ABSTRACT

NEWMAN, ZOE. All Rights Reserved. A Comparison of Natural and Synthetic Yarns in Common Knit Footwear Structures. (Under the direction of Dr. Andre West).

The purpose of this study was to evaluate how the physical properties of three different commonly used knit footwear fabric structures changed with relation to fiber content. This study was prompted by consumer demand for sustainable products due to our current environmental climate. The Shima Seiki APEX SDS-ONE program was used to develop the common knit footwear structures, while the Shima Seiki N. SVR 123 SP 14 Gauge knitting machine was used for knitting. Yarns evaluated in the study include 100% Repreve®, 100% hemp, and 100% cotton fiber. Physical tests assessed abrasion resistance, air permeability, moisture regain, fabric thickness, weight, burst and elongation.

Results of the research concluded that hemp provides the greatest degree of air permeability and moisture regain attributes. While natural fibers such as hemp and cotton may not be directly comparable to a synthetic fiber, the evaluation of such yarns is important in the consideration of material sourcing for future footwear offerings. The integration of natural yarns with reported physical testing data comparing a popular synthetic fiber will allow for companies and consumers to make more friendly decisions to contribute positively contribute to our ecosystem and future.

A Comparison of Natural and Synthetic Yarns in Common Knit Footwear Structures

by
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North Carolina State University
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requirements for the degree of
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DEDICATION

This thesis is dedicated to all the educators and mentors who have touched my life with inspiration.

BIOGRAPHY

Zoe Newman is a student in the Wilson College of Textiles at North Carolina State University studying textile innovation through the integration of specialized knitting techniques. Zoe is passionate about knit programming and sustainability. Her career goal is to enter academia where she may contribute to the development of comprehensive textile curricula for students and industry and continue to make ground-breaking contributions to sustainability initiatives in the 21st century.

Zoe grew up in Chapel Hill, North Carolina where she enjoyed spending time with her triplet siblings. Her interest in textiles was always present, but even more-so developed through the exploration of forms, surfaces, and textures found in clay. The experimentation in ceramics class in high school further inspired Zoe to investigate studying design. The College of Design at NC State was home for multiple summers, as Zoe attended Design Camp hosted by the College of Design where she learned about Industrial Design, Architecture, and Graphic Design. After touring the Wilson College of Textiles at NC State and participating the Summer Textile Exploration Program (STEP), she was sold on studying Textile Design. The melding of art, science, and textiles was everything she could have asked for in a college degree.

ACKNOWLEDGMENTS

"Thank you" does not express my gratitude to all of the professors, lecturers, and instructors at the Wilson College of Textiles. The continuous encouragement, support, and learning opportunities provided throughout my time at the university has formed me in the most positive way, and I cannot thank you enough.

Dr. West, thank you for being a great sounding board for all of my ideas, and garnering my interest in knitting machines and technology. I would not be in this position without you, and I am ever so grateful for your guidance throughout this process.

Leah, thank you for teaching me about knit programming, and for allowing me to grasp as much of your knowledge as possible since you have been a part of the Wilson College of Textiles. I always enjoy the time I spend talking and learning with you.

Thank you to Tim Pleasants and Teresa White for assisting me with yarn development and fabric analysis testing. Your expertise is much appreciated, and your professional relationship is greatly valued.

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CHAPTER 1: INTRODUCTION

1.1 Textiles and Global Warming

The gradual increase in the overall temperature of the earth's atmosphere was globally recognized at the Paris Climate Agreement conference in December 2015. The 21st Conference on the parties of the United Nations Framework Convention on Climate Change brought all global nations together to develop stronger global climate efforts and reduce global warming (Encyclopedia Britannica, 2012). The goals to reduce global warming contribute to the concept of sustainability, defined as the "economic and social development that meets the needs of future generations without undermining the ability of future generations to meet their own needs" (World Commission on Environmental Development, 1987). Sustainability may also more directly be tied to the concept of how natural systems function, remain diverse, and produce everything it needs for ecology to remain in balance (Mason, 2020).

Global warming is a major issue for our generation. In particular, the textile industry is one of the largest contributors to the global environmental crisis. Synthetic fibers (such as polyester, polyamide, acrylic, and others) contribute to 60% of the materials that make up our clothes worldwide (Resnick, 2019). Figure 1 below displays the gradual increase in synthetic fiber production in the United States from 1975 through 2015, noting that polyester, polyamide, and other synthetic fibers make up a large (and growing) percentage of the textile industry (Textile Exchange, 2019).

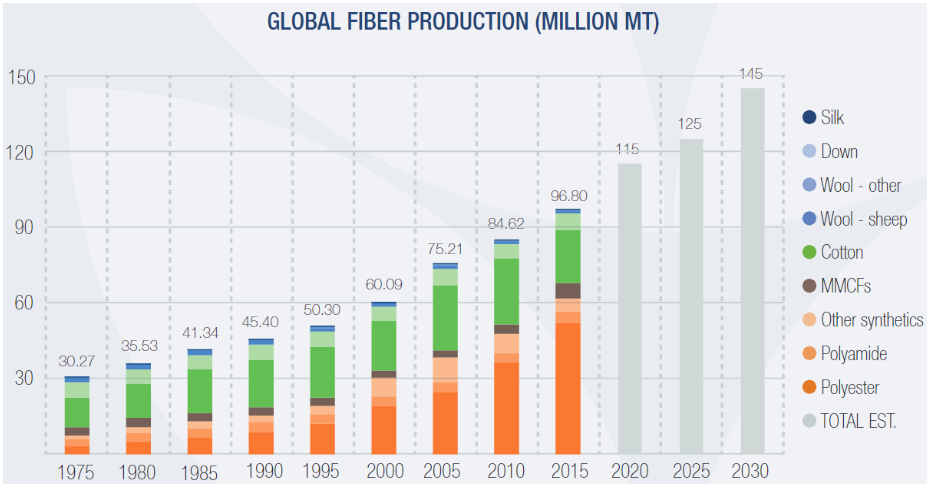


Figure 1. Global Fiber Production – Textile Exchange, 2019

1.2 Textile Contributions to Global Warming

As a t-shirt or a pair of shoes is discarded, the post-consumer synthetic or natural textile waste will sit in the landfill. Landfill disposal is the primary method of solid waste disposal in the United States (Wang, 2009). On average, a cotton t-shirt will take 2-5 months to degrade in a landfill, while nylon will take anywhere from 30-40 years (How Long It Takes For Trash To Decompose, n.d.). Nearly 8.74 billion pounds of post-consumer waste is accounted for annually in the United States - amounting to 35 pounds per person (Steinbring, et. al., 2003). Figure 2.1 below shows the impact of the textile industry on landfills. While consumers may have good intentions through donation centers and re-use scenarios, eventually all sources lead back to the landfill. Figure 2.2 shows footwear in a landfill.

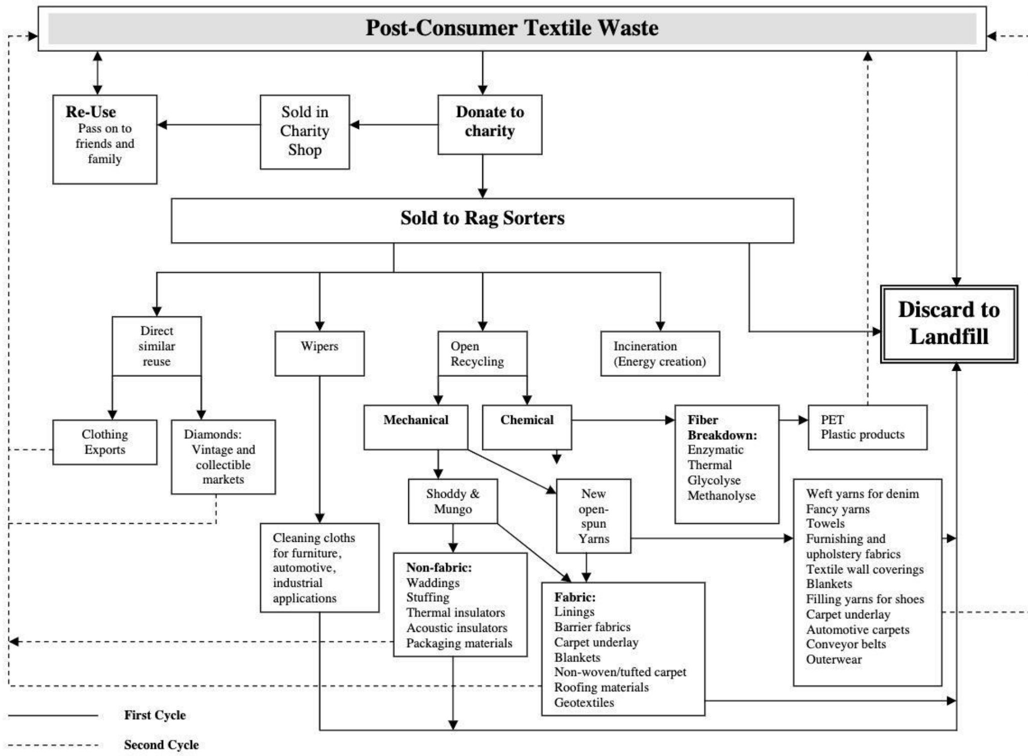


Figure 2.1. Post-consumer textile options (Hawley, 2008)

Figure 2.2. Shoes in a landfill (Sands, 2020)

The footwear industry consists of more than just textile components. In addition to textile or leather uppers, rubber, PVA, or other materials are used for the sole and other parts of shoes. Traditional footwear production requires more than 200 different individual pieces in 10 sizes (Klimovski, 2016), and the cutting and construction of shoes is usually done by hand. The materials used in footwear may be harmful to the environment. Figure 3 displays material consumption in the average shoe.

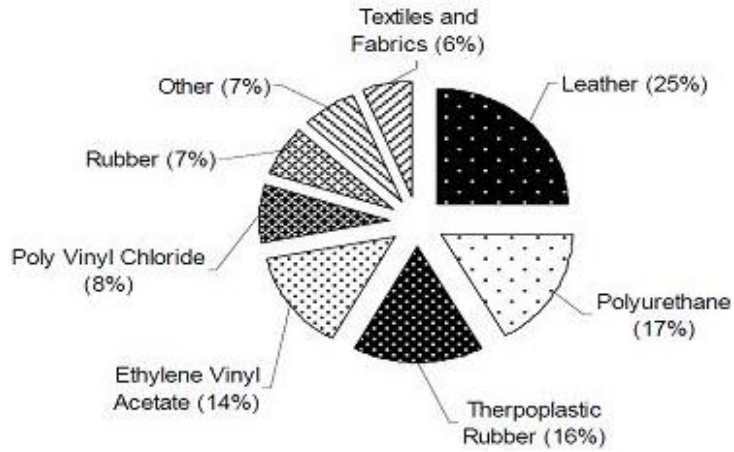


Figure 3. Material consumption in the average shoe (Waste Management Techniques in Footwear Industries)

Nearly 80% of the plastics that enter our oceans are thought to originate from land, this is possible through runoff. Runoff is where a portion of precipitation on land ultimately reaches streams with dissolved or suspended material (Merriam-Webster, 2020). The runoff from landfills storing waste is known to impact fish ecosystems, especially when synthetic materials are present. Humans may suffer from inflamed tissues, necrosis, and compromised immune cells as a result of unintended microplastic consumption from fish (Smith et al., 2018).

Synthetic fibers are man-made fibers derived from chemical resources. The first fully man-made synthetic fiber, nylon, was made by DuPont in 1938 (Kavita, 2016). One of the many issues with synthetics such as polyester, nylon, acrylic, and other materials being used in the textile industry is that when we wash our clothes, the microparticles make their way to the ocean where fish and other organisms may ingest them, thinking they are food (Wang, et. al. 2020).

Microplastics are considered small plastic particles below 5mm in size, whereas larger plastic waste consists of items such as water bottles, plastic tubs, etc. (Thevenon et. al., 2014). In 2017, the *International Union for Conservation of Nature* stated that 35% of microplastics in the oceans come from synthetic textiles (Boucher et al., 2017). Figure 4 below displays the impact textile and other synthetic polymers have on marine environments.

