ABSTRACT

HOLLOWELL, KENDALL BIRCKHEAD. Hybrid Mixed Media Nonwovens: An Investigation of Structure-Property Relationships. (Under the direction of Dr. Behnam Pourdeyhimi.)

There have been myriad studies on utilizing bicomponent splittables produced through spunbond/spunlace processes. These production methods have proven to yield microfibers which increase the surface area of the nonwoven structures. There has been recent focus on studying the microfibers within these nonwoven structures as well as using a multiplicity of deniers of fibers within the nonwoven. There have also been studies on producing nonwovens with fibers of differing cross-sectional shapes and diameters. The purpose of this study is to examine the properties of a nonwoven structure, marrying the concepts of multi-denier fibers with multi-shaped fibers in two configurations: three-layer and alternating. The basis for this study will be US Patent 6,964,931 B2 “Method of making Continuous Filament Web with Statistical Filament Distribution” as well as US Patent 7,981,336 B2 “Process of Making Mixed Fibers and Nonwoven Fabrics”.

This study addresses the melt-spinning and hydroentanglement of nonwoven webs made from bicomponent fibers in three-layer and alternating configurations. The bicomponent cross-sections that will be used include 16-segmented pie and 7-islands-in-the-sea. In this study the establishment of the utility of mixed media nonwovens will take place through property and structure analysis in order to
determine the inherent properties of the mixed media structures as well as the structure-property relationships of the nonwoven fabric. Property and structure analysis will also take place on mixed media structures containing poly(lactic acid) as a sacrificial component in the bicomponent fiber after optimizing the removal conditions of the poly(lactic acid) in a sodium hydroxide (NaOH) bath.
Hybrid Mixed Media Nonwovens: An Investigation of Structure-Property Relationships

by
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A dissertation submitted to the Graduate Faculty of North Carolina State University in partial fulfillment of the requirements for the degree of Doctor of Philosophy

Fiber and Polymer Science
Raleigh, North Carolina
2012

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BIOGRAPHY

Kendall Hollowell was born on January 27, 1986 to Thomas and Susan Birckhead of Edenton, North Carolina. She remained in Edenton with her parents and older sister until graduating from John A. Holmes High School in 2004. She was accepted at North Carolina State University to study Textile Technology and graduated Magna Cum Laude in 2008 with a Bachelor's Degree. Kendall immediately enrolled in graduate school at North Carolina State University to begin pursuing an integrated doctoral degree in Fiber and Polymer Science under the direction and supervision of Dr. Behnam Pourdeyhimi. She received a Graduate Certificate in Nonwovens Science and Technology in the summer of 2009.

After graduation, Kendall will be employed by Freudenberg Nonwovens in Durham, North Carolina, as a Product Development Engineer.
ACKNOWLEDGMENTS

I express my deepest gratitude to Dr. Behnam Pourdeyhimi for taking me on as a student and mentoring and supporting me through this whole process. Thank you for the candid conversations and in-depth meetings we shared.

Thank you, Benoit Mazé, for our hard-core blackboard sessions and for lending me the SigmaPlot instructional tome. You do not know how much your sincere (and unsugar-coated) honesty meant to me and contributed to my success as a graduate student.

Thank you, Nagendra Anantharamaiah, for showing me the ropes of the NCRC and helping me to come out of my shell as a graduate student. I will miss your gentle suggestions and immense insight.

I would like to thank my committee for their support throughout this entire endeavor and The Nonwovens Institute for making graduate school financially possible for me. I would also like to thank my friends, colleagues, and most of all, my office mates for being my cheerleaders and confidantes for the past 4 years.

I would like to express thanks of paramount significance to my parents for instilling perseverance and compassion in me, as well as my sister for providing inspiration
for life at its most basic. Without you, I would not be who I am today. To my best friend and husband, thank you for being the calm in my storm and for your understanding and patience.

All my life’s a circle, sunrise and sundown;
The moon rolls through the nighttime, till the daybreak comes around.

All my life’s a circle, but I can’t tell you why;
The seasons spinning round again, the years keep rolling by.

No straight lines make up my life, and all my roads have bends;
There’s no clear-cut beginnings, and so far no dead ends.

-Harry Chapin
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CHAPTER 1: INTRODUCTION

Bicomponent fibers have been employed in the manufacture of nonwovens for several decades to achieve properties not easily obtained by using homocomponent fibers. The use of exotic bicomponent micro- and nanofibers in spunbond nonwoven production is expanding in many critical applications. Spunbonding bicomponent extrusion technology involves the spinning of continuous filaments composed of two polymers deposited onto a forming belt followed by mechanical, thermal or chemical bonding. Filaments produced via the spunbond process are usually no smaller than 10 to 15 microns. Reducing the fiber size further requires the use of special bicomponent fibers. The book by Nakajima published in the early 1990’s makes reference to the use of bicomponent splittables utilizing spunbond/spunlace processes [1]. One of the key patents in this area is assigned to Freudenberg (Robert Groten, et al) detailing the method for splitting segmented pie fibers in a continuous process [2]. The fabric thus formed is now known as Evolon® and is the first commercial spunbond reusable, durable micro-denier fabric, and arguably the best known micro-denier nonwoven in use today[3].

There have been myriad studies on the utilization of bicomponent splittables produced through spunbond/spunlace processes. These production methods have proven to yield microfibers which increase the surface area of the nonwoven (Figure 1.1[4]). This can be seen in the study by Shim et al., where the effect of bicomponent fiber splitting on fiber sizes and surface area was examined[5]. There
has been recent focus on studying the microfibers within these nonwoven structures as well as using a multiplicity of deniers of the fibers within the nonwoven [6]. There have also been studies on producing nonwovens with fibers of differing cross-sectional shapes and diameters [7]. The use of microfibers within a nonwoven fabric results in significantly larger surface area, improving properties such as flexibility, durability, sound and thermal insulation, liquid and gaseous filtration, and oil absorption, and has potential in applications such as battery separators, medical products, high performance wipes, and perhaps even military gear [8–15]. Discontinuous (staple) splittable fibers have also been used in various applications including wipes, leather and suede products. These, however, do not offer the same level of strength or durability as their spunbond counterparts.

Various techniques have been historically used for splitting bicomponent fibers. These include mechanical, thermal and chemical means as well as ultrasonic energy, steam, and laundering, which can also split these fibers. Different methods may form different structures with varying degrees of splittability, leading to distinct fabric properties and performance [5].
The term splittable refers to bicomponent fibers in which the two polymer phases share only one common interface such as side-by-side, segmented ribbon or segmented pie (see an example in Figure 1.2). The number of segments can be controlled fairly easily through the spinpack design, where 4, 8, 16 and 24 segments are regularly achieved [16]. Achieving a higher number of segments is theoretically possible. However, due to the increased shear during spinning, the formation of the cross-section becomes challenging. The resulting fabric containing split fibers is soft, flexible and durable. But the fibers, when split, form wedges and pack tightly resulting in low permeability and often, low tear resistance. This is precisely why
islands-in-the-sea structures exhibit superior properties when compared to 100% segmented pie bicomponent structures [17], [18].

![Figure 1.2: Representation of 16-segmented pie splittable fiber](image)

Recently, it has been demonstrated that the tear properties can be significantly improved through the use of a reinforcement layer in between two layers of segmented pie fibers [19]. A three-layer composite however, has the potential for delamination, and the problem of dense fiber packing within the bicomponent layer(s) of the composite remains. Additionally, the scrim is often noticeable through the structure and may adversely affect the surface texture and appearance.

The use of hybrid structures is not a new concept. Bond et al. [7] utilized mixed shaped fibers (by utilizing a specific spinneret) and Wang et al. [6] used different sized islands within an islands-in-the-sea configuration to achieve larger
fibers co-mingled with smaller sub-micron fibers. The motivation in Wang’s work was primarily to improve the dyability of the islands-in-the-sea fibers [6]; it is well established that micro-denier fibers cannot be dyed easily in deep shades.

A different system – hereafter referred to as mixed media, where some of the fibers in the same spin beam and spinpack are composed of splittable bicomponent fibers as well as non-splittable homocomponent fibers – will be the focus of this study. The properties of a nonwoven structure marrying the concepts of multi-denier fibers with multi-shaped fibers will be studied in two configurations: three-row and alternating.

The improvements expected from the Mixed Media are three-fold: 1) alleviate the effects of dense packing; 2) as the fibers tend to co-mingle when they are laid down because they are spun from the same spinbeam, the interface between the homocomponent fibers and the bicomponent (splittable in this case) fibers becomes “fuzzy” and therefore, the potential for layer delamination is virtually eliminated; and 3) the presence of larger fibers has the potential to improve the tear properties of the final product because the fibrous structure is not as tightly packed [20], [21].


Nonwoven webs made from bicomponent fibers in three-layer and alternating configurations will be melt spun and hydroentangled. The bicomponent cross-
sections that will be used include 16-segmented pie and 7-islands-in-the-sea. In this study, there will be two phases in the establishment of the utility of mixed media nonwovens; 1) Initial fabric characterization and mechanical analysis will take place in order to establish the inherent properties of the mixed media structures as well as the structure-property relationships of the nonwoven fabric; and 2) Property and structure analysis will take place on mixed media structures containing poly(lactic acid) as a sacrificial component in the bicomponent fiber after optimizing the removal conditions of the poly(lactic acid) in a sodium hydroxide (NaOH) bath.
CHAPTER 2: LITERATURE REVIEW

2.1 SPUNBOND TECHNOLOGY

The spunbond web formation process is one of three types of spunlaid technology; the other two types being melt blown and flash spinning [23]. Spunbond webs differ from other nonwoven fabrics due to the one-step polymer-to-fabric manufacturing process [24] and can be defined as fabrics composed of spun continuous filaments of molten polymer that are subsequently bonded. A primary factor of spunbond fabrics is the control of four sequential operations: filament extrusion, drawing, lay-down and bonding [23–28]. Spunbond technology grew out of antecedent technologies including the synthetic fiber spinning industry and dry laying, which evolved from conventional textile processes including carding and wet laying [25].

2.1.1 Historical Background

The spunbond process was originally developed for the production of glass wool by Slayter and Thomas of Owens-Corning Fiberglas Corporation in 1940 [29] and further developed by Callander, who introduced a method for producing mineral wool that would be self-sustaining [30]. Du Pont introduced a polyester spunbond product called Reemay in 1959 [1] and the commercialization of the spunbond process began around 1960 with Du Pont in the United States and Carl Freudenberg in Europe [1], [24], [25], [27], [28], [31], [32]. A patent entitled “Charged Web
Collecting Apparatus” was assigned to E.I du Pont de Nemours and Company in 1967 [33]. Progress continued in the 1960s with the commercialization of the estelle spunbond under the name Lee-May in 1965 and the early 1970s proved to be a prominent growth period for spunbond nonwovens with the years between 1970 and 1972 being especially significant for Japan. However, the oil crisis of the 1970s dampened growth in the latter part of the decade due to the dependence on petroleum-based raw materials. Following the oil crisis recovery, spunbond production proliferated thanks to the elimination of manufacturing steps that other textile producers had to pay for, thereby making it an inherently low-cost nonwoven process [31]. The 1990s proved to be prosperous for spunbonding equipment suppliers including Kobelco, Nordson and Hills [27]. Examples of spunbond processes and products include Reemay, Typar, Tyvek, Lutratil, Lutrabond, Lutradur, Corovin, Evolon, and Cerex. Below is an overview of the developmental history of spunbond technology [26], [28]:

1940—Spunbond process patented by Owens-Corning Fiberglas Corp.

US Pat. No. 2,206,058-Manufacture of Glass Wool

1945—Spunbond process with self-sustaining web patented by Callander

US Pat. No. 2,382,290-Manufacture of Mineral Wool

1950—Internal developments by major fiber producers
1959—DuPont introduces Reemay

1967—DuPont’s first spunbonding patent


1968—Freudenberg’s first U.S. patent

US Pat. No. 3,379,811-Apparatus and process for production of filaments

1968—Lurgi (DOCAN) process (Licensable in US in 1971)

1969—Kimberly-Clark develops their own version of spunbonding technology

1970—Monsanto’s patent on spunbonding nylon (Cerex)


1970—Freudenberg’s patent on producing nonwoven fleece


1976—Tuff Spun Products patents nonwoven fabric with a rough and a smooth side

US Pat. No 3,949,130-spun bonded fabric and articles made therefrom

1984—Reifenhauser turnkey spunbonding lines (REICOFIL®)

offered for sale
1988—Benoit obtains patent on centrifugal spinning spunbonding process
US Pat. No. 4,790,736-Apparatus for centrifugal fiber spinning with pressure extrusion

1991—Corovin obtains U.S. patent on its modification of spunbonding process
US Pat. No. 4,999,080-Apparatus for producing a nonwoven fabric from continuous filaments

1994—Fiberweb patents apparatus and method for forming a spunbond web

2000—Hills Inc. introduces open spunbond system

2.1.2 Process Description

The spunbond process (Figure 2.1) is initiated with the melting of polymer pellets or granules through the mechanical action of a screw extruder, where additives can be integrated into the polymer melt. Common additives include, but are not limited to, stabilizers, spin dyestuffs and resin modifiers [27]. As the polymer is conveyed from the feed hopper to the opposite end of the screw toward the filter, the polymer is gradually heated to a predetermined temperature. The temperatures and
pressures utilized in the melting process are determined by the polymer resin(s) being used.

After exiting the extruder tip, the molten polymer is transported to a filter which subsequently removes metals, unmelted polymer and other foreign particles, which have the potential to cause filament inadequacies or blockages within the spinneret holes. After leaving the filter, the molten polymer is channeled into a metering pump which precisely determines the volumetric flow rate of the polymer to the die block assembly, also known as the spinpack. It is important to retain a uniform temperature within the metering pump (in the range of +/-1°C) to ensure extrusion rate consistency [27], [34], [35].

The spinpack includes a polymer feed distribution and a spinneret, which contains thousands of holes of approximately 0.2mm diameter. In many commercial spunbonding operations, spinnerets are placed side-by-side, in what is referred to as a bank, to produce a wide web. The molten polymer is extruded through the multitude of holes, or orifices, that are found in the spinnerets and immediately quenched by chilled air. After quenching, pneumatic attenuation assists in the orientation of the molecular chains of the fibers, which subsequently increases the strength and decreases the extendibility of the spun filaments [24], [28], [36], [37]. Zhang et al. demonstrated that the molecular orientation in the filaments is higher for lower primary air temperature, leading to better tenacity and lower elongation at break [38]. The pneumatic attenuation of the filaments can occur at speeds of 6,000
meters per minute or greater [17], [27], [34], [36], [37]. The high speeds produce partially oriented fibers at high production rates [37].

Subsequent to filament drawing, filament deposition onto a moving collection belt is performed by way of pneumatic forces, including a vacuum under the collection belt. In order to maintain filament separation and uniform distribution, certain processes are utilized including pneumatic and mechanical oscillation (Figures 2.2a and 2.2b), charging on the filaments (Figures 2.3a and 2.3b), slot attenuation (Figure 2.4), full-width draw rolls, double sided secondary/tertiary air processes, and centrifugal forming [24], [27], [34], [36], [39–44]. The newly-formed, unbonded web of filaments is held to the moving belt through the use of vacuum (tertiary air) and can be either wound up on a roll or sent straight down the processing line toward bonding, which can include calendaring, hydroentangling, needling and/or bonding by means of chemicals or adhesives [45]. Most spunbond webs are between 3 and 5.2 meters wide to ensure high productivity, with fiber sizes most commonly ranging from 1.5 to 20 dtex (1.36 to 18 denier), however a range of 0.8 to 50 dtex (0.07 to 45 denier) can be achieved. The fabric basis weight can be as low as 5 g/m² (grams per square meter) or as high as 1000 g/m², but the common production range is between 10 and 200 g/m² [26], [46].

The variability in a spunbond nonwoven can be attributed to polymer properties as well as operating variables, and by closely regulating these variables, spunbond nonwovens can be produced with predetermined properties. The spunbond process variables that influence properties of the filaments and web
include polymer characteristics, melt viscosity and temperature, air temperature and flow rate, draw speed, polymer throughput rate, collection speed, and bonding method and conditions [45], [47].

Figure 2.1: Schematic diagram of the open spunbond process with belt collector
Figure 2.2: Filament bundle oscillators: a) pneumatic [39]; and b) mechanical [44]

Figure 2.3: Filament separation due to charging: a) high voltage electrostatic charge [41]; and b) corona charge [42]
2.1.3 Spunbond Structures and Properties

Spunbond webs can range from light and flexible, to heavy and stiff, and can range in thickness from 0.1 to 4 mm with the range of 0.2-1.5 mm most common. The thickness can be influenced by subsequent bonding methods. Due to the lay-down action of the spun filaments onto a moving belt, most spunbond processes create webs with anisotropic fiber orientation in the machine direction, which is determined mostly by the filament extrusion-to-belt speed ratio. The anisotropy of the web can be analyzed using image analysis techniques. It is the anisotropy of the web that usually causes higher tear strength in the cross direction due to the greater
resistance of the filaments largely oriented in the machine direction. Common web properties include high opacity per unit area, fray and crease resistance, high in-plane shear resistance, low drapability and high strength-to-weight ratios [28], [37], [46], [47].

2.1.4 Commercial Spunbond Systems

Commercial spinning systems that are commonly used in spunbonding include, but are not limited to, REICOFIL®, Lurgi DOCAN® and Lutravil. The Reifenhäuser REICOFIL® process has been in continuous development since 1986 and includes the following components: preparation of raw material, dosing unit for primary polymer, pigments and additives, extruder, melt filter, spin pump to ensure a constant throughput to the spin unit, sheet distributor with spinneret, filament cooling, filament extension, discharge unit (diffuser), web forming apparatus for discharge and conveyance of the filaments, bonding, calendaring (if required) and winding. The closed-process REICOFIL® system utilizes a coathanger die which feeds the molten polymer to the spinneret, thereafter forming a curtain of filaments. The continuous filaments are pulled through a high-velocity, low-pressure zone, also known as a venturi system, and then through a distribution chamber to ensure that the filaments are entangled [28], [38]. Once the filaments have been cooled, drawn and deposited onto the perforated conveyor as a nonwoven web, the parameters of calendaring, including heat and pressure, can be set to attain specific web properties. The low energy consumption of this process (1-1.2 kwh/kg) makes it an

The Lurgi DOCAN® process was developed in 1970 by the Lurgi Kohle & Mineral-öltechnik Gmbh of Germany [26], [37]. The steps in the licensable DOCAN® process are based on the melt spinning technique and include forcing the molten polymer through spinnerets by spin pumps, aerodynamic cooling and stretching, high pressure draw-off, filament separation and fanning after passing through a guide tube, and random filament deposition onto a moving belt through the mechanism of suction [28], [37]. The DOCAN® process can be run at high speeds and is based on long-spinning which requires a large, tall space to form the filaments [27].

