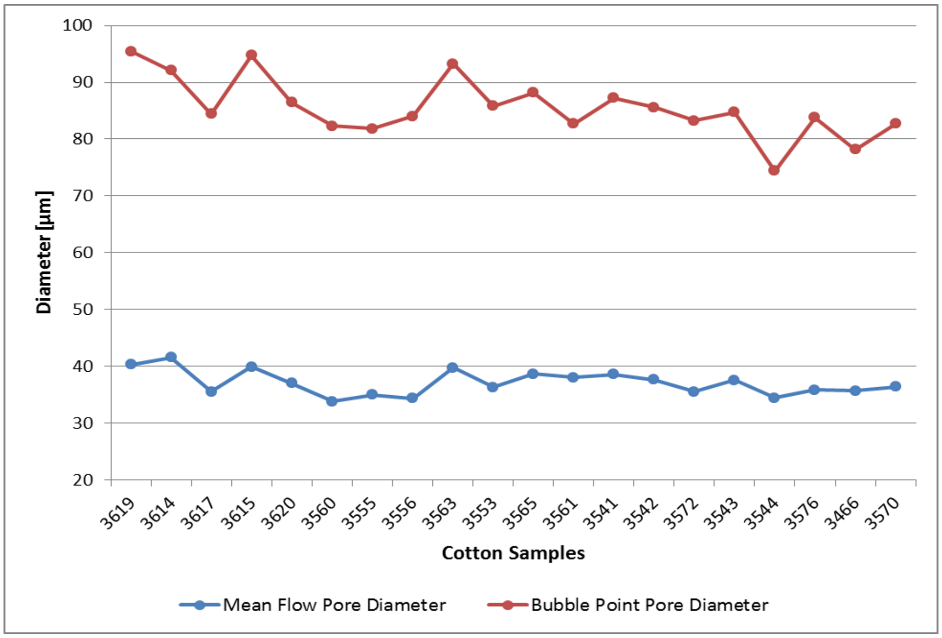

Figure 4.42 Plots of Mean Flow Pore Diameter and Bubble Point Pore Diameter for all Cotton Samples

4.4.5.2 Permeability (Specific Flow) Characteristics

The permeability or specific flow is the rate of flow of gas through the nonwoven specimen. The rate of flow of the gas at a pressure of 125 Pa was taken as the specific flow according to the WSP 70.1(05) standard [62]. The values of specific flow from the two tested replications of each of the cotton were averaged to give the permeability of the cotton sample. The permeability values of the different cottons were between 30 – 52 $cc/s/cm^2$ as given in Figure 4.43.

