ABSTRACT

Vyas, Khyati. Microfiber Nylon Spunbond: Production and Characterization. (Under the direction of Dr. Trevor Little)

The research is to produce and characterize microfiber nylon spunbonds using Sixteen Segmented Pie bicomponent configuration with one of the components as water-soluble polymer. In addition, the entire process of making microfiber nylon spunbond is optimized. The influence of fiber size and the basis weight of the fabrics on Exceval^{TM} removal process and the properties of nonwoven fabrics at each process are analyzed.

Combining aqueous polymer removal with Sixteen Segmented Pie bicomponent fiber cross-section, microfiber spunbond nonwovens of various basis weights and fiber size were produced. The spunbond fabrics of solid Sixteen Segmented Pie bicomponent fibers using Nylon (70%) and Exceval^{TM} (30%) as alternate components were made, and then fabrics were recalendared at an optimized calendaring condition to increase web integrity and achieve web strength to withstand washing treatment as well as to facilitate ease of Exceval^{TM} removal. FTIR and SEM were used to verify Exceval^{TM} removal. As a next step, the recalendared fabrics were processed for the washing treatment to remove water dispersive polymer Exceval^{TM} from the fabrics without causing damage to the Nylon component and suggestions were made about optimized washing conditions for the removal of Exceval^{TM} from the fabrics of different basis weight and fiber size. Hydroentangling was carried out for all fabrics to improve strength and aesthetic properties of the washed fabrics. Further, characterization of the fabrics was made using FAST (Fabric Assurance by Simple Testing) system and MTS Sintech tensile tester. Properties of the fabrics including basis weight, tensile strength, elongation, compression, surface thickness, bending and extensibility (%), were analyzed for each process. Additionally, the influence of fiber size (denier per filament) and basis weight of the fabrics on Exceval^{TM} removal process as well as the fabric properties were studied.

Microfiber Nylon Spunbond:
Production and Characterization

by

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Dedicated to my parents

Dr. Bhasker Vyas and Dr. Kalpana Vyas

BIOGRAPHY

The author was born in Ahmedabad, India on April 21st, 1979. She received her Bachelor of Engineering in Textile Technology from Gujarat University, India in June 2000. She is a valedictorian and a recipient of a Gold Medal for the same. In August 2002, she joined College of Textiles at North Carolina State University to purse Master of Science in Textiles. She is elected by National Honor Society, Phi Kappa Phi, for academic excellence. She is enthusiastic and passionate about research related with nonwovens and wants to pursue it as her career path.

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CHAPTER - 1

INTRODUCTION

The definition of nonwovens most commonly used is those by the Association of the Nonwovens Fabric Industry (INDA) and the European Disposables and Nonwoven Association (EDANA).

INDA Definition: "Nonwovens are a sheet, web or batt of natural and/or man-made fibers or filaments, excluding paper, that have not been converted into yarn, and that are bonded to each other by any of several means. The various methods for bonding are" [INDA Nonwovens Glossary, 2002]**:**

(a) Adding an adhesive
(b) Thermally fusing the fibers or filaments to each other or to the other meltable fibers or powders
(c) Fusing fiber by first dissolving, and then resolidifying their surface
(d) Creating physical tangles or tuft among the fibers
(e) Stitching the fibers or filament in place.

EDANA Definition: "Nonwovens are a manufactured sheet, web or batt of directionally or randomly oriented fibers, bonded by friction, and/or cohesion, and/or adhesion, excluding paper or products which are woven, knitted, tufted, stitch-bonded incorporating binding yarns or filaments, or felted by wetmilling, whether or not additionally needled. The fibers may be of natural or man-made origin. They may be staple or continuous or formed in situ. To distinguish wetlaid nonwovens from wetlaid papers, a material shall be regarded as a nonwoven if more than, 50% by mass of its fibrous content is made up of fibers (excluding chemically digested vegetable fibers) with a length to diameter ratio greater than 300. Or more than 30% by mass of its fibrous content is made up of fibers (excluding chemically digested vegetable fibers) with a length to diameter ratio greater than 300 *and* its density is less than 0.40 g/cm3" [EDANA, 1988].

Recently with the increase in production, applications and demand rate of the nonwovens, a lot of research work is underway for nonwovens in the textile sector. Apart from the use of conventional fibers, microfibers are of prime research interest due to their potential applications in various textile products including apparel. The term microfiber is generally used for fibers with denier per filament of less than one (1 to 10 micron) [www.fibersource.com] and nano fiber is the term used for fibers with less than 1 micron size.

Bicomponent fiber technology is an economical route to microfiber fabrics. Today, bicomponent fiber technology is the fastest growing group of manufactured fibers for its application in nonwovens due to the possibility of spinning a variety of fiber cross-sections and a wide selection of polymers and their properties. Spunbond and Meltblown are two techniques widely used for the production of bicomponent nonwovens. Spunbond process is a one step nonwoven manufacturing method in which direct conversion of polymer chips is made into fabric. Polymer is prepared, melted, extruded, drawn and quenched into continuous oriented filaments which are collected on a moving belt in a random manner and then bonding of the nonwoven web is carried out. Spunbond process is unique because it can be used for the production of a variety of bicomponent fiber cross-sections including Islands-in-Sea, Splittable and Segmented Pie cross-sections, which facilitates the production of microfiber. The latest approach to make microfiber fabrics of good strength and high barrier properties is the use of bicomponent technology together with spunbond process.

Microfiber spunbond nonwovens have various applications depending on the polymers selection and fiber cross-sectio. These include ultrasuede, artificial leather, women's silk-like blouses and dresses, wiping cloth, clean room wipes, surgical gowns, masks and high performance filters, artificial blood vessels, acoustic materials and seat covers in automobiles. It is also possible to use a variety of finishing processes like calendaring, sanding, raising, tumbling, printing, dyeing and mechanical or chemical handle improvement on microfiber nonwovens, for example Evolon™, as well as to apply various coatings to achieve functional characteristics like anti-microbial, anti-allergen, self-decontamination etc. In microfiber fabric, due to lower denier or fiber size, the size of the openings in the fabric decreases compared to the fabric of same fabric weight with high denier fibers, increases the surface area of the fibers, and results in a more flexible fabric. If a hydrophobic coating is applied on the fibers or fabric surface, this can result in a great improvement in the barrier properties [Hagewood John, August 2001].

For example, Polypropylene (PP) microfiber spunbonds have application in wound-care, where they are used as hydrophobic backings to prevent exudates strike-through for extra protection against contamination. At the same time, the air permeability and breathability of these nonwovens promotes healing and their softness and flexibility allows excellent adaptation to the skin. In addition, Polypropylene (PP) microfiber spunbonds have potential application in disposable surgical gowns and masks where spunlaced fabrics are widely used. The barrier properties of these spunbonds are more than 25% better than the spunlaced fabrics at about half their weight (35 grams per square meter). Their softness, high permeability and breathability guarantee a high level of comfort in wearing when used as surgical gowns, and for application as surgical face masks; the hydrophobic outer layer prevents fluid strike-through in case of splashes [Chemiefasern Textil Industrie, March 1990]. Polyethylene (PE) base microfiber spunbonds are being used as comfort covers for ostomy bags to avoid the unpleasant skin contact with the plastic, and these spunbonds can be welded to the plastic without any problem. Since, these microfiber spunbonds are very soft, air permeable, rustle-free and dermatologically safe; they enhance the patient's comfort. Their flexibility and good tear strength are additional advantages in terms of safety for ostomist [Chemiefasern Textil Industrie, March 1990].

Purpose of the current Research:

Today, sixteen Segmented Splittable bicomponent microfiber nonwoven fabrics of Polyester and Nylon are commercially available for the use in making synthetic suede and synthetic leather. Another application is as wiping cloth or technical wipes, where small fibers are useful in picking up smaller pieces of dust and other particles. However, they are not ideal for the application in synthetic suede or synthetic leather, because the fabric is often dyed. Since, both the Polyester (PET) and Nylon must be dyed; two separate dyeing must be performed. The shade fading rate is also different for both the types of dyes in response to light, laundering and abrasion [Dugan Jeff, 1999]. This requires manufacturing of homopolymer microfiber nonwovens according to its end use by keeping cost factor in mind. Several efforts have been done in the area to produce 100% Polyester (PET) microfiber fabric with Segmented Pie fiber so that the fabric can be dyed with one type of the dye. This includes, spinning Polyester and Co-Polyester as a bicomponent but they can not be separated easily because of too high adhesion to each other [Dugan Jeff, 1999]. In some recent work, it was found that Polyester (PET) and Polylactic acid (PLA) can be used because this allows the segments of two components to split apart and the fabric can be dyed with the same disperse dyes used to dye Polyester (PET). In addition, Polylactic acid (PLA) is hydrophilic making the PET/PLA combination with Segmented Pie cross-section a potential in apparel fabric [Dugan Jeff, 1999].

However, none of the efforts has been directed to developing 100 % Nylon microfiber spunbond nonwoven with Segmented Pie cross-section using water-soluble polymer as one of the components. Therefore, the present research, produces and characterizes microfiber Nylon spunbond nonwoven; using bicomponent fiber technology with sixteen Segmented Pie fiber cross-section and water-dispersive polymer, Exceval^{TM}. This research combines the aqueous polymer removal concept with sixteen Segmented Pie fiber cross-section. The best possible method(s) or machine(s) and optimized washing conditions for the removal of the Exceval^{TM} from the fabrics of different fabric weight and fiber size are studied. In addition, the influence of various parameters like fiber size (denier per filament), through-put rate (gram per hole per minute) and fabric weight of the fabric on the Exceval^{TM} removal process and the fabric properties are evaluated. Further, characterization of the fabrics uses the FAST (Fabric Assurance by Simple Testing) system, and MTS Sintech tensile tester. In other words, various properties of the fabrics like fabric weight, tensile strength, elongation, compression, compressed thickness, bending and extensibility (%) are analyzed at each process and a comparison is made.

CHAPTER - 2
LITERATURE REVIEW

2.1 Microfibers:

The term microfiber is generally used for fibers with denier per filament of less than one (1 to 10 micron) [www.fibersource.com] and nano fiber is the term used for fibers with less than 1 micron in dimension. The characteristics of these fibers are; strong, durable, light weight and supple, good stability and shape retention, wrinkle resistant, washable and dries quickly, water repellent, wind resistant, and comfortable to wear, as they are more porous [Tondl Rose Marie, July 1995]. Microfiber can be produced in four different ways: (1) direct melt-spinning, (2) Electro-Spinning (3) Flash Spinning (4) using Bicomponent Technology.

Microfibers can be melt-spun directly in about 0.15 denier per filament (dpf) but owing to the need for throughput economies and efficiencies, in practice, the fineness of the fibers is limited to 0.5 denier per filament. They are costly to produce and costly to convert into conventional textile products or into nonwovens [Ward Derek, December 1997]. Normally, sueding, sanding or caustic weight reduction is carried out as a finishing process to enhance microfiber fabrics. However, fabric finishing is critical due to the need of greater care in handling. Microfiber fabrics provide good value but are not a cheap commodity.

Electrospinning is not a new process. It has been known from past many years and a number of patents covering art and scientific papers discussing science exist in the literature [Doshi Jayesh, August-September 2001]. However, it is minimally commercialized process to generate smaller fibers because the production rate is only 0.03 grams/hole/minute. Electospun fibers offer very small fiber size generally in the range of 40 to 300 nanometers (0.04 to 0.3 micron) or larger, but on the other side, these fibers are very weak ["Multi-component", Hills Inc]. The nano-web produced using Electrospinning has relatively poor tensile properties and is very hard to handle because of small fiber diameter. Therefore, nano-webs need to be supported on a substrate for improved strength and better handleability

[Doshi Jayesh, August-September 2001]. These fibers are often used in composites with larger and stronger fibers.

Flash-spinning is different from the conventional melt spinning process. In flash-spinning, pure solvent droplets and highly saturated polymer /solvent mixtures are decompressed through a spin orifice. As the pressurized solution is allowed to expand rapidly through the orifice, the low-boiling point solvent is instantaneously "flashed off," leaving behind a three-dimensional film-fibril network. The microfibers that are produced via this process are interconnected in a continuous network and collected on a moving belt. Then, the sheet is subjected to either area bonding, which creates a stiff, paper-like sheet, or point bonding, followed by in-line softening which creates a drapeable, fabric-like sheet. No binders or fillers are used [www.fiber2fashion.com].

An alternative route to microfiber fabrics is the use of bicomponent technology to produce nonwovens. Bicomponent fiber technology is the fastest growing group of manufactured fibers for its application in nonwovens due to the possibility of spinning various fiber cross-sections, selection of polymers and their properties. The production of bicomponent nonwovens currently uses Spunbond and Meltblown processes. Spunbond process is unique because it can be used for the production of a variety of bicomponent fiber cross-sections including Islands-in-Sea and Segmented Pie or Splittable cross-sections, which facilitates the production of microfiber. The Meltblown fibers are generally of 500 to 10,000 nanometers (0.5 to 10 micron) and the production rate is 0.5 grams/hole/minute. The Meltblown technology and Electrospun fibers offer much lower fiber size than Spunbond fibers, but using modern bicomponent technology with Islands-in-Sea and Segmented Pie or Splittable fiber cross-sections; reduced fiber size in the range of 200 to 5000 nanometers (0.2 to 5 micron) and increased surface area can be achieved [“Multi-component”, Hills Inc]. In addition, even micro-sized or nano-sized bicomponent staple or spunbond fibers have excellent tensile properties because these fibers are crystallized, and oriented in the same manner as conventional melt-spun fibers, while meltblown fibers are very weak due to low crystallinity and orientation.

Applications of Microfibers:

One of the most important applications of microfiber is in fabrics for fashionable garments, where the soft, silky, and improved draping properties are highly desirable. Microfibers made from bicomponent technology have many uses, including in apparel. High surface area of the microfiber also provides improved absorption and insulation properties to fabrics therefore; they have application in inner liners for gloves and underwear [Cooke T. F., 1996]. In addition, the small diameter and high surface area of the microfibers have led to the development of fabrics with functional properties. These properties according to Heidenreich and Ninow include water-tightness, wind-proof, and permeability to water vapor while still retaining softness and drape [Cooke T. F., 1996]. For example, “Evolon” fabrics produced by Freudenberg Nonwovens have good draping properties, decorative appearance, good processability, and good wash and wear properties, together with functional characteristics like comfort and UV protection [Groten Robert, April 2001].

2.2 Bicomponent Fibers:

Bicomponent fiber can be made by, “extruding two polymers of different chemical composition and/or physical properties simultaneously from the same spinneret with both the polymers contained within the same filament” [www.fibersource.com]. The main objective of producing these fibers is to exploit capabilities not existing in either polymer alone. It improves the material performance suitable for specific needs by tailoring one or more properties of two polymers so as to engineer multifunctional properties.

Bicomponent fibers are not new. Photomicrographs of cross-sections of wool fibers show that wool fibers have multiphase region and are composed of two halves, each roughly semi-circular in cross-section. These two components adhere strongly to each other and rotate spirally around each other as they run the length of the fiber. The difference in shrinkage leads to the helically crimped configuration of the wool fiber. Wool is, in fact, a natural bicomponent fiber [R. Jefferies, 1971]. This discovery indicated the possibilities of spinning two polymers into the one fiber to make man-made self crimping fibers. The first commercial bicomponent product “Cantrece” was introduced by DuPont in 1960s, made from nylon side-by-side bicomponent fibers to offer significant stretch in ladies stockings. Simultaneously

I.C.I in the U.K. developed “Heterofil” fibers, concentric sheath core nylon6/nylon66 bicomponent fibers to produce fabrics like “Cambrelle” which is used in shoe linings and “Terram” a spunbonded geotextile [Morgan David, 1992].

The bicomponent fiber can be classified according to the component distribution within the cross-sectional area of the fiber; like one around the other - Sheath Core, one situated layer-wise with the other - Side-by-Side or as a mixture of one with the other - Matrix Fibril. Within these three main categories, various kinds of cross sections have been developed in accordance with the function and end use of the objective fiber. **Figure 2.1** shows major bicomponent fiber cross-sections currently being used in various applications.

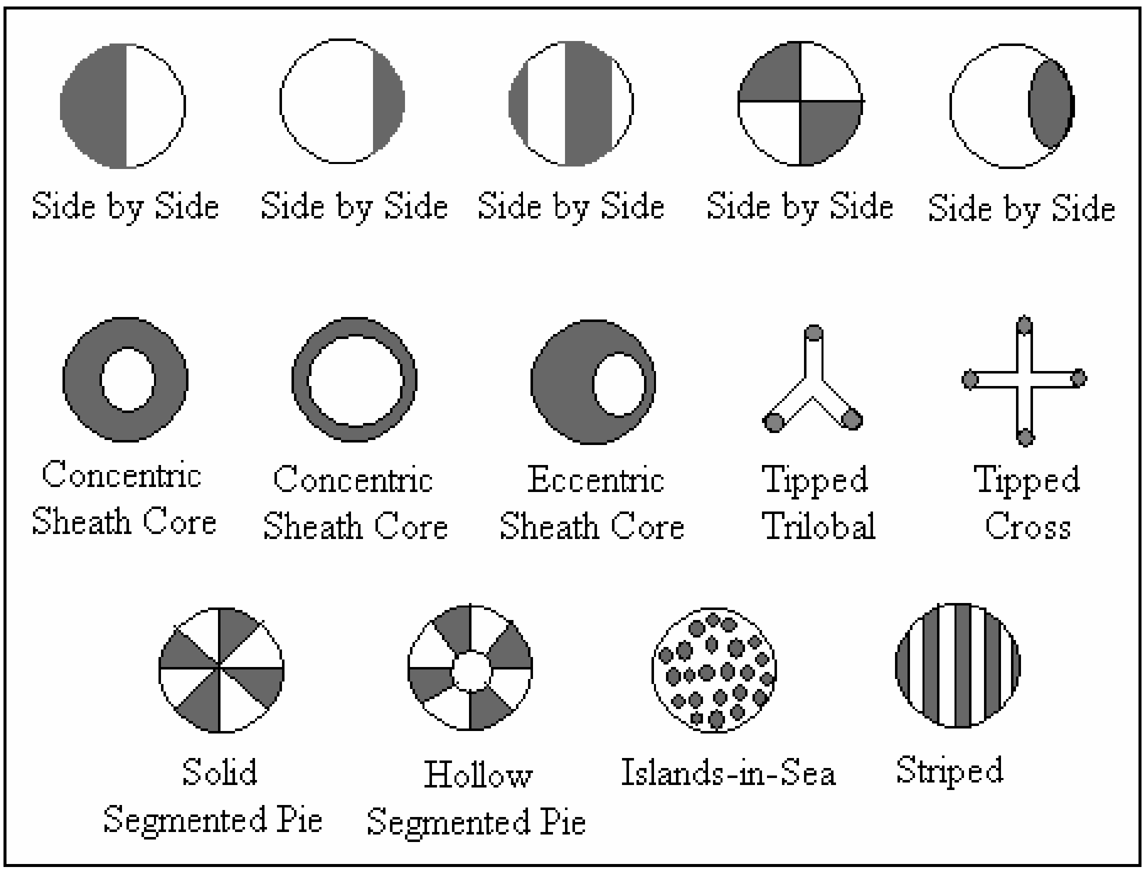


FIGURE 2.1, Bicomponent Fiber Cross-sections

2.2.1 Side-by-Side

Side-by-Side bicomponent fibers are produced by spinning two components layer-wise together so that they are joined longitudinally. It is necessary that both the components have good adhesion to each other; otherwise, the process will result in two fibers of different compositions [Zapletalova Terezie, June 1998]. The reason to produce Side-by-Side fibers is to obtain self-crimping and bulky fibers. These fibers have applications in knitted fabrics, sweaters, stockings, carpets, pillows, beddings, mattresses, automotive, super bulky spunbonded nonwovens and heat insulators [Masao Matsui, 2000].

Self crimping fibers can be made to provide helical crimp caused by the difference in the amount of shrinkage between the components. All commercially available fibers are of this type. Fiber curvature development can be influenced by the difference between modulus of the components, the thickness of the fiber or the overall cross-sectional fiber shape and individual cross-sectional shapes of each component [R. Jefferies, 1971]. In addition, variation in orientation across the fiber causes crimping due to strain with applied heat or relaxation. Some types of Side-by-Side fibers crimp spontaneously as the drawing tension is removed while others have "latent crimp", that appears when certain ambient conditions are obtained. Furthermore, Side-by-Side fibers are considered to be a base fiber for producing "Splittable" fibers, which are designed to be "split" at some stage of processing to yield fine filaments of sharp edged cross section [Kathiervelu S. S., July – September 2002]. Different melting points on the sides of the fibers are advantageous when nonwovens are thermally bonded.

2.2.2 Sheath Core

Sheath Core bicomponent fibers consist of two components where one of the components (core) is fully surrounded by the second component (sheath); the arrangement may be concentric (to give a non-self-crimping fiber) or eccentric (to give a fiber with self-crimping potential) [R. Jefferies, 1971]. This structure is employed when it is desirable for the surface to have the property of one of the polymers such as luster, dyeability or stability, while the core may contribute to strength, reduced cost and additives or conductive material [Zapletalova Terezie, June 1998].

The most common use of Sheath Core bicomponent fibers is as binder fibers, self crimped or bulky fibers and conductive fibers. Normally, concentric Sheath Core fibers are used as binder fibers where core is of high melting component surrounded by low melting sheath. During bonding either calendaring or through air heating, at an elevated temperature the sheath component of the fiber melts and it creates bond with adjacent fibers. Binder fibers become the part of nonwoven structure and add integrity.

The first commercial Sheath Core binder fiber "Heterofil" was produced by I.C.I. Fibers Ltd. and it has application in carpets and upholstery fabrics. The fiber sheath is a polyamide of a lower melting point than that of the polyamide of the core [R. Jefferies, 1971]. Binder fibers have applications in absorbents, filtration, bedding, furniture, apparel, medical, wipes and geo-textiles [Bouchillon Randall E., April 1992]. Self crimped or bulky fibers can be made using eccentric Sheath Core, where core is shifted off-center. The difference in shrinkage rates of the two components causes the fiber to curl into a helix when heated under relaxation. This allows the fiber to develop crimp and bulk. Sheath Core fibers are also being used in developing low cost fabrics of desired surface properties, where sheath component is of better quality and required special characteristics while core component is inexpensive. Toyobo (Japan) developed a highly water absorbent fiber having Sheath Core structure with highly water absorbable polymer arranged in the sheath portion while acrylic as a core to provide enough tensile strength to the fiber. This fiber absorbs water about 150 times to the weight of the fiber [Masao Matsui, 2000]. Danaklon has developed a Sheath Core fiber for use with fluff pulp in absorbent personal products as well as in paper making, which could benefit from a strong, hydrophilic and bondable fiber. A surfactant is incorporated into the sheath polymer at about the 2% level. The fiber has substantive hydrophilic characteristics as indicated by a sinkage time in water of less than five seconds [Morgan David, 1992]. Sheath Core fibers can also be used as conductive fibers having carbon black as a core and spinnable polymer as a sheath.

2.2.3 Matrix-Fibril or Islands-in-Sea

Matrix-fibril bicomponent fibers are spun from a mixture of two polymers in the desired proportion, where one polymer is suspended in the form of droplets in the matrix of a second polymer. These fibers are also called "Islands-in-Sea" fibers. These types of bicomponent structure facilitate the generation of microfiber. The term microfiber is generally used for fibers with denier per filament (dpf) of less than one [www.fibersource.com]. The "island" component becomes the residual microfiber after the "sea" or "matrix" is dissolved after nonwoven or woven fabric processing. Usually, the "islands" are of any melt spinnable polymer such as polyester, nylon or polypropylene etc. While the "sea" component is a polymer, such as polystyrene, water dispersive polymer, co-Polyester, Polylactic acid and plasticized or saponified polyvinyl alcohol, which can be chemically removed without causing damage to the islands [Wilson John, August – September 2001]. Islands-in-Sea fibers can be costly to produce and process but the cost can be reduced by decreasing the ratio of the sea polymer (20 – 30%) as well as optimizing the selection of sea component. Furthermore, with the newest spinning technology, the spinneret-hole density and spinning yields are essentially the same as for homo-polymer fibers, resulting in little or no additional cost in the extrusion process [Hagewood John, October 1998].

The first commercial product of Islands-in-Sea bicomponent microfiber was in artificial suede "Alcantara" (Ecsaine)™ which was developed by Toray, Japan in 1970. The structure of the fiber was made with 16 islands of Polyester component in Polystyrene sea. The matrix polymer Polystyrene was dissolved with a solvent to obtain microfibers [Masao Matsui, 2000]. Before dissolving the sea polymer with alkaline or water treatment the needle punched nonwoven fabric can be coated with elastic Polyurethane. Therefore, after dissolving the sea, fine diameter fibers having polyurethane coating can give soft feel of suede to the fabric and this process of making artificial suede is inexpensive [Masao Matsui, 2000]. Artificial suede is used mainly for coats, jackets, gloves, bags, shoes and furniture. A matrix-fibril fiber called "Source" is produced by Allied Chemicals Limited. It is based on Polyester (PET) fibrils embedded in a matrix of Nylon 6. The presence of Polyester (PET) fibril is supposed to increase the modulus of the fiber, to reduce moisture regain, to reduce the dyeability, improve the texturing ability and give the fiber a unique lustrous appearance [Kathiervelu S. S., 2002].

Islands-in-Sea fibers have applications in nonwovens, synthetic leather, artificial suede, specialty wipes, ultra-high filtration media, artificial arteries and many other specialized products. Twenty-four and thirty-two Islands-in-Sea fibers have been produced for a number of years and are used to make products such as ultra-suede and artificial leather. Today, Hills Inc. (USA) has designed spin packs that allowed spinning higher island counts 1000 or more in fibers with a total denier as small as 2 denier per filament (12 Microns). The island fiber diameters range from 100-800 nanometers, after being fully drawn and the sea polymer dissolved away. This technology was developed internally at Hills Inc. (USA) and it has potential application in filtration [Hagewood John, August-September 2000].

2.2.4 Splittable fibers or Segmented Pie

The fiber consists of segments of two different polymers; each wedge of polymer A has a wedge of polymer B on either side. These fibers are designed to split into the wedges by mechanical (hydroentanglement), chemical or heat treatment to produce microfiber. Therefore, Segmented Pie fibers are also called “Splittbale fibers”. This technique can be used to make ultra microfiber in the range of 0.1 to 0.03 denier per filament (dpf). The technology of producing ultra microfibers or nanofibers requires spinning of 2 to 5 denier per filament (dpf) bicomponent fibers, and then the fibers are split into microfibers of 0.1 denier or even less [Hagewood John, October 1998]. For example, using a 3.0 denier per filament (dpf) segmented pie bicomponent fiber with 16 segments, microfiber of 0.18 dpf can be obtained after splitting if the components are equal in weight. However, the range of 0.1 to 0.3 denier per filament (dpf) is more typical [Ward Derek, December 1997].

Splittable fibers are commonly used in making synthetic leather for shoes, bags, upholstery fabric and garments, and synthetic suedes. Another end use is in technical wipes where small fibers are useful for picking up smaller pieces of dust [Dugan Jeff, 1999]. They are also being evaluated having application in filtration, insulation material, synthetic blood vessels and other special implants as well as in automobiles as seat cover and trimming textiles etc.

[”New Concepts for Producing Microdenier Bicomponent Split Fibers”, *International Fiber Journal*].

The microfiber made using Segmented Pie or Islands-in-Sea cross-sections can be electro-statically charged and these fibers bring value to applications where properties such as sound and temperature insulation, fluid holding capacity, softness, strength and durability, luster, high surface area, barrier property enhancement and filtration performance are needed [Dugan Jeff, “Synthetic Split Micro-fiber Technology for Filtration”] .

In 1972, Kanebo Ltd (Japan) developed a new Splittable radial bicomponent fiber “Belima” for silk-like fabrics and entered the artificial suede market with “Bellseime” in 1977. The fiber has four triangular Polyester segments and a radial polyamide segment in a single fiber. Kanebo Ltd (Japan) also developed a flower like cross-section of “Cosmo-alpha”, having eight triangular Polyester segments, one circular Polyester segment in center and a radial segment of modified polyester which can be easily dissolved by an alkaline treatment. These fibers were used for high class fabric “Nazca” for dresses and blouses [Masao Matsui, 2000].

In woven or knitted fabrics, after the fabric is produced using the standard technique a mild caustic solution is used to swell and split the fibers. Some type of mechanical process such as combing or brushing is then used to fully separate the tiny fibers. Splittable fibers can also be spun into staple form to make needle punched nonwoven fabric, which is treated to split the fibers apart and then coated with Polyurethane to make artificial leather or polishing cloth [Hagewood John, “Splitting Bicomponent Fibers in Spunbond Fabrics”]. As far as nonwoven webs are concerned, hydroentanglement is still the best splitting technique and some of the fabrics made this way are extremely soft and show potential for some apparel uses.

The most important thing a Splittable fiber should do is to split to make microfiber. The selection of polymers and fiber cross-section both influences the splitting process. There are various types of cross-sections that can be used to make Splittable fibers. One of those cross-sections is Segmented Pie with round shape. Segmented Pie cross-section can be made either solid or with hollow in the center. Solid segmented pie cross-section is difficult to split and depending on the polymers used, it may require both chemical as well as mechanical processing to achieve splitting. Polypropylene and Polyethylene (PP/PE) combination, which would be the polymers of choice for spunbond webs unless dyeing is required, do not readily split apart. The most common polymer combination for segmented pie is Polyester and Nylon (PET/PA6) that offers a good balance of splittability and cardability. It can be split easily when soaked in a hot caustic solution of 5 to 10% NaOH or during hydroentanglement. With segmented pie cross-section, if water soluble or water dispersive polymers are used as alternate segments in the initial fiber, the resultant microfibers are of the same polymer. The volume and weight ratios of the two components (polymers) can be varied to adjust weight loss, physical properties of the fabric and cost [Ward Derek, December 1997]. However, two of the major concerns with this concept are cost and disposal of the dissolved polymer.

Splittable fibers can be split without the use of a caustic solution if hollow segmented pie cross-section is used. It requires relatively expensive spinnerets compare to solid cross-section but it is often a good cross-section for polymers that can be split only with some difficulty [Dugan Jeff, 1999]. Hollow segmented pie is similar to segmented pie except it has a hollow center core that prevents the inner tips of the wedges from joining; thus makes splitting easier. This type of fiber is easily spun and can generally be split with drawing or simple mechanical agitation. In sixteen hollow segmented pie fiber, Polyester and Polypropylene (PET/PP) as well as Nylon and Polypropylene (PA6/PP) pies stay together during spinning but come apart with various types of down-stream processing including mechanical drawing [Hagewood John, October 1998].

Apart from solid or hollow segmented pie cross-section, Splittable fibers can be produced with Tipped trilobal cross-section. Tipped trilobal bicomponent fiber is a new concept in which the second polymer is placed in a small quantity on the tip of a trilobal or delta cross-section core. After spinning, the fibers are twisted and then wet heat is applied. Therefore, the polymer on tips of the fiber breaks apart into microfibers and spiral around the core polymer [Hagewood John, December 2001]. Hills Inc. (USA) developed a tipped trilobal fiber using above technique with melt spinnable Polyurethane core (70 %) and Polypropylene (30 %) as the tip polymer. The resulting yarn has over 100% elastic stretch as the

Polyurethane core shrank during the heating process and the Polypropylene micro-fibers spiral around the core. This yarn looks similar to a standard core/spun yarn, except the processing costs are substantially reduced and the fibers ringing the core are micro-fibers [Hagewood John, December 2001].

2.3 Spunbond Technology:

It is well known that the melt spinning technique was developed and commercialized for man-made fiber production by Dupont in 1958. In 1960s, Dupont (U.S.A.) and Freudenberg (Germany) adopted this technique into spunbond technology. The spunbond technology among other nonwoven technologies has shown outstanding record in terms of the annual growth rate, the production volume and the expansion of product end-uses for the past three decades due to its advantageous capability of producing wide variety of products at high production rate and low cost [Fumin Lu and Anders Moller, March 1996]. It is one step nonwoven fabric manufacturing system that makes nonwoven directly from polymer chips. It is the most cost effective method of making bicomponent nonwovens. Using spunbond nonwoven technology various bicomponent fiber cross-section, like Side-by-Side, Sheath Core, Segmented Pie, Islands-in-Sea and Tipped Trilobal, can be made. Filament diameter in the range of 15 to 45 micron is possible. The filament spinning speed is in a range of 2000 to 3000 meter per minute but lot of research is going-on to improve the speed [Fumin Lu and Anders Moller, March 1996].

One of the recent developments in this area is filament spinning speed up to 6000 meter per minute with Polyester, and 4500 meter per minute or higher with Polypropylene. These can be reached using Ason spunbond technology (Ason Engineering Inc., U.S.A.) with a compact line and a balanced quench system. In addition, with this Ason slow-draw process, filament diameter 5 to 25 micron; specifically as small as 0.7 denier with Polypropylene (PP) and 0.5 denier with Polyester (PET), has been achieved [Fumin Lu and Anders Moller, March 1996]. This development is in the direction of incorporating advantages of spunbond as well as meltblown process into the spunbond technology. New techniques are being developed to improve uniformity and barrier properties of spunbond fabrics to allow spunbond to compete successfully with carded thermal bonded nonwovens [Hagewood John, February 2000]. An ongoing effort is to continue to improve the properties of the existing spunbond products. The activity level to develop new polymers for fiber spinning is also at an all time high, and it can bring new and exciting properties to the spunbond fabric world [Hagewood John, February 2000]. Fabric from new polymers and polymer combinations are poised to enter the market. Because of all these, spunbond products will continue to rapidly increase market share and penetrate new markets including some portions of the apparel market is also possible.

2.3.1 Manufacturing Procedure

The spunbond manufacturing is very similar to the fiber producing process. The primary difference between these two systems is in the filament drawing mechanism. Rather than mechanical take-up rolls used in the fiber producing process, the air drawing device is used in the spunbonding process. That creates pressure difference for providing the force to attenuate filaments.

Spunbond process involves four operations in one system; extrusion, drawing and lay down or web formation and web bonding. Polymer is prepared, melted, extruded, drawn and quenched into continuous oriented filaments which are collected onto a moving belt in a random manner and then bonding of the nonwoven web is carried out. A typical spunbonding process consists of extruder, filters, metering system, spin-pack, quench system, suction device or blower, air compressors, air gun or attenuator, and take-up device. In spunbonding, fiber spinning with web formation can be combined with web bonding by placing the bonding device in the production line. Sometimes, web bonding is done as a separate step. Variety of bonding techniques can be used to bond the spun web and the choice of a particular bonding method depends on the ultimate fabric applications and properties desired. These include calendar (thermal) bonding, mechanical needle punching, hydro-entanglement, ultrasonic bonding, stitch, and through air bonding. Occasionally, two or more bonding methods are employed in combination. Since, the fabric production is combined with fiber production; the spunbond process is generally more economical than using staple fiber to make nonwoven fabric.

2.3.2 Basic Properties of Spunbond Fabrics

In spunbond process as fibers are drawn, they are highly crystallized and oriented and for this reason, fiber strength is good. Fiber orientation distribution (ODF) in the Spunbond fabric at high speed manufacturing is more or less isotropic, which means mechanical strength is practically the same in machine direction (MD) and in cross direction (CD). The fibers in the web are continuous in length and the shape of the fiber along its length is non-crimped. Spunbond nonwoven fabrics provide much higher mechanical strength than carded ones, but because of the non-crimped fibers, characteristics such as softness, drapability etc. are comparably worse than with carded nonwovens. The characteristics of conventional spunbonds have been unfavorable for many traditional textile applications [Dieter Groitzsch, August- September 2001]. However, the use of bicomponent fiber technology together with spunbond process and new polymer combinations can improve the nonwoven properties and can expand end-use applications of spunbond nonwovens.

Freudenberg Nonwovens Group has developed a new class of nonwovens called “Evolon” which combined the benefits of both carded and spunbond fabrics. Transferring textile properties into a spunbond can be accomplished through one of two methods: (1) create crimping during quenching and aerodynamic stretching, optionally enhanced by thermal post-treatment and, (2) reduce the fiber fineness down to microfiber denier [Dieter Groitzsch, August- September 2001]. Spiral crimp in the fiber can be developed using Side-by-Side or eccentric Sheath Core bicomponent configuration and to reduce the fiber fineness to microfiber, Splittable or Segmented Pie or Islands-in-sea bicomponents can be used. After the spunbonding, the fabric is subjected to hydroentanglement which results into fiber splitting. In Evolon, the most commonly used polymers with 16 Segmented Pie cross-section are Polyester/Nylon (PET/PA6,6) with a weight ratio of 65/35. Evolon fabrics offer outstanding drape, wear comfort and mechanical strength comparable to woven or knitted textiles in terms of properties [Dieter Groitzsch, August- September 2001].

2.3.3 Application of Spunbond Nonwovens

Spunbond nonwovens are being used in variety of products as listed below [Hagewood John, February 2000 and Kawahisa Shin, February 2000]. The key to most of these markets has been a low cost covering material with sufficient tensile properties to fit the application.

Agriculture: Plant cover, inner curtains in green house

Apparel: Interlinings, high-loft insulation, protective clothing, embroidery backings [Jarvis Christine, May 1997]

Automotive: backing for tufted automobile floor carpets, trim parts, trunk liners, interior door panel and seat covers.

Construction and civil engineering: roofing upper-sheet, house-wrap, erosion control, canal and reservoir lining protection, highway and blacktop cracking prevention

Geo-synthetics: earth reinforcement, tunnel drainage, soil separation

Household: bags, wrapping paper, carpet backing, furniture dust covers

Industrial: cable sheath, battery separator, air and liquid filters

Medical: coverstock for diapers, incontinence devices, medical wipes, hygiene products, medical gowns and drapes, barrier fabrics

Packing: metal-core wrap, medical sterile packing, floppy disk liners

CHAPTER - 3

EXPERIMENTAL PROCEDURES

3.1 Materials:

For the current research, Nylon 6, Ultramid BS-400N (BASF) and Exceval^{TM}, CP-4104B2 (Kurary Co., Ltd., Japan) was used in 70/30 ratio with Sixteen Segmented Solid Pie fiber cross-section to make bicomponent configuration.

3.1.1 Nylon 6:

[www.corporate.basf.com, Ultramid Brochure - BASF The chemical company]

Ultramid BS 400N is the trade name of polyamide-6 (Nylon-6) supplied by BASF for application in high speed spinning. It is a light-stable and heat-stable Nylon-6 for the production of bright textile fibers. Ultramid BS 400N is of semi-crystalline structure. The structure of the Nylon-6 (Polycaprolactam) is shown in **Figure 3.1.**

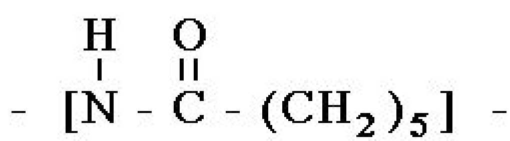


FIGURE 3.1, Structure of Nylon-6

The amide group (-CO-NH-) provides hydrogen bonding between polyamide chains and due to this, nylon retains its shape and strength even at elevated temperatures close to the melting range. In addition, it offers good mechanical and thermal properties. However, nylons are moisture sensitive. Moisture considerably influences the rheological behavior and mechanical properties. A rapid drop in viscosity can occur when the melt is extremely moist or hot or subjected to high mechanical shear forces. Oxidation can also cause the viscosity to fall [Ultramid Brochure, BASF The chemical company]. In addition, high moisture levels causes degradation and foaming, while relatively low levels of moisture act as plasticizer in Nylon-6 during melt processing. All types of the nylons absorb moisture depending on crystallinity, temperature and humidity. Therefore, before processing Nylon-6 polymer chips must be dried to avoid polymer degradation. The drying temperature for Ultramid™ lies in the range of about 80^0 to 110^0C.

Basic Properties of Ultramid BS 400:

Melting point approximately 220^0C (428^0F)

Density -1.12 to1.15 gm/cm^3

Moisture Regain – 4 to 4.5 %

The most important characteristics of Ultramid™ are:

- High strength and rigidity
- Simple processing
- Very good impact strength
- Good elastic properties
- Lustrous
- Outstanding resistance to chemicals
- Dimensional stability
- Low tendency to creep
- Exceptional sliding friction properties

Nylon's characteristic in textile industry is its versatility due to its properties. It is strong enough to have application as tire cords, fine enough for sheer, high fashion hosiery and light enough for parachute cloth and backpacker's tents. It washes easily, dries quickly, needs little pressing and holds its shape well. Due to nylon's excellent physical properties including tear strength and toughness, it has major application in nonwoven carpet market as well as needle-punched floor covering products. However, nylon fiber is not considered comfortable in contact with skin, combining two or more nonwoven web forming and bonding technologies together with bicomponent technology can open-up a new sector for Nylon applications in nonwoven product market.

At this moment, Sixteen Segmented Pie Nylon/ Polyester nonwoven is in the market as a commercial product having its application as synthetic suede or artificial leather as well as in technical wipes. In addition, according to a method described in US Patent: 6,692,541, a precursor web can be made by carding and cross-lapping Nylon/ Polyester Segmented Pie fibers. Later hydroentanglement can be done to split the segments of the fibers and it claims to improve the physical properties of the nonwoven including tensile strength, elongation, taber abrasion resistance as well as good drapeability and hand. It also discloses the use of three-dimensional image transfer device with hydroentangling to impart patterns or images on nonwoven fabrics. This method claims that the nonwovens made according to this patent has potential applications in medical gowns, personal hygiene articles and filter media.

In current research, Nylon is selected together with water-soluble polymer Exceval™ to make Sixteen Segmented Pie bicomponent configuration. Here, bicomponent technology is combined together with spunbonding, calendaring, Exceval™ removal process and hydroentangling to create a new approach towards microfiber Nylon spunbond nonwovens. The present research can bring value for durable nonwoven products as well as applications in functional fabrics like anti-microbial, anti-allergen, self-decontamination etc.

3.1.2 Exceval™:

[Exceval™ Brochure, Kuraray Co., Ltd., Kuraray America, Inc. Website, Kuraray Co., Ltd., Japan Website] EXCEVAL™ is a water soluble polymer developed by Kuraray Co., Ltd. (Japan) from the original technology accumulated in Polyvinyl Alcohol (PVOH) and Ethylene Vinyl Alcohol copolymer EVAL™.

To obtain water resistance and solution stability in Exceval™, two technologies of PVOH, fully hydrolyzed and partially hydrolyzed are included together. Polyvinyl Alcohols (PVOH) contain vinyl alcohol and vinyl acetate units. In partially hydrolyzed grades the vinyl alcohol content is such that the entire molecule is freely soluble in water, while in fully hydrolyzed grades the crystallization tendency and crystallinity of Polyvinyl Alcohols increases with the increase in hydrolysis and are therefore less soluble in cold water. Exceval™ is a combination of fully and medium hydrolyzed. Therefore, Kuraray Exceval™ is controlled in hydrophobic-hydrophilic balance and it provides good water resistance, sufficient viscosity stability of its aqueous solution and water solubility together. High crystallization performance of Exceval™ provides its dry film with extremely high water resistance and the water resistance can be improved using heat treatment. The following **Figure 3.2** shows the structure of EXCEVAL™.

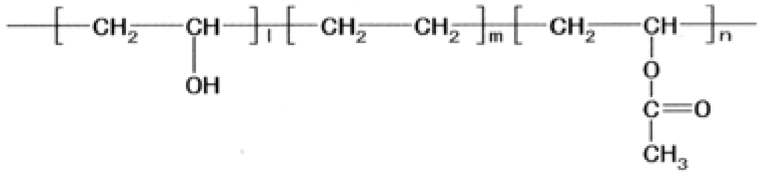


FIGURE 3.2, Structure of Kuraray EXCEVAL™

Source: Kuraray America, Inc. (Japan)

Due to these properties of Exceval™, it has applications in water soluble fibers and textiles, water soluble films, water resistant adhesives and paper processing agents. Exceval™ has also advantage in paper application due to high barrier performance, where the conventional Polyvinyl Alcohol (PVOH) has been used. Polyvinyl Alcohol (PVOH) is also a water-soluble polymer and used in various applications. However, it cannot be used in melt-spinning application due to insufficient heat stability and therefore Vinylon™ (PVA fiber) is being produced using wet spinning process. While Exceval™ has various applications including melt-spinning depending on the polymer grades or types.

Major grade list or types of Exceval™ includes

- RS - Polymer series: It is white or pale yellowish powder or granule. It is used as an aqueous solution. It is not for melt molding and melt spinning application.
- HR - Polymer series: It is specialized as a stabilizer for Polyvinyl Acetate emulsion with quite high water resistance.
- CP – Polymer series: It is either white or yellowish clear and odorless pellet. It is used in melt-molding and melt-spinning application.

Out of these three polymer series of EXCEVAL™, CP- Polymer series is applicable to melt-spinning, melt-molding, film-forming, injection-molding and blow-molding. **Table 3.1** describes the grades, their particular applications and some physical properties of CP – Polymer series of Exceval™.

TABLE 3.1, Types of Exceval™ CP – Polymer Series and Basic Physical Properties

Grades	Melt Flow Rate (g/10 min, at 230^{0}C, 2.16 kg)	Melting Point (^{0}C)	Moisture Content (Weight %, max)	Main applications
CP – 7000	9	212	0.5	Molded Products
CP – 4103B1	248	206	0.5	Meltblown nonwovens
CP – 4104B2	81	210	0.5	Fiber, Spunbond Nonwovens

Figure 3.3 and **Figure 3.4** shows melt viscosity curves of Exceval™ CP-4103B1 and CP-4104B2 respectively.

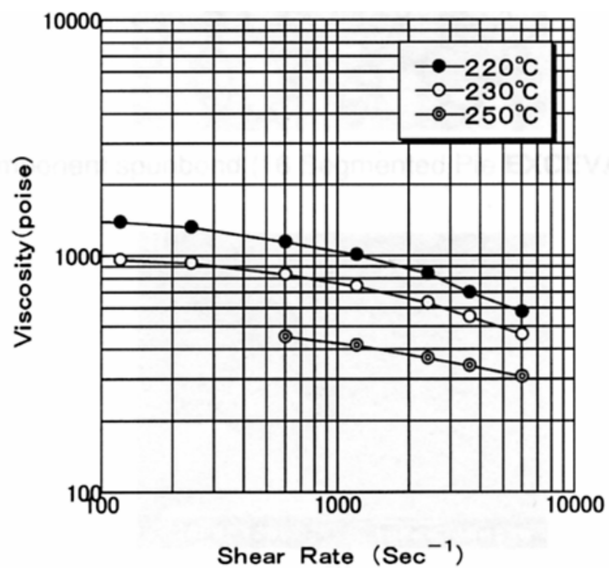


FIGURE 3.3, Melt Viscosity of Exceval™ CP – 4103B1

Source: Kuraray Co. Ltd., Exceval™ Brochure

It is obvious that increase in the temperature decreases the viscosity of both the polymers. However, for the same temperature (^{0}C) and shear rate (sec^{-1}), the melt viscosity of CP – 4103B1 Exceval™ is less than CP – 4104B2. In other words, CP – 4104B2 is more viscous than CP – 4103B1.

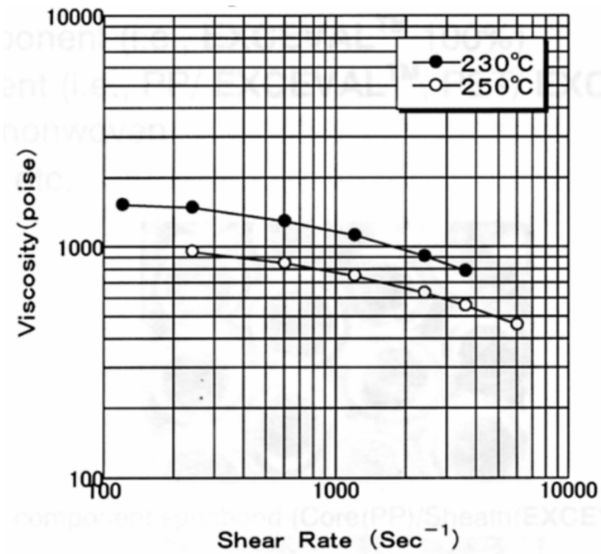


FIGURE 3.4, Melt Viscosity of Exceval™ CP – 4103B2

Source: Kuraray Co. Ltd., Exceval™ Brochure

For the present research CP – 4104B2 polymer was choice of interest due to its applications and properties like melting point, melt viscosity and Melt Flow Rate (MFR). It has better heat stability than other polymer series of Exceval™ and therefore it has been used in melt spinning as well as in various fields related to textile fiber and nonwovens either as 100 % component products or bicomponent products with Polypropylene (PP), Nylon, Polyester (PET), and so on. Exceval™ based 100% spunbond nonwovens have high resistance to oil and solvent, high affinity to water (water absorption and water solubility) and high biodegradability. These characteristics of Exceval™ based nonwovens are useful in surgical gown, drape, mask, industrial wipes and base cloth for embroidery (chemical lace) etc. Similarly, Exceval™ based bicomponent spunbonds and meltblowns can also be utilized in various products. For example, ultrafine Polyester (PET) spunbond can be made after dissolving Exceval™ in water from 16 Segmented Pie Polyester/ Exceval™ spunbond nonwoven and it can be utilized in apparel, clothing, wipes, leather goods, and filtration. As well as light weight spunbonds after dissolving Exceval™ can be made using bicomponent configurations like Sheath(PP or PET)/Core(Exceval™), 16 Segmented Pie (PET or PP or Nylon with Exceval™) and Islands-in-Sea (PP or PET with Exceval™).

In current research, 16 Segmented Pie bicomponent fiber configuration will be used with Nylon/ Exceval^{TM} in 70/30 ratio to make spunbond nonwovens and later-on Exceval^{TM} will be removed from the fabrics to obtain light weight Nylon spunbonds. Therefore, water solubility of Exceval^{TM} and related conditions of it are very important to consider. **Table 3.2** describes water solubility and water absorption of 100% Exceval^{TM} (CP – 4104B2) based spunbond nonwovens of different fabric weights and fiber size.

TABLE 3.2, Water Solubility and Water Absorption of 100% Exceval^{TM} (CP – 4104B2) based Spunbond Nonwovens ***

Source: Exceval^{TM} Brochure, Kuraray Co., Ltd.

NO.	Fabric weight (gm/m^2)	Fiber Fineness (decitex)	Water Solubility (^{0}C)			Equilibrium Water Content (%)	Absorption Ratio (%)	Absorption Speed (mm)
			60	80	> 90			
1	25	2.1	N	P	D	11.7	860	40
2	35	2.6	N	P	D	11.6	715	63
3	65	2.2	N	P	D	11.0	700	65
4	45	2.4	N	P	D	9.6	620	62

*** **Specifications about the Table 3.2:**

- Calendar temperature - NO. 1 to 3 -150^{0}C and NO. 4 - 180^{0}C
- Water Solubility: N – Not dissolved, P - Partially dissolved, D – Dissolved
- Equilibrium Water Content: condition 20^{0}C, 65% RH
- Absorption Ratio: After 200mm X 200mm nonwoven was soaked in pure water of 20^{0}C for 5 minutes and then taken away, the total weight was measured at the point in time when no water drops.
- Absorption Speed: After 250mm X 250mm nonwoven was weighted at the lower end and then dipped in water-soluble ink (ink/water = 1/5) at lower end by 10mm for 1 minute, the wet length was measured.