The Lutravil spunbonding system was developed by Freudenberg Company of Germany in 1965 to produce Viledon M® from mixed polyamides [28]. Due to its proprietary nature, the Lutravil system is not available for commercial licensing, however it is based on a melt spinning technique that utilizes primary (chilled) and secondary (ambient) air as well as tertiary (suction) air for drawing and orienting the filaments [28], [37] US Patent 3,975,224, assigned to Lutravil Spinnvlies GmbH & Co. describes the process for creating dimensionally stable, high-tenacity non-woven webs [53]. US Patent 3,991,250 describes a spunbond fabric made from Nylon 6, also assigned to Lutravil Spinnvlies GmbH & Co [54].
In addition to the REICOFIL®, DOCAN® and Lutravil processes, the Rieter PERFO-bond™ system has become a major constituent in the spunbond manufacturing world by integrating spunbond and spunlace processes. Rieter expanded their business in 2000 by adding the PERFO-bond™ spunbond technology to their product line [55]. A defining aspect of PERFO-bond™ spunbond technology is the replacement of Lurgi tubes with a slot draw system in addition to a corona treatment. The slot draw system employs a pneumatic attenuator in the shape of an elongated rectangle spanning the width of the web [56]. US Patent 5,397,413 describes the production of spunbond webs using a slot draw attenuation apparatus (Figure 2.5) [57].

Figure 2.5: Slot draw attenuation apparatus [57]
2.1.5 Raw Materials (Polymers)

The method of spunbond manufacture determines the web characteristics. However, the intrinsic properties of the web are determined by the polymer utilized. Some properties that are a function of the polymer are fiber density, temperature resistance, chemical stability, light stability, dyability and surface energy [46]. Theoretically, any filament-forming polymer that has relatively low melt viscosity at processing temperature can be used in the spunbond process. However, most commercially available spunbond fabrics are made from either isotactic polypropylene or polyester, with a small percentage made from nylon, high density polyethylene and polyurethane. There has been interest in the use of linear low density polyethylene in spunbonding due to its ability to impart softness on the fabric but, when compared to polypropylene, the cost is not economically justifiable for widespread use [1], [24], [47]. Polymer variables that influence the processability include polymer type, molecular weight, molecular weight distribution, additives, polymer degradation, and the form of the raw material (pellets or granules) [37], [47]. Most polymers that are used in spunbonding have high molecular weight and broad molecular weight distribution to ensure a more uniform web, for example polypropylene (PP), polyester (PET) and polyamide (PA), also known as nylon [37]. Polypropylene and polyethylene are both common examples of low melt flow rate (MFR) polymers used in spunbonding but high MFR polymers can also be used to allow higher rates of throughput and lower operating temperatures [47].
Polypropylene

Isotactic polypropylene (PP) was first used in commercial spunbond fabrics in the 1960s and has since become the most widely used polymer in the spunbonding process because of its versatility and low density, leading to high yield (fiber per kilogram) and covering power at a low cost. In addition, polypropylene fibers can be repelletized and blended with virgin polypropylene polymer to produce high grade spunbond fabrics. One problem with polypropylene is that it is rapidly degraded by ultraviolet light if not stabilized. However, with the addition of stabilizers, the life of the fabric can be greatly extended [24], [27], [37], [46], [47]. The absence of dye receptor sites on the molecular backbone of polypropylene prevents fibers from being dyed or stained. Instead, pigments can be added to the polymer melt during spunbonding, allowing the color to reside within the fiber after the polymer has been spun. This method of coloration leads to higher fade resistance and less color variation in production lots of polypropylene fibers [24].

Polyester

Although polyester (PET) is more costly than polypropylene, its advantages over polypropylene include higher strength, modulus and dimensional stability at higher temperatures when properly drawn. It is also easily dyed and/or printed using conventional equipment. Unlike polypropylene, polyester scrap is not readily recycled in spunbond manufacturing [24], [27], [37], [46], [47], [58]. Zhang et al, investigated the use of polytrimethylene terephthalate (PTT) in melt-spun
nonwovens including spunbonding. The attractive properties of this form of polyester include elastic recovery and high elongation at break, decent gamma radiation resistance, low shrinkage and high resistance to caustic soda (NaOH). However, fibers made from PTT are softer than conventional polyester and demonstrate lower initial modulus and tenacity [59].

*Nylon (Polyamide)*

Nylon (PA) 6 and nylon 6,6 are used in spunbonding applications where excellent cover and high strength are required at low basis weights (as low as 10 g/m²). Spunbond fabrics made from nylon are more expensive than polypropylene or polyester fabrics due to the cost of the materials used in the production of the resins for the pellets. There is also the disadvantage of static generation in Nylon due to its positive ranking in the triboelectric series. If nylon is processed on equipment made of steel, a charge would be generated due to the distance between nylon and steel in the triboelectric series. This problem of static generation usually requires that an antistatic agent is added to the polymer melt before extrusion. Nylon fabrics readily absorb water through the hydrogen bonding between the amide group and water molecules [24], [27], [37], [46], [47], [60], [61].

*Polyethylene*

Polyethylene (PE) is more expensive than polypropylene with slightly lower fabric yield and filament strength, although the processing is cheaper and easier
than polypropylene due to the lower melting point. Fiber-grade PE resin was first introduced in late 1986 but experienced slow acceptance because of the cost. Its good chemical resistance and hydrophobicity, excellent electrical insulation, and ability to be sterilized with gamma rays contributed to its importance in the spunbond nonwovens market [24], [27], [34], [37], [46], [47].

**Polyurethane**

Polyurethane’s (PU) importance as a spunbonding fiber can be attributed to its high stretchability and high elongation recovery, although it is very expensive. Its application areas include sportswear interlinings, medical tape and simulated leather. Kanebo Ltd. of Japan developed the first commercial process and apparatus for producing melt spun thermoplastic urethanes for apparel and in applications requiring stretch and recovery [62]. Mitsui Chemicals, Inc., also of Japan, has recently developed a method for producing an elastic nonwoven spunbond fabric containing thermoplastic polyurethane fibers [63].

### 2.1.6 Bonding and Finishing Methods

Most of the bonding methods currently being used for spunbond webs were developed for staple fibers and later adapted to continuous filament processes. The most common techniques utilized include thermal bonding, chemical/adhesive bonding and mechanical bonding, including needle punching and hydroentangling. The application or end use of the bonded web dictates the technique or combination
of techniques employed [37], [46], [47]. In the past, using spunbonding and hydroentangling in series was not economical because of the high speed of spunbonding and the slow speed of hydroentangling, however the hydroentangling process has been improved and is now the preferred in-line bonding method for spunbonded nonwoven webs [64]. The capacity of the hydroentangling process to bond, entangle and split bicomponent fibers makes it an attractive nonwovens process and therefore will be the primary bonding method described.

Hydroentangling

Hydroentangling, also known as spunlacing, is a process which employs high pressure water jets to entangle fibers in a loose web thereby creating a fabric held together by frictional forces between the said fibers [65]. Hydroentangling can produce spunbond webs at higher speeds, with higher initial modulus and tensile strength and lower basis weights, than needled webs. Final bonded webs can be produced at speeds of up to 900 meters per minute (m/min) with 5-300 m/min typical and have basis weights ranging from 20 to 800 g/m² with working widths ranging from 1.2-5.4 meters [46], [64], [66–68]. The popularity of hydroentangling can be attributed to the ability to produce multi-layered nonwovens, the elimination of the need for binders, high operating speeds, the ability to bond and split bi- and multi-component fibers, and the ability to bond spunbond webs in-line. One of the more interesting applications for hydroentangling is the splitting of bicomponent fibers [64].
Hydroentanglement was investigated in the 1960s and 1970s by DuPont and Chicopee and was officially commercialized by DuPont in 1973 with the Sontara® product. Since then, major developments have been made in hydroentanglement technology to make it a more efficient and cost effective mode of mechanical bonding of fibrous webs [69].

Gong et al. studied segmented pie bicomponent fiber splitting in carded webs and found that the degree of fiber splitting during hydroentanglement depends on jet pressure and fiber position in the web thickness direction. They also concluded that bicomponent microfiber nonwovens that have been split have increased fiber entanglement and a denser structure, and that increasing jet pressure increases fiber splitting while simultaneously increasing the risk of fiber damage [70]. Sun et al. also found that excessive hydroentangling can make a nonwoven fabric weak because of fiber breakage. Additionally, it was found that basis weight increased after hydroentangling due to shrinkage of the web [71]. In a study by Hajiani et al., it was found that as the jet pressure increased, the mass density increased while the thickness, water vapor permeability and capillary pore size decreased. A schematic of the hydroentangling process can be seen in Figure 2.6.
2.1.7 Bicomponent Fibers

*Fibersource* defines bicomponent fibers as “single fibers comprised of two polymers of different chemical and/or physical properties extruded from the same spinneret with both polymers within the same filament” [72]. Bicomponent fibers can be utilized as an alternative route to the production of microfiber fabrics by subsequent splitting or fibrillation of the components. The current methods of producing bicomponents include meltblowing and spunbonding, although the preferred method is spunbonding due to the higher crystallinity and orientation. A representation of a bicomponent spunbonding system can be seen in Figure 2.7 below. Bicomponents were first commercialized by DuPont in the 1960s with the nylon side-by-side Cantrece product. Around the same time, the British company...
Imperial Chemical Industries (I.C.I), which is now a part of Akzo Nobel, developed Heterofil™ fibers, produced from sheath-core nylon 6/nylon 6,6 fibers [73–76]. One major reason for the importance and popularity of bicomponent fibers is the ability to spin large denier fibers using conventional melt-spinning equipment with bicomponent dies and use subsequent splitting or fibrillation processes to transform the large denier fibers into micro-denier fibers (usually less than 1 denier). The ease of splitting or fibrillating can be attributed to the immiscibility of the polymer components, the melting point differences, crystallization properties, viscosity, and triboelectric charge development potential. The polymer combinations must be incompatible (small diffusion coefficients) but comparable to ensure splitting occurs without fiber defects or processing problems. Common polymer combinations include polyester and polypropylene, polyester and polyethylene, nylon and polypropylene, nylon and polyethylene, nylon and polyester, and nylon and poly(lactic acid) [21], [71], [77]. Jiang et al. studied the segregation of polymer-polymer blend composites during melt spinning and concluded that the immiscibility of the polymers is imperative if splitting or segregation is to occur [78]. In some bicomponent applications, one of the polymers can function as a binder if it has the lower melting temperature. This is sometimes utilized as a lower-melting sheath covering a higher-melting core [37], [46]. Bicomponents are classified according to the component distribution within the cross-sectional area of the fiber. The main types of bicomponent fibers include matrix-fibrils and splittables. Matrix-fibril bicomponent fibers include sheath-core, and islands-in-the-sea, whereas splittables
include side-by-side, segmented pie, tipped-trilobal, and ribbon. Examples of these can be seen in Table 2.1 below [74], [75].

Figure 2.7: Bicomponent spunbond schematic [79]
Table 2.1: Examples of bicomponent fiber cross sections

<table>
<thead>
<tr>
<th>Family</th>
<th>Bicomponent Fibers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sheath-Core</td>
<td><img src="image" alt="Sheath-Core Fibers" /></td>
</tr>
<tr>
<td>Lobed</td>
<td><img src="image" alt="Lobed Fibers" /></td>
</tr>
<tr>
<td>Side-by-Side</td>
<td><img src="image" alt="Side-by-Side Fibers" /></td>
</tr>
<tr>
<td>Micro-Denier</td>
<td><img src="image" alt="Micro-Denier Fibers" /></td>
</tr>
</tbody>
</table>
2.1.7.1 Segmented Pie

The most well-known commercially available segmented pie nonwoven is Evolon® made by Freudenberg. Generally, it contains 16 alternating segments of 70% PET / 30% PA [19], [21], [79]. Evolon® debuted in Atlanta, Georgia at the TechTextil exhibition in 2000. Segmented pie fibers are considered to be a part of the class of bicomponents known as “splittables” where the interface between the two polymer components controls the separation of the components through mechanical force or thermal action [1], [18]. Segmented-pie bicomponents usually contain 16-24 segments made from nylon and polyester, however they can be made from any of the immiscible polymer combinations addressed previously. Nonwoven fabrics made from segmented pie microfibers are dense and compact due to the packing of the microfiber wedges and therefore have low permeability and the tensile and tear properties can prove inadequate for certain applications [21]. In a study by Shim et al., the splitting of segmented pie bicomponents was investigated through three-dimensional digital volumetric imaging and addressed the importance of expanding the understanding of the materials-process-performance interactions in splittable bicomponent nonwovens [5].

2.1.7.2 Islands-in-the-Sea

Islands-in-the-sea fibers are part of the class of bicomponents known as fibrillatables. The definition of a fibrillatable bicomponent refers to the ability to separate the fibrils within a matrix through the use of either mechanical action or the
removal of the matrix through dissolution. Since there is not one single interface shared by the two components, as is the case with splittables, more force is usually required to break apart the fiber [1], [18], [80]. Islands-in-the-sea solvent-based sea removal technology was first developed by Toray and has since become an integral part of bicomponent and microfiber technology [81]. This bicomponent technology has been proven to provide excellent fiber diameter control and can be utilized in applications where fabric pore size specification is critical [82]. A great deal of research has been done on the fibrillation of islands-in-the-sea bicomponents using hydroentangling as either a method for bonding or splitting, or both. For example, Fedorova and Pourdeyhimi studied islands-in-the-sea fibers with up to 360 islands in order to produce relatively high strength micro- and nanofiber based nonwovens [9]. Durany et al. investigated the use of islands-in-the sea bicomponent fibers to produce high surface area nonwovens through the mechanical action of fibrillation via hydroentangling [12]. Anantharamaiah et al. studied the mechanical properties of islands-in-the-sea fibers after fracturing and concluded that fabric strength and surface area can be enhanced by using islands-in-the-sea fibers in conjunction with certain types of bonding techniques [8]. Islands-in-the-sea fibers have applications in nonwovens, synthetic leather, artificial suede, specialty wipes and filtration media [21], [75].
CHAPTER 3: HYBRID MIXED MEDIA NONWOVEN TECHNOLOGY

3.1 RATIONALE BEHIND MIXED MEDIA CONCEPT

It has been a long-standing issue to be able to produce a strong fabric with relatively small pores and high air permeability. There are well-known methods to address each attribute separately however, when one variable is changed, the effects of that single change have repercussions on other fabric properties and characteristics. For example, the strength can easily be improved by increasing the basis weight. If there is a requirement to produce a fabric with high strength and a low basis weight, another option must be investigated to solve the problem.

One common method for creating a nonwoven fabric with adequate strength, small pores and high air permeability involves utilizing a blend of small and large denier staple fibers. However, this process is slow and would therefore be an expensive finished product. Another common method that has been investigated utilizes layers, wherein the two outer layers are comprised of large-denier fibers and the inner layer contains small-denier fibers. The problem with this method is that delamination of the layers is common, due to the fact that the three layers are produced separately and subsequently incorporated into one single composite structure. An example of such a layered composite structure is spunbond/meltblown/spunbond (SMS). Newkirk et al and Bornslaeger studied this type of composite structure [56], [83]. Other types of composite structures include SM, and SMMS (Figure 3.1).
The method being investigated here involves the spinning of homocomponent and bicomponent fibers in specified arrangements to create a nonwoven with adequate strength, small pore sizes and a low basis weight, in addition to eliminating the problem of layer delamination.

The use of bicomponent fibers in conjunction with homocomponent fibers also leads to a range of fiber diameters in the final structure after the bicomponent fibers are split. The result is a nonwoven fabric with micro-denier and large denier fibers intermingled, preventing significant compaction and potentially enhancing properties including loft, breathability, strength and flexibility, as well as filtration efficiency and thermal properties. The increased strength compared to conventional 100% segmented pie structures comes from larger diameter homocomponent fibers acting as a “rip-stop” mechanism in the structure. In mixed media nonwoven technology, bicomponent fibers and homocomponent fibers are simultaneously formed in a

Figure 3.1: Example of a composite structure with a central scrim
predetermined ratio into the nonwoven structure by customizing the spinpack in one of many configurations: three-layer, alternating, random, etc.

This study deals with the design of mixed media spunbonded nonwoven fabric containing bicomponent filaments and homocomponent filaments to enhance the properties of the fabric through the control of the packing and consolidation of the fibers. As in regular bicomponent fibers, splitting is made possible by the immiscibility between the two polymers used in the bicomponent system (for example, polyester and nylon), thus making the interface between the two polymers weak. The novelty of such a configuration is that, in a traditional spunbonding set-up, one would require multiple spin-beams (at least three in this case, with each beam corresponding to spinning one type of filament cross-section, either bicomponent or homocomponent) (Figure 3.2), whereas in the three-layer mixed media configuration, for example, only one spin-beam yields the intended fabric formation (Figure 3.3). This could result in immense value addition, with low capital investment costs to existing spunbonding lines. Furthermore, by using the appropriate polymer for the homocomponent filaments, one can enhance such properties as strength and dyability, while maintaining the appropriate microfiber features on the surface(s). This study compares the properties of the mixed media three-layer configuration of 16-segmentedpie spunbond fabric with those of the only commercially available 100% 16-segmentedpie fabric. This study will verify whether the homocomponent layer sandwiched in between two layers of 16-segmentedpie bicomponent layers will prevent dense packing, allowing for higher air permeability.
while concurrently preserving, or even improving the web integrity, surface smoothness, uniformity and strength.

Figure 3.2: Conventional spunbonding set-up to achieve three-layered structure
Important processing parameters for mixed media nonwovens include hydroentangling energy administered and polymer ratio. The hydroentangling energy should be sufficient enough to entangle the fibers for web integrity and if intended, split or fibrillate the bicomponent fibers. If the hydroentangling energy is too high, the fibers could be damaged, leading to a nonwoven fabric with decreased strength[9], [12], [71]. Since every other wedge in a segmented pie bicomponent configuration is also the same polymer as the homocomponent in a mixed media nonwoven, the input polymer ratio (amount of polymer A / amount of polymer B) changes the size of the wedges, which could impact splitting and/or thermal bonding. Since mixed media technology is relatively new, methods are still being explored to optimize the hydroentangling energy and polymer ratios for specific
Applications in which mixed media nonwoven technology would be advantageous include aerosol and liquid filtration, personal care, medical and automotive products [21].