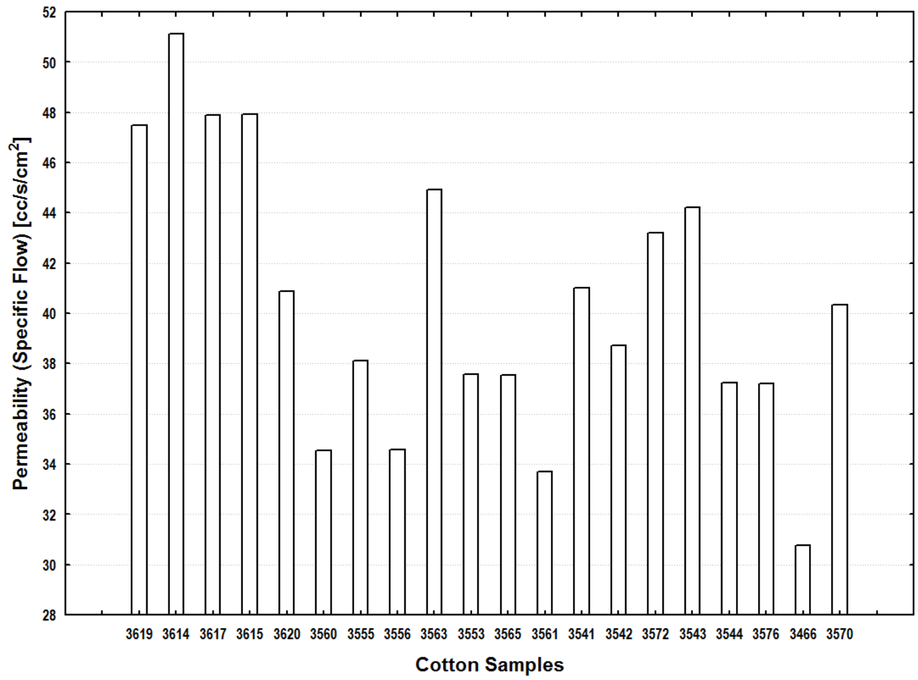

Figure 4.43 Average Permeability (Specific Flow) of all Cotton Samples

4.4.5.3 Effect of Fabric Density on Pore Diameter and Permeability

As seen in the correlation matrix (Table B.2 in Appendix B), significant correlations at 95% confidence level were observed between the AFIS raw fiber fineness and maturity parameters and the pore structure characteristics. No significant relations were observed between length parameters and pore structure characteristics. The correlations seen between pore diameters and AFIS fineness and maturity seemed to be influenced by the relationship of the parameters with fabric density. Also according to the study by Anandjiwala and Boguslavsky, the pore size and permeability of fabrics are dependent on the density of the needlepunched fabric [61]. Hence the effect of density on the pore characteristics and permeability will be investigated in this study.

Figure 4.44 and Figure 4.45 show the relationship of fabric density with mean flow pore diameter and bubble point pore diameter respectively.