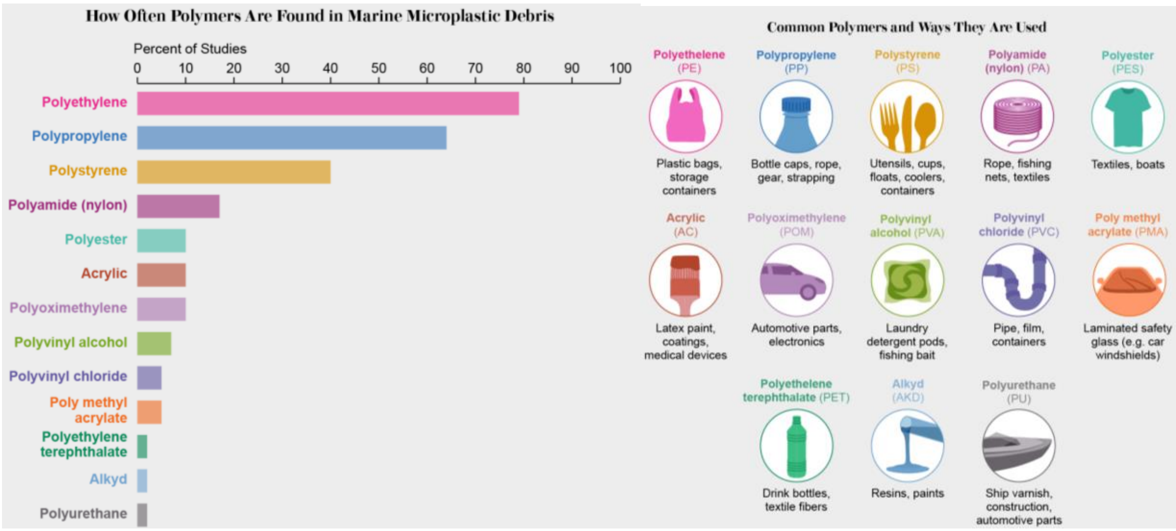


Figure 4. How Often Polymers Are Found in Marine Microplastic Debris (Scientific American, A. Thompson 2018)

While Nike's release resulted in footwear companies adopting initiatives using more eco-friendly production processes, the materials used in the development of fully fashioned knit uppers are primarily synthetic yarns due to their strength in order to achieve the common properties that are seen in footwear made from woven structures. In 2014, the imports of synthetic fibers to the United States surpassed the imports of cotton (Prentice, 2014) – and the footwear industry is a culprit in this contribution. New developments of synthetic yarns have emerged to decrease detrimental effects on global warming. Figure 5 shows the global production and market share of recycled polyester.

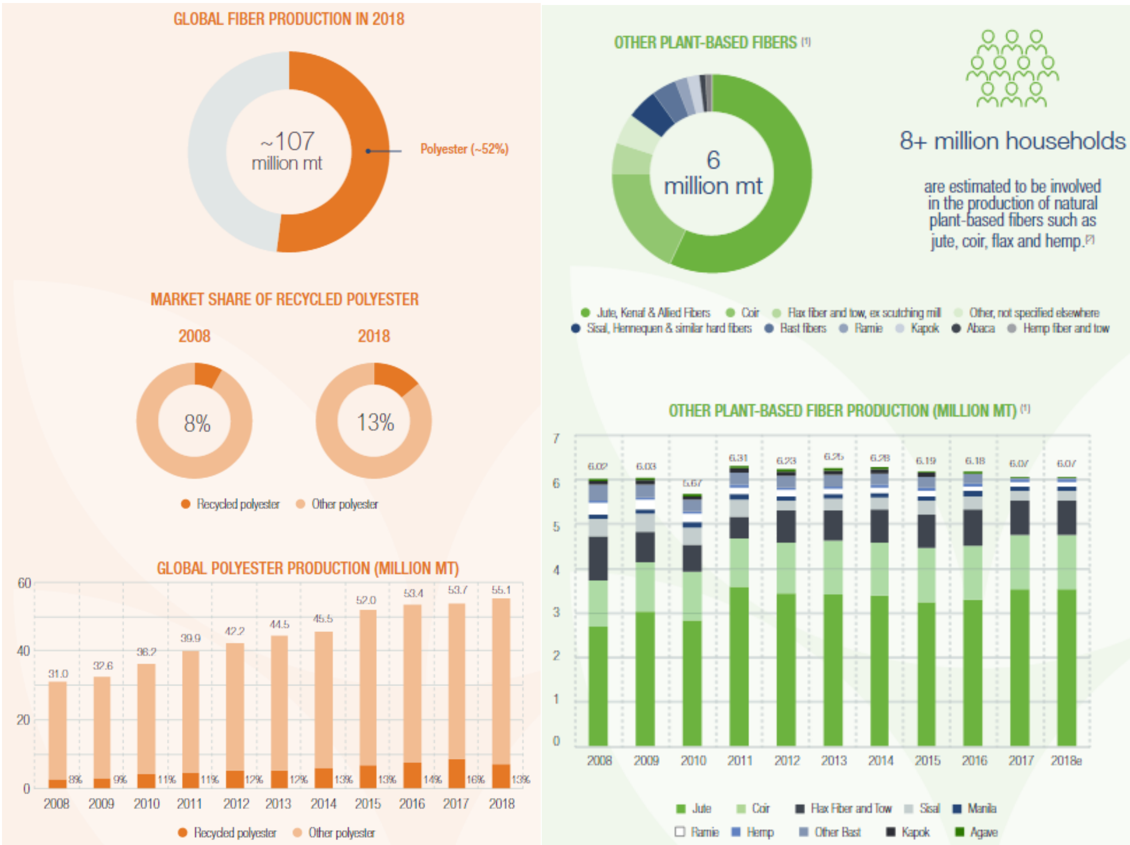


Figure 5. Recycled Polyester Global Production and Market Share, Other Plant Based Fibers (Textile Exchange, 2019)

1.3 Industry Accountability and Consumer Demand

It is important to note that humans created (and are constantly contributing to) what has become a worldwide issue through the consumption of synthetic apparel and accessories. The development of synthetic fibers has continued into the 21st century, where petroleum and petrochemicals are used in melt-spinning and extrusion processes for synthetic fibers (Jamir et al., 2018).

As a result of the impending environmental crisis due to synthetic fiber development, textile companies have had no choice but to initiate sustainability goals and hold themselves accountable for such detrimental impacts. In fact, sustainability acts as a tool for textile companies to create a competitive edge for customers, as there is a steady increase in conscious attitude and knowledge of sustainability practices in the textile industry (Kumar et al., 2017). Companies are contributing through practicing corporate social responsibility, the process of running a business through a social, ethical, and environmentally-aware lens (Szewczyk, 2017). Adidas, for example, has partnered with brands such as Stella McCartney and Parley for the Oceans to develop textile products using as little waste as possible and recycled plastics from the ocean (Moschetti, 2019).

Many companies have been working to release socially responsible messages with their sustainable product releases. In fact, Patagonia has taken a step to commission a life cycle assessment of hemp yarn to evaluate effects the fiber may have on the supply chain (S. Karba, Personal Communication, July 2020). While Patagonia has taken the next step in the realm of natural and sustainable fiber considerations, many companies have not; and the difference to our world and environment will not be made solely through messages and encouragement of sustainable practices. The industry must be intentional about their fiber and yarn decisions; sustainability of recycled synthetics is not everlasting, although it is a step in the right direction. The textile industry is one of the most highly polluting and resource consuming industries; thus, it may be used as a "springboard" to reach environmental and socially-conscious customers (De Brito et al., 2008) in order to initiate sustainable change.

1.4 Sustainability Initiatives

The introduction of shaped knit footwear provided a platform for innovative production processes for athletic footwear. Nike led the innovation of "green" products with the introduction of the Flyknit™ shoe in 2012. In fact, Nike's developments led to a reduction of waste by approximately 80% in the new Flyknit™ Lunar 1+ (Hunter, 2013).

Following an array of lawsuits and avoidance of patent infringement, the developments by Adidas and Nike provided a platform for a new type of athletic shoe. The introduction of knitted footwear by Adidas and Nike provided a “segway” for athletic brands to be considered sustainable. The creation of a knit footwear upper made from one piece of fabric eliminated the need for traditional cut-and-sew production processes. While a footwear upper using a single panel of fabric may be developed using woven fabric, the process of designing a knit structure for such an application allows for different zones to be defined for optimal comfort. The development of a knitted upper for footwear (due to machinery and design innovations) has positively cut down the product development process of the footwear industry. A cut-and-sew operation requires multiple fabric pieces in one shoe, while a knit upper can be shaped to-scale as a single piece with defined structure zones - resulting in anywhere from 1-3 components required for a shoe, and providing increased comfort. The elimination of seams and waste from the cut-and-sew process resulted in a more comfortable and sustainable shoe. Figure 6 shows the Adidas Primeknit™ shoe as an example of such a product.

Figure 6. Adidas Primeknit™ Shoe (image courtesy of https://www.adidas.com/us/blog)

While the reduction of waste in the footwear industry is important, the use of synthetic yarns for footwear is still prevalent. Particularly, the polymerization of synthetic materials allows for a nicely oriented, crystalline chemical structure with a high strength for fibrous, synthetic textiles (Jamir, 2018). Thus, synthetic, man-made yarns allow for prime applications in the footwear industry. As a result, this has driven the industry to prefer the use of synthetic yarns for many pieces needed in production. In fact, the imports of synthetic fibers to the United States surpassed the imports of cotton in the year 2014 (Prentice, 2014). While sustainable initiatives have been achieved through the development of footwear made from a single panel, the content of many of the panels are purely synthetic. Other fiber contents could be considered for the development of an even more sustainable item.

1.5 Statement of the Problem

The development of knit footwear has greatly helped to reduce waste in the footwear manufacturing process, but the yarns used in such applications are primarily synthetic, which continues to impact the environment. There are some casual footwear companies (such as Allbirds®, Oat®, and others) that are using biodegradable materials in their footwear, but how can this trend be developed for more robust, casual athletic footwear applications?

1.6 Purpose of the Study

The purpose of this study is to evaluate natural fibers for use in footwear uppers of casual athletic shoes. While synthetic fibers provide advanced performance features in comparison to natural yarns, they ultimately result in a prolongation of the life cycle of plastic before it enters the landfill. Adidas, Nike, and other companies producing knit footwear have sustainability goals in mind as they develop products. We should consider the possible positive outcomes that are presented in making a product from natural fibers as opposed to synthetic fibers. If this can be addressed, it will be easier and more acceptable to use natural fibers in the footwear market. Regenerated synthetic fibers have different cross-sections and physical properties compared to natural fibers, as they offer UV protection, antimicrobial properties, and other benefits (Alay, 2010). This work aims to evaluate and compare the performance properties of knitted fabrics made of synthetic and natural materials. It is anticipated that the synthetic yarn-derived fabrics will inherently be stronger than natural yarn-derived fabrics due to their crystalline structure. An evaluation of how weft knit structures with natural yarns may impact the physical properties of casual footwear will be performed, considering how the properties of different knit structures change when comparing natural and synthetic yarn.

1.7 Natural and Synthetic Fiber Classifications

The basis of the textile industry relies on fibers which may be categorized into two classifications: natural and synthetic fibers. Textile fibers are "the raw materials of the yarns into which they are spun (Spencer, 2001)". Natural fibers are derived from plants or vegetables and include flax, hemp, jute, banana leaves, and cotton. They are comprised of hollow cellulose fibrils held together by natural lignin and cellulose matrices (Hassan, 2012). The physical properties of the cellulose allow for a naturally linear and crystalline structure developed by the hydrogen bonds present in the fibers. Natural fibers are often short in length and require spinning or twisting together in order to produce a satisfactory length of strong yarn.

Synthetic (or "filament") fibers are fibers of indefinite length; therefore, they are able to be sufficiently bulky and strong (Hassan, 2012). Synthetic fibers are defined by the International Organization for Standardization (ISO) as fibers manufactured from chemical elements or compounds as opposed to natural fibers, which are made from naturally occurring polymers (McIntyre, 2004). Synthetic fibers have increased oil and petroleum consumption (Blackburn, 2005), resulting in contributions to global warming. Biodegradable, natural fibers alternatively can be broken down into simpler substances that may more easily decompose. While many synthetic fibers are not biodegradable, some biodegradable polymers have been developed. Synthetic polymers such as poly (lactic acid) and *Repreve®* (by Unifi), a fiber made from the repurposing of water bottles (PET components) from oceans, are able to contribute to sustainability initiatives in textile developments (Repreve®, 2020). A schematic of fiber classifications may be seen in Figure 7 below.

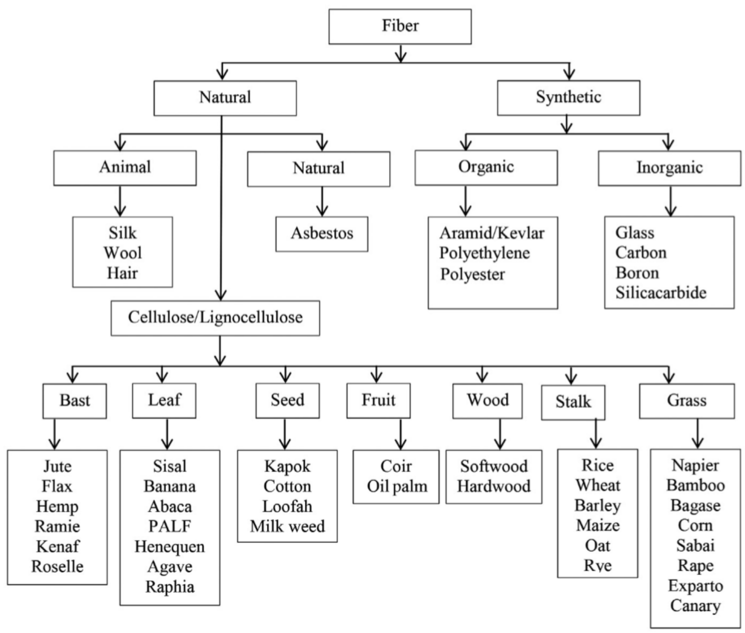


Figure 7. Classification of Natural and Synthetic Fibers (Jamir, 2018).