This study combines previous technologies that aimed to create a mixed-polymer, mixed denier or mixed filament shape (in some cases) nonwoven fabric using spunbond technology. The previous technologies serving as a basis for this study include the development of the islands-in-the-sea technique [1], the separation of multi-component fibers to create a nonwoven fabric with fine filaments [2] and islands-in-the-sea fibers with differing diameters, therefore creating mixed denier filaments after splitting [6]. In addition, this study utilizes the technique of combining two or more fibers of different cross-sections and different comparable diameters [7] as well as zoned placement of filaments within the fabric [22] (Figure 3.4).
Figure 3.4: Basis technology for mixed media nonwovens
3.2 Mixed Media Configuration Designation

The three-layer 16-segmented pie configuration (Figure 3.5) was modeled after the layered composite structure that is commonly referred to as spunbond-meltblown-spunbond (SMS). It should be noted that in SMS composite structures, the small meltblown filaments are on the interior layer of the fabric and the large denier spunbond filaments are on the top and bottom layers. In the three-layer mixed media configuration, the homocomponent (large denier) filaments are on the interior of the fabric and the bicomponents, which are subsequently split, forming the microfibers, are on the outer layers of the fabric. The reason for this is that the bicomponent fibers would not be sufficiently split by hydroentanglement if they were on the interior of the fabric. The effect of using a three-layer structure is a difference in fiber size along the thickness (Z-direction) of the fabric, and depending on the end-use of the nonwoven, this may or may not be preferred. As discussed previously, one drawback of using segmented pie bicomponent fibers is that after splitting, the microfibers are wedge-shaped and pack tightly. This leads to a densified fibrous structure and has a negative impact on the air permeability, strength, and pore size (Figure 3.6). The three-layer 16-segmented pie mixed media nonwoven fabric will be referred to hereafter as MM-3L-SP.
Figure 3.5: MM-3L-SP

Figure 3.6: Graphic representation of the packing of wedge-shaped microfibers after splitting
The reason for utilizing an alternating configuration (Figure 3.7), hereafter referred to as MM-ALT-SP, is to create a nonwoven web with intimately blended micro- and macro-fibers in a continuous spunbonding and hydroentangling process. Producing a consistent and homogeneous fiber mixture, represented in the entirety of the web, ensures that the characteristics of the web can be easily predicted or predetermined for specific applications [84], [85]. Historically, the only way to produce a uniform nonwoven web with multiple fiber types or deniers was to utilize the carding process followed by bonding [86].

Carding is the mechanical process which opens fiber tufts into individual fibers, blends the fibers, and produces a fiber web through the teasing action of wire-dressed rollers rotating at different speeds to allow for fiber transfer from one roller to another [60], [84], [85], [87–89]. Carding generally produces webs under 80 g/m² and requires a cross-lapper to increase the basis weight. There is also the potential for nep formation and fiber damage due to fiber-to-fiber and fiber-to-wire friction. In order to minimize fiber damage, the throughput rate of carding is generally kept slow, most commonly between 75 and 200 m/min, however Dilo Spinnbau high speed cards can have web infeed speeds of up to 400 m/min [85], [87–90]. Utilizing mixed media spunbond nonwovens allows for throughput rates to be greatly increased (up to 800 m/min) and eliminates the need for bale and tuft opening and fiber blending. The fiber damage due to the mechanical carding action of the wire-dressed rolls is nonexistent and the basis weight can range from 5 to 1,000 g/m²,
with the range between 10 g/m² and 200 g/m² most common [26], [46], [91]. A schematic of the carding process can be seen in Figure 3.8 below.

Figure 3.7: MM-ALT-SP

Figure 3.8: Representation of roller-top carding action [96]
The 7-islands-in-the-sea alternating configuration (Figure 3.9) was investigated to solve the problem of creating an intimate blend of large and small fibers to fulfill the requirements of strength, small pores, high permeability, and low basis weight without having to layer the fabric, therefore eliminating the gradient effect in the fabric while simultaneously eliminating the dense packing of wedge-shaped microfibers. This configuration will be referred to hereafter as MM-ALT-IS.

![Figure 3.9:MM-ALT-IS](image)

### 3.3 Discussion on Configuration Ratios

In the control fabric utilized, there is one important ratio: the input amount of polymer A to the amount of polymer B into the spunbonding system. In mixed media nonwovens, due to the complex nature of utilizing a mixture of homocomponents and bicomponents, as well as multiple polymers within the same nonwoven web, there is a need to define the ratio of homocomponent fibers to bicomponent fibers.
and the ratio of segment A to segment B, or islands to sea, respectively, in addition to the input amounts of the polymers. For each sample, regardless of configuration, the ratio of polymer A to polymer B is known as well as the total number of holes in the spinpack and the amount of those holes which are homocomponent and those which are bicomponent. Assuming that the polymer flows through the homocomponent and bicomponent channels in the same manner, these parameters can be utilized to predict the amount of polymer that will go into each component in one single bicomponent fiber, therefore determining the size of each component; in this case, a wedge or an island.

3.3.1 100% 16-Segmented Pie Control Fabric

In the case of the control fabric made from 100% 16-segmented pie bicomponent fibers with 75% Polymer A and 25% Polymer B, the following equations will define the ratio of Segment A to Segment B in any single bicomponent fiber.

Ratio of Polymer A to Polymer B (in total fabric):

Given: \( P_A(\%) = 75\% \) \hspace{1cm} \( P_B(\%) = 25\% \)

Ratio of Homocomponent (\( H_A \)) to 16-SP Bicomponent (\( X \)) (in total fabric):

\[
\text{Ratio of } H_A : X = 0\% : 100\%
\]
Ratio of Segment A ($S_A$) to Segment B ($S_B$) (in one 16-SP fiber):

$$S_A = \frac{P_A}{8} \quad \text{(Eq. 3.1)}$$

$$S_A = \frac{0.75}{8}$$

$$S_A = 0.09375$$

$$S_A(\%) = 9.375\% \text{ per A segment}$$

$$S_B = \frac{P_B}{8} \quad \text{(Eq. 3.2)}$$

$$S_B = \frac{0.25}{8}$$

$$S_B = 0.03125$$

$$S_B(\%) = 3.125\% \text{ per B segment}$$

**Ratio of $S_A$ to $S_B = 9.375\% : 3.125\%**

These equations can be used to calculate the ratios for any 100% 16-segmented pie configuration by utilizing the known number of holes in the spinpack and the percent amounts of Polymers A and B fed into the system.
Table 3.1: Ratio comparison breakdown for control configuration

<table>
<thead>
<tr>
<th>Ratio of Polymer A to Polymer B</th>
<th>75% : 25%</th>
<th>50% : 50%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ratio of Homocomponent to Bicomponent</td>
<td>0% : 100%</td>
<td>0% : 100%</td>
</tr>
<tr>
<td>Ratio of Segment A to Segment B</td>
<td>9.375% : 3.125%</td>
<td>6.25% : 6.25%</td>
</tr>
</tbody>
</table>

3.3.2 Mixed Media Three-Layer Segmented Pie Configuration

In the case of MM-3L-SP with 75% Polymer A and 25% Polymer B, the following equations will define the ratio of homocomponent to bicomponent as well as the ratio of Segment A to Segment B in any single bicomponent fiber.

Ratio of Polymer A to Polymer B (in total fabric)

Given: \( P_A(\%) = 75\% \quad P_B(\%) = 25\% \)
Ratio of Homocomponent ($H_A$) to 16-SP Bicomponent ($X$) (in total fabric):

$$H_A(\%) = \left(\frac{N_H}{N_T}\right) \times 100$$  \hspace{1cm} (Eq. 3.3)

$$H_A(\%) = \left(\frac{806}{2,222}\right) \times 100$$

$$H_A(\%) = 0.36 \times 100$$

$$H_A(\%) = 36\%$$

$$X(\%) = \left(\frac{N_B}{N_T}\right) \times 100$$  \hspace{1cm} (Eq. 3.4)

$$X(\%) = \left(\frac{1,416}{2,222}\right) \times 100$$

$$X (\%) = 0.64 \times 100$$

$$X (\%) = 64\%$$

**Ratio of $H_A$ to $X = 36\% : 64\%$**

Where $H_A$ is the percent of homocomponent and $X$ is the percent of bicomponent in a given unit of fabric and $N_H$, $N_B$ and $N_T$ are the number of homocomponent holes, the number of bicomponent holes, and the total number of holes in the spinpack, respectively.

The amount of Polymer $A$ in a homocomponent layer in MM-3L-SP can be defined as:

$$H_{PA} = P_A \times H_A$$  \hspace{1cm} (Eq. 3.5)

$$H_{PA} = 0.75 \times 0.36$$

$$H_{PA}(\%) = 27\%$$
Where $H_{PA}$ is the amount of Polymer A in the homocomponent layer, and $P_{A}$ is the total amount of Polymer A in the nonwoven web.

The amount of polymer in one bicomponent layer in MM-3L-SP can be defined as:

$$B_{PA} = \frac{(P_{A} - H_{PA})}{2} \quad (Eq. 3.6)$$

$$B_{PA} = \frac{(0.75 - 0.27)}{2}$$

$$B_{PA} = 0.48/2$$

$$B_{PA} = 0.24$$

$$B_{PB} = \frac{P_{B}}{2} \quad (Eq. 3.7)$$

$$B_{PB} = 0.25/2$$

$$B_{PB} = 0.125$$

Where $B_{PA}$ is the amount of Polymer A and $B_{PB}$ is the amount of Polymer B in a bicomponent layer, respectively, and $P_{B}$ is the known percentage of polymer in the nonwoven web.

Ratio of Segment A ($S_{A}$) to Segment B ($S_{B}$) (in one 16-SP fiber):

$$S_{A} = \frac{B_{PA}}{n_{A}} \quad (Eq. 3.8)$$

$$S_{A} = 0.24 / 8$$

$$S_{A} = 0.03$$

$S_{A}(\%) = 3\% \text{ per A segment}$
\[ S_B = \frac{B_{PB}}{n_B} \]  
\[ S_B = 0.125 / 8 \]
\[ S_B = 0.0156 \]

\[ S_B(\%) = 1.56\% \text{ per } B \text{ segment} \]

\textbf{Ratio of } S_A \text{ to } S_B = 3\% : 1.56\%

Where \( n \) is the number of segments within a single bicomponent fiber composed of the specified polymer.

These equations can be used to calculate the ratios for any MM-3L-SP configuration by utilizing the known number of holes in the spinpack and the percent amounts of Polymers \( A \) and \( B \) fed into the system. A comparison of the three ratios of MM-3L-SP can be seen in Table 3.2 below.
Table 3.2: Ratio comparison breakdown for MM-3L-SP configuration

<table>
<thead>
<tr>
<th>Ratio of Polymer A to Polymer B</th>
<th>75% : 25%</th>
<th>50% : 50%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ratio of Homocomponent to Bicomponent</td>
<td>36% : 64%</td>
<td>36% : 64%</td>
</tr>
<tr>
<td>Ratio of Segment A to Segment B</td>
<td>3% : 1.6%</td>
<td>2% : 3.1%</td>
</tr>
</tbody>
</table>

### 3.3.3 Mixed Media Alternating Segmented Pie Configuration

In the case of MM-ALT-SP with 75% Polymer A and 25% Polymer B, the following equations will define the ratio of homocomponent to bicomponent fibers as well as the ratio of Segment A to Segment B in any single bicomponent fiber.

**Ratio of Polymer A to Polymer B (in total fabric):**

Given: $P_A(\%) = 75\%$ \quad $P_B(\%) = 25\%$
The ratio of homocomponent fibers to bicomponent fibers in MM-ALT-SP can be calculated using Equations 3.3 and 3.4 from above. After calculating, it is determined that the ratio of homocomponent (H_A) fibers to 16-segmented pie bicomponent (X) fibers in the fabric is 50% to 50%, respectively.

Equation 3.5 from above can be utilized again to calculate the amount of Polymer A used to create the homocomponent portion (H_PA) of MM-ALT-SP, which is 37.5% of the given 75% of Polymer A.

The amount of polymers A and B in the bicomponent portion of MM-ALT-SP can be defined as:

\[ B_{PA} = P_A - H_{PA} \]  \hspace{1cm} (Eq. 3.10)

\[ B_{PA} = 0.75 - 0.375 \]

\[ B_{PA} = 0.375 \]

\[ B_{PA} (\%) = 0.375 \times 100 \]

\[ B_{PA} (\%) = 37.5\% \]

\[ B_{PB} = P_B \]  \hspace{1cm} (Eq. 3.11)

\[ B_{PB} = 0.25 \]

\[ B_{PB} (\%) = 0.25 \times 100 \]

\[ B_{PB} (\%) = 25\% \]
Where $B_{PA}$ is the amount of Polymer A and $B_{PB}$ is the amount of Polymer B in the sum of bicomponent fibers in the configuration, respectively, and $P_B$ is the known percentage of Polymer B in the nonwoven web.

The ratio of Segment A ($S_A$) to Segment B ($S_B$) in a single 16-segmented pie fiber in an alternating configuration can be calculated reusing Equations 3.8 and 3.9 from above.

$$S_A = \frac{B_{PA}}{n_A} \quad \text{(Eq. 3.8)}$$

$$S_A = 0.375 \div 8$$

$$S_A = 0.0469$$

$S_A(\%) = 4.69\% \text{ per A segment}$

$$S_B = \frac{B_{PB}}{n_B} \quad \text{(Eq. 3.9)}$$

$$S_B = 0.25 \div 8$$

$$S_B = 0.03125$$

$S_B(\%) = 3.125\% \text{ per B segment}$

**Ratio of $S_A$ to $S_B = 4.69\% : 3.125\%$**

Where $n$ is the number of segments within a single bicomponent fiber composed of the specified polymer.

These equations can be used to calculate the ratios for any MM-ALT-SP configuration by utilizing the known number of holes in the spinpack and the percent
amounts of Polymers A and B fed into the system. A comparison of the three ratios of MM-ALT-SP can be seen in Table 3.3 below.

Table 3.3: Ratio comparison breakdown for MM-ALT-SP configuration

<table>
<thead>
<tr>
<th></th>
<th>75% : 25%</th>
<th>50% : 50%</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Ratio of Polymer A to Polymer B</strong></td>
<td>75% : 25%</td>
<td>50% : 50%</td>
</tr>
<tr>
<td><strong>Ratio of Homocomponent to Bicomponent</strong></td>
<td>50% : 50%</td>
<td>50% : 50%</td>
</tr>
<tr>
<td><strong>Ratio of Segment A to Segment B</strong></td>
<td>4.7% : 3.1%</td>
<td>3.1% : 6.25%</td>
</tr>
</tbody>
</table>

3.3.4 Mixed Media Alternating Islands-in-the-Sea

In the case of MM-ALT-IS with 75% Polymer A and 25% Polymer B, the following equations will define the ratio of homocomponent to bicomponent as well as the ratio of islands to sea in any single bicomponent fiber in the configuration.
Ratio of Polymer A to Polymer B (in total fabric):

Given: \( P_A(\%) = 75\% \) \( P_B(\%) = 25\% \)

The ratio of homocomponent fibers to bicomponent fibers in MM-ALT-IS can be calculated using Equations 3.3 and 3.4 from above. After calculating, it is determined that the ratio of homocomponent (\( H_A \)) fibers to 7-Islands-in-the-sea bicomponent (\( X \)) fibers in the fabric is 50% to 50%, respectively.

Equation 3.5 from above can be utilized again to calculate the amount of Polymer A used to create the homocomponent portion (\( H_{PA} \)) of MM-ALT-IS, which is 37.5%.

The amount of polymers A and B in a single bicomponent fiber of MM-ALT-IS can be calculated using equations 3.10 and 3.11 from above:

\[
B_{PA} = P_A - H_{PA} \quad \text{(Eq. 3.10)}
\]

\[
B_{PA} = 0.75 - 0.375
\]

\[
B_{PA} = 0.375
\]

\[
B_{PA}(\%) = 0.375 \times 100
\]

\[
B_{PA}(\%) = 37.5\%
\]

\[
B_{PB} = P_B \quad \text{(Eq. 3.11)}
\]

\[
B_{PB} = 0.25
\]

\[
B_{PB}(\%) = 0.25 \times 100
\]

\[
B_{PB}(\%) = 25\%
\]
Where $B_{PA}$ is the amount of Polymer A in the sum of the islands, $B_{PB}$ is the amount of Polymer B in the sea and $P_B$ is the known percentage of polymer B in the nonwoven web.

The amount of polymer in a single island in any given 7-islands-in-the-sea bicomponent fiber in an alternating configuration ($I_{PA}$) can be calculated using the following equations:

$$I_{PA} = \frac{B_{PA}}{7 \text{ Islands}} \tag{Eq. 3.12}$$

$$I_{PA} = 0.375 / 7$$

$$I_{PA} = 0.0536$$

$I_{PA}(\%) = 5.36\%$ of the initial 75% A goes into one island

The ratio of islands ($S_A$) to sea ($S_B$) in a single 7-islands-in-the-sea fiber in an alternating configuration can be calculated using the following equations:

$$S_A = \frac{B_{PA}}{(B_{PA} + B_{PB})} \tag{Eq. 3.13}$$

$$S_A = 0.375 / (0.375 + 0.25)$$

$$S_A = 0.375 / 0.625$$

$$S_A = 0.6$$

$S_A(\%) = 60\%$

$$S_B = \frac{B_{PB}}{(B_{PA} + B_{PB})} \tag{Eq. 3.14}$$

$$S_B = 0.25 / (0.375 + 0.25)$$

$$S_B = 0.25 / 0.625$$

54
$S_B = 0.4$

$S_B(\%) = 40\%$

**Ratio of $S_A$ to $S_B = 60\% : 40\%$**

These equations can be used to calculate the ratios for any MM-ALT-IS configuration by utilizing the known number of holes in the spinpack and the percent amounts of Polymers A and B fed into the system. A comparison of the three ratios of the MM-ALT-IS can be seen in Table 3.4 below.

### Table 3.4: Ratio comparison breakdown for MM-ALT-IS configuration

<table>
<thead>
<tr>
<th>Ratio of Polymer A to Polymer B</th>
<th>75% : 25%</th>
<th>50% : 50%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ratio of Homocomponent to Bicomponent</td>
<td>50% : 50%</td>
<td>50% : 50%</td>
</tr>
<tr>
<td>Ratio of Islands to Sea</td>
<td>60% : 40%</td>
<td>33% : 66%</td>
</tr>
</tbody>
</table>
CHAPTER 4: MATERIALS AND METHODS

4.1 SAMPLE PRODUCTION AND RAW MATERIALS

4.1.1 Polymer Selection

The polymer type utilized in bicomponent structures is an important factor in determining fabric properties and characteristics. It is the polymer type that dictates how easily the bicomponent fiber will split or fibrillate due to the interfacial adhesion between the two polymers. Polymer pairs are chosen for their incompatibility and small diffusion coefficients, which limits interdiffusion of macromolecules across the component interface into the other component. If there is low interdiffusion, there will be low interfacial adhesion, and therefore a low amount of mechanical strength will be required to separate the two components [71]. Some examples of polymers with low affinity for each other and can be relatively easily mechanically separated include polyester/polypropylene, polyester/polyethylene, polyester/nylon, nylon/polyethylene, nylon/polypropylene, and nylon/poly(lactic acid) [21], [71].

The nonwoven fabrics produced in this study include combinations of nylon 6/poly(lactic acid) and polyester/nylon 6 at specified ratios as well as 100% segmented pie bicomponent samples of the same polymer combinations for control purposes. Nylon 6 (BASF Ultramid® B27 02) with a density of 1.13 g/cm$^3$ was used as well as poly(lactic acid) (NatureWorks LLC 6202 D) with a density of 1.24 g/cm$^3$. The polyester (Eastman F61HC) used had a density of 1.40 g/cm$^3$. All fabrics were
produced with a target basis weight of 100 g/m² and contained polymer ratios of either 50% polymer A / 50% polymer B or 75% polymer A / 25% polymer B.