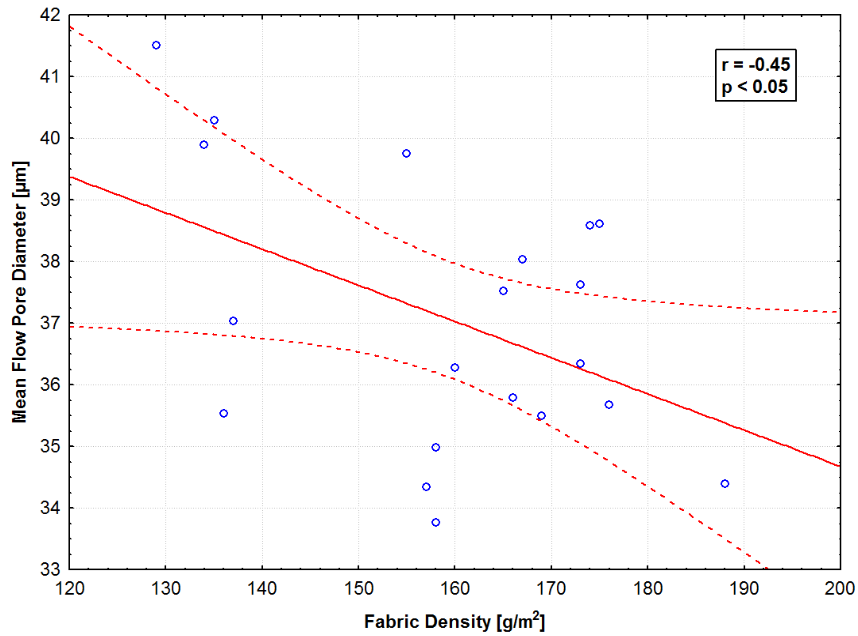

Figure 4.44 Mean Flow Pore Diameter vs. Fabric Density

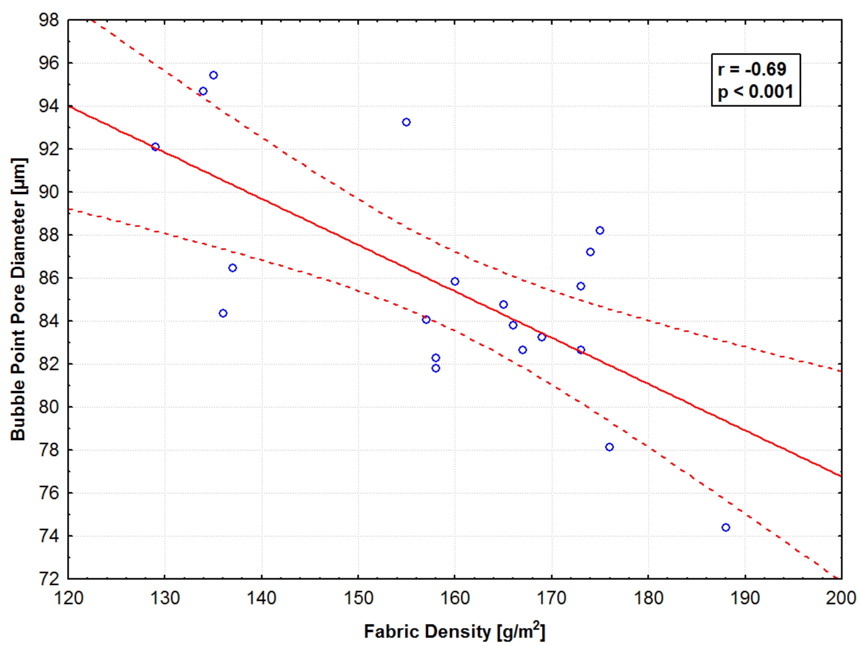

Figure 4.45 Bubble Point Pore Diameter vs. Fabric Density

It is seen that as fabric density increases, both the mean flow pore diameter and bubble point pore diameter decrease. In Figure 4.45, there is a highly significant negative relation between bubble point pore diameter and density with R = -0.69. As the fabric density increases, the fibers in the fabric are packed more tightly, thereby reducing the inter-fiber space or pore size in the nonwoven.

A similar relation is seen in Figure 4.46 between permeability and fabric density. There is a highly significant negative relation between the two variables with R = -0.69. As the density of the fabric increases, the size of the pores in the nonwoven fabric reduces due to closer fiber arrangement in the structure. The smaller pores constrict the flow of the fluid through the nonwoven structure, thereby decreasing the permeability. This is further confirmed by the relationship between permeability and bubble point pore diameter shown below in Figure 4.47. The relationship is highly significant with R=0.70. Permeability is seen to increase with an increase in the bubble point pore diameter, and the same is observed with permeability and mean flow pore diameter as well.