Ultimately, the properties of a more eco-friendly, biodegradable shoe may be achieved from the use of biodegradable synthetic polymers. However, natural yarns may be introduced into the footwear market with the intention of possessing similar properties to synthetic fibers. Ultimately the integration of synthetic fibers and the combination of additional components (such as glue) might make the shoe impossible to separate. Natural fibers will degrade into the environment, while synthetic fibers will continue the regenerative process, using energy in the process.

The outcome of using natural fibers in textiles, specifically in the footwear industry will be better for the environment and the footwear industry alike. Through a combination of knit structures and natural, strong materials, casual athletic footwear may be able to be developed without sacrificing performance or environmental ecosystems.

1.8 Research Design

1.8.1 Significance of the Study

This study is significant because the textile industry is one of the main contributors to the environmental crisis; and, as mentioned previously nearly 8.74 billion pounds of post-consumer waste is accounted for annually in the United States - amounting to 35 pounds per person (Steinbring, et. al., 2003). The evaluation of yarns used in various weft knit fabrics will provide a baseline study for the comparison of knit footwear structures and fibers; is there an alternative to the use of synthetic yarns? Even if a product may not possess the same properties as synthetic yarns, waste may be reduced through the integration of natural fibers. As seen in Figure 8, the global fiber consumption of synthetic yarns has increased. If natural yarns can be more thoroughly incorporated in the footwear industry, we can make a difference in the future of the textile industry and combat the negative impact synthetic fibers have on the environment.

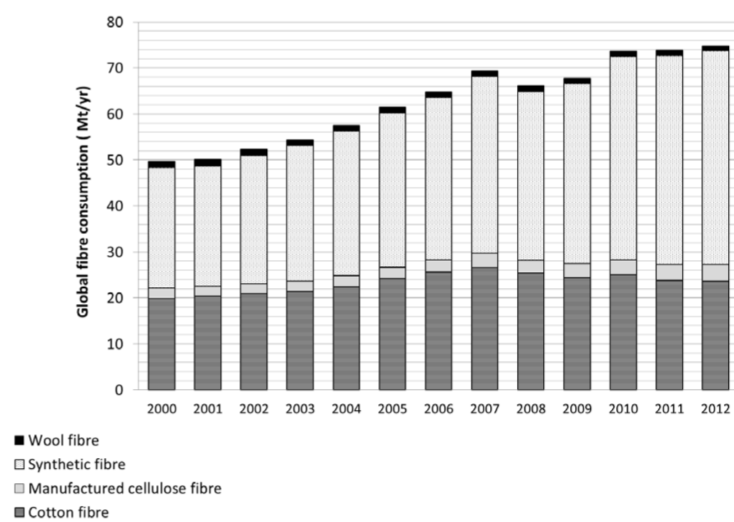


Figure 8. Global Fiber Consumption, Year 2000-2012 (Zamani, 2014)

1.8.2 Assumptions of the Study

Aesthetic considerations are not a component of this study. The color/design of the fabric (excluding structure) is not a component that will be considered. It is assumed all of the structures developed in this study could be reproduced by others in industry using the right machines/resources. Since the knit structures are envisioned for use in low impact athletic footwear applications (e.g. walking shoes), it is assumed the knit structures developed may not be a good fit for all athletic footwear or activities.

1.8.3 Limitations of the Study

One limitation of the study is that research is limited to Shima Seiki weft knit flatbed machinery, as the lab used for research did not have access to other brands of flatbed knit machinery. Additionally, not all synthetic yarns variations or natural yarns/hemp variations were able to be tested. Yarn count and number of ends used was controlled for the most appropriate fabric hand and specifications possible with the limitations imposed upon the sourcing of yarn, especially hemp (due to the restricted USA market). The fabrics were not developed into final products and were not tested on human subjects due to COVID-19 limitations; however, this is an opportunity for future research. Finally, the student researcher was limited with their time available to perform research.

CHAPTER 2: REVIEW OF LITERATURE

2.1 Knitwear Manufacturing Methods

The textile and apparel supply chain contains a vast array of garments and accessories with varying production methods. Primarily, “cut and sew”; the process where fabric is cut into pattern pieces then assembled into a product (The Cutting Class, 2011), dominated the footwear market until the introduction of seamless footwear developed by Nike and Adidas in 2012. Seamless knitting is the process of developing a knit piece without a seam, resulting in higher productivity, mass customization, and minimal yarn consumption (Zolotaryova). The first seamless knitting technology was introduced at the 1995 International Textile Machinery Association (Chen, 2020). Figure 9.1 and 9.2 below illustrate the difference between cut and sew knitwear, fully fashioned (shaped) knitwear, and seamless knitwear.

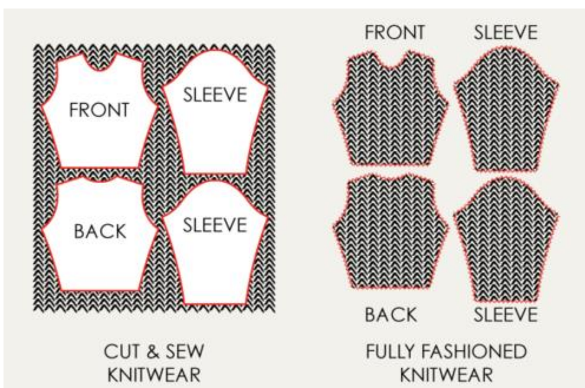


Figure 9.1. Cut and Sew Knitwear and Fully Fashioned Knitwear (The Cutting Class, 2011)

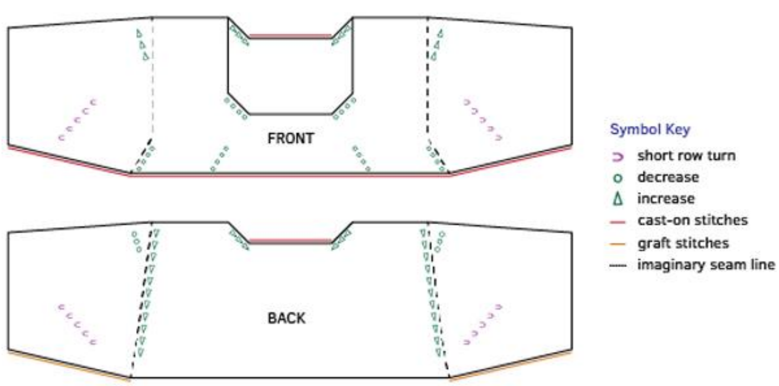


Figure 9.2. Seamless Tee Shirt (Voth, 2018)

2.2 Knitting Machine Technology

There are two types of knitting: warp and weft knitting. Both technologies develop fabric as a product and are popular in the development of knitted footwear uppers. This section will introduce such processes of fabric development.

2.2.1 Weft Knit Flatbed Advanced Technology

Whole garment, flatbed knitting machines produce weft knit fabric. The fabric is formed with loops interlocking horizontally building up row by row (Spencer, 2001). Specifically, WHOLEGARMENT® knitting is the world's first seam-free knitwear produced on Shima Seiki's WHOLEGARMENT® knitting machines using their proprietary APEX software (Shima Seiki, 2020). In weft knitting on whole garment/flatbed machines, fewer yarn packages are required than in circular knitting production due to the nature and design of the machinery. Products can be knit in three dimensions without any seams. It is important to note that such machines are capable of knitting with an array of yarn contents and may handle up to 10 colors in one design (Motawi, 2017). New innovations of technology by competitors such as Stoll and Steiger have resulted in an improvement of technology across the knitting machine industry, resulting in increased capability (Power, 2018). This improvement in technology has been driven by consumer interest in sustainability, speed to market, and increased customization opportunities.

2.2.2 Warp Knitting Technology

Warp knit fabric is produced by a machine with yarns running in the vertical direction (Merriam Webster, 2020). Such knits, specifically spacer knits, are "an ideal group of energy absorbers for cushioning applications" (Rajan, 2014). Thus, spacer knits are important to mention in the development of knit footwear uppers. Spacer knits have two surface layers with a monofilament yarn traditionally connecting the two layers. Such techniques are common in car textiles and backpack/hiking sacks. Figure 9 displays the difference between weft and warp knitting.

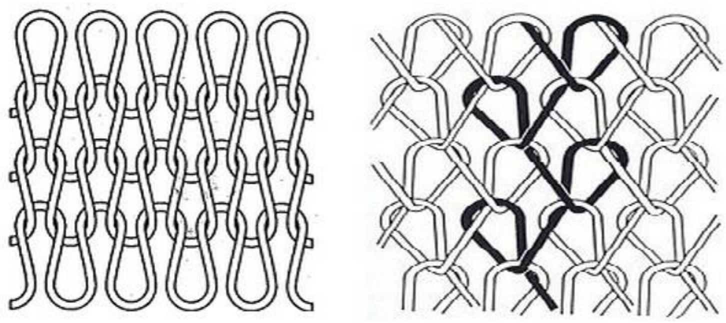


Figure 10. Weft vs. Warp Knitting (Islam, 2020).

2.3 Technology Innovations

Consumer demand in the textile industry has driven technology innovations. In particular, flat knitting technology also referred to as weft knitting, has advantages specifically with relation to athletic footwear. Particular advantages include reduced side seam failures, improved stretch and recovery, increased comfort and a better fit, increased aesthetics (logos can be integrally knit), reduced chafing, and the option to knit different structures in different areas of a single panel (Power, 2018). However, there are also disadvantages when using specialized machinery such as product demand. The product development process and the cultural change in relation to the process of advanced design may also present disadvantages. Designers must understand more than just the knitting concepts; they must also understand the technology. Furthermore, highly skilled programmers are needed, as advances in technology have led to a wider skill gap between the knitwear designers and the machine technologists. These components must be considered in the development of footwear.

2.4 Footwear Development

Footwear - shoes, boots, or any other outer covering for the human foot (Cambridge Dictionary, 2020), is a part of the textile industry, as there is fabric present in such products. The first sandals/shoes are believed to have been worn 30,000-40,000 years ago by Homo sapiens in Eurasia (DeMello, 2009). Generally, there are two types of footwear: athletic footwear and non-athletic footwear such as loafers and boots (Credence Research, 2019). Depending on the type of shoe produced, the product will be constructed differently for its end-use. Considerations such as yarn and sole materials impact the final performance of the product. As of 2017, the footwear market is valued at $222.4 billion, and the sustainable footwear market is steadily growing in consumer demand (Credence Research, 2019). Furthermore, consumer interest in sustainable materials and textiles has been increasing (Kumar, 2017).

2.4.1 Physiology of Footwear

Since footwear is for the comfort and protection of human feet, the physiology of the foot is important to consider in the development of footwear. Physiology is the ability of an organ to work in a normal state. Physiology of the foot includes regulating temperature, secreting sweat, and managing evaporation (Lu, et. al., 2016). Studies on the impact of flatbed knit footwear on the physiology of the foot have found that the planar pattern of flat knitted uppers can successfully achieve a combination of function and structural support. Furthermore, the shaped uppers play a wrapping and supporting role for the foot in the process of walking and sports. It not only helps to keep the foot warm but also provides safety and stability like any other shoe (Lu, et. al., 2016).

When considering textile materials, one must consider the physiology of footwear, as it is important for the comfort and breathability of the materials used in the shoe, as "liquid transporting and the drying rate of fabrics are two vital factors affecting the physiological comfort of garments (Doran, 2017)". It is also suggested that an elastomeric yarn should be added for the knitting process to achieve not only good tensile properties and rebound effects, but also a curve in the natural state (Lu, et.al., 2016). There are many different considerations in relation to materials for footwear, including functional, aesthetic, and comfort requirements. In order for a textile to be functional, it should be lightweight, have high tenacity, and be quick drying. Aesthetically, the textile should be soft and easy to wear. The alternative to a synthetic, man-made material is a natural yarn such as cotton, wool, or other biodegradable plant or animal-derived fibers.

2.5 Common Knit Footwear Structures

Knit structures for human use must be developed with physiological considerations in mind. The sections below focus on the structure of common knit footwear uppers, as they have been tested in the market and chosen by brands in industry. It is important to consider that it is possible to provide different structural "zones" in a footwear upper, as one may see in the examples of current footwear offerings below and in the development of the knit footwear strucures used in this study.

2.5.1 Cross-Tuck Knit Structures

Figure 11 below displays current offerings in the knit footwear market using a cross-tuck knitting technique. The tuck stitch is composed of a held loop when a needle holding a previous stitch receives a new loop, but it is not intermeshed through the old loop (Spencer, 2001). Tuck loops reduce fabric length and width-wise elasticity due to the higher yarn tension on the tuck and held loops, resulting in a robust structure appropriate for footwear. Figures 12.1-12.2 are cross-tuck and tubular knit structure schematics for reference as to how this structure is developed using the Shima Seiki SDS-ONE APEX System. For more detailed information, please see the methodology section.