4.1.2 Control Sample Web Production

The control nonwoven fabric produced for this study was modeled after the only commercially available 16-segmented pie nonwoven fabric. The control fabrics were produced at the Nonwovens Institute’s Partners’ Pilot facilities using the Nordson spunbonding equipment and a slot-draw aspirator with spin packs designed by Hills Inc. according to the specifications for the 2,222-hole 100% segmented pie bicomponent configuration shown in Figure 4.1. The control fabrics produced include combinations of nylon 6/poly(lactic acid) and polyester/nylon 6 at ratios of 50/50 and 75/25 for each sample (Table 4.1).
Table 4.1: Web Specifications for 100% segmented pie control samples

<table>
<thead>
<tr>
<th>Polymer A</th>
<th>Polymer B</th>
<th>Ratio</th>
<th>Target Basis Weight (g/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PA6</td>
<td>PET</td>
<td>75/25</td>
<td>100</td>
</tr>
<tr>
<td>PA6</td>
<td>PET</td>
<td>50/50</td>
<td>100</td>
</tr>
<tr>
<td>PA6</td>
<td>PLA</td>
<td>75/25</td>
<td>100</td>
</tr>
<tr>
<td>PA6</td>
<td>PLA</td>
<td>50/50</td>
<td>100</td>
</tr>
</tbody>
</table>

Figure 4.1: Configuration of 100% segmented pie control sample
4.1.3 Mixed Media Web Production

The mixed media nonwoven fabrics were also produced at the Nonwovens Institute’s Partners’ Pilot facilities using the spunbonding equipment with spin packs designed by Hills Inc. according to the specifications for the 2,222-hole three-layer and alternating bicomponent configurations.

4.1.4 Hydroentangling

Hydroentangling was the chosen method of bonding utilized for the spunbond nonwoven fabric for entangling, splitting and consolidation of the fibers using high-pressure water jets from 5 manifolds, with the first manifold as a pre-wetter, the second and third manifolds on a belt for fabric face hydroentangling and the fourth and fifth manifolds on a drum for fabric back hydroentangling (Figure 4.2). Each of the aforementioned spunbond webs was passed through the hydroentangling system 1-4 times (corresponding to a hydroentangling energy of 14.4 – 57.5 MJ/kg) in order to determine the effect of specific energy on splitting, consolidation, and such properties as air permeability, pore structure, and mechanical properties (see Table 4.2).
Table 4.2: Equivalency of number of passes to specific energy

<table>
<thead>
<tr>
<th># of Passes</th>
<th>Specific Energy (MJ/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>14.4</td>
</tr>
<tr>
<td>2</td>
<td>28.8</td>
</tr>
<tr>
<td>3</td>
<td>43.1</td>
</tr>
<tr>
<td>4</td>
<td>57.5</td>
</tr>
</tbody>
</table>

Figure 4.2: Schematic of the hydroentangling unit at the Nonwovens Institute’s Partners Facility utilized in this study [10]
It has been demonstrated that the degree of fiber splitting in a bicomponent nonwoven depends on the specific energy imparted to the web during hydroentangling and that the higher the specific energy, the higher the degree of splitting and entanglement, leading do a denser structure [70]. The Bernoulli equation can be used as the basis for calculating the hydroentangling energy, ignoring viscous losses throughout the system.

The jet velocity can be calculated by:

\[ V_t = \sqrt{\frac{2P}{\rho}} \]  

(Eq. 4.1)

Where \( P \) is the pressure of the manifold in Pascals and \( \rho \) is the density of water at room temperature (998.2 kg/m\(^2\)), [11], [15], [18].

The rate of energy transferred by the water jet in J/s can be calculated as follows:

\[ E = \frac{\pi}{8} \rho d^2 C_d V^2 \]  

(Eq. 4.2)

Where \( d \) is the orifice’s capillary section diameter in meters and \( C_d \) is the discharge coefficient [11], [15], [18].
Specific hydroentangling energy can be determined by:

\[ \text{SE (J/kg}_\text{fabric}) = \frac{E}{M} \tag{Eq. 4.3} \]

Where \( E \) is the rate of energy transferred by the water jet in J/sec and \( M \) is the mass flow rate of the fabric in kg/sec [11], [15], [18].

\( M \) can be calculated by the following formula:

\[ M = \text{Sample width (m)} \times \text{Basis weight (kg/m}^2\text{)} \times \text{Belt speed} \tag{Eq. 4.4} \]

### 4.2 Analysis of Fabric Properties and Characteristics

The fabric property analysis and characterization will include basis weight and thickness measurement as well as tensile and tear testing, pore structure analysis and porosity calculation, air permeability measurement and scanning electron microscopy. Each fabric sample’s properties and characteristics will be compared to its corresponding 100% segmented pie nonwoven counterpart as a control.
**Air Permeability Analysis**

Air permeability analysis was carried out to measure the rate of air flow passing through the nonwoven fabric according to ASTM D 737-04 using a TexTest air permeability tester. Six specimens of each fabric were tested and results were recorded in units of \( \text{cm}^3/\text{cm}^2/\text{sec} \).

**Basis Weight Measurement**

Basis weight measurement was carried out according to ASTM D3776 Option C using ten square specimens of each fabric of 6” x 6” (15.24cm x 15.24cm) averaged and subsequently converted to units of grams per square meter (gsm or g/m\(^2\)).

**Thickness Measurement**

Thickness measurement was carried out according to ASTM D1777 with eight measurements taken per 6” x 6” (15.24cm x 15.24cm) in units of millimeters (mm) and averaged.

**Pore Structure Analysis and Porosity Calculation**

Pore structure analysis was carried out using a PMI Capillary Flow Porometer (model CFD-1100-AX). One specimen of each fabric was tested. Porosity was calculated by using the following equation:
\[ \varepsilon = 100 \times \left(1 - \frac{\delta}{e \times \rho_{(polymer)}}\right) \]  

(Eq. 4.5)

Where \( \varepsilon \) is the percent porosity, \( \delta \) is the fabric basis weight in g/m\(^2\), \( e \) is the fabric thickness in \( \mu \)m, and \( \rho \) is the calculated density of the two polymers in g/cm\(^3\).

**Mechanical Property Analysis**

Grab tensile strength analysis was carried out according to ASTM D 5034-09 by using specimens measuring 4" x 8" (10cm x 20cm). 5 specimens were tested in the machine direction (MD) and 5 specimens were tested in the cross direction (CD).

Tongue (single rip) tear strength analysis was carried out according to ASTM D2261-07 using specimens measuring 3" x 8" (7.5cm x 20cm). 5 specimens were tested in the machine direction (MD) and 5 specimens were tested in the cross direction (CD).

**Scanning Electron Microscopy**

Scanning electron micrographs were obtained using a Hitachi S3200 variable pressure scanning electron microscope using 5 KV accelerating voltage at magnifications of 30x, 60x, 90x, 120x, 500x and 1000x.
4.3 Removal of Poly (lactic acid) from Mixed Media

Achieving microfibers within nonwoven structures can be done not only with splitting, but with the use of a sacrificial component as well. The mixed media nonwoven samples produced with poly(lactic acid), henceforth referred to as PLA, were subjected to a washing process to remove the PLA component, leaving the remaining polymer within the nonwoven structure as microfibers. There have been studies done on PLA removal within nonwoven fabrics however there has been no investigation into the removal of PLA within mixed media fabrics since mixed media technology is in its infancy [92–94]. In order to establish the optimum PLA removal conditions, fabrics were subjected to a 10% (w/w) sodium hydroxide (NaOH) solution heated to 90 °C for 10, 20, 30 and 60 minutes. The optimum residence time of the sample in the bath, pre- and post-removal fabric properties were measured and compared. Once the optimum residence was established, it was utilized in the washing of the mixed media fabrics in order to yield microfiber nonwovens consisting of the remaining polymer following the PLA removal. The apparatus that was used in the PLA removal process contained a flask with a porous ceramic plate inserted into the mouth of the flask. The flow of the solution through the fabric was controlled by a stopper valve at the end of a tube connected to the porous ceramic plate. (Figure 4.3) After the fabrics were washed at the newly established optimum conditions, the mechanical properties were measured once again and compared to the properties of the 100% segmented pie nonwovens with the corresponding polymers and ratios.
Figure 4.3: PLA removal bath apparatus
5.1 16-Segmented Pie Three-Layer Mixed Media

This section deals with the analysis of a mixed media spunbonded nonwoven fabric with a three-layer configuration, where the two outer layers consist of 16-segmented pie bicomponent fibers and the central layer is made up of only homocomponent fibers. As in regular segmented pie fibers, splitting is made possible by the incompatibility between the two polymers used in the bicomponent system (for example, polyester and nylon), thus making the interface between the two polymers weak. The value in such a configuration is that hydroentangling can be used to split the bicomponent fibers into wedge-shaped microfibers. The homocomponent fibers on the interior of the fabric do not split and therefore remain large denier fibers. This three-layer structure is similar to spunbond-meltblown-spunbond composite structures, however, recalling Figure 3.3, only one spin beam is required to produce the nonwoven and the problem of layer delamination is eliminated. For clarity, each fabric property will be discussed separately following the establishment of the optimum amount of hydroentangling energy required for splitting the bicomponent fibers and entangling the spunbond web.

5.1.1 Establishment of Optimum Hydroentangling Energy

Figures 5.1 and 5.2 show how the air permeability is influenced by the amount of specific energy imparted to the web during hydroentangling. Generally,
the air permeability decreases as the specific energy imparted to the fabric during hydroentangling increases, leading to the assumption that the web is more consolidated due to the splitting of the two components within the fiber and the entangling of the fibers in the structure. The pore size decreases initially, and then does not change significantly with increasing specific energy. This could be due to the fact that initially, the web is not well bonded and must go through an initial entanglement period. As the web becomes entangled and the amount of fiber splitting plateaus, the change in pore size also remains relatively consistent. Although the pore size initially decreases, the porosity does not appear to change significantly with increasing specific energy. The reduction in pore size during hydroentangling would lead one to infer that there is an optimum amount of specific energy during hydroentangling determined by the level of splitting balanced with adequate entangling for integrity of the web. After a total specific energy of 43.1 MJ/kg was imparted to the web, the fibers appear to have been split and entangled and a further increase in specific energy would potentially damage the fiber. The air permeability values can be referred to in Table A.1 in Appendix A. Figures 5.3 and 5.4 show the scanning electron micrographs (SEMs) of the entangled and split 50% Nylon / 50% PLA and 75% Nylon / 25% PLA at a specific energy of 43.1 MJ/kg. The mixture of bicomponent and mono-component fibers can be clearly observed in Figure 5.3a.
Figure 5.1: Air permeability of the 50% PA6 / 50% PLA100 g/m² MM-3L-SP and control fabrics as a function of the specific energy used during hydroentangling.

Figure 5.2: Air permeability of the 75% PA6 / 25% PLA 100 g/m² MM-3L-SP and control fabrics as a function of the specific energy used during hydroentangling.
Figure 5.3: Cross-section (a); and surface (b) SEM images of 50% Nylon/50% PLA 100 g/m² MM-3L-SP and control fabrics hydroentangled with a specific energy of 43.1 MJ/kg

Figure 5.4: Cross-section (a); and surface (b) SEM images of 75% Nylon / 25% PLA 100 g/m² MM-3L-SP and control fabrics hydroentangled with a specific energy of 43.1 MJ/kg
5.1.2 Air Permeability

Figure 5.5 shows the air permeability values for the fabrics with reference to the polymer combinations utilized, hydroentangled with a specific energy of 43.1 MJ/kg. The air permeability values reported are in units of cm³/cm²/sec (cubic centimeters per square centimeters per second). Higher air permeability values signify that more air is able to penetrate through the fabric in less time, whereas lower air permeability values signify that the fabric allows less air to pass through the fabric per unit time. It is clear that in both polymer ratios, the mixed media fabric has higher air permeability than the 100% segmented pie control made from the same polymer ratio. Although the PET/PA6 mixed media fabric has slightly higher air permeability, the difference in the air permeabilities of both mixed media samples is small enough to argue that the polymer ratio does not play an influential role in the splitting or separation of bicomponent filaments during hydroentangling. Although slight, the difference in the air permeabilities of the two mixed media samples could be caused by insufficient splitting during hydroentangling due to the affinity level the two polymers have for each other in comparison with the other polymer combination. This would result in less splitting and therefore, fewer microfibers within the fabric structure leading to a less consolidated structure. The PA6/PLA combination however, appears to have the lower air permeability of the two mixed media fabrics, indicating that better splitting is possible with this polymer combination as opposed to the PET/PA6 combination. The higher air permeability of the mixed media samples, when compared to the control samples, can be attributed to the existence
of a central layer of homocomponent fibers which prevents such dense packing of the microfiber wedges. The control samples do not have homocomponent fibers, meaning that all fibers in the nonwoven structure have to potential to split and become microfiber wedges, leading to a more dense fibrous structure.

![Air Permeability Chart](image)

**Figure 5.5:** Air permeability as a function of the polymer combination of 100 g/m² MM-3L-SP and control fabrics hydroentangled with a specific energy of 43.1 MJ/kg
5.1.3 Basis Weight

All webs were produced with a target basis weight of 100 g/m$^2$, however as the hydroentangling energy was increased, the basis weight increased. This was due to densification and compaction of the web in combination with web-width shrinkage during hydroentangling. Figure 5.6 shows the effect of consolidation as evidenced by basis weight as a function of hydroentangling energy. The post-hydroentangling basis weight measurements can be seen in Table A.2 in Appendix A. In Figure 5.7, the PA6/PLA fabrics generally have higher basis weights than the PET/PA6 fabrics. A reason for this could be that the PA6/PLA bicomponent fibers split more readily, leading to a higher number of wedge-shaped microfibers within the structure allowing for more compaction and a denser structure.

![Figure 5.6: Post-hydroentangling basis weight of the PA6/PLA MM-3L-SP and control fabrics as a function of the specific energy used during hydroentangling](image-url)
5.1.4 Thickness

Figure 5.8 shows the measured thickness for the MM-3L-SP configuration as well as the control fabric, both hydroentangled with a specific energy of 43.1 MJ/kg. It can be easily observed that the PA6/PLA polymer combination was thicker than the PET/PA6 polymer combination. Recall that the PA6/PLA polymer combination also had lower air permeability than its PET/PA6 counterpart as well as higher basis weight. This suggests that the PA6/PLA polymer combination leads to a denser fibrous structure. Referring again to Figure 5.8, in both polymer combinations, the
75/25 ratio of the mixed media fabric displayed higher thickness values. This could be attributed to the ability of the homocomponent layer of fibers sandwiched in between two bicomponent layers to aid in the prevention of such dense fiber packing. Generally, as the hydroentangling energy increases, the thickness increases. This is attributed to fibers being drawn into the Z plane of the web during hydroentangling as well as web-width shrinkage. The measured thickness values for the MM-3L-SP fabrics can be seen in Table A.3.

![Thickness of the MM-3L-SP as a function of the polymer combination, hydroentangled with a specific energy of 43.1 MJ/kg](image)

Figure 5.8: Thickness of the MM-3L-SP as a function of the polymer combination, hydroentangled with a specific energy of 43.1 MJ/kg
5.1.5 Pore Properties

Figures 5.9 and 5.10 show the pore sizes for the PA6/PLA MM-3L-SP and control fabrics in ratios of 50/50 and 75/25. In both the 50/50 and 75/25 ratios, the mixed media displays larger pore sizes than the control counterpart. The largest pore sizes out of all the PA6/PLA fabrics tested with the three-layer configuration can be found in the ratio of 75/25. This proves that the polymer ratio has an effect on the splitting of the wedges and therefore, the structure. Although the diameter of the largest detected pore was higher than the control, the average pore size was not significantly different, confirming our expectation that the pore sizes could be kept comparable to the control without inhibiting the permeability of the structure. Figures 5.11 and 5.12 show the pore sizes for the PET/PA6 MM-3L-SP and control fabrics in ratios of 50/50 and 75/25. The smallest, average and largest pore diameters are not significantly different when the PET/PA6 fabrics are compared as a function of their ratio, however the ratio of 75/25 does have a higher average pore diameter value, which would be expected since this was also the three-layer fabric with the highest air permeability. Both MM-3L-SP fabric ratios in the PET/PA6 combination had larger pores than the control fabrics, as was the case with the PA6/PLA polymer combination. The larger pore sizes in all of the MM-3L-SP fabrics can be attributed to the homocomponent layer sandwiched in between the outer layers of bicomponent fibers. Without this homocomponent layer, every bicomponent fiber in the control fabrics has the potential to split into microfiber wedges, contributing to a
more consolidated structure with less space between fibers. The pore size data can be seen in Table A.4.

The porosity of the MM-3L-SP fabrics and their control counterparts can be seen in Figure 5.13. It is interesting to note that the PET/PA6 fabrics display lower porosity values than the PA6/PLA fabrics, however it was the PET/PA6 fabrics which had the larger pore sizes. Recalling that the PET/PA6 samples also had lower thickness and basis weight, and higher air permeability than the PA6/PLA samples could support the argument that the PET/PA6 fabrics shrank less in the web-width direction during hydroentangling but still had a high degree of splitting. More investigation into the pore tortuosity could help to explain this further. Table A.5 summarizes the porosity data for the MM-3L-SP and control fabrics as a function of specific energy used during hydroentangling.

![Figure 5.9: Pore size of 50% PA6 / 50% PLA100 g/m² MM3L-SP and control fabrics hydroentangled with a specific energy of 43.1 MJ/kg](image-url)
Figure 5.10: Pore size of 75% PA6 / 25% PLA100 g/m² MM-3L-SP and control fabrics hydroentangled with a specific energy of 43.1 MJ/kg

Figure 5.11: Pore size of 50% PET / 50% PA6100 g/m² MM-3L-SP and control fabrics hydroentangled with a specific energy of 43.1 MJ/kg
Figure 5.12: Pore size of 75% PET / 25% PA6100 g/m² MM-3L-SP and control fabrics hydroentangled with a specific energy of 43.1 MJ/kg

Figure 5.13: Porosity of MM-3L-SP fabrics as a function of the polymer combination, hydroentangled with a specific energy of 43.1 MJ/kg
5.1.6 Mechanical Properties

Figure 5.14 shows the tear strength of the 50% / 50% MM-3L-SP fabrics as well as the control fabrics. Figure 5.15 shows the tear strength for the 75% / 25% MM-3L-SP fabrics as well as the control fabrics. In both figures, the cross direction (CD) tear strength values are consistently higher than the machine direction (MD) values. This can be attributed to the anisotropic orientation of the fibers in the MD due to the web-forming process. The highest tear strength was found to exist in the 75% PA6 / 25% PLA mixed media fabric, which was expected since it contained the largest amount of PA6. This high tear strength was due to a combination of the high strength of PA6 and the large homocomponent fibers acting as a “rip-stop” mechanism in the fabric. The tensile strength of the fabrics with ratios of 50/50 and 75/25 can be seen in Figures 5.16 and 5.17, respectively. The highest tensile strength can be found in the 75% PA6 / 25% PLA mixed media fabric. Recall that this was also the fabric with the highest tear strength. Note that the machine direction tensile values are higher than the cross direction values in every sample tested. This is opposite of the tear strength values due to the anisotropy of the fibers in the machine direction, which would provide more resistance to the tensile stress. The mechanical property data for the MM-3L-SP and control samples can be found in TableA.6.
Figure 5.14: Tear strength (kgf) of 50% / 50% 100 g/m² MM-3L-SP and control fabrics hydroentangled with a specific energy of 43.1 MJ/kg.