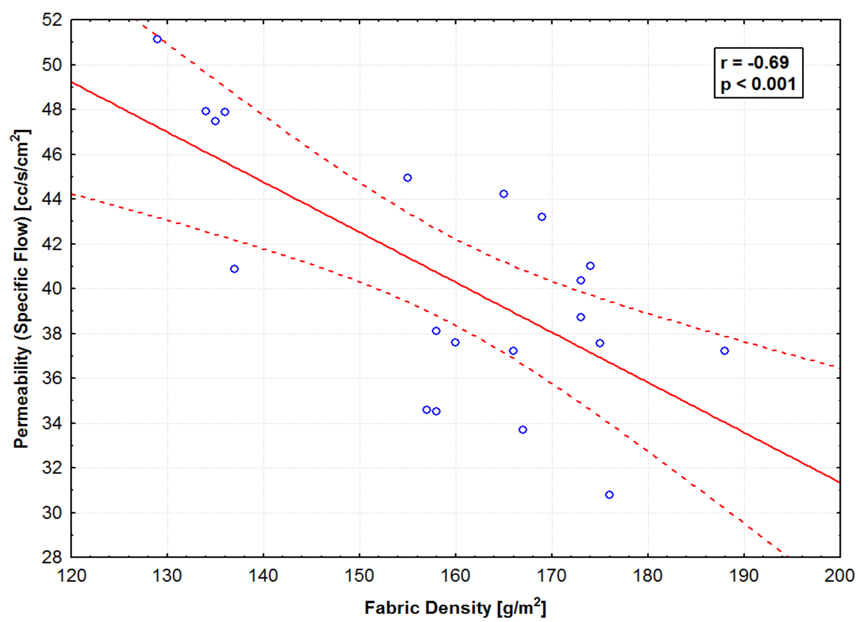

Figure 4.46 Permeability vs. Fabric Density

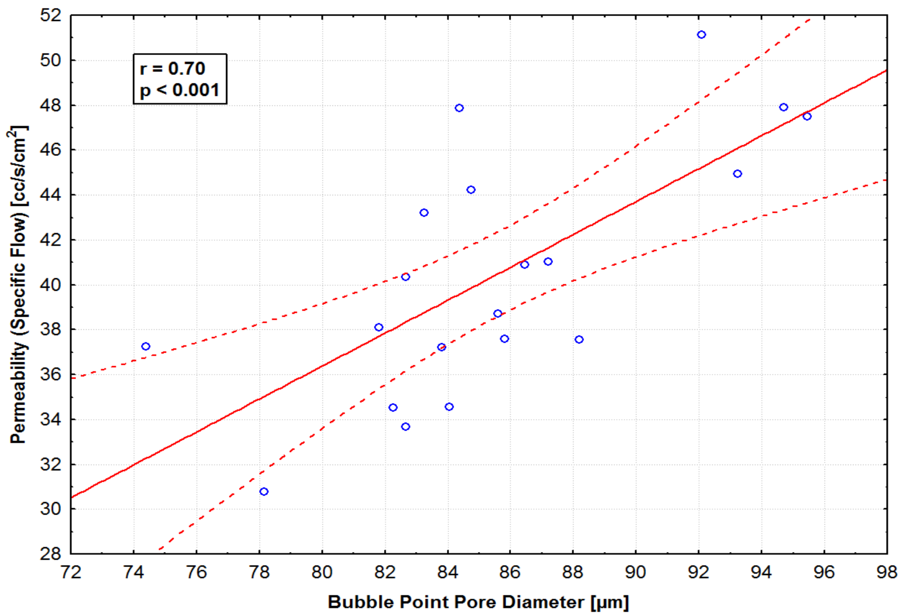

Figure 4.47 Permeability vs. Bubble Point Pore Diameter

The observed results are in accordance with results from previous studies on pore distributions which conclude that greater fabric density results in smaller pore size and therefore lower permeability in the fabric structure [61].

Further studies on the pore characteristics, entanglements and the surface structure properties of the nonwoven fabric by image analysis method would be able to throw more light on the effect of fiber parameters on the pore size and permeability of nonwoven fabrics.

4.4.6 Effect of Multiple Parameters on the Nonwoven Fabric Characteristics

Few inexplicable results were observed in some of the single variable regression analyses due to significant interactional effects of fiber parameters on the fabric properties. This makes it necessary to analyze the significant variables and their relationship with the fabric properties using multiple regressions, which takes the effect of multiple predictor variables into account during analysis. The forward step-wise multiple regression analysis was adopted for this purpose. This method adds predictor variables to the model at each level and selects it if found significant. The analysis was performed using Statistica (StatSoft Inc., Tulsa, OK).

Based on all the correlations observed earlier, AFIS raw fiber mean length (L_n), AFIS short fiber content (SFC_n), fiber fineness, fiber maturity ratio, and fabric density were used as the independent predictor variables. These variables were used to predict the specific breaking strength, specific burst strength, and permeability of the nonwoven fabric.

The step-wise multiple regression of all the independent predictor variables on specific breaking strength gave maturity ratio and fiber length (L_n) as the most significant predictor variables. The resultant regression table with the coefficients of each predictor variable, its t-value and its significance is given in Table 4.3. As seen in the individual regressions earlier, fiber length and maturity value showed the most significant relationships with fabric breaking strength. Both the parameters are seen to have a positive relation with breaking strength. Even though fineness showed significant positive relation with breaking strength, due to the dependence of fineness on fiber maturity, the effect of maturity was dominant in the model.

Table 4.3 Regression Table for linear regression model for nonwoven fabric specific breaking strength

	Standardized β	*B*	*Coefficient p-value*	*Adjusted R^2*	*F(2,17)*	*Model p-value*
				0.86	57.105	0.000
Intercept		-1.50	0.000			
Maturity Ratio	0.55	1.40	0.009			
Mean Length (L_n)	0.42	0.79	0.037			

The equation developed to predict the specific breaking strength is as follows,

$$\text{Specific Breaking Strength} = -1.50 + 1.40X_1 + 0.79X_2 \qquad (1)$$

where X_1 is the fiber maturity ratio and X_2 is the mean fiber length, L_n (in inches). The adjusted $R^2 = 0.86$ for the model shows that the predictive power of the model is highly significant.

Thus, the breaking strength of the fabric increases with increase in fiber length (L_n) and fiber maturity. Hence, longer and mature fibers will impart greater strength to the nonwoven fabric. This result is in concurrence with the relations observed between the individual fiber properties and fabric breaking strength.

The adoption of step-wise multiple regression to see the effect of fiber properties on nonwoven burst strength was not efficient. The analysis returned only a single variable, mean fiber length (L_n) as the significant parameter influencing burst strength of the nonwoven. This result is similar to that shown by the simple regressions in Section 4.4.3.1, where length was seen to have a significant effect on the burst strength. Though significant relations were seen between fiber maturity and fineness on the bursting strength of the fabric earlier, these parameters seem to have no significant influence in the overall model. Thus, the bursting strength of the fabric also increases with increase in fiber length (L_n).