It is obvious from the **Table 3.2** that, EXCEVAL™ (100%) based spunbond nonwoven shows solubility in water at 90^0C or more for all four fabric weights and its water absorption in also excellent. These hydrophilic properties shown in the table are controllable by changing the heat treatment temperature during emboss processing of nonwovens.

The information given in this section about EXCEVAL™ is based on the literature review from Exceval™ Brochure, Kuraray Co., Ltd., Kuraray America, Inc. Website and Kuraray Co., Ltd., Japan Website.

3.2 Spunbonding:

Spunbond manufacturing facility of Hills Inc., U.S.A. was used, to produce spunbond nonwoven fabrics for the current research. Hills Inc. has invented an improved melt/solution polymer spinning method and apparatus for extruding multi-component fibers including various bicomponent configurations [Hills Inc., Method of making plural component fibers]. Hills spin pack utilizes one or more disposable distributor plates and it facilitates spinning of various bicomponent and plural component configuration with maximized density of spinneret orifice. According to this invented method, for bicomponent configuration, two polymer streams are extruded, passed through filters, metering pump and distributor plates to form a conjugate stream to pass through the spinneret hole.

Figure 3.5 shows, a schematic diagram of open spunbond process with belt collector. This method was used for making spunbonds of the present research. As shown in the figure, polymer is extruded, filtered and then melt polymer is forced by gear pumps through a proprietary spin-pack of Hills having a large number of holes. By suitable choice of extrusion and spinning conditions, desired filament denier is attained. Fibers are formed as the molten polymer exits the spinnerets, and is quenched by cool air. Before deposition on a moving belt or conveyor, the output of a spinneret usually consists of hundred or more individual filaments which must be attenuated to orient molecular chains within the fibers to increase fiber strength and decrease extensibility. For this reason, an air gun or slot attenuator is used today. The degree of stretching controls the ultimate strength of the fibers [Alex James, April 2000]. After that, mechanical or aerodynamic forces are used to separate the filaments using suction or blower and then, filaments are laid down randomly on the moving belt. As a last step of the process, web bonding is carried out.

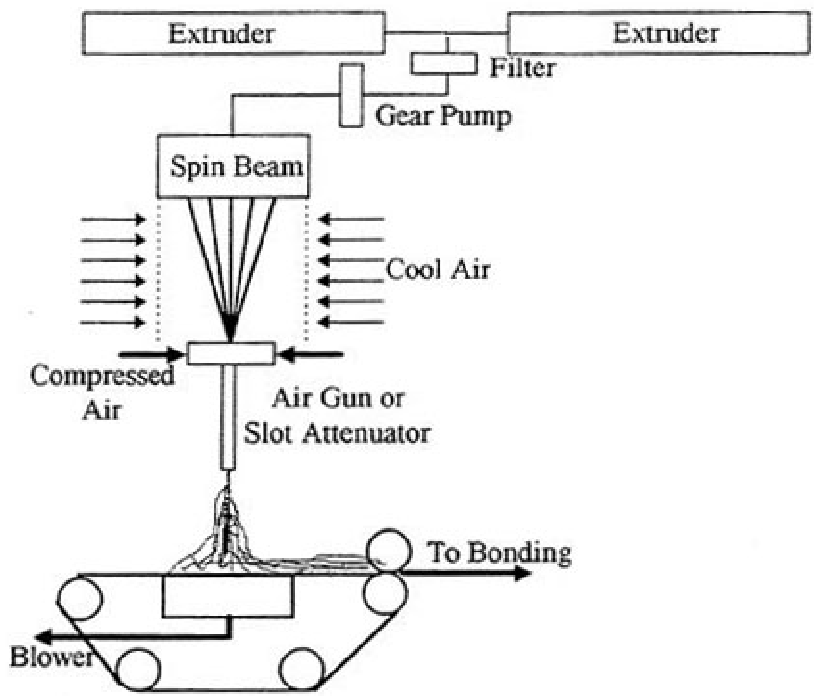


FIGURE 3.5, Schematic of Spunbond Process

Source: Hills Inc. (USA)

Spunbond nonwovens were made at Hills Inc. (Florida, USA) having 16 segmented bicomponent fiber cross-section of 70 % Nylon (BS 400N) and 30% Exceval^{TM} (CP 4104 B2) with various throughput rates, denier per filament and fabric weights as shown in **Table 3.3**. Before polymer extrusion and spinning, Nylon polymer chips were dried at 250^0F (121^0C) for 24 hours and Exceval^{TM} polymer chips were dried at 170^0F (76.67^0C) temperature. After Spunbonding process, calendar point bonding was used as a method of bonding the fibers in a web. During point bonding, the calendar top and bottom roller temperature was 120^0C (248^0F), and the calendar pressure was 320 PLI (Pounds per Linear Inch) for all thirteen fabrics. The calendar rollers used were; bottom one smooth and top with oval patterned with approximately 18% bonding area. The following table specifies the parameters used in the spunbond manufacturing process.

TABLE 3.3, Design of Experiment - Specifications of Spunbonding Process

Fabric Run Number	Through-put rate (ghm)	Denier per filament (dpf)	Total Denier	Filament Speed (meter per minute)	Fabric weight in grams per square meter (gsm)	Belt Speed (meter per minute)
1	0.9	2.5	5555	3240	100	40
2	0.9	2.5	5555	3240	80	50
3	0.9	2.5	5555	3240	60	66
4	0.9	2.5	5555	3240	40	99
5	0.7	2.0	4444	3150	100	31
6	0.7	2.0	4444	3150	80	39
7	0.7	2.0	4444	3150	60	51
8	0.7	2.0	4444	3150	40	77
9	0.5	1.5	3333	3000	100	22
10	0.5	1.5	3333	3000	80	28
11	0.5	1.5	3333	3000	60	37
12	0.5	1.5	3333	3000	40	55
13	0.7	1.0	2222	6300	80	39

Total Denier = Denier per Filament * Spin Pack Size

$$\text{Filament Speed (meter per minute)} = \frac{\text{Through-put rate} * 9000}{\text{Denier per Filament}}$$

Free fall fibers for each though-put rate 0.5, 0.7 and 0.9 gram per hole per minute (ghm) were collected to examine the fiber cross-section and denier per filament. In addition, the fabric rolls were collected for all 13 fabric Run numbers and the fabric weight was determined for each.

3.3 Marking of the Samples:

For the fabric weight measurement, 4 X 4 inch areas were pre-marked randomly on the as-made fabrics. The as-made fabrics were later on re-calendared, jet washed and hydroentangled. After each of these processes, those pre-marked samples were weighted.

3.4 Exceval^{TM} Removal Preliminary Study:

After making spunbond nonwovens, a small experiment was conducted to see the feasibility of the research. Samples of the as-made fabrics were washed to dissolve the water-soluble component (Exceval^{TM}) from the fabric using Jet Dyeing machine, JFO. This machine provides circular agitation as well as water jets action on the fabric. The characteristics of the machine are; liquor content 6-20 liters, fabric content 100-1500 gram, fabric speed 4-30 meter/min, heat up speed 2-4 ^{0}C/min, temperature 20-150^{0}C, water flow capacity of the jets 20 -100 % and pressure 0-4 bars [MATHIS Laboratory Overflow Jet Dyeing Apparatus Type JFO, Brochure].

Fabric samples of ¼ meter length and width were stitched in a rope form. All the fabric samples with different specifications; fabric weights, denier per filament and through-put rate; were subjected for 5 minutes washing time at three different temperatures 85^{0}C, 105^{0}C and 125 ^{0}C with 6 liter water content, and 100 % flow capacity of the water jets for 10 as well as 15 meter per minute fabric speed. Since, Exceval^{TM} based spunbond nonwoven shows solubility rapidly in hot water at 80^{0}C or more [Kuraray Co. Ltd., Exceval^{TM} Brochure], the temperatures selected for the experiment were more than 80^{0}C. For this preliminary experiment, the washing time specified here does not include the time to heat-up the machine at the required temperature.

3.5 Calendar Bonding:

After the preliminary study of Exceval^{TM} removal, all the fabrics were required to be bonded so as to improve fiber bonding and web integrity. For this purpose, calendar bonding method was used, which works on the principle of heat conduction by passing the fabric between two heated calendar-rollers; bottom roller is smooth and top is patterned. Due to the heat transfer from the rollers to the fabric, the polymer of the fibers on the surface softens or melts and it forms a bonding site with the neighbor or contact fibers. Calendar bonding can be either overall (area) bonding or point bonding. Area or overall bonding is done by passing the fabric between two smooth heated calendar rollers and thus creating maximum number of bonds between the fibers. If point bonding is used, the fabric is less stiff compared to the area or overall bonding due to less number of bonds. For calendar bonding, the important parameters of the process are calendar roller temperature, which is more significant than calendar roller pressure, the time for which fabric is in contact with the rollers and melting as well as glass transition temperatures of the fiber polymer or polymers.

For the current research, all the fabrics were re-calendared using calendar point bonding method. It was essential to find the optimized calendaring condition for all the fabrics so as to ensure web integrity as well as ease of Exceval^{TM} removal in the washing treatment. Besides, sustaining constant calendaring condition for all the fabrics and thus to keep minimum number of variables during the product development was very important to ease understanding of the nonwoven characterization and drawing conclusions.

To optimize calendaring conditions, calendar bonding process was carried out for fabric Run numbers 3 and 9 with the following specifications to prepare hand-sheets. Fabric Run number 3 is of 46.97 gsm fabric weight and 2.5 denier per filament (dpf) made at 0.9 ghm through-put rate while fabric Run number 9 is of 82.93 gsm fabric weight and 1.5 denier per filament (dpf) made at 0.5 ghm though-put rate.

Calendar Point Bonding Parameters:

- Calendar top and bottom roller temperatures: 120^{0}C, 140^{0}C and 160^{0}C
- Calendar roller pressures: 272, 326, 381 and 435 PLI (pounds per linear inch)
- Calendar roller dimensions: 14 inch diameter and 26 inch wide
- Smooth calendar bottom roller and top roller with diamond pattern and approximately 18% bonding area
- Calendaring speed: 5 feet/ minute

After preparing the hand-sheets of the re-calendared fabrics with these specifications, the fabrics were washed in Jet Dyeing Machine (JFO) and the fabric weights were measured for all the samples after washing, which are shown in results section. After looking at the results of the washing treatment, the optimized calendaring condition was found for the fabric samples. Finally, all the fabrics (fabric run number 1 to 13) were re-calendared at 140^0C top and bottom roller temperature with 435 PLI (pounds per linear inch) calendar roller pressure and 5 feet/minute calendaring speed.

3.6 Exceval™ Removal Process using Jet Dyeing Machine:

After re-calendaring, the fabric samples were washed to dissolve the water-soluble component from the fabric using Paddle Washer, Skein dyeing machine, as well as Jet Dyeing machine to find out the suitable machine for the Exceval™ removal process. A comparison of features for these three machines is shown in the **Table 3.4**.

TABLE 3.4, Comparison of Machine Features for washing treatment

Features	JFO - Jet Dyeing Machine, Werner Mathis AQ	Paddle Washer – Burlington Engineering Company Inc.	Skein Dyeing Machine
water level required	6 liters	48 liters	115 liters
Heating of water and content is via	Electricity	steam	Steam
Heating-up time to reach 85^0C temperature	9 to 11 minutes, typically 10 minutes and initial temperature in between 40 to 45 ^{0}C	10 minutes for the initial temperature 38 ^{0}C (100 F)	55 minutes for the initial temperature 30 ^{0}C (85 F)
Maximum Fabric Content	1.5 Kg	4 Kg	6 Kg
Type of mechanical action	mechanical action of water jets on the fabric in addition to circular agitation of water and fabric content	rotary agitation of fabric in water	Water circulation to provide agitation of the fabric

Out of these three machines, Jet Dyeing machine is ideal for Exceval^{TM} removal process because it provides circular agitation as well as water jets action on the fabric. The heating-up time of the machine to reach 85^{0}C in JFO is comparable with Paddle washer but heating is expensive since electricity is used rather than steam. However, the water content required is much less compare to other two machines which helps in reducing the cost for the waste water treatment. In addition, a unique feature of the Jet Dyeing machine (JFO) is the water flow capacity of the jets is adjustable which helps in controlling the mechanical action on the fabrics. This feature is very useful for the low fabric weight fabrics.

The characteristics of the Jet Dyeing machine (JFO) are; liquor content 6-20 liters, fabric content 100-1500 gram, fabric speed 4-30 meter/min, heat up speed 2-4 ^{0}C/min, temperature 20-150^{0}C, water flow capacity of the jets 20 -100 % and pressure 0-4 bars [MATHIS Laboratory Overflow Jet Dyeing Apparatus Type JFO, Brochure].

Fabric samples of ¼ meter length and width were stitched in a rope form and washed at various washing conditions to optimize the washing time and water flow capacity of the jets for particular fabric Run number. **TABLE 3.5** shows the experiment trials carried out at various washing conditions for each fabric Run number. In total, 62 experimental trials were done in Jet Dyeing machine (JFO) to find the optimized washing conditions for the thirteen fabrics (run numbers). For each experiment, the washing temperature was 85^{0}C and the fabric speed was 10 meter/minute. These two parameters were kept constant except washing time in minutes and water flow capacity of the jets (%).

For each experiment trial of the washing treatment, the fabric weights of the samples were measured according to ASTM D3776-96 after conditioning the samples according to ASTM standard D1776. A comparison of the fabric weights and percentage Exceval^{TM} removed from the fabrics as well as physical examination of the samples was done to find the optimized washing conditions. It is included in the results and discussion section. The following formula was used to find out the percentage Exceval^{TM} removed from the fabrics after each washing trial.

Percentage Exceval™ removed =

$$\frac{\underline{[(\text{Fabric weight of unwashed fabric - Fabric weight of washed fabric}) * 100]}}{(\text{Fabric weight of unwashed fabric} * 30)} * 100$$

TABLE 3.5, Design of Experiment – Washing conditions for Jet Dyeing Machine ***

Fabric Run Number	Actual Washing Time (minute) at 50 % Flow Capacity							Actual Washing Time (minute) at 25 % Flow Capacity			Actual Washing Time at 20 % Flow Capacity
	12	10	8	6	4	2	1	4	2	1	1
1		Δ		Δ	Δ	▲	▲			▲	
2		Δ		Δ	Δ	Δ	Δ				▲
3						Δ	Δ		▲	▲	▲
4						Δ	Δ		Δ	Δ	▲
5		Δ	▲	▲	▲	▲			▲		
6		Δ	Δ	▲	▲	▲				▲	
7						▲	▲	▲	▲	▲	
8						Δ	Δ		▲		▲
9	▲	▲									
10	▲	▲	▲								
11						▲	▲	▲	▲		
12						▲	▲	▲	▲		
13		Δ		Δ	▲	▲	▲			▲	

Δ & ▲ – These marks in the table show that the experiment was carried out at a particular washing condition (washing time and water flow capacity).

▲ – This mark means the fabric weight of the fabric and percentage Exceval™ removed from the fabric were measured after washing treatment.

Δ - This mark shows that the fabric got torn and it was not possible to measure the fabric weight after washing.

*** In **Table 3.5**, Washing Time does not include the time to heat-up the machine up to 85^0C, which is around 9 – 11 minutes for JFO. The Total washing time is a sum of the actual washing time and the time to heat-up the machine.

After finding the optimized washing conditions in Jet Dyeing Machine, fabric Run number 3, 4, 6, 7, 10, 11 and 12 were washed in Paddle Washer, Skein Dyeing Machine and Jet Dyeing Machine (JFO) to compare the machine performance in terms of Exceval™ removal. The specifications of these fabrics are shown in the **Table 3.3**, "Design of Experiments – Specifications of Spunbonding Process". Fabric Run number 3, 4, 6, 7, 11 and 12 were washed for 1 minute and Run number 10 was washed for 12 minutes in all three machines. The only exception was; the Fabric Run number 10 was not washed in Skein Dyeing Machine. This is because the heat up time to reach 85^0C temperature for Skein Dyeing Machine is 55 minutes and the washing time for fabric Run 10 is 12 minutes, so the total washing time is 67 minutes.

In Jet Dyeing Machine and Skein Dyeing Machine, the fabric samples of ¼ meter length and width were stitched in a rope form and washed. While in Paddle Washer, the samples of the same size were placed in a loose form in the cages of the machine during washing. All the fabric samples were conditioned after washing treatment according to ASTM standard D1776 and the fabric weights were measured considering fabric shrinkage according to ASTM standard D3776-96. For all three machines, a comparison of difference in the fabric weights before and after washing for fabric Run number 3, 4, 6, 7, 10, 11 and 12 is discussed in the results.

3.7 Hydroentanglement:

Hydroentanglement is also known as spunlace, jet entanglement or jet lace method. It is one of the mechanical bonding techniques, which entangles the fibers using water jets to give strength to the web. In this method, a web of loose fibers on a porous belt or moving perforated or patterned screen is subjected to multiple rows of high speed water jets to strike a web so that the fibers entangle with each other. Thus, it is a process of transferring high energy via system from water jets to fiber web so as to rearrange the fibers. Normally, water pressure of a hydroentanglement unit ranges from 30 bars to 250 bars and it is increased stepwise from injector to injector. Therefore, the first manifold operates at low pressure compare to the last one. Usually, air-laid or water-laid webs are hydroentangled but sometimes spunbond or meltblown are also used. In addition, hydroentanglement can be used to combine conventionally formed webs together with spunbonds, meltblowns or other textiles to make composites and to achieve properties not existing in a single web. After web-entanglement, excess water is removed using vacuums placed directly under the supporting belt and later on web-drying is done using conventional steam dryers.

In hydroentanglement, web support system is very important since the design or pattern of the final fabric is directly influenced by the conveyor wire type and shape. A fine mesh forming wire supporting the web produces a strong and non-apertured product with no wire mark. On the contrary**,** an apertured or textured nonwoven fabric is formed by using a high-knuckled forming wire [Begenir Asli, December 2002]. A wide variety of aperture shapes like circles, ovals, squares and rectangles etc as well as straight lines or diagonal lines are possible through appropriate wire or embossing pattern selection.

The characteristics of the hydroentangled fabrics that make them unique among nonwoven fabrics are mainly; soft, limp and flexible hand, drapability, conformable and moldable, high strength without binders, high bulk, stretchable without thickness loss, delamination resistance, low linting and pattern possibilities [Begenir Asli, December 2002].

For the present research, hydroentanglement of all the washed fabrics (Run 1 to 13) was done to improve tensile and aesthetic properties of the fabrics. Since the weight of these fabrics are in the range of 24 to 62 gram/meter^2, it was necessary to optimize the process conditions so as to make sure adequate bonding of fabrics with higher weight as well as to prevent damage of the fabrics with lower fabric weight. A preliminary trial was done at NCRC partner's lab using 4 manifolds of 50, 150, 150 and 175 bar pressures respectively with 10 meter per minute needling belt speed. The fabrics were hydroentangled only on one side. However, after this preliminary trial it was realized that the mechanical action was harsh on some of the fabrics even with single pass. Therefore, the second trial was done according to the specifications given in **TABLE 3.6** and the fabrics were hydroentangled on both the sides. Physical examination of these fabric samples was done.

Later on, 3 meter long samples of the washed fabrics for each fabric Run (1 to 13 except Run 4) were cut and sewn together to make a fabric roll. This fabric roll was hydroentangled using a Fleissner Aqua jet according to the specifications given in **TABLE 3.6.** Hydroentangling was done by passing the fabric with the same machine set-up as described in the table for both the sides of the fabric. Afterwards, pre-marked fabric samples of Run 1 to 13 were cut and the fabric weights were measured. The fabric weights are reported in **Chapter 4** together with standard deviation. It was noticed that after hydroentanglement, fabrics were shrink in cross direction.

TABLE 3.6, Specifications of Hydroentanglement ***

Jet Head Pressure 1	50 BAR
Jet Head Pressure 2	75 BAR
Jet Head Pressure 3	100 BAR
Jet Head Pressure 4	0 BAR
Jet Head Pressure 5	0 BAR
Suction Fan 1 Speed	85 %
Suction Fan 2 Speed	85 %
Dryer Fan Speed	80 %
Dryer Flap Position	100 %
Dryer Temperature	140 C

Needling Belt Speed	10 MPM
Compaction Belt Speed	10 MPM
Needling Drum Speed	10 MPM
Dryer Drum Speed	10 MPM

*** **Two Passes of the fabric, one on each side of the fabric.**

CHAPTER - 4

EXCEVAL^{TM} REMOVAL VERIFICATION – METHODS, RESULTS AND DISCUSSIONS

4.1 Fabric Weight Measurement:

In this current research, fabric weight of the conditioned fabric samples was measured after each process according to ASTM standard D 3776 – 96 standard test method for Mass per Unit Area of Fabric. Fabric samples of each Run (1 to 13) were selected randomly to measure fabric weight. Affixed 4 X 4 inch area was weighted before and after each process, to determine the amount of Exceval^{TM} removed so that after the process when fabric weight is measured it considers shrinkage or extension that may have occurred during the process. This was necessary since each process, calendaring, washing and hydroentangling influences the fabric state and, if not taken into account, can result in a wrong fabric weight measurement. In current research, fabric weight measurements of the re-calendared fabrics before washing and after washing treatment are considered as important results to determine the percentage Exceval^{TM} removed from the fabrics. Therefore, care was taken while marking, cutting, handling and conditioning fabrics, as well as in measuring fabri weight to avoid errors.

Table 4.1 includes the results obtained from measuring the fabric weights of the samples, which were pre-marked 4 X 4 inch areas on the as-made fabrics and the same amount of fabric was measured after each process. In addition, standard deviation is reported together with these values. The last column of this table shows the percentage Exceval^{TM} removed from the fabric out of 30 %. The formula used to calculate it is as follows:

% Exceval^{TM} removed from the fabric

$$= \frac{[(\text{Fabric Weight of the as-made fabric}) - (\text{Fabric Weight of the jet washed fabric})] * 100}{\text{Fabric Weight of the as-made fabric (4 X 4 inch)}}$$

TABLE 4.1, Comparison of Average Fabric Weight (gram * 100) of the 4 X 4 inch samples – As-made Spunbonds, Re-calendared, Washed and Hydroentangled Fabrics

Fabric Run Number	As-made Fabrics (gram * 100)	Re-calendared Fabrics (gram * 100)	Jet Washed Fabrics (gram * 100)	Hydroentangled Fabrics (gram * 100)	Percentage reduction in the fabric weight after washing
1	78.25 σ = 3.58	75.90 σ = 3.52	56.08 σ = 0.69	55.87 σ = 2.86	28.33 %
2	61.07 σ = 5.19	60.99 σ = 4.00	44.23 σ = 3.99	45.17 σ = 3.96	27.57 %
3	46.97 σ = 1.60	46.26 σ = 2.17	35.90 σ = 0.58	34.06 σ = 1.52	23.57 %
4	32.27 σ = 0.58	31.54 σ = 1.38	-	-	N. A.
5	80.71 σ = 2.59	80.19 σ = 1.55	60.29 σ = 2.24	59.05 σ = 1.32	25.30 %
6	64.62 σ = 2.20	61.68 σ = 2.19	47.84 σ = 2.35	46.97 σ = 1.03	25.97 %
7	50.51 σ = 1.47	47.95 σ = 1.39	36.48 σ = 1.96	35.67 σ = 1.79	27.77 %
8	33.90 σ = 0.59	32.46 σ = 0.50	24.55 σ = 0.35	25.60 σ = 0.66	27.58 %
9	82.93 σ = 2.43	82.17 σ = 3.65	61.67 σ = 0.69	62.73 σ = 3.09	25.63 %
10	63.91 σ = 3.55	63.74 σ = 4.98	48.17 σ = 1.07	48.60 σ = 1.38	24.63 %
11	49.72 σ = 2.76	49.49 σ = 3.38	38.21 σ = 1.06	37.78 σ = 2.02	23.15 %
12	33.03 σ = 2.29	31.61 σ = 3.36	25.06 σ = 0.75	24.79 σ = 0.85	24.13 %
13	70.01 σ = 4.69	69.54 σ = 4.44	50.99 σ = 3.09	51.01 σ = 1.78	27.17 %
Average	57.53 (gram * 100)	56.42 (gram * 100)	44.12 (gram * 100)	43.94 (gram * 100)	25.9 %

Further, a comparison of the fabric weights for each process is made and shown in **Figure 4.1**.

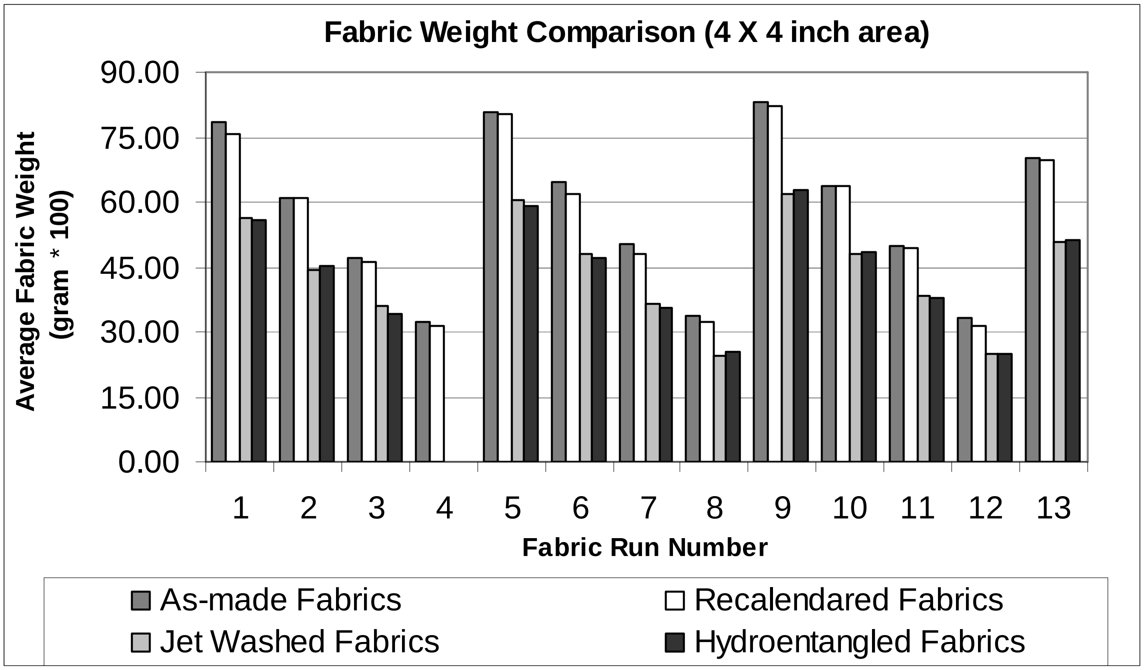


FIGURE 4.1, Fabric Weight (4 X 4 inch area) Comparison for each process

From the chart, it is clear that the difference in the fabric weight (4 X 4 inch area) due to calendaring is not significant. In other words, the fabric weight of any particular re-calendared fabric is not drastically different than the fabric weight of the same Run number before calendaring. Therefore, the value of the fabric weight (4 X 4 inch area) for the as-made fabrics and the re-calendared fabric is very close to each other for any fabric Run number from 1 to 13. While the fabric weight (4 X 4 inch area) is reduced after the washing treatment, and the reduction in the fabric weight is in the range of 23 to 28 %, as shown in the above table. Since, Exceval™ is contributing around 30 % of the total fabric weight, this loss in the fabric weight after the washing treatment in water is due to Exceval™ removal. Therefore, for washed fabrics the fabric weight (4 X 4 inch area) is less compare to as-made fabrics and re-calendared fabrics for each Fabric Run (1 to 13). The data for washed fabric Run 4 is not available because the fabric got torn at many places during washing and it was not possible to measure the fabric weight. In addition, it is also noticeable from the graph as well as the table of the fabric weight comparison that the fabric weights (4 X 4 inch area) of the jet washed fabrics and the hydroentangled fabrics are very close to each other. Thus, major change in the fabric weight occurs only after the washing treatment and that's because of Exceval^{TM} removal from the fabrics.

4.2 Fourier Transform Infrared Spectroscopy (FTIR):

Fourier Transform Infrared Spectroscopy (FTIR) is an analytical technique used to identify organic materials and in some cases inorganic materials. This technique measures the absorption of various infrared light wavelengths by the material of interest. These infrared absorption bands identify specific molecular components and structures [Handbook of Analytical Methods for Materials]. Because chemical bonds absorb infrared energy at specific wavelengths or frequencies, it is possible to determine structure of the compounds by the spectral location of their infrared (IR) absorptions.

Interpretation of Infrared Spectra:

The output from the spectroscopy is in the form of a spectrum which shows infrared (IR) % transmission or absorbance vs. wavelength (frequency) as a plot. If no radiation is absorbed at a particular frequency, then the line on a graph will be at 100% transmission or 0% absorption at the corresponding wavelength. Absorption bands in the range of 4000 to 1500 cm^{-1} wavelength are typically due to functional groups (for example, -OH, C=O, N-H, CH3, etc.). While between 1500 to 400 cm^{-1} wavelength region is referred as the fingerprint region [Handbook of Analytical Methods for Materials]. Every molecule produces a unique pattern in this region, so if an unknown sample produces a spectrum which matches that of a known compound, the sample can be confirmed to be that compound. In addition, the output spectrum of a particular material can be compared to reference spectrum or spectra available in the computer library database to identify the compounds of the unknown material or can be used to compare known materials.

In present research, after washing treatment of the spunbond nonwovens in Jet Dyeing Machine at an optimized condition it was necessary to conduct FTIR testing. This testing is essential since the goal of the research is to obtain microfiber 100% nylon spunbond nonwovens by using Sixteen Segmented Pie bicomponent configuration with water soluble polymer Exceval^{TM} as one of the components to make bicomponent spunbonds, and later-on dissolving Exceval™ in hot water during washing. Therefore, all the fabrics (Run Number 1 to 13) were tested on FTIR except Run 4, since this fabric got torn at many places during the washing treatment. Randomly selected 5 samples of each fabric (Run Number 1 to 13) were tested on Thermo Nicolet Spectrometer. A comparison of spectra was made between as-made bicomponent fabric samples obtained after spunbonding and fabric samples after washing treatment in Jet Dyeing Machine (JFO) as well as spectra available in the computer library database. Since, all of the fabric samples (Fabric Run 1 to 13 except 4) showed an identical spectrum comparison, only three spectra comparison for Fabric Run 2, 5 and 11 are shown in **Figure 4.2, Figure 4.3 and Figure 4.4** respectively. The spectra of the remaining fabrics are included in **Appendix - B**.**2**.

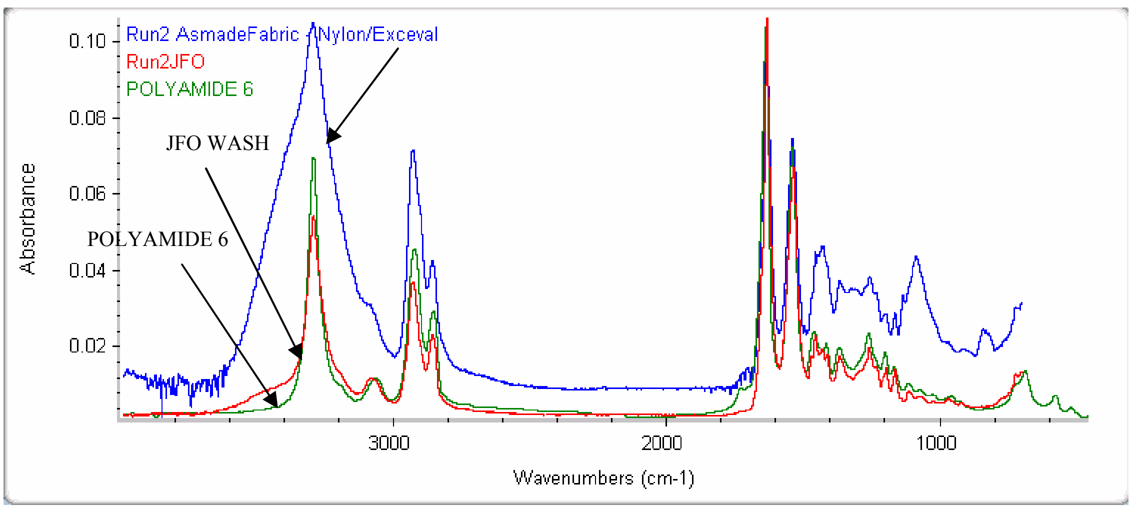


FIGURE 4.2, Comparison of Spectra for Fabric Run 2 – As-made bicomponent Spunbond fabric, Jet Wash Fabric and Polyamide 6

It is obvious from the spectra that the spectrum of washed fabric is similar in shape to the spectrum of Polyamide 6 except at around 3500 cm^{-1} and 1700 cm^{-1} wavelength. The computer software demonstrated that the spectra of all washed fabrics were matched around 93 % with Polyamide 6 (Nylon 6) spectrum of the computer database. This result confirms success at removing most of the Exceval™ from the bicomponent spunbonds of Nylon/ Exceval™ (70/30). In other words, after removing Exceval™ wedges from the Sixteen Segmented Pie fibers the washed fabrics contain mostly Nylon wedges. Therefore, now the fiber size in the spunbond nonwovens is reduced from the 1 to 2.5 denier per filament to the approximately 0.088 to 0.22 denier per filament (dpf). Thus, one of the research goals is accomplished, successfully producing microfiber spunbond nonwoven of mostly nylon polymer and of different fabric weights and fiber sizes.

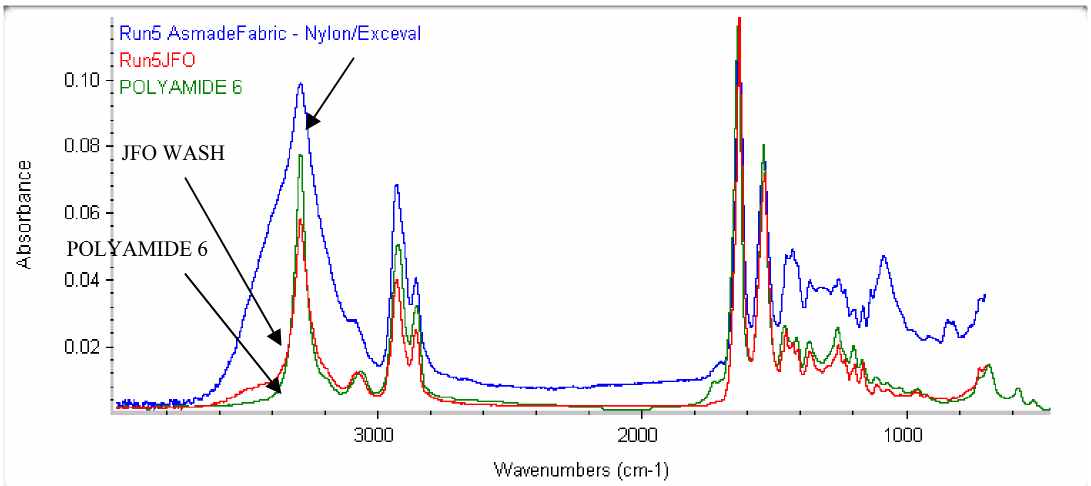


FIGURE 4.3, Comparison of Spectra for Fabric Run 5 – As-made bicomponent spunbond fabric, Jet Wash Fabric and Polyamide 6

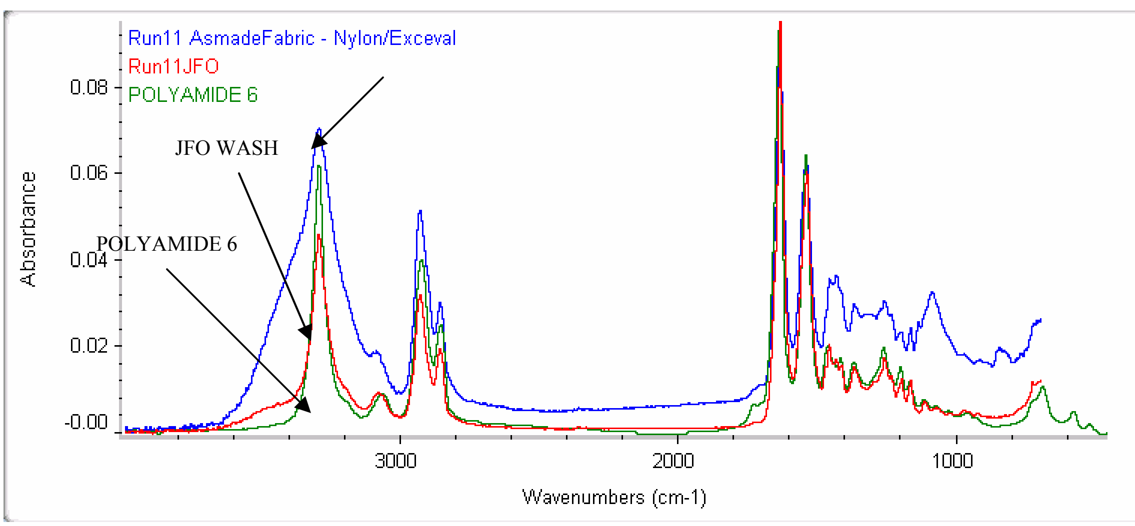


FIGURE 4.4, Comparison of Spectra for Fabric Run 11 – As-made bicomponent spunbond fabric, Jet Wash Fabric and Polyamide 6

Further, an analysis of peaks for each spectrum was performed using FTIR software for all of the bicomponent spunbonds and washed fabrics to make sure that most of the Exceval^{TM} is now removed from the fabrics after washing. The analysis of peaks was done in 4000 to 400 cm^{-1} wavelength region of each spectrum. A comparison of peaks was done for as-made unwashed fabrics, washed fabrics and Polyamide 6 (Nylon 6 polymer) spectra. The results acquired after the analysis are shown here in **Table 4.2** as a range of values obtained from all the fabrics.

TABLE 4.2, Comparison of Spectrum Peaks for

As-made Bicomponent Spunbonds, Jet Washed Fabrics and Polyamide 6

As-made Bico-Fabrics		Jet Washed Fabrics		Polyamide 6	
Position - Wave length (cm^{-1})	Normalized Intensity	Position - Wave length (cm^{-1})	Normalized Intensity	Position - Wave length (cm^{-1})	Normalized Intensity
3296 - 3300	0.92	3297 - 3299	0.50	3298.20	0.66
-	-	3081 – 3087	0.10	3070.17	0.10
2933 - 2935	0.57	2933 – 2934	0.34	2927.46	0.42
2860 - 2862	0.30	2860 – 2861	0.21	2857.58	0.27
1637 - 1639	1.00	1637 - 1638	1.00	1641.33	1.00
1544 - 1547	0.67	1541 - 1544	0.68	1544.09	0.68
1436 - 1441	0.37	1462 – 1463	0.21	1464.01	0.21
-	-	1371 – 1372	0.16	1371.44	0.18
1261 - 1264	0.29	1262 – 1264	0.19	1264.32	0.21
1201 – 1202	-	1201 – 1202	0.13	1202.96	0.16
1169 - 1172	0.22	1169 – 1171	0.13	-	-
1092 - 1093	0.34	-	-	-	-
842 - 848	0.19	-	-	-	-
-	-	-	-	690.40	0.12

It is clear from the **Table 4.2** that the spectra of the washed fabrics are nearly identical to those of Nylon 6, indicating that most of the Exceval™ has been removed. It can be observed from the table that there is a sharp peak in wavelength range 3296 to 3300 cm^{-1} for as-made fabrics, 3297 to 3299 cm^{-1} for washed fabrics and at 3298.20 cm^{-1} for Nylon 6, which shows the presence of Amide functional group in all of them. Because, Amides show strong broad

N - H stretching bands in the region of 3100 to 3400 cm^{-1} wavelength. In addition, the presence of strong Amide group is also obvious due to the infrared absorption at about 1640 cm^{-1} and a spectrum peak between 1541 cm^{-1} to 1547 cm^{-1} wavelength.

For the as-made bicomponent spunbonds and the jet washed fabrics, there is only one position of infrared absorption from 1169 to 1171 cm^{-1} wavelength which shows medium – C-C stretching vibration band. This infrared absorption position is not present in Nylon 6 spectra. This band indicates that Exceval™ started degrading during spinning and thus, it is present in both as-made and jet washed fabrics because it can not be removed during washing. However, there are two spectral peaks in the as-made fabrics between 1092 to 1093 cm^{-1} and 842 to 848 cm^{-1}, but not in the jet washed fabrics spectra or in Nylon 6 spectra.

Using Fourier Transform Infrared Spectroscopy for the spectra comparison and peak analysis proved that most of the Exceval™ is removed from the fabrics after washing treatment at optimized conditions in the Jet Dyeing Machine. In addition, the computer software Omnic-6.1 showed 93 % match between Nylon – 6 spectrum and spectra of the jet washed fabrics.

4.3 Scanning Electron Microscopy (SEM):

4.3.1 AS-MADE FABRICS

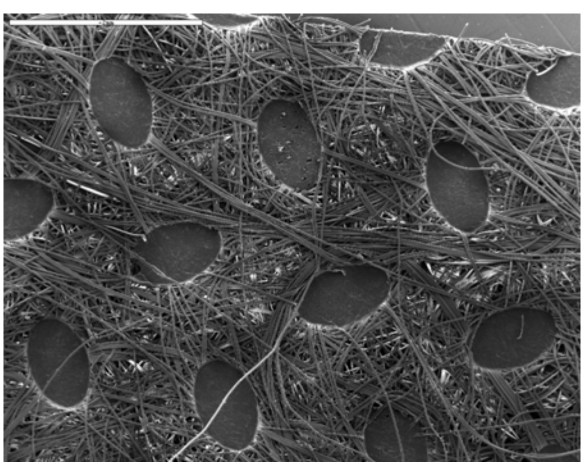


FIGURE 4.5, Fabric Run 1, 25X

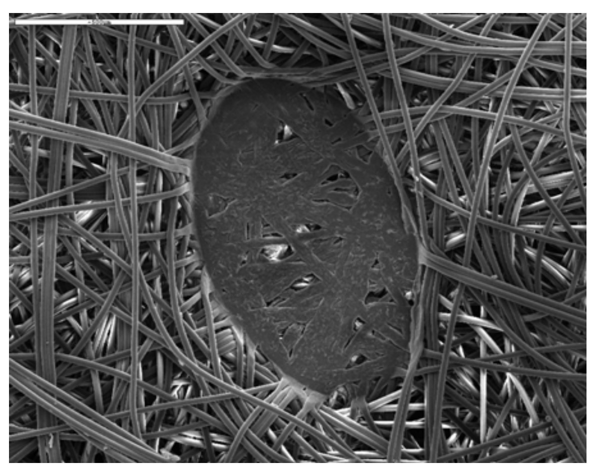
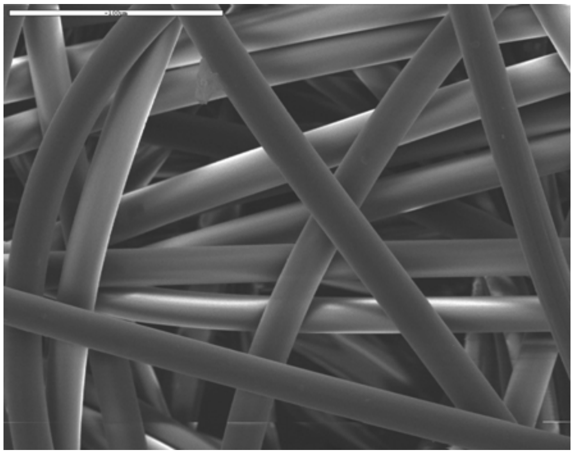


FIGURE 4.6, Fabric Run 1, 70X



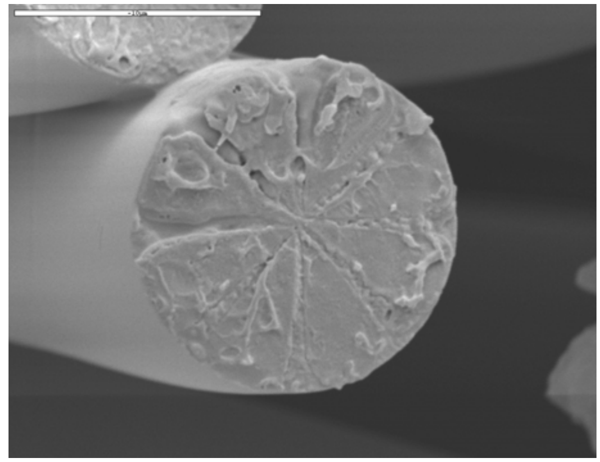
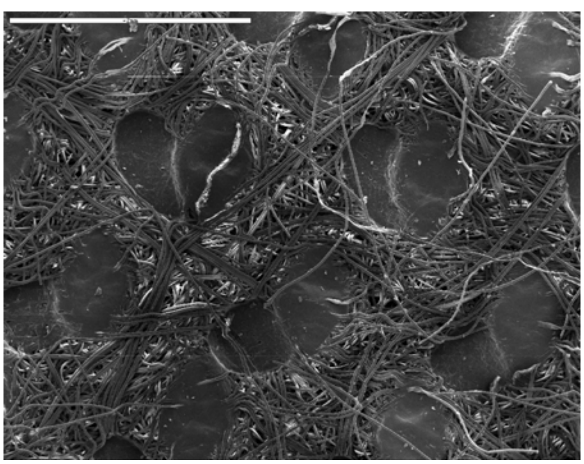


FIGURE 4.7, Fabric Run 1, 450X

FIGURE 4.8, Fabric Run 13, 5000X

Figure 4.5 and **4.6** shows the calendar bonds made at 120^0C with 325 PLI (pounds per linear inch) calendaring pressure. From **Figure 4.8**, it is obvious that the fiber cross-section in the bicomponent spunbonds is of Sixteen Segmented Pie with Nylon 6 and Exceval^{TM} as alternate wedges. It can be observe that Exceval^{TM} is wrapping around Nylon 6 wedges.

4.3.2 RE-CALENDARED FABRICS



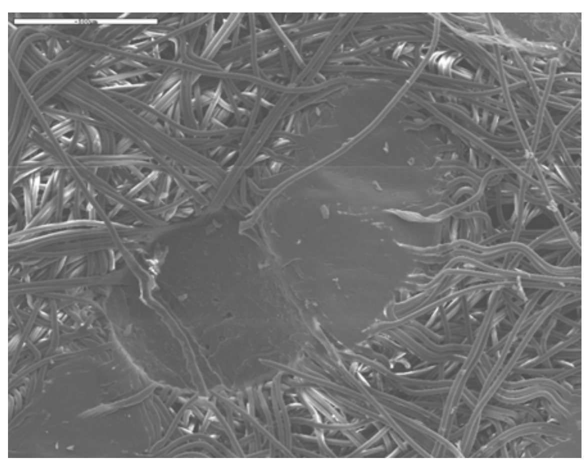
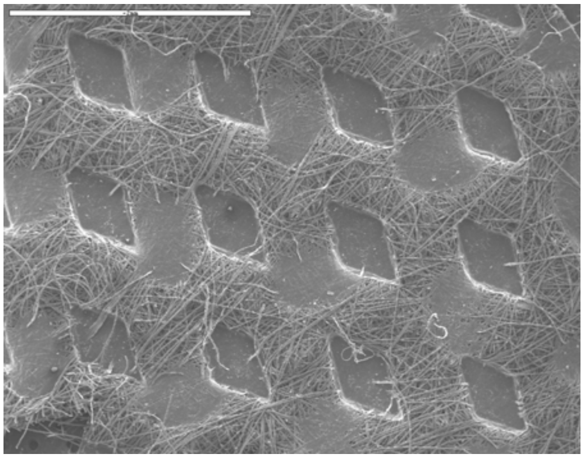


FIGURE 4.9, Fabric Run 1, 25X

FIGURE 4.10, Fabric Run 1, 60X



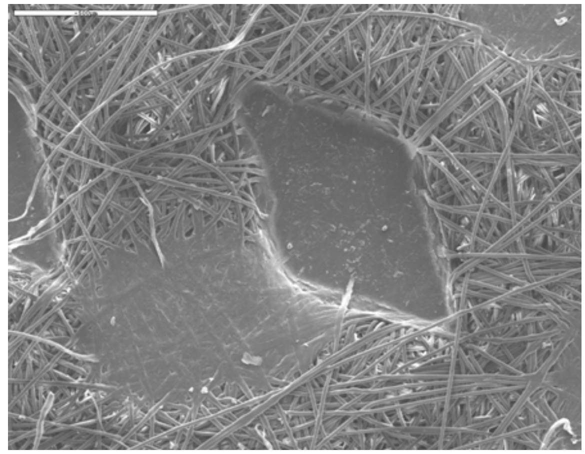
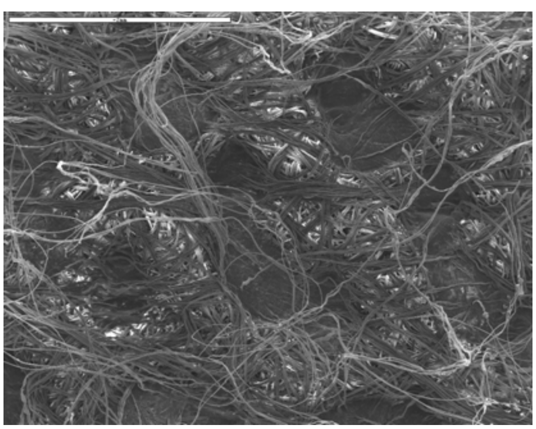


FIGURE 4.11, Fabric Run 13, 25X **FIGURE 4.12,** Fabric Run 13, 60X

These images illustrate the positions of the bonds during calendaring and re-calendaring processes. In the fabric Run 1 sample, the bonds during re-calendaring are places more or less on top of the previous bonds. While in the sample of fabric Run 13, the bonds during re-calendaring are placed in between of the bonds previously made. The positions of the bonds play an important role in mechanical property measurement in the current research.