Figure 5.15: Tear strength (kgf) of 75% / 25% 100 g/m² MM-3L-SP and control fabrics hydroentangled with a specific energy of 43.1 MJ/kg.
Figure 5.16: Tensile strength (kgf) of 50% / 50% 100 g/m² MM-3L-SP and control fabrics hydroentangled with a specific energy of 43.1 MJ/kg

Figure 5.17: Tensile strength (kgf) of 75% / 25% 100 g/m² MM-3L-SP and control fabrics hydroentangled with a specific energy of 43.1 MJ/kg
5.1.7 Summary and Conclusions

The optimum hydroentangling energy for the MM-3L-SP fabric was found to be 43.1 MJ/kg. Although not all MM-3L-SP polymer combinations and ratios displayed similar values, there was at least one mixed media combination that surpassed the performance of the control fabric in air permeability, tear strength and tensile strength. For air permeability, it was 50% PET / 50% PA6 mixed media, and for tear and tensile strength it was 75% PA6 / 25% PLA mixed media. The air permeability for both the mixed media samples and the control samples followed the same trend of decreasing with increasing hydroentangling energy. The basis weight trend was opposite that of the air permeability: increasing with increasing hydroentangling energy. Both the air permeability and basis weight data demonstrate that the compaction and densification of the nonwoven structure is dependent upon the splitting and packing of the microfibers, which is caused by the amount of hydroentangling energy imparted to the web. Referring again to Tables A.4 and A.5, it can be argued that the polymer ratio or combination does not have much influence on the structure pore size or porosity beyond the first pass of hydroentangling equaling 14.4 MJ/kg. The slightly larger pores and porosity can be attributed to the homocomponent layer preventing such dense packing of the microfiber wedges.

5.2 16-Segmented Pie Alternating Mixed Media

This section deals with the production of a 16-segmented pie spunbonded nonwoven fabric with a checkerboard design, where every-other fiber is a
bicomponent fiber with a homocomponent fiber in between. As in regular segmented pie fibers, splitting is made possible by the incompatibility between the two polymers used in the bicomponent system (for example, polyester and nylon), thus making the interface between the two polymers weak. The value in such a configuration is that an intimate blend of macro- and microfibers can be achieved from one spin beam after splitting through the utilization of hydroentangling, without the slow process of carding staple fibers [95]. As with the previously investigated three-layer configuration, using the appropriate polymer homocomponent filaments can yield enhanced properties such as strength and dyability, while maintaining the appropriate microfiber features on the surface(s) of the fabric.

5.2.1 Establishment of Optimum Hydroentangling Energy

As indicated previously, the first step in the process of fabric analysis is to establish the energy required to both split and consolidate the web. Since the hydroentangling unit in the Nowovens Institute’s pilot facility is limited to a total of 5 manifolds, the webs were passed through the unit up to four times. It was expected that the structure would continue to consolidate with increasing levels of energy and that the consolidation would plateau when the structure could no longer be further consolidated. At this point, the level of energy would be the maximum energy required to entangle and split the fibers. Table A.7 summarizes the air permeability data for PET/PA6 with ratios of 50%/50% and 75%/25% as well as the control samples. Figures 5.18 and 5.19 show the scanning electron micrographs (SEMs)
for 50% PET / 50% PA6 and 75% PET / 25% PA6, respectively, hydroentangled with a specific energy of 43.1 MJ/kg. It can be recalled from Chapter 3 that the simultaneous formation of these fibers will lead to an intimate blend of micro- and macro denier fibers. Note the mixture of bicomponent and homocomponent fibers co-mingled in the cross-sectional SEM in Figure 5.18a. Note also that not all segmented pie fibers are split. The amount of splitting will increase with increasing hydroentangling energy and will continue to split with usage after production. The optimum hydroentangling energy was found to be 43.1 MJ/kg.
Figure 5.18: Cross-section (a); and surface (b) SEM images of 50% PET / 50% PA6 MM-ALT-SP hydroentangled at a specific energy of 14.4 MJ/kg

Figure 5.19: Cross-section (a); and surface (b) SEM images of 75% PET / 25% PA6 MM-ALT-SP hydroentangled at a specific energy of 14.4 MJ/kg
5.2.2 Air Permeability

Figures 5.20 and 5.21 show the effect of web consolidation as evidenced by air permeability as a function of hydroentangling energy. The data confirms the claims in existing literature that as hydroentangling energy increases, the air permeability decreases, indicating that the web is further consolidated due to the splitting of the two components within the bicomponent fiber and the entangling of the constituent fibers. Note that beyond 28 MJ/kg, there is little or no further entanglement. Note that the segmented pie control and mixed media exhibit similar trends. Note also that the mixed media consistently exhibits a higher degree of permeability. This confirms the hypothesis that a hybrid structure, like mixed media, will have a higher degree of permeability than the 100% bicomponent control sample. Figure 5.22 shows that the ratio of 50% PET / 50% PA6 has higher air permeability than the 75/25 ratio in both the mixed media and control samples. A possible reason for this could be that when the amount of PET is increased, the readiness of the fibers to split during hydroentangling is also enhanced, leading to a more densified microfiber structure, and therefore lower air permeability.
Figure 5.20: Air permeability of the 50% PET / 50% PA6 100 g/m$^2$ MM-ALT-SP and control fabrics as a function of the specific energy used during hydroentangling.

Figure 5.21: Air permeability of the 75% PET / 25% PA6 100 g/m$^2$ MM-ALT-SP and control fabrics as a function of the specific energy used during hydroentangling.
5.2.3 Basis Weight

The post-hydroentangling basis weight measurement data can be seen in Table A.8. Figure 5.23 shows the effect of consolidation as evidenced by basis weight as a function of hydroentangling energy. The webs were produced with a target basis weight of 100 g/m² however, as the hydroentangling energy increased, the basis weight increased. This was due to densification and compaction of the web as well as web-width shrinkage.
In Figure 5.23a, the 50% PET / 50% PA6 mixed media fabric can be seen to have higher basis weight than the 50% PET / 50% PA6 control. Figure 5.23b shows the 75% PET / 25% PA6 mixed media fabric having lower basis weight than the 75% PET / 25% PA6 control. In order to more clearly understand this reversal, the mixed media and control fabrics for both ratios were plotted all together in one graph (Figure 5.24a). This clarifies that the mixed media values do not differ greatly from the 50/50 ratio to the 75/25 ratio. The control values do, however, differ significantly, with the 50/50 ratio having much lower basis weight than the 75/25 ratio. This can be attributed to the absence of non-splitting homocomponents within the control samples. Since there is no polymer being utilized in homocomponents in the control samples, the amount of polymer in each wedge has a greater effect on the bending of the microfibers and therefore influences entanglement and compaction of the fibers. The control fabric with a ratio of 50% PET / 50% PA6 has fibers with each PA6 wedge containing 6.25%, as opposed to the 75% PET / 25% PA6 control fabric with each PA6 wedge containing 3.125%. The larger PA6 microfiber wedges in the 50/50 sample would have a higher bending rigidity than the smaller fibers in the 75/25 control sample, which would prevent the fibers from entangling as densely, therefore creating a less compact structure with lower basis weight. This is also the case for the mixed media, however the difference between the amount of polymer in each wedge is smaller, leading to a smaller difference in basis weight between the two ratios of the mixed media. This explains why the two mixed media samples have basis weight values that fall in between the two control samples, as seen in
Figure 5.24b. Figure 5.25 shows that there is a strong correlation between the amount of PET and PA6 in each bicomponent fiber and the basis weight of the hydroentangled sample. It can be observed that, as the difference in the amount of each polymer within a single bicomponent fiber increases, the basis weight increases. This is evidence that the size of each wedge, which is influenced by the polymer ratio, has an impact on the nonwoven structure after hydroentangling and therefore the fabric properties. This also helps to explain why the mixed media fabric has higher basis weight than the control in Figure 5.23a, but lower basis weight than the control in Figure 5.23b. The data for the difference in polymer amounts can be referred to in Table A.9.
Figure 5.23: Post-hydroentangling basis weight of the MM-ALT-SP and control fabrics as a function of the specific energy used during hydroentangling: a)50% PET / 50% PA6; b)75% PET / 25% PA6
Figure 5.24: Post-hydroentangling basis weight of the MM-ALT-SP and control fabrics as a function of the specific energy used during hydroentangling: a) mixed media and control comparison with linear regression lines; b) linear regression lines only.
5.2.4 Thickness

Figure 5.26 shows the measured thickness for the MM-ALT-SP fabrics in comparison to the control fabrics, both hydroentangled with a specific energy of 43.1 MJ/kg. It can be easily observed that the mixed media fabric is thicker than the control in both ratios. This can be attributed to the existence of large-denier homocomponent fibers within the mixed media structure, which do not split into microfibers, preventing tight packing of wedges. Generally, as the specific energy increases, the thickness increases, which is an effect of shrinkage of the web width during hydroentangling. The measured thickness values for the 50% PET / 50% PA6 and 75% PET / 25%PA6 MM-ALT-SP fabrics can be seen in Table A.10.
5.2.5 Pore Properties

It can be observed from Figures 5.27 and 5.28 that the mixed media fabrics had only slightly larger pore sizes than the control sample. The slightly larger pores can be attributed to the prevention of dense packing of wedge-shaped microfibers by homocomponent fibers interspersed throughout the thickness (Z-direction) of the web in the mixed media samples. It can also be observed that the polymer ratio did not have any significant impact on the average pore size. The porosity of the mixed media fabrics compared to the control fabrics can be seen in Figure 5.29. In both ratios of 50/50 and 75/25, the porosity was highest in the alternating mixed media configuration. The control sample had lower porosity than both mixed media
configurations. One would assume that since the pore size was not significantly
different between the mixed media and control samples, the porosity would not be
either, however this is not the case. This discrepancy could possibly be attributed to
the tortuosity of the pores however, further investigation would be required to
confirm this. Tables A.11 and A.12 summarize the data for pore size and porosity as
a function of the specific energy used during hydroentangling, respectively.

![Pore size graph](image)

**Figure 5.27:** Pore size of 50% PET / 50% PA6 100 g/m² MM-ALT-SP and control
fabrics hydroentangled with a specific energy of 43.13 MJ/kg
Figure 5.28: Pore size of 75% PET / 25% PA6 100 g/m² MM-ALT-SP and control fabrics hydroentangled with a specific energy of 43.13 MJ/kg

Figure 5.29: Porosity of 100 g/m² MM-ALT-SP and control fabrics hydroentangled with a specific energy of 43.13 MJ/kg
5.2.6 Mechanical Properties

Figure 5.30 shows the tear strength of the 50% / 50% and 75% / 25% PET/PA6 fabrics as well as the control sample. The cross-direction values are consistently higher in all samples tested. This is attributed to the anisotropic fiber orientation of the fabrics. The highest tear strength value is observed in the MM-ALT-SP sample with a polymer ratio of 50% PET / 50% PA6. This is due partly to the higher amount of nylon in the structure, which is stronger than polyester, and partly due to the intimately blended micro- and macrofiber configuration. Figure 5.31 shows the tensile strength of the 50% / 50% and 75% / 25% PET/PA6 fabrics as well as the control sample. Again, the anisotropic fiber orientation of the fabric influences the strength; in this case, the machine direction displays higher tensile strength than the cross direction in all samples tested. In the 50% PET / 50% PA6 ratio, the alternating configuration has comparable tensile strength values to those of the control sample. The mechanical property values for the alternating mixed media and control samples for 50% PET / 50% PA6 and 75% PET / 25%PA6 can be seen in Table A.13.
Figure 5.30: Tear strength of 100 g/m² MM-ALT-SP and control fabrics hydroentangled with a specific energy of 43.13 MJ/kg: a)50% PET / 50% PA6; b)75% PET / 25% PA6
Figure 5.31: Tensile strength of 100 g/m² MM-ALT-SP and control fabrics hydroentangled with a specific energy of 43.13 MJ/kg: a) 50% PET / 50% PA6; b) 75% PET / 25% PA6
5.2.7 Summary and Conclusions

The optimum hydroentangling energy for the MM-ALT-SP structure was found to be 43.1 MJ/kg. The MM-ALT-SP configuration performed better than its 100% 16-segmented pie bicomponent control counterpart in air permeability and tear strength testing. The tensile strength proved to be comparable to that of the control fabrics, which already demonstrated adequate strength after hydroentangling. The air permeability for both the mixed media samples and control samples followed the same trend by decreasing with increasing hydroentangling energy. The basis weight trend was opposite that of the air permeability: increasing with increasing hydroentangling energy. Both the air permeability and basis weight data prove that as the hydroentangling energy increased, the bicomponent fibers were split and the structure became more compact and condensed. The basis weight data also proves that the polymer ratio influences the wedge size, and therefore other properties and characteristics of the web. However, the said influence of the wedge size is not as significant in the mixed media nonwoven due to the homocomponent. The greater thickness of the mixed media web was an expected result due to the lower amount of wedge-shaped microfibers and interspersed homocomponent fibers, concurrently preventing the dense packing observed in the control fabrics. The slightly larger pores and higher porosity of the mixed media can also be attributed to the homocomponent fibers.
5.3 7-ISLANDS-IN-THE-SEA ALTERNATING MIXED MEDIA

By utilizing the alternating configuration previously investigated and changing the bicomponent cross-section from 16-segmented pie to 7-islands-in-the-sea, an intimate blend of macro- and microfibers was achieved in conjunction with the elimination of the problem of dense packing of wedge-shaped microfibers (since they do not exist in this bicomponent cross-section). Due to the fact that the most common commercially available bicomponent nonwoven is 100% 16-segmented pie, and there is no commercially available 100% 7-islands-in-the-sea nonwoven fabric, the 100% 16-segmented pie bicomponent fabric is utilized as the control for the 7-islands-in-the-sea mixed media fabric.

5.3.1 Establishment of Optimum Hydroentangling Energy

As with the previously discussed mixed media structures, the optimum amount of hydroentangling energy was established using a comparison of air permeability data for PET/PA6 and PET/PLAMM-ALT-IS to the control sample. Once past the optimum hydroentangling energy, damage to the fibers would occur, changing the properties and characteristics of the fabric. It can be seen in Figure 5.32 that the optimum hydroentangling energy for MM-ALT-IS is 43.1 MJ/kg.

The air permeability data, found in Table A.14, confirms the claims in existing literature that as hydroentangling energy increases, the air permeability decreases. It also confirms the original hypothesis that the mixed media nonwoven fabric would have significantly higher air permeability due to the non-splittable homocomponent
fibers throughout the fabric configuration preventing dense packing of the microfibers. In Figures 5.32 and 5.33, the mixed media fabrics have higher air permeability than the control. Figures 5.34 and 5.35 show the cross-sectional and surface-view scanning electron micrographs of 50% PET / 50% PA6 as well as 75% PET / 25% PA6. The micrographs show that fibrillation has occurred in both ratios and that microfibers are intermingled throughout the structure. When compared to the SEM micrographs of the PET/PA6 control fabrics (Figures 5.36 and 5.37), it can be observed that the fiber packing density is much lower in the mixed media configuration that is hydroentangled with the same amount of specific energy.

![Graph](image)

Figure 5.32: Air permeability of (cm$^3$/cm$^2$/sec)50% PET / 50% PA6 MM-ALT-IS fabrics as a function of the specific energy imparted to web during hydroentangling
Figure 5.33: Air permeability (cm$^3$/cm$^2$/sec) of the 75% PET / 25% PA6 MM-ALT-IS fabrics as a function of the specific energy imparted to web during hydroentangling.
Figure 5.34: Cross-section (a); and surface (b) SEM images of 50% PET /50% PA6MM-ALT-IS at a specific energy of 43.1 MJ/kg

Figure 5.35: Cross-section (a); and surface (b) SEM images of 75% PET /25% PA6MM-ALT-IS at a specific energy of 43.1 MJ/kg
Figure 5.36: Cross-section (a) and surface (b) SEM images of 50% PET / 50% PA6 control fabrics at a specific energy of 43.1 MJ/kg

Figure 5.37: Cross-section (a) and surface (b) SEM images of 75% PET / 25% PA6 control fabrics at a specific energy of 43.1 MJ/kg
5.3.2 Air Permeability

Figure 5.38 shows the air permeability of the MM-ALT-IS fabric hydroentangled at the optimum specific energy of 43.1 MJ/kg. Higher air permeability values signify that more air is able to penetrate through the fabric in less time hence the fabric has higher air permeability, whereas lower air permeability values signify that the fabric allows less air to pass through the fabric per unit time. It is easily observed that the mixed media has higher air permeability than the control counterpart in both ratios. Note that in the mixed media fabric, the ratio of 50/50 is lower than the ratio of 75/25, however in the control sample, the ratio of 50/50 is higher than that of the 75/25; this is due to the size of the islands. In the mixed media sample, the ratio of 50% PET / 50% PA6 contains bicomponent fibers with each PET island accounting for 3.57% of the total input amount of PET. In the ratio of 75% PET / 25% PA6, each bicomponent fiber contains PET islands consisting of 5.36% of the total input amount of PET. Since the islands of PET are smaller in the 50/50 ratio, they have greater ability to pack more tightly than the larger islands found in the 75/25 ratio. In the control sample, the split microfibers of the 50/50 ratio are the same size, each utilizing 6.25% of the input polymer and the microfibers of the 75/25 ratio utilize 9.37% and 3.13% for the PET and PA6 components, respectively. Due to the fact that the smaller components, which pack more tightly, can be found in the 75/25 ratio, it confirms the finding that the 75/25 ratio would have lower air permeability.
5.3.3 Basis Weight

Figure 5.39 shows the effect of consolidation as evidenced by basis weight as a function of hydroentangling energy. The webs were produced with a target basis weight of 100 g/m$^2$, however as the hydroentangling energy increased, the basis weight increased. This was due to consolidation and compaction of the web as well as web-width shrinkage. In Figure 5.39a, the 50% PET / 50% PA6 mixed media fabric can be seen to have higher basis weight than the 50% PET / 50% PA6 control. Figure 5.39b shows the 75% PET / 25% PA6 mixed media fabric having lower basis weight than the 75% PET / 25% PA6 control. This reversal follows the
same pattern as the MM-ALT-SP configuration. The basis weight data indicates that the control fabrics are more significantly impacted by the polymer ratio than the mixed media fabrics due to the absence of homocomponent fibers. The post-hydroentangling basis weight can be correlated to the amount of each polymer in a single bicomponent fiber. As the percent difference in the amount of polymer within each bicomponent increases, the post-hydroentangling basis weight will also increase. A larger difference in the amount of polymer in each bicomponent fiber dictates that there will also be a larger difference in the size of each component in the cross-section, in this case, islands and sea. Therefore, as the size difference of components increases, the potential for the packing of microfiber components increases as well, leading to a more densified and compact structure (Figure 5.40). The post-hydroentangling basis weight measurement data can be seen in Table A.15, along with the data for the percent difference in polymer amounts in a single bicomponent fiber in Table A.16.
Figure 5.39: Post-hydroentangling basis weight of the MM-ALT-IS and control fabrics as a function of the specific energy used during hydroentangling: a) 50% PET / 50% PA6; b) 75% PET / 25% PA6.
5.3.4 Thickness

Figure 5.41 shows the measured thickness for the MM-ALT-IS in comparison to the control fabric, both hydroentangled with a specific energy of 43.1 MJ/kg. It can be easily observed that the mixed media fabric is thicker than the control fabric in both ratios of 50/50 and 75/25. Like the MM-3L-SP and MM-ALT-SP configurations, the higher thickness in the MM-ALT-IS configuration can be attributed to the existence of large denier homocomponents within the structure.
which do not split into microfibers, preventing the high level of packing that would occur with the 100% bicomponent control fabric structure. Generally, as the specific energy increases, the thickness increases then begins to decrease again, in a parabolic trend. This could be a sign that if the specific energy imparted to the web is too high, the fibers are damaged. When the increase in thickness is combined with the increase in basis weight as hydroentangling increases, it can be argued that the web-width decreases during hydroentangling. The measured thickness values for the MM-ALT-IS fabrics can be seen in Table A.17.