Multiple regression analysis for permeability also returned a single predictor variable and showed the same results as that observed earlier from the simple regressions. Of all the independent variables provided in the model, fabric density was found to be the most significant predictor for permeability. A significant positive relationship was seen between fabric density and permeability. This is in accordance with the results in Section 4.4.5.3, and previous studies that have determined permeability to decrease with an increase in fabric density [61]. Other fiber parameters such as gravimetric fineness and fiber maturity were seen to have significant correlations with permeability. Though included as predictors in the multiple regression analysis, those parameters did not significantly increase the model's R^2 due to their interactional effect on the fabric density parameter.

Thus, the multiple regression analysis gives us the significant fiber parameters influencing the nonwoven fabric properties. The breaking strength of nonwoven fabric is seen to be influenced by both fiber length and maturity. The analysis gives an empirical equation involving both parameters that can be used for the prediction of the specific breaking strength of cotton needlepunched nonwovens. Experimental results showed significant effects of single parameters on the specific bursting strength and permeability of the nonwoven fabric. Fiber length is seen to have a significant impact on the specific breaking strength of the nonwoven fabric, whereas permeability was influenced by fabric density. Though significant results were obtained, further research is necessary to understand the interactional effects of fiber attributes and their effect on the fiber-nonwoven fabric relation which will help in improving the predictability of the nonwoven fabric parameters.

CHAPTER 5

Conclusion

5.1 SUMMARY

The nonwoven industry is a fast growing segment of the non-conventional textile industry. With increasing demand for environment friendly and biodegradable materials, there exists tremendous potential for cotton utilization in the nonwovens sector. At present, cotton finds limited use in nonwovens. It is mainly used in the manufacturing of absorbent and disposable products for hygiene applications, and in combination with synthetics for other industrial fabrics. 100% cotton nonwovens are hardly used in industrial textiles. The main reason for this is the high variability and lack of uniformity in cotton fiber properties. The fiber properties are known to have significant effects on the final product attributes in the case of traditional textiles. A similar relationship between fiber and fabric properties also exists in the case of nonwovens. Correspondence with cotton based nonwoven manufacturers made it clear that current industrial practices do not take cotton fiber properties into account during selection of raw material. There is a lack of research and understanding of the effect of fiber properties on the nonwoven fabric attributes and its importance to the industry. Years of research about fiber-fabric relations in the conventional textile industry have been helpful in overcoming the challenges posed by variation in cotton fiber properties and have been able to improve the prediction of final product characteristics. Similar studies need to be conducted to determine the fiber-fabric properties and improve prediction of final product characteristics of cotton nonwovens. Such studies will help in increasing cottons' marketability in the nonwoven industry and increase its market share in the textile industry.

The purpose of this research was to investigate the effect of fiber properties on the final fabric properties of nonwovens produced by needlepunching technique. 20 different samples of cotton with various combinations of fiber length and maturity parameters were used for this research. The tensile strength and elongation, burst strength and elongation, pore structure characteristics and permeability of the samples were measured and investigated. The effects of fiber properties such as, the raw fiber length parameters, fiber fineness and fiber maturity, on the nonwoven fabric properties were analyzed.

5.2 CONCLUSIONS

The cotton nonwoven fabrics for this study were prepared according to the procedure mentioned in Chapter 3. A significant variation was observed in the fabric densities of the prepared samples though a tight control was maintained on the input fiber feed weight. It was seen that fiber fineness has a significant effect on the fabric area and the density. As fineness of the constituent fibers increased, the area of the fabric decreased and the density of the fabric increased. Fineness is seen to have an impact on the packing density of fibers and loftiness of the fabric. This may be the reason for the variation in fabric densities between the cottons used for the study. As fabric density is important factor that influences the mechanical properties of nonwovens, measurements of breaking force and bursting force were converted to their specific strength by taking the ratio of force to density.

From the results of the correlation analysis and simple regressions, it is seen that both the specific breaking strength and specific bursting strength of the fabric had significant relations with mean fiber length (L_n), the length variation (L_n CV), short fiber content, fiber fineness, maturity ratio and immature fiber content. The strength of the fabric increased with higher fiber length and lower length variability and short fiber content. Longer fibers have greater surface area for inter-fiber contact and therefore impart greater strength to the nonwoven fabric. Although finer fibers are known to have better packing density and therefore impart better strength in nonwovens, the opposite was observed in this study. This may be attributed to the complex fiber structure of cotton and the fact that gravimetric fiber fineness (linear density) of cotton is dependent on fiber maturity. Finer cotton fibers have lower weight per unit length due to absence of cellulose in its structure. Immature fine cotton fibers are susceptible to breakage easily and this affects the strength. Hence a positive relation between fineness and strength in cotton nonwovens was observed.