Figure 11. Knit footwear offerings using cross-tuck structures

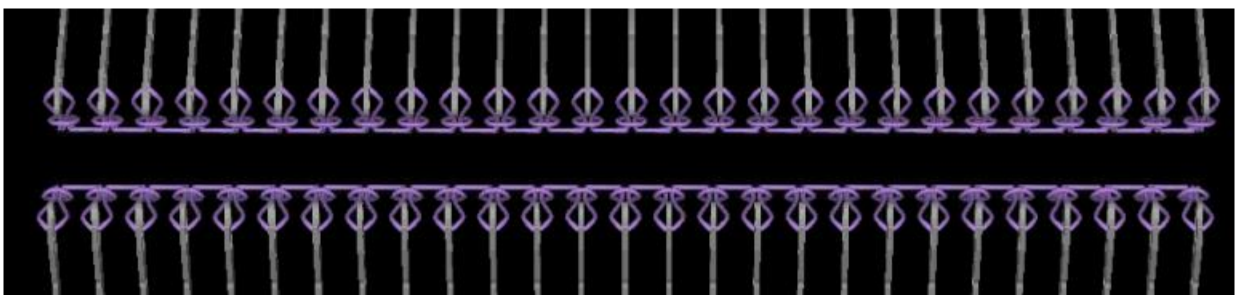


Figure 12.1. Row one of knitting, tubular jersey

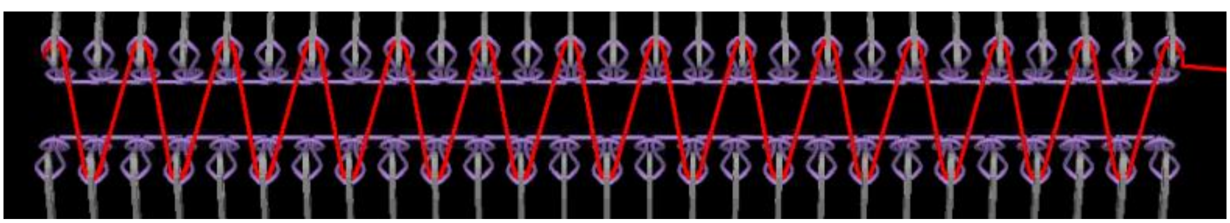


Figure 12.2. Row two of knitting, cross-tucks across front and back beds

All Knitting simulations in this section were developed by the researcher using the Shima Seiki SDS-ONE APEX system.

2.5.2 Mock Mesh Knit Structures

Figure 13 below displays current offerings in the knit footwear market using a mock-mesh structure. A mesh structure allows for surface with voids in certain areas, resulting in great breathability, permeability, and moisture conductivity properties (Zhang et al, 2018). A moch mesh structure is similar to a mesh structure, but provides the appearance of voids on the surface of the fabric without true openings. There is still increased breathability and permeability in such knit structures. Figures 14.1-14.4 display simulations of the steps used to develop the mock mesh structure using the Shima Seiki SDS-ONE APEX knitting software.

Figure 13. Knit footwear offerings using mock-mesh knitting structures

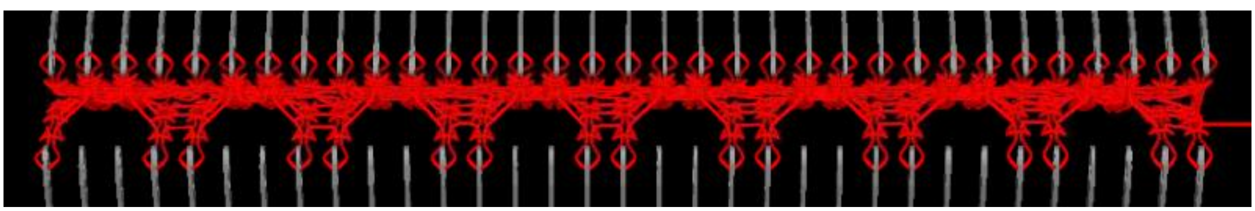


Figure 14.1. Row 1 of knitting, two front knit stitches, two back knit stitches

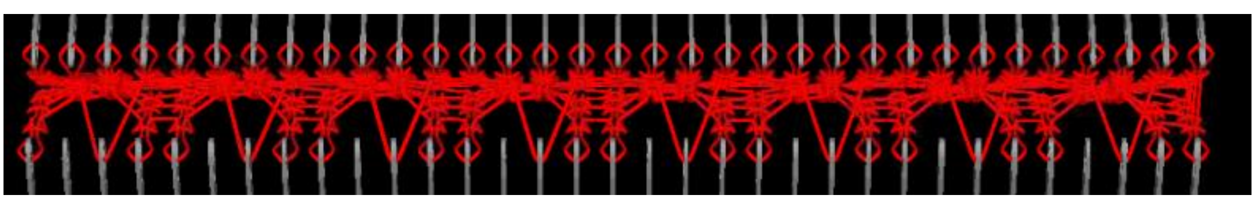


Figure 14.2. Row 2 of knitting, three knit stitches on the back, one knit stitch on the front (appears as tuck since yarn is picked up on a new needle)

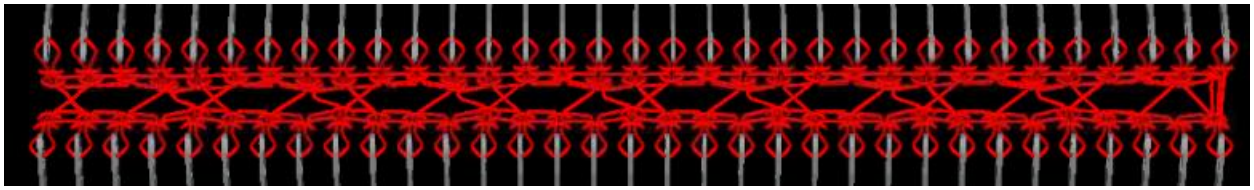


Figure 14.3. Row 3 and 4 of knitting, tubular

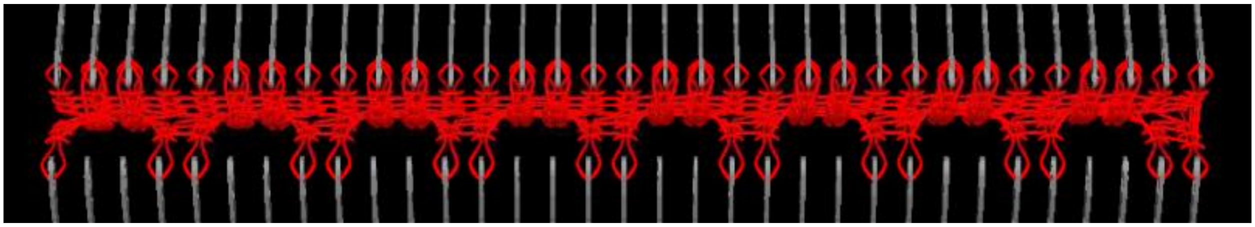


Figure 14.4. (row not applicable; transfer of stitches) - two stitches transfer from front to back

2.5.3 Inlay Knit Structures

Figure 15 below presents current footwear offerings in the market using an inlaid yarn. Inlaid yarns are trapped between the two needles beds during knitting, and may be used to modify stability, weight, visual appearance, and elasticity and recovery (Ray, 2012). Introducing an inlay yarn in between two layers (and incorporating tucks), provides decreased extensibility in the lengthwise direction. Figures 15.1-15.3 display visual representations of an inlay structure developed using the Shima Seiki SDS-ONE APEX knitting system. The pink yarn is inlaid across the needle bed and stabilized by a consecutive row of cross-tucking (purple yarn).

Figure 15. Knit footwear offerings using inlay knitting techniques

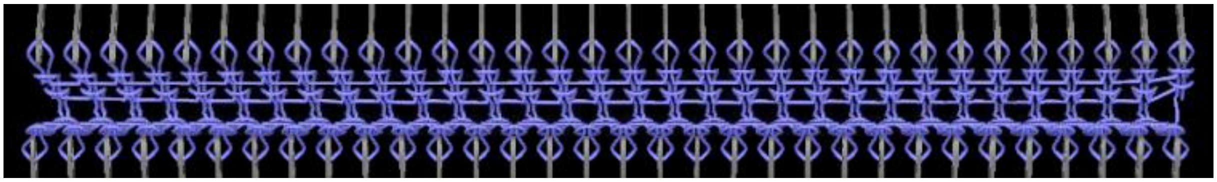


Figure 15.1. Row 1, tubular knitting on front and back beds

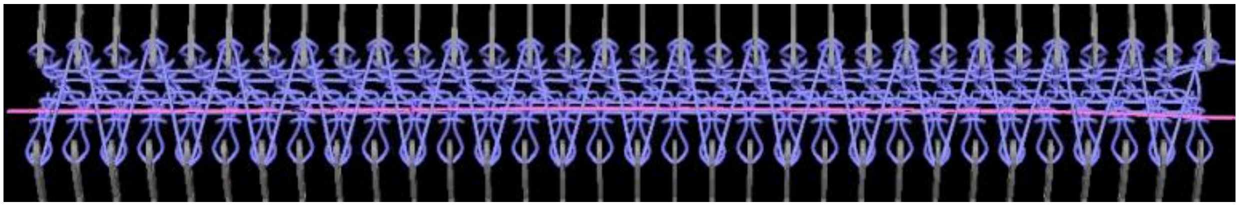


Figure 15.2. Row 2, inlay yarn (pink) inserted with system one, system two of knitting performs half-gauge cross tuck

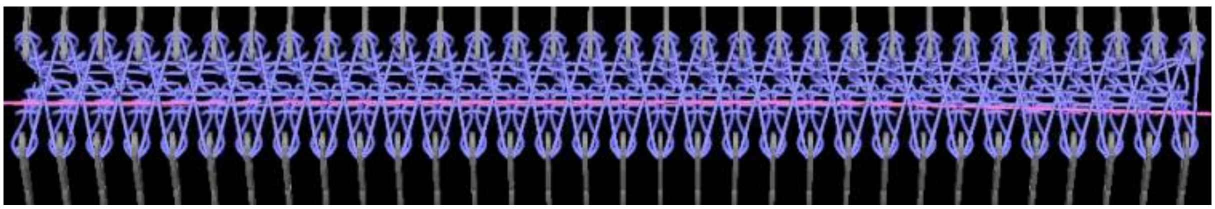


Figure 15.3. Row 3, half-gauge cross tuck to occupy every needle

2.6 Material Considerations

The introduction of recycled polyester yarn has been popular for many companies around the world. Companies producing knit footwear have sustainability goals in mind as they develop products. Common options for innovative raw materials in footwear include wool (Allbirds), hemp (Oat Shoes), and linen (Ahinsa). Repreve®, a synthetic yarn developed by Unifi, is also an option for companies who may not be ready to make the switch to a natural yarn. Figure 16 below shows the shoes mentioned.

Figure 16. Natural footwear offerings (images courtesy of Allbirds®, Ahinsa®, and Oat Shoes® respectively)

2.6.1 Repreve®

Repreve® (by Unifi) is a recycled polyester yarn made from recycled plastic bottles collected from the ocean. The bottles are cleaned, melted, and turned into a resin which is processed into yarn. Once the product made from the Repreve® yarn is put into the landfill, the process of recycling may continue. However, the popularity of synthetic and recycled man-made fibers in knitting footwear products ultimately only prolongs the life cycle of plastic before it enters the landfill. Figure 17 displays the process of Repreve® fiber development.

Figure 17. Repreve® yarn production process. Image courtesy of Repreve®. (2020).

2.6.2 Cotton

Cotton is a natural cellulosic fiber grown around the world. It is a desirable fiber due to its moisture absorption properties, good drape, and durability (Shahbandeh, 2019). The top cotton producing countries include China, India, and the United States as noted in Figure 18 below. One of the benefits of using cotton in the textile industry is its association with low climate impact (Sandin, 2018). However, due to the use of fertliziers and pesticides it is also associated with water depletion, toxicity, and depletion of soil quality subsequently resulting in biodiversity impacts (World Wildlife Fund). Issues commonly found in cotton fiber growth are not found in hemp farming, as hemp does not require as many pesticides in the growing process. In fact, hemp may also be used as cellulosic biomass addiditves in automobile fuel (Hemp FAQ's | National Hemp Association, n.d.)