![Figure 5.41: Thickness of the PET / PA6 100 g/m² MM-ALT-IS and control fabrics hydroentangled with a specific energy of 43.1 MJ/kg](image)
5.3.5 Pore Properties

It can be observed from Figures 5.42 and 5.43 that the mixed media fabrics have slightly larger pores than the control samples. The larger pores can be attributed to the prevention of the dense packing of wedge-shaped microfibers by homocomponent fibers interspersed throughout the thickness of the web in the mixed media samples. It can also be observed that the polymer had a slight effect on the average pore size (Figure 5.44). The porosity of the mixed media fabrics compared to the control fabrics can be seen in Figure 5.45. The mixed media had higher porosity values than the control in both ratios of 50/50 and 75/25. It is interesting to note that the porosity was increased in the mixed media without significantly increasing the pore size. This could be attributed to the tortuosity of the pores caused by the co-mingling of the microfibers and homocomponent fibers, which needs further investigation. Tables A.18 and A.19 summarize the data for pore size and porosity, respectively, as a function of the specific energy imparted to the web during hydroentangling. After an initial decrease in pore size, the pore size increases again in the mixed media samples after 43.1 MJ/kg of hydroentangling energy. This follows the same pattern that the segmented pie samples followed. The increase is due to the high level of hydroentangling energy causing breakage and damage to the fibers, therefore loosening and weakening the structure, instead of contributing to further entanglement of the fibers.
Figure 5.42: Pore size of 50% PET / 50% PA6 100 g/m² MM-ALT-IS and control fabrics hydroentangled with a specific energy of 43.1 MJ/kg

Figure 5.43: Pore size of 75% PET / 25% PA6 100 g/m² MM-ALT-IS and control fabrics hydroentangled with a specific energy of 43.1 MJ/kg
Figure 5.44: Average pore size of MM-ALT-IS PET/PA6 fabrics as a function of hydroentangling energy

Figure 5.45: Porosity of 100 g/m² MM-ALT-IS and control fabrics hydroentangled with a specific energy of 43.1 MJ/kg
5.3.6 Mechanical Properties

Figure 5.46 shows the tear strength of the 50%/50% and 75%/25% PET/PA6 fabrics as well as the control fabrics. The cross direction values are consistently higher in all samples tested. This can be attributed to the anisotropic fiber orientation of the fabrics. In both ratios, the mixed media performs with higher tear strength than the corresponding control samples. The highest tear strength value is observed in the 75% PET / 25% PA6 mixed media sample, suggesting that the polymer ratio has an influence on the mechanical properties of the mixed media fabrics, whereas the control fabrics do not have significantly different tear strength values when comparing ratios. Figure 5.47 shows the tensile strength of the 50%/50% and 75%/25% PET/PA6 fabrics as well as the control fabrics. Again, the anisotropic fiber orientation of the fabric influences the strength; in this case, the machine-direction displays higher tensile strength than the cross-direction in all samples tested. The cross-direction strength values for the mixed media fabrics and control fabrics were not significantly different. The fabric with the highest tensile strength was the 75% PET / 25% PA6 control, however it was only minutely higher than the mixed media sample with the same polymer ratio. The mechanical property values for the MM-ALT-IS and control samples for 50%/50% and 75%/25% PET/PA6 can be seen in Table A.20.
Figure 5.46: Tear strength of 100 g/m² MM-ALT-IS and control fabrics hydroentangled with a specific energy of 43.1 MJ/kg: a) 50% PET / 50% PA6; b) 75% PET / 25% PA6
Figure 5.47: Tensile strength of 100 g/m² MM-ALT-IS and control fabrics hydroentangled with a specific energy of 43.1 MJ/kg:  

(a) 50% PET / 50% PA6;  
(b) 75% PET / 25% PA6
5.3.7 Summary and Conclusions

The MM-ALT-IS configuration performed better than its 100% bicomponent control counterpart in air permeability and tear strength. The tensile strength proved to be comparable to that of the control fabrics, which already demonstrated adequate strength after hydroentangling. The air permeability for both the mixed media and control samples followed the same trend by decreasing with increasing hydroentangling energy. This was also the case for pore size. The basis weight trend was opposite that of the air permeability: increasing with increasing hydroentangling energy. Both the air permeability and basis weight data prove that as the hydroentangling energy increased, the bicomponent fibers were split and the structure became more compact and consolidated. The basis weight data also indicates that the control fabrics are more significantly impacted by the polymer ratio than the mixed media fabrics due to the absence of homocomponent fibers. The higher thickness values of the mixed media structures were expected, due to the round cross-section of the microfiber components after splitting and the interspersed homocomponent fibers concurrently preventing the dense packing of microfibers observed in the control fabrics. The slightly larger pores and higher porosity of the mixed media can also be attributed to the presence of the homocomponent fibers.
5.4 Removal of PLA from Mixed Media

5.4.1 Establishment of Optimum Washing Time

An interesting facet of using poly (lactic acid) as one of the polymers in bicomponent fibers is that it can be removed while retaining the other polymer in the bicomponent fiber. This could serve as a method of creating a multi-denier spunbond fabric from one single spinpack made up of only one polymer type, after the PLA has been removed. Utilizing this method would eliminate the need for multiple spinpacks, or producing multiple deniers of staple fibers which would have to be carded. It also ensures that, contrary to splitting via hydroentangling, every component is separated. In order to fully remove the PLA from the nonwoven, it is imperative to first establish the dwell time required for the PLA to be fully removed without damaging the remaining fibers not made from PLA. In order to do this, fabrics with a PLA component were subjected to a 10% w/w sodium hydroxide (NaOH) solution at 90°C for 10, 20, 30, and 60 minutes.

Table A.21 summarizes the nonwoven webs utilized in the determination of adequate dwell time in the NaOH bath. Figure 5.48 shows the normalized percent weight remaining after subjecting each nonwoven fabric to the NaOH bath for the specified amount of time. Theoretically, all of the PLA should be washed out, so for example, a fabric with 75% PA6 and 25% PLA should be 75% of the initial basis weight if all of the PLA is removed. It can be observed that in each of the four
fabrics tested, the normalized percent weight remaining confirms that all of the PLA is removed between 10 and 20 minutes. The initial weights all start at 100% and abruptly decrease after dwelling in the NaOH bath for 10 minutes then plateau. The shortest dwell time possible is preferred to prevent damage to the non-PLA fibers.

Figure 5.48: Normalized percent weight remaining after subjecting each nonwoven fabric to the NaOH bath for the specified amount of time
5.4.2 Air Permeability

The air permeability data for the fabrics before and after washing out the PLA can be seen in Table A.22. Figures 5.49 and 5.50 show the air permeability values for MM-ALT-IS and MM-3L-SP, respectively, in comparison to the control samples. Both figures show that the air permeability is increased after washing out the PLA. This would be expected since there are fewer fibers within the nonwoven structure after washing out the PLA.

Figure 5.49: Air Permeability of the control fabrics and MM-ALT-IS fabrics in ratios of 50/50 and 75/25
Table A.23 summarizes the basis weight data for the fabrics before and after washing the PLA out. Figure 5.51 shows the weight remaining after exposure to NaOH bath for the MM-ALT-IS and MM-3L-SP in comparison to the control samples. It can be observed that there was a definite decrease in the basis weight of the fabrics after the removal of the PLA. It is interesting to note that the percent decrease in the basis weight of the MM-ALT-IS fabric does not correspond with the percent amount of PLA in the structure. This could be a sign that the PET used as
the islands and homocomponent in the mixed media is not able to withstand the NaOH bath and is therefore removed in addition to the PLA or that, contrary to the hydroentangling process, the fabric was relaxed while in the processing bath. In the control samples and in the MM-3L-SP samples, the percent decrease closely follows the amount of PLA initially incorporated into the mixed media fabric. For example, when the ratio of PA6 to PLA was 75/25, the data shows that approximately 24% of the PLA was removed.

![Graph showing percent weight remaining for mixed media and control fabrics after PLA removal bath, hydroentangled with a specific energy of 43.1 MJ/kg](image)

**Figure 5.51:** Percent weight remaining for mixed media and control fabrics after PLA removal bath, hydroentangled with a specific energy of 43.1 MJ/kg
5.4.4 Thickness

Table A.24 summarizes the thickness data for the fabrics before and after washing the PLA out. Figure 5.52 shows the thickness values for MM-ALT-IS and MM-3L-SP, in comparison to the control samples. As expected, the thickness is lower in the samples with the PLA removed. It is interesting to note that even though the mixed media samples started with thickness values that were not significantly different when comparing the 50/50 and 75/25 ratios, the mixed media samples with the PLA removed (with a polymer ratio of 50/50) had lower thickness than the corresponding samples with the ratio of 75/25. This can be attributed to the higher initial amount of PLA in the ratio: in the ratio of 50/50 there was initially 50% PLA, whereas in the ratio of 75/25, the initial PLA amount was only 25%, therefore less fibers were removed. This can be confirmed in Figure 5.53, which displays the percent decrease in thickness for all the mixed media and control fabrics tested. The less the initial amount of PLA, the less the amount decrease in thickness is observed. The thickness is the lowest in the PET/PLA samples, which corresponds to the highest percentage decrease in thickness. This is expected since the percent basis weight remaining was lowest in the PET/PLA samples.
Figure 5.52: Thickness (µm) of the control and mixed media fabrics, before and after the removal of PLA, hydroentangled with a specific energy of 43.1 MJ/kg

Figure 5.53: Decrease in thickness (%) for the control and mixed media fabrics, after the removal of PLA, hydroentangled with a specific energy of 43.1 MJ/kg
5.4.5 Pore Properties

Tables A.25 and A.26 summarize the pore size data and porosity data, respectively, for the mixed media fabrics and control fabrics before and after being exposed to the PLA removal bath. Figures 5.54 and 5.55 show the average pore size and percent porosity, respectively, for the control and mixed media fabrics before and after exposure to the NaOH solution. It was expected that the MM-ALT-IS fabric would have higher values for the average pore size and porosity since it was the fabric with the highest air permeability. It is interesting to note that MM-3L-SP had only a very slight difference in pore size and porosity when compared to the control sample. This is important because one of the aims of mixed media fabrics is to increase the permeability while keeping the pore size relatively small. This data proves that the mixed media fabric can have comparable pore properties to the conventional 16-segmented pie control sample without inhibiting permeability. Figure 5.56 shows SEM micrographs of 75% PA6 / 25% PLA control hydroentangled at 43.1 MJ/kg before and after removing the PLA. It can be observed that the micrographs of the fabric after PLA removal appear to be less dense structures, which agrees with the data showing the fabrics having higher porosity after removal of the PLA.
Figure 5.54: Average pore size (µm) of control and mixed media fabrics, before and after the removal of PLA, hydroentangled with a specific energy of 43.1 MJ/kg
Figure 5.55: Porosity (%) of control and mixed media fabrics, before and after the removal of PLA, hydroentangled with a specific energy of 43.1 MJ/kg.
Figure 5.56: Scanning electron micrographs of 75% PA6 / 25% PLA control hydroentangled with a specific energy of 43.1 MJ/kg: a) Before PLA removal 30x; b) Before PLA removal 120x; c) Before PLA removal 500x; d) After PLA removal 30x; e) After PLA removal 120x; f) After PLA removal 500x
5.4.6 Summary and Conclusions

The ratio does not have as much of an effect on the ability of PLA to be removed from the fabric as the polymer combination. The polymer, other than PLA in the bicomponent, must be able to withstand the washing conditions. If not, the PLA will be removed and the remaining polymer will be damaged or removed as well. This is what seems to have happened in the case of the PET/PLA, since the percent weight remaining shows that more than the initial percentage of PLA has been removed from the fabric. This could mean that some of the PET has been removed as well. In the PA6/PLA samples, it would be expected that the initial amount of PLA (50% or 25%) would dictate that the basis weight would decrease by that same amount after subjecting the samples to the NaOH bath. The basis weight data shows that, for the most part, this is in fact true and that the mixed media samples behave in the same manner as the control samples when removing PLA in an NaOH bath at 90°C for 15 minutes. The thickness loss after PLA removal was higher in the mixed media samples because they were loftier structures to begin with. Since the control sample was a denser and more compact structure without homocomponent fibers, it would be assumed that they would have less of a tendency to move into the voids left by the PLA fibers since they were already very close together. Because of the looser structure of the mixed media, the fibers would have more of a tendency to move into the voids left by the PLA fibers, thereby making the fabric thinner. The more open structures after PLA removal can be observed in the SEM micrographs in Figure 5.56.
CHAPTER 6: OVERALL CONCLUSIONS

In this study, mixed media nonwovens of three different configurations were analyzed and compared. The mixed media configurations included a three-layer configuration with 16-segmented pie bicomponent fibers (MM-3L-SP), an alternating configuration with 16-segmented pie bicomponent fibers (MM-ALT-SP) and an alternating configuration with 7-islands-in-the-sea bicomponent fibers (MM-ALT-IS). The control nonwoven was composed of 16-segmented pie bicomponent fibers throughout.

It can be seen in Figure 6.1 that the mixed media nonwovens achieved higher air permeability than the control fabrics in all three configurations, with the 75% PET/25% PA6 MM-ALT-IS configuration reaching the highest air permeability of 32.7 cm$^3$/cm$^2$/sec. In Figure 6.2, the highest thickness can be found in the MM-ALT-SP configuration. The remaining two mixed media configurations also display higher thickness values than the control. The combination of higher thickness and air permeability in the mixed media samples when compared to the control samples proves that a loftier, less compact fibrous structure has been produced. This can be attributed to the existence of homocomponent fibers preventing the dense packing of the microfibers. Because the mixed media structures are less compact, it can be assumed that the pores will be larger than those of the control sample. This assumption is proven to be true in Figure 6.3 where it can be easily observed that all three of the mixed media samples have larger average pore sizes than the control.
sample. It is interesting to note that although the pores are larger in the mixed media samples, the porosity is not significantly different for any of the samples (Figure 6.4). This could be due to the tortuosity of the pores in the mixed media samples however, this needs to be explored further. One of the aims of mixed media nonwoven fabric was to achieve better tear strength than the control fabric made from 100% 16-segmented pie bicomponent fibers. It can be observed in Figures 6.5 and 6.6 that the cross-direction tear strength is consistently higher than the machine-direction tear strength, which is expected due to the anisotropic fiber orientation in the machine-direction. More force is required to tear across the multitude of fibers oriented perpendicular to the tear propagation. It can also be observed from Figure that the highest tear strength was found in the MM-ALT-IS configuration, proving that mixed media fabrics can achieve higher tear strength than their control counterparts. Figure 6.7 shows that the highest tensile strength of the 50% PET / 50% PA6 control and mixed media samples is found in the MM-3L-SP structure. In the ratio of 75% PET / 25% PA6, the MM-3L-SP and MM-ALT-IS structures display tensile strength values that are comparable to the control sample (See Figure 6.8). Figure 6.9 shows the SEM micrographs of 50% PET / 50% PA6 MM-ALT-IS and control nonwoven fabrics hydroentangled with a specific energy of 43.1 MJ/kg. Figure 6.10 shows the SEM micrographs of 50% PET / 50% PA6 MM-3L-SP and control nonwoven fabrics hydroentangled with a specific energy of 43.1 MJ/kg.
Based on the properties and characteristics analyzed for the MM-3L-SP, MM-ALT-SP and MM-ALT-IS nonwoven fabrics, the results show promise in using mixed media in applications where high surface area microfibrous nonwovens are needed, which exhibit strength, permeability and porosity at a limited basis weight. Mixed media nonwovens provide an opportunity to engineer spunbond structures in order to tailor properties for specific applications.

Figure 6.1: Air permeability of the 50% PET / 50% PA6 and 75% PET / 25% PA6 mixed media and control fabrics hydroentangled with a specific energy of 43.1 MJ/kg
Figure 6.2: Thickness of the 50% PET / 50% PA6 and 75% PET / 25% PA6 mixed media and control fabrics hydroentangled with a specific energy of 43.1 MJ/kg

Figure 6.3: Average pore size of the 50% PET / 50% PA6 and 75% PET / 25% PA6 mixed media and control fabrics hydroentangled with a specific energy of 43.1 MJ/kg
Figure 6.4: Porosity of the 50% PET / 50% PA6 and 75% PET / 25% PA6 mixed media and control fabrics hydroentangled with a specific energy of 43.1 MJ/kg

Figure 6.5: Tear strength of the 50% PET / 50% PA6 mixed media and control fabrics hydroentangled with a specific energy of 43.1 MJ/kg
Figure 6.6: Tear strength of the 75% PET / 25% PA6 mixed media and control fabrics hydroentangled with a specific energy of 43.1 MJ/kg

Figure 6.7: Tensile strength of the 50% PET / 50% PA6 mixed media and control fabrics hydroentangled with a specific energy of 43.1 MJ/kg
Figure 6.8: Tensile strength of the 75% PET / 25% PA6 mixed media and control fabrics hydroentangled with a specific energy of 43.1 MJ/kg
Figure 6.9: Scanning electron micrographs of 50% PET / 50% PA6 hydroentangled with a specific energy of 43.1 MJ/kg: a) Control 30x; b) Control 120x; c) Control 500x; d) MM-3L-SP 30x; e) MM-3L-SP 120x; f) MM-3L-SP 500x; g) MM-ALT-SP 30x; h) MM-ALT-SP 120x; i) MM-ALT-SP 500x; j) MM-ALT-IS 30x; k) MM-ALT-IS 120x; l) MM-ALT-IS 500x
Figure 6.10: Scanning electron micrographs of 75% PET / 25% PA6 hydroentangled with a specific energy of 43.1 MJ/kg: a) Control 30x; b) Control 120x; c) Control 500x; d) MM-3L-SP 30x; e) MM-3L-SP 120x; f) MM-3L-SP 500x; g) MM-ALT-SP 30x; h) MM-ALT-SP 120x; i) MM-ALT-SP 500x; j) MM-ALT-IS 30x; k) MM-ALT-IS 120x; l) MM-ALT-IS 500x
CHAPTER 7: FUTURE RECOMMENDATIONS

In the presented dissertation, the structure-property relationships of hybrid mixed media nonwovens were addressed through the property and characteristic analysis of three-layer and alternating 16-segmented pie mixed media structures as well as alternating 7-islands-in-the-sea mixed media structures. In order to make this research more complete, a three-layer 7-islands-in-the-sea structure (Figure 7.1) should be produced, as well as a 100%7-islands-in-the-sea bicomponent fabric (Figure 7.2), and property and characteristic analysis should be performed. It would also be interesting to investigate the pore tortuosity in all mixed media fabrics and the influence that the structure and bicomponent cross-section has on said tortuosity.