4.3.3 JET WASHED FABRICS



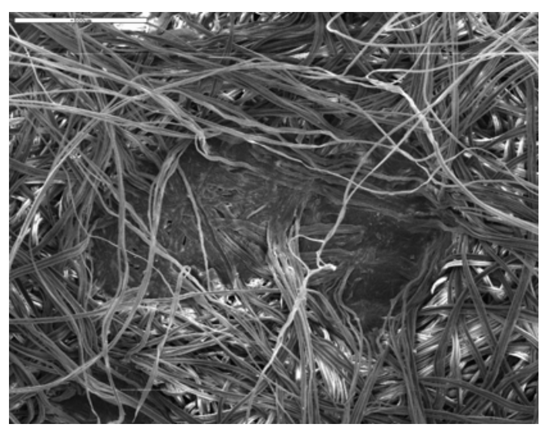


FIGURE 4.13, Fabric Run 1, 25X **FIGURE 4.14,** Fabric Run 1, 60X

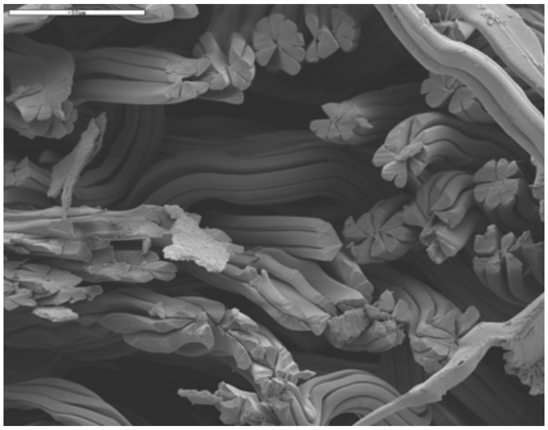


FIGURE 4.15, Fabric Run 1, 600X

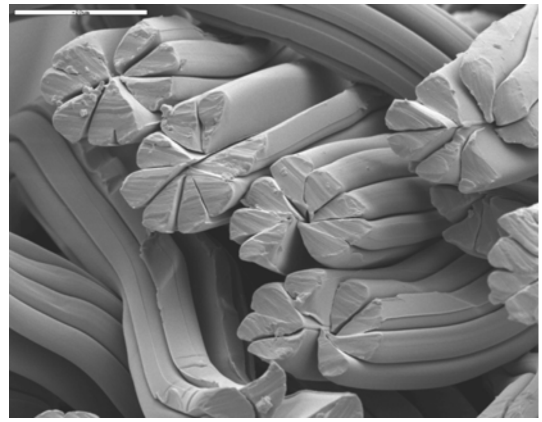


FIGURE 4.16, Fabric Run 1, 1500X

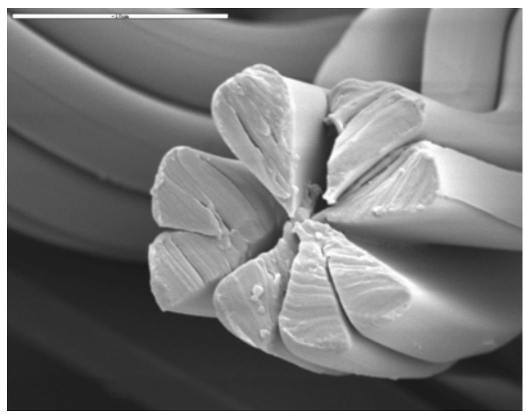


FIGURE 4.17, Fabric Run 13, Magnification 5000X

From **Figure 4.13** and **4.14**, it is clear that after the washing treatment in Jet Dyeing Machine, the bonds are weakened and fibers are protruding from the fabric surface. However, it is difficult to remove Exceval™ from the fibers fused at the bonds. **Figure 4.15**, **4.16** and **4.17** clearly shows that most of the Exceval™ is removed from the bicomponent fibers of the spunbonds. It can be observed as well that, the Nylon 6 wedges are not completely separated from each other. They are connected with each other from the center.

4.3.4 HYDROENTANGLED FABRICS:

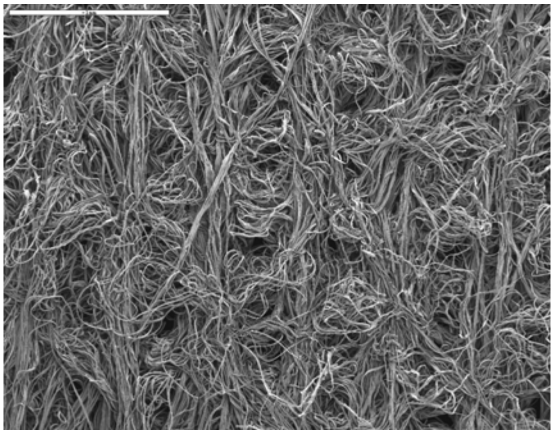


FIGURE 4.18, Fabric Run 1, 35X

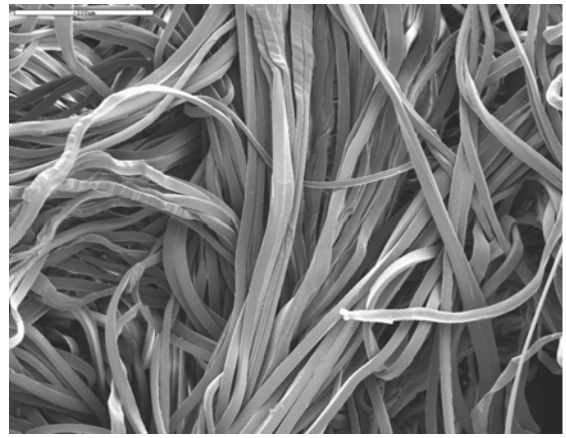


FIGURE 4.19, Fabric Run 1, 300X

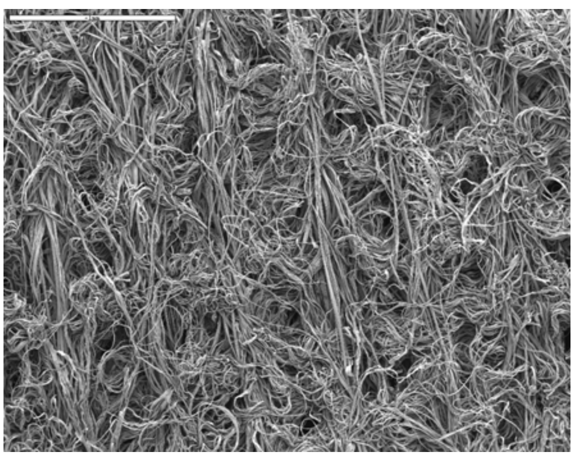


FIGURE 4.20, Fabric Run 13, 35X

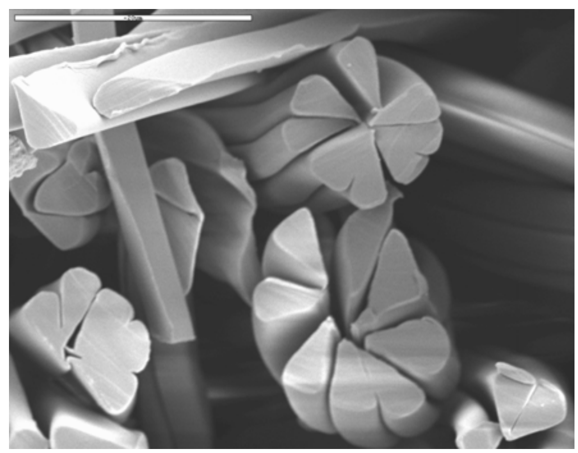


FIGURE 4.21, Fabric Run 13, 2500X

From **Figure 4.18** and **4.20,** it is noticeable that the calendar bonds made during calendaring as well as re-calendaring are completely gone from the hydroentangled fabrics. **Figure 4.19** illustrates fibers in the fabric looks like ribbons entangled together.

CHAPTER - 5
RESULTS AND DISCUSSION

5.1 Spunbonding:

Microscopic analysis of free fall fibers was done to find out the correctness of the fiber cross-section shape and the denier per filament for 0.5, 0.7 and 0.9 gram per hole per minute (ghm) throughput rate. The following Figures show the images of cross-sections taken by polarized light microscope with 20x magnification.

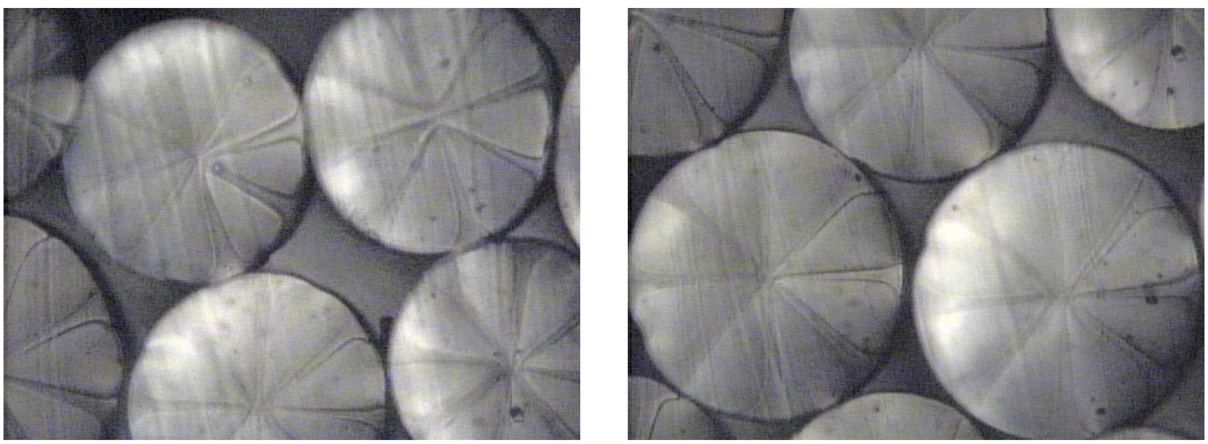


FIGURE 5.1, Fiber Cross section at 0.5 gram per hole per minute throughput rate

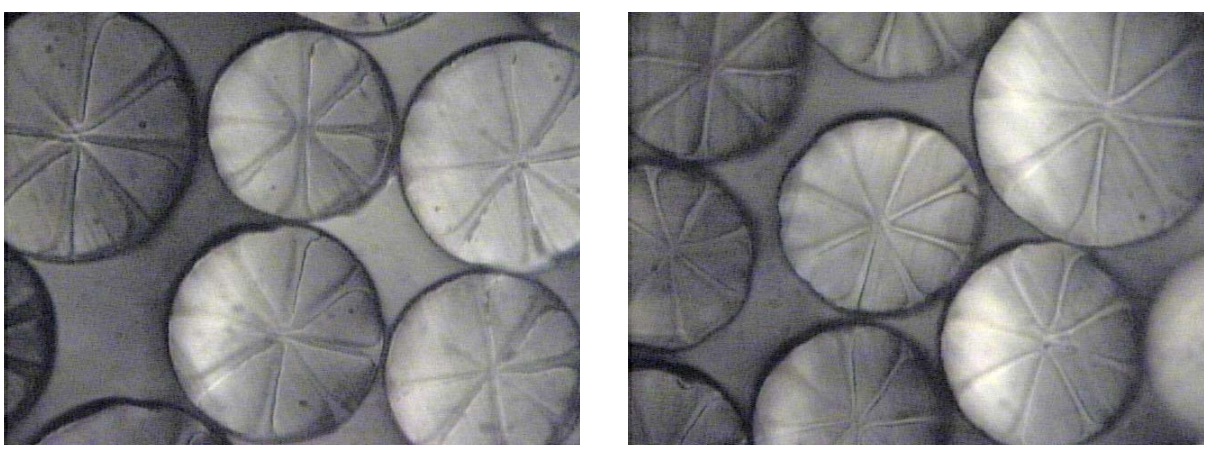


FIGURE 5.2, Fiber Cross section at 0.7 gram per hole per minute throughput rate

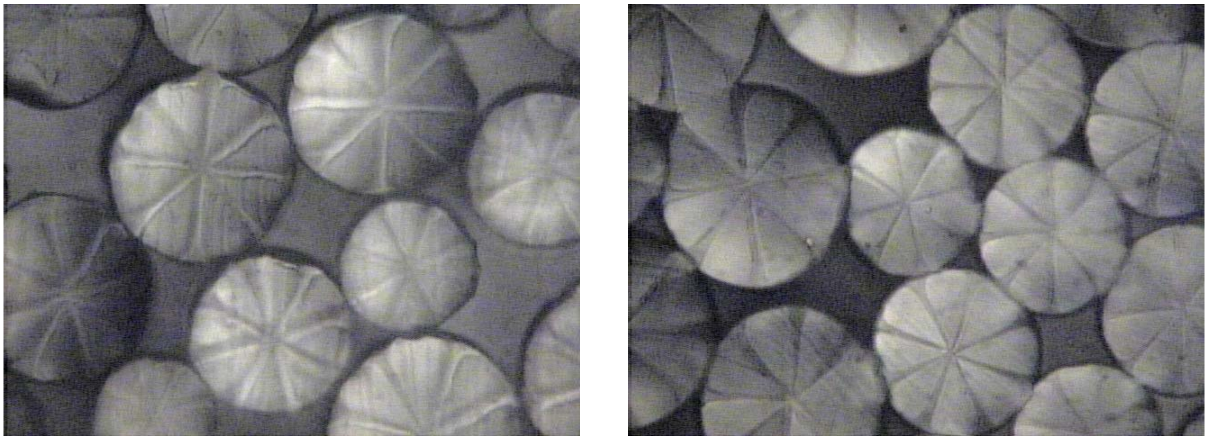


FIGURE 5.3, Fiber Cross section at 0.9 gram per hole per minute throughput rate

The cross-sections look perfect; with 16 slices of polymers arranged in a pie wedge shape with alternate larger and smaller slices of Nylon (70%) and Exceval^{TM} (30%) respectively.

Furthermore, the average weights of the as-made fabrics (4 X 4 inch area) were measured after conditioning the fabric samples and are shown in **Table 5.1**. It is obvious from the table that the actual fabric weights are different than the selected fabric weights according to the Design of Experiment. The actual fabric weight is in the range of 32 to 83 (grams * 100) and the standard deviation falls in the range of 0.59 to 5.19. Except for two fabrics, the standard deviation is more than 1 but for spunbond nonwovens of this fabric weight range it is acceptable.

The ratio of desired weight of the fabrics to the actual fabric weight is in the range of 1.2 to 1.3, which means the actual fabric weights are approximately 12 to 24 % less than the desired. Since, the ratio of desired to actual fabric weight is consistent, it is possible that even though extra care was taken during the Spunbonding trial to avoid unnecessary errors it could happened that the winding speed of the fabric was around 20% higher than the belt speed. It is also possible that the weighing balance was not calibrated properly on the trial day and thus the fabric weights measured are not the representative of the actual.

TABLE 5.1, Fabric Weight (Grams * 100) – 4 X 4 inch area of As-made Fabrics

Run Number	Through-put rate (grams hole per minute)	Denier per Filament (dpf)	Actual Fabric weight in grams per square meter (Grams * 100)	Fabric Weight (Grams * 100) according to Design of Experiment	Ratio of Desired/Actual fabric weight
1	0.9	2.5	78.25 σ = 3.58	100	1.3
2	0.9	2.5	61.07 σ = 5.19	80	1.3
3	0.9	2.5	46.97 σ = 1.60	60	1.3
4	0.9	2.5	32.27 σ = 0.58	40	1.2
5	0.7	2.0	80.71 σ = 2.59	100	1.2
6	0.7	2.0	64.62 σ = 2.20	80	1.2
7	0.7	2.0	50.51 σ = 1.47	60	1.2
8	0.7	2.0	33.90 σ = 0.59	40	1.2
9	0.5	1.5	82.93 σ = 2.43	100	1.2
10	0.5	1.5	63.91 σ = 3.55	80	1.3
11	0.5	1.5	49.72 σ = 2.76	60	1.2
12	0.5	1.5	33.03 σ = 2.29	40	1.2
13	0.7	1.0	70.01 σ = 4.69	80	1.1

5.2 EXCEVAL™ Removal Preliminary Study:

After the washing treatment in Jet Dyeing Machine (JFO), it was found that bonding of the fibers is not sufficient to maintain the web integrity. Most of the fabrics were completely torn except Fabric Run 5, 6, 9, 10 and 13 (the specifications of these fabrics are shown in the **Table 5.1**). The interesting fact is these fabrics are having weight (of 4 X 4 inch area) in the range of 60 to 80 (gram * 100) and even though fabric Run 1 and 2 falls in this fabric weight range, they got torn badly. This shows that the parameter other than the weight of the fabrics, and in this research the fiber size of these fabrics plays an important role. However, at this point it was realized that it is necessary to have a bonding process before the washing treatment so as to improve web integrity and strength. The most important outcome of this study is removal of Exceval™ can be done easily above 80^0C in practice.

For fabric Run 5, 6, 9, 10 and 13, the fabric weight before and after washing treatment were determined according to ASTM standard D3776-96 considering fabric shrinkage. From **TABLE 5.2,** it can be seen that about 83 to 99 % of the Exceval™ can be removed from the fabric assuming that the loss in the weight of the fabrics is due to Exceval™ removal.

TABLE – 5.2, Fabric Weight (Grams * 100) of 4 X 4 inch area of the fabrics before and after the Washing Treatment in Jet Dyeing Machine (JFO)

Fabric Run Number	Unwashed Samples (Grams * 100)	85 ^{0}C, 5 minutes wash (Grams * 100)	% Exceval™ removed	105 ^{0}C, 5 minutes wash (Grams * 100)	% Exceval™ removed	125 ^{0}C, 5 minutes wash (Grams * 100)	% Exceval™ removed
5	80.71 σ = 2.59	59.21 σ = 0.80	88.81%	56.61 σ = 4.61	99.54%	56.81 σ = 0.57	98.73%
6	64.62 σ = 2.20	45.55 σ = 0.52	98.38%	46.25 σ = 2.10	94.78%	45.38 σ = 0.68	99.25%
9	82.93 σ = 2.43	61.79 σ = 1.36	84.97%	62.00 σ = 2.48	84.12%	58.44 σ = 5.34	98.43%
10	63.91 σ = 3.55	47.26 σ = 3.90	86.83%	47.13 σ = 4.19	87.52%	46.69 σ = 3.67	89.80%
13	70.01 σ = 4.56	51.24 σ = 3.05	89.38%	52.28 σ = 0.62	84.43%	52.63 σ = 0.76	82.75%

Percentage Exceval™ removed =

$$\frac{[(\text{Weight of unwashed fabric - Weight of washed fabric}) * 100]}{(\text{Weight of unwashed fabric} * 30)} * 100$$

Figure 5.4 shows the percentage Exceval^{TM} removed from the fabric at three different temperatures. There is no clear trend related with the increase in temperature for all fabrics. However, for Run 5 and 9 there is a significant difference in the percentage Exceval^{TM} removed for the fabrics washed at 85^{0}C and 125^{0}C. SAS programming was done to find out whether this statement is statistically true. Assumptions were made to conduct two sided t-test that data has normal distribution, the fabric samples are independent and randomly selected and both population's standard deviation is unknown and unequal. The value of percentage Exceval^{TM} removed from the fabric samples of Run 5 or Run 9 washed at 85^{0}C and 125^{0}C are equal is the null hypothesis for the t-test. The value of probability for two sided t-test at 95 % confidence interval for the percentage Exceval^{TM} removed from the samples of fabric Run 5 is 0.0250 (< 0.05). Similarly, the probability of t-test for percentage Exceval^{TM} removed from fabric samples of Run 9 is 0.0302 (< 0.05). That means at 95 % confidence interval we are rejecting the null hypothesis. In other words, the percentage Exceval^{TM} removed from the fabric washed at 85^{0}C and 125^{0}C for fabric Run 5 and 9 are significantly and statistically different.

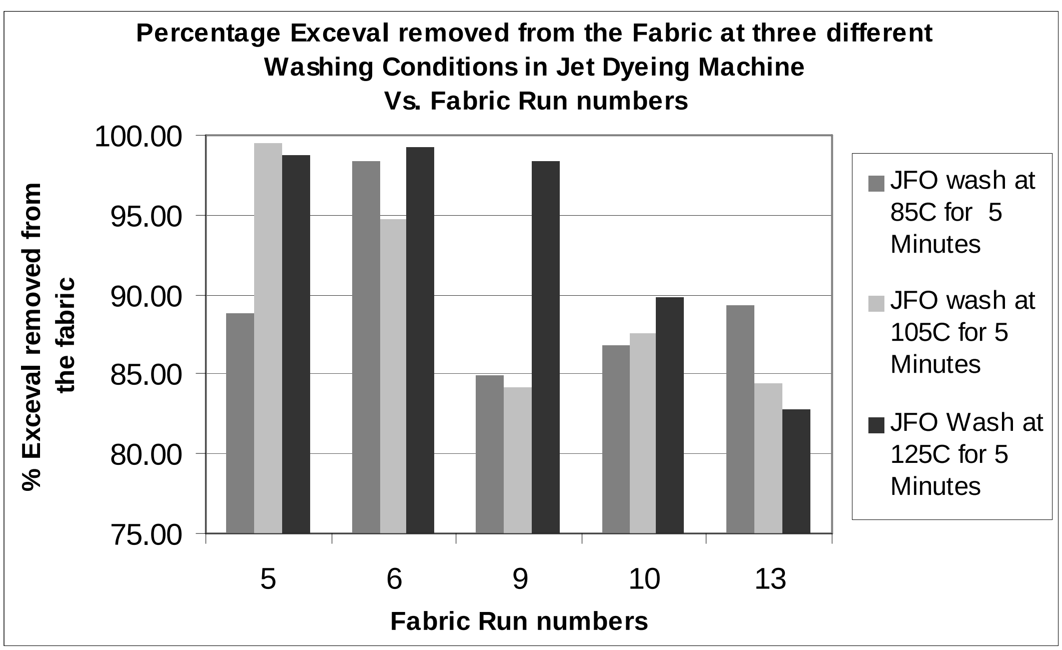


FIGURE 5.4, Comparison of percentage Exceval^{TM} removed from the Fabric at three different Washing Temperatures in Jet Dyeing Machine (JFO)

After examination of all the samples, it was found that the fabrics washed at 125⁰C for 5 minutes were damaged more compared to the fabrics washed at 85⁰C for 5 minutes. That means the loss in the fabric weight is not only due to the removal of Exceval™ but also due to the fiber loss.

Further, ratio of average fabric weights of the as-made fabrics to the jet washed fabrics were determined and plotted in a chart for each temperature as shown in **Figure 5.5**. The comparison of ratio shows that, for fabrics; washed at 85⁰C the ratio is higher for Run number 6 and 13 than the fabrics washed at 105⁰C, while the ratio is equal for Run 9 and 10 fabrics washed at 85⁰C and 105⁰C. Except for Run 5, the ratio of fabric weights is less at 85⁰C than 105⁰C, but the fabric samples of Run 5 washed at 105⁰C and 125⁰C are torn at many places. For fabrics washed at 125⁰C, percentage Exceval™ removed and the ratio of fabric weight is higher for fabric Run 5, 6, 9 and 10 except 13. However, all these fabric samples were torn at many places.

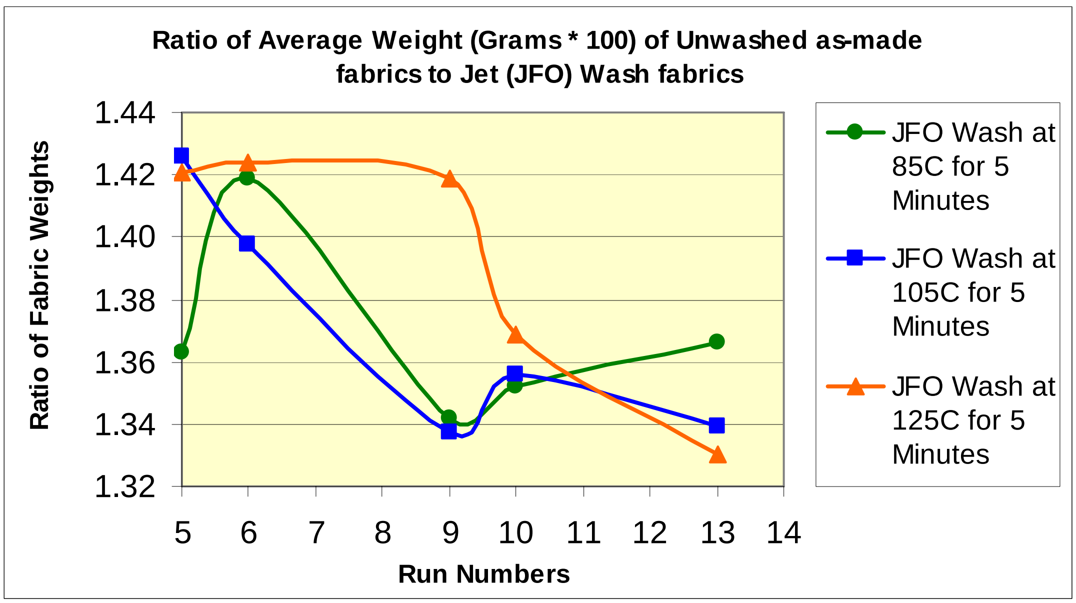


FIGURE 5.5, Ratio of Average Fabric weight of As-made Fabrics to Jet wash Fabrics

The Jet Dyeing machine – JFO takes approximately 10 - 11 minutes to heat up-to 85⁰C and 22 - 25 minutes for 125⁰C which increases the total washing time of the fabrics. Increasing the temperature for the washing treatment helps in removing the Exceval™ but due to increase in the total washing time for the fabrics results into fiber loss and damage to the fabrics. This limits washing the fabrics at higher temperatures than 85^0C in this machine. Since, Exceval™ based spunbond nonwoven shows solubility rapidly in hot water at 80^0C or more [Kuraray Co. Ltd., Exceval™ Brochure], it is reasonable to wash the fabrics at 85^0C but due to the difference in the fabric weight for each fabric Run number, the washing time is require to be optimized.

From this small experiment, it can be concluded that the removal of water dispersive polymer Exceval™ from the spunbond nonwovens of bicomponent (Nylon/ Exceval™) 16 Segmented Solid Pie fibers is practically possible. Further, the fabrics can be washed at 85^0C but due to the difference in the fabric weights and denier per filament for each fabric, the washing time and water flow capacity of the jets needs to be adjusted if Jet Dyeing Machine is selected to use for the washing treatment. In addition, recalendaring of the fabric samples before washing treatment is essential to ensure web integrity and strength during washing.

5.3 Calendar Bonding:

During calendar bonding process for recalendaring the samples, it was necessary to maintain constant condition for all the samples and so as to keep minimum number of variables during the product development process of the present research. In addition, it was very important in optimizing calendaring condition that fabrics acquire good web strength as well as facilitate ease of Exceval™ removal in the washing treatment. It is very important to keep in mind that for calendar bonding, the key parameters of the process are calendar roller temperature, which is more significant than calendar roller pressure, the time for which fabric is in contact with the rollers and melting as well as glass transition temperatures of the fiber polymer or polymers. In present research, calendaring speed was kept constant, 5 feet / minute and since the fabrics are of the same polymer components, they have the same melting and glass transition temperatures.

Table 5.3 shows the results of washing treatment at 85^0C using 100 % water flow capacity of the jets, 10 meter/minute fabric speed and 3 minutes washing time in Jet Dyeing Machine after recalendaring fabric Run 3 at four different calendaring pressures and three temperatures. Fabric Run number 3 is of 46.97 (gram per square meter) fabric weight and 2.5

denier per filament (denier per filament) made at 0.9 (gram per hole per minute) through-put rate.

TABLE 5.3, Average Fabric weight (Grams * 100) and percentage Exceval™ removed from the recalendared fabric Run 3 after 3 Minutes wash at 85^0C – Re-calendaring conducted at 120^0C, 140^0C, 160^0C Calendar roller temperature and four different Calendar Pressures

Calendar Pressure (Pounds Linear Inch)	Average Fabric weight of As-made fabric	120^0C Calendar Temp after Wash	% Exceval™ removed from the fabric	140^0C Calendar Temp after Wash	% Exceval™ removed from the fabric	160^0C Calendar Temp after Wash	% Exceval™ removed from the fabric
272	46.97	-	-	-	-	33.47	95.80%
326	46.97	-	-	33.80	93.45%	33.26	97.29%
381	46.97	-	-	33.08	98.56%	34.02	91.89%
435	46.97	-	-	32.37	103.60%	33.86	93.03%

As shown in **Table 5.3,** the fabric samples of Run 3 recalendared at 120^0C calendar roller temperature and four different pressures got completely torn after 3 minutes wash at 85^0C with 100 % flow capacity of the jets in Jet Dyeing Machine. In addition, fabric samples recalendared at 140^0C calendar roller temperature with 272 PLI (Pounds Linear Inch) calendaring pressure got torn as well. For 140^0C calendar roller temperature, the samples recalendared at 326, 381 and 435 PLI after washing treatment showed a steady increase in percentage Exceval™ removed from the fabric and for 435 PLI it is more than 100 % indicating fiber loss. But the physical condition of the samples was opposite to this fact; fabrics recalendared at 326 PLI and 381 PLI calendaring pressure were torn at several places after washing while fabric samples recalendared at 435 PLI were torn at only few places.

If the percentage Exceval™ removed for the calendar pressure 272 PLI and 326 PLI are compared for 140^0C and 160^0C calendar temperatures, it shows better results for 160^0C in terms of percentage Exceval™ removed and the physical condition of the fabrics. However, for 160^0C calendar rollers temperature with 381 PLI and 435 PLI pressures it shows better physical condition with less percentage Exceval^{TM} removal compare to 140^0C calendar rollers temperature. The comparison of percentage Exceval^{TM} removed and the physical condition of the fabric samples shows that the calendaring conditions for fabric Run 3 can be suggested as 140^0C calendar rollers temperature with 435 PLI calendar roller pressure or 160^0C temperature with 272 PLI or 326 PLI calendaring pressure. However, if 140^0C temperature is selected with 435 PLI pressure then the water flow capacity of the jets is required to be optimized and the actual washing time should also be less than 3 minutes to avoid fiber loss and damage to the fabric.

To optimize the calendaring conditions, it was necessary to recalendar and wash the fabric samples of maximum fabric weight and that is fabric Run 9. It is of 82.93 (grams * 100) fabric weight and 1.5 denier per filament (dpf) made at 0.5 (gram per hole per minute) though-put rate. **Table 5.4** shows the results of washing treatment at 85^0C using 100 % water flow capacity of the jets, 10 meter/minute fabric speed and 15 minutes washing time in Jet Dyeing Machine after recalendaring fabric Run 9 at four different calendaring pressures and three temperatures.

TABLE 5.4, Average Fabric weight (grams * 100) and percentage Exceval^{TM} removed from the fabric at various Calendaring Conditions for Fabric Run number - 9

Calendar Pressure (PLI)	As-made fabrics (grams * 100)	120^0C, 15 Minutes (grams * 100)	% Exceval^{TM} removed from the fabric	140^0C, 15 Minutes (grams * 100)	% Exceval^{TM} removed from the fabric	160^0C, 15 Minutes (grams * 100)	% Exceval^{TM} removed from the fabric
272	82.92	61.82	84.82%	66.09	67.66%	58.65	97.56%
326	82.92	67.14	63.43%	58.93	96.44%	68.31	58.73%
381	82.92	57.96	100.34%	65.84	68.66%	65.96	68.18%
435	82.92	56.52	106.13%	59.52	94.07%	66.74	65.04%

It is necessary to keep constant calendaring conditions for all the fabrics, Run 1 to 13 (the specifications of them can be found in **TABLE 5.1**). Therefore, there is no reason in looking the results for fabric samples of Run 9 washed after recalendaring at 120^0C with all four pressures and at 140^0C temperature with 272 PLI calendar rollers pressure because fabric Run 3 got very badly torn during washing for all these conditions.

For 160^0C calendar roller temperature with 326, 381 and 435 PLI calendaring pressures, the percentage Exceval^{TM} removed is much less even after 15 minutes wash with 100 % water flow capacity of the jets. That means none of these conditions are good for fabric Run 9 except if the actual washing time is increased from 15 minutes but then it increases the total washing time since the heat –up time of Jet Dyeing Machine to reach 85^0C is around 10 minutes. It is not meaningful to increase the total washing time more than half an hour from cost and time standpoint. For 140^0C calendar roller temperature with 326 and 435 PLI calendaring pressures, the percentage Exceval^{TM} removed from the fabric is better as well as the physical state of the samples.

In short, the suggested recalendaring conditions for fabric Run 9 are 140^0C calendar rollers temperature with 326 or 435 PLI calendar roller pressure, or 160^0C temperature with 272 PLI calendaring pressure. Recalling the suggested optimize calendaring conditions for fabric Run 3, which is 140^0C calendar rollers temperature with 435 PLI calendar roller pressure or 160^0C temperature with 272 PLI or 326 PLI calendaring pressure. After comparing the calendaring conditions and the results of the washing treatment for fabric Run 3 and 9, it is obvious that either 140^0C calendar rollers temperature can be used with 435 PLI calendar roller pressure or 160^0C calendaring temperature with 272 PLI pressure.

In the present research, the purpose of recalendaring the fabric samples is to improve web strength so that the fabrics can withstand washing treatment and at the same time to facilitate ease of Exceval^{TM} removal. For this reason, it would be better to select 140^0C calendar rollers temperature and 435 PLI calendar roller pressure as an optimized calendaring condition for all the fabrics (Run 1 to 13).

Further, samples of fabric Run 9 recalendared at 140^0C temperature with 272, 326, 381 and 435 PLI calendar roller pressures were washed in Jet Dyeing Machine at 85^0C with 100 % water flow capacity of the jets for 8 and 10 minutes. The fabric weight of the fabrics and percentage Exceval^{TM} removed from them are shown in **Table 5.5.** The results demonstrate that percentage Exceval^{TM} removed for fabrics recalendared using 326 and 435 PLI calendaring pressures are better than the remaining two calendaring pressures and it is true for washing treatment of 8 and 10 minutes both.

TABLE 5.5, Average Fabric weight (grams * 100) and percentage Exceval^{TM} removed from the recalendared fabric Run number 9 - Recalendaring conducted at 140^0C calendar roller temperature and four different Calendaring Pressures

Calendar Pressure (PLI)	Average Fabric weight of As-made fabrics (grams * 100)	Fabric weight (grams * 100) - 85^0C, 8 Minutes	% Exceval^{TM} removed from the fabric	Fabric weight (grams * 100) - 85^0C, 10 Minutes	% Exceval^{TM} removed from the fabric
272	82.92	64.28	74.93%	61.10	87.70%
326	82.92	62.77	81.02%	60.16	91.49%
381	82.92	63.29	78.91%	61.58	85.79%
435	82.92	60.04	91.98%	56.70	105.42%

The results of **Table 5.5** are plotted in a chart for percentage Exceval^{TM} removal from the fabrics and shown in **Figure 5.6**. It is obvious from the figure that the trend line for two different washing times are almost parallel to each other and shows a steady increase in the percentage Exceval^{TM} removed from the fabric with increase in calendaring pressure. However, it is essential to take into account while selecting calendaring pressure that too much pressure can tear apart the fabric samples during calendaring. Since in the current research, we are dealing with a range of fabric weight of the fabrics from 32 to 83 (grams * 100) it is advisable not to use too high pressure and keep 435 PLI as an optimized calendaring pressure.

In brief, all the fabric samples (Run 1 to 13) can be recalendared at 140^0C calendar rollers temperature, 5 feet/minute calendaring speed with 435 PLI calendaring pressure. This condition can ensure nonwoven web integrity during washing as well as effortlessness Exceval™ removal from the fabrics.

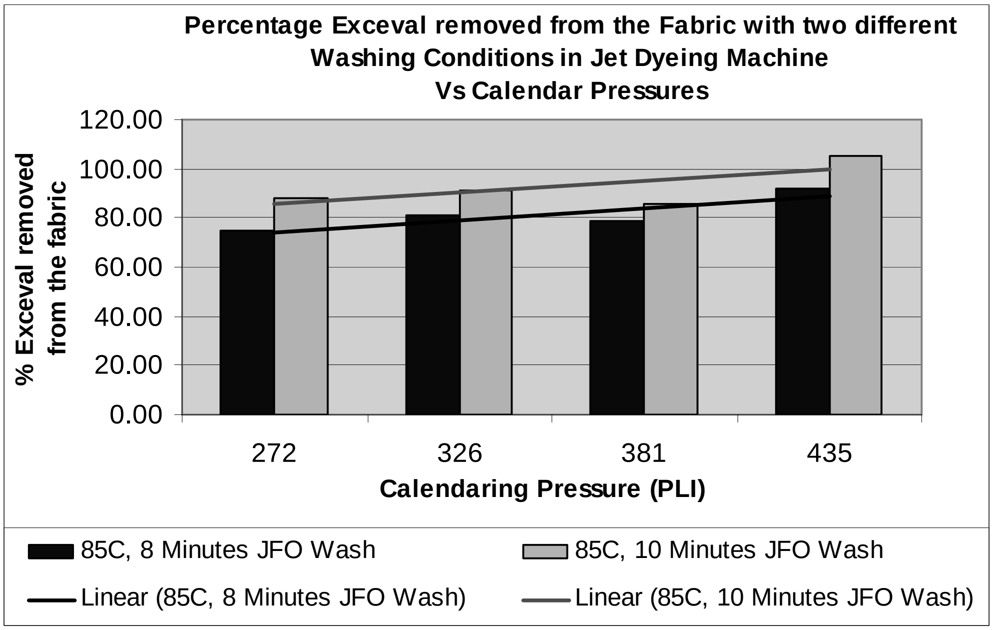


FIGURE 5.6, Percentage Exceval™ removed from the Fabric Run 9 using two different Washing Conditions after re-calendaring at 140^0C and four Calendaring Pressures

5.4 Exceval™ Removal Process using Jet Dyeing Machine:

According to the design of experiment, **Table 3.3**, total 62 washing trials were conducted in Jet Dyeing Machine. Fabric weights of all the fabric samples were measured after washing treatment and a careful physical examination of the samples was done. It was observed that the fabrics of higher denier per filament, here 2.5 and 2, have pills and protruding fibers on the fabric surface while the fabrics with 1.5 and 1 denier per filament have very smooth surface. This is obvious because even in woven fabrics during washing treatment; fabrics with higher denier per filament forms pills while fabrics with low denier per filament breaks and that’s why they have smooth surface. The same concept is applicable for nonwovens.

The results and the fabric weights are included in the **Appendix A**. From the results, the optimized washing conditions were found for each fabric and are shown in **Table 5.6**. In addition, the fabric weights and % Exceval™ removed from the fabric was determined after washing the fabrics at optimized conditions of **Table 5.6**. Further, all these samples were tested on FTIR – Fourier Transform Infrared Spectrometer for chemical analysis of the polymers in the fabric. A comparison of spectrum was done for unwashed as-made fabrics, fabrics washed at optimized washing conditions and the available library spectrums for detailed analysis. This testing was very important to make sure that Exceval™ is removed from the fabric. The results of FTIR testing are included in the chapter-4.

TABLE – 5.6, Optimized Washing Conditions *, Average Fabric weight (gram * 100) and percentage Exceval™ removed from the fabrics**

Fabric Run Number	Unwashed Fabrics - Fabric weight (grams * 100)	Average Fabric weight (grams * 100)	Standard Deviation σ	% Exceval™ removed from the fabric	Jet Dyeing Machine - JFO Washing Conditions - Washing time (minute) and Water flow capacity of the jets (%)
1	78.25	56.08	0.69	96.35%	1 Minute, 25% Flow Capacity
2	61.07	44.23	3.99	91.89%	1 Minute, 20% Flow Capacity
3	46.97	35.90	0.58	78.58%	1 Minute, 20% Flow Capacity
4	32.27	-	-	-	1 Minute, 20% Flow Capacity
5	80.71	60.29	2.24	84.36%	2 Minutes, 25% Flow Capacity
6	64.62	47.84	2.35	86.57%	1 Minute, 25% Flow Capacity
7	50.51	36.48	1.96	92.62%	1 Minute, 25% Flow Capacity
8	33.90	24.55	0.35	91.93%	1 Minute, 20% Flow Capacity
9	82.93	61.67	0.69	85.47%	12 Minutes, 50% Flow Capacity
10	63.91	48.17	1.07	82.08%	12 Minutes, 50% Flow Capacity
11	49.72	38.21	1.06	77.18%	1 Minute, 50% Flow Capacity
12	33.03	25.06	0.75	80.49%	1 Minute, 50% Flow Capacity
13	70.01	50.99	3.09	90.57%	1 Minute, 25% Flow Capacity

*** Washing temperature 85^0C and fabric speed 10 meter/min are constant for all the fabrics.

The following formula is used to find the percentage Exceval™ removed from the fabrics.

Percentage Exceval™ removed =

$$\frac{[(\text{Fabric weight of unwashed fabric - Fabric weight of washed fabric}) * 100]}{(\text{Fabric weight of unwashed fabric} * 30)} * 100$$

From **Table 5.6,** it is obvious that between 77 to 96 % of the Exceval™ is removed from the fabrics. In other words, since Exceval™ is contributing for 30 % of the total fabric weight of the fabrics, almost 23 to 28 % of the Exceval™ is removed from the fabrics. It can be observed from the table, that fabric Run 1, 5 and 9 have fabric weight in the range of 80 ± 3, while fabric Run 2, 6, and 10 are in the range of 62 ± 3. Similarly, fabric Run 3, 7 and 11 have fabric weight in the range of 47 ± 3, and fabric Run 4, 8 and 12 falls in the range of 31 ± 3. Comparing the washing conditions of the fabrics falling in the same fabric weight range it is obvious that even though the fabrics have similar fabric weights, the optimized washing conditions are not the same. This shows the significant role of the parameter other than fabric weight and in the present research the fiber size during polymer removal process. In addition, it can be observed that fabrics with smaller fiber size require higher water flow capacity of the jets during washing compare to the others. In other words, they are strong enough to withstand intense mechanical action compare to the fabrics made of higher denier per filament.

After finding the optimized washing conditions using Jet Dyeing Machine, it was necessary to wash few of the fabrics for the same amount of time in Skein Dyeing Machine and Paddle Washer to make sure that the decision of using Jet Dyeing Machine for this research was correct, since this decision was taken based on the comparison of machine features. Fabric Run number 3, 4, 6, 7, 10, 11 and 12 were washed in all three machines for the same washing time according to optimized conditions. The specifications of these fabrics are shown in **Table 3.1.** After washing, the fabric weights and percentage Exceval™ removed from the fabric samples were determined and are shown in **Table 5.7**.

As shown in the below table, fabric Run 3 was torn in Paddle Washer during the washing treatment. Likewise, fabric Run 4 got very badly torn in Paddle Washer and Skein Dyeing Machine, while in Jet Dyeing Machine, it was torn at many places but it was not possible to measure the fabric weight of the fabric sample after this washing trial. For fabric Run 10, the washing treatment was not carried out in Skein Dyeing Machine because the time to heat up this machine at 85^0C temperature is 55 minutes, and the actual washing time for fabric Run 10 is 12 minutes which makes total washing time around 67 minutes. In practice, it is not worthwhile to run this washing trial from time and cost point of view.

TABLE 5.7, Average Fabric weight (grams * 100) of particular Fabric Runs after Washing in Paddle Washer, Skein Dyeing Machine and Jet Dyeing Machine

	Paddle Washer		**Skein Dyeing Machine**		**Jet Dyeing Machine (JFO)**	
Fabric Run Number	Average Fabric weight (grams * 100) after wash	% Exceval™ removed from the fabric	Average Fabric weight (grams * 100) after wash	% Exceval™ removed from the fabric	Average Fabric weight (grams * 100) after wash	% Exceval™ removed from the fabric
3	–	–	34.47 σ = 1.99	88.73 %	36.27 σ = 0.88	75.97 %
4	–	–	–	–	–	–
6	51.19 σ = 1.32	69.27 %	46.48 σ = 1.09	93.57 %	47.84 σ = 2.35	86.56 %
7	35.19 σ = 2.40	101.08 %	34.00 σ = 1.50	108.95 %	36.48 σ = 1.96	92.62 %
10	54.09 σ = 0.91	51.23 %	N. A.	N. A.	48.17 σ = 1.07	82.08 %
11	36.71 σ = 1.51	87.21 %	38.00 σ = 1.76	78.56 %	38.21 σ =1.06	77.18 %
12	24.30 σ = 2.29	88.16 %	26.60 σ = 0.77	64.95 %	25.06 σ = 0.75	80.49 %

Hyphen shows that the fabric samples got completely torn and that's why the fabric weight could not be measured.

Further analysis was carried out by plotting a comparison of percentage Exceval^{TM} removed from the fabric during washing trials in three different machines and it is shown in **Figure 5.7**. As shown in the chart, percentage Exceval^{TM} removed from the fabric Run 3, 6 and 7 in Skein Dyeing Machine is more than other two machines but for fabric Run 7 it is more than 100 % and thus shows that the loss of fibers occurred during washing. The greatest disadvantage of using Skein Dyeing Machine is the heat up time which is 55 minutes and it can not be justified with the percentage Exceval^{TM} removal from the fabric because it is not significantly different than the percentage Exceval^{TM} removed using other two machines.

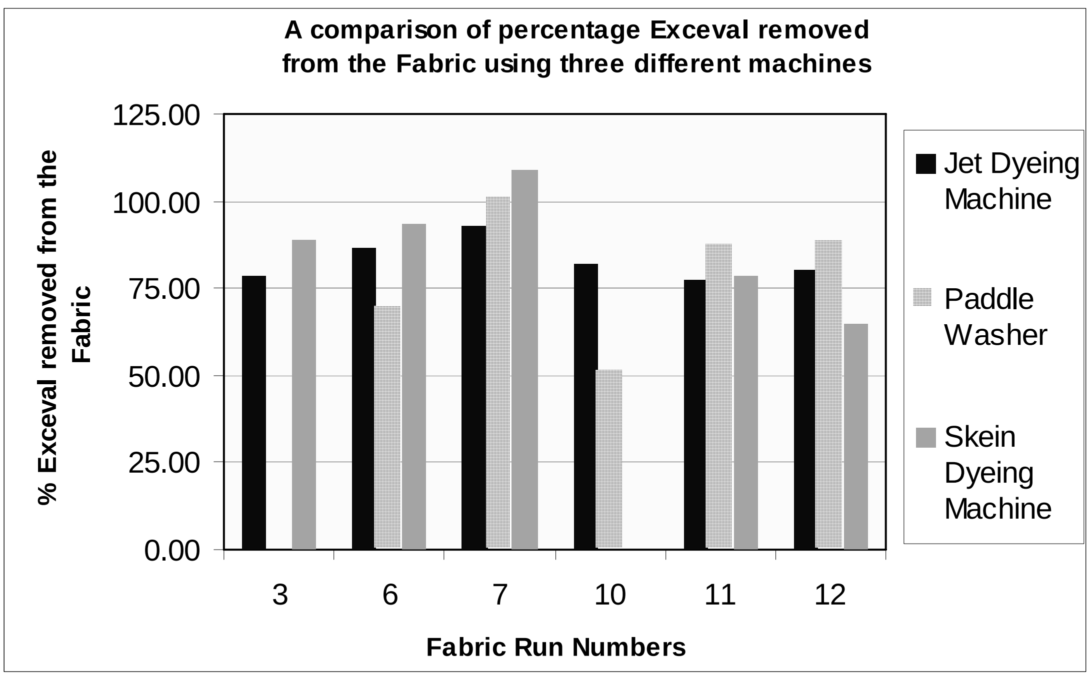


FIGURE 5.7, A Comparison of percentage Exceval^{TM} removed from the Fabric using Jet Dyeing Machine, Paddle Washer and Skein Dyeing Machine

Therefore, here it is more reasonable to compare Jet Dyeing Machine and Paddle Washer in terms of their performance in removing Exceval^{TM} from the fabric, time to heat up the machines and cost related with the washing treatment. Both these machines take approximately same amount of time to heat up to 85^0C, around 10 minutes. Paddle Washer has the advantage in terms of cost related with heating up because steam is used instead of electricity in Jet Dyeing Machine. However, the water content required for Paddle Washer is 48 liters compare to 6 liters in Jet Dyeing Machine and thus minimizing the cost related with waste water treatment. In terms of performance for these seven fabrics, Jet Dyeing machine is definitely better than Paddle Washer. Fabric Run 3 and 4 got completely torn in Paddle Washer while Jet Dyeing Machine removed 75.97 % Exceval™ from the fabric Run 3 and fabric Run 4 survived in washing treatment in this machine but it was not possible to measure the fabric weight or percentage Exceval™ removed due to fabric variations. The percentage Exceval™ removed from fabric Run 7 in Paddle Washer is more than 100 % and thus it shows loss in fibers while Jet Dyeing Machine removed 92.62 % Exceval™ from the same sample without damaging the fabric. For fabric Run 6 and 10, Jet Dyeing Machine removed 86.56 % and 82.08 % Exceval™ respectively, compare to 69.27 % and 51.23 % respectively in Paddle Washer, which shows obviously better performance of JFO in removing Exceval™ from the fabric during washing. Except for fabric Run 11 and 12, the Jet Dyeing Machine removed less Exceval™ than Paddle Washer. That is 77.18 % and 80.49 % respectively for fabric Run 11 and 12 compared to 87.21 % and 88.16 % in Paddle Washer. However, the selection of machine should be based on overall performance since washing conditions needs to be optimized and the same machine is being used for washing all the fabrics. The comparison shows that the use of Jet Dyeing Machine – JFO in this research for washing the fabrics for Exceval™ removal is preferred. Further, this machine can also be used for washing a mass of the similar kind of micro-denier fabrics in the industry, which is definitely an advantage for the commercialization of such a product.

5.5 Fabric Assurance by Simple Testing (FAST):

SiroFAST™ system has been developed by CSIRO Textile and Fiber Technology in Australia. This system is a unique integrated set of three instruments and test methods for fabric mechanical property measurement. This is used for assessing the appearance, handle and performance properties of fabrics as well as helping in predicting fabric performance in garment manufacturing [Textile and Fibre Technology, Achievements, SiroFAST]. SiroFAST™ system is simple and easy to use; results can be obtain quickly and are in graphical plot to facilitate interpretation. This system incorporates Fast-1 compression meter, Fast-2 Bending meter, Fast-3 Extension meter and Fast-4 Dimensional stability test. The software of the system automatically plots the appropriate values and joins the various plotted points together to form a "Fabric Fingerprint" as a result, which is unique to each particular fabric.

In the current research, FAST system is used only for measuring mechanical properties of the as-made, recalendared, jet washed and hydroentangled fabrics. The results obtained after testing fabrics on FAST system are used to draw a comparison of the mechanical properties of the as-made, recalendared, jet washed and hydroentangled fabrics.

Further, an average value of each measured property was determined for individual denier per filament fabric to compare the FAST results of each process. However, before comparing the values, it was necessary to normalize the data and that's why the normalized ratio was calculated for each fabric run. **Table 5.8** illustrates the values of fabric weights (4 X 4 inch area) as well as normalized ratio for the weight of each fabric run and for each process. The formula used in calculating normalized ratio is as follow and it normalizes the values for the average weight of the fabrics.

$$\textbf{Normalized ratio} = \frac{\textbf{Average Weight of the fabrics (4 X 4 inch area) for the process}}{\textbf{Weight of the fabric Run Number (4 X 4 inch area) for that process}}$$

The average weight of the fabrics for each process is used to normalize the data because after each process fabric weight is changing, especially, after washing the fabrics due to Exceval^{TM} removal. Therefore, using the average fabric weight after the various processes helps in gaining a comparison across processes.

Using the normalized ratio of each fabric (Run Number) from the following table, the normalized values of the mechanical properties were calculated for the fabrics using following formula.

Normalized Value = (Normalized Ratio * The Original Value of the measured property)

The values of fabric Run 3, 4, 8 and 12 are eliminated while calculating the normalized as well as normalized average values since these fabrics are irregular in appearance.

TABLE 5.8, Normalized ratio for the Weight (gram * 100) of 4 X 4 inch area of the As-made, Re-calendared, Jet Washed and Hydroentangled Fabrics

Fabric Run Number	Weight of As-made Fabrics	Norma-lized ratio	Weight of Re-calendared Fabrics	Norma-lized ratio	Weight of Jet Washed Fabrics	Norma-lized ratio	Weight of Hydro-entangled Fabrics	Norma-lized ratio
1	78.25	0.85	75.90	0.87	56.08	0.88	55.87	0.88
2	61.07	1.09	60.99	1.08	44.23	1.12	45.17	1.09
5	80.71	0.83	80.19	0.82	60.29	0.82	59.05	0.83
6	64.62	1.03	61.68	1.07	47.84	1.03	46.97	1.05
7	50.51	1.32	47.95	1.37	36.48	1.35	35.67	1.38
9	82.93	0.81	82.17	0.80	61.67	0.80	62.73	0.78
10	63.91	1.05	63.74	1.03	48.17	1.02	48.60	1.01
11	49.72	1.34	49.49	1.33	38.21	1.29	37.78	1.30
13	70.01	0.95	69.54	0.95	50.99	0.97	51.01	0.96
Average	**66.86 gram**		**65.74 gram**	-	**49.33 gram**	-	**49.21 gram**	-

5.5.1 Results of FAST - 1, Compression Meter:

This equipment measures the fabric thickness under two fixed loads, 2 gram/cm^2 and 100 gram/cm^2. The difference between these two thicknesses is a measure of “Compressed Thickness”. It is the amount of compressible fibers on the fabric surface. Compressed thickness is a useful indicator of any variation in fabric handle. It gives information about bulkiness or hairiness of the fabrics [Textile and Fibre Technology, Achievements, SiroFAST]. Following formula is used for calculating compressed thickness.

$$\textbf{Compressed thickness (mm)} = T_2 - T_{100}$$

Where, T_2 = Compressed Thickness under 2 gram/cm^2 load

T_{100} = Compressed Thickness under 100 gram/cm^2 load

For the present research, the compressed thickness under two different loads and the difference of these two thicknesses were obtained for as-made, re-calendared, jet washed and hydroentangled fabrics. The testing was done according to the manual of SiroFAST^{TM}, and also the sample size and number of samples were selected from it.