Multiple variable regression analysis, taking all the important fiber parameters such as mean fiber length (L_n), SFC_n, fiber fineness, fiber maturity, and fabric area gave a significant equation to predict the breaking strength of a fabric. The obtained equation is as given below,

$$\text{Specific Breaking Strength} = -1.50 + 1.40(\text{Maturity Ratio}) + 0.79(L_n)$$

The apparent elongation during tensile testing exhibited exactly opposite relationships to those between strength and the AFIS fiber properties. The elongation was greater in samples with lower mean fiber length, greater variability and higher short fiber content. Short fibers contribute less area of contact in the nonwoven structure and therefore fiber slippage occurs easily on loading. Lower maturity ratio and fiber fineness were also observed in samples with high elongation values.

Simple regression analysis of specific bursting strength gave results similar to those of breaking strength. Specific bursting strength was seen to have significant relationships with most fiber attributes. But the multiple regression analysis showed only mean fiber length to have a significant impact on the burst strength of nonwovens.

The analysis of pore structure characteristics and permeability showed interesting results. A bimodal pore diameter distribution was observed for almost all the cottons. It was seen that these distributions were not affected by the fiber length or micronaire value of the constituent cotton. The measured pore diameters and permeability of the fabric had highly significant correlations with the fabric density. It was seen that pore diameters and permeability decreased with increase in fabric density. Nonwovens with high fabric density have more fibers per unit area which results in increased inter-fiber area of contact. As fibers are closer to each other in the structure, this would reduce the size of the pores formed in the structure. Reduction in the pore size would lead to lower permeability in the fabric. This is seen in the results of the study where pore size and permeability show a significant positive relation. Multiple regression analysis to determine the effect of fiber parameters on the permeability of nonwoven showed a relationship that was entirely dependent on fabric density. The effect of other influential parameters such as fineness and maturity were cancelled out due to their interactional effects with fabric density.

5.3 IMPLICATIONS AND FUTURE RESEARCH

This study was an exploratory research to investigate the effect of fiber properties on nonwoven fabric properties. The results show a significant variability in needlepunched fabric properties, with significant relationships with fiber properties. At present, cotton nonwoven industries procure readily available cotton for nonwoven production irrespective of its properties. The significant relationships observed from this study indicates that taking fiber properties into consideration while selecting cotton for nonwoven processing could help manufacturers optimize quality, and also predict final product characteristics.

Very few studies have focused on 100% cotton nonwovens and there is a lack of literature and research on cotton fiber properties and its effects on nonwoven fabric properties. This research is only a small part of what needs to be done to fully understand the effect of fiber properties on the final needlepunched nonwoven fabric properties. Future research in this field should build on these results with a fundamental study of the inter-fiber interactions within the nonwoven structure in order to gain understanding of how fiber properties impact fiber cohesion in the nonwoven. Since this was only an experimental study, it would be interesting to compare the performance of nonwovens from selected cottons with an industrial benchmark of cotton or even synthetic nonwoven. Also, comparison of 100% cotton nonwovens with cotton-blended nonwovens can help point out the weaknesses of cotton nonwovens, and how they can be overcome by blending in other fiber components. Such in-depth research studies, similar to the numerous studies that have been carried out on cotton yarns and woven fabrics, is essential for the successful adoption of cotton in the non-conventional nonwoven industry.