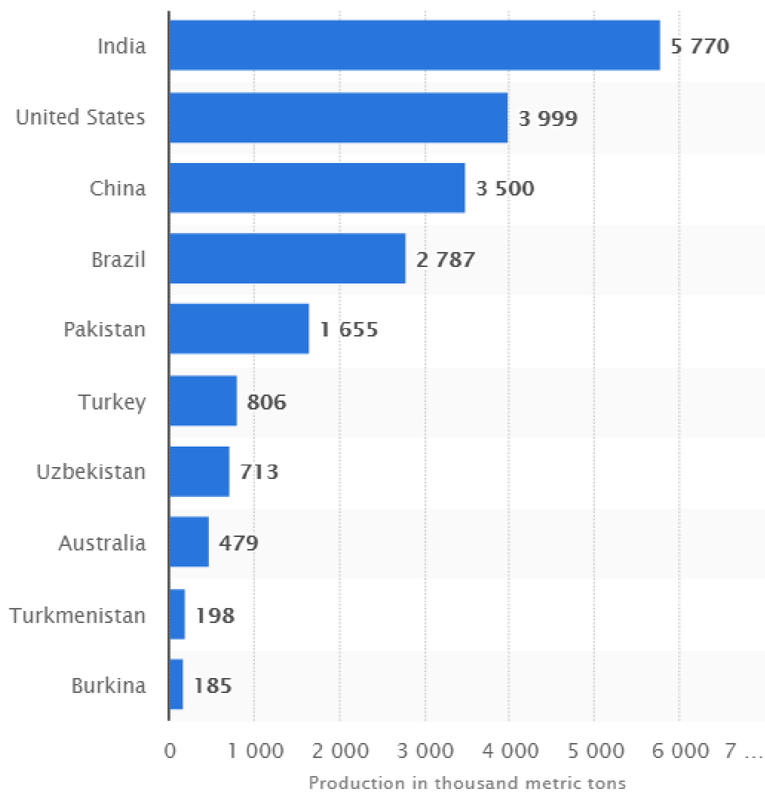


Figure 18. Cotton production by country worldwide in 2018/2019 (Shahbandeh, 2019).

2.6.3 Hemp

Alternatively, hemp does not use as much water as the cotton fiber in the field. Hemp uses about half as much water per season as cotton and grows in 90-100 days, as opposed to 150-180 days consecutively (Jasmin, 2019). The world production of hemp fiber grew from 50,000 tons (year 2000) to almost 90,000 tons in 2005. Most recently, nearly half of the world's industrial hemp supply is grown in China (Shahzad, 2011). However, as seen in Figure 19, the U.S. industrial hemp market size is steadily growing for fiber applications.

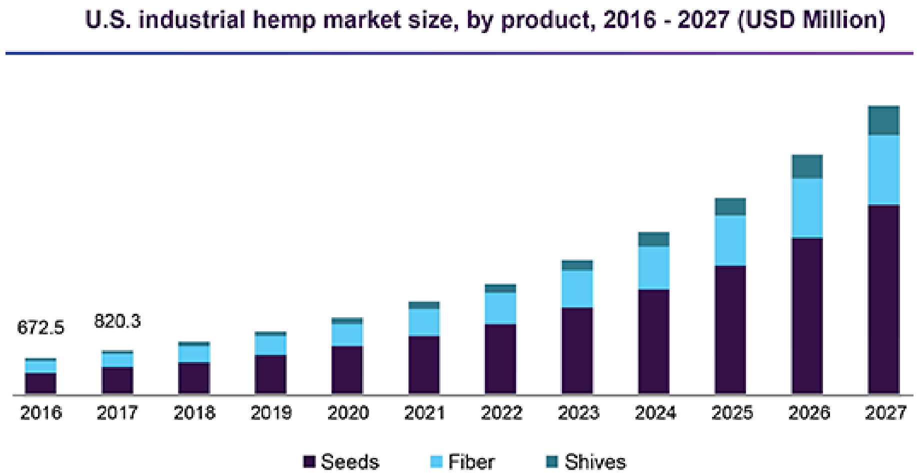


Figure 19. U.S. Industrial Hemp Market Size by Product for 2016-2027 ($USD Million) (Grandview Research, 2020)

The steady growth in the industrial hemp market is most likely due to the December 2018 passing of the United States Farm Bill, which classifies hemp as an agricultural commodity rather than a controlled substance – which it had been mislabeled as for decades (Fibershed, 2019). Hemp (also known as Cannabis Sativa, or "CBD"), is non-psychoactive, and contains 0.3% tetrahydrohannabinol (THC) or less; the active component which results in a psychoactive "high" (Alphagreen, 2020). Alternatively, the Marijuana species of cannabis contains 15-20% THC and is very psychoactive. Therefore, it is not possible to classify hemp as a psychoactive drug, although it originates from the same plant species. Figure 20 displays such differences in the species of the plant.

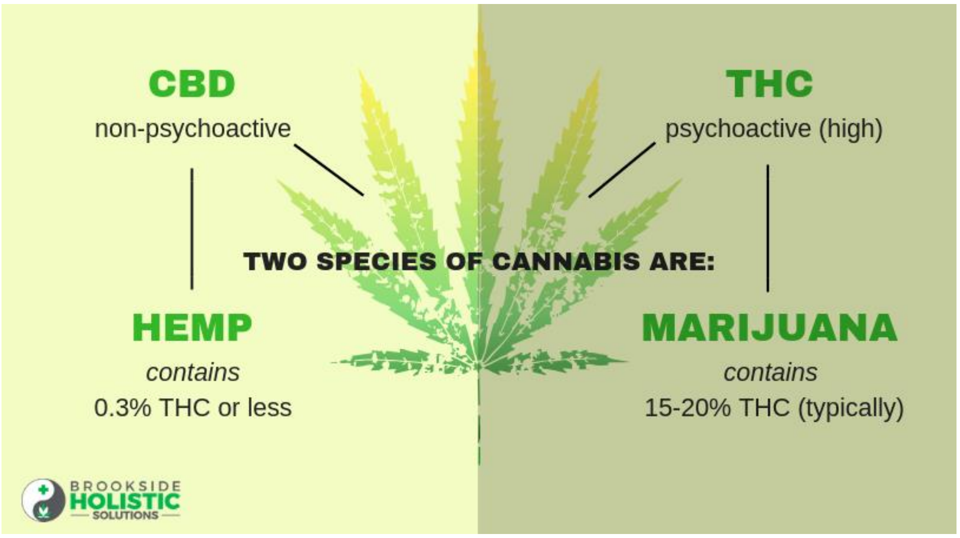


Figure 20. Hemp vs. THC (Alphagreen, 2020).

The new accessibility of hemp in the United States has allowed for reports such as "*Economic Viability of Industrial Hemp in the United States: A Review of State Pilot Programs*" from the Economic Research Service via the United States Department of Agriculture (USDA). This report may be found in the references sections of this paper and allows for the development of data seen in Figure 21 – noting the years of the planting of industrial hemp in the United States from 2014 to 2019.

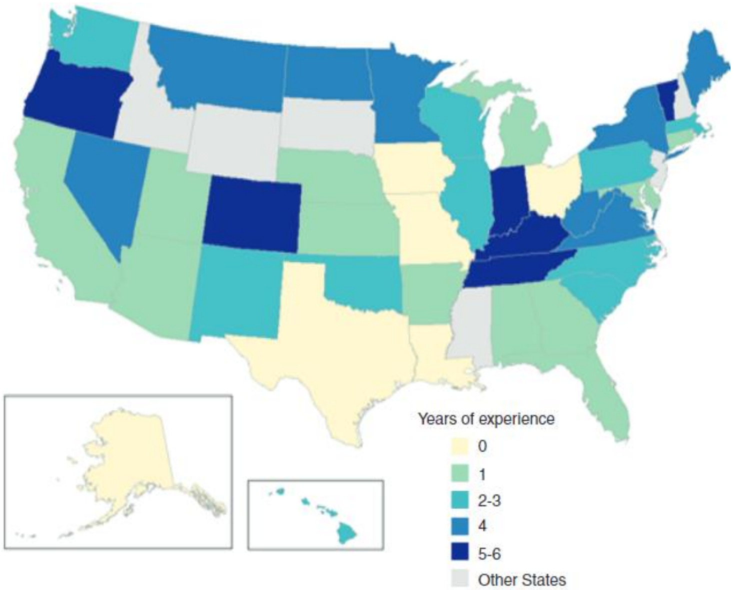


Figure 21. Years of Industrial Hemp Planting Reported by States from 2014 to 2019 (Mark et al., 2020).

As the industrial hemp planting increases in the United States, the applications of hemp have been more thoroughly researched. Hemp seeds may be used for oil and food while the stalks may be used for textile fiber, insulation, and composite materials. Figure 22 displays some of the various uses developed from hemp.

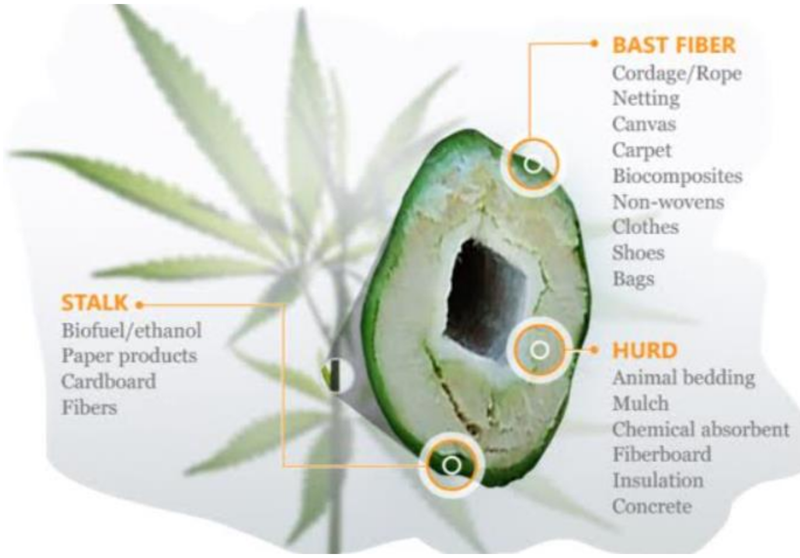


Figure 22. Hemp Uses. Image courtesy of Hemp Farming, n.d.

Biodegradable fibers such as hemp and cotton may not last as long as synthetic materials. However, hemp can be used for more than just textiles in a shoe; composites and other applications may be considered. Thus, this study will compare natural-yarn-content-derived footwear fabric (made of hemp and cotton) with the evaluation of the physical properties of fabrics in comparison to synthetic (Repreve®) yarn.

CHAPTER 3: METHODOLOGY

3.1 Research Problem

The development of knit footwear has greatly helped reduce waste in the footwear market, but the yarns used in such applications are still primarily synthetic - continuing to pose an impact by contributing to the global environmental crisis. There are some casual footwear companies (such as Allbirds, Oat and others) that are using biodegradable materials in their footwear, so how can this trend be developed for a wider footwear market? This study will develop and evaluate common weft knit footwear structures made from biodegradable and synthetic yarns.

3.2 Research Questions

It is anticipated that structures using synthetic yarn will inherently be stronger than structures using natural yarn in knitting due to their less amorphous structure, increased crystallinity/linear orientation and extrusion processes. It is also anticipated that the 100% cotton yarn will be more strong than the 100% hemp yarn due to its natural crystalline properties compared to hemp. However, this research is aiming to evaluate how common weft knit structures found in casual athletic footwear change in performance when natural and synthetic yarns are used. The goal of this research is to incorporate findings into the future casual athletic footwear market through the consideration of knit structure in the development of footwear.

Specifically, the following research questions will be addressed:

1. How does yarn content impact performance attributes of knit structures?
2. How does knit structure impact the physical properties of fabrics for footwear applications?

3.3 Early Development and Research

The development of new fabrics may be important for considerations in the knit footwear market. A combination of yarn content may allow for desired properties in the market. Below are some examples of 100% natural fabric, using a cotton base and a hemp inlay yarn for the early research and development stages of this project.

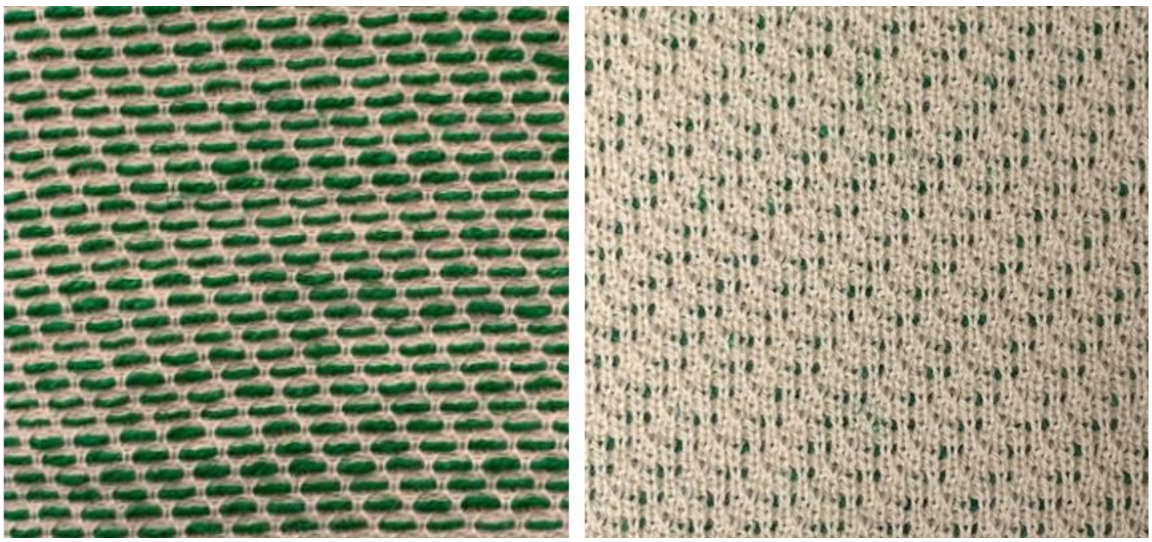


Figure 23. Hemp and cotton fabric samples. Own work.