RESULTS OF TESTING COMPRESSED THICKNESS UNDER 2 gram/cm^2 LOAD

TABLE 5.9, Average Compressed Thickness (mm) under 2 gram/cm^2 load Normalized for Average Weight (gram * 100) of the Fabric (4 X 4 inch area) at each Process**

Run No.	As -made Fabrics Original Compressed Thickness	Norma-lized Ratio	Normalized Compressed Thickness of As-made Fabrics	Recalendared Fabrics Original Compressed Thickness	Norma-lized Ratio	Normalized Compressed Thickness of Recalendared Fabrics
1	0.417	0.85	0.356	0.385	0.87	0.333
2	0.373	1.09	0.408	0.345	1.08	0.372
3	0.317	-	-	0.340	-	-
4	0.318	-	-	0.328	-	-
5	0.404	0.83	0.335	0.357	0.82	0.293
6	0.387	1.03	0.400	0.340	1.07	0.362
7	0.337	1.32	0.446	0.296	1.37	0.406
8	0.237	-	-	0.261	-	-
9	0.371	0.81	0.299	0.334	0.80	0.267
10	0.353	1.05	0.369	0.314	1.03	0.324
11	0.295	1.34	0.397	0.257	1.33	0.341
12	0.217	-	-	0.222	-	-
13	0.417	0.95	0.398	0.336	0.95	0.318

**** Normalized Value = Normalized Ratio * Value of the fabric property**

TABLE 5.10, Average Compressed Thickness (mm) under 2 gram/cm^2 load Normalized for Average Weight (gram * 100) of the Fabric (4 X 4 inch area) at each Process**

Run Number	Jet (JFO) Wash Fabrics Original Compressed Thickness	Norma-lized Ratio	Normalized Compressed Thickness of Jet Washed Fabrics	Hydro-entangled Fabrics Original Compressed Thickness	Norma-lized Ratio	Normalized Compressed Thickness of Hydro-entangled Fabrics
1	0.394	0.88	0.347	0.422	0.88	0.372
2	0.363	1.12	0.405	0.379	1.09	0.413
3	0.301	-	-	0.360	-	-
4	-	-	-	-	-	-
5	0.390	0.82	0.319	0.422	0.83	0.352
6	0.343	1.03	0.354	0.370	1.05	0.388
7	0.309	1.35	0.418	0.339	1.38	0.468
8	0.274	-	-	0.321	-	-
9	0.380	0.80	0.304	0.451	0.78	0.354
10	0.333	1.02	0.341	0.406	1.01	0.411
11	0.285	1.29	0.368	0.329	1.30	0.428
12	0.235	-	-	0.272	-	-
13	0.377	0.97	0.365	0.410	0.96	0.395

** **Normalized Value = Normalized Ratio * Value of the fabric property**

The Comparison of the Original Value of the Compressed Thickness (mm) under 2 gram/cm^2 load for Different Processes:

- The compressed thickness value for the re-calendared fabrics is less than the as-made fabrics, except fabric Run 3, 4, 8 and 12. During re-calendaring, the bonding of the fibers is carried out by passing the fabrics between two rollers at 140^{0}C temperature and 435 PLI calendaring pressure, and thus it makes fabrics more compressed compared to the as-made fabrics. If the bonds during re-calendaring are placed exactly on the same position, or, more or less on the previous bonds then this also influences fabric measured values of compression. Fabric Run 3, 4, 8 and 12 are of low fabric weight; that is 46.26, 31.54, 32.46 and 31.61 gram/meter^2 respectively. The physical appearance of these fabrics is irregular compared to the heavy fabric weight fabrics of 50 to 80 gram/meter^2. Thus, a fabric with irregular fiber distribution can result in improper measurement due to the irregularity present in the fabric it self.

- Fabric Run 3 and 4 recalendared fabrics have high compressed thickness compared to the as-made and jet washed fabrics. These two fabrics have a lousy appearance due to irregular fiber distribution and thus this could be the reason for the same.
- Most of the jet washed fabrics have compressed thickness less than the as-made fabrics except fabric Run 8, 9 and 12. Here, the washing conditions of these fabrics and the removal of Exceval™ segments from the bicomponent configuration play an important role. In addition, fabric Run 8 and 12 are of low fabric weights and irregular in appearance; this could be also the reason for the improper compression value of the jet washed fabrics.
- Majority of the hydroentangled fabrics have maximum compressed thickness value compared to the fabrics from the other processes except fabric Run 6 and 13. This outcome indicates that, for most of the fabrics, hydroentanglement process resulted into improving bulkiness. However, fabric Run 6 and 13 hydroentangled fabrics have lower compressed thickness value than the corresponding as-made fabrics. Since; the whole process of developing microfiber nylon spunbond involves a large number of variables; this outcome could be influenced by them.

After looking these individual results, additional analysis was done by finding an average of the normalized compressed thickness values for each denier per filament fabric and for each process as shown in **Table 5.11.** It is necessary to normalize the values of compressed thickness for the average weight of the fabrics so that these values of the different fabrics can be compared on the same chart and meaningful conclusions can be drawn. The value of the normalized ratio for each fabric is shown in **Table 5.8.**

TABLE 5.11 Summary of Normalized Average Compressed Thickness (mm) under 2 gram/cm^2 load for each process

denier per filament	As-made Fabrics	Recalendared Fabrics	Jet (JFO) Wash Fabrics	Hydroentangled Fabrics
1	0.398	0.318	0.365	0.395
1.5	0.355	0.311	0.338	0.398
2	0.394	0.354	0.364	0.402
2.5	0.382	0.353	0.376	0.392

- The compressed thickness of the 1, 1.5, 2, and the 2.5 denier per filament re-calendared fabrics is less than the as-made fabrics of the same denier per filament respectively. In other words, after re-calendaring the fabrics are more compact than the as-made ones.
- After washing treatment, the compressed thickness values are increased compared to the re-calendared fabrics and it is obviously because of the Exceval™ removal from the fabrics. This makes the fabric structure loose and thus fibers protrude from the surface.
- The compressed thickness of the hydroentangled fabrics is higher than the re-calendared as well as jet washed fabrics for all four fiber sizes.
- For the 1.5, 2 and 2.5 denier per filament hydroentangled fabrics, the compressed thickness is higher than the as-made fabrics of the respective fiber size. However, the compressed thickness of the 1 denier per filament as-made fabrics is higher than the 1 denier per filament hydroentangled fabrics. The difference between these two values is not high. This could be due to the experimental error related with the fabric weight measurement since the normalized ratio is used, or due to the fact that the value for the 1 denier per filament is derived from one fabric weight.

From the summary **Table 5.11**, a chart was created in Excel to perceive the influence of the fiber size of the fabrics and influence of the each process on the compressed thickness value.

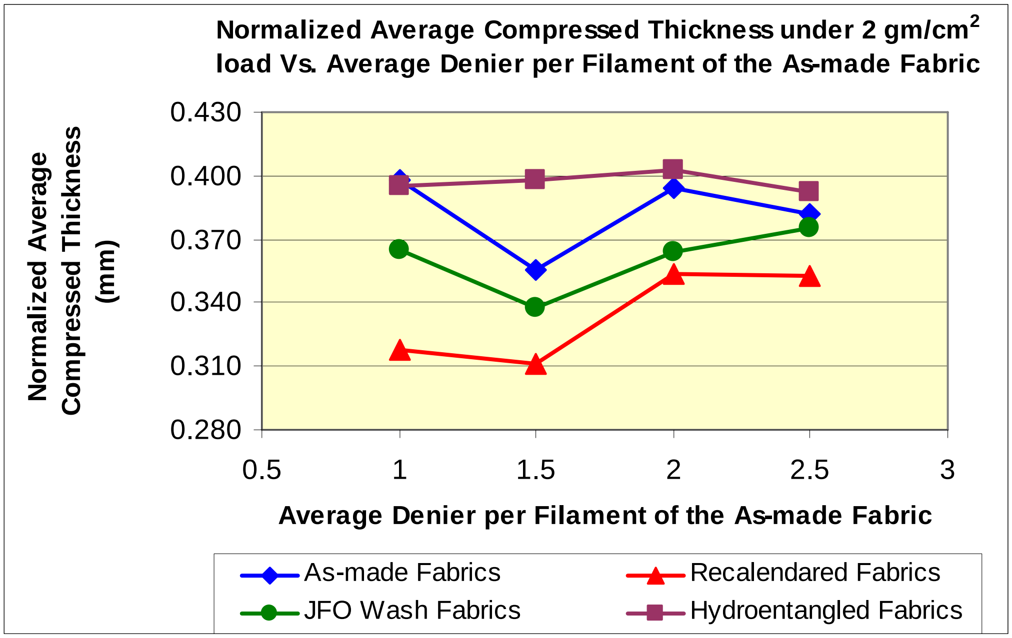


FIGURE 5.8, Comparison of the Normalized Average Compressed Thickness under 2 gram/cm^2 load of the Fabrics from different process

- It is obvious that the compressed thickness of the hydroentangled fabrics under 2 gram/cm^2 load is maximum compared to other processes, while for the re-calendared fabrics these values are the least. This is because calendaring process makes the fabrics structure compact by introducing bonds between the fibers and thus restricting their movements. On other hand, hydroentanglement was carried out after washing away the Exceval™ segments therefore after washing treatment the fabric structure became loose and now there are 8 fibers instead of 1. These resulted in providing highest bulkiness after fiber interlacement during hydroentangling.
- The jet washed fabrics have compressed thickness values higher than the re-calendared fabrics but lower than the as-made fabrics for all four denier per filament fabrics. After removing Exceval™ in the washing treatment, the fabric structure is quite loose compared to the compact structure of the re-calendared fabrics and thus the re-calendared fabrics have high compressed thickness. While, the compressed thickness of the jet washed fabrics is lower than the as-made fabrics due to the fact that the fabrics were re-calendared before jet wash and this lowers the compressed thickness values.

RESULTS OF TESTING COMPRESSED THICKNESS UNDER 100 gram/cm^2 LOAD

The results of the compressed thickness measurement are given in the **Table 5.12** and **Table 5.13.**

TABLE 5.12, Average Compressed Thickness (mm) under 100 gram/cm^2 load Normalized for Average Weight (gram * 100) of the Fabric (4 X 4 inch area) at each Process**

Run Number	As-made Fabrics Original Compressed Thickness	Norma-lized Ratio	Normalized Compressed Thickness of As-made Fabrics	Recalendared Fabrics Original Compressed Thickness	Norma-lized Ratio	Normalized Compressed Thickness of Recalendared Fabrics
1	0.358	0.85	0.306	0.322	0.87	0.279
2	0.319	1.09	0.349	0.284	1.08	0.306
3	0.261	-	-	0.278	-	-
4	0.231	-	-	0.250	-	-
5	0.351	0.83	0.291	0.305	0.82	0.250
6	0.329	1.03	0.340	0.286	1.07	0.305
7	0.272	1.32	0.360	0.236	1.37	0.324
8	0.184	-	-	0.180	-	-
9	0.323	0.81	0.260	0.283	0.80	0.226
10	0.294	1.05	0.308	0.265	1.03	0.273
11	0.237	1.34	0.319	0.209	1.33	0.278
12	0.164	-	-	0.160	-	-
13	0.355	0.95	0.339	0.279	0.95	0.264

** **Normalized Value = Normalized Ratio * Value of the fabric property**

TABLE 5.13, Average Compressed Thickness (mm) under 100 gram/cm^2 load Normalized for Average Weight (gram * 100) of the Fabric (4 X 4 inch area) at each Process**

Run Number	JFO Wash Fabrics Original Compressed Thickness	Norma-lized Ratio	Normalized Compressed Thickness of Jet (JFO) Wash Fabrics	Hydro-entangled Fabrics Original Compressed Thickness	Norma-lized Ratio	Normalized Compressed Thickness of Hydro-entangled Fabrics
1	0.299	0.88	0.263	0.337	0.88	0.297
2	0.267	1.12	0.298	0.296	1.09	0.322
3	0.219	-	-	0.273	-	-
4	-	-	-	-	-	-
5	0.307	0.82	0.251	0.350	0.83	0.292
6	0.265	1.03	0.273	0.295	1.05	0.309
7	0.240	1.35	0.325	0.264	1.38	0.364
8	0.169	-	-	0.237	-	-
9	0.292	0.80	0.234	0.376	0.78	0.295
10	0.257	1.02	0.263	0.333	1.01	0.337
11	0.216	1.29	0.279	0.267	1.30	0.348
12	0.162	-	-	0.210	-	-
13	0.292	0.97	0.282	0.339	0.96	0.327

** **Normalized Value = Normalized Ratio * Value of the fabric property**

The Comparison of the Original Value of the Compressed Thickness (mm) under 100 gram/cm^2 load for Different Processes:

- Under 100 gram/cm^2 load, the compressed thickness for the as-made fabrics is higher than the recalendared and jet washed fabrics except fabric Run 3 and 4. The as-made fabrics have been recalendared at a constant condition and recalendaring process increases the compactness of the fabrics. However, fabric Run 3 and 4 as-made fabrics are very lousy fabrics due to the irregular fiber distribution during spunbonding process and thus the measured values can give error due to this reason.

- The compressed thickness for the jet washed fabrics is less than the as-made fabrics for all thirteen fabrics. Because, the structure of the as-made fabrics is compact compared to the loose structure of the jet washed fabrics due to Exceval™ removal.
- After washing, the compressed thickness of the fabric Run 5, 7, 9, 11, 12 and 13 is more than the re-calendared fabrics. This could be due to the optimized washing conditions of these fabrics, the mechanical action of the jets, the influence of the Exceval™ removal process, and the way nylon segments behave inside these fabrics.
- All of the hydroentangled fabrics show higher compressed thickness values than the re-calendared and the jet washed fabrics.
- Most of the hydroentangled fabrics show less compressed thickness than the as-made fabrics of the same fabric Run except 8, 9, 10, 11 and 12 Run numbers. Here the washing conditions of these five fabrics and the nylon segment behavior are the factors influencing this result.

The summary **Table 5.14** illustrates an average normalized value of the compressed thickness under 100 gram/cm^2 load for fabrics of four different denier per filament and of four different processes. While calculating an average, fabric Run 3, 4, 8 and 12 are not included due to the excessive fabric variation.

TABLE 5.14, Summary of Normalized Average Compressed Thickness (mm) under 100 gram/cm^2 load for each process

denier per filament	As-made Fabrics	Recalendared Fabrics	Jet (JFO) Wash Fabrics	Hydroentangled Fabrics
1	0.339	0.264	0.282	0.327
1.5	0.296	0.259	0.259	0.327
2	0.330	0.293	0.283	0.322
2.5	0.328	0.293	0.280	0.310

- It is obvious from the table that the average compressed thickness under 100 gram/ cm^2 load; for all the re-calendared and the jet washed fabrics is less than the as-made fabrics.
- The average value of the compressed thickness, for the 1 denier per filament re-calendared fabrics is less than the jet washed fabrics of the same fiber size. While, the average compressed thickness for the 1.5 denier per filament re-calendared as well as jet washed fabrics is similar. However, for the 2 and the 2.5 denier per filament re-calendared fabrics, this value is more than the jet washed fabrics of the same fiber size respectively.
- The compressed thickness of the hydroentangled fabrics is higher than the compressed thickness of the re-calendared and jet washed fabrics.
- The hydroentangled fabrics of the 1, 2 and 2.5 denier per filament have low compressed thickness compared to the as-made fabrics of the respective fiber size. However, the 1.5 denier per filament hydroentangled fabric has higher compressed thickness than the as-made fabric of the same fiber size. This is because of the high compressed thickness values of the fabric Run 9, 10 and 11.

Further analysis was necessary to compare the influence of each process and the fabrics of different denier per filament for better understanding of the changes in compressed thickness value of the fabrics. For this reason, relevant graphs were created in Excel and are shown here.

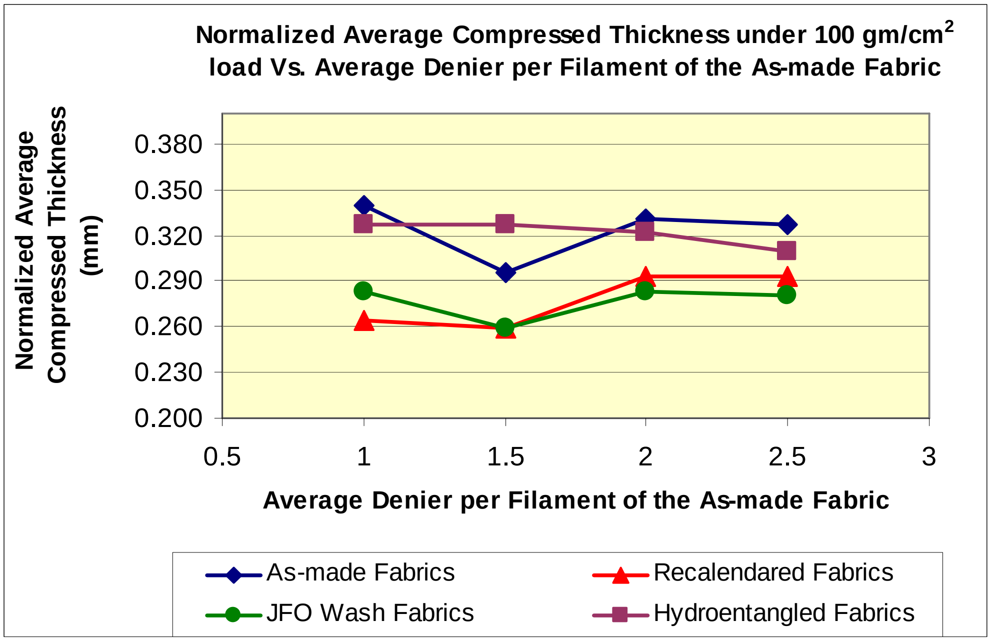


FIGURE 5.9, Comparison of the Normalized Average Compressed Thickness under 100 gram/cm^2 load of the Fabrics from different process

- The compressed thickness measured from the re-calendared fabrics is very low compared to the fabrics from other processes. The reason behind this is during re-calendaring the fibers are fused together to create bonds and this obstructs the free movement of the fibers as well as makes the fabric structure compact.
- The as-made and the jet washed fabrics shows a similar trend for the values of each fiber size but the compressed thickness of the as-made fabrics is higher than of the jet washed fabrics. This is because the washing treatment is carried out after re-calendaring the as-made fabrics and, as mentioned earlier, re-calendaring makes the fabric structure compact. However, during washing Exceval^{TM} is removed from the bicomponent configuration of the fibers and this makes fabric structure loose. Therefore, both of these factors influence this outcome.
- The compressed thickness of the hydroentangled fabrics under 100 gram/cm^2 load is high for the 1.5 denier per filament fabric and it is due to the high compressed thickness values of the fabric Run 9, 10 and 11. For the 1, 2 and 2.5 denier per filament hydroentangled fabrics, the compressed thickness values are very close to the as-made fabrics of the same fiber size.

RESULTS OF TESTING COMPRESSED THICKNESS

TABLE 5.15, Compressed Thickness (mm) Normalized for Average Weight (gram * 100) of the Fabric (4 X 4 inch area) at each Process**

Run Number	As-made Fabrics Original Compressed Thickness	Norma-lized Ratio	Normalized Compressed Thickness of As-made Fabrics	Recalendared Fabrics Original Compressed Thickness	Norma-lized Ratio	Normalized Compressed Thickness of Recalendared Fabrics
1	0.059	0.85	0.050	0.063	0.87	0.055
2	0.054	1.09	0.059	0.061	1.08	0.066
3	0.056	-	-	0.062	-	-
4	0.087	-	-	0.087	-	-
5	0.052	0.83	0.043	0.052	0.82	0.043
6	0.058	1.03	0.060	0.054	1.07	0.058
7	0.065	1.32	0.086	0.059	1.37	0.081
8	0.053	-	-	0.081	-	-
9	0.048	0.81	0.039	0.051	0.80	0.041
10	0.058	1.05	0.061	0.048	1.03	0.050
11	0.058	1.34	0.078	0.049	1.33	0.065
12	0.054	-	-	0.063	-	-
13	0.062	0.95	0.059	0.057	0.95	0.054

** **Normalized Value = Normalized Ratio * Value of the fabric property**

TABLE 5.16, Compressed Thickness (mm) Normalized for Average Weight (gram * 100) of the Fabric (4 X 4 inch area) at each Process****

Run Number	Jet Wash Fabrics Original Compressed Thickness	Norma-lized Ratio	Normalized Compressed Thickness of Jet Washed Fabric	Hydro-entangled Fabrics Original Compressed Thickness	Norma-lized Ratio	Normalized Compressed Thickness of Hydro-entangled
1	0.095	0.88	0.084	0.085	0.88	0.075
2	0.096	1.12	0.107	0.083	1.09	0.090
3	0.082	-	-	0.087	-	-
4	-	-	-		-	-
5	0.083	0.82	0.068	0.073	0.83	0.061
6	0.077	1.03	0.079	0.076	1.05	0.080
7	0.070	1.35	0.095	0.075	1.38	0.103
8	0.105	-	-	0.084	-	-
9	0.087	0.80	0.070	0.075	0.78	0.059
10	0.076	1.02	0.078	0.073	1.01	0.074
11	0.069	1.29	0.089	0.062	1.30	0.081
12	0.072	-	-	0.062	-	-
13	0.085	0.97	0.082	0.071	0.96	0.068

** **Normalized Value = Normalized Ratio * Value of the fabric property**

The Comparison of the Original Value of the compressed thickness (mm) for Different Processes:

- The original value of the compressed thickness for all of the jet washed fabrics is maximum except Run 7 and this can be due to some experimental error or any of the variables between the processes. Since, compressed thickness is the measure of the amount of compressible fibers on the fabric surface, after washing the Exceval^{TM} from the fabrics it is expected that the number of the fibers protruding from the fabric surface increase due to loose structure of the fabrics.

- The compressed thickness of the hydroentangled fabrics is higher than the values measured from the as-made and re-calendared fabrics.
- For hydroentangled fabrics, the compressed thickness is less than the jet washed fabrics for most of the fabrics as the interlacement of the fibers is carried out during the process. However, fabric Run 3 and 7 of the hydroentanglement process show more compressed thickness value than the jet washed fabrics. Fabric Run 3 is of low fabric weight and very irregular, which directly influences the compressed thickness measurement under two different loads and thus, the compressed thickness.
- There is no clear relationship between the compressed thickness values of the as-made and re-calendared fabrics. In general, after calendaring, the compressed thickness is reduced but in the current research, two calendaring processes are used. The fabrics were calendared after spunbonding to maintain web integrity and then they were re-calendared to improve fabrics strength. Therefore, the positions of the bonds play a very important role in the measured values apart from the fiber size of the fabrics.

From the calculated normalized values of the compressed thickness, the average value was calculated for each denier per filament fabrics and for the each process. These values are shown in the summary **Table 5.17.**

TABLE 5.17, Summary of Normalized Average Compressed Thickness (mm) of the fabrics at each process

denier per filament	As-made Fabrics	Recalendared Fabrics	Jet (JFO) Wash Fabrics	Hydroentangled Fabrics
1	0.059	0.054	0.082	0.068
1.5	0.059	0.052	0.079	0.071
2	0.063	0.060	0.081	0.081
2.5	0.055	0.060	0.095	0.083

- The average compressed thickness of the as-made fabrics, re-calendared fabrics and the hydroentangled fabrics is less than the jet washed fabrics for all four denier per filament fabrics, except, the average value of the 2 denier per filament jet washed and the hydroentangled fabrics is same. After washing treatment, the fabrics have very loose structure compared to any other process due to Exceval™ removal and thus, the jet washed fabrics have maximum hairiness compared to the fabrics from any other process.

- The comparison of the compressed thickness for the as-made and the re-calendared fabrics shows that the 1, 1.5 and 2 denier per filament as-made fabrics have higher compressed thickness than the re-calendared fabrics of the same fiber size. This is because of fusing the fibers at 140^0C and 435 PLI calendaring pressure, which makes re-calendared fabric structure compact. While the compressed thickness for the 2.5 denier per filament as-made fabrics is less than the re-calendared fabrics. The positions of the bonds placed during calendaring and recalendaring is a factor of influence on this property.

After finding the average value of the compressed thickness for each denier per filament fabric and for each process, detailed analysis was done by plotting these values in Excel to create graphs. The following charts illustrate the comparison of the compressed thickness value and the denier per filament of the fabrics for each process.

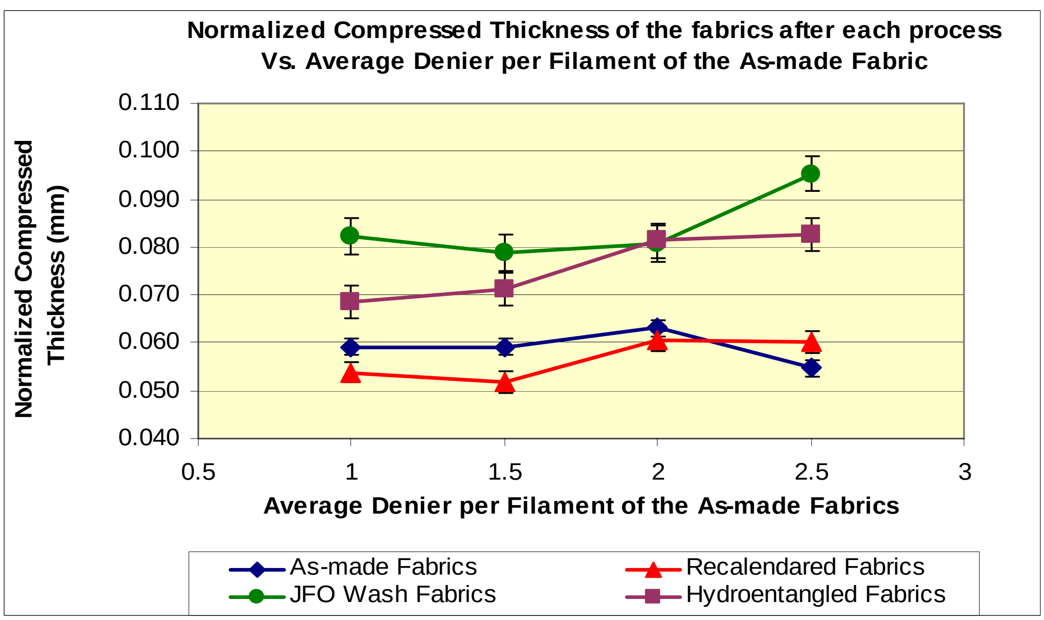


FIGURE 5.10, Comparison of the Normalized Average Compressed Thickness of the Fabrics from different process

- The compressed thickness of the re-calendared fabrics is less than that of the as-made fabrics except the 2.5 denier per filament fabrics and this is due to the positions of the bonds during two calendaring processes.
- The compressed thickness of the jet washed fabrics is maximum for all denier per filament of the fabrics except the 2.5 denier per filament fabrics.
- For hydroentangled fabrics, the compressed thickness is higher than the as-made and re-calendared fabrics. Thus, they are bulkier than the fabrics from these two processes.

5.5.2 Results of FAST - 2, Bending Meter:

FAST-2 as its name implies measures the bending length of the fabric and it is used to measure fabric stiffness or flexibility. This instrument works on the cantilever principle, which involves pushing a fabric over a vertical edge until it has bent to 41.5^0. The length of the fabric pushed over the edge to reach 41.5^0 angle is measured and it is known as bending length. A stiff fabric needs pushing further to bend to this angle while limp fabric falls quickly. In addition, bending length measurement is used together with fabric weight to find value of "Bending Rigidity". Bending rigidity is the measure of fabric resistance to bending.

$$\textbf{Bending Rigidity (B)} = W * C^3 * 9.81 * 10^{-6}\ \mu N.M.$$

Where, W = Mass per unit area in gram/meter2

C = Bending Length in mm

In current research, bending length and bending rigidity were measured of all the fabrics for each process to determine flexibility of the fabrics. Fabric with very high value of bending length feels stiffer while fabric with very low value is difficult to handle. This measurement can also be a useful indicator of changes or variations in fabric handle. The results obtained after measuring bending length are given in the **Table 5.18** and **Table 5.19.**

RESULTS OF TESTING BENDING LENGTH (mm) IN MACHINE DIRECTION

TABLE 5.18, Bending Length (mm) in Machine Direction Normalized for Average Weight (gram * 100) of the Fabric (4 X 4 inch area) at each Process**

Run Number	As-made Fabrics Original Bending Length	Norma-lized Ratio	Normalized Bending Length of As-made Fabrics	Recalendared Fabrics Original Bending Length	Norma-lized Ratio	Normalized Bending Length of Recalendared Fabrics
1	30.60	0.85	26.14	33.50	0.87	29.02
2	27.50	1.09	30.11	27.20	1.08	29.32
3	24.00	-	-	23.10	-	-
4	19.90	-	-	22.90	-	-
5	34.90	0.83	28.91	36.30	0.82	29.76
6	32.80	1.03	33.94	28.80	1.07	30.69
7	26.40	1.32	34.95	29.70	1.37	40.72
8	21.60	-	-	28.90	-	-
9	33.80	0.81	27.25	38.40	0.80	30.72
10	26.90	1.05	28.14	35.50	1.03	36.62
11	23.40	1.34	31.47	27.70	1.33	36.79
12	18.30	-	-	23.60	-	-
13	34.70	0.95	33.14	28.60	0.95	27.04

**** Normalized Value = Normalized Ratio * Value of the fabric property**

TABLE 5.19, Bending Length (mm) in Machine Direction Normalized for Average Weight (gram * 100) of the Fabric (4 X 4 inch area) at each Process**

Run Number	Jet (JFO) Wash Fabrics Original Bending Length	Normalized Ratio	Normalized Bending Length of Jet (JFO) Wash Fabrics	Hydro-entangled Fabrics Original Bending Length	Normalized Ratio	Normalized Bending Length of Hydro-entangled Fabrics
1	19.80	0.88	17.42	28.80	0.88	25.36
2	19.10	1.12	21.30	30.60	1.09	33.33
3	17.70	-	-	25.60	-	-
4	-	-	-	-	-	-
5	23.20	0.82	18.98	33.10	0.83	27.58
6	17.00	1.03	17.53	31.60	1.05	33.11
7	18.50	1.35	25.02	25.20	1.38	34.76
8	13.00	-	-	24.20	-	-
9	22.70	0.80	18.16	33.20	0.78	26.04
10	17.90	1.02	18.33	31.30	1.01	31.69
11	18.80	1.29	24.27	28.80	1.30	37.51
12	15.10	-	-	23.60	-	-
13	21.30	0.97	20.61	31.20	0.96	30.09

** **Normalized Value = Normalized Ratio * Value of the fabric property**

The Comparison of the Original Values of the Bending Length (mm) in Machine Direction of the fabrics for Different Processes:

- For all thirteen fabrics, the original value of the bending length of the jet washed fabrics is less than the values measured from the as-made, re-calendared and the hydroentangled fabrics.
- It is obvious from the bending length measurement results, that the bending length of the re-calendared fabrics is more than the as-made fabrics except fabric Run 2, 3, 6 and 13. In other words, the re-calendared fabrics are stiffer than the as-made fabrics except

fabric Run 2, 3, 6 and 13. This could be due to the positions of the bonds during calendaring and re-calendaring processes. If during re-calendaring, the bonds are placed somewhere in between the previously made bonds; then the bonded portion per unit area of the fabric is higher within these fabrics compare to if the bonds during re-calendaring are placed more or less on top of the previously placed bonds. After Scanning Electron Microscopy (SEM) of fabric Run 1 and 13, it was found that the above statement is true. The images of these fabrics are shown in the **Chapter 4**.In the inspected area of the fabric Run 1, the bonds during re-calendaring are placed more or less on top of the previously made bonds, while in fabric Run 13, the bonds are placed in the area between the previously placed bonds. Thus, the bonded portion per unit area of the fabric is higher for the measured area of the fabric Run 13 than the fabric Run 1. This influences the bending length of these two fabrics. However, it is difficult to predict the positions of the bonds in each fabric due to two calendaring processes and this parameter plays an important role in the bending length measurement.

- The bending length of the hydroentangled fabrics is more than the jet washed fabrics for all the fabric Run numbers. However, the bending length of fabric Run 2, 3, 8, 10, 11 and 12 is higher for the hydroentangled fabrics than the re-calendared ones.

From the above individual results of the bending length of each fabric, the average value was calculated from the normalized values. The average values of these fabrics in machine direction are given below in **Table 5.20**.

TABLE 5.20, Summary of Normalized Average Bending Length (mm) in Machine Direction for each process

denier per filament	As-made Fabrics	Recalendared Fabrics	Jet (JFO) Wash Fabrics	Hydroentangled Fabrics
1	33.14	27.04	20.61	30.09
1.5	28.95	34.71	20.25	31.75
2	32.60	33.72	20.51	31.82
2.5	28.13	29.17	19.36	29.35

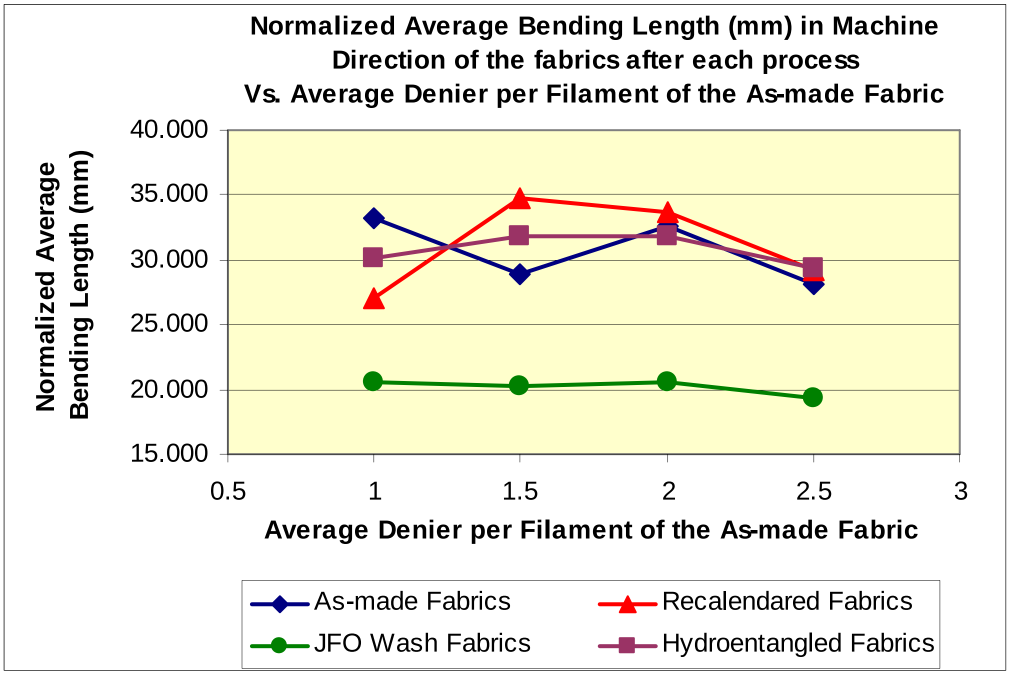


FIGURE 5.11, Comparison of the Normalized Average Bending Length in Machine Direction of the Fabrics from different process

- It is obvious from the table that for all four denier per filament jet washed fabrics the bending length in machine direction is very low compare to the as-made, re-calendared and hydroentangled fabrics of the corresponding fiber size. That means, after washing treatment, fabrics are more flexible. This is because of the loose structure of the fabrics after washing due to Exceval^{TM} removal from the bicomponent fibers of the fabrics. In addition, the mechanical action of the water jets on the fabrics as well as the bonded area of the fabrics during washing treatment is also influencing the fabric flexibility.
- It can be noticed from the summary table as well as **Figure 5.11** that the 1.5, 2 and 2.5 denier per filament re-calendared fabrics are stiffer than the as-made fabrics; while the 1 denier per filament as-made fabric is stiffer than the re-calendared fabrics. This is due to the positions of the bonds in fabric Run 13 during calendaring and re-calendaring as mentioned earlier. Besides, the average for 1 denier per filament fabric is from the values of only one fabric sample.
- Similarly, the 1.5 and the 2.5 denier per filament hydroentangled fabrics are stiffer than the as-made fabrics while the 1 and 2 denier per filament hydroentangled fabrics is less stiff than the as-made fabrics of the same fiber size.

- There is no obvious relationship between the bending length of the as-made, re-calendared and hydroentangled fabrics. This is because of two calendaring processes were carried out which makes it difficult to predict the positions of the bonds and this surely influences the bending length. In addition, fabrics were washed after re-calendaring where the bonds were weakened and later-on in hydroentangling they were almost gone. However, there are number of variables between the processes that are influencing this property and it makes difficult to draw any relationship between these three processes.

<u>RESULTS OF TESTING BENDING LENGTH (mm) IN CROSS DIRECTION</u>

The results of the bending length measurement in cross direction of the fabrics are given in **Table 5.21** and **Table 5.22.**

The Comparison of the Original Values of the Bending Length (mm) in Cross Direction of the fabrics for Different Processes:

- The original value of the bending length in cross direction is less than the original value measured in machine direction for each fabric Run (1 to 13) and for all the processes.
- The jet washed fabrics are flexible in cross direction compare to the as-made, re-calendared and the hydroentangled fabrics in the same direction.
- The comparison of individual corresponding value for the as-made and the recalendared fabrics shows that the bending length measured is high for the recalendared fabrics except for fabric Run 1, 2, 4, 6, 8 and 13. This is because two calendaring processes. Due to this, the positions of the bonds placed during these two processes influence the bending length of each fabric. In addition, fabric Run 4 and 8 are of low weight and irregular in appearance which also influences the bending length measured.
- For hydroentangled fabrics, the original value of the bending length is less than the as-made and re-calendared fabrics.

TABLE 5.21, Bending Length (mm) in Cross Direction Normalized for Average Weight (gram * 100) of the Fabric (4 X 4 inch area) at each Process**

Run Number	As-made Fabrics Original Bending Length	Norma-lized Ratio	Normalized Bending Length of As-made Fabrics	Recalendared Fabrics Original Bending Length	Norma-lized Ratio	Normalized Bending Length of Recalendared Fabrics
1	28.90	0.85	24.69	24.60	0.87	21.31
2	24.70	1.09	27.04	20.10	1.08	21.66
3	16.70	-	-	18.10	-	-
4	12.90	-	-	12.40	-	-
5	32.40	0.83	26.84	34.30	0.82	28.12
6	29.30	1.03	30.32	26.00	1.07	27.71
7	23.70	1.32	31.37	24.70	1.37	33.86
8	13.90	-	-	12.50	-	-
9	31.30	0.81	25.23	35.20	0.80	28.16
10	26.60	1.05	27.83	31.80	1.03	32.80
11	19.50	1.34	26.22	22.90	1.33	30.42
12	12.70	-	-	14.70	-	-
13	33.20	0.95	31.71	25.30	0.95	23.92

**** Normalized Value = Normalized Ratio * Value of the fabric property**

TABLE 5.22, Bending Length (mm) in Cross Direction Normalized for Average Weight (gram * 100) of the Fabric (4 X 4 inch area) at each Process**

Run Number	Jet (JFO) Wash Fabrics Original Bending Length	Normalized Ratio	Normalized Bending Length of Jet (JFO) Wash Fabrics	Hydro-entangled Fabrics Original Bending Length	Normalized Ratio	Normalized Bending Length of Hydro-entangled Fabrics
1	12.30	0.88	10.82	17.40	0.88	15.32
2	12.90	1.12	14.39	16.40	1.09	17.86
3	11.50	-	-	12.80	-	-
4		-	-		-	-
5	14.40	0.82	11.78	19.90	0.83	16.58
6	14.50	1.03	14.95	16.00	1.05	16.76
7	12.70	1.35	17.18	15.70	1.38	21.66
8	10.80	-	-	11.70	-	-
9	16.10	0.80	12.88	20.70	0.78	16.24
10	15.00	1.02	15.36	17.70	1.01	17.92
11	11.60	1.29	14.98	16.30	1.30	21.23
12	10.90	-	-	13.20	-	-
13	13.20	0.97	12.77	18.30	0.96	17.65

** **Normalized Value = Normalized Ratio * Value of the fabric property**

From these individual results, the average bending length for each denier per filament fabrics in cross direction were calculated and are given in the summary **Table 5.23**. The average values given here are normalized by multiplying the original measured value with the normalized ratio of **Table 5.8.** Fabric Run 3, 4, 8 and 12 are not included for the average calculations.

TABLE 5.23, Summary of Normalized Average Bending Length (mm) in Cross Direction for each process

denier per filament	As-made Fabrics	Recalendared Fabrics	Jet (JFO) Wash Fabrics	Hydroentangled Fabrics
1	31.71	23.92	12.77	17.65
1.5	26.43	30.46	14.40	18.46
2	29.51	29.90	14.64	18.33
2.5	25.87	21.49	12.60	16.59

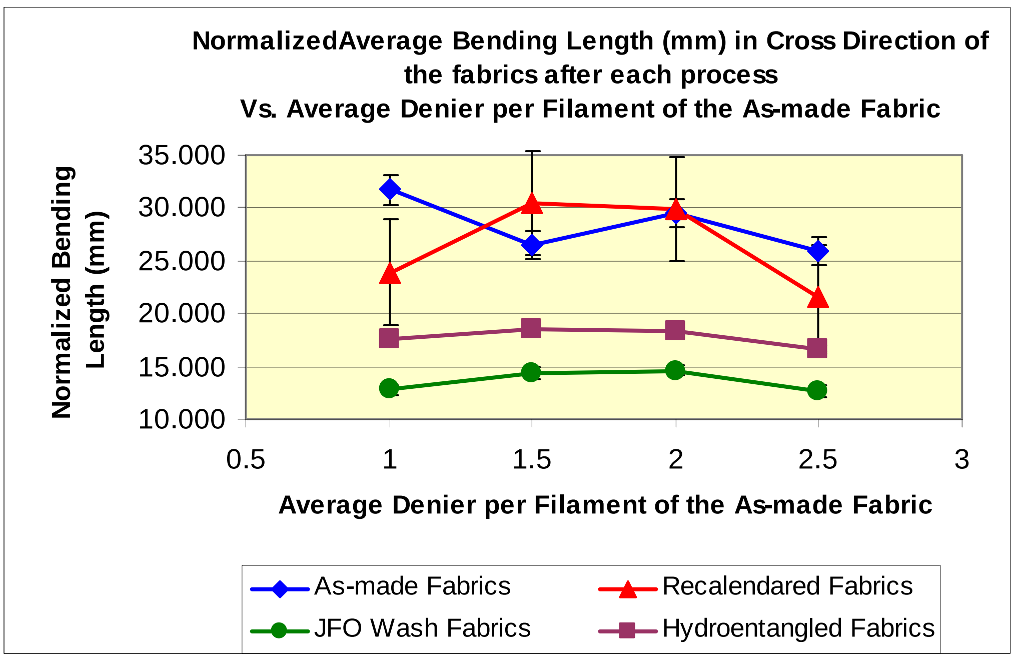


FIGURE 5.12, Comparison of the Normalized Average Bending Length in Cross Direction of the Fabrics from different process

- For each denier per filament jet washed fabrics, the bending length in cross direction is less than that of the as-made, re-calendared and the hydroentangled fabrics.
- There is no clear relationship between the average bending length of the as-made and the re-calendared fabrics of different denier per filament. The 1.5 and 2 the denier per filament re-calendared fabrics are stiffer than the as-made ones while the 1 and 2.5 denier per filament as-made fabrics are stiffer than the re-calendared fabrics. Here, mainly the positions of the bonds are responsible for this outcome.

- The average bending length of the hydroentangled fabrics is less than the as-made as well as the re-calendared fabrics.
- The hydroentangled fabrics are stiffer than the jet washed fabrics and this is due to the interlacement of the fibers during bonding procedure.

RESULTS OF TESTING BENDING RIGIDITY IN MACHINE DIRECTION

The results obtained after calculating the bending rigidity in machine direction of the fabrics for each process are given below in **Table 5.24**. The original values of the bending rigidity have been calculated by the software of the FAST system.

TABLE 5.24, Bending Rigidity (μNm) in Machine Direction - Original Value

Run Number	As-made Fabrics	Re-calendared Fabrics	Jet (JFO) Wash Fabrics	Hydroentangled Fabrics
1	21.9	28.0	4.3	13.0
2	12.4	12.1	3.0	12.7
3	6.4	5.6	2.0	5.6
4	2.5	3.7		
5	33.7	37.7	7.4	21.0
6	22.4	14.5	2.3	14.5
7	9.1	12.4	2.3	5.6
8	3.3	7.7	0.5	3.6
9	31.2	45.7	7.1	22.6
10	12.2	27.9	2.7	14.5
11	6.3	10.4	2.5	8.8
12	2.0	4.1	0.8	3.2
13	28.6	15.9	4.8	15.1

The Comparison of the Original Values of the Bending Rigidity (µN.m) in Machine Direction of the fabrics for Different Processes:

- The bending rigidity in machine direction of the jet washed fabrics is less than the bending rigidity of the as-made, re-calendared and hydroentangled fabrics. This is because the bending rigidity is a function of the bending length and the fabric weight of the fabrics. The jet washed fabrics have low fabric weight as well as less bending length than the corresponding as-made, re-calendared and hydroentangled fabrics (Run numbers).
- The bending rigidity for the heavier fabric weight fabrics is higher than the low fabric weight fabrics, and this is true for each fiber size and for each process.
- The re-calendared fabrics have higher bending rigidity in machine direction than the as-made fabrics, except fabric Run 2, 3, 6 and 13. This is because; the measured bending length in machine direction of the as-made fabric Run 2, 3, 6 and 13 is high compare to the re-calendared fabrics.
- The average bending length in machine direction of the hydroentangled fabrics is less than the measured property for the re-calendared fabrics except fabric Run 2. This is because the bending length of the hydroentangled fabric Run 2 is higher than that of the re-calendared fabric Run 2.

From the individual values, the average bending rigidity in machine direction of the fabrics was calculated for each denier per filament fabrics and is shown in the summary **Table 5.25**. The fabric Run 3, 4, 8 and 12 are of low basis weight and irregular so they are not included in average.

TABLE 5.25, Summary of Average Bending Rigidity (μN.m) in Machine Direction for each process – Original Values

denier per filament	As-made Fabrics	Recalendared Fabrics	Jet (JFO) Wash Fabrics	Hydroentangled Fabrics
1	28.60	15.90	4.80	15.10
1.5	16.57	28.00	4.10	15.30
2	21.73	21.53	4.00	13.70
2.5	17.15	20.05	3.65	12.85

From this table, values are plotted in a graph to compare bending rigidity in machine direction of the fabrics for different processes.

- It is clear from the table that the average value for the jet washed fabric is much less compared to the as-made, re-calendared and the hydroentangled fabric.
- The average bending rigidity of the hydroentangled fabrics is less than the as-made and re-calendared fabrics.

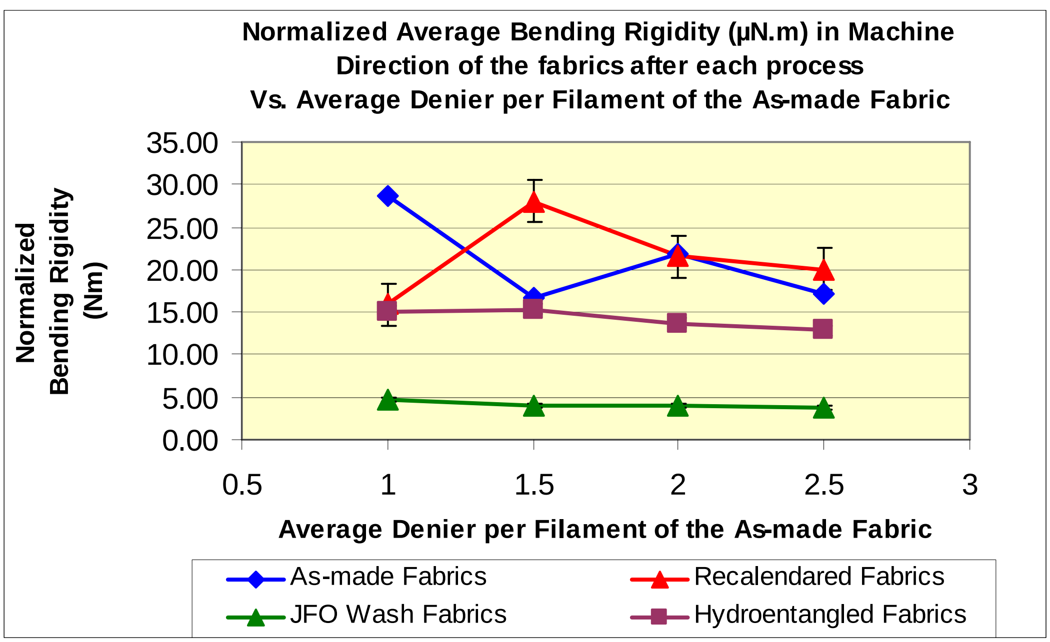


FIGURE 5.13, Comparison of the Average Bending Rigidity (μN.m) in Machine Direction of the Fabrics from different process – Original values

- The average bending rigidity is higher for the 1.5 and 2.5, denier per filament re-calendared fabrics than the corresponding as-made fabrics. That means, for these fiber sizes, the re-calendared fabrics showed higher resistance of the fabrics to bending than the as-made fabrics. Only the 1 denier per filament re-calendared fabrics showed less bending rigidity compared to the as-made fabrics. This is because of less bending length of the re-calendared fabric Run 13 compared to the as-made fabric Run 13 due to the positions of the bonds placed during calendaring and the re-calendaring processes.

RESULTS OF TESTING BENDING RIGIDITY IN CROSS DIRECTION

TABLE 5.26, Bending Rigidity (μN.m) in Cross Direction – Original Values

Run Number	As-made Fabrics	Recalendared Fabrics	Jet (JFO) Wash Fabrics	Hydroentangled Fabrics
1	18.5	11.1	1.0	2.9
2	9.0	4.8	0.9	2.0
3	2.2	2.7	0.5	0.7
4	0.7	0.6		
5	26.9	31.8	1.8	4.6
6	16.0	10.6	1.4	1.9
7	6.6	7.1	0.7	1.3
8	0.9	0.6	0.3	0.4
9	25.0	35.3	2.5	5.5
10	11.8	20.2	1.6	2.6
11	3.6	5.8	0.6	1.6
12	0.7	1.0	0.3	0.6
13	25.2	11.1	1.1	3.1

The Comparison of the Original Values of the Bending Rigidity (μN.m) in Cross Direction of the fabrics for Different Processes:

- The bending rigidity of the jet washed fabrics is less than that of the as-made, re-calendared and hydroentangled fabrics. This is because of low bending length value as well as reduction in the fabric weight due to Exceval™ removal from the jet washed fabrics. Since, the bending rigidity is a function of the bending length and fabric weight of the fabrics; this results in low value of the bending rigidity.
- For the heavier fabric weight fabrics, the bending rigidity in cross direction is higher than the low fabric weight fabrics of each fiber size and from each process. This outcome was also observed for the bending length measurement in machine direction.
- The average bending rigidity measured in cross direction of the hydroentangled fabrics is less than that of the as-made and re-calendared fabrics. Hydroentangling was carried out after the washing treatment and thus reduction in the fabric weight results in reduced bending rigidity.