Appendix A

Table A.1. AFIS Test Results for all Cotton Samples

Sample #	Raw Fiber								Fibers after One Card Passage								Fibers after Two Card Passages							
	UQL(w) [in]	L(n) [in]	L(n) CV [%]	SFC(n) [%]	L5%(n) [in]	Fine [mTex]	IFC [%]	Maturity Ratio	UQL(w) [in]	L(n) [in]	L(n) CV [%]	SFC(n) [%]	L5%(n) [in]	Fine [mTex]	IFC [%]	Maturity Ratio	UQL(w) [in]	L(n) [in]	L(n) CV [%]	SFC(n) [%]	L5%(n) [in]	Fine [mTex]	IFC [%]	Maturity Ratio
3619	1.17	0.75	52.8	28.9	1.33	150	6.6	0.90	1.14	0.73	53.3	30.5	1.31	148	7.8	0.87	1.16	0.75	52.2	29.3	1.33	149	6.7	0.89
3614	1.18	0.69	59.9	37.0	1.34	145	6.7	0.88	1.15	0.66	59.7	38.3	1.31	144	8.2	0.86	1.15	0.66	60.5	38.7	1.32	144	7.5	0.86
3617	1.23	0.69	63.0	38.1	1.39	149	7.1	0.88	1.19	0.67	63.1	39.9	1.36	148	8.2	0.86	1.21	0.69	61.5	37.6	1.38	148	7.5	0.87
3615	1.27	0.79	55.1	28.5	1.43	146	5.3	0.93	1.25	0.79	53.9	28.1	1.41	148	6.3	0.91	1.23	0.73	58.2	32.8	1.39	146	6.6	0.91
3620	1.27	0.79	54.9	28.9	1.44	155	6.2	0.93	1.24	0.78	54.1	29.2	1.41	155	6.8	0.91	1.24	0.76	55.8	30.9	1.43	154	6.1	0.91
3560	1.26	0.77	55.1	29.8	1.43	157	5.5	0.93	1.25	0.78	54.3	29.5	1.42	161	6.1	0.93	1.26	0.77	54.7	29.1	1.43	159	5.8	0.93
3555	1.29	0.78	56.9	30.6	1.45	159	5.5	0.94	1.27	0.77	55.8	30.3	1.44	160	6.1	0.92	1.26	0.75	57.7	32.3	1.43	158	5.7	0.93
3556	1.17	0.74	52.7	29.9	1.32	168	5.7	0.92	1.16	0.75	50.8	28.3	1.32	168	6.5	0.91	1.15	0.73	52.5	30.7	1.31	167	5.6	0.92
3563	1.19	0.78	50.6	26.4	1.36	164	4.2	0.97	1.18	0.77	50.5	26.5	1.35	161	5.2	0.95	1.19	0.78	50.0	25.5	1.36	163	4.7	0.96
3553	1.18	0.74	53.5	30.7	1.34	168	5.6	0.92	1.16	0.73	51.7	29.5	1.32	169	6.4	0.91	1.16	0.75	50.6	28.0	1.33	169	5.8	0.92
3565	1.20	0.75	54.4	29.7	1.37	159	5.1	0.94	1.18	0.73	54.7	30.4	1.35	160	6.2	0.92	1.17	0.73	54.4	30.6	1.34	161	5.2	0.93
3561	1.20	0.81	48.7	23.9	1.38	165	4.1	0.98	1.18	0.78	49.8	25.9	1.36	164	5.2	0.96	1.18	0.77	50.2	26.6	1.35	163	5.0	0.96
3541	1.20	0.77	51.7	27.7	1.37	171	4.2	0.97	1.16	0.75	50.8	28.1	1.32	170	5.5	0.95	1.16	0.74	50.7	28.0	1.32	171	5.1	0.96
3542	1.18	0.74	54.5	29.4	1.35	173	4.7	0.95	1.17	0.76	51.5	27.4	1.33	174	5.2	0.93	1.18	0.75	53.0	28.3	1.34	173	4.8	0.95
3572	1.22	0.82	47.4	22.1	1.39	170	3.5	1.00	1.21	0.84	45.6	20.2	1.39	171	4.2	0.99	1.21	0.82	47.2	22.4	1.38	169	4.0	1.00
3543	1.25	0.86	46.2	20.5	1.41	171	3.6	1.00	1.24	0.85	46.4	21.0	1.40	171	4.1	0.99	1.24	0.82	48.8	23.1	1.40	171	3.6	1.00
3544	1.24	0.78	53.4	27.7	1.40	178	4.1	0.99	1.22	0.78	52.4	27.7	1.38	179	4.6	0.97	1.21	0.76	53.0	28.1	1.37	180	3.8	0.98
3576	1.27	0.88	45.7	18.8	1.45	173	3.5	1.00	1.25	0.87	45.1	19.1	1.42	173	4.0	1.00	1.25	0.86	45.9	19.9	1.43	172	3.3	1.00
3466	1.27	0.88	46.0	19.6	1.44	170	3.4	1.01	1.25	0.86	47.2	20.9	1.42	170	4.0	1.00	1.26	0.85	47.5	21.2	1.43	170	3.4	1.01
3570	1.30	0.88	46.9	19.7	1.49	172	3.6	1.01	1.30	0.88	46.2	19.8	1.48	171	3.9	1.00	1.30	0.90	45.1	18.3	1.49	172	3.4	1.01