Figure 24. Hemp and cotton fabrics envisioned in footwear with 100% hemp sole. Own work.

3.4 Procedures and Knit Design

The three common knit structures mentioned in section 2.5 will be evaluated for physical properties including abrasion resistance, tenacity, burst strength, elongation, air permeability, and moisture regain. They will be replicated in the best manner possible using the Shima Seiki N. SVR 123 SP 14 gauge (GG) knitting machine (Figure 25) and the SDS-One Apex3 Software. This machine was chosen due to its loop presser bed and powerful sinkers (Figure 26), allowing full control for inlay patterns and gentle hold-down during knitting (Shima Seiki, 2020).

Figure 25. Shima Seiki N. SVR 123 SP 14 Gauge Knitting Machine (Image courtesy of Shima Seiki, n.d.)

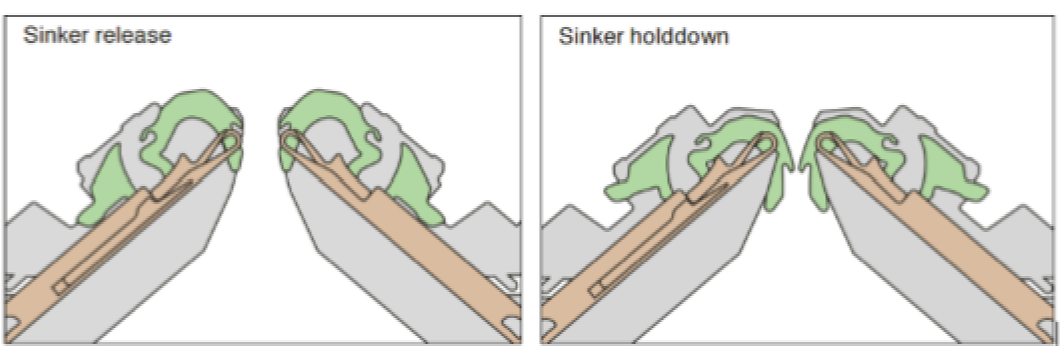


Figure 26. Shima Seiki illustration of sinker hold down capabilities on flatbed machine (Shima Seiki, n.d.)

The structures evaluated in this study originate from The Development of the Flat-Knitted Shaped Uppers based on Ergonomics (Lu et al., 2016). The research was used as a basis for determining structures commonly found in the knit footwear market, and upon evaluation of market offerings the structures are indeed commonly found in casual footwear. It is important to note that in the footwear market, it is possible to have different terms for a single knit structure across companies or individuals. In this study, terms will be re-evaluated and changed as deemed necessary for accuracy and clarity. Each knit structure will be evaluated for performance through a comparison of the tensile strength ASTM D5034 method, abrasion resistance ASTM D3885-07a (2019) method, air permeability D737-18 method, and burst strength D3787 method. The structures will each be knit thrice, with dimensions of approximately 9”W x 18”L. All samples will be knit on the N. SVR 123LP 14 gauge Shima Seiki machine.

3.4.1 Knit Design Style 1

Figure 27 below shows the structure described as a “Tubular Stitch with Tucked Loop” structure (Lu et al., 2016). This structure was chosen due to the incorporation of tucks (line 2), creating strength in both the horizontal and vertical directions. As mentioned previously, the tuck stitch is composed of a held loop when a needle holding a previous stitch receives a new loop, but it is not intermeshed through the old loop (Spencer, 2001). Tuck loops reduce fabric length and width-wise elasticity due to the higher yarn tension on the tuck and held loops, resulting in a robust structure appropriate for footwear.

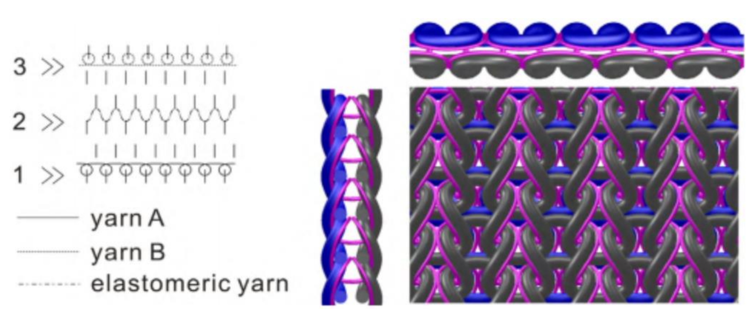


Figure 27. “Tubular Stitch with Tucked Loop” (Lu et al., 2016)

The program and knit visualization based off The Development of the Flat-Knitted Shaped Uppers based on Ergonomics may be seen in Figure 27.1 below. The piece measured 448 wales × 2318 courses, and knitting time was estimated as 19 minutes, 12 seconds.

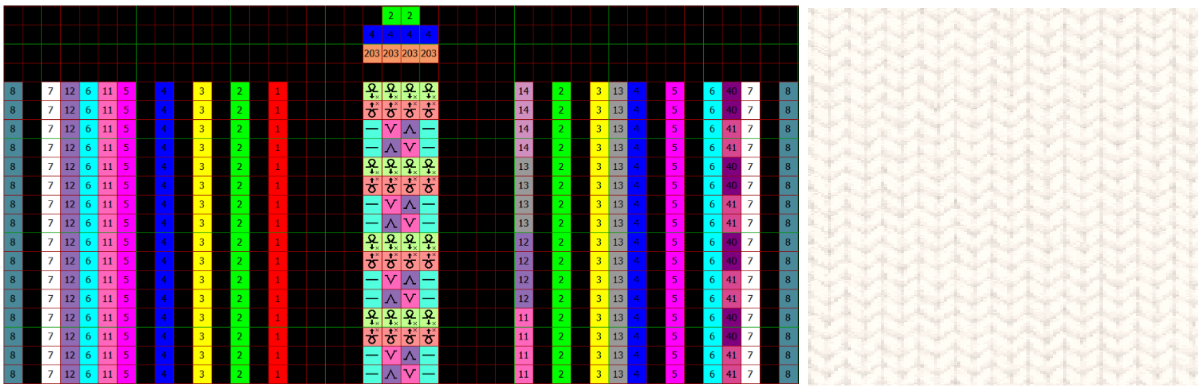


Figure 27.1. Style 1 Program (left) and visualization (right) – developed for N. SVR 123 SP 2-System 14GG - “Tubular Cross-Tuck”. Own work.

3.4.2 Knit Design Style 2

It must be noted that the “breathing holes” structure in The Development of the Flat-Knitted Shaped Uppers based on Ergonomics is a *mock* mesh structure without true “breathing holes”; therefore, terminology will be changed to “*mock mesh*”. True holes in the fabric are not present in order to be appropriately classified as a true mesh structure. As mentioned previously, the open surface allows for a breathable outlet in footwear applications. Mesh fabrics often have great breathability, permeability, and moisture conductivity properties (Zhang et al., 2018). Figure 26 below displays Lu’s “Breathing Holes” structure, while Figure 28.1 displays the “mock mesh” structure developed for this study. The piece developed for this stud measured 448 wales × 2288 courses, and knitting time was estimated as 17 minutes, 3 seconds.

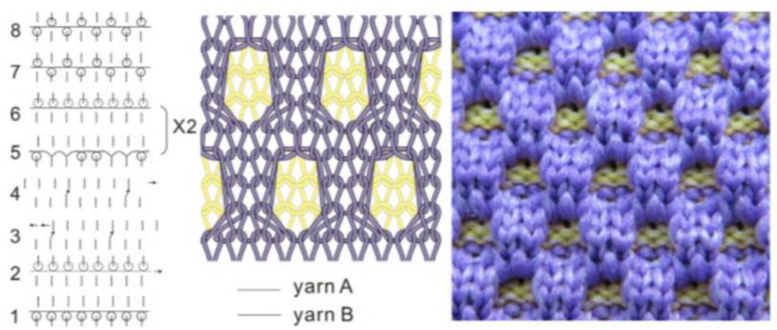


Figure 28. “Breathing Holes Structure” (Lu et al 2016)

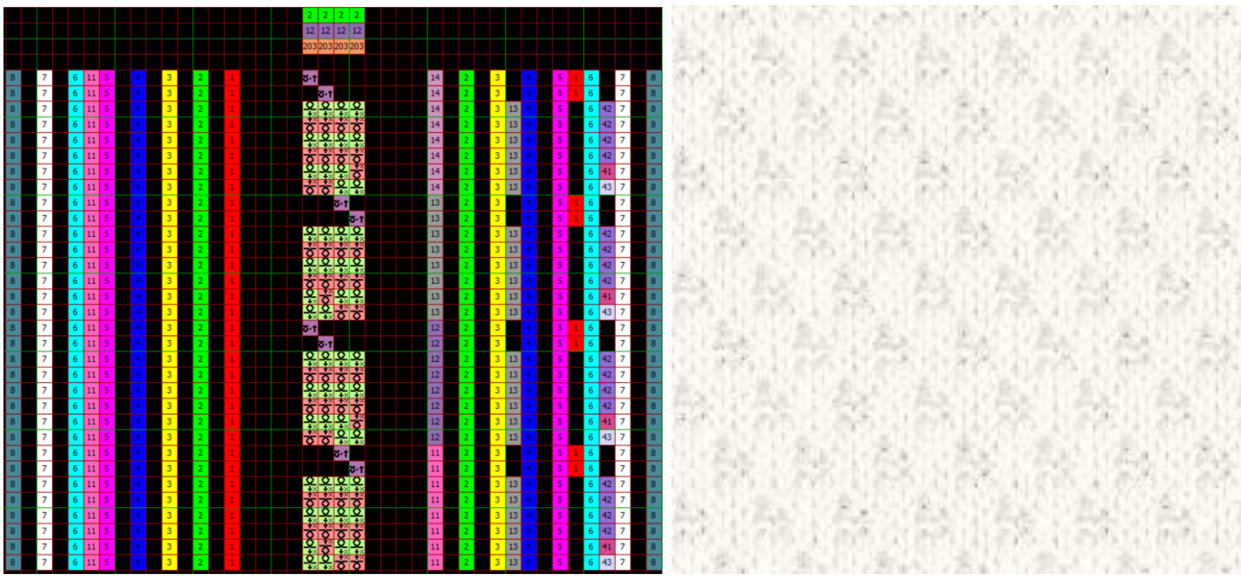


Figure 28.1. Style 2 Program (left) and visualization (right) – developed for N. SVR 123 SP 2-System 14GG - “Mock Mesh”. Own work.

3.4.3 Knit Design Style 3

The “topline rib” structure in Figure 29. is tubular; therefore, it will *not* be considered for research due to low stability levels. The structure in 29.1 developed by the researcher provides a similar concept, presenting an inlay yarn in between two layers (and incorporating tucks) for decreased extensibility in the lengthwise direction, resulting in an overall anticipated increase in strength.

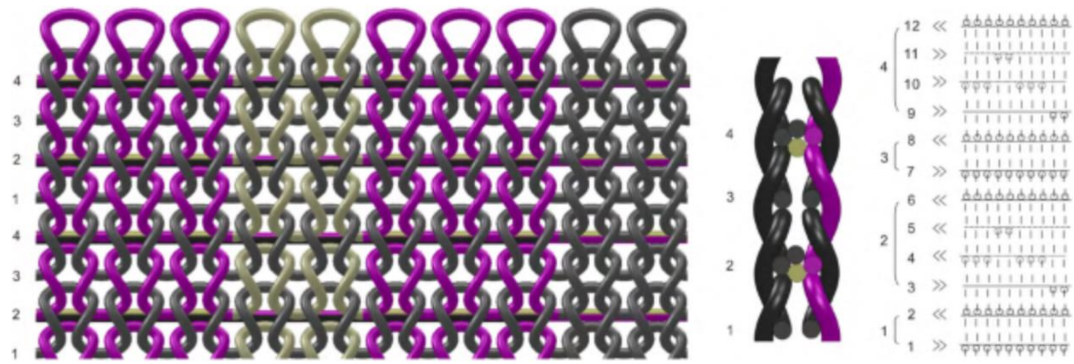


Figure 29. “Topline Rib” (Lu et al 2016)

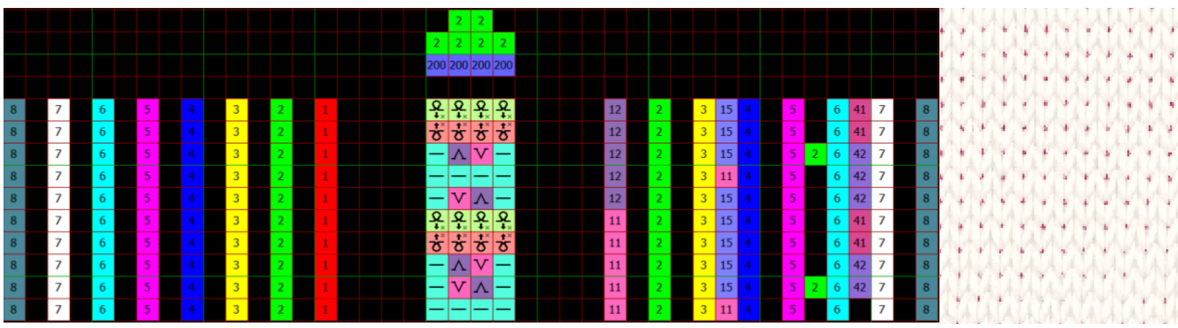


Figure 29.1. Style 3 Program (left) and visualization (right) developed for N. SVR 123 SP 2-System 14GG “Tubular, Tuck, and Inlay”. Own work.