The average bending rigidity in cross direction was calculated from the original values of the fabrics from each process but the fabric Run 3, 4, 8 and 12 are not included. This is because; these fabrics are of low fabric weights and very irregular in appearance which can influence the measured property value. The values are shown in **Table 5.27**.

TABLE 5.27, Summary of Average Bending Rigidity (μN.m) in Cross Direction for each process – Original Values

denier per filament	As-made Fabrics	Recalendared Fabrics	Jet (JFO) Wash Fabrics	Hydroentangled Fabrics
1	13.0	11.1	1.1	3.1
1.5	10.0	20.4	1.6	3.2
2	6.0	16.5	1.3	2.6
2.5	1.5	8.0	1.0	2.5

For better understanding of the influence of each process on the bending rigidity measurement in cross direction of the fabrics, the comparisons was made and plotted in **Figure 5.14**.

- The average bending rigidity in cross direction is less than the values measured in machine direction of the as-made, re-calendared, jet washed and hydroentangled fabric of all four fiber sizes,
- The average bending rigidity of the jet washed fabrics is least out of all four processes and for each fiber size. The reason behind this is the low value of the bending length as well as fabric weight because most of the Exceval™ is removed from these fabrics during washing.

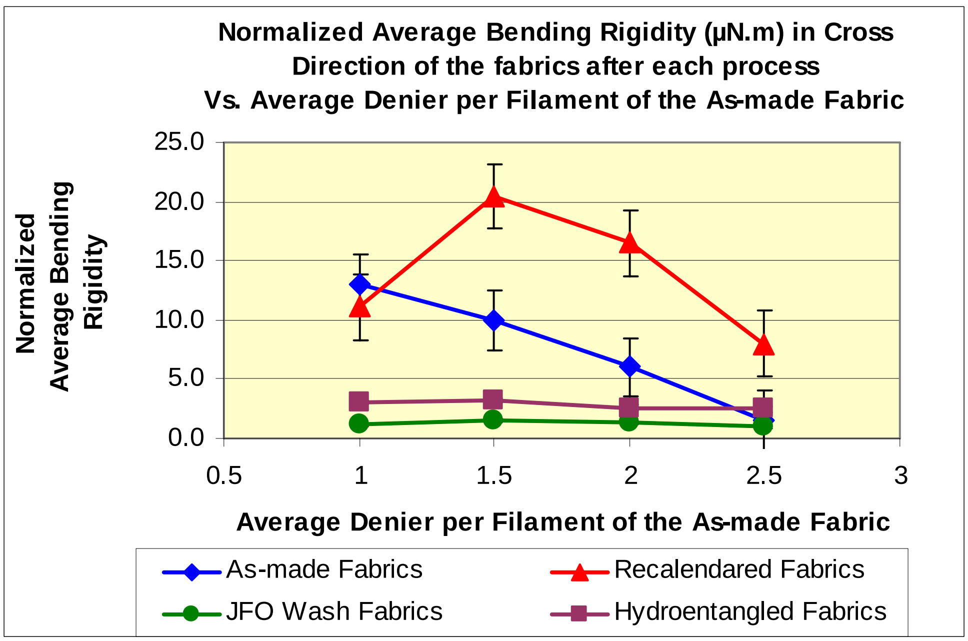


FIGURE 5.14, Comparison of the Average Bending Rigidity (µN.m) in Cross Direction of the Fabrics from different process –Original values

- For hydroentangled fabrics, the average bending rigidity in cross direction of the fabrics less than the average bending rigidity of the as-made and re-calendared fabrics.
- For the as-made and re-calendared fabrics, the average bending rigidity of the re-calendared fabrics is more than the as-made fabrics except the 1.0 denier per filament

fabrics. This is due to the low value of the average bending length in cross direction of the 1.0 denier per filament re-calendared fabric.

5.5.3 Results of FAST - 3, Extension Meter:

FAST-3 is an extension meter and it measures the amount in percentage that a fabric will stretch under three fixed low loads, 5, 20 and 100 gram/cm. Fabrics are tested for extensibility under all three loads for warp and weft direction in woven, and in nonwovens for machine and cross direction of the fabrics. While for measuring extensibility in bias direction of 45^0, only 5 gram/cm load is used for both wovens and nonwovens. Both high and low extensibility in machine and cross-direction can be a problem. From the value of bias extensibility, “Shear Rigidity” is calculated. The formula for shown below.

$$\textbf{Shear Rigidity} = \frac{123}{\textbf{Bias Extension at 5 gram/cm (\%)}}$$

Shear rigidity is a measure of the ease with which a fabric can be distorted in a trellising action. High value of shear rigidity indicates difficulty of fabric to be formed into smooth three-dimensional shapes while low value indicates that the fabric will be easily distorted in forming into a product.

Further, from the results of FAST – 2 and FAST – 3 equipments, formability is calculated. Formability is a measure of the ability of a fabric to absorb compression in its own plane without buckling. Low formability is a major reason of buckling or seam pucker during sewing.

$$\textbf{Formability} = \textbf{Bending Rigidity X } \frac{(\textbf{Extension at 20 gram/cm – Extension at 5 gram/cm})}{14.7}$$

In present research, extensibility was evaluated in machine, cross as well as bias direction of as-made, recalendared, jet washed and hydroentangled fabrics to study the influence of each process on these properties. The results of the tests conducted in machine direction of the fabrics are given in **Table 5.30** and **Table 5.31** while the results of testing in cross direction of the fabrics are given in **Table 5.33** and **Table 5.34.** In addition, the shear rigidity and the formability are reported.

RESULTS OF TESTING EXTENSIBILITY IN MACHINE DIRECTION – FAST 3

TABLE 5.28, Extensibility (%) at 100 gm/cm in Machine Direction Normalized for Average Weight (gram * 100) of the Fabric (4 X 4 inch area) at each Process**

Run Number	As-made Fabrics Original Extensibility	Norma-lized Ratio	Normalized Extensibility of As-made Fabrics	Recalendared Fabrics Original Extensibility	Norma-lized Ratio	Normalized Extensibility of Recalendared Fabrics
1	1.8	0.85	1.54	2.0	0.87	1.73
2	2.2	1.09	2.41	1.7	1.08	1.83
3	2.0	-	-	3.1	-	-
4	5.4	-	-	2.5	-	-
5	1.1	0.83	0.91	1.5	0.82	1.23
6	1.1	1.03	1.14	2.2	1.07	2.34
7	1.8	1.32	2.38	1.3	1.37	1.78
8	2.5	-	-	2.5	-	-
9	1.0	0.81	0.81	2.7	0.80	2.16
10	2.5	1.05	2.62	3.2	1.03	3.30
11	3.5	1.34	4.71	3.9	1.33	5.18
12	10.5	-	-	2.9	-	-
13	1.2	0.95	1.15	1.5	0.95	1.42

**** Normalized Value = Normalized Ratio * Value of the fabric property**

TABLE 5.29, Extensibility (%) at 100 gm/cm in Machine Direction Normalized for Average Weight (gram * 100) of the Fabric (4 X 4 inch area) at each Process**

Run Number	Jet (JFO) Wash Fabrics Original Extensibility	Norma-lized Ratio	Normalized value of Jet (JFO) Wash Fabrics	Hydro-entangled Fabrics Original Extensibility	Norma-lized Ratio	Normalized Extensibility of Hydro-entangled Fabrics
1	2.4	0.88	2.11	2.2	0.88	1.94
2	4.0	1.12	4.46	3.0	1.09	3.27
3	5.2	-	-	3.5	-	-
4		-	-		-	-
5	3.9	0.82	3.19	2.3	0.83	1.92
6	3.3	1.03	3.40	2.7	1.05	2.83
7	3.6	1.35	4.87	4.8	1.38	6.62
8	7.2	-	-	6.0	-	-
9	4.3	0.80	3.44	2.3	0.78	1.80
10	3.7	1.02	3.79	3.0	1.01	3.04
11	4.6	1.29	5.94	3.0	1.30	3.91
12	6.9	-	-	6.0	-	-
13	3.3	0.97	3.19	2.9	0.96	2.80

**** Normalized Value = Normalized Ratio * Value of the fabric property**

For As-made Fabrics, the Original Value of Extensibility (%) in Machine Direction:

- Out of thirteen as-made fabrics, six have very low extensibility. That is fabric Run 1, 5, 6, 7, 9 and 13 have extensibilities less than 2 %. While fabric Run 2, 3, 8, 10 and 11 showed extensibility (%) in machine direction between 2 to 4 %.
- Fabric Run 4 and 12 of as-made fabrics have extensibility 5.4 % and 7.0 % in machine direction under 100 gm/cm load respectively. The reason behind such a high extensibility can be due to very low fabric weight of these fabrics, 32.27 and 33.03 gram/meter^2 respectively. Due to low fabric weight, these two fabrics contain fewer fibers per unit area, so during extensibility test, fibers have enough space for free

movement. In other words, the structure of these fabrics is loose compare to the higher fabric weight fabrics.

For Re-calendared Fabrics, the Original Value of Extensibility (%) in Machine Direction:

- After recalendaring the fabrics, four fabrics showed very low extensibility. That is fabric Run 2, 5, 7 and 13 have extensibility less than 2 %. While fabric Run 1, 3, 4, 6, 8, 9, 10, 11 and 12 showed extensibility (%) in machine direction between 2 to 4 %.
- All the fabrics were once calendared (120^{0}C, 320 PLI) to maintain web integrity after spunbonding and then later on they were recalendared (140^{0}C, 435 PLI) to improve the web strength so that the fabrics can withstand the washing treatment. The reason behind the reduction in extensibility (%) between 2 to 4 % from 5.4 % and 7.0 % respectively for Fabric Run 4 and 12 after recalendaring is the positions of the bonds placed during calendaring and re-calendaring process. There is a possibility during recalendaring that the bonds are placed more or less in between of the bonds made during the first calendaring. This results into more number of bonds in the fabrics and less fiber movement.

For Jet Washed Fabrics, the Original Value of Extensibility (%) in Machine Direction:

- After the washing treatment, the extensibility % in machine direction for all the fabrics is increased and the value is higher than the values obtained for the as-made and recalendared fabrics of the each fabric Run. This happened because of the removal of Exceval^{TM} from the fabrics. Removing the segments of the Exceval^{TM} from Sixteen Segmented Pie bicomponents, which is contributing 30 % of the total fabric weight of the fabrics results into the loss in the fabric weight between 23 to 28 % (from the weight measurement results after the washing treatment, **Table 4.1**) and thus causes free movements of the nylon microfiber (segments) under low load.

For Hydroentangled Fabrics, the Original Value of Extensibility (%) in Machine Direction:

- The extensibility (%) of the hydroentangled fabrics is higher than the as-made and re-calendared fabrics, except fabric Run 9 and 11 re-calendared fabrics. While, the extensibility of the hydroentangled fabrics is less than the jet washed fabrics and the reason behind this is compact structure of these fabrics compared to the washed ones.
- The fabric Run 2, 6, 10, 11 and 13 have extensibility between 2 to 4 % while; the fabric Run 1, 5 and 9 showed extensibility less than 2 %. This can be due to compact structure of these three fabrics due to heavier fabric weight compared to the rest.
- The fabric Run 3, 7, 8 and 12 have extensibility between 4 to 11 %. The reason behind such a high extensibility is the low fabric weight of these fabrics which allows free fiber movement when load is applied.

Further, averages of the normalized values were calculated for each denier per filament fabrics and are shown in the summary **Table 5.30.** The comparison of the extensibility (%) in the machine direction of the fabrics is made by plotting the average values in a graph, **Figure 5.15**.

TABLE 5.30, Summary of Normalized Average Extensibility (%) at 100 gm/cm in Machine Direction for each process

denier per filament	As-made Fabrics	Recalendared Fabrics	Jet (JFO) Wash Fabrics	Hydroentangled Fabrics
1	1.1	1.4	3.2	2.8
1.5	2.7	3.5	4.4	2.9
2	1.5	1.8	3.8	3.8
2.5	2.0	1.8	3.3	2.6

- It is obvious from the table that the percentage extensibility in machine direction increases after washing the fabrics for each denier per filament fabrics.

- The re-calendared fabrics showed increase in the extensibility (%) compared to the as-made fabrics for the 1, 1.5 and 2 denier per filament fabrics, while for the 2.5 denier per filament fabrics the extensibility (%) is reduced.
- The average extensibility (%) in machine direction for the hydroentangled fabrics is lower than the jet washed fabrics because of fiber entanglement, which obstructs the fiber movement when load is applied. While in jet washed fabrics, due to Exceval™ removal and the mechanical action of the jets, the structure became very loose.
- For hydroentangled fabrics, the extensibility value is more than that of the as-made fabrics for all four fiber sizes.
- The extensibility (%) value of the 1, 2 and 2.5 denier per filament hydroentangled fabrics is higher than the re-calendared fabrics of the corresponding fiber sizes. However, for the 1.5 denier per filament re-calendared fabric, the extensibility (%) is higher than the hydroentangled fabric of the same fiber size. Generally, the extensibility of the re-calendared fabrics should be less than that of the hydroentangled fabrics but this outcome can be influenced by the positions of the bonds in these fabrics.

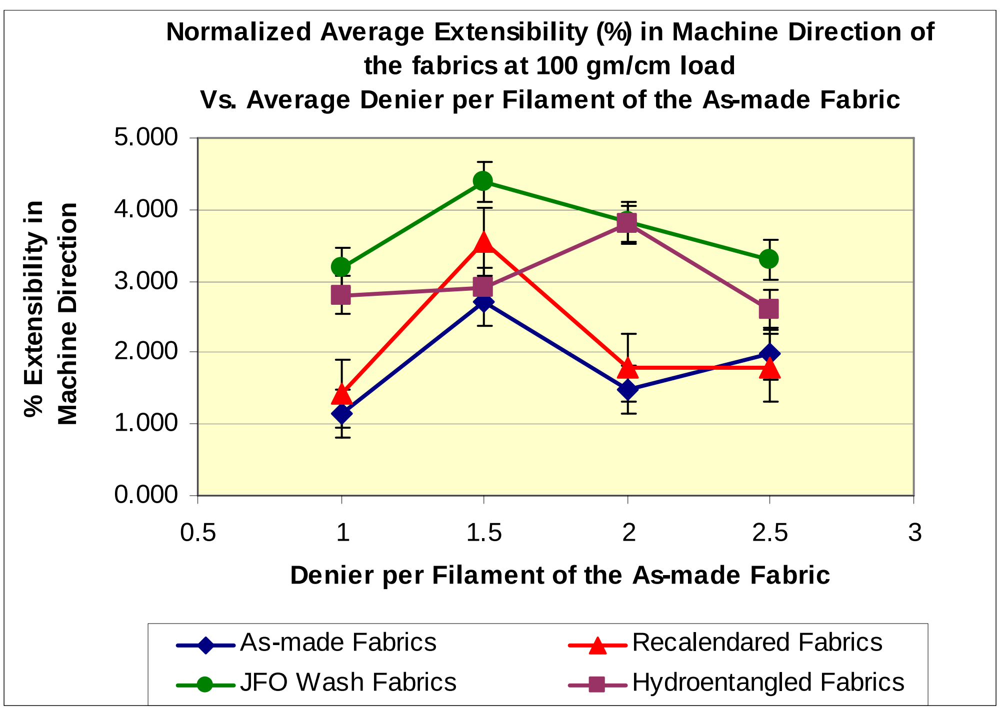


FIGURE 5.15, Comparison of the Normalized Average Extensibility in Machine Direction of the Fabrics from different process

RESULTS OF TESTING EXTENSIBILITY IN CROSS DIRECTION – FAST 3

TABLE 5.31, Extensibility (%) at 100 gm/cm in Cross Direction Normalized for Average Weight (gram * 100) of the Fabric (4 X 4 inch area) at each Process

Run Number	As-made Fabrics Original Value	Normalized Ratio	Normalized value of As-made Fabrics	Recalendared Fabrics Original Value	Normalized Ratio	Normalized value of Recalendared Fabrics
1	2.0	0.85	1.71	2.6	0.87	2.25
2	3.5	1.09	3.83	5.2	1.08	5.60
3	7.7	-	-	8.1	-	-
4	20.2	-	-	20.1	-	-
5	0.9	0.83	0.75	2.4	0.82	1.97
6	3.0	1.03	3.10	2.9	1.07	3.09
7	3.1	1.32	4.10	3.3	1.37	4.52
8	8.4	-	-	19.4	-	-
9	1.6	0.81	1.29	6.1	0.80	4.88
10	2.2	1.05	2.30	3.7	1.03	3.82
11	4.5	1.34	6.05	6.2	1.33	8.24
12	11.8	-	-	18.1	-	-
13	1.6	0.95	1.53	2.2	0.95	2.08

** **Normalized Value = Normalized Ratio * Value of the fabric property**

TABLE 5.32, Extensibility (%) at 100 gm/cm in Cross Direction Normalized for Average Weight (gram * 100) of the Fabric (4 X 4 inch area) at each Process**

Run Number	JFO Wash Fabrics	Normalized Ratio	Normalized value of Jet (JFO) Wash Fabrics	Hydro-entangled Fabrics	Normalized Ratio	Normalized value of Hydro-entangled Fabrics
1	7.6	0.88	6.68	21.5	0.88	20.87
2	9.5	1.12	10.59	21.5	1.09	26.69
3	19.7	-	-	21.5	-	-
4		-	-		-	-
5	6.5	0.82	5.32	18.0	0.83	16.91
6	8.6	1.03	8.87	21.5	1.05	25.35
7	8.2	1.35	11.09	21.5	1.38	36.28
8	19.9	-	-	21.5	-	-
9	7.4	0.80	5.92	13.4	0.78	12.32
10	7.6	1.02	7.78	21.5	1.01	24.81
11	8.7	1.29	11.23	21.5	1.30	31.91
12	15.4	-	-	21.5	-	-
13	6.5	0.97	6.29	21.0	0.96	23.05

** **Normalized Value = Normalized Ratio * Value of the fabric property**

For As-made Fabrics, Original Value of Extensibility (%) in Cross Direction:

- The extensibility (%) in cross direction is higher than the extensibility (%) in machine direction for all of the as-made fabrics except fabric Run 1, 5, 9 and 13. These fabrics have fabric weight 78.25, 80.71, 82.93 and 70.01 gram/cm^2 respectively. For these fabrics, the values of extensibility in both the directions are very similar, which indicates the isotropic structure of these fabrics.
- The extensibility value is very high for fabric Run 4, 12, 8 and 3, which is 20.2 %, 11.8 %, 8.4 % and 7.7 % respectively. These fabrics are of 32.27, 33.03, 33.90 and 46.97 gram/cm^2 fabric weight respectively. Thus, these fabrics have fewer fibers per unit area

compared to the fabrics having fabric weight 60 to 80 gram/cm^2 and therefore, they allow ease of fiber movement in the fabric structure when low loads are applied.

For Recalendared Fabrics, Original Value of Extensibility (%) in Cross Direction:

- The extensibility in cross direction is higher than the extensibility in machine direction for all of recalendared fabrics.
- The surprising fact is the value of the extensibility (%) in cross direction after recalendaring is increased over the value of the extensibility under 100 gram/cm load for as-made fabrics.

For Jet Washed Fabrics, Original Value of Extensibility (%) in Cross Direction:

- The extensibility value (%) in cross direction after the washing treatment is very high compare to the value measured from as-made and recalendared fabrics under 100 gram/cm load. This is because, during washing treatment, 23 to 28 % out of 30 % of the Exceval™ from the fabrics is removed. This results in approximately 23 to 28 % reduction of the total fabric weight of the washed fabrics and thus makes the fabric structure relatively loose compared to the as-made and recalendared fabrics.
- In addition, the extensibility of the jet washed fabrics in cross direction is much higher than the extensibility in machine direction.

From the normalized values of the extensibility in cross direction of the fabrics, an average was calculated for each denier per filament fabrics and further analysis was done by plotting chart from summary **Table 5.36.** The chart is illustrated in **Figure – 5.15**. It was necessary to normalize the extensibility values for the average fabric weight of the fabrics, so that a comparison can be made between fabrics of different denier per filament and of different processes. The value of the normalized ratio is shown in the **Table 5.8.**

TABLE 5.33, Summary of Normalized Average Extensibility (%) at 100 gm/cm in Cross Direction for each process

denier per filament	As-made Fabrics	Recalendared Fabrics	Jet (JFO) Wash Fabrics	Hydroentangled Fabrics
1	1.5	2.1	6.3	20.3
1.5	3.2	5.6	8.3	20.1
2	2.7	3.2	8.4	22.4
2.5	2.8	3.9	8.6	21.2

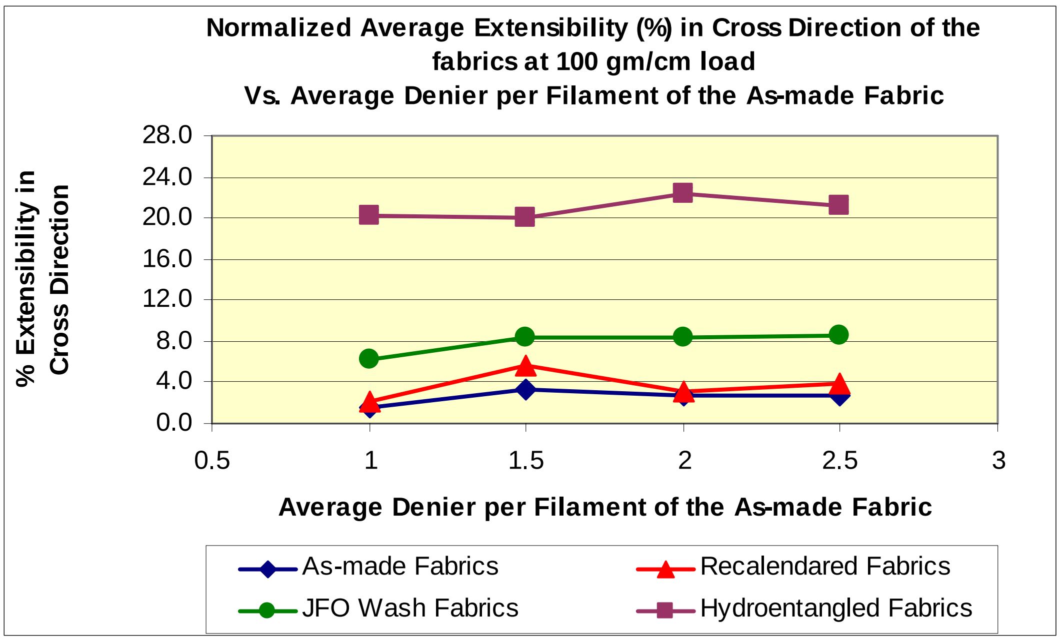


FIGURE 5.16, Comparison of the Normalized Average Extensibility in Cross Direction of the Fabrics from different process

- The average extensibility in cross direction is higher than the average extensibility in the machine direction for all fabrics of each process and each denier per filament.
- For each denier per filament fabric, the percentage extensibility in cross direction is higher for recalendared fabrics than the as-made fabrics and the extensibility (%) is higher for the jet washed fabrics than the recalendared fabrics.

- The extensibility (%) is very high after washing the fabrics in Jet Dyeing Machine. This is obviously due to the Exceval^{TM} removal from the bicomponent configuration of the fibers which makes jet washed fabric structure very loose.
- For hydroentangled fabrics, the extensibility (%) is the maximum and this is because the thermal bonds are completely removed from the hydroentangled fabrics. Thus, when load is applied the fibers extend, as they are continuous filaments. This is the characteristic of the spunbond nonwoven that contains continuous filaments in the fabrics.

RESULTS OF TESTING SHEAR RIGIDITY – FAST 3

TABLE 5.34, Average Shear Rigidity Normalized for Average Weight (gram * 100) of the Fabric (4 X 4 inch area) at each Process

Run Number	As-made Fabrics Original Shear Rigidity	Normalized Ratio	Normalized Shear Rigidity	Recalendared Fabrics Original Shear Rigidity	Normalized Ratio	Normalized Shear Rigidity
1	615000	0.85	525450	615000	0.87	532688
2	615000	1.09	673347	615000	1.08	662851
5	3675	0.83	3044	615000	0.82	504177
6	615000	1.03	636333	615000	1.07	655458
7	923	1.32	1221	615000	1.37	843169
9	1842	0.81	1484	615	0.80	492
10	671	1.05	701	7307	1.03	7536
11	369	1.34	496	351	1.33	466
13	1475	0.95	1408	615000	0.95	581358

** **Normalized Value = Normalized Ratio * Value of the fabric property**

TABLE 5.35, Average Shear Rigidity Normalized for Average Weight (gram * 100) of the Fabric (4 X 4 inch area) at each Process**

Run Number	Jet (JFO) Wash Fabrics Original Shear Rigidity	Normalized Ratio	Normalized Shear Rigidity	Hydro-entangled Fabrics Original Shear Rigidity	Normalized Ratio	Normalized Shear Rigidity
1	3675	0.88	3232	7307	0.88	6435
2	3672	1.12	4094	2452	1.09	2671
5	615000	0.82	503216	3675	0.83	3062
6	7307	1.03	7534	738	1.05	773
7	615000	1.35	831704	2453	1.38	3383
9	819	0.80	655	2453	0.78	1924
10	1474	1.02	1509	1841	1.01	1864
11	308	1.29	397	273	1.30	355
13	615000	0.97	594977	7307	0.96	7048

** **Normalized Value = Normalized Ratio * Value of the fabric property**

The Comparison of the Original Values of the Shear Rigidity (N/m) of the fabrics for Different Processes:

- The fabrics that are inextensible in the bias direction have highest value of the shear rigidity, that is 615000.0 N/m calculated by the software. From the original value of the as-made fabrics, it is clear that the as-made fabric Run 1, 2 and 6 are inextensible in bias direction.
- For re-calendared fabrics, most of the fabrics are inextensible in bias direction except fabric Run 9, 10 and 11. In the re-calendared fabrics, the bonds are holding the fibers together and thus restrict the fiber movement and thus, extension. That is the reason why most of these fabrics are inextensible. However, the fabric Run 9, 10 and 11 show extensibility and here, the positions of the bonds could be a reason for this behavior.

- The original values of the shear rigidity for most of the jet washed fabrics indicate that the jet washed fabrics are extensible in bias direction. However, the fabric Run 5, 7 and 13 have the maximum value calculated by the software and it is clear that these fabrics are not extensible in the bias direction. The surprising fact is all these three fabrics are of more or less similar weight.
- All of the hydroentangled fabrics are extensible in bias direction. The shear rigidity value is not too low but it is not the maximum either. It is between 273 to 3675 N/m. However, for the nonwoven fabrics, this range of measured values is acceptable.

The average shear rigidity was calculated for each denier per filament fabric and for each process so that an overall comparison can be made.

TABLE 5.36, Summary of Normalized Average Shear Rigidity of the fabrics for each process

denier per filament	As-made Fabrics	Recalendared Fabrics	Jet (JFO) Wash Fabrics	Hydroentangled Fabrics
1	1409	581358	594977	7048
1.5	894	2832	854	1381
2	213533	667601	447485	2406
2.5	599399	597770	3664	4553

- The value of the shear rigidity should be higher for the re-calendared fabrics than the as-made fabrics due to fusing the fibers together and restricting their movement. This trend can be observed for the measured average shear rigidity of the as-made and re-calendared fabrics.
- During washing treatment, due to Exceval^{TM} removal the fabric structure becomes loose and thus, the shear rigidity should decrease compare to the re-calendared fabrics. This can be observed for the 1.5, 2 and 2.5 denier per filament fabrics. However, for the 1 denier per filament fabrics the value is increased. The main factor influencing this result is the positions of the bonds placed on fabric Run 13. In addition, the average value of the 1 denier per filament washed fabrics is from only one sample.

- Hydroentangling resulted in decreasing the average shear rigidity for the 1 and the 2 denier per filament fabrics compare to the jet washed fabrics. However, the value is increased for the 1.5 and 2.5 denier per filament fabrics.
- The average shear rigidity of the hydroentangled fabric is less than the re-calendared fabrics for all four fiber sizes.

5.6 Tensile Testing:

Tensile testing was performed on MTS sintech Universal Tensile Tester at North Carolina State University to analyze tensile properties of the re-calendared fabrics, washed fabrics and the hydroentangled fabrics. **Figure 5.17,** shows two pictures of the CRE type (Constant Rate of Extension) tensile tester used in this research. The testing procedure and the specifications were selected according to ASTM standard D 5035 – 95 - Strip Method. In Strip tensile testing, the full width of the fabric is gripped in the clamps therefore the sample size and the clamp size were selected accordingly.

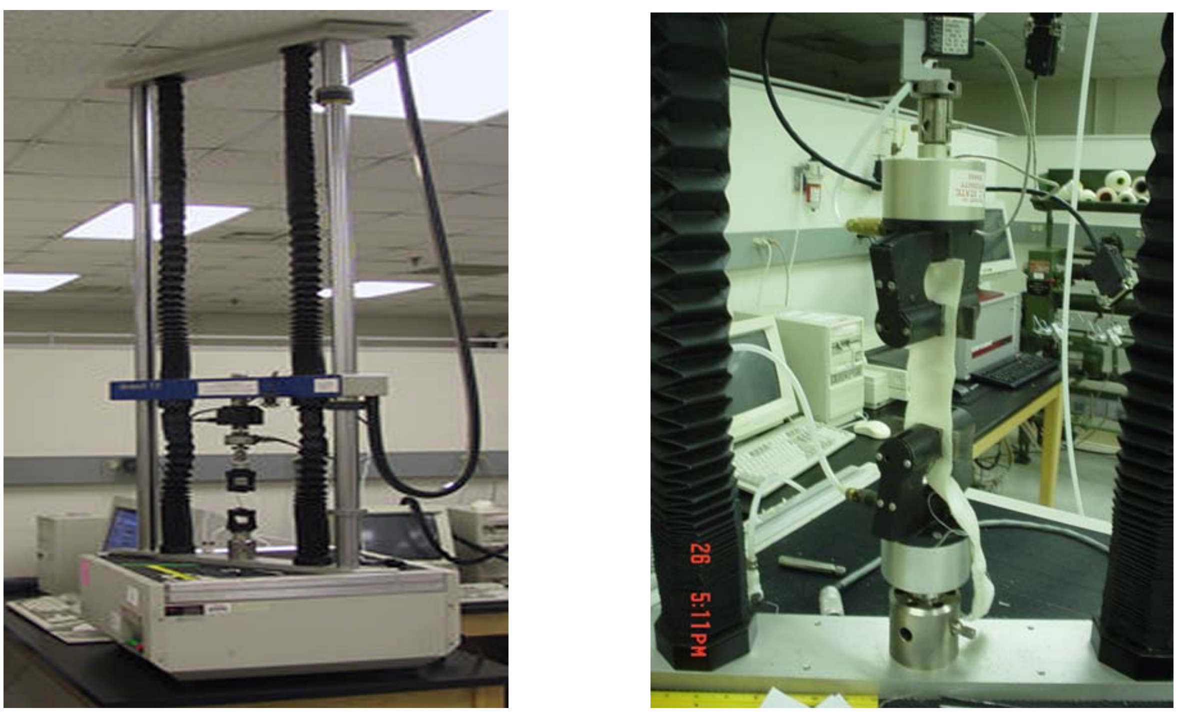


FIGURE 5.17, MTS Sintech Universal Tensile Tester

The samples of 6” X 2” (length X width) dimensions were tested on tensile testing machine using a 250N load cell and 90 % break sensitivity. The samples were tested for evaluating tensile properties in both machine and cross direction. The test gauge length used was 3” and the samples were pneumatically clamped by rubber jaws of 2.5”x 1.5”size. The additional specifications of the tensile testing were; initial speed = 6 inch/minute, secondary speed = 12 inch/minute, load limit Hi = 250 N and speed change point = 10%.

For the re-calendared and jet washed, time limit to break the sample was 20 seconds, while for the hydroentangled fabrics, the time limit to break the fabric sample used was 40 seconds. The results obtained from the tensile tester were exported using the software TestWorks version 3.10 into Excel to calculate outputs and make relevant graphs for detailed analysis. The results obtained are shown in the **Appendix C, Table C.1 to C.4** for re-calendared fabrics, **Table C.5 to C.8** for jet washed fabrics and **Table C.9 to C.12** for the hydroentangled fabric. TestWorks software was also used to calculate the average value of the samples for each fabric run in machine as well as cross direction. Further, an average was determined for each denier per filament to compare the results of tensile testing using the same software.

Table 5.37, Comparison of the Peak Load and Elongation at Peak Load (inch) for the fabrics in Machine as well as Cross Direction

	Peak Load (lb)			Elongation at Peak Load (inch)		
Average	Re-calendared	Jet Washed	Hydro-entangled	Re-calendared	Jet Washed	Hydro-entangled
Run1-MD	19.4	6.2	32.1	0.94	0.40	3.47
Run1-CD	10.1	3.3	11.2	0.78	0.82	4.29
Run2-MD	12.5	5.1	22.3	0.7	0.33	2.34
Run2-CD	5.1	2.9	7.4	0.7	0.7	3.88
Run3-MD	9.9	2.7	15.9	0.74	0.29	1.82
Run3-CD	2.9	1.3	5.0	0.72	0.75	5.19
Run5-MD	21.0	12.9	33.9	0.66	0.85	3.59
Run5-CD	11.6	7.9	15.1	0.76	1.16	4.81
Run6-MD	15.5	8.3	30.2	1.03	0.74	3.41
Run6-CD	6.9	4.3	10.6	0.73	1.08	4.35
Run7-MD	12.6	5.6	21.1	0.73	0.39	2.7
Run7-CD	4.3	3.5	6.5	0.87	1.04	3.45
Run8-MD	9.2	2.4	16.6	0.36	0.35	1.72
Run8-CD	1.7	0.7	2.4	1.18	1.00	3.6
Run9-MD	31.8	18.8	38.9	1.1	1.44	3.8
Run9-CD	16.9	14.2	18.3	0.99	1.63	5.32
Run10-MD	20.6	17.7	28.3	1.17	1.49	2.93
Run10-CD	11.1	8.9	15	1.01	1.32	5.84
Run11-MD	14.6	12.6	23.2	1.08	1.31	2.85
Run11-CD	9.4	7	8.8	0.99	1.28	4.46
Run12-MD	9.5	8	15.9	0.58	0.86	1.78
Run12-CD	3.4	3.3	3.4	0.96	1.26	2.85
Run13-MD	24.2	12.9	33.2	0.86	0.86	2.98
Run13-CD	10.9	6.1	12.7	0.51	0.81	4.71

The Comparison of the Original Values of the Peak Load (lbs) of the fabrics for Different Processes from the Table 5.37:

- For each fabric Run and each denier per filament fabrics, the average peak load in machine direction is higher than the average peak load in the cross direction.
- The value of peak load for the re-calendared fabric Runs is higher than the values obtained from the jet washed fabrics of the corresponding Run number. This is an expected result, as during washing treatment, the Exceval™ is removed and 23 to 28 % reduction in the fabric weight occurred. This makes fabric structure loose and also due to the mechanical action of the jets, the bonds are weakened in the washed fabrics compared to the re-calendared fabrics.
- The peak load of each hydroentangled fabric is higher than the jet washed fabrics as well as the re-calendared fabrics. After washing, the jet washed fabrics have higher number of the fibers per unit area than the re-calendared fabrics due to the Exceval™ removal. However, because of the mechanical action of the water jets, the bonds in the fabrics are weakened and the fabric structure is very open. That is why the peak load for the jet washed fabrics is very low compared to the re-calendared and hydroentangled fabrics. While, during hydroentangling, the fibers are entangled together and this increases the fabric strength.

The Comparison of the Original Values of the Elongation at Peak Load (Inch) of the fabrics for Different Processes:

- The values of elongation at peak load, for the hydroentangled fabrics are higher than the values measured from the re-calendared and jet washed fabrics in both machine as well as cross direction. This is because the bonds are removed from the hydroentangled fabrics, which allows the free fiber movement. In addition, spunbond fabrics are made of continuous filaments so when load is applied they have tendency to extend in length.
- The values measured from testing the re-calendared fabrics in machine direction have higher values than that of the jet washed fabrics except the fabric Run 5, 9, 10, 11 and 12. While, the elongation at peak load in cross direction is high for the jet washed fabrics compared to the re-calendared fabrics except the fabric Run 8.

From the original values, the average peak load and the elongation at peak load were calculated for each process and for each fiber size.

Table 5.38, Average Peak Load (lb) in Machine and Cross Direction - Original Values

	Machine Direction			Cross Direction		
Average Denier per Filament	Re-calendared Fabrics	Jet (JFO) Washed Fabrics	Hydro-entangled Fabrics	Re-calendared Fabrics	Jet (JFO) Washed Fabrics	Hydro-entangled Fabrics
1.00	24.2	12.9	33.2	10.9	6.1	12.7
1.50	22.1	16.3	28.6	12.4	9.8	13
2.00	15.3	8.1	26	7.5	5.2	10.4
2.50	15.7	5.4	25.6	7.6	3.1	9

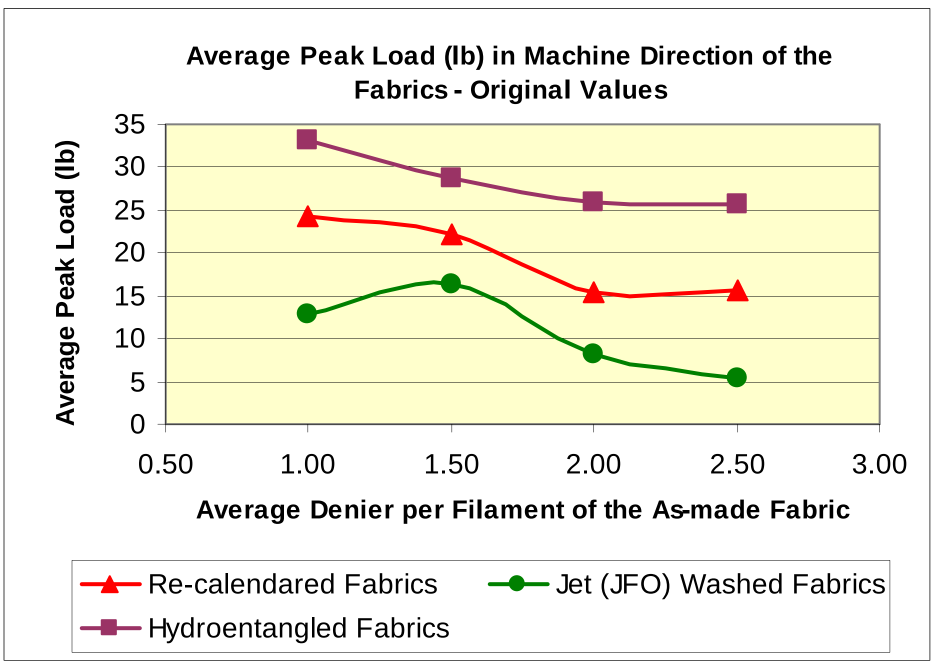


FIGURE 5.18, Average Peak Load in Machine Direction of the Fabrics –Original Values

- It is clear from **Table 5.38** as well as the chart that the average peak load values are high for the hydroentangled fabrics in both directions compared to the re-calendared and jet washed fabrics.
- The jet washed fabrics have lower average peak loads compare to the other two fabrics for all four fiber sizes.
- The trend of increase and decrease in the values is similar for all three fabrics.

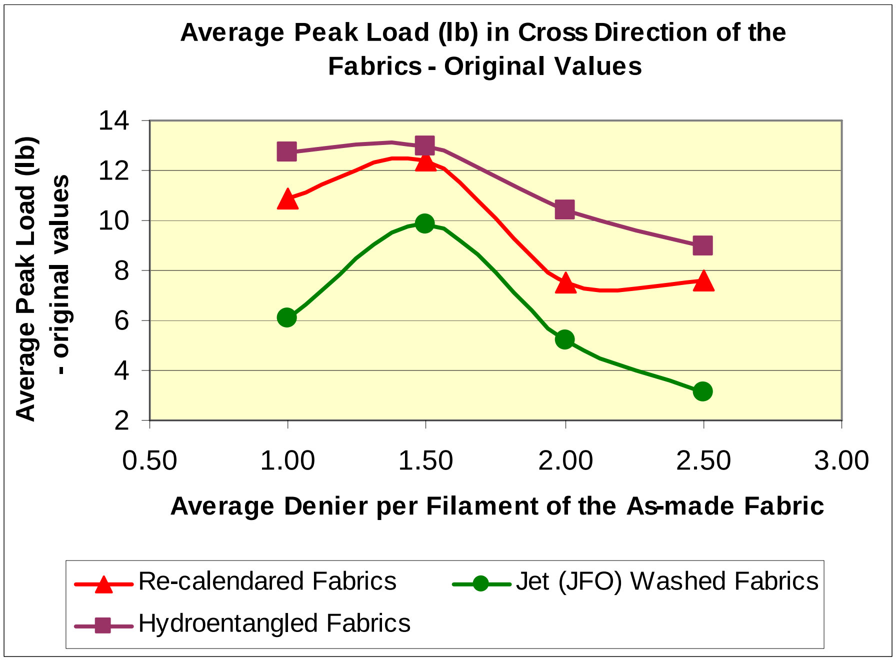


FIGURE 5.19, Average Peak Load in Cross Direction of the Fabrics –Original Values

- The average peak load of the hydroentangled fabrics in cross direction is higher than the recalendared and jet washed fabrics for all fiber sizes.
- The recalendared fabrics show higher peak load compare to washed fabrics however, lower than the hydroentangled fabrics.

Further, the original values of the elongation at peak load were also analyzed for both the directions.

Table 5.39, Average Elongation at Peak Load (Inch) in Machine and Cross Direction - Original Values

	Machine Direction			Cross Direction		
Average Denier per Filament	Re-calendared Fabrics	Jet (JFO) Washed Fabrics	Hydro-entangled Fabrics	Re-calendared Fabrics	Jet (JFO) Washed Fabrics	Hydro-entangled Fabrics
1.00	0.86	0.86	2.98	1.07	0.81	4.71
1.50	1.12	1.42	2.85	0.99	1.41	5.2
2.00	0.75	0.74	2.71	0.77	1.05	4.36
2.50	0.77	0.33	2.68	0.7	0.74	3.89

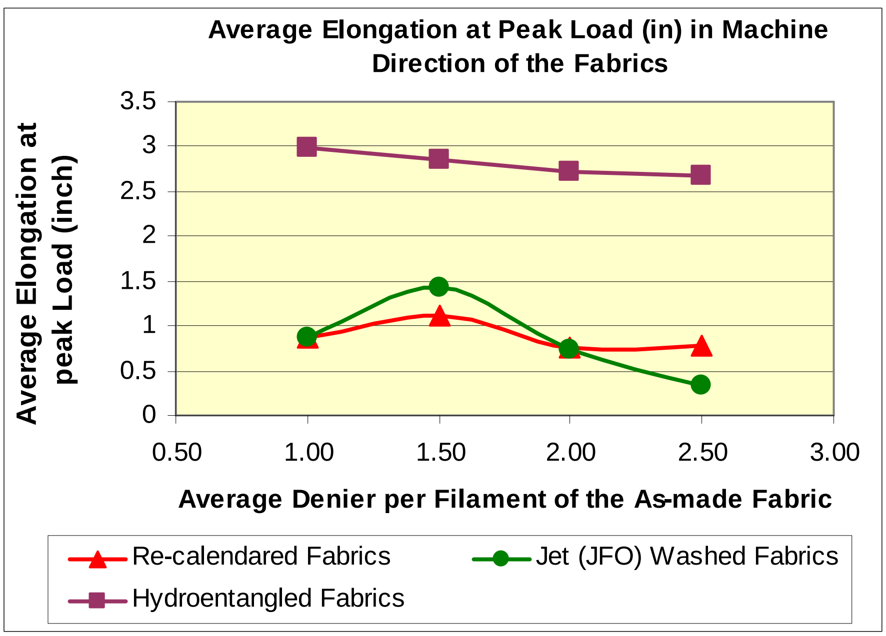


FIGURE 5.20, Average Elongation at Peak Load in Machine Direction of the Fabrics – Original Values

- It is obvious from the graph that the hydroentangled fabrics have very high elongation at the peak load in machine direction of the fabrics. The values are around 300 % higher than the values measured from the re-calendared and the jet washed fabrics.

- The 1, 1.5 and 2 denier per filament re-calendared fabrics show less or equal amount of elongation at peak load compare to the jet washed fabrics, except the 2.5 denier per filament fabrics. This outcome represents the original values and the reason behind getting higher elongation for the 2.5 denier per filament re-calendared fabrics could be due to the fabric Run 3 and 4. These two fabrics are very irregular and thus, it introduces some amount of error here.

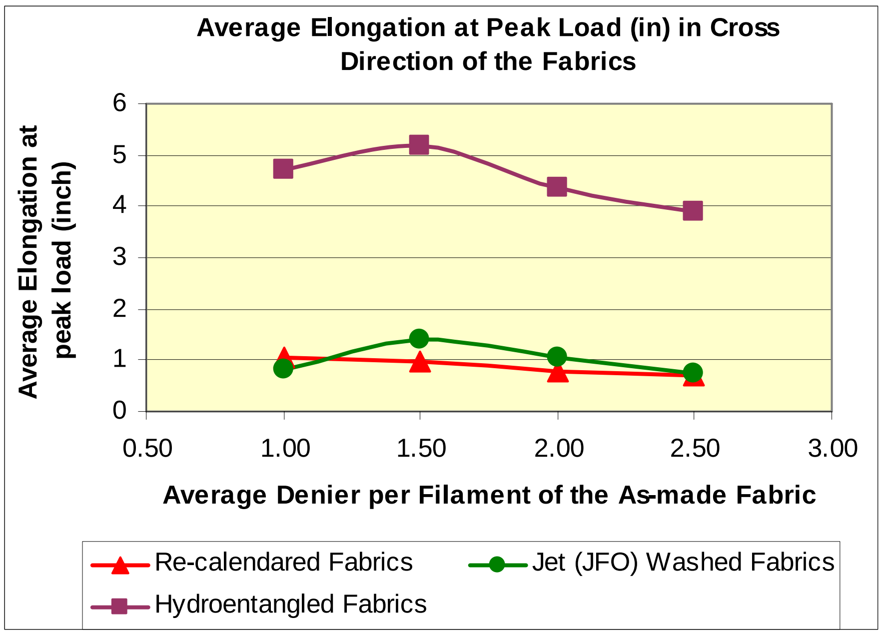


FIGURE 5.21, Average Elongation at Peak Load in Cross Direction of the Fabrics – Original Values

- Similar to the machine direction results, the elongation at peak load in cross direction of the hydroentangled fabrics is highest than the re-calendared and jet washed fabrics.
- The values obtain for the re-calendared and jet washed fabrics are very close to each other.

From the original values of the average peak load, the normalized values were calculated by multiplying the original values with the normalized ratio. The normalized ratio is illustrated in **Table 5.8.**

Table 5.40, Comparison of the Average Peak Load (lb) for the re-calendared, jet washed and hydroentangled fabrics in Machine Direction – Original and Normalized values

	Re-calendared Fabrics			Jet Washed Fabrics			Hydroentangled Fabrics		
Sample I.D.	Peak Load (Lb)	Norma-lized Ratio	Norma-lized Peak Load	Peak Load (Lb)	Norma-lized Ratio	Norma-lized Peak Load	Peak Load (Lb)	Norma-lized Ratio	Norma-lized Peak Load
Run1	19.40	0.87	16.80	6.2	0.88	5.45	32.1	0.88	28.27
Run2	12.50	1.08	13.47	5.1	1.12	5.69	22.3	1.09	24.29
Run5	21.00	0.82	17.22	12.9	0.82	10.56	33.9	0.83	28.25
Run6	15.50	1.07	16.52	8.3	1.03	8.56	30.2	1.05	31.64
Run7	12.60	1.37	17.27	5.6	1.35	7.57	21.1	1.38	29.11
Run9	31.80	0.80	25.44	18.8	0.80	15.04	38.9	0.78	30.51
Run10	20.60	1.03	21.25	17.7	1.02	18.12	28.3	1.01	28.66
Run11	14.60	1.33	19.39	12.6	1.29	16.27	23.2	1.30	30.22
Run13	24.20	0.95	22.88	12.9	0.97	12.48	33.2	0.96	32.02

The comparison of the average peak load was made for each denier per filament fabrics and for each process; it is shown in **Table 5.41**. Fabric Run 3, 4, 8 and 12 are not included in calculating the average values due to possible errors related with these fabrics, since they are very irregular in appearance and of low fabric weight.

- It is clear from the summary table, that the normalized values show a very similar trend to the original values. The peak load of the hydroentangled fabrics is the highest compared to the re-calendared and jet washed fabrics.
- The jet washed fabrics were measured to have low peak load compared to the re-calendared and hydroentangled fabrics.

Table 5.41, Summary of the Normalized Average Peak Load (lb) in Machine Direction of the Fabrics

Average Denier per Filament of the Fabric	Recalendared Fabrics	Jet (JFO) Wash Fabrics	Hydroentangled Fabrics
1	22.88	12.48	32.02
1.5	22.03	16.48	29.80
2	17.00	8.90	29.66
2.5	15.14	5.57	26.28

Further, a chart was plotted to visualize the change in the normalized values of the average peak load for each process as shown in **Figure 5.22.**

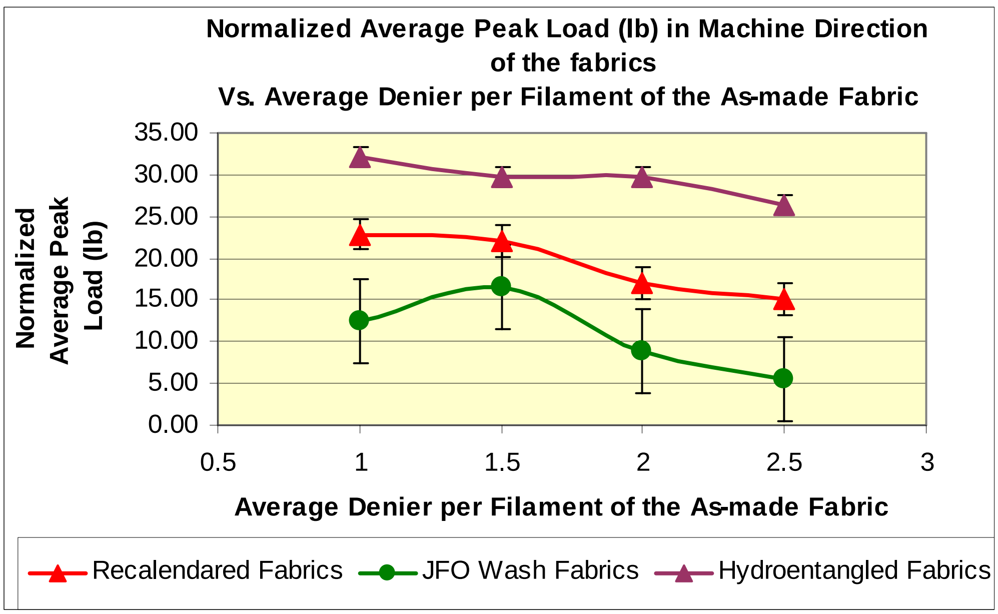


FIGURE 5.22, Normalized Average Peak Load (lb) in Machine Direction

- It is clear from the graph that the average peak load of the hydroentangled fabrics is higher than the re-calendared and the jet washed fabrics. While, the average peak load of the re-calendared fabrics is higher than the jet washed fabrics.
- The hydroentangled fabrics show very high increase in the peak load compare to the jet washed fabrics. The increase in the peak load between these two processes is around 200 to 500%.