Appendix B

Table B.1 Correlation Matrix between Fabric Density Parameters and AFIS Raw Fiber Properties

Correlations
Marked correlations are significant at $p < .05000$
N=20 (Casewise deletion of missing data)

Variable	AFIS Raw Fiber UQL [in]	AFIS Raw Fiber L_n [in]	AFIS Raw Fiber L_n CV [%]	AFIS Raw Fiber SFC_n [%]	AFIS Raw Fiber L5% [in]	AFIS Raw Fiber Fineness [mTex]	AFIS Raw Fiber IFC [%]	AFIS Raw Fiber Maturity Ratio	Raw Fiber Standard Fineness	Average Fabric Weight [g]	Average Fabric Area [m^2]
Fabric Density [g/m^2]	0.02	0.31	-0.41	-0.39	0.06	0.80	-0.62	0.59	0.63	0.58	-1.00
Average Fabric Weight [g]	0.35	0.50	-0.44	-0.48	0.37	0.55	-0.72	0.66	0.13	1.00	-0.56
Average Fabric Area [m^2]	-0.02	-0.32	0.43	0.40	-0.05	-0.82	0.62	-0.59	-0.65	-0.56	1.00

Table B.2 Correlation Matrix between AFIS Raw Fiber Properties and Needlepunched Fabric Characteristics

Correlations
Marked correlations are significant at $p < .05000$
N=20 (Casewise deletion of missing data)

Variable	Fabric Density [g/m^2]	Breaking Force (Max Load) [N]	Apparent Elongation (Extension at Max Load) [mm]	Fabric Apparent Elongation [%]	Fabric Specific Breaking Strength [N/gm^{-2}]	Bursting Strength (Max Load) [N]	Elongation at Peak Load [mm]	Fabric Specific Bursting Strength [N/gm^{-2}]	Permeability (Specific Flow) [$cc/s/cm^2$]	Mean Flow Pore Pressure [PSI]	Mean Flow Pore Diameter [µm]	Bubble Point Pressure [PSI]	Bubble Point Pore Diameter [µm]
AFIS Raw Fiber UQL [in]	0.11	0.47	-0.45	-0.45	0.55	0.48	0.00	0.59	-0.18	0.39	-0.41	0.42	-0.41
AFIS Raw Fiber L_n [in]	0.49	0.85	-0.74	-0.74	0.90	0.85	-0.25	0.89	-0.39	0.21	-0.26	0.38	-0.38
AFIS Raw Fiber L_n CV [%]	-0.58	-0.81	0.70	0.70	-0.81	-0.81	0.34	-0.78	0.42	-0.08	0.13	-0.25	0.26
AFIS Raw Fiber SFC_n [%]	-0.57	-0.87	0.75	0.75	-0.89	-0.86	0.30	-0.86	0.41	-0.14	0.19	-0.32	0.32
AFIS_Raw Fiber L5% [in]	0.16	0.52	-0.48	-0.48	0.60	0.53	0.01	0.64	-0.21	0.35	-0.38	0.41	-0.40
AFIS Raw Fiber Fineness [mTex]	0.89	0.79	-0.72	-0.72	0.67	0.81	-0.35	0.62	-0.60	0.43	-0.48	0.61	-0.64
AFIS Raw Fiber IFC [%]	-0.79	-0.93	0.88	0.88	-0.88	-0.90	0.48	-0.79	0.44	-0.17	0.22	-0.45	0.45
AFIS Raw Fiber Maturity Ratio	0.77	0.94	-0.90	-0.90	0.91	0.92	-0.42	0.84	-0.45	0.25	-0.29	0.51	-0.51
Raw Fiber Standard Fineness	0.57	0.19	-0.12	-0.12	0.03	0.25	-0.07	0.04	-0.47	0.43	-0.46	0.41	-0.46
Fabric Density [g/m^2]	1.00	0.77	-0.72	-0.72	0.61	0.76	-0.37	0.50	-0.69	0.41	-0.45	0.67	-0.69

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