Figure 7.1: 7-islands-in-the-sea three-layer mixed media configuration
Finally, each mixed media structure should be analyzed for its filtration potential through liquid permeability testing, filtration efficiency testing, and filtration mechanism identification. The factors which are predicted to influence the liquid filtration performance are the bicomponent cross-sectional size and shape (segmented pie versus islands-in-the-sea), the spinpack configuration (three-layer versus alternating), the ratio of one polymer to another, and the amount of specific energy imparted to the web through hydroentangling. Liquid permeability testing could be performed using a capillary flow porometer and filtration efficiency could be performed using a dead-end filter tester. Moreover, the Darcy equation could be utilized as a method to calculate the face velocity of a medium by using the permeability constant of the medium, fluid viscosity, thickness of fabric, and pressure drop across the fabric thickness.

Figure 7.2: 100% 7-islands-in-the-sea bicomponent nonwoven fabric
CHAPTER 8: REFERENCES


CHAPTER 9: APPENDIX
Table A.1: Air permeability (cm\(^3\)/cm\(^2\)/sec) of 100 g/m\(^2\) MM-3L-SP and control fabrics as a function of the specific energy used during hydroentangling

<table>
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<th>Material</th>
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<th>28.8</th>
<th>43.1</th>
<th>57.5</th>
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<td>50% PA6 / 50% PLA</td>
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<td>MM-3L-SP</td>
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<td>75% PA6 / 25% PLA</td>
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<td>MM-3L-SP</td>
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<tr>
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<tr>
<td>MM-3L-SP</td>
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<td>10.4 ± 0.2</td>
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Table A.2: Post-hydroentangling basis weight (g/m$^2$) of MM-3L-SP and control fabrics as a function of the specific energy experienced by the webs

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<th>43.1</th>
<th>57.5</th>
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<tr>
<td>50% PA6 / 50% PLA</td>
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<tr>
<td>MM-3L-SP</td>
<td>118.3 ± 0.5</td>
<td>127.4 ± 0.7</td>
<td>135.1 ± 6.7</td>
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<td>105.5 ± 1.1</td>
<td>119.6 ± 1.1</td>
<td>125.3 ± 0.9</td>
<td>-</td>
</tr>
<tr>
<td>75% PA6 / 25% PLA</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MM-3L-SP</td>
<td>111.1 ± 1.3</td>
<td>115.0 ± 0.7</td>
<td>120.5 ± 0.8</td>
<td>141.3 ± 2.4</td>
</tr>
<tr>
<td>Control</td>
<td>108.1 ± 2.0</td>
<td>116.8 ± 1.7</td>
<td>123.6 ± 1.5</td>
<td>-</td>
</tr>
<tr>
<td>50% PET / 50% PA6</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MM-3L-SP</td>
<td>108.9 ± 0.5</td>
<td>113.5 ± 0.6</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Control</td>
<td>105.6 ± 1.3</td>
<td>109.7 ± 1.0</td>
<td>111.7 ± 0.4</td>
<td>-</td>
</tr>
<tr>
<td>75% PET / 25% PA6</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MM-3L-SP</td>
<td>116.8 ± 1.8</td>
<td>123.6 ± 1.6</td>
<td>126.9 ± 1.0</td>
<td>-</td>
</tr>
</tbody>
</table>
Table A.3: Thickness (µm) of MM-3L-SP and control fabrics as a function of the specific energy experienced by the webs

<table>
<thead>
<tr>
<th>Specific Energy (MJ/kg)</th>
<th>14.4</th>
<th>28.8</th>
<th>43.1</th>
<th>57.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Materials</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>50% PA6 / 50% PLA MM-3L-SP</td>
<td>490 ± 11</td>
<td>472 ± 7</td>
<td>598 ± 11</td>
<td>610 ± 30</td>
</tr>
<tr>
<td>50% PA6 / 50% PLA Control</td>
<td>440 ± 4</td>
<td>570 ± 8</td>
<td>639 ± 7</td>
<td>-</td>
</tr>
<tr>
<td>75% PA6 / 25% PLA MM-3L-SP</td>
<td>398 ± 8</td>
<td>410 ± 6</td>
<td>572 ± 7</td>
<td>602 ± 7</td>
</tr>
<tr>
<td>75% PA6 / 25% PLA Control</td>
<td>433 ± 5</td>
<td>431 ± 5</td>
<td>545 ± 7</td>
<td>-</td>
</tr>
<tr>
<td>50% PET / 50% PA6 MM-3L-SP</td>
<td>-</td>
<td>438 ± 5</td>
<td>516 ± 4</td>
<td>-</td>
</tr>
<tr>
<td>50% PET / 50% PA6 Control</td>
<td>406 ± 4</td>
<td>433 ± 4</td>
<td>444 ± 3</td>
<td>-</td>
</tr>
<tr>
<td>75% PET / 25% PA6 MM-3L-SP</td>
<td>-</td>
<td>-</td>
<td>522 ± 15</td>
<td>454 ±4</td>
</tr>
<tr>
<td>75% PET / 25% PA6 Control</td>
<td>400 ± 3</td>
<td>444 ± 4</td>
<td>421 ± 3</td>
<td>-</td>
</tr>
</tbody>
</table>
Table A.4: Pore Size of 100 g/m² MM-3L-SP and control fabrics as a function of the specific energy used during hydroentangling

<table>
<thead>
<tr>
<th>Specific Energy (MJ/kg)</th>
<th>Smallest Detected Pore Size (Micron)</th>
<th>Average Pore Size (Micron)</th>
<th>Largest Detected Pore Size (Micron)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>14.4</td>
<td>28.8</td>
<td>43.1</td>
</tr>
<tr>
<td>50% PA6 / 50% PLA MM-3L-SP</td>
<td>12.7</td>
<td>3.4</td>
<td>3.8</td>
</tr>
<tr>
<td>50% PA6 / 50% PLA Control</td>
<td>5.2</td>
<td>3.4</td>
<td>2.6</td>
</tr>
<tr>
<td>75% PA6 / 25% PLA MM-3L-SP</td>
<td>6.5</td>
<td>3.1</td>
<td>3.8</td>
</tr>
<tr>
<td>75% PA6 / 25% PLA Control</td>
<td>2.3</td>
<td>2.3</td>
<td>2.3</td>
</tr>
<tr>
<td>50% PET / 50% PA6 MM-3L-SP</td>
<td>-</td>
<td>5.9</td>
<td>4.9</td>
</tr>
<tr>
<td>50% PET / 50% PA6 Control</td>
<td>6.1</td>
<td>3.8</td>
<td>3.4</td>
</tr>
<tr>
<td>75% PET / 25% PA6 MM-3L-SP</td>
<td>-</td>
<td>-</td>
<td>3.8</td>
</tr>
<tr>
<td>75% PET / 25% PA6 Control</td>
<td>2.8</td>
<td>1.7</td>
<td>2.0</td>
</tr>
</tbody>
</table>
Table A.5: Porosity (%) of 100 g/m² MM-3L-SP and control fabrics as a function of the specific energy used during hydroentangling

<table>
<thead>
<tr>
<th>Materials</th>
<th>Specific Energy (MJ/kg)</th>
<th>Porosity (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>14.4</td>
<td>28.8</td>
</tr>
<tr>
<td>50% PA6 / 50% PLA MM-3L-SP</td>
<td>82.8 ± 0.8</td>
<td>82.1 ± 0.6</td>
</tr>
<tr>
<td>50% PA6 / 50% PLA Control</td>
<td>80.8 ± 0.4</td>
<td>85.2 ± 0.4</td>
</tr>
<tr>
<td>75% PA6 / 25% PLA MM-3L-SP</td>
<td>78.3 ± 0.8</td>
<td>78.9 ± 0.6</td>
</tr>
<tr>
<td>75% PA6 / 25% PLA Control</td>
<td>80.0 ± 0.4</td>
<td>80.0 ± 0.5</td>
</tr>
<tr>
<td>50% PET / 50% PA6 MM-3L-SP</td>
<td>-</td>
<td>80.4 ± 0.3</td>
</tr>
<tr>
<td>50% PET / 50% PA6 Control</td>
<td>79.4 ± 0.5</td>
<td>80.0 ± 0.4</td>
</tr>
<tr>
<td>75% PET / 25% PA6 MM-3L-SP</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>75% PET / 25% PA6 Control</td>
<td>78.1 ± 0.5</td>
<td>79.1 ± 0.4</td>
</tr>
</tbody>
</table>
Table A.6: Mechanical properties of 100 g/m² MM-3L-SP and control fabrics hydroentangled with a specific energy of 43.1 MJ/kg

<table>
<thead>
<tr>
<th>Property</th>
<th>Tear Strength (kgf)</th>
<th>Tensile Strength (kgf)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MD</td>
<td>CD</td>
</tr>
<tr>
<td>50% PA6 / 50% PLA</td>
<td>0.95 ± 0.05</td>
<td>1.94 ± 0.12</td>
</tr>
<tr>
<td>MM-3L-SP</td>
<td></td>
<td></td>
</tr>
<tr>
<td>50% PA6 / 50% PLA</td>
<td>0.71 ± 0.04</td>
<td>1.21 ± 0.09</td>
</tr>
<tr>
<td>Control</td>
<td></td>
<td></td>
</tr>
<tr>
<td>75% PA6 / 25% PLA</td>
<td>1.00 ± 0.05</td>
<td>3.54 ± 0.11</td>
</tr>
<tr>
<td>MM-3L-SP</td>
<td></td>
<td></td>
</tr>
<tr>
<td>75% PA6 / 25% PLA</td>
<td>0.97 ± 0.03</td>
<td>1.68 ± 0.21</td>
</tr>
<tr>
<td>Control</td>
<td></td>
<td></td>
</tr>
<tr>
<td>50% PET / 50% PA6</td>
<td>0.81 ± 0.02</td>
<td>1.74 ± 0.10</td>
</tr>
<tr>
<td>MM-3L-SP</td>
<td></td>
<td></td>
</tr>
<tr>
<td>50% PET / 50% PA6</td>
<td>1.09 ± 0.05</td>
<td>1.80 ± 0.07</td>
</tr>
<tr>
<td>Control</td>
<td></td>
<td></td>
</tr>
<tr>
<td>75% PET / 25% PA6</td>
<td>0.86 ± 0.05</td>
<td>1.73 ± 0.06</td>
</tr>
<tr>
<td>MM-3L-SP</td>
<td></td>
<td></td>
</tr>
<tr>
<td>75% PET / 25% PA6</td>
<td>1.13 ± 0.06</td>
<td>1.94 ± 0.06</td>
</tr>
<tr>
<td>Control</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table A.7: Air permeability (cm³/cm²/sec) of 100 g/m² MM-ALT-SP and control fabrics as a function of the specific energy experienced by the webs

<table>
<thead>
<tr>
<th>Specific Energy (MJ/kg)</th>
<th>14.4</th>
<th>28.8</th>
<th>43.1</th>
<th>57.5</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Materials</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>50% PET / 50% PA6</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MM-ALT-SP</td>
<td>34.2 ± 1.9</td>
<td>25.4 ± 1.3</td>
<td>24.0 ± 1.3</td>
<td>22.6 ± 1.1</td>
</tr>
<tr>
<td>Control</td>
<td>20.2 ± 1.2</td>
<td>11.5 ± 0.7</td>
<td>6.8 ± 0.2</td>
<td>-</td>
</tr>
<tr>
<td>75% PET / 25% PA6</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MM-ALT-SP</td>
<td>45.4 ± 1.7</td>
<td>28.4 ± 0.7</td>
<td>20.3 ± 0.5</td>
<td>16.9 ± 0.4</td>
</tr>
<tr>
<td>Control</td>
<td>5.8 ± 0.5</td>
<td>3.1 ± 0.1</td>
<td>2.9 ± 0.0</td>
<td>-</td>
</tr>
</tbody>
</table>

Table A.8: Measured basis weight (g/m²) of MM-ALT-SP and control fabrics as a function of the specific energy experienced by the webs

<table>
<thead>
<tr>
<th>Specific Energy (MJ/kg)</th>
<th>14.4</th>
<th>28.8</th>
<th>43.1</th>
<th>57.5</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Materials</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>50% PET / 50% PA6</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MM-ALT-SP</td>
<td>114.3 ± 0.8</td>
<td>122.8 ± 0.6</td>
<td>119.1 ± 0.7</td>
<td>127.4 ± 0.7</td>
</tr>
<tr>
<td>Control</td>
<td>105.6 ± 1.3</td>
<td>109.7 ± 1.0</td>
<td>111.7 ± 0.4</td>
<td>-</td>
</tr>
<tr>
<td>75% PET / 25% PA6</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MM-ALT-SP</td>
<td>113.2 ± 0.5</td>
<td>117.3 ± 1.7</td>
<td>118.3 ± 0.5</td>
<td>118.8 ± 1.0</td>
</tr>
<tr>
<td>Control</td>
<td>116.8 ± 1.8</td>
<td>123.6 ± 1.6</td>
<td>126.9 ± 1.0</td>
<td>-</td>
</tr>
</tbody>
</table>
Table A.9: Differences in the amounts of polymer in a single bicomponent fiber in the MM-ALT-SP and the average basis weight of the corresponding fabric

<table>
<thead>
<tr>
<th>Material</th>
<th>Amt. of PET (%)</th>
<th>Amt. of PA6 (%)</th>
<th>Difference (%)</th>
<th>Average Basis Weight (g/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control 50/50</td>
<td>50</td>
<td>50</td>
<td>0</td>
<td>109.0</td>
</tr>
<tr>
<td>MM-ALT-SP 75/25</td>
<td>60</td>
<td>40</td>
<td>20</td>
<td>116.9</td>
</tr>
<tr>
<td>MM-ALT-SP 50/50</td>
<td>33</td>
<td>66</td>
<td>33</td>
<td>120.9</td>
</tr>
<tr>
<td>Control 75/25</td>
<td>75</td>
<td>25</td>
<td>50</td>
<td>122.4</td>
</tr>
</tbody>
</table>

Table A.10: Thickness (µm) of 100 g/m² MM-ALT-SP and control fabrics as a function of the specific energy experienced by the webs

<table>
<thead>
<tr>
<th>Specific Energy (MJ/kg)</th>
<th>Materials</th>
<th>14.4</th>
<th>28.8</th>
<th>43.1</th>
<th>57.5</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>50% PET / 50% PA6 MM-ALT-SP</td>
<td>537 ± 5</td>
<td>573 ± 7</td>
<td>599 ± 4</td>
<td>621 ± 3</td>
</tr>
<tr>
<td></td>
<td>50% PET / 50% PA6 Control</td>
<td>406 ± 4</td>
<td>433 ± 4</td>
<td>444 ± 3</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>75% PET / 25% PA6 MM-ALT-SP</td>
<td>512 ± 13</td>
<td>528 ± 5</td>
<td>563 ± 8</td>
<td>553 ± 10</td>
</tr>
<tr>
<td></td>
<td>75% PET / 25% PA6 Control</td>
<td>400 ± 3</td>
<td>444 ± 4</td>
<td>421 ± 3</td>
<td>-</td>
</tr>
</tbody>
</table>
Table A.11: Pore Size (µm) of 100 g/m² MM-ALT-SP and control fabrics as a function of the specific energy used during hydroentangling

<table>
<thead>
<tr>
<th>Materials</th>
<th>Smallest Detected Pore Size (Micron)</th>
<th>Average Pore Size (Micron)</th>
<th>Largest Detected Pore Size (Micron)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Specific Energy (MJ/kg)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>50% PET / 50% PA6</td>
<td>14.4 28.8 43.1</td>
<td>14.4 28.8 43.1</td>
<td>14.4 28.8 43.1</td>
</tr>
<tr>
<td>MM-ALT-SP</td>
<td>7.1 5.7 8.0</td>
<td>22.6 ± 3.4 17.6 ± 2.5 18.7 ± 2.6</td>
<td>81.0 60.1 66.0</td>
</tr>
<tr>
<td>50% PET / 50% PA6</td>
<td>6.1 3.8 3.4</td>
<td>17.9 ± 2.1 9.8 ± 1.1 7.1 ± 1.5</td>
<td>74.2 33.0 33.6</td>
</tr>
<tr>
<td>Control</td>
<td>2.8 1.7 2.0</td>
<td>9.8 ± 1.2 6.8 ± 1.0 4.5 ± 0.6</td>
<td>31.5 23.8 22.6</td>
</tr>
<tr>
<td>75% PET / 25% PA6</td>
<td>11.5 6.4 5.2</td>
<td>30.8 ± 4.4 18.7 ± 2.5 17.3 ± 2.4</td>
<td>104.0 63.0 63.0</td>
</tr>
<tr>
<td>MM-ALT-SP</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>75% PET / 25% PA6</td>
<td>2.8 1.7 2.0</td>
<td>9.8 ± 1.2 6.8 ± 1.0 4.5 ± 0.6</td>
<td>31.5 23.8 22.6</td>
</tr>
<tr>
<td>Control</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table A.12: Porosity (%) of 100 g/m² MM-ALT-SP and control fabrics as a function of increasing hydroentangling energy

<table>
<thead>
<tr>
<th>Materials</th>
<th>Specific Energy (MJ/kg)</th>
<th>Porosity (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>14.4</td>
<td>28.8</td>
</tr>
<tr>
<td>50% PET / 50% PA6 MM-ALT-SP</td>
<td>83.2 ± 0.3</td>
<td>83.1 ± 0.3</td>
</tr>
<tr>
<td>50% PET / 50% PA6 Control</td>
<td>79.4 ± 0.5</td>
<td>80.0 ± 0.4</td>
</tr>
<tr>
<td>75% PET / 25% PA6 MM-ALT-SP</td>
<td>83.4 ± 0.5</td>
<td>83.3 ± 0.4</td>
</tr>
<tr>
<td>75% PET / 25% PA6 Control</td>
<td>78.1 ± 0.5</td>
<td>79.1 ± 0.4</td>
</tr>
</tbody>
</table>