- The increase in the average peak load between the re-calendared and hydroentangled fabrics is around 80 to 250 %.

Table 5.42, Comparison of the Average Peak Load (lb) for the re-calendared, jet washed and hydroentangled fabrics in Cross Direction – Original and Normalized values

	Re-calendared Fabrics			Jet Washed Fabrics			Hydroentangled Fabrics		
Sample I.D.	Peak Load (Lb)	Norma-lized Ratio	Norma-lized Peak Load	Peak Load (Lb)	Norma-lized Ratio	Norma-lized Peak Load	Peak Load (Lb)	Norma-lized Ratio	Norma-lized Peak Load
Run1	10.10	0.87	8.75	3.3	0.88	2.90	11.2	0.88	9.86
Run2	5.10	1.08	5.50	2.9	1.12	3.23	7.4	1.09	8.06
Run5	11.60	0.82	9.51	7.9	0.82	6.46	15.1	0.83	12.58
Run6	6.90	1.07	7.35	4.3	1.03	4.43	10.6	1.05	11.11
Run7	4.30	1.37	5.90	3.5	1.35	4.73	6.5	1.38	8.97
Run9	16.90	0.80	13.52	14.2	0.80	11.36	18.3	0.78	14.36
Run10	11.10	1.03	11.45	8.9	1.02	9.11	15	1.01	15.19
Run11	9.40	1.33	12.49	7	1.29	9.04	8.8	1.30	11.46
Run13	10.90	0.95	10.30	6.1	0.97	5.90	12.7	0.96	12.25

From the normalized values, the average peak load in cross direction of the fabrics for each process was calculated and shown in the summary **Table 5.43.**

Table 5.43, Summary of the Normalized Average Peak Load (lb) in Cross Direction of the Fabrics

Average Denier per Filament of the Fabric	Recalendared Fabrics	Jet (JFO) Wash Fabrics	Hydroentangled Fabrics
1	10.30	5.90	12.25
1.5	12.49	9.84	13.67
2	7.59	5.21	10.88
2.5	7.12	3.07	8.96

- The peak load of the fabrics is reduced after the washing treatment and this is because 23 to 28 % out of 30 % of Exceval™ is removed from the fabrics.
- For hydroentanglement fabrics, the average peak load is higher than the values obtained for the recalendared fabrics of the corresponding fiber sizes.
- The percentage increase in the average peak load in cross direction is less than the increase in machine direction between the jet washed and hydroentangled fabrics.

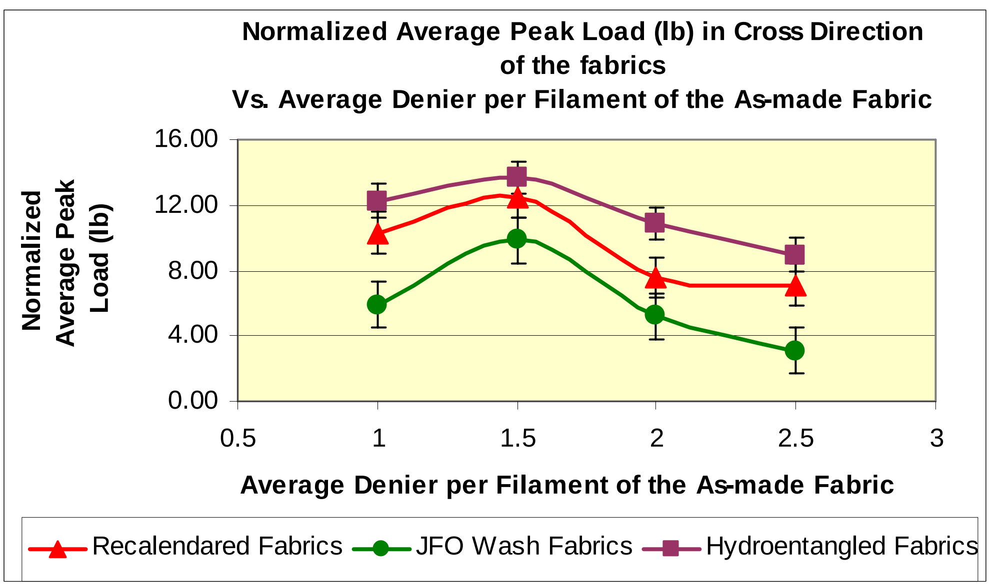


FIGURE 5.23, Normalized Average Peak Load (lb) in Cross Direction

CHAPTER - 6
CONCLUSIONS AND FUTURE WORK

6.1 Conclusions:

- Microfiber nylon spunbonds are feasible to produce using this research approach.
- It is practically possible to spin Nylon and Exceval (water-dispersive polymer) in Solid Sixteen Segmented Pie bicomponent configuration.
- Lower basis weight spunbonds (< 40 gram/meter^2) are very irregular.
- Exceval^{TM} can be removed feasibly from the Exceval^{TM} based bicomponent spunbond nonwovens during washing treatment with water in Jet Dyeing Machine at 85^{0}C temperature. Further, the suggested machine for the Exceval^{TM} removal is Jet Dyeing Machine out of Paddle Washer, Skein Dyeing Machine and Jet Dyeing Machine.
- The Jet Dyeing Machine is efficient in removing Exceval^{TM} from the bicomponent spunbonds having basis weight in the range of 33 to 83 gram/meter^2. However, the water flow capacity and the actual washing time of the fabrics are required to be optimized according to the fiber size and the basis weight of the fabric.
- The calendar bonds made at 140^{0}C temperature and 435 PLI (pounds per linear inch) calendaring pressure can be removed completely from the Nylon/Exceval spunbond nonwovens after hydroentanglement, if proper calendaring temperature, washing conditions and hydroentanglement setting are used.
- The hydroentangled fabrics made according to the procedure described in this research were found to have
    - 0.062 to 0.085 mm compressed thickness
    - 23 to 33 mm bending length in machine direction of the fabric
    - 11 to 21 mm bending length in cross direction of the fabric
    - 3.2 to 22.6 µNm bending rigidity in machine direction of the fabric
    - 0.4 to 5.5 µNm bending rigidity in cross direction of the fabric
    - 2.2 to 6 % extensibility in machine direction of the fabric at 100 gram/cm load
    - 13.4 to 21.5 % extensibility in cross direction of the fabric at 100 gram/cm load

- 273 to 7303 shear rigidity of the fabric
- 15.9 to 38.9 lbs peak load in machine direction of the fabric
- 2.4 to 18.3 lbs peak load in cross direction of the fabric
- 1.72 to 3.8 inch elongation at peak load in machine direction of the fabric
- 2.85 to 5.84 inch elongation at peak load in cross direction of the fabric

6.2 Future Work:

- Polymers of higher melting point temperature can be used with Exceval^{TM} for similar kind of research.
- More than Sixteen Segments can be used in Nylon/ Exceval bicomponent configuration to make nylon microfiber spunbonds for similar studies.
- The influence of fiber size on the properties of fabrics of different basis weights can be further studied in detail by creating model for each individual property.
- The influence of percentage Exceval removed from the fabrics on the fabric properties can be studied.
- Additional finishing, dyeing, coating as anti-microbial or self decontamination, etc. can be applied on the hydroentangled fabrics produced according to this research and the influence of fiber diameter as well as higher surface area on the functional properties of these fabrics can be analyzed.

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APPENDICES

APPENDIX A

TABLE A.1, Results of Exceval™ Removal Preliminary Experiment

Jet (JFO) Wash – 85^{0}C, 5 Minutes

Run Number	Fabric Weight (gram * 100) of Samples				Average Fabric Weight	Standard Deviation
5	58.45	60.03	58.60	59.75	59.21	0.80
6	45.27	45.52	46.28	45.12	45.55	0.52
9	60.42	61.20	63.61	61.93	61.79	1.36
10	42.40	50.06	45.85	50.74	47.26	3.90
13	51.78	54.38	51.73	47.06	51.24	3.05

Jet (JFO) Wash - 105^{0}C, 5 Minutes

Run Number	Fabric Weight (gram * 100) of Samples				Average Fabric Weight	Standard Deviation
5	51.02	62.30	56.46	56.65	56.61	4.61
6	45.19	43.98	47.03	48.78	46.25	2.10
9	59.07	65.04	61.42	62.48	62.00	2.48
10	51.41	48.85	46.71	41.55	47.13	4.19
13	52.82	51.60	52.41		52.28	0.62

Jet (JFO) Wash - 125^{0}C, 5 Minutes

Run Number	Fabric Weight (gram * 100) of Samples				Average Fabric Weight	Standard Deviation
5	56.40	57.21			56.81	0.57
6	45.15	44.85	46.14		45.38	0.68
9	51.02	62.81	58.14	61.80	58.44	5.34
10	49.16	42.47	48.45		46.69	3.67
13	52.09	53.17			52.63	0.76

TABLE A.2, Ratio of the Unwashed as-made Fabric Weight to Jet Washed Fabric Weight

Fabric Run Number	Unwashed Samples (gram * 100)	85^0C, 5 Minutes (gram * 100)	Ratio of unwashed samples to JFO Wash	105^0C, 5 Minutes (gram * 100)	Ratio of unwashed samples to JFO Wash	125^0C, 5 Minutes (gram * 100)	Ratio of unwashed samples to JFO Wash
5	80.71	59.21	1.36	56.61	1.43	56.81	1.42
6	64.62	45.55	1.42	46.25	1.40	45.38	1.42
9	82.93	61.79	1.34	62.00	1.34	58.44	1.42
10	63.91	47.26	1.35	47.13	1.36	46.69	1.37
13	70.01	51.24	1.37	52.28	1.34	52.63	1.33

TABLE A.3, Average Fabric Weight (Grams * 100) after washing treatment in Jet Dyeing Machine (JFO) at 85^{0}C and 10 meter/min fabric speed

Fabric Run Number	Water Flow Capacity %	Washing Time in Minutes	Average Basis Weight (gsm) after washing treatment	Standard Deviation σ	% Exceval removed from the fabric	Remark
1	50%	2	54.51	2.53	103.00%	Fabric torn at many places and indicates fiber loss
1	50%	1	54.80	2.20	101.76%	Fabric torn at many places and indicates fiber loss
1	25%	1	56.08	0.69	96.35%	Fabric is in good condition
2	20%	1	44.23	3.99	91.89%	
3	25%	2	33.33	1.64	96.80%	Fabric torn at many places
3	25%	1	33.57	1.20	95.11%	Abrasion at few places on the fabric
3	20%	1	35.90	0.58	78.58%	
4	20%	1	-	-	-	Fabric is not completely torn but it is not possible to measure weight.
5	50%	8	58.40	2.98	92.14%	Fabric torn at many places
5	50%	6	58.38	2.54	92.24%	Fabric torn at many places
5	50%	4	57.83	1.11	94.52%	Fabric torn at many places
5	50%	2	58.20	1.50	92.96%	Sever abrasion on the fabric.
5	25%	2	60.29	2.24	84.36%	Fabric is in good state but abrasion at few places
6	50%	6	46.33	2.04	94.35%	Fabric torn at many places
6	50%	4	46.18	2.14	95.13%	Fabric torn at few places
6	50%	2	48.27	1.28	84.34%	Abrasion on the fabric
6	25%	1	47.84	2.35	86.57%	Fabric is in good condition

TABLE A.4, Average Fabric Weight (Grams * 100) after washing treatment in Jet Dyeing Machine (JFO) at 85^0C and 10 meter/min fabric speed

Fabric Run Number	Water Flow Capacity %	Washing Time in Minutes	Average Basis Weight (gsm) after washing treatment	Standard Deviation σ	% Exceval removed from the fabric	Remark
7	50%	2	35.22	1.21	100.90%	Fabric torn at many places and indicates fiber loss
7	50%	1	35.98	1.55	95.89%	Abrasion at few places on the fabric
7	25%	4	32.14	3.11	121.21%	Fabric torn at many places and indicates fiber loss
7	25%	2	34.58	1.19	105.11%	Fabric torn at many places and indicates fiber loss
7	25%	1	36.48	1.96	92.62%	Fabric is in good condition
8	25%	2	24.33	0.37	94.10%	Abrasion at few places on the fabric
8	20%	1	24.55	0.35	91.93%	
9	50%	12	61.67	0.69	85.47%	Fabric is in good condition.
9	50%	10	62.87	1.77	80.65%	Fabric is in good condition.
10	50%	12	48.17	1.07	82.08%	Fabric is in good condition.
10	50%	10	47.91	0.67	83.46%	Fabric is in good condition.
10	50%	8	47.34	1.83	86.42%	Fabric is in good condition.
11	50%	2	32.14	2.99	117.86%	Fabric torn at many places and indicates fiber loss.
11	50%	1	38.21	1.06	77.18%	Fabric is in good condition.
11	25%	4	32.39	3.64	116.20%	Fabric torn at many places and indicates fiber loss

TABLE A.5, Average Fabric Weight (Grams * 100) after washing treatment in Jet Dyeing Machine (JFO) at 85^{0}C and 10 meter/min fabric speed

Fabric Run Number	Water Flow Capacity %	Washing Time in Minutes	Average Basis Weight (gsm) after washing treatment	Standard Deviation σ	% Exceval removed from the fabric	Remark
11	25%	2	36.40	1.09	89.28%	Fabric is in good condition
12	50%	2	24.74	1.01	83.72%	Abrasion at few places on the fabric
12	50%	1	25.06	0.75	80.49%	Fabric is in apparently good condition.
12	25%	4	23.72	2.30	93.98%	Abrasion at many places on the fabric
12	25%	2	21.73	1.63	114.09%	Fabric torn at many places and indicates fiber loss
13	50%	4	50.38	2.47	93.47%	Fabric torn at many places
13	50%	2	49.78	2.68	96.31%	Fabric torn at many places
13	50%	1	50.70	1.04	91.96%	Abrasion at few places on the fabric
13	25%	1	50.99	3.09	90.57%	Fabric is in good condition

TABLE A.6, Fabric Weight (Grams * 100) after the JFO Wash at 85^{0}C, 50% water Flow Capacity and 10 meter/min fabric speed

Run #	Fabric Washing Time	Average Basis Weight (gsm) after wash	Standard Deviation σ	% Exceval removed from the fabric	Remark
1	2 Minutes	54.51	2.53	103.00%	Fabric torn at many places and indicates fiber loss
1	1 Minute	54.80	2.20	101.76%	Fabric torn at many places and indicates fiber loss
5	8 Minutes	58.40	2.98	92.14%	Fabric torn at many places
5	6 Minutes	58.38	2.54	92.24%	Fabric torn at many places
5	4 Minutes	57.83	1.11	94.52%	Fabric torn at many places
5	2 Minutes	58.20	1.50	92.96%	Sever abrasion on the fabric
6	6 Minutes	46.33	2.04	94.35%	Fabric torn at many places
6	4 Minutes	46.18	2.14	95.13%	Fabric torn at few places
6	2 Minutes	48.27	1.28	84.34%	Abrasion at few places on the fabric
7	2 Minutes	35.22	1.21	100.90%	Fabric torn at many places and indicates fiber loss
7	1 Minute	35.98	1.55	95.89%	Abrasion at few places on the fabric
9	12 Minutes	61.67	0.69	85.47%	Fabric is in good condition
9	10 Minutes	62.87	1.77	80.65%	Fabric is in good condition
10	12 Minutes	48.17	1.07	82.08%	Fabric is in good condition
10	10 Minutes	47.91	0.67	83.46%	Fabric is in good condition
10	8 Minutes	47.34	1.83	86.42%	Fabric is in good condition
11	2 Minutes	32.14	2.99	117.86%	Fabric torn at many places and indicates fiber loss
11	1 Minute	38.21	1.06	77.18%	Fabric is in good condition
12	2 Minutes	24.74	1.01	83.72%	Abrasion at few places on the fabric
12	1 Minute	25.06	0.75	80.49%	Fabric is in good condition.
13	4 Minutes	50.38	2.47	93.47%	Fabric torn at many places
13	2 Minutes	49.78	2.68	96.31%	Fabric torn at many places
13	1 Minute	50.70	1.04	91.96%	Abrasion at few places on the fabric

TABLE A.7, Fabric Weight (Grams * 100) after the JFO Wash at 85^{0}C, 25% water Flow Capacity and 10 meter/min fabric speed

Run #	Washing Time	Average Basis Weight (gsm) after wash	Standard Deviation σ	% Exceval removed from the fabric	Remark
1	1 Minute	56.08	0.69	96.35%	Fabric is in good condition
3	2 Minutes	33.33	1.64	96.80%	Fabric torn at many places
3	1 Minute	33.57	1.20	95.11%	Abrasion at few places on the fabric
5	2 Minutes	60.29	2.24	84.36%	Fabric is in good condition but abrasion at few places.
6	1 Minute	47.84	2.35	86.57%	Fabric is in good condition
7	4 Minutes	32.14	3.11	121.21%	Fabric torn at many places and indicates fiber loss
7	2 Minutes	34.58	1.19	105.11%	Fabric torn at many places and indicates fiber loss
7	1 Minute	36.48	1.96	92.62%	Fabric is in good condition
8	2 Minutes	24.33	0.37	94.10%	Abrasion at few places on the fabric
11	4 Minutes	32.39	3.64	116.20%	Fabric torn at many places and indicates fiber loss
11	2 Minutes	36.40	1.09	89.28%	Fabric is in good condition
12	4 Minutes	23.72	2.30	93.98%	Abrasion at many places on the fabric
12	2 Minutes	21.73	1.63	114.09%	Fabric torn at many places and indicates fiber loss
13	1 Minutes	50.99	3.09	90.57%	Fabric is in good condition

TABLE A.8, Fabric Weight (Grams * 100) after the JFO Wash at 85^0C, 20% water Flow Capacity and 10 meter/min fabric speed

Run Number	Washing Time	Average Basis Weight (gsm) after washing treatment	Standard Deviation σ	% Exceval removed from the fabric	Remark
2	1 Minute	44.23	3.99	91.89%	
3	1 Minute	35.90	0.58	78.58%	
4	1 Minute	-	-	-	Fabric got torn at many places and it is not possible to measure basis weight.
8	1 Minute	24.55	0.35	91.93%	

APPENDIX B

B.1 FTIR Results - Group Spectra: As-made Fabrics and Jet Washed Fabrics

FIGURE 1, Group Spectra of As-made Fabrics – Fabric Run 1 to 6

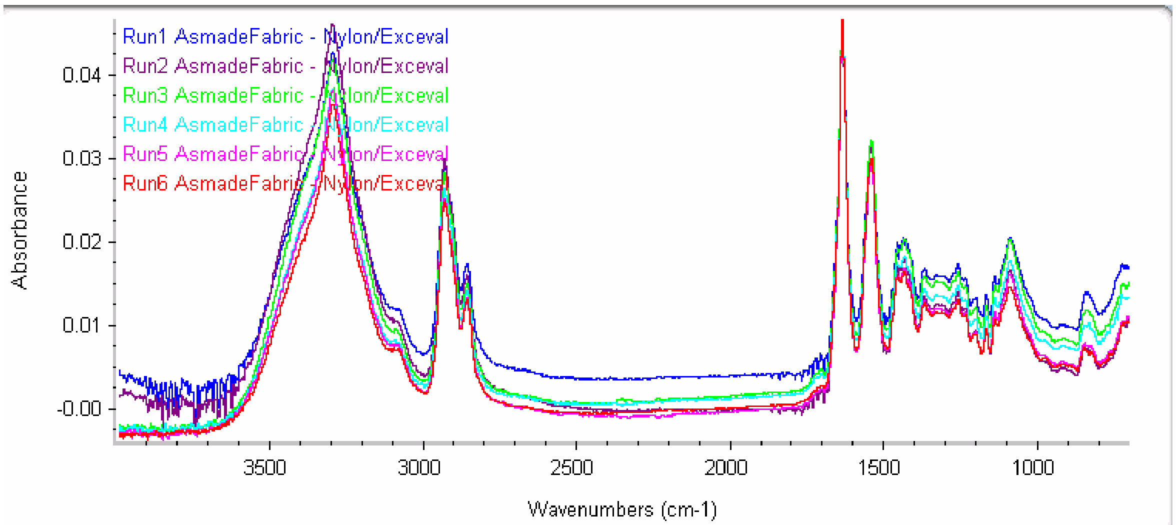


FIGURE 2, Group Spectra of As-made Fabrics – Fabric Run 7 to 13

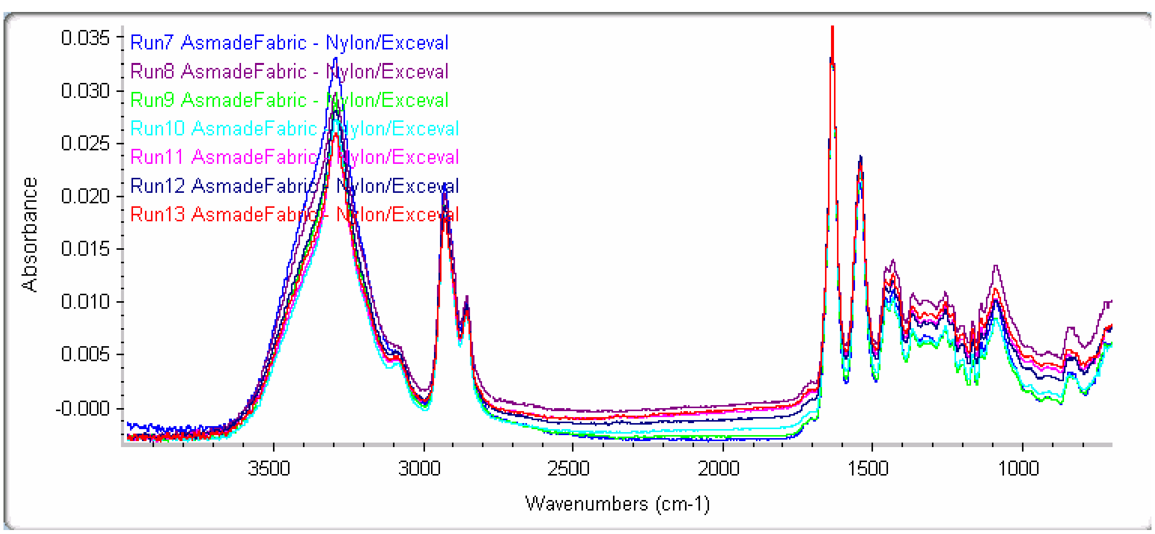


FIGURE 3, Group Spectra of Washed Fabrics – Fabric Run 1 to 7 (except 4)

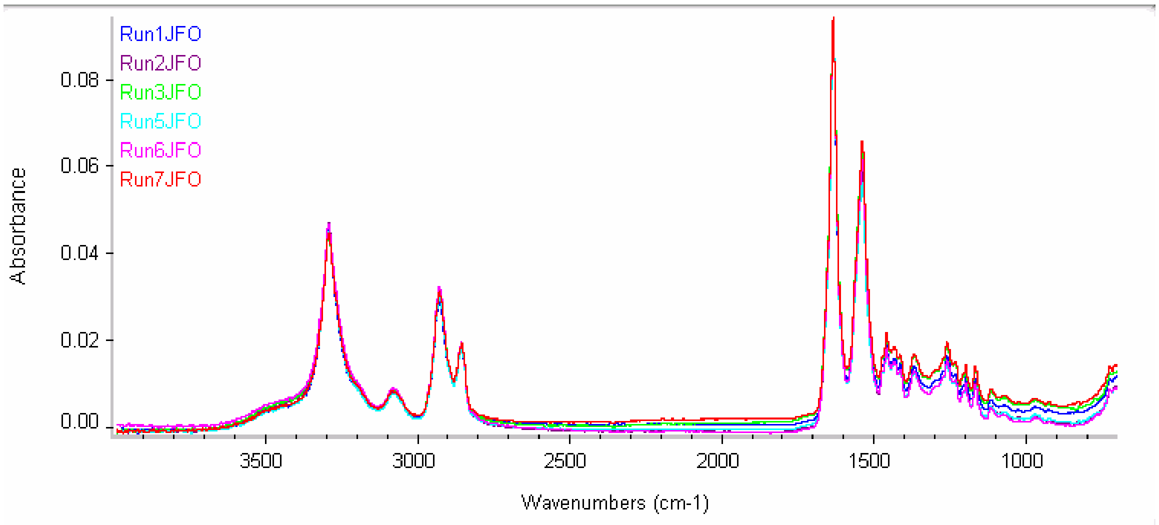
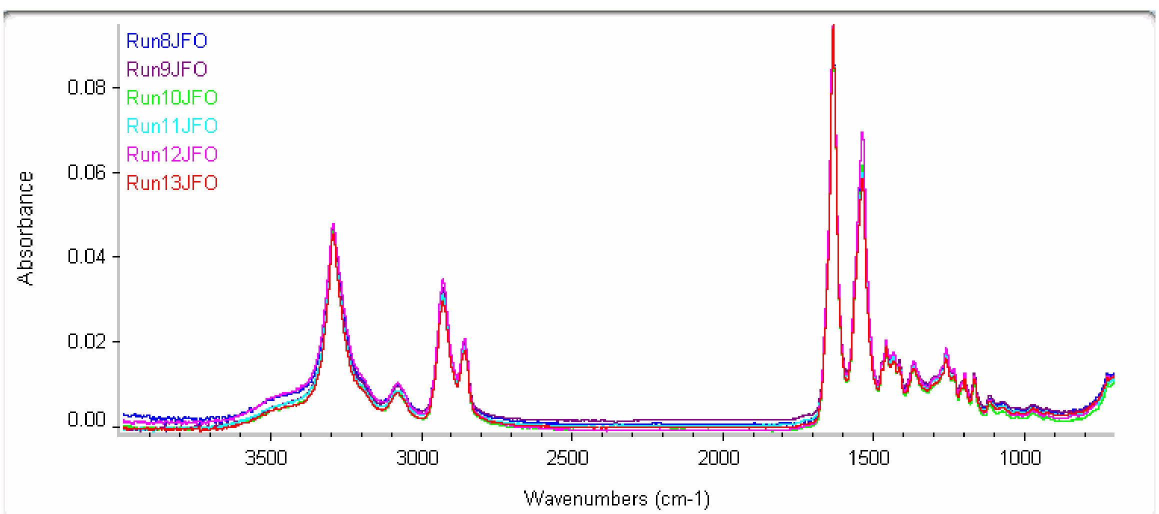


FIGURE 4, Group Spectra of Washed Fabrics – Fabric Run 8 to 13



B.2 FTIR Results - A Comparison of Spectra for each Fabric (Run 1 to13) – As-made bicomponent spunbond fabric, JFO Wash Fabric and Polyamide – 6

FIGURE – 1, A Comparison of Spectra for Fabric Run 1

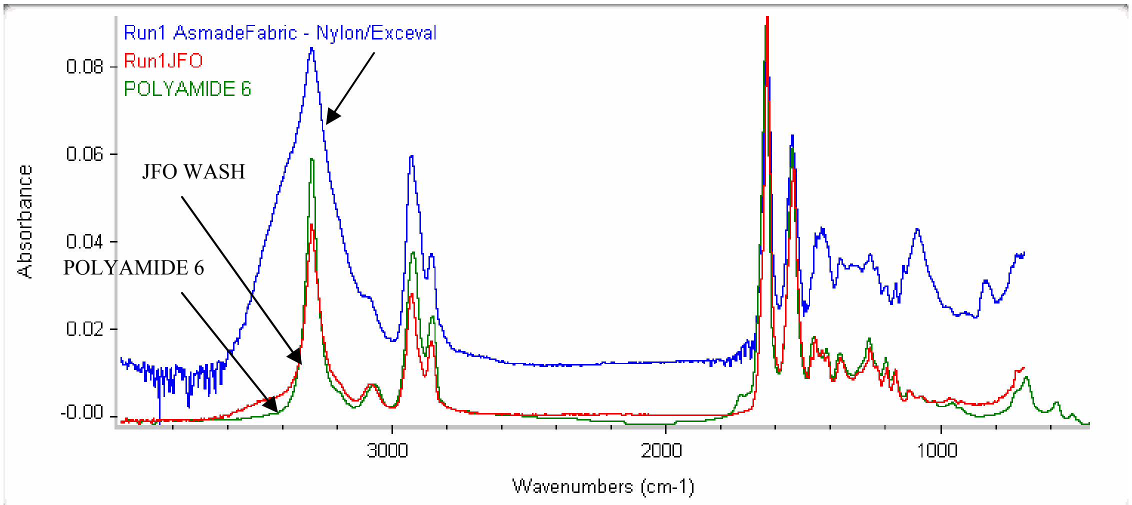


FIGURE – 2, A Comparison of Spectra for Fabric Run 2

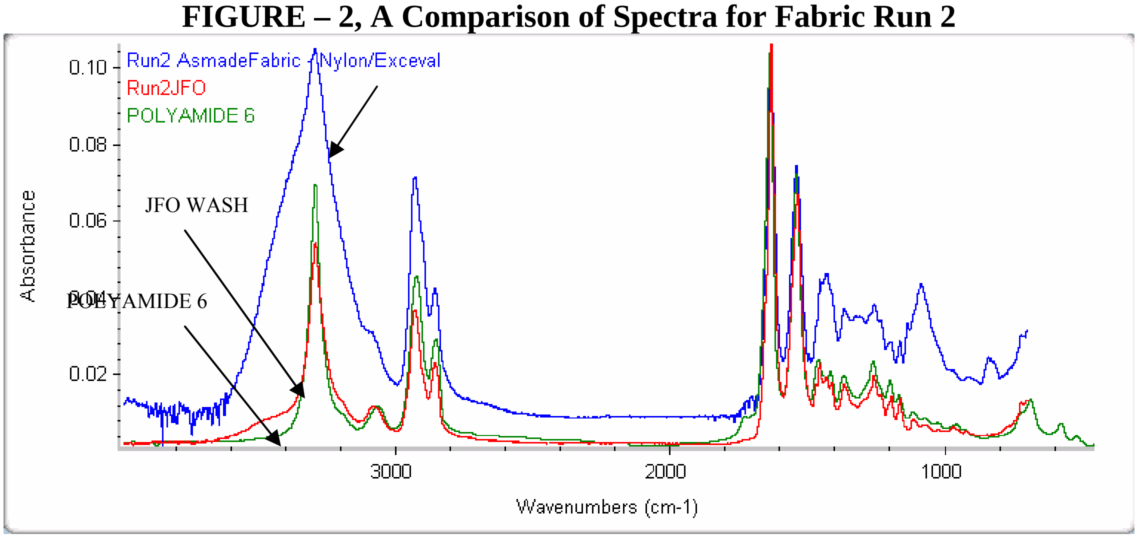


FIGURE – 3, A Comparison of Spectra for Fabric Run 3

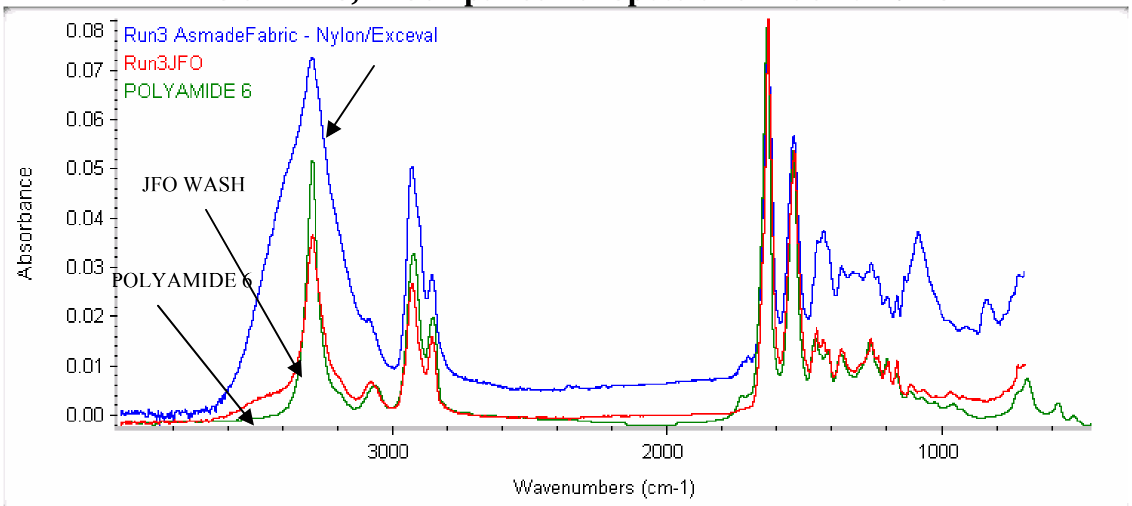


FIGURE – 4, A Comparison of Spectra for Fabric Run 5

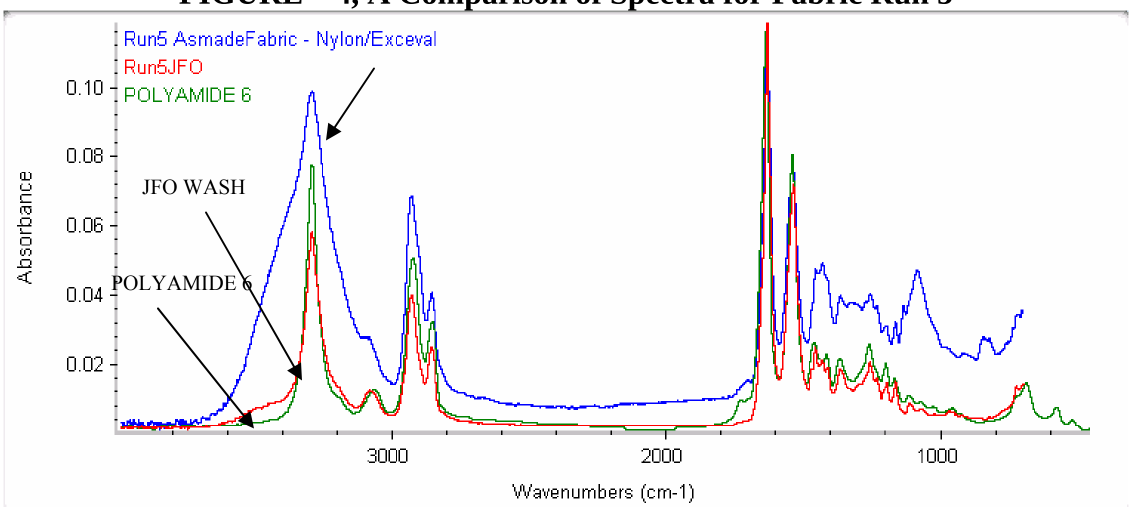


FIGURE – 5, A Comparison of Spectra for Fabric Run 6

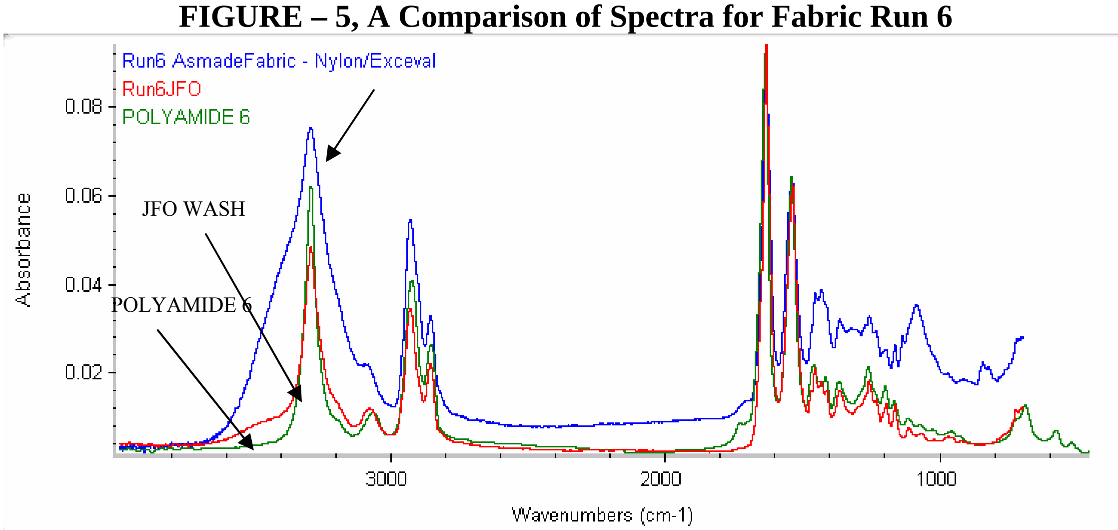


FIGURE – 6, A Comparison of Spectra for Fabric Run 7

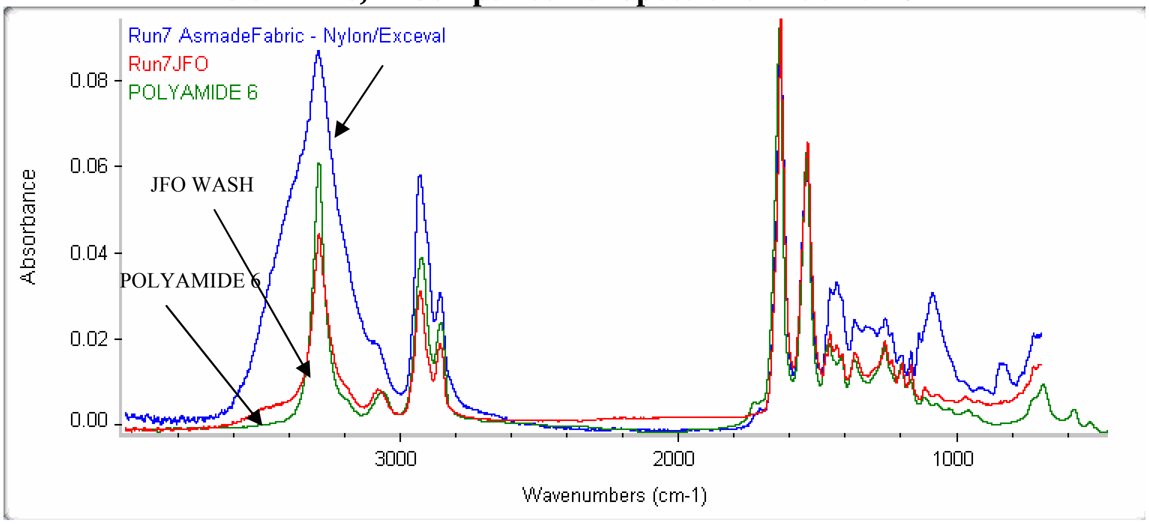


FIGURE – 7, A Comparison of Spectra for Fabric Run 8

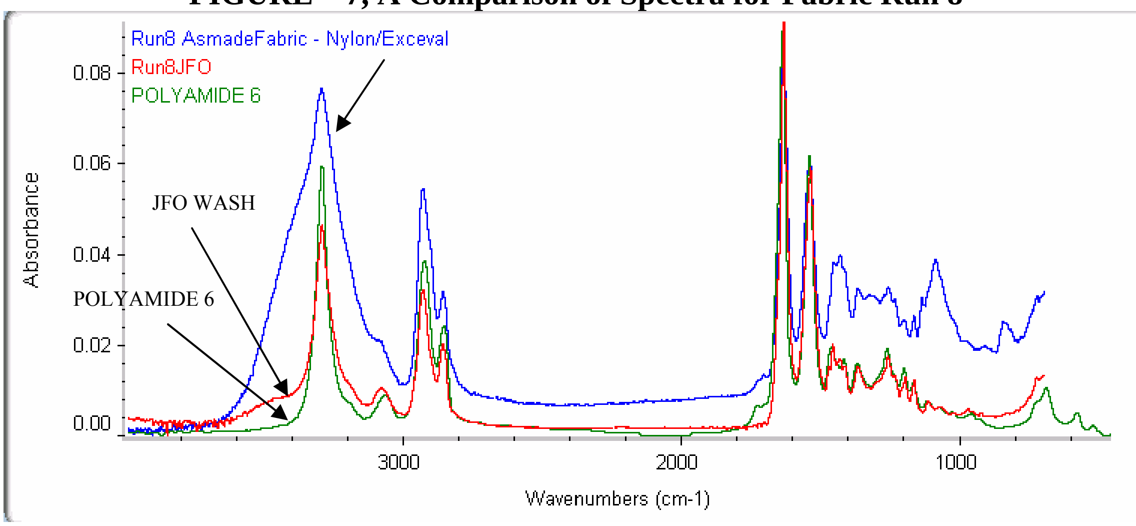


FIGURE – 8, A Comparison of Spectra for Fabric Run 9

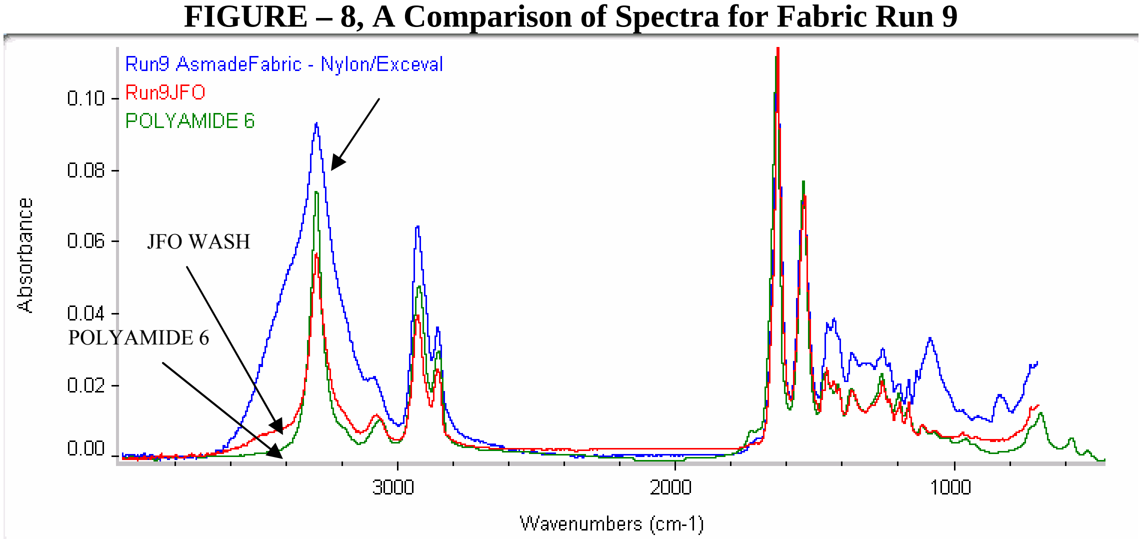


FIGURE – 9, A Comparison of Spectra for Fabric Run 10

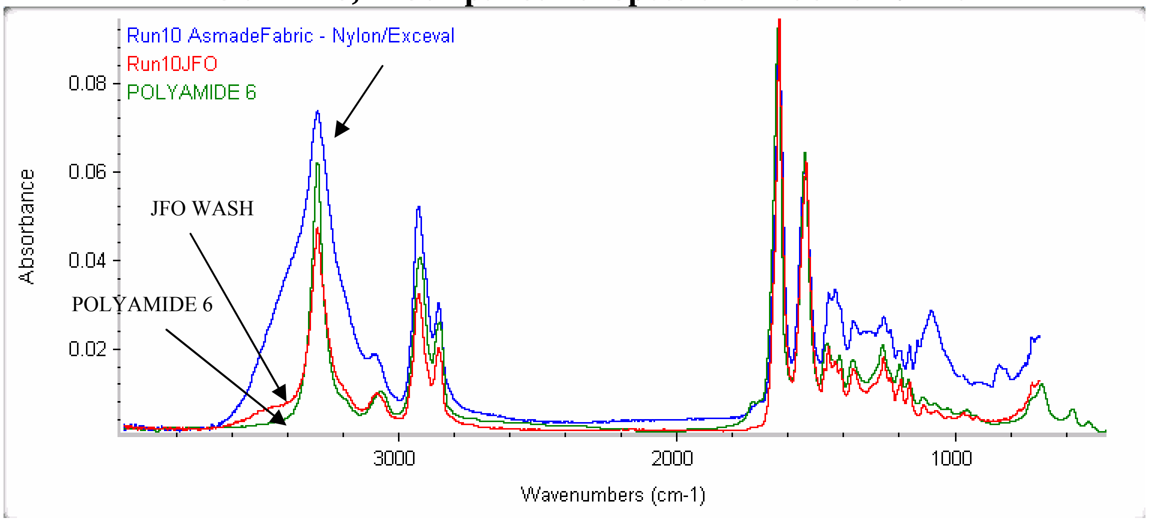


FIGURE – 10, A Comparison of Spectra for Fabric Run 11

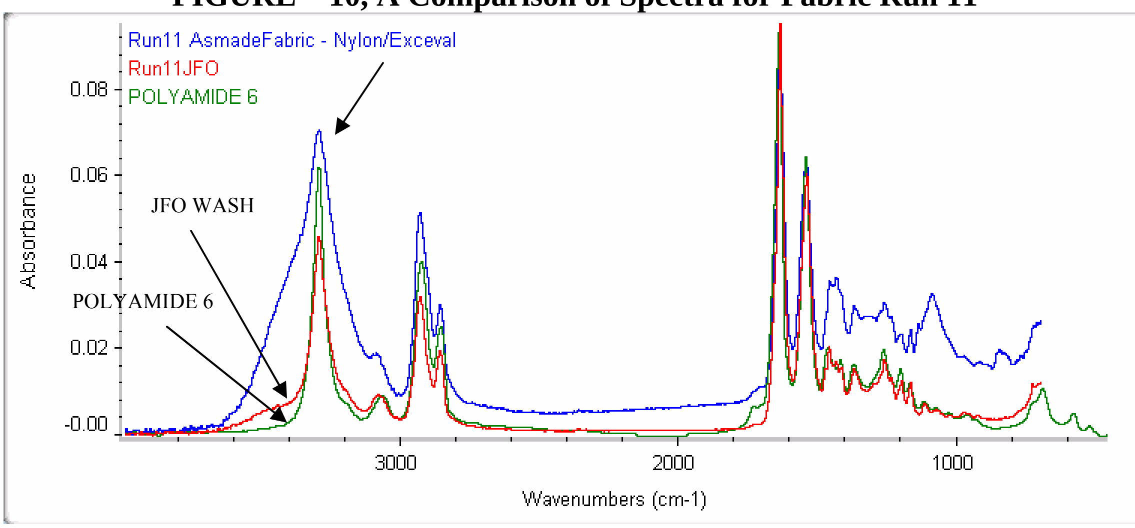


FIGURE – 11, A Comparison of Spectra for Fabric Run 12

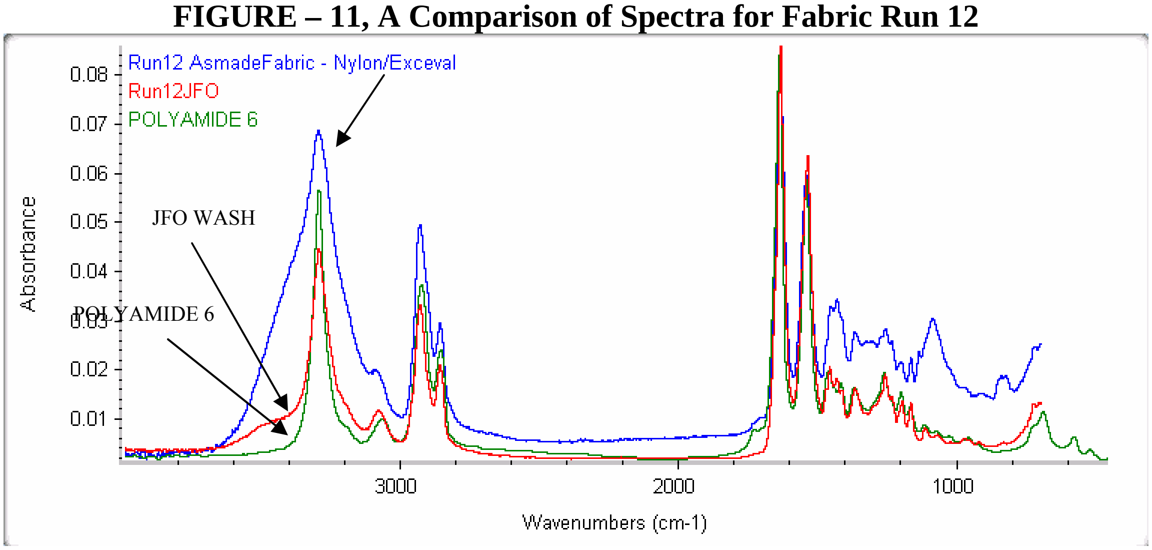
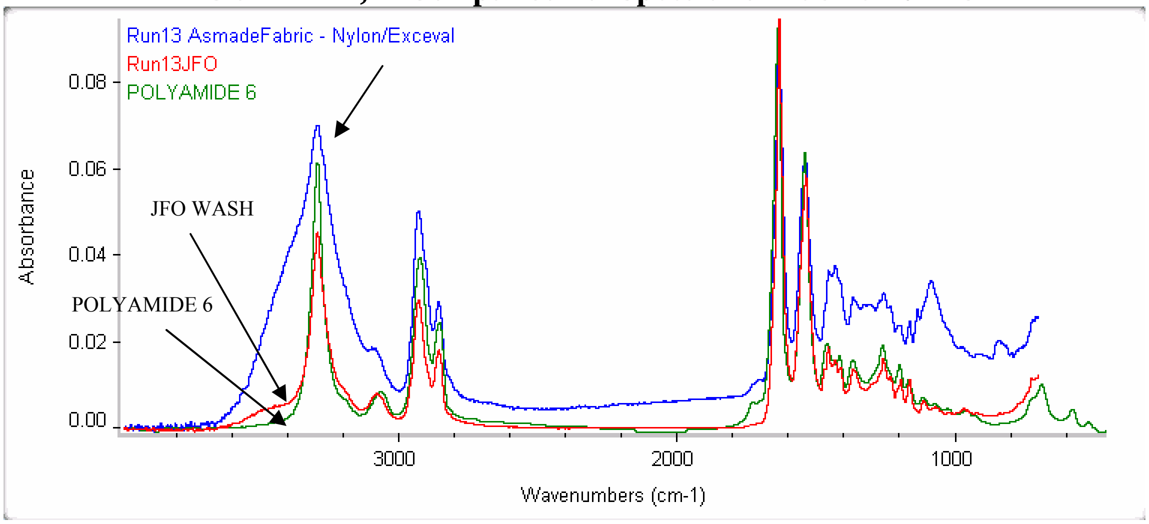
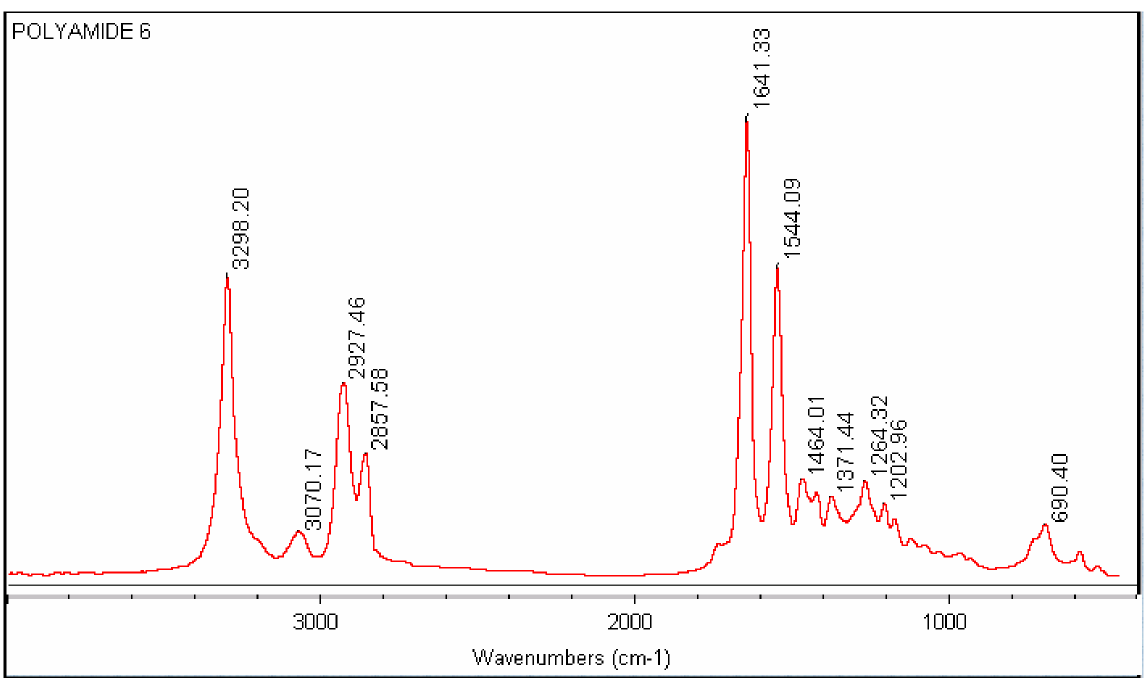