The program shown in Figure 29.1 (above) incorporates the previous cross-tuck knitting and an inlaid yarn. The piece measured 448 wales × 714 courses, and knitting time was estimated as 6 minutes, 3 seconds. As aforementioned, inlaid yarns are trapped between the two needles beds during knitting, and may be used to modify stability, weight, visual appearance, and elasticity and recovery (Ray, 2012). Introducing an inlay yarn in between two layers (and incorporating tucks), provides decreased extensibility in the lengthwise direction. Thus, these combinations of techniques are anticipated to produce a suitable fabric for a knit footwear upper.

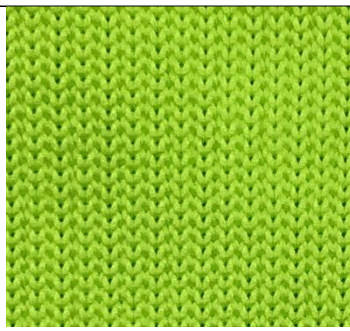
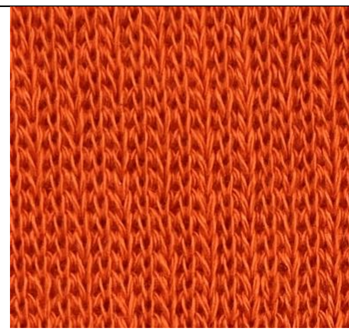
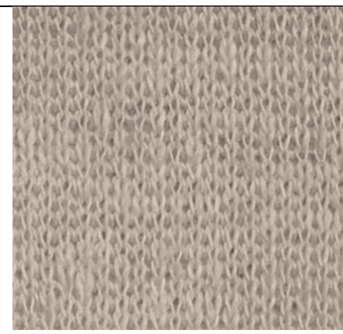
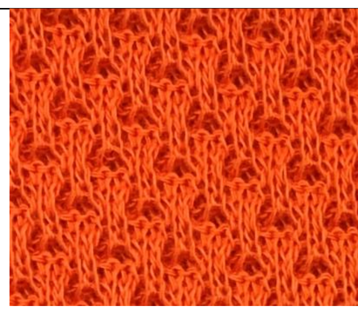
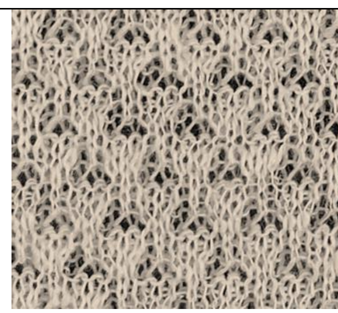
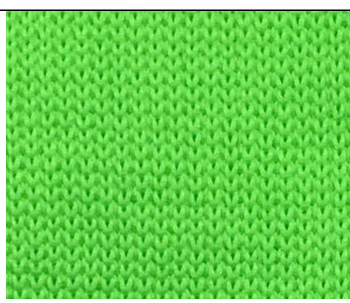
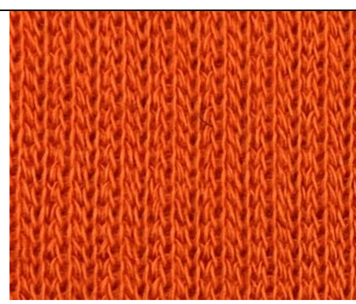
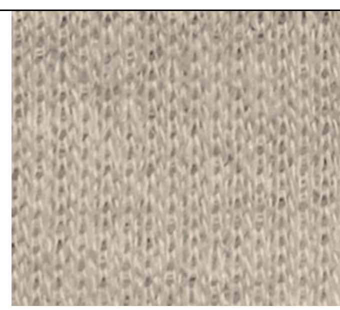
3.5 Yarn and Machine Settings, Final Knit Fabrics

The yarns knit on the machine (and subsequently tested) include 3 ends of 1/150/96 Repreve®, 2 ends of 20/1 100% cotton, and one end of 10/1 bleached and waxed 100% hemp yarn. As mentioned in the limitations section of this study, yarn size was controlled for the most appropriate fabric hand and specifications possible with the limitations imposed upon the sourcing of yarn, especially hemp. The following yarns were used in the development of the three different fabrics:

Table 1. Extrapolated yarn size based on number of ends used in knitting. Own work.

Yarn	**Content**	**Yarn Type**	**Color**	**Denier**
Repreve®	100% polyester (tri-set)	Filament	Neon Green	156 (3 ends) = 468 denier
Cotton	100% cotton	Staple	Jupiter Orange	221 (2 ends) = 442 denier
Hemp	100% cotton	Staple	Natural (Undyed)	489 (1 end) = 489 denier

Table 2. Photographs of the fabrics developed and evaluated for the study. Own work.

	100% Repreve® 1/150/96 Tri-Set Poly Neon Green - *3 ends*	**100% Cotton** 20/1 Jupiter Orange - *2 ends*	**100% Hemp** 10/1 bleached, waxed - *1 end*
Style 1 Cross-Tucks			
Style 2 Mock Mesh			
Style 3 Tubular, Tuck, and Inlay			

CHAPTER 4: RESULTS

4.1 Knitting Specifications

Table 3. Stitch Addresses (length is controlled by stitch length column). Own work.

		Stitch Address	Structure Type	Stitch Length
Style 1 Cross-Tucks	**100% Repreve®** 1/150/96 Tri-Set Poly - Neon Green - *3 ends*	40	tucks	16
		41	tubular	46
	100% Cotton 20/1 Jupiter Orange - *2 ends*	40	tucks	18
		41	Tubular	44
	100% Hemp 10/1 bleached, waxed - *1 end*	40	tucks	16
		41	tubular	42
Style 2 Mock Mesh	**100% Repreve®** 1/150/96 Tri-Set Poly - Neon Green - *3 ends*	41	1 front knit stitch 3 back knit stitches	18 40
		42	tubular	44
		43	2 front knit stitches 2 back knit stitches	36 36
	100% Cotton 20/1 Jupiter Orange - *2 ends*	41	1 front knit stitch 3 back knit stitches	16 38
		42	tubular	40
		43	2 front knit stitches 2 back knit stitches	36
	100% Hemp 10/1 bleached, waxed - *1 end*	41	1 front knit stitch 3 back knit stitches	18 40
		42	tubular	40
		43	2 front knit stitches 2 back knit stitches	32
Style 3 Tubular, Tuck, and Inlay	**100% Repreve®** 1/150/96 Tri-Set Poly - Neon Green - *3 ends*	41	tubular	40
		42	tucks	18
	100% Cotton 20/1 Jupiter Orange - *2 ends*	41	tubular	38
		42	tucks	16
	100% Hemp 10/1 bleached, waxed - *1 end*	41	tubular	40
		42	tucks	18

4.2 Physical Testing Results

4.2.1 Yarn Count

Yarn count was measured using ASTM D1907 – Yarn Number by the Skein Method. Yarn count is defined as the linear density to which a particular yarn has been spun (Spencer, 2001); the fineness of the yarn may influence which machine gauge may be used in knitting, weight of fabric, hand, and cost of production. All yarn count measurements in Table 4 account for one end of yarn.

Table 4. Yarn Count

	Length of Skein (yd)	Weight of Skein (g)	Denier	Cotton Count
Repreve®	120.0	1.90	156	34.1
Cotton	120.0	2.70	221	24.0
Hemp	120.0	5.96	489	10.9

4.2.2 Yarn Tenacity

Tensile strength (yarn tenacity) was measured using ASTM Method D2256. The machine used for testing was the USTER TENSORAPID 4. Tenacity is a measurement of strength in a yarn. The Repreve® yarn was the strongest, followed by hemp and cotton respectively. Due to the length of the hemp fibers, it is not surprising the tenacity is greater than cotton, as shorter fibers result is lower strength values (Shuvo, 2020).

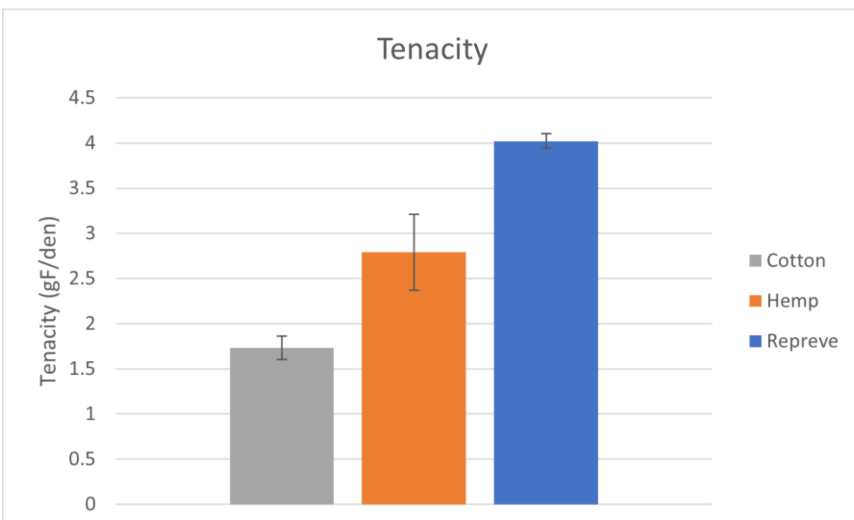


Figure 30. Yarn Tenacity

4.3 Fabric Testing

4.3.1 Fabric Thickness

Fabric thickness was measured using ASTM Method D1777-96 2015. The AMES 99 06970 measurement machine was used for evaluations. Each sample was tested 10 times, measured in inches.

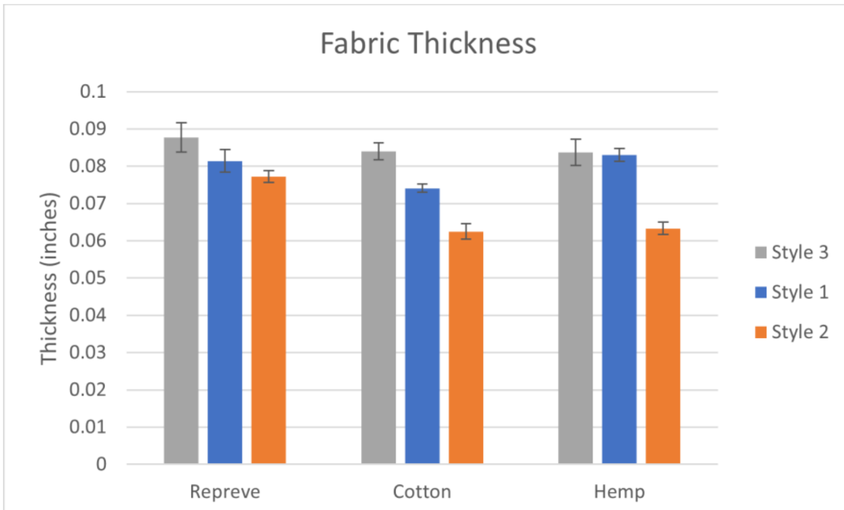


Figure 31. Fabric Thickness

As seen above, the styles of fabrics were divided by the yarn content of each piece. It is important to identify why the two natural fibers provide results with different thicknesses.The properties of natural fibers can change depending on their source/location of origin, age, and separating techniques of fibers (Hassan, 2012). Therefore, hemp and cotton, the two natural fibers derived from different plants, are expected to perform differently in the physical testing of in this research study.

4.3.2 Fabric Weight

Fabric weight is defined as the mass per unit area (Chowdhary, 2018), and in this situation is measured the fabrics were weighed in grams. Fabric weight was measured using ASTM Method D3776, option C with a normal scale. The test method was modified due to fabric restrictions, and all fabrics were weighed in 3x3" squares. Among the three separate fabrics, Style 3 (Tubular, Tucks, and Inlay) was the heaviest fabric structure due to the integration of an inlay yarn in the fabric. The lightest fabric structure was Style 2 (Mock Mesh) due to the voids in the fabric contributing to decreased weight. Generally, the Repreve® fabric was the heaviest likely due to the synthetic extrusion process, resulting in a more dense fiber compared to the natural spun production process as seen in cotton and hemp processing.