Table A.13: Mechanical properties of 100 g/m² MM-ALT-SP and control fabrics hydroentangled with a specific energy of 43.13 MJ/kg

<table>
<thead>
<tr>
<th>Materials</th>
<th>Tear Strength (kgf)</th>
<th>Tensile Strength (kgf)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MD</td>
<td>CD</td>
</tr>
<tr>
<td>50% PET / 50% PA6 MM-ALT-SP</td>
<td>2.4 ± 0.1</td>
<td>2.8 ± 0.1</td>
</tr>
<tr>
<td>50% PET / 50% PA6 Control</td>
<td>1.1 ± 0.1</td>
<td>1.8 ± 0.1</td>
</tr>
<tr>
<td>75% PET / 25% PA6 MM-ALT-SP</td>
<td>1.1 ± 0.1</td>
<td>2.1 ± 0.1</td>
</tr>
<tr>
<td>75% PET / 25% PA6 Control</td>
<td>1.1 ± 0.1</td>
<td>1.9 ± 0.1</td>
</tr>
</tbody>
</table>
Table A.14: Air permeability (cm³/cm²/sec) of MM-ALT-IS and control fabrics as a function of the specific energy experienced by the webs

<table>
<thead>
<tr>
<th>Specific Energy (MJ/kg)</th>
<th>14.4</th>
<th>28.8</th>
<th>43.1</th>
<th>57.5</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Materials</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>50% PET / 50% PA6</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MM-ALT-IS</td>
<td>-</td>
<td>34.1 ± 1.5</td>
<td>21.4 ± 1.1</td>
<td>15.8 ± 0.6</td>
</tr>
<tr>
<td>Control</td>
<td>20.2 ± 1.2</td>
<td>11.5 ± 0.7</td>
<td>6.8 ± 0.2</td>
<td>-</td>
</tr>
<tr>
<td>75% PET / 25% PA6</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MM-ALT-IS</td>
<td>-</td>
<td>50.0 ± 1.2</td>
<td>32.7 ± 0.6</td>
<td>19.8 ± 0.6</td>
</tr>
<tr>
<td>Control</td>
<td>5.8 ± 0.5</td>
<td>3.1 ± 0.1</td>
<td>2.9 ± 0.04</td>
<td>-</td>
</tr>
</tbody>
</table>

Table A.15: Measured basis weight (g/m²) of MM-ALT-IS and control fabrics as a function of the specific energy experienced by the webs

<table>
<thead>
<tr>
<th>Specific Energy (MJ/kg)</th>
<th>14.4</th>
<th>28.8</th>
<th>43.1</th>
<th>57.5</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Materials</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>50% PET / 50% PA6</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MM-ALT-IS</td>
<td>-</td>
<td>110.3 ± 1.9</td>
<td>117.3 ± 2.1</td>
<td>122.9 ± 1.2</td>
</tr>
<tr>
<td>Control</td>
<td>105.6 ± 1.3</td>
<td>109.7 ± 1.0</td>
<td>111.7 ± 0.4</td>
<td>-</td>
</tr>
<tr>
<td>75% PET / 25% PA6</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MM-ALT-IS</td>
<td>-</td>
<td>102.5 ± 2.3</td>
<td>108.3 ± 1.1</td>
<td>111.5 ± 1.3</td>
</tr>
<tr>
<td>Control</td>
<td>116.8 ± 1.8</td>
<td>123.6 ± 1.6</td>
<td>126.9 ± 1.0</td>
<td>-</td>
</tr>
</tbody>
</table>
Table A.16: Differences in the amounts of polymer in a single bicomponent fiber in the MM-ALT-IS and the average basis weight of the corresponding fabric

<table>
<thead>
<tr>
<th></th>
<th>Amt. of PET (%)</th>
<th>Amt. of PA6 (%)</th>
<th>Difference (%)</th>
<th>Average Basis Weight (g/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control 50/50</td>
<td>50</td>
<td>50</td>
<td>0</td>
<td>109.0</td>
</tr>
<tr>
<td>MM-ALT-IS 75/25</td>
<td>60</td>
<td>40</td>
<td>20</td>
<td>116.7</td>
</tr>
<tr>
<td>MM-ALT-IS 50/50</td>
<td>33</td>
<td>66</td>
<td>33</td>
<td>116.8</td>
</tr>
<tr>
<td>Control 75/25</td>
<td>75</td>
<td>25</td>
<td>50</td>
<td>122.4</td>
</tr>
</tbody>
</table>

Table A.17: Thickness (µm) of 100 g/m² MM-ALT-IS and control fabrics as a function of the specific energy experienced by the webs

<table>
<thead>
<tr>
<th>Materials</th>
<th>Specific Energy (MJ/kg)</th>
<th>14.4</th>
<th>28.8</th>
<th>43.1</th>
<th>57.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>50% PET / 50% PA6 MM-ALT-IS</td>
<td>-</td>
<td>482 ± 6</td>
<td>520 ± 7</td>
<td>498 ± 9</td>
<td></td>
</tr>
<tr>
<td>50% PET / 50% PA6 Control</td>
<td>406 ± 4</td>
<td>433 ± 4</td>
<td>444 ± 3</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>75% PET / 25% PA6 MM-ALT-IS</td>
<td>-</td>
<td>528 ± 8</td>
<td>530 ± 15</td>
<td>498 ± 8</td>
<td></td>
</tr>
<tr>
<td>75% PET / 25% PA6 Control</td>
<td>400 ± 3</td>
<td>444 ± 4</td>
<td>421 ± 3</td>
<td>-</td>
<td></td>
</tr>
</tbody>
</table>
Table A.18: Pore Size (µm) of 100 g/m² MM-ALT-IS and control fabrics as a function of the specific energy used during hydroentangling

<table>
<thead>
<tr>
<th>Specific Energy (MJ/kg)</th>
<th>Materials</th>
<th>Smallest Detected Pore Size (Micron)</th>
<th>Average Pore Size (Micron)</th>
<th>Largest Detected Pore Size (Micron)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>14.4 28.8 43.1 57.5</td>
<td>14.4 28.8 43.1 57.5</td>
<td>14.4 28.8 43.1 57.5</td>
</tr>
<tr>
<td>50% PET / 50% PA6</td>
<td>MM-ALT-IS</td>
<td>- 10.1 9.4 6.21</td>
<td>- 20.2 ± 2.1 20.4 ± 2.2 19.0 ± 2.3</td>
<td>- 62.7 67.8 79.1</td>
</tr>
<tr>
<td>50% PET / 50% PA6</td>
<td>Control</td>
<td>6.1 3.8 3.4 -</td>
<td>17.9 ± 2.1 9.8 ± 1.1 7.1 ± 1.5</td>
<td>- 74.2 33.0 33.6 -</td>
</tr>
<tr>
<td>75% PET / 25% PA6</td>
<td>MM-ALT-IS</td>
<td>- 12.3 9.3 6.9</td>
<td>- 24.6 ± 2.2 20.7 ± 2.2 15.9 ± 1.6</td>
<td>- 67.0 63.0 46.6</td>
</tr>
<tr>
<td>75% PET / 25% PA6</td>
<td>Control</td>
<td>2.8 1.7 2.0 -</td>
<td>9.8 ± 1.2 6.8 ± 1.0 4.45 ± 0.6</td>
<td>- 31.5 23.8 22.6 -</td>
</tr>
</tbody>
</table>
Table A.19: Porosity (%) of 100 g/m² MM-ALT-IS and control fabrics as a function of increasing hydroentangling energy

<table>
<thead>
<tr>
<th>Materials</th>
<th>Specific Energy (MJ/kg)</th>
<th>Porosity (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>14.4</td>
<td>28.8</td>
</tr>
<tr>
<td>50% PET / 50% PA6 MM-ALT-IS</td>
<td>-</td>
<td>81.9 ± 0.6</td>
</tr>
<tr>
<td>50% PET / 50% PA6 Control</td>
<td>79.4 ± 0.5</td>
<td>80.0 ± 0.4</td>
</tr>
<tr>
<td>75% PET / 25% PA6 MM-ALT-IS</td>
<td>-</td>
<td>85.4 ± 0.5</td>
</tr>
<tr>
<td>75% PET / 25% PA6 Control</td>
<td>78.1 ± 0.5</td>
<td>79.1 ± 0.4</td>
</tr>
</tbody>
</table>

Table A.20: Mechanical properties of 100 g/m² MM-ALT-IS and control fabrics hydroentangled with a specific energy of 43.13 MJ/kg

<table>
<thead>
<tr>
<th>Materials</th>
<th>Property</th>
<th>Tear Strength (kgf)</th>
<th>Tensile Strength (kgf)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>MD</td>
<td>CD</td>
</tr>
<tr>
<td>50% PET / 50% PA6 MM-ALT-IS</td>
<td>Tear Strength</td>
<td>1.6 ± 0.1</td>
<td>2.9 ± 0.1</td>
</tr>
<tr>
<td></td>
<td>Tensile Strength</td>
<td>1.6 ± 0.1</td>
<td>2.9 ± 0.1</td>
</tr>
<tr>
<td>50% PET / 50% PA6 Control</td>
<td>Tear Strength</td>
<td>1.1 ± 0.1</td>
<td>1.8 ± 0.1</td>
</tr>
<tr>
<td></td>
<td>Tensile Strength</td>
<td>1.1 ± 0.1</td>
<td>1.8 ± 0.1</td>
</tr>
<tr>
<td>75% PET / 25% PA6 MM-ALT-IS</td>
<td>Tear Strength</td>
<td>2.2 ± 0.1</td>
<td>3.7 ± 0.2</td>
</tr>
<tr>
<td></td>
<td>Tensile Strength</td>
<td>2.2 ± 0.1</td>
<td>3.7 ± 0.2</td>
</tr>
<tr>
<td>75% PET / 25% PA6 Control</td>
<td>Tear Strength</td>
<td>1.1 ± 0.1</td>
<td>1.9 ± 0.1</td>
</tr>
<tr>
<td></td>
<td>Tensile Strength</td>
<td>1.1 ± 0.1</td>
<td>1.9 ± 0.1</td>
</tr>
</tbody>
</table>
Table A.21: Nonwoven webs utilized in the determination of optimum dwell time of fabrics in NaOH bath.

<table>
<thead>
<tr>
<th>Polymer A</th>
<th>Polymer B</th>
<th>Ratio</th>
<th>Mixed Media Configuration</th>
<th>Initial Basis Weight (g/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PA6</td>
<td>PLA</td>
<td>50/50</td>
<td>MM-3L-SP</td>
<td>110.6</td>
</tr>
<tr>
<td>PA6</td>
<td>PLA</td>
<td>75/25</td>
<td>MM-3L-SP</td>
<td>108.3</td>
</tr>
<tr>
<td>PA6</td>
<td>PLA</td>
<td>50/50</td>
<td>MM-ALT-SP</td>
<td>108.1</td>
</tr>
<tr>
<td>PA6</td>
<td>PLA</td>
<td>75/25</td>
<td>MM-ALT-SP</td>
<td>111.5</td>
</tr>
</tbody>
</table>

Table A.22: Air permeability (cm³/cm²/sec) of mixed media and control fabrics before and after PLA removal bath, hydroentangled with a specific energy of 43.1 MJ/kg

<table>
<thead>
<tr>
<th></th>
<th>Before PLA Removal</th>
<th>After PLA Removal</th>
<th>Percent Increase</th>
</tr>
</thead>
<tbody>
<tr>
<td>50% PA6 / 50% PLA Control</td>
<td>3.9 ± 0.1</td>
<td>11.0 ± 0.3</td>
<td>182%</td>
</tr>
<tr>
<td>75% PA6 / 25% PLA Control</td>
<td>4.7 ± 0.1</td>
<td>10.7 ± 0.7</td>
<td>128%</td>
</tr>
<tr>
<td>50% PET / 50% PLA MM-ALT-IS</td>
<td>49.9 ± 2.0</td>
<td>120.4 ± 1.1</td>
<td>141%</td>
</tr>
<tr>
<td>75% PET / 25% PLA MM-ALT-IS</td>
<td>43.1 ± 1.4</td>
<td>101.1 ± 3.4</td>
<td>135%</td>
</tr>
<tr>
<td>50% PA6 / 50% PLA MM-3L-SP</td>
<td>9.4 ± 0.2</td>
<td>20.8 ± 0.9</td>
<td>121%</td>
</tr>
<tr>
<td>75% PA6 / 25% PLA MM-3L-SP</td>
<td>8.6 ± 0.2</td>
<td>15.3 ± 0.4</td>
<td>78%</td>
</tr>
</tbody>
</table>
Table A.23: Basis weight (g/m²) of mixed media and control fabrics before and after PLA removal bath, hydroentangled with a specific energy of 43.1 MJ/kg

<table>
<thead>
<tr>
<th></th>
<th>Before PLA Removal</th>
<th>After PLA Removal</th>
<th>Percent Decrease</th>
</tr>
</thead>
<tbody>
<tr>
<td>50% PA6 / 50% PLA</td>
<td>125.3 ± 0.9</td>
<td>64.6 ± 0.0</td>
<td>48%</td>
</tr>
<tr>
<td>Control</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>75% PA6 / 25% PLA</td>
<td>123.6 ± 1.5</td>
<td>98.3 ± 0.4</td>
<td>21%</td>
</tr>
<tr>
<td>Control</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>50% PET / 50% PLA</td>
<td>105.0 ± 2.8</td>
<td>23.1 ± 0.1</td>
<td>78%</td>
</tr>
<tr>
<td>MM-ALT-IS</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>75% PET / 25% PLA</td>
<td>105.2 ± 4.1</td>
<td>34.6 ± 0.1</td>
<td>67%</td>
</tr>
<tr>
<td>MM-ALT-IS</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>50% PA6 / 50% PLA</td>
<td>127.4 ± 0.7</td>
<td>63.9 ± 0.3</td>
<td>50%</td>
</tr>
<tr>
<td>MM-3L-SP</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>75% PA6 / 25% PLA</td>
<td>120.5 ± 0.8</td>
<td>91.7 ± 0.3</td>
<td>24%</td>
</tr>
<tr>
<td>MM-3L-SP</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table A.24: Thickness (µm) of mixed media and control fabrics before and after PLA removal bath, hydroentangled with a specific energy of 43.1 MJ/kg

<table>
<thead>
<tr>
<th></th>
<th>Before PLA Removal</th>
<th>After PLA Removal</th>
<th>Percent Decrease</th>
</tr>
</thead>
<tbody>
<tr>
<td>50% PA6 / 50% PLA Control</td>
<td>639 ± 7</td>
<td>540 ± 17</td>
<td>16%</td>
</tr>
<tr>
<td>75% PA6 / 25% PLA Control</td>
<td>545 ± 7</td>
<td>540 ± 19</td>
<td>1%</td>
</tr>
<tr>
<td>50% PET / 50% PLA MM-ALT-IS</td>
<td>544 ± 5</td>
<td>365 ± 11</td>
<td>33%</td>
</tr>
<tr>
<td>75% PET / 25% PLA MM-ALT-IS</td>
<td>536 ± 7</td>
<td>438 ± 26</td>
<td>18%</td>
</tr>
<tr>
<td>50% PA6 / 50% PLA MM-3L-SP</td>
<td>598 ± 11</td>
<td>460 ± 9</td>
<td>23%</td>
</tr>
<tr>
<td>75% PA6 / 25% PLA MM-3L-SP</td>
<td>572 ± 7</td>
<td>545 ± 8</td>
<td>5%</td>
</tr>
</tbody>
</table>
Table A.25: Pore size (µm) of mixed media and control fabrics before and after PLA removal bath, hydroentangled with a specific energy of 43.1 MJ/kg

<table>
<thead>
<tr>
<th>Fabric Composition</th>
<th>Smallest Detected Pore Size (µm)</th>
<th>Average Pore Size (µm)</th>
<th>Largest Detected Pore Size (µm)</th>
<th>Smallest Detected Pore Size (µm)</th>
<th>Average Pore Size (µm)</th>
<th>Largest Detected Pore Size (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50% PA6 / 50% PLA Control</td>
<td>2.6</td>
<td>4.4 ± 0.6</td>
<td>26.0</td>
<td>3.3</td>
<td>8.9 ± 1.2</td>
<td>25.2</td>
</tr>
<tr>
<td>75% PA6 / 25% PLA Control</td>
<td>2.3</td>
<td>7.1 ± 1.1</td>
<td>29.7</td>
<td>5.9</td>
<td>13.3 ± 1.9</td>
<td>54.9</td>
</tr>
<tr>
<td>50% PET / 50% PLA MM-ALT-IS</td>
<td>17.4</td>
<td>29.1 ± 2.7</td>
<td>71.6</td>
<td>15.2</td>
<td>30.0 ± 2.9</td>
<td>69.2</td>
</tr>
<tr>
<td>75% PET / 25% PLA MM-ALT-IS</td>
<td>10.7</td>
<td>22.2 ± 2.1</td>
<td>61.3</td>
<td>14.6</td>
<td>28.9 ± 3.0</td>
<td>69.3</td>
</tr>
<tr>
<td>50% PA6 / 50% PLA MM-3L-SP</td>
<td>3.8</td>
<td>7.6 ± 0.8</td>
<td>37.3</td>
<td>5.3</td>
<td>12.7 ± 1.5</td>
<td>41.5</td>
</tr>
<tr>
<td>75% PA6 / 25% PLA MM-3L-SP</td>
<td>3.8</td>
<td>9.2 ± 1.2</td>
<td>42.1</td>
<td>6.0</td>
<td>14.2 ± 2.0</td>
<td>57.0</td>
</tr>
</tbody>
</table>
Table A.26: Porosity (%) of mixed media and control fabrics before and after PLA removal bath, hydroentangled with a specific energy of 43.1 MJ/kg

<table>
<thead>
<tr>
<th></th>
<th>Before PLA Removal</th>
<th>After PLA Removal</th>
<th>Percent Increase</th>
</tr>
</thead>
<tbody>
<tr>
<td>50% PA6 / 50% PLA Control</td>
<td>83.5 ± 0.3</td>
<td>89.4 ± 0.3</td>
<td>7.1%</td>
</tr>
<tr>
<td>75% PA6 / 25% PLA Control</td>
<td>80.4 ± 0.5</td>
<td>83.9 ± 0.6</td>
<td>4.4%</td>
</tr>
<tr>
<td>50% PET / 50% PLA MM-ALT-IS</td>
<td>85.4 ± 0.5</td>
<td>95.5 ± 0.2</td>
<td>11.8%</td>
</tr>
<tr>
<td>75% PET / 25% PLA MM-ALT-IS</td>
<td>85.6 ± 0.7</td>
<td>94.3 ± 0.4</td>
<td>10.2%</td>
</tr>
<tr>
<td>50% PA6 / 50% PLA MM-3L-SP</td>
<td>82.0 ± 0.4</td>
<td>87.7 ± 0.3</td>
<td>7.0%</td>
</tr>
<tr>
<td>75% PA6 / 25% PLA MM-3L-SP</td>
<td>81.8 ± 0.4</td>
<td>85.1 ± 0.3</td>
<td>4.0%</td>
</tr>
</tbody>
</table>