FIGURE – 12, A Comparison of Spectra for Fabric Run 13



B.3: Analysis of Spectrum Peaks for Nylon – 6:



B.4: Analysis of Spectrum Peaks for Washed Fabrics:

FIGURE – 1, Analysis of Spectrum Peaks - Washed Fabric Run 1

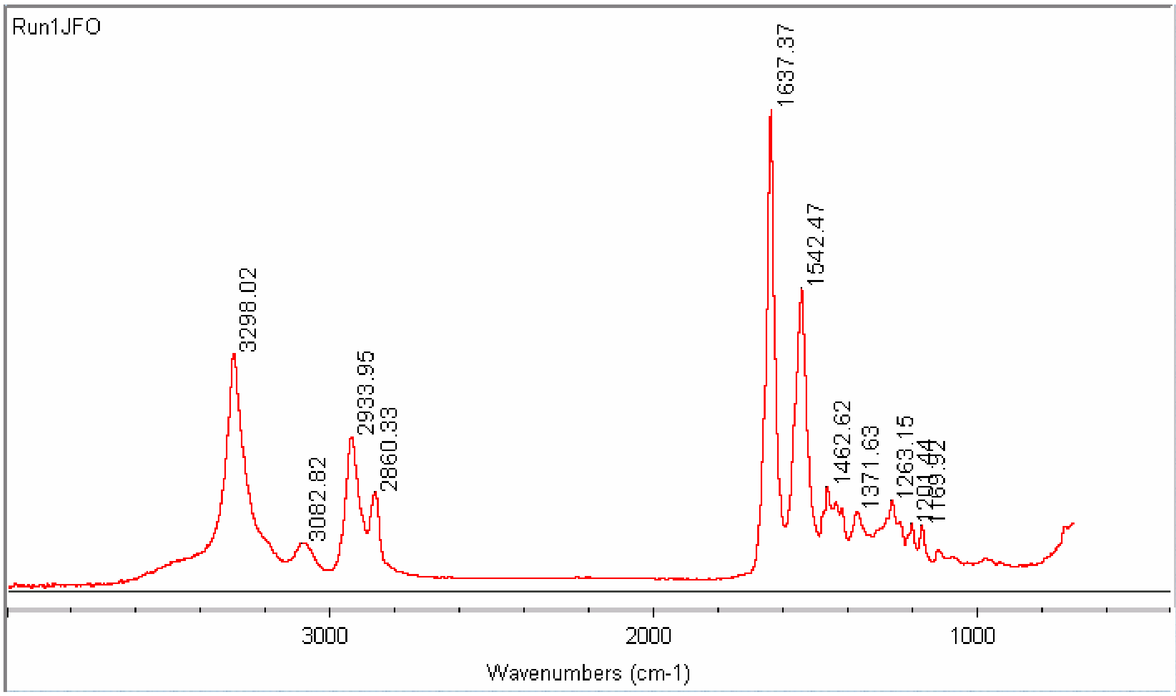
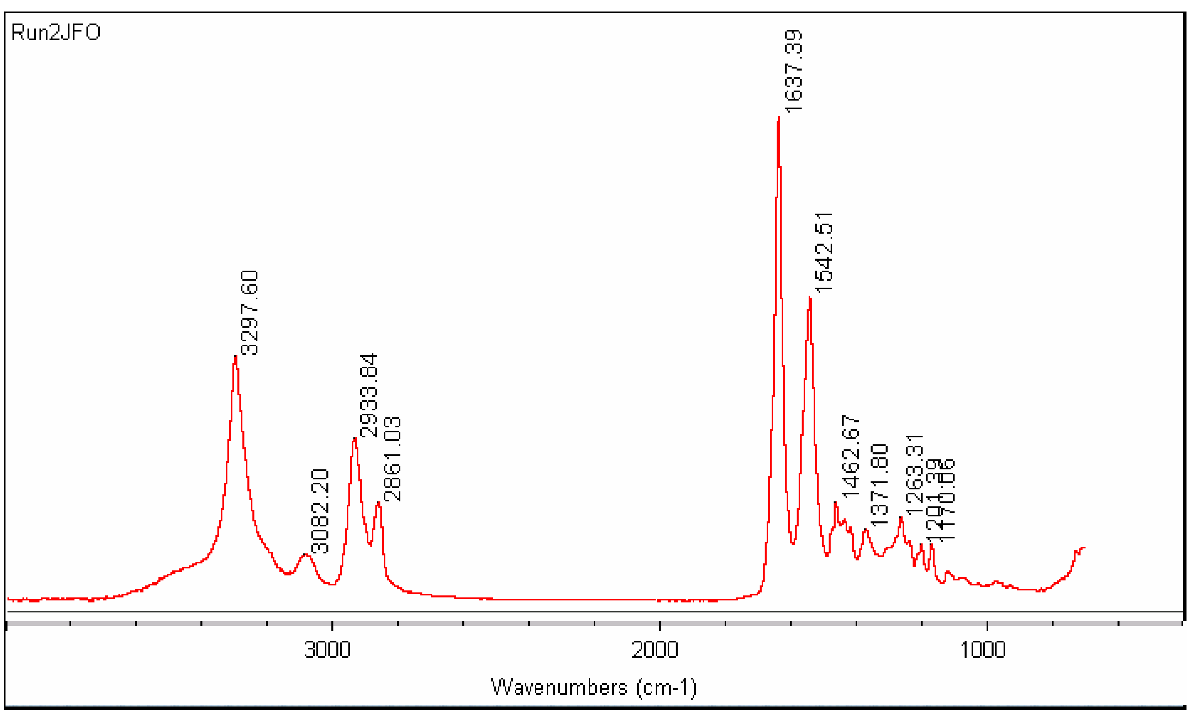


FIGURE – 2, Analysis of Spectrum Peaks - Washed Fabric Run 2



B.4: Analysis of Spectrum Peaks for Washed Fabrics

FIGURE 1, Analysis of Spectrum Peaks - Washed Fabric Run 1

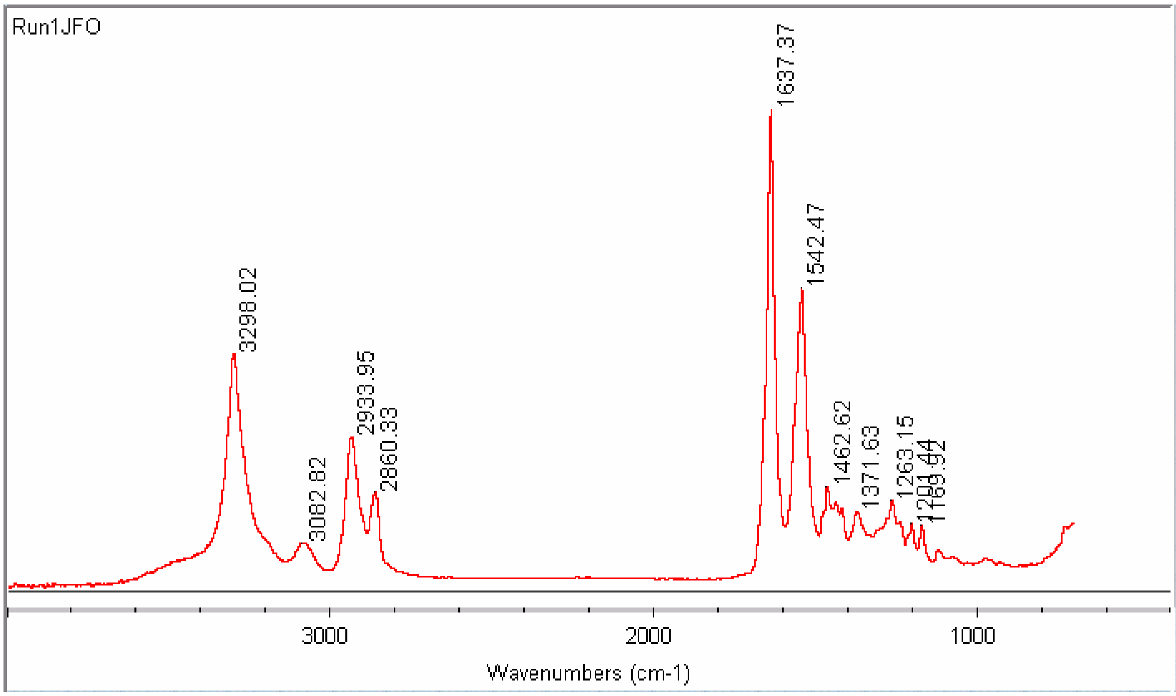


FIGURE 2, Analysis of Spectrum Peaks - Washed Fabric Run 2

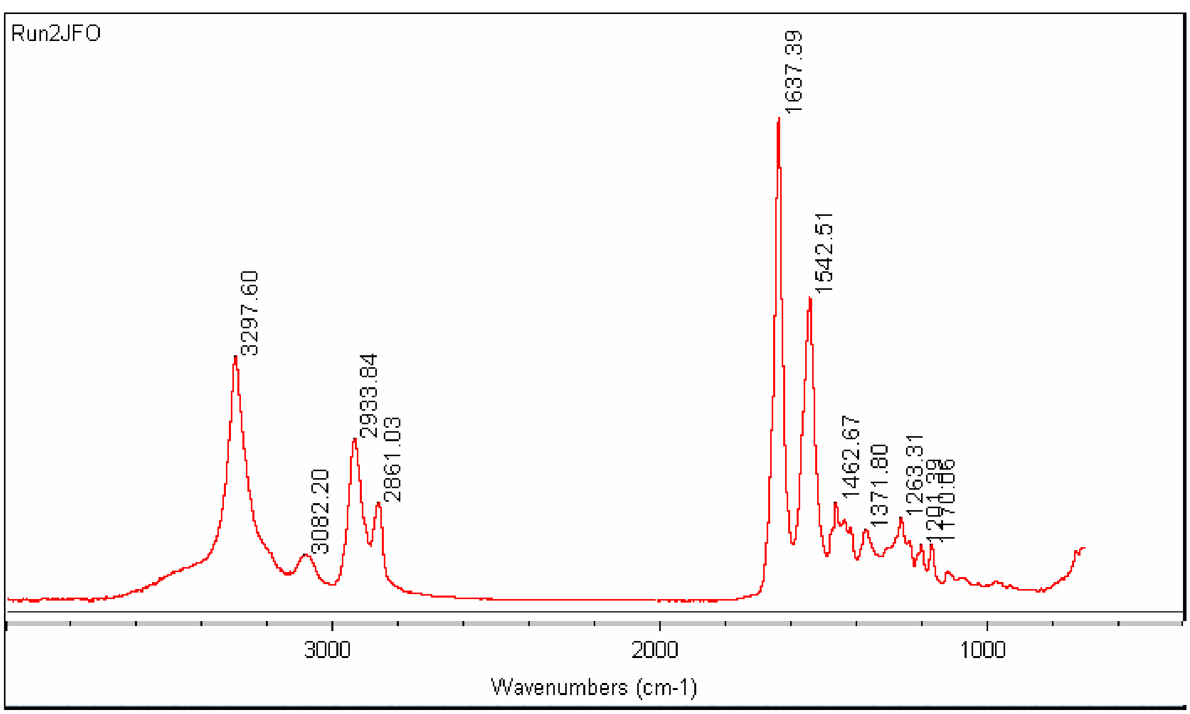


FIGURE 3, Analysis of Spectrum Peaks - Washed Fabric Run 3

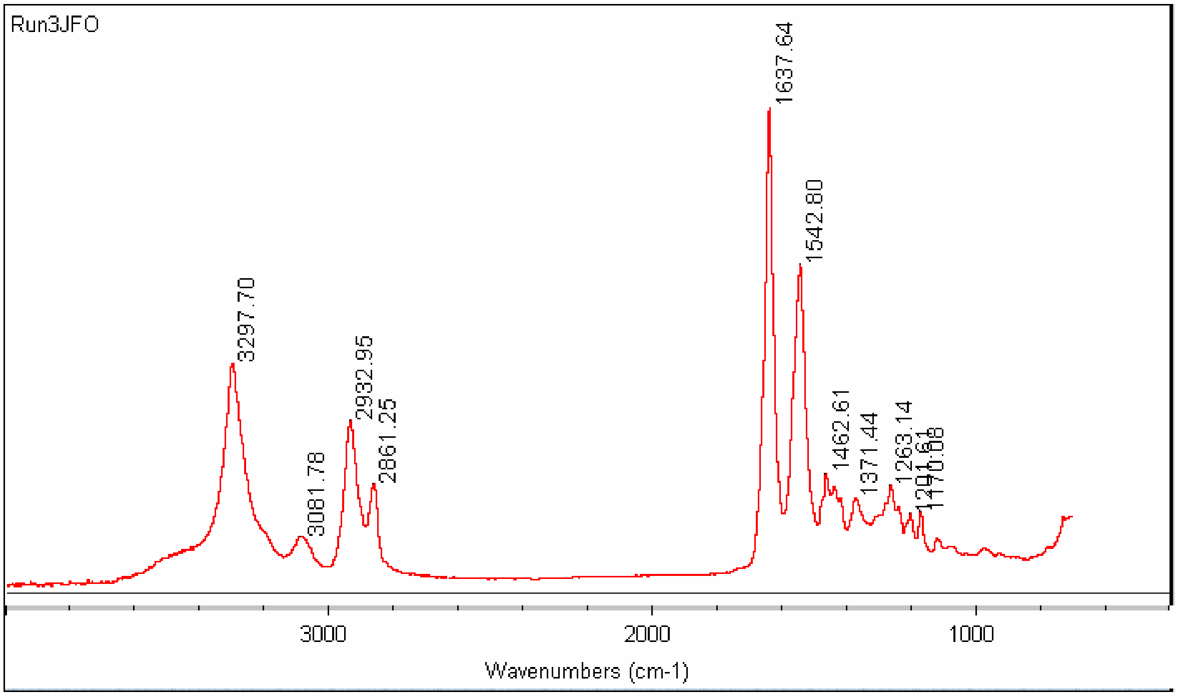


FIGURE 4, Analysis of Spectrum Peaks - Washed Fabric Run 5

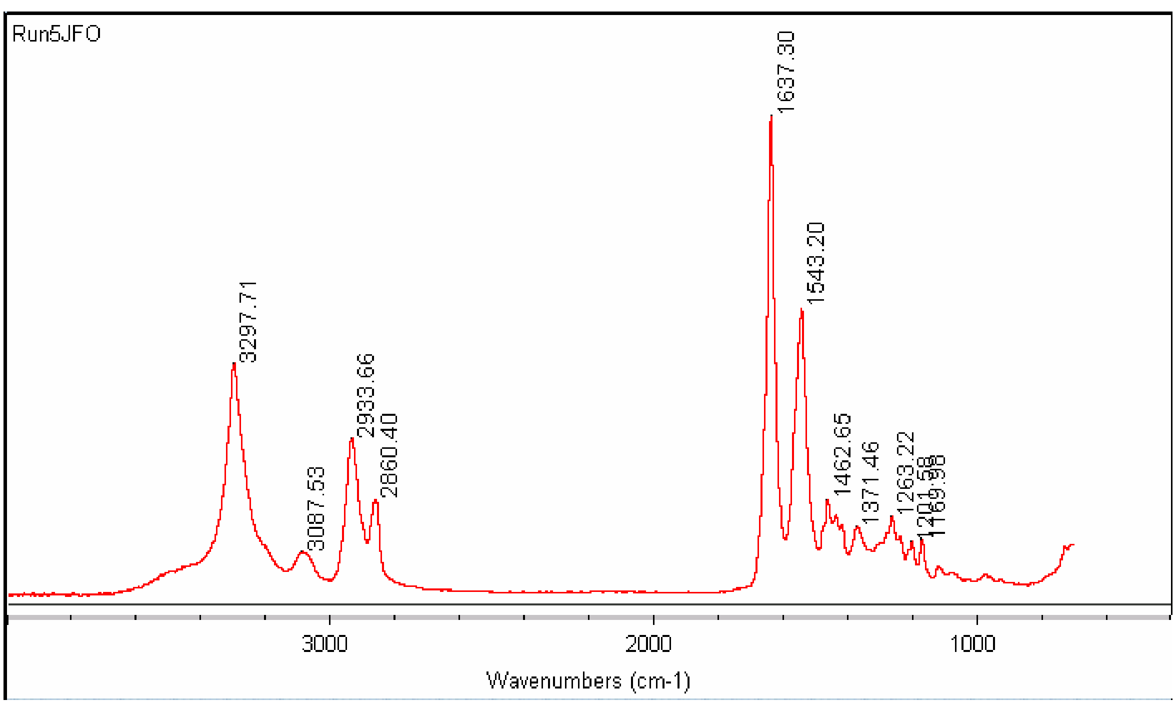


FIGURE 5, Analysis of Spectrum Peaks - Washed Fabric Run 6

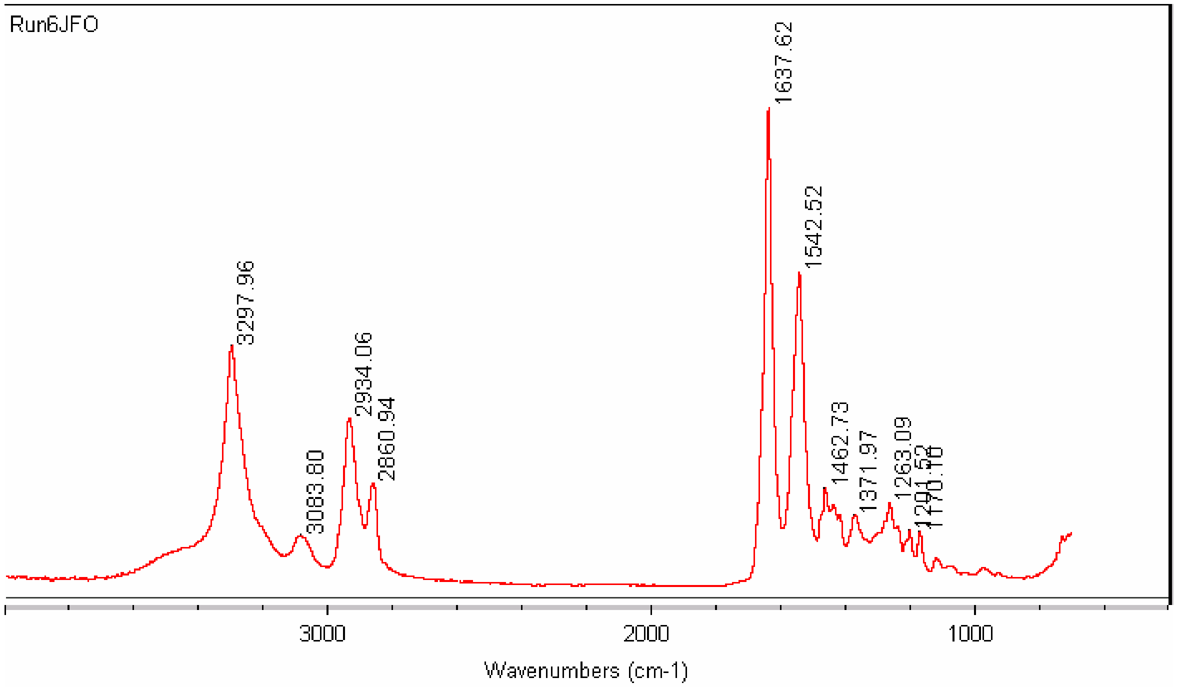


FIGURE 6, Analysis of Spectrum Peaks - Washed Fabric Run 7

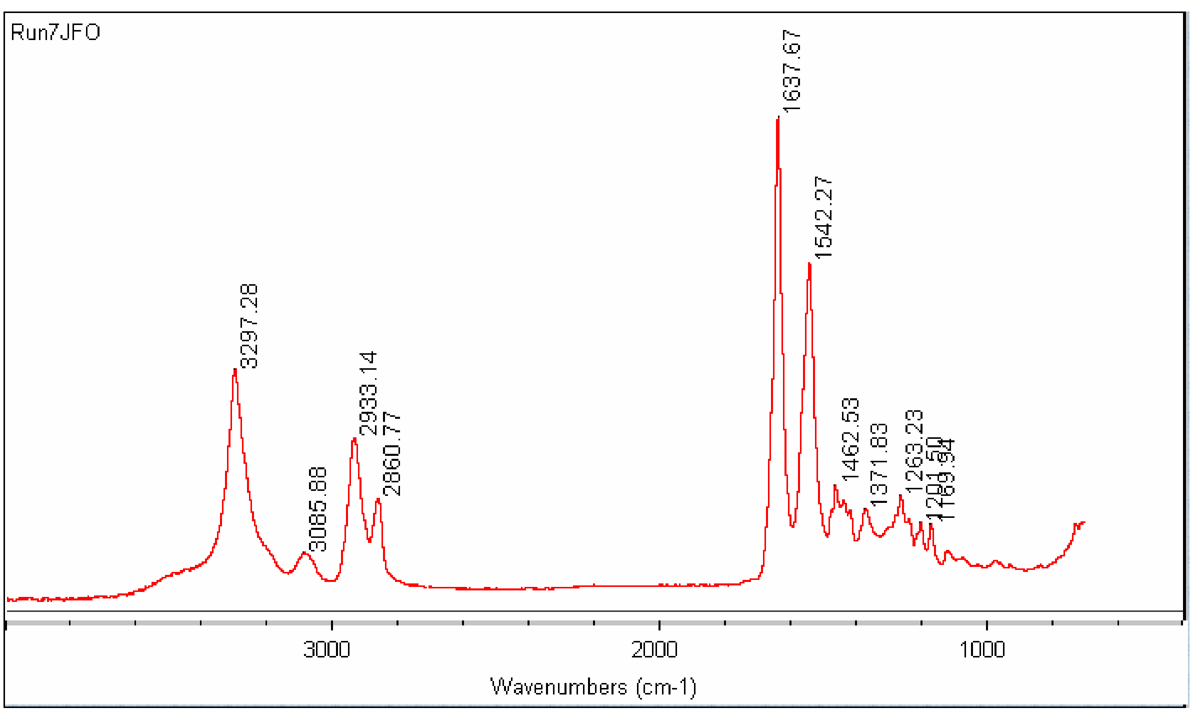


FIGURE 7, Analysis of Spectrum Peaks - Washed Fabric Run 8

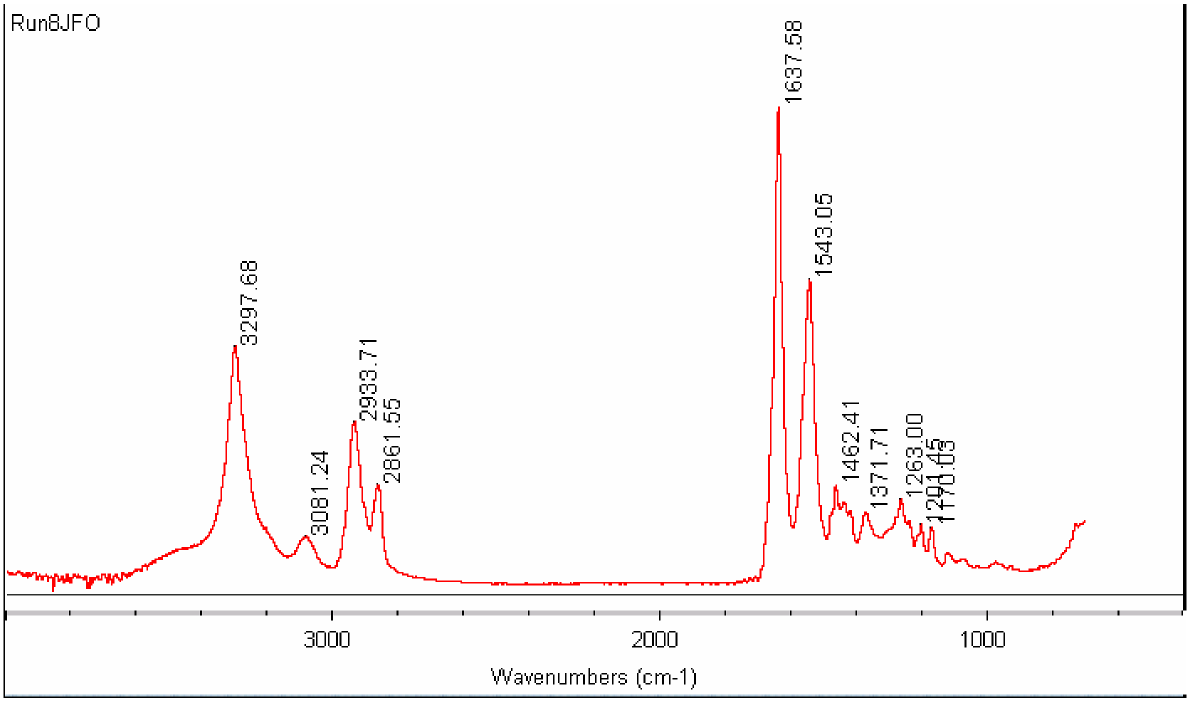


FIGURE 8, Analysis of Spectrum Peaks - Washed Fabric Run 9

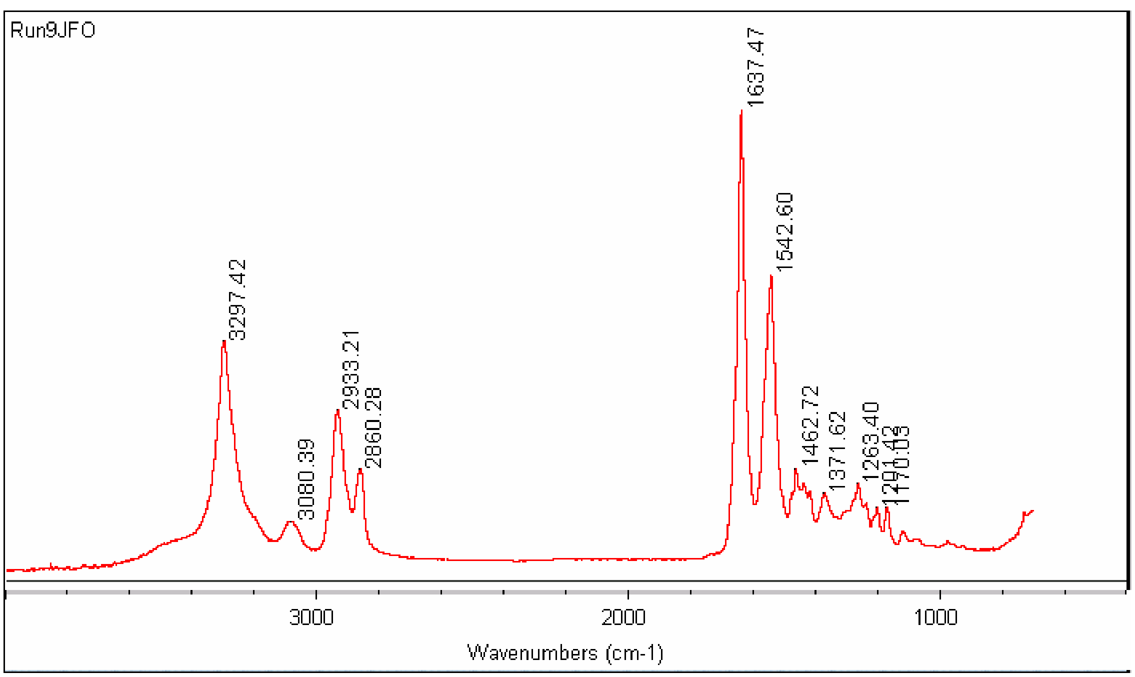


FIGURE 9, Analysis of Spectrum Peaks - Washed Fabric Run 10

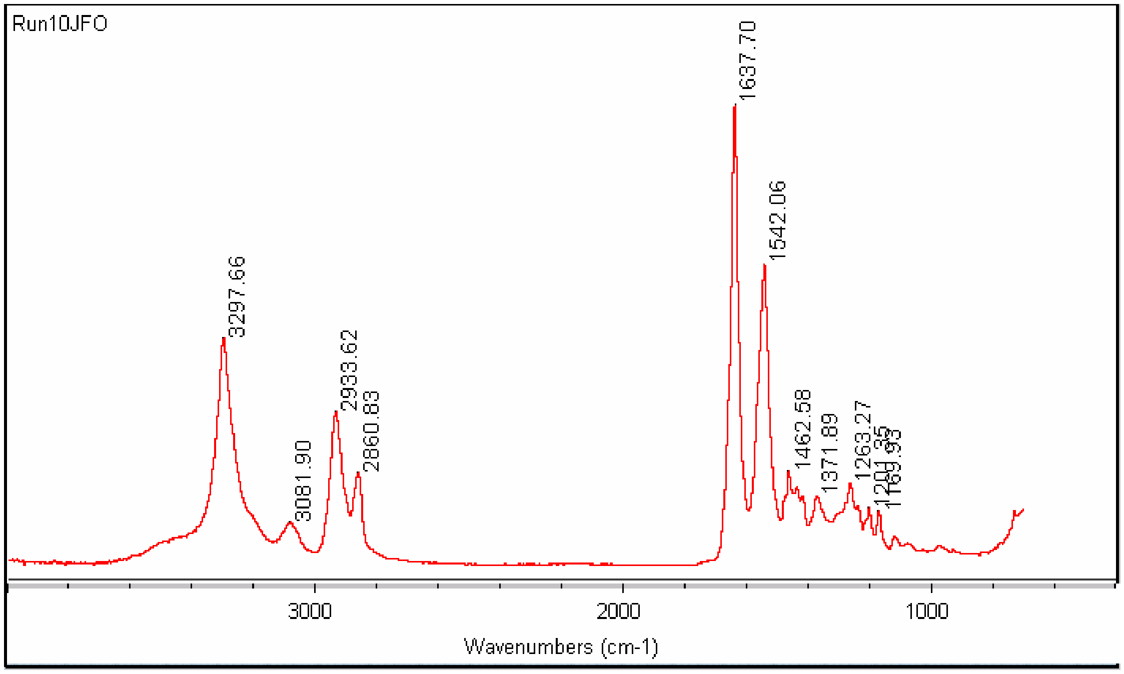


FIGURE 10, Analysis of Spectrum Peaks - Washed Fabric Run 11

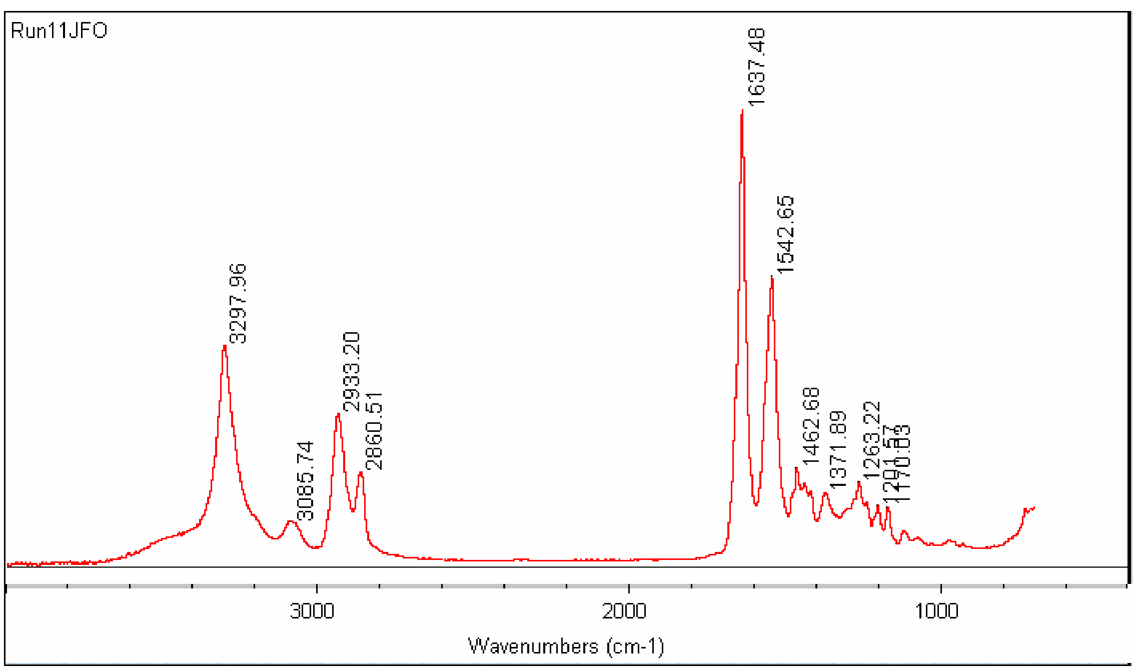


FIGURE 11, Analysis of Spectrum Peaks - Washed Fabric Run 12

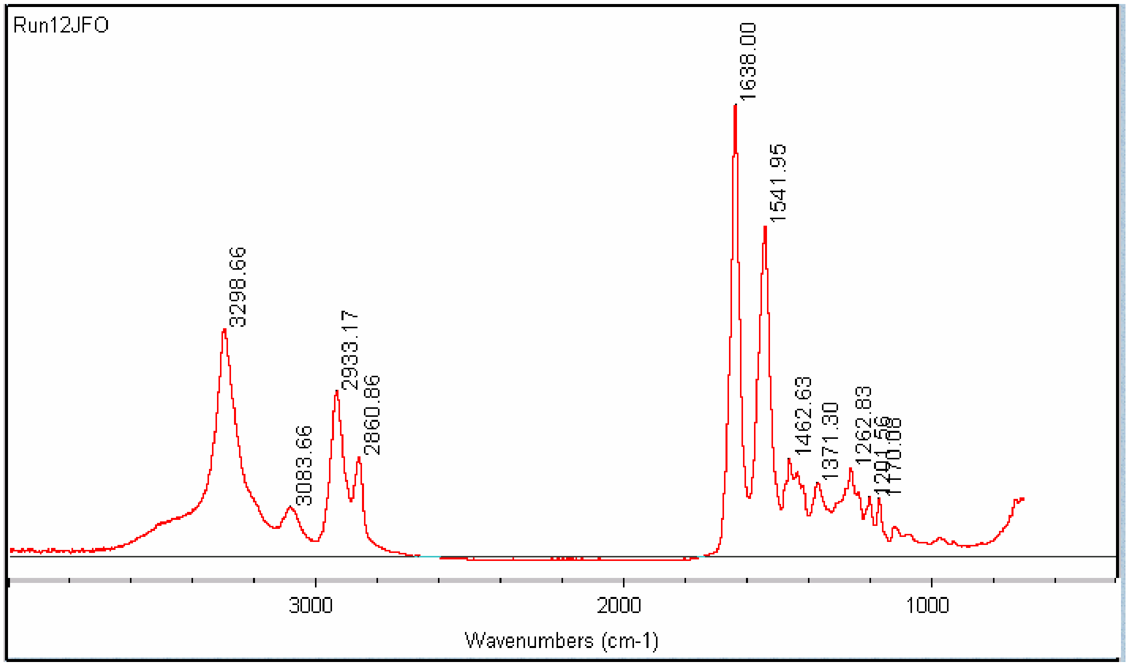
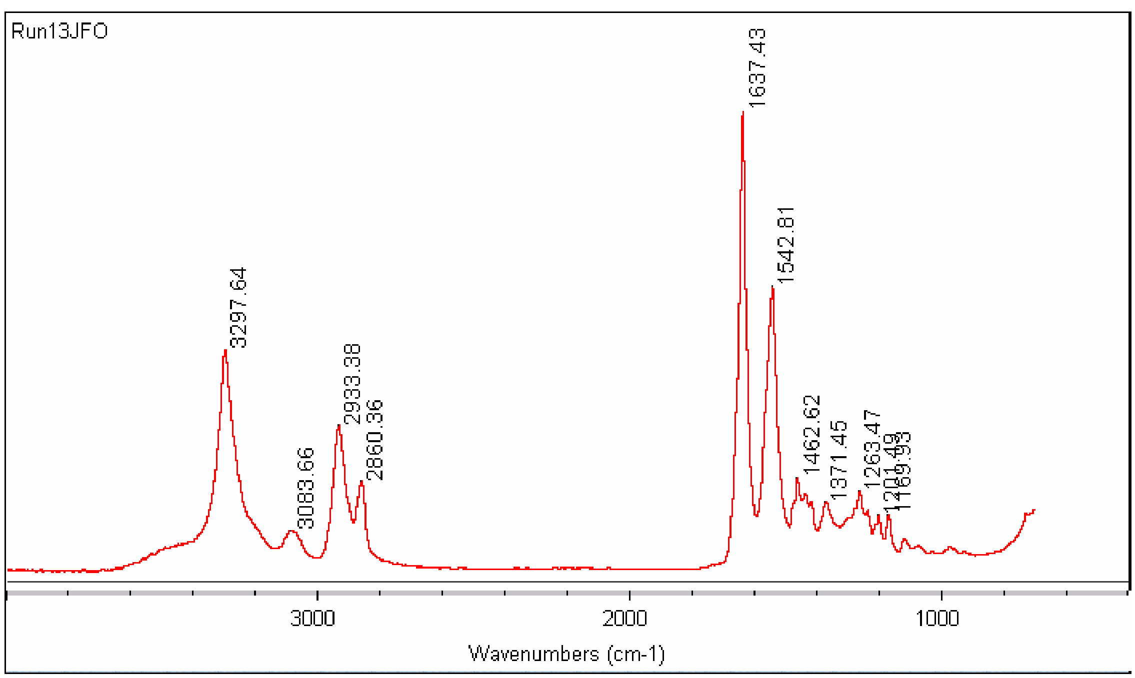