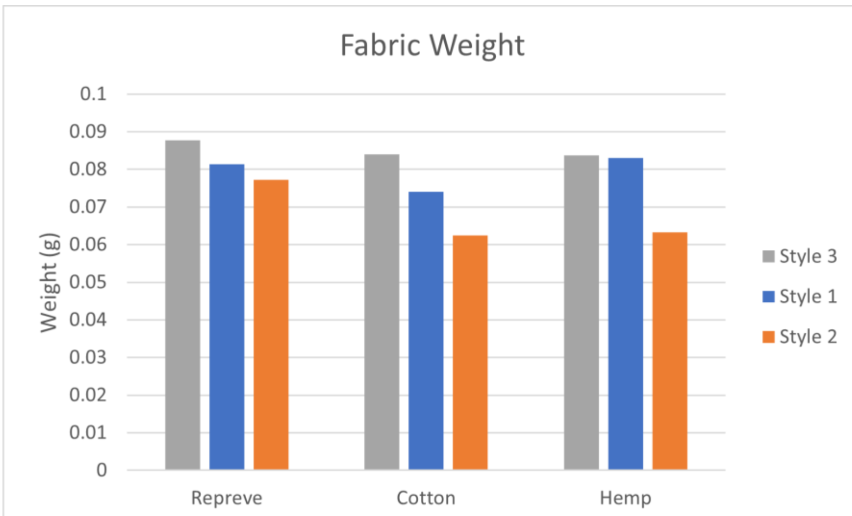


Figure 32. Fabric Weight

4.3.3 Fabric Abrasion Resistance

Abrasion Resistance is the ability of a surface to resist being worn away by rubbing or friction (Henry, 2018). ASTM Method D4966 was used for such measurements. The Martindale machine was used for this testing, and 10,000 rubs/movements were performed using a 9kPa head weight and a standard wool abradant. The technical face of the fabric was tested in this instance. Figure 32 displays the results. The fabric pieces were measured before and after 10,000 movements, with results showing hemp abraded the most, while Repreve® abraded the least. Table 3 shows before and after images of the fabrics. It is evident the two natural fibers performed differently. This is most likely to due the differing twist ratio and yarn count/density

(Alay, 2010) or spinning method. The production processes of the two fibers are different. Cotton, a short staple fiber, has a different spinning process than hemp fibers. Cotton is commonly spun on a short staple spinning machine, while hemp yarn is commonly processed using long-staple machinery due to the fiber orientation.

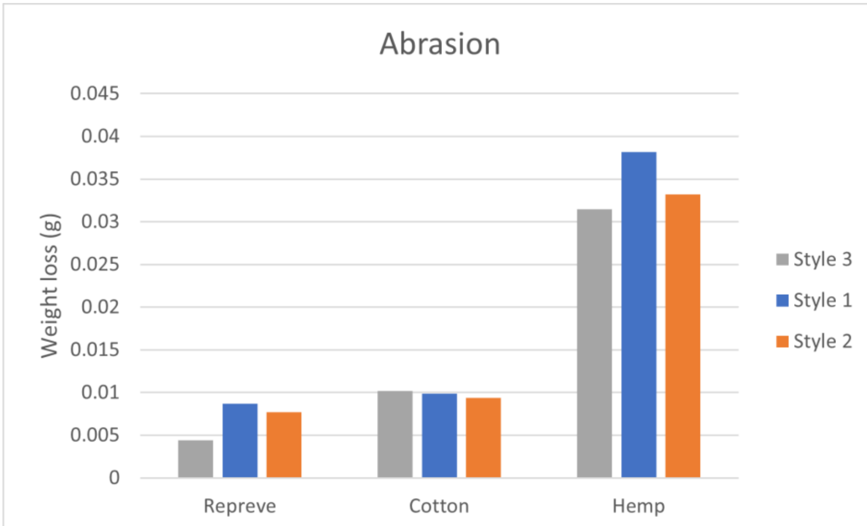
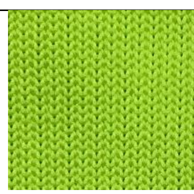
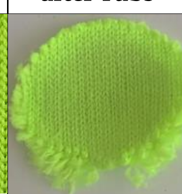
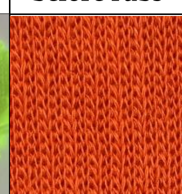
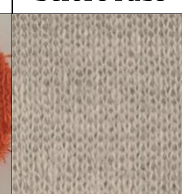
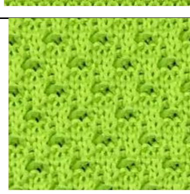
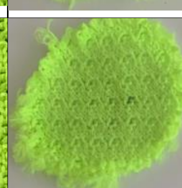
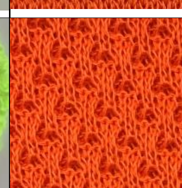
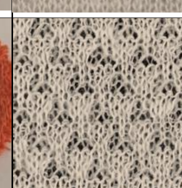
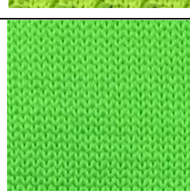
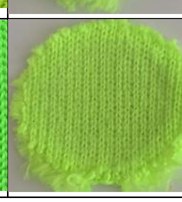
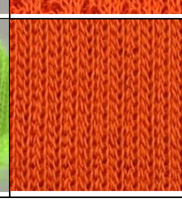
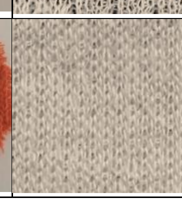


Figure 33. Abrasion Resistance

Table 5. Abrasion Results (before and after)

	100% Repreve® 1/150/96 Tri-Set Poly - Neon Green - *3 ends*		**100% Cotton** 20/1 Jupiter Orange - *2 ends*		**100% Hemp** 10/1 bleached, waxed - *1 end*	
	before rubs	**after rubs**	**before rubs**	**after rubs**	**before rubs**	**after rubs**
Style 1 Cross-Tucks						
Style 2 Mock Mesh						
Style 3 Tubular, Tuck, and Inlay						

4.3.4 Fabric Air Permeability

Air Permeability was tested using ASTM Method D737-16. Air permeability is defined as "the rate of airflow passing perpendicularly through a known area under a prescribed air pressure differential between two pieces of material (Patanaik, 2011)". The ASTM method was modified due to fabric limitations; five tests were performed 5 instead of 10 due to the limitations of the amount of fabric produced. A test area of 2.75 inches was used with the Frasier Air Permeability Machine. Figure 33 below shows Style 2 (Mock Mesh) was the most permeable, while Style 3 (Tubular, Tucks, Inlay) was the least permeable. Overall, the hemp fabric was the most air permeable, followed by cotton and Repreve®, respectively.

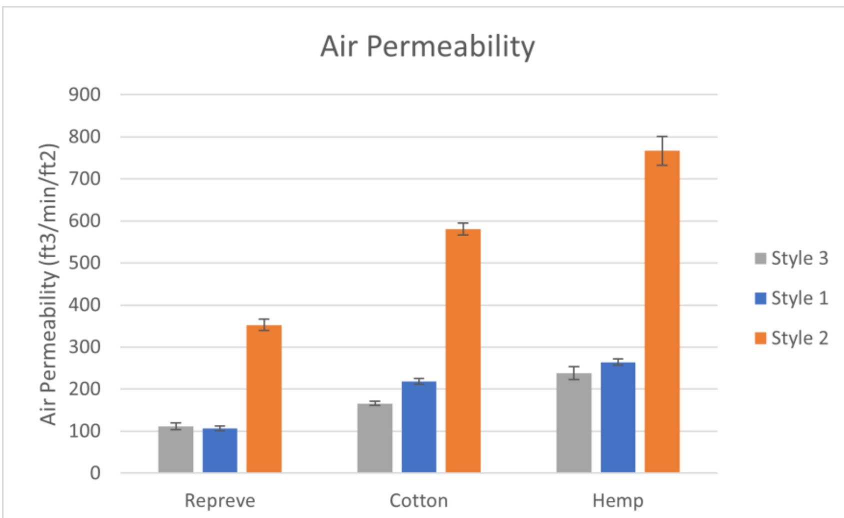


Figure 34. Fabric Air Permeability

The air permeability differences in the fiber categories of the fabrics are due to the natural properties of the yarns. It is expected for the two natural fibers to have increased air permeability results, as amorphorous regions in the fiber allow for increased air flow. Comparitively, the Repreve® yarn is a polymer without any voids. Due to non open-source standards in the footwear industry specifying air permeability measurements, it is unknown what value may be preferred. However, one may personally consider the importance of air flow in a footwear structure.

4.3.5 Fabric Moisture Regain

Moisture Regain was measured using the CEM Smart System 5 Microwave *MoistureSolids* Analyzer based on ASTM Method D629-15 section 9. Moisture regain is defined as the amount of moisture a material can absorb after is has been dried (CAMEO Materials Database, 2016). The ASTM test was modified and performed once due to fabric availability limitations. Figure 35 displays the results; hemp had the most regain overall, followed by cotton and Repreve®, respectively. Moisture regulation is directly tied to temperature regulation, which is important for the microclimate within a shoe. If there is too much moisture regain in a shoe, the humidity will increase, resulting in the growth of fungus and general footwear discomfort (Serweta et al., 2018). Thus, conforming to internally identified moisture regain standards is imperative in the footwear industry.

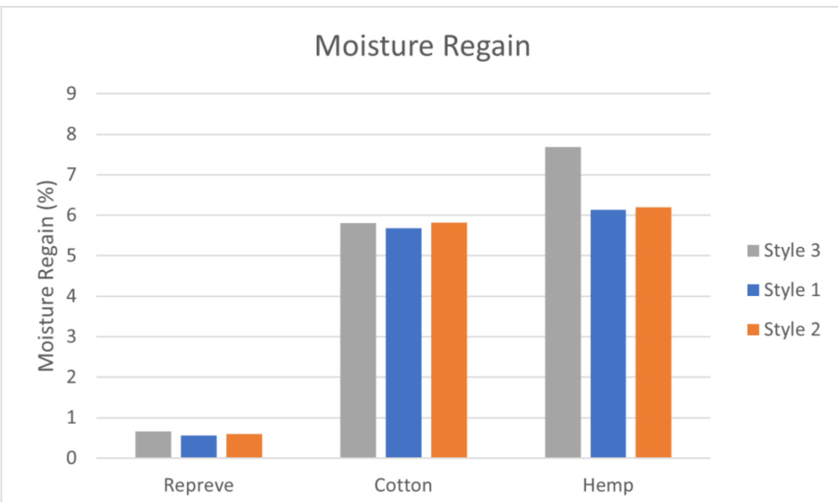


Figure 35. Moisture Regain

4.3.6 Fabric Burst Strength

Fabric burst strength was measured using ASTM Method D3789. Fabric burst strength measures the force needed to break or rupture the fabric when applied perpendicularly

(Chowdhary, 2018). The burst strength for the Repreve® fabrics was greater than 500 lbs/f. Overall, Repreve® had the greatest burst strength, followed by cotton and hemp, respectively. Figure 36 displays such results.

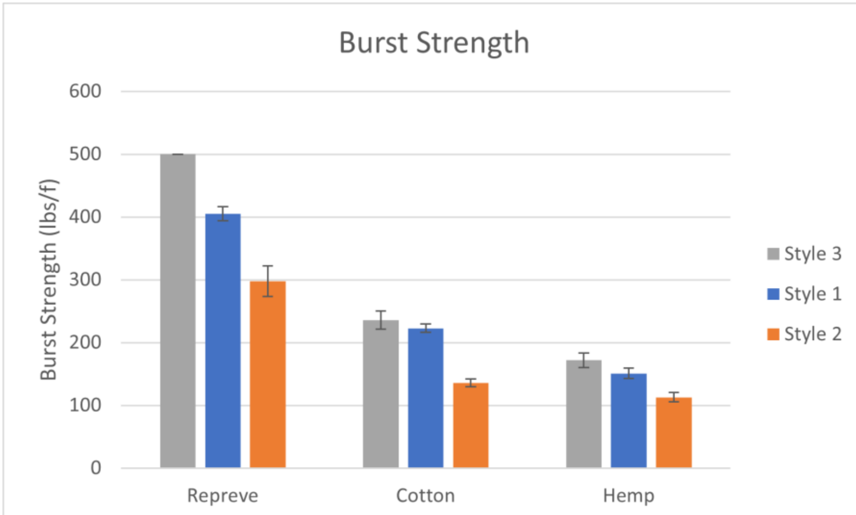


Figure 36. Burst Strength

4.3.7 Fabric Elongation

Fabric Elongation was measured using ASTM Method D5035. Fabric elongation is defined as the ultimate stretch possible in a particular direction using a predetermined amount of force (Davis, 2014). The MTS Q-Test/5 Universal Testing Machine was used for data collection. The results may be seen in Figure 35 below, where Style 2 (Mock Mesh) was the most extensible. Generally, the Repreve® fabric was the most extensible due to its nature as a polymer, followed by cotton and hemp respectively. The development of processing standards in the United States is likely a contributor to the elongation results of hemp in this particular test, as long staple machinery is not easy to find in the United States and therefore may have impacted the performance of this fiber.