FIGURE 12, Analysis of Spectrum Peaks - Washed Fabric Run 13



B.4: Analysis of Spectrum Peaks for As-made Bicomponent Spunbonds

FIGURE 1, Analysis of Spectrum Peaks – As-made Fabric Run 1

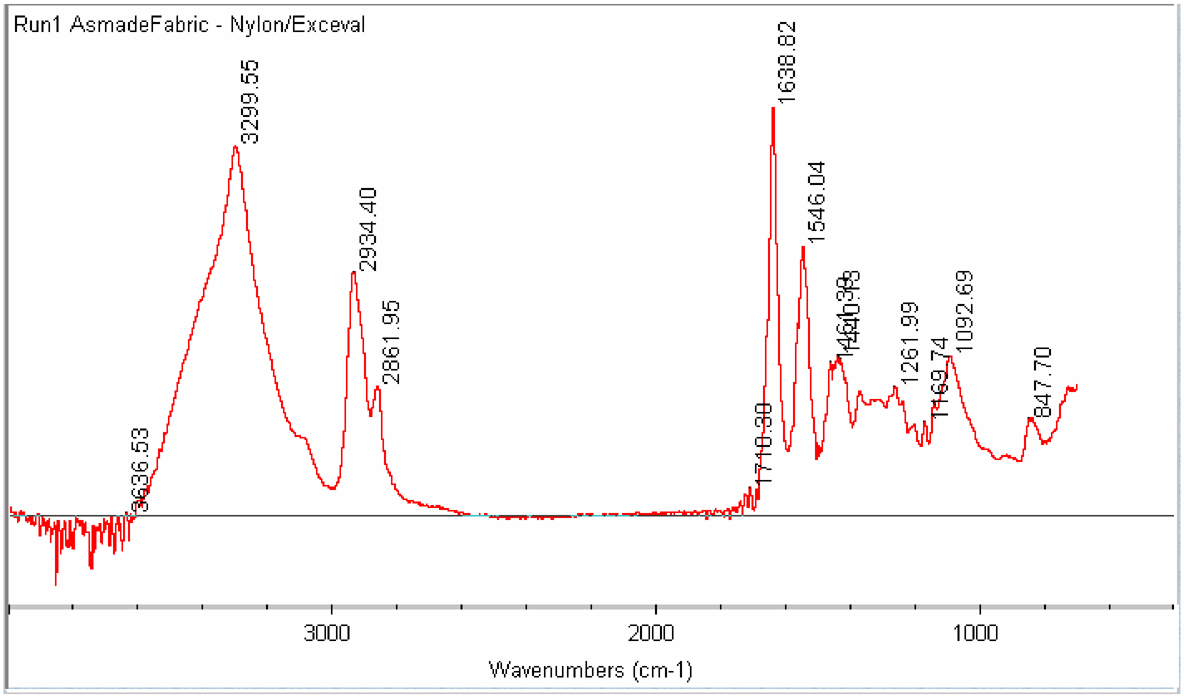


FIGURE 2, Analysis of Spectrum Peaks – As-made Fabric Run 2

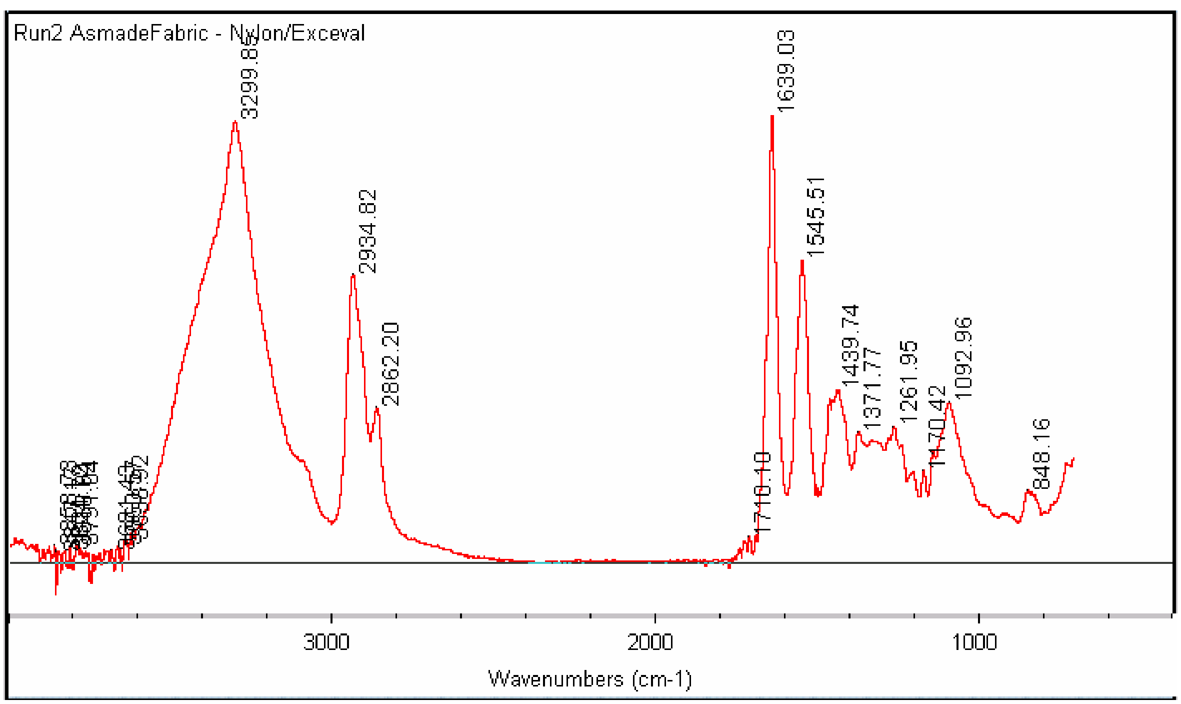


FIGURE 3, Analysis of Spectrum Peaks – As-made Fabric Run 3

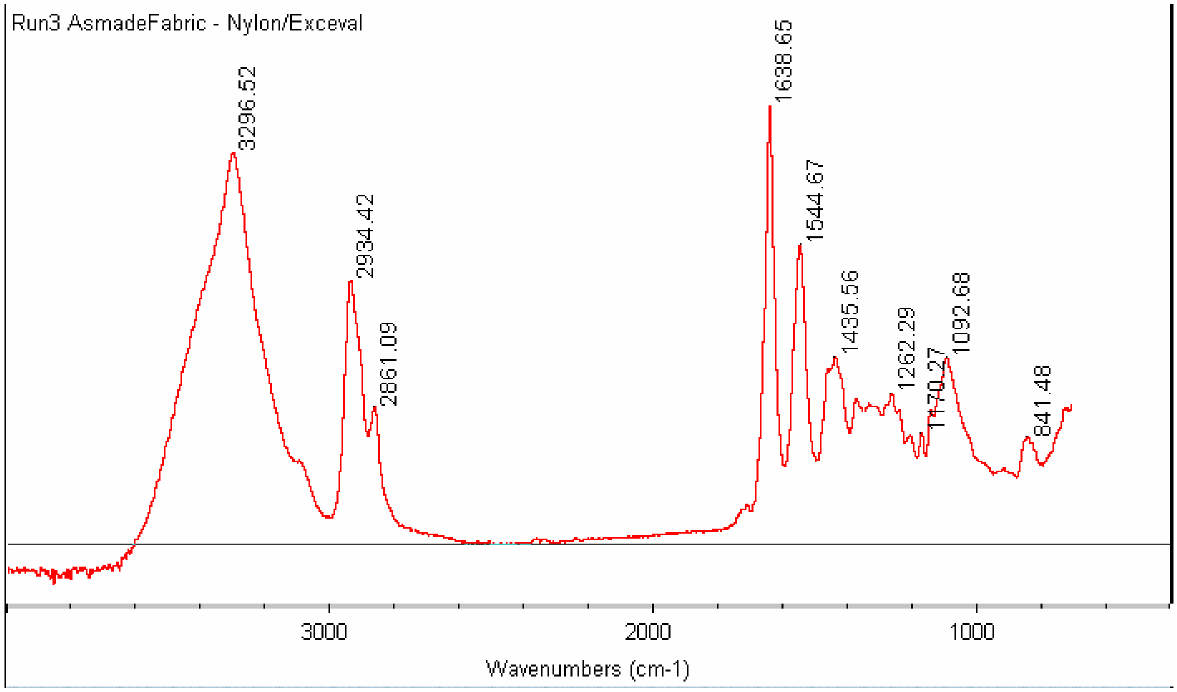


FIGURE 4, Analysis of Spectrum Peaks – As-made Fabric Run 4

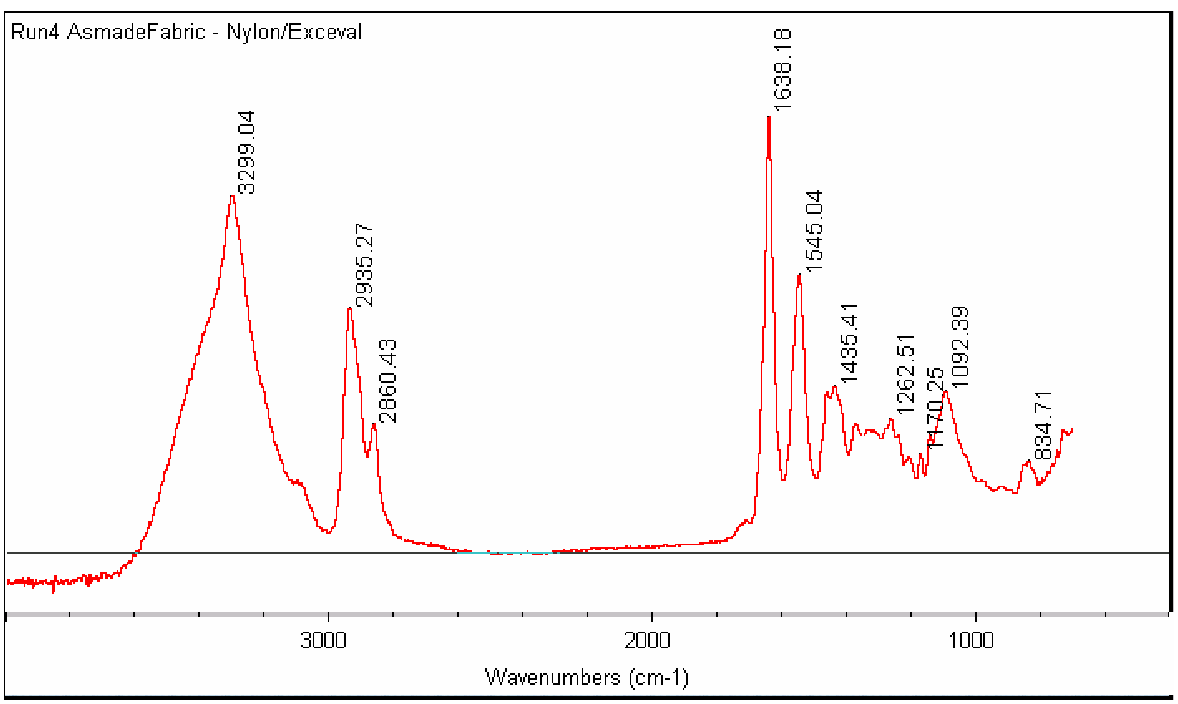


FIGURE 5, Analysis of Spectrum Peaks – As-made Fabric Run 5

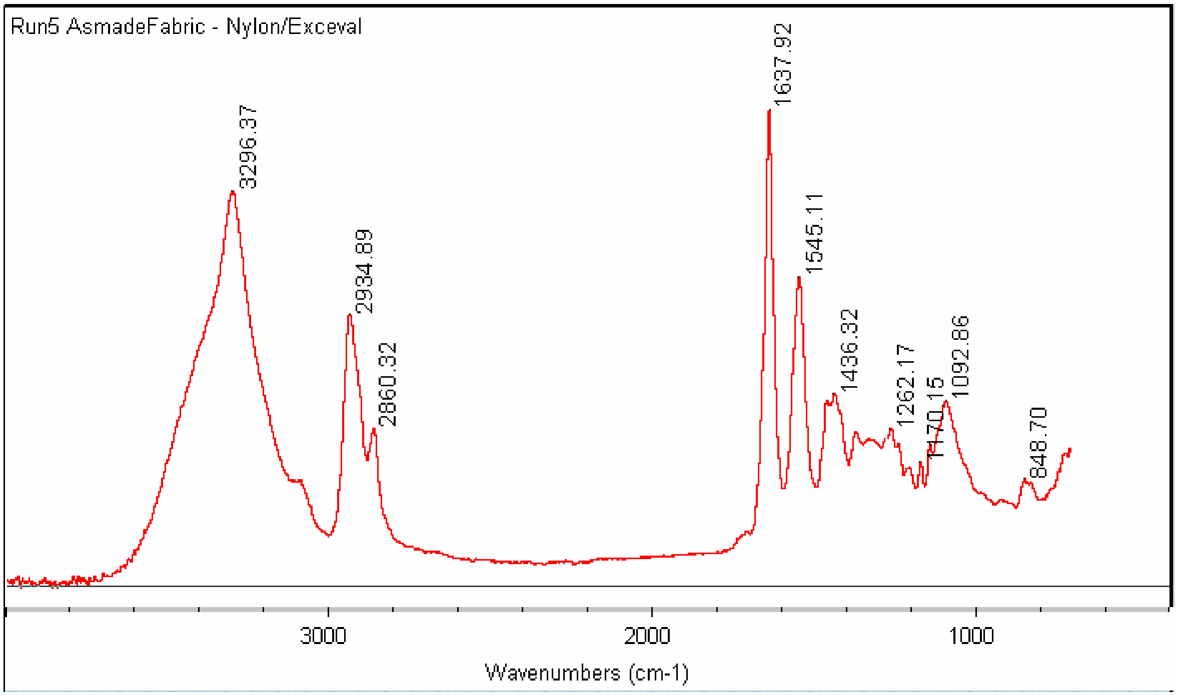


FIGURE 6, Analysis of Spectrum Peaks – As-made Fabric Run 6

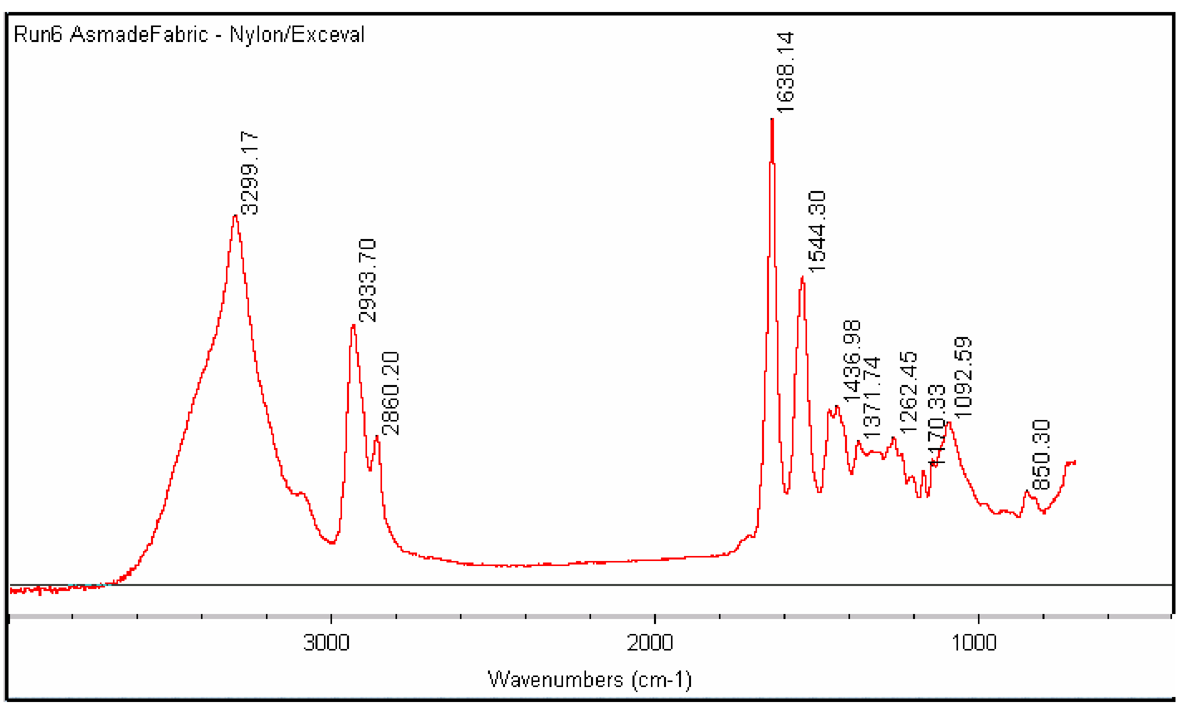


FIGURE 7, Analysis of Spectrum Peaks – As-made Fabric Run 7

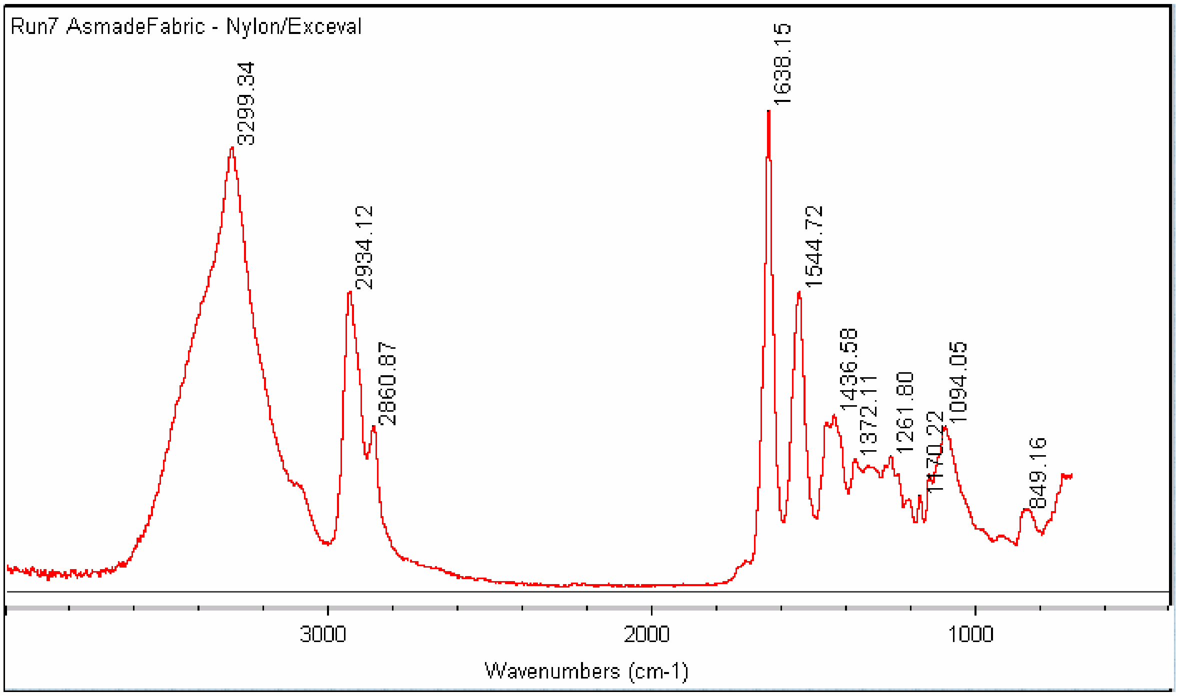


FIGURE 8, Analysis of Spectrum Peaks – As-made Fabric Run 8

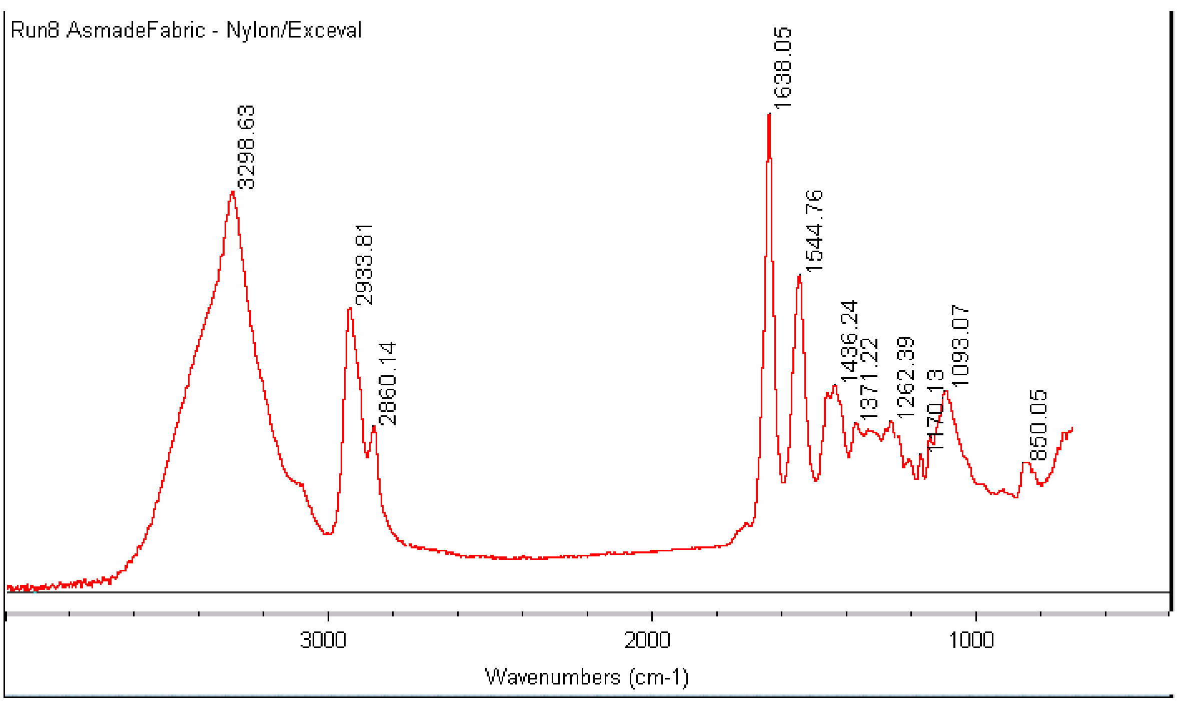


FIGURE 9, Analysis of Spectrum Peaks – As-made Fabric Run 9

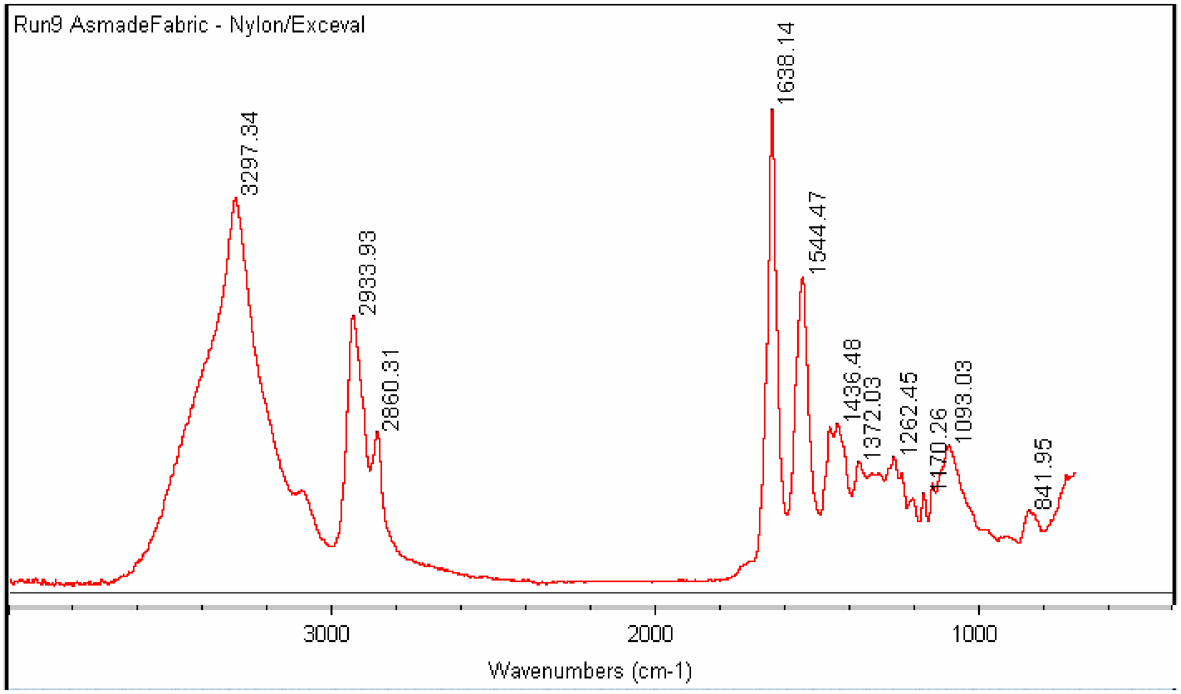


FIGURE 10, Analysis of Spectrum Peaks – As-made Fabric Run 10

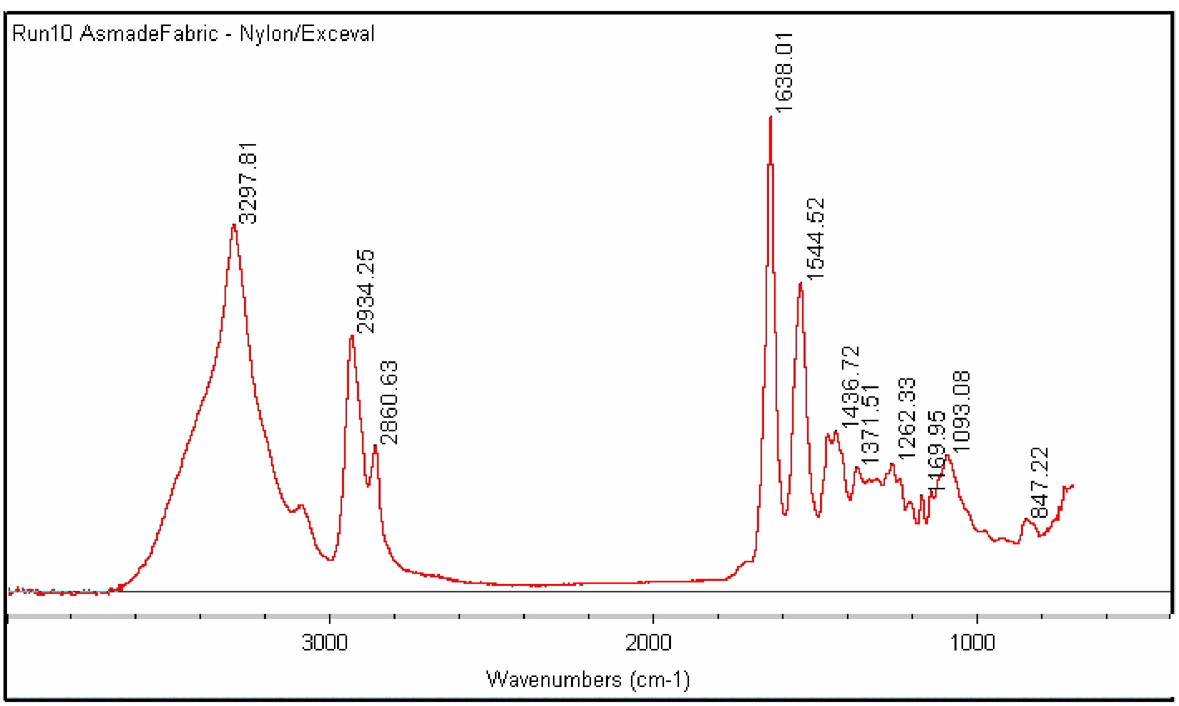


FIGURE 11, Analysis of Spectrum Peaks – As-made Fabric Run 11

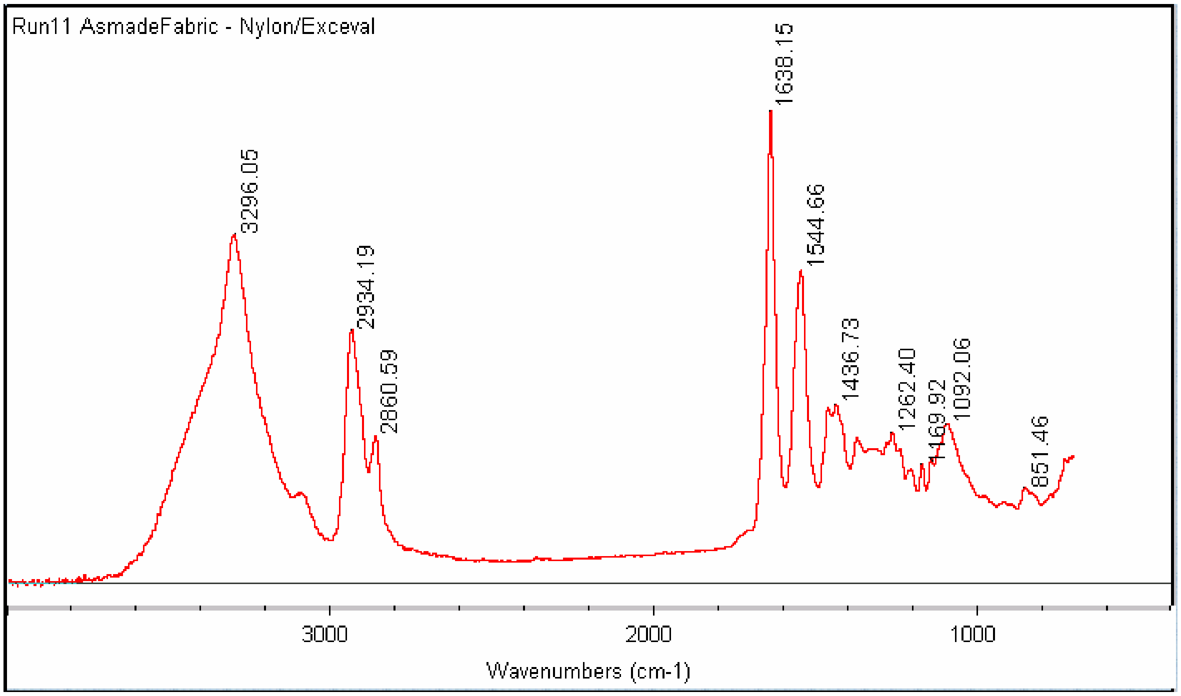


FIGURE 12, Analysis of Spectrum Peaks – As-made Fabric Run 12

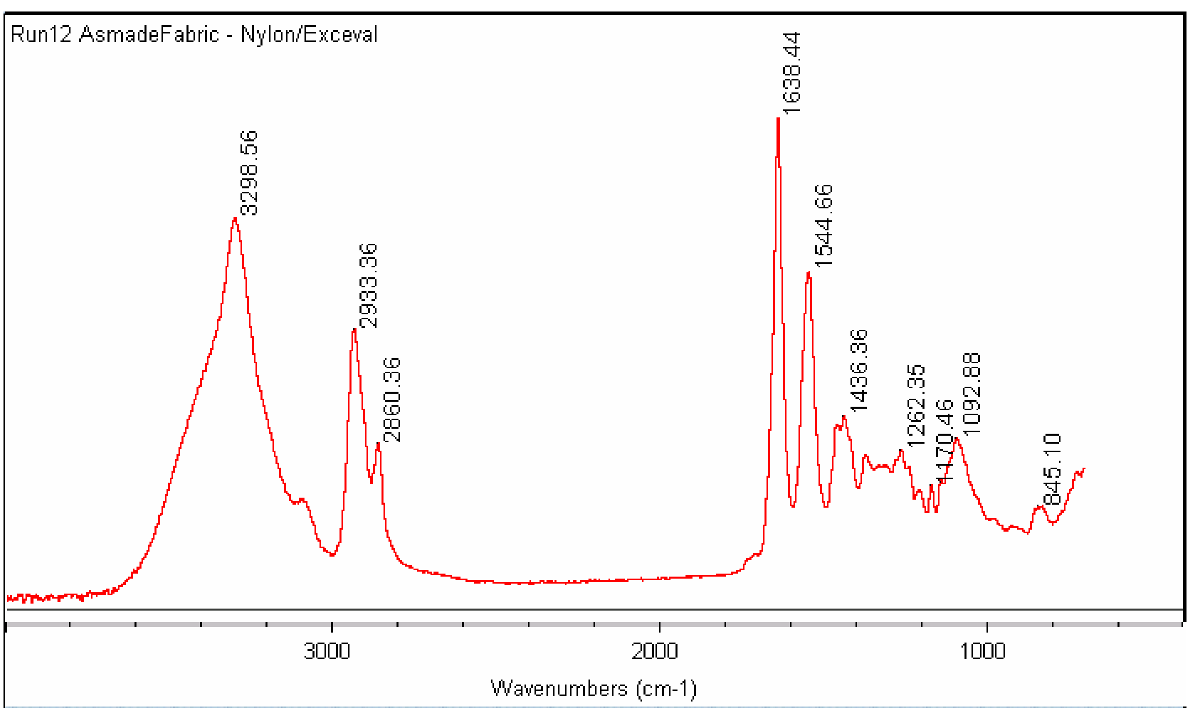
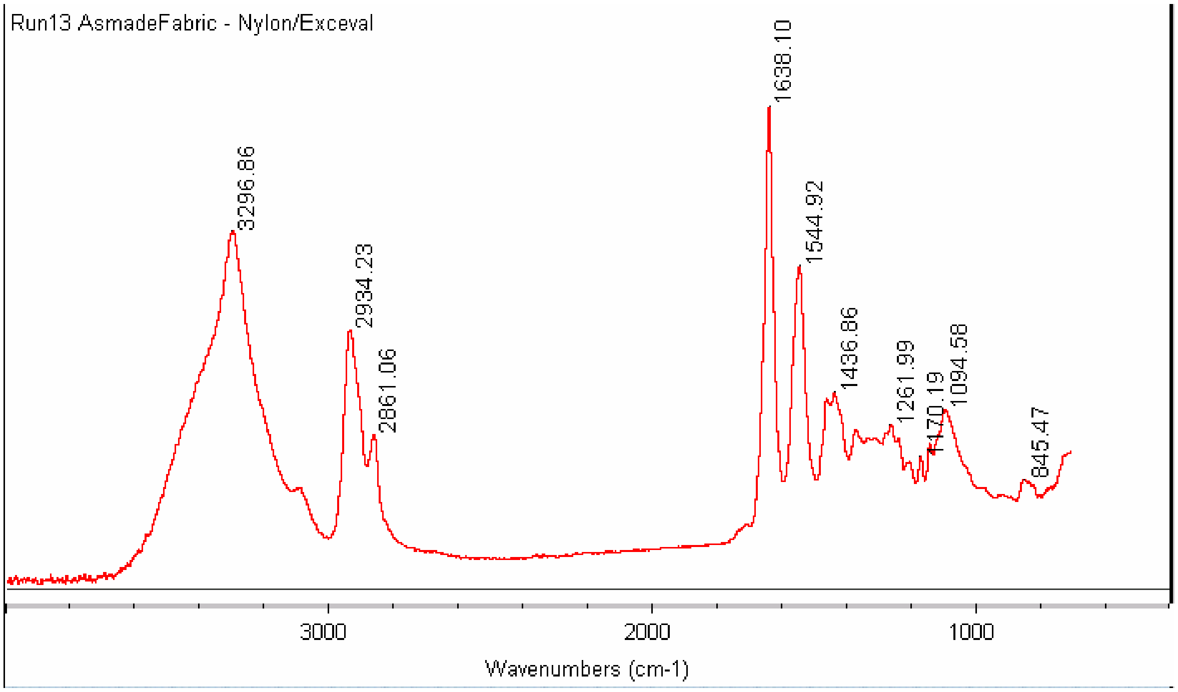


FIGURE 13, Analysis of Spectrum Peaks – As-made Fabric Run 13



APPENDIX C

C.1: Tensile Testing: Re-calendared, Jet Washed and Hydroentangled Fabrics

TABLE C.1, Results of Tensile Testing for Recalendared Fabrics – Fabric Run 1 to 3

Identification Number	Sample No.	Width Inch	Height Inch	Peak Load Lb	Peak Stress PSI	Elong @ Pk Ld Inch	%Strn @ Pk Ld Inch	Modulus PSI
RECAL-Run1-MD	1	2	6	18.5	147	0.77	25.72306	976.79
	2	2	6	22.4	177	1.02	33.88367	1092.17
	3	2	6	21.2	168	1.08	35.89453	870.23
	4	2	6	21.4	170	1.05	34.83928	917.88
	5	2	6	23.1	183	0.95	31.80267	1252.18
RECAL-Run1-CD	1	2	6	9.7	77	0.78	26.07404	496.68
	2	2	6	10	79	0.81	26.87898	479.71
	3	2	6	13.4	106	0.87	29.06688	666.26
	4	2	6	8.4	66	0.56	18.77958	510.68
	5	2	6	11	88	0.64	21.36151	689.02
RECAL-Run2-MD	1	2	6	14.3	113	0.85	28.34366	603.13
	2	2	6	13.2	105	0.74	24.74195	648
	3	2	6	13.7	109	0.75	24.91275	813.74
	4	2	6	12.6	100	0.7	23.47482	737.48
	5	2	6	12.2	97	0.62	20.54616	791.14
RECAL-Run2-CD	1	2	6	6	48	0.71	23.7513	259.73
	2	2	6	6.5	51	0.88	29.42034	257.77
	3	2	6	5.1	40	0.83	27.64408	198.68
	4	2	6	4.3	34	0.57	18.88183	223.96
	5	2	6	4.7	37	0.6	19.9487	230.02
RECAL-Run3-MD	1	2	6	10	80	0.74	24.74092	411.8
	2	2	6	9.5	76	0.72	23.89614	409.94
	3	2	6	11.4	90	0.77	25.77386	567.78
	4	2	6	9	71	0.7	23.33405	384.34
	5	2	6	9.9	79	0.69	22.85393	539.37
RECAL-Run3-CD	1	2	6	2.9	23	0.71	23.70185	110.96
	2	2	6	2.8	22	0.76	25.4581	104.33
	3	2	6	2.9	23	0.78	26.05025	106.58
	4	2	6	3	24	0.79	26.23568	116.14
	5	2	6	3.1	24	0.67	22.45652	130.4

TABLE C.2, Results of Tensile Testing for Recalendared Fabrics – Fabric Run 5 to 7

Identification Number	Sample No.	Width Inch	Height Inch	Peak Load Lb	Peak Stress PSI	Elong @ Pk Ld Inch	%Strn @ Pk Ld Inch	Modulus PSI
RECAL-Run5-MD	1	2	6	24.2	192	0.88	29.495	1704.59
	2	2	6	26.4	209	1.19	39.58884	1263.74
	3	2	6	21	166	0.89	29.78628	1095.58
	4	2	6	27.4	218	0.96	32.03883	2260.82
	5	2	6	23.3	185	0.63	20.89608	2518.67
RECAL-Run5-CD	1	2	6	14.3	113	0.85	28.28194	798.66
	2	2	6	10.7	85	0.64	21.38804	742.65
	3	2	6	11.6	92	0.8	26.78923	648.32
	4	2	6	12.1	96	0.89	29.55509	643.73
	5	2	6	11	87	0.71	23.75885	743.72
RECAL-Run6-MD	1	2	6	14.5	115	1.02	33.91399	520.44
	2	2	6	18.2	144	1.13	37.54442	636.82
	3	2	6	17.5	139	1.1	36.652	538.15
	4	2	6	18.1	144	1.25	41.65396	478.27
	5	2	6	13.7	109	0.89	29.67876	633.12
RECAL-Run6-CD	1	2	6	5.4	42	0.63	20.8406	290.41
	2	2	6	6.2	49	0.63	21.01047	331.78
	3	2	6	7.5	60	0.74	24.66455	371.85
	4	2	6	9.5	75	1.02	33.86451	338.32
	5	2	6	9.7	77	1.08	36.07061	347.81
RECAL-Run7-MD	1	2	6	12.3	98	0.74	24.75725	693.06
	2	2	6	12.5	100	0.78	25.86111	770.73
	3	2	6	11.5	92	0.71	23.51038	656.33
	4	2	6	14.2	113	0.75	24.98719	937.45
	5	2	6	13.3	106	0.83	27.50539	719.41
RECAL-Run7-CD	1	2	6	4.8	38	0.9	30.06474	180.19
	2	2	6	4.5	36	0.75	25.04971	192.75
	3	2	6	6.2	50	0.93	30.8592	231.42
	4	2	6	4.9	39	0.99	32.86584	175.79
	5	2	6	1.9	15	0.42	13.98289	126.14

TABLE C.3, Results of Tensile Testing for Recalendared Fabrics – Fabric Run 8 to 10

Identification Number	Sample No.	Width Inch	Height Inch	Peak Load Lb	Peak Stress PSI	Elong @ Pk Ld Inch	%Strn @ Pk Ld Inch	Modulus PSI
RECAL-Run8-MD	1	2	6	8	63	0.34	11.4007	772.77
	2	2	6	9.3	74	0.36	12.0333	871.27
	3	2	6	9.8	78	0.41	13.73433	879.8
	4	2	6	10.5	83	0.43	14.45399	910.86
	5	2	6	9.7	77	0.38	12.71595	903.48
RECAL-Run8-CD	1	2	6	1.8	14	1.21	40.27225	41.77
	2	2	6	1.3	11	0.62	20.78303	54
	3	2	6	1.8	15	1.04	34.81088	45.58
	4	2	6	2.2	17	1.29	42.98489	45.43
	5	2	6	2.4	19	1.48	49.42669	50.32
RECAL-Run9-MD	1	2	6	31.3	248	1.09	36.41559	1757.52
	2	2	6	30.6	243	1.24	41.38151	1523.95
	3	2	6	38.4	305	1.56	52.14109	******
	4	2	6	34.1	270	1.31	43.77016	1774.52
	5	2	6	39.7	315	1.65	54.83785	2126.9
RECAL-Run9-CD	1	2	6	20	158	1.15	38.34342	971.43
	2	2	6	15.6	124	1.01	33.81724	877.29
	3	2	6	19.7	156	1.31	43.52531	833.29
	4	2	6	15.8	126	0.96	32.07938	798.7
	5	2	6	16.6	132	0.96	31.98296	781.34
RECAL-Run10-MD	1	2	6	21	167	1.16	38.78201	703.59
	2	2	6	28.7	228	1.9	63.49775	677.52
	3	2	6	22.9	182	1.31	43.51411	660.49
	4	2	6	17.3	137	1.15	38.41325	499.23
	5	2	6	23.3	185	1.46	48.76431	638.83
RECAL-Run10-CD	1	2	6	14.8	118	1.39	46.30418	477.83
	2	2	6	16.5	131	1.66	55.32467	502.66
	3	2	6	8.8	70	0.99	33.12565	312.45
	4	2	6	10.3	82	0.99	33.13539	363.83
	5	2	6	12.7	101	1.42	47.28836	360.59

TABLE C.4, Results of Tensile Testing for Recalendared Fabrics – Fabric Run 11 to 13

Identification Number	Sample No.	Width Inch	Height Inch	Peak Load Lb	Peak Stress PSI	Elong @ Pk Ld Inch	%Strn @ Pk Ld Inch	Modulus PSI
RECAL-Run11-MD	1	2	6	15.3	121	1.06	35.33073	461.41
	2	2	6	19.1	152	1.4	46.80998	533.65
	3	2	6	17.9	142	1.42	47.44339	467.74
	4	2	6	18.2	144	1.4	46.57161	518.82
	5	2	6	8.4	67	1.12	37.45235	285.31
RECAL-Run11-CD	1	2	6	8.6	68	0.94	31.38416	324.99
	2	2	6	8.4	66	1.08	35.87011	273.09
	3	2	6	7.3	58	0.94	31.42759	277.19
	4	2	6	7.5	59	0.98	32.83138	262.29
	5	2	6	18.6	147	1.37	45.60625	577.19
RECAL-Run12-MD	1	2	6	10.7	85	0.62	20.50089	668.42
	2	2	6	9	71	0.58	19.21605	650.9
	3	2	6	8	64	0.54	17.95926	614.89
	4	2	6	9.4	75	0.57	18.98149	548.39
	5	2	6	13.3	105	0.87	29.04443	568.56
RECAL-Run12-CD	1	2	6	3.4	27	0.9	30.00474	102.69
	2	2	6	4.1	32	1.2	39.83474	105.27
	3	2	6	4.3	34	1.04	34.52801	136.39
	4	2	6	2.3	18	0.93	30.89469	71.61
	5	2	6	3.9	31	1.05	34.96785	108.88
RECAL-Run13-MD	1	2	6	24.6	195	0.92	30.61455	1249.58
	2	2	6	24.6	195	0.85	28.36097	1474.43
	3	2	6	27.2	216	0.88	29.37415	1492.93
	4	2	6	20.7	165	0.9	29.90451	953.12
	5	2	6	26	207	0.94	31.26691	1304.98
RECAL-Run13-CD	1	2	6	11.8	94	0.78	26.00295	647.36
	2	2	6	10.8	86	0.48	15.89799	866.64
	3	2	6	10.2	81	0.46	15.47292	781.41
	4	2	6	14.1	112	0.65	21.59121	934.14
	5	2	6	12.6	100	0.62	20.50678	921.21

TABLE C.5, Results of Tensile Testing for Jet Washed Fabrics – Fabric Run 1 to 3

Identification Number	Sample No.	Width Inch	Height Inch	Peak Load Lb	Peak Stress PSI	Elong @ Pk Ld Inch	%Strn @ Pk Ld Inch	Modulus PSI
JFO-Run1-MD	1	2	6	4.2	33	0.36	12.12043	381.75
	2	2	6	5.9	47	0.45	14.86509	502.84
	3	2	6	7	56	0.38	12.50953	587.35
	4	2	6	7.9	62	0.48	15.84167	556.18
	5	2	6	7	56	0.42	14.04263	556.78
JFO-Run1-CD	1	2	6	2.8	22	0.71	23.57644	164.14
	2	2	6	3	24	0.48	16.0956	174.63
	3	2	6	4.6	37	1.07	35.54478	193.67
	4	2	6	3.5	28	0.81	26.83392	164.95
	5	2	6	4	32	1	33.41626	169.91
JFO-Run2-MD	1	2	6	4.6	36	0.32	10.53997	420.14
	2	2	6	5.3	42	0.33	11.05089	551.98
	3	2	6	4.9	39	0.31	10.45596	505.41
	4	2	6	4.7	37	0.3	10.04535	477.55
	5	2	6	6.2	49	0.34	11.42949	553.03
JFO-Run2-CD	1	2	6	2.4	19	0.54	18.01773	136.54
	2	2	6	3.6	28	0.72	23.98039	165.9
	3	2	6	2.8	22	0.74	24.68324	130.61
	4	2	6	3.3	26	0.98	32.75758	135.36
	5	2	6	3	24	0.74	24.74359	139.66
JFO-Run3-MD	1	2	6	2.1	17	0.3	10.07954	342.98
	2	2	6	3.7	29	0.34	11.18	339.06
	3	2	6	2.4	19	0.28	9.48039	210.55
	4	2	6	3.6	29	0.31	10.39575	371.36
	5	2	6	1.6	13	0.28	9.4099	206.97
JFO-Run3-CD	1	2	6	1	8	0.61	20.32051	59.15
	2	2	6	2.1	16	1.41	47.13062	119.94
	3	2	6	1.1	9	1.27	42.22798	46.69
	4	2	6	1.2	10	0.67	22.21242	60.05
	5	2	6	1.2	10	0.55	18.44842	73.8

TABLE C.6, Results of Tensile Testing for Jet Washed Fabrics – Fabric Run 5 to 7

Identification Number	Sample No.	Width Inch	Height Inch	Peak Load Lb	Peak Stress PSI	Elong @ Pk Ld Inch	%Strn @ Pk Ld Inch	Modulus PSI
JFO-Run5-MD	1	2	6	14.4	114	1.08	35.85487	458.9
	2	2	6	13.9	110	0.84	28.05366	630.78
	3	2	6	15.3	121	1.05	35.09559	722.49
	4	2	6	11	87	0.85	28.37657	414.95
	5	2	6	15.6	124	1.2	40.13121	656.22
JFO-Run5-CD	1	2	6	7.8	62	1.25	41.786	269.11
	2	2	6	6.9	55	0.88	29.3775	275.62
	3	2	6	9.5	76	1.2	39.95072	327.53
	4	2	6	9.6	76	1.41	47.10781	333.56
	5	2	6	6.3	50	0.99	32.94138	300.14
JFO-Run6-MD	1	2	6	9.1	73	0.66	21.939	541.85
	2	2	6	6.3	50	0.43	14.42144	427.27
	3	2	6	10.6	84	0.73	24.49295	536.44
	4	2	6	12	95	0.96	32.05998	557.3
	5	2	6	8	63	0.61	20.33378	593.84
JFO-Run6-CD	1	2	6	5.9	47	1.1	36.6719	220.46
	2	2	6	3.2	25	0.67	22.3876	139.67
	3	2	6	2.4	19	0.56	18.67629	130.42
	4	2	6	8.2	65	1.52	50.75709	230.83
	5	2	6	3.6	28	1.06	35.33352	203.6
JFO-Run7-MD	1	2	6	5.7	45	0.39	12.9908	540.77
	2	2	6	6.9	55	0.49	16.39209	521.9
	3	2	6	7.4	59	0.56	18.62138	470.75
	4	2	6	5.1	40	0.39	13.02716	426.52
	5	2	6	4.9	39	0.49	16.45932	375.22
JFO-Run7-CD	1	2	6	2.6	21	0.97	32.26348	133.48
	2	2	6	3.7	29	0.94	31.36106	164.14
	3	2	6	4	32	0.88	29.23213	178.62
	4	2	6	3.3	26	1.04	34.68519	164.51
	5	2	6	4.4	35	1.05	35.12324	166.63

TABLE C.7, Results of Tensile Testing for Jet Washed Fabrics – Fabric Run 8 to 10

Identification Number	Sample No.	Width Inch	Height Inch	Peak Load Lb	Peak Stress PSI	Elong @ Pk Ld Inch	%Strn @ Pk Ld Inch	Modulus PSI
JFO-Run8-MD	1	2	6	3.1	24	0.29	9.77095	267.62
	2	2	6	1.8	14	0.6	20.00997	197.9
	3	2	6	3.6	28	0.47	15.55094	348.08
	4	2	6	1.9	15	0.23	7.6835	278.98
	5	2	6	2.4	19	0.46	15.36339	207.41
JFO-Run8-CD	1	2	6	0.7	5	0.89	29.69292	25.68
	2	2	6	0.7	6	1.29	42.89597	18.58
	3	2	6	0.5	4	1.18	39.29824	12.71
	4	2	6	0.8	6	1.67	55.79639	17.97
	5	2	6	0.8	7	1.43	47.67739	19.84
JFO-Run9-MD	1	2	6	30.5	242	2.87	95.79174	566.3
	2	2	6	27.6	219	2.46	81.84551	546.11
	3	2	6	29	230	2.62	87.29082	504.3
	4	2	6	17.5	139	1.2	39.89603	509.27
	5	2	6	16.8	133	1.17	38.8989	573.68
JFO-Run9-CD	1	2	6	14.3	113	1.93	64.42125	365.64
	2	2	6	19.9	158	3.2	106.70527	351.47
	3	2	6	20.1	159	2.5	83.34344	434.36
	4	2	6	22.6	179	3.21	106.98408	403.78
	5	2	6	12.8	102	1.37	45.55798	368.62
JFO-Run10-MD	1	2	6	16.1	128	1.48	49.29457	484.3
	2	2	6	24.6	195	2.55	85.02482	545.67
	3	2	6	15.4	122	1.43	47.78299	463.76
	4	2	6	21	167	1.88	62.59213	614.23
	5	2	6	20.5	163	1.91	63.52393	610.79
JFO-Run10-CD	1	2	6	13.1	104	2.04	67.87446	309.53
	2	2	6	8.2	65	1.3	43.24586	242.38
	3	2	6	6.3	50	1.1	36.67286	223.34
	4	2	6	14.5	115	2.66	88.67094	324.5
	5	2	6	9.6	76	1.45	48.27136	264.14

TABLE C.8, Results of Tensile Testing for Jet Washed Fabrics – Fabric Run 11 to 13

Identification Number	Sample No.	Width Inch	Height Inch	Peak Load Lb	Peak Stress PSI	Elong @ Pk Ld Inch	%Strn @ Pk Ld Inch	Modulus PSI
JFO-Run11-MD	1	2	6	14.2	113	1.86	61.90418	479.45
	2	2	6	15.1	120	1.5	49.99572	441.82
	3	2	6	11.4	91	1.21	40.19144	492.41
	4	2	6	14.1	112	1.67	55.67877	393.29
	5	2	6	12.1	96	1.26	42.07595	416.22
JFO-Run11-CD	1	2	6	6.2	49	1.27	42.21986	201.22
	2	2	6	6.6	53	1.28	42.51921	208.41
	3	2	6	6.9	55	1.4	46.56881	196.63
	4	2	6	8.4	67	1.51	50.31935	243.46
	5	2	6	7.5	60	1.41	46.90105	234.02
JFO-Run12-MD	1	2	6	6.9	55	0.77	25.63807	322.51
	2	2	6	9.3	74	1.02	33.98281	492.31
	3	2	6	8.9	71	0.87	28.92281	394.12
	4	2	6	7.2	57	0.65	21.56993	385.86
	5	2	6	8.5	68	0.92	30.65746	351.66
JFO-Run12-CD	1	2	6	4	32	1.55	51.77292	100.12
	2	2	6	3.4	27	1.62	54.06176	78.67
	3	2	6	3.9	31	1.25	41.64266	122.44
	4	2	6	2.8	22	1.33	44.35001	83.21
	5	2	6	2.7	22	1.21	40.49499	100.17
JFO-Run13-MD	1	2	6	13.8	109	0.96	32.00822	477.52
	2	2	6	15.1	120	1.03	34.39179	539.14
	3	2	6	12.1	96	0.75	24.88112	609.44
	4	2	6	13.2	104	0.74	24.79728	649.23
	5	2	6	13.8	110	0.89	29.61127	556.75
JFO-Run13-CD	1	2	6	5.7	45	0.81	26.9171	244.25
	2	2	6	5.9	47	0.85	28.18702	246.83
	3	2	6	6.8	54	1.03	34.26831	283.58
	4	2	6	5.8	46	0.69	22.87315	266.48
	5	2	6	6.9	55	1	33.24978	299.01

TABLE C.9, Results of Tensile Testing for Hydroentangled Fabrics – Fabric Run 1 to 3

Identification Number	Sample No.	Width Inch	Height Inch	Peak Load Lb	Peak Stress PSI	Elong @ Pk Ld Inch	%Strn @ Pk Ld Inch	Modulus PSI
HYDRO-Run1-MD	1	2	6	33.7	268	3.96	131.93335	861.03
	2	2	6	33.8	268	3.45	115.1338	905.93
	3	2	6	30.9	245	3.77	125.65376	780.98
	4	2	6	31.6	251	3.48	115.91252	*********
	5	2	6	34.1	271	4.18	139.47819	813.58
HYDRO-Run1-CD	1	2	6	12.3	98	4.89	162.99384	68.87
	2	2	6	14.5	115	6.36	211.96054	*********
	3	2	6	15.3	121	6.76	225.25692	*********
	4	2	6	10.4	83	4.25	141.55348	67.28
	5	2	6	13.1	104	5.19	172.90862	71.64
HYDRO-Run2-MD	1	2	6	28	222	3.45	114.95134	*********
	2	2	6	22.1	175	2.68	89.18972	722.75
	3	2	6	29.1	231	3.52	117.40235	*********
	4	2	6	24.5	195	3.08	102.67143	732.95
	5	2	6	20.7	164	2.34	77.99642	646.63
HYDRO-Run2-CD	1	2	6	7.3	58	3.56	118.78926	51.94
	2	2	6	10.7	85	6.04	201.32342	*********
	3	2	6	8.6	68	4.84	161.40862	*********
	4	2	6	8.8	70	4.54	151.46355	*********
	5	2	6	11	87	6.34	211.38382	*********
HYDRO-Run3-MD	1	2	6	17.3	137	2.26	75.49804	582.02
	2	2	6	18.4	146	2.21	73.771	652.41
	3	2	6	17.6	140	2.48	82.7727	606.86
	4	2	6	15.7	125	1.81	60.19894	608.15
	5	2	6	16.7	133	2.33	77.75196	575.21
HYDRO-Run3-CD	1	2	6	6.1	48	5.53	184.20471	*********
	2	2	6	6.4	51	5.65	188.37625	*********
	3	2	6	4.5	35	3.31	110.35005	32.91
	4	2	6	7.1	57	5.68	189.17727	*********
	5	2	6	6	47	4.75	158.49942	*********

TABLE C.10, Results of Tensile Testing for Hydroentangled Fabrics – Fabric Run 5 to 7

Identification Number	Sample No.	Width Inch	Height Inch	Peak Load Lb	Peak Stress PSI	Elong @ Pk Ld Inch	%Strn @ Pk Ld Inch	Modulus PSI
HYDRO-Run5-MD	1	2	6	35.2	279	4.28	142.736	*********
	2	2	6	31.5	250	3.46	115.17598	757.04
	3	2	6	35.6	282	4.08	135.85069	792.06
	4	2	6	39	310	4.55	151.52122	*********
	5	2	6	37.5	298	4.18	139.42573	792.77
HYDRO-Run5-CD	1	2	6	16.8	133	5.97	199.00055	*********
	2	2	6	17.2	136	6.43	214.47883	*********
	3	2	6	17.1	136	5.77	192.18897	*********
	4	2	6	14.4	114	4.93	164.20566	*********
	5	2	6	16.7	133	5.61	187.01458	*********
HYDRO-Run6-MD	1	2	6	35.4	281	4.06	135.37509	853.95
	2	2	6	26.3	209	3.32	110.65258	667.21
	3	2	6	33.2	263	3.96	132.11047	748.35
	4	2	6	32.3	257	3.65	121.69954	807.87
	5	2	6	31.9	253	3.79	126.48235	*********
HYDRO-Run6-CD	1	2	6	11	87	5.16	171.8599	*********
	2	2	6	12.2	97	5.86	195.38651	*********
	3	2	6	13.9	110	6.29	209.51593	*********
	4	2	6	12.3	97	5.57	185.63047	*********
	5	2	6	9.8	78	4.72	157.4261	*********
HYDRO-Run7-MD	1	2	6	21.6	172	2.69	89.73624	*********
	2	2	6	21.6	172	2.82	94.01831	598.42
	3	2	6	21.3	169	3.19	106.47698	565.24
	4	2	6	21.9	173	3.05	101.74858	573.87
	5	2	6	23.4	186	3.23	107.6827	607.28
HYDRO-Run7-CD	1	2	6	7.3	58	4.74	157.87145	*********
	2	2	6	8.5	68	5.31	176.91895	*********
	3	2	6	9.5	75	6.19	206.22228	*********
	4	2	6	9.2	73	5.59	186.3065	*********
	5	2	6	6.9	54	3.88	129.36967	44.85

TABLE C.11, Results of Tensile Testing for Hydroentangled Fabrics – Fabric Run 8 to 10

Identification Number	Sample No.	Width Inch	Height Inch	Peak Load Lb	Peak Stress PSI	Elong @ Pk Ld Inch	%Strn @ Pk Ld Inch	Modulus PSI
HYDRO-Run8-MD	1	2	6	18.3	145	1.74	58.04073	693.61
	2	2	6	13.9	110	1.19	39.58329	580.6
	3	2	6	19.8	157	1.92	63.90894	691.17
	4	2	6	14.6	116	1.34	44.50341	618.79
	5	2	6	18.5	147	1.72	57.42163	670.48
HYDRO-Run8-CD	1	2	6	2.4	19	3.69	122.96952	16.24
	2	2	6	2.6	20	3.94	131.38944	16.23
	3	2	6	3.6	29	6.21	207.01044	*********
	4	2	6	3.6	29	5.23	174.19677	18.18
	5	2	6	2.7	22	5.78	192.69519	*********
HYDRO-Run9-MD	1	2	6	36.6	291	3.73	124.30787	896.56
	2	2	6	36.5	290	4.12	137.31811	*********
	3	2	6	41.6	330	3.81	127.11512	916.45
	4	2	6	42.8	340	4.17	138.97134	*********
	5	2	6	40.3	320	3.95	131.55057	958.99
HYDRO-Run9-CD	1	2	6	23.1	183	7.68	256.10457	*********
	2	2	6	20.1	159	6.46	215.17733	*********
	3	2	6	20.2	160	6.77	225.82725	*********
	4	2	6	20	159	5.51	183.73695	*********
	5	2	6	21	166	6.93	231.14582	*********
HYDRO-Run10-MD	1	2	6	25.7	204	2.88	96.1278	672.3
	2	2	6	28.9	229	3.4	113.4615	*********
	3	2	6	29.5	234	3.46	115.31641	736.12
	4	2	6	36.5	290	3.87	128.92056	*********
	5	2	6	30.4	241	3.44	114.69428	776.83
HYDRO-Run10-CD	1	2	6	14.7	117	5.85	195.10776	*********
	2	2	6	17.2	137	7.15	238.21049	*********
	3	2	6	13.5	107	5.84	194.74892	*********
	4	2	6	15.4	122	5.98	199.23125	*********
	5	2	6	16.3	129	5.85	195.06611	*********

TABLE C.12, Results of Tensile Testing for Hydroentangled Fabrics – Fabric Run 11 to 13

Identification Number	Sample No.	Width Inch	Height Inch	Peak Load Lb	Peak Stress PSI	Elong @ Pk Ld Inch	%Strn @ Pk Ld Inch	Modulus PSI
HYDRO-Run11-MD	1	2	6	24.3	193	2.86	95.33367	719.57
	2	2	6	27.1	215	3.39	112.97449	*********
	3	2	6	21.9	174	2.93	97.55388	*********
	4	2	6	20.5	163	2.85	94.98111	*********
	5	2	6	25.3	201	3.25	108.44084	700.18
HYDRO-Run11-CD	1	2	6	8.7	69	4.92	164.09352	*********
	2	2	6	8.9	71	4.56	152.11659	53.06
	3	2	6	9.8	77	5.42	180.59067	*********
	4	2	6	9.9	79	5.79	192.83938	*********
	5	2	6	10.4	82	5.07	168.94497	55.43
HYDRO-Run12-MD	1	2	6	17.4	138	2.21	73.53144	593.24
	2	2	6	18.1	143	2.24	74.5217	598
	3	2	6	19.3	153	2.37	79.0157	598.32
	4	2	6	18.7	148	2.14	71.47262	621.32
	5	2	6	14.3	113	1.63	54.22229	554.54
HYDRO-Run12-CD	1	2	6	5.2	41	5.6	186.78389	*********
	2	2	6	5.7	45	5.49	183.1314	*********
	3	2	6	5	40	4.96	165.30462	*********
	4	2	6	3.9	31	3.26	108.67973	30.62
	5	2	6	4.9	39	5.17	172.36933	*********
HYDRO-Run13-MD	1	2	6	38.6	306	4.13	137.50383	868.15
	2	2	6	35.8	284	4.06	135.37344	837.73
	3	2	6	33.3	265	2.96	98.65568	988.98
	4	2	6	39.3	312	4	133.26111	993.64
	5	2	6	35.9	285	4.06	135.34692	861.67
HYDRO-Run13-CD	1	2	6	15.4	122	6.14	204.68116	*********
	2	2	6	10.5	84	5.06	168.63673	*********
	3	2	6	18.8	149	7.56	252.04836	*********
	4	2	6	15.1	120	5.98	199.20562	*********
	5	2	6	15.1	120	6.78	225.91694	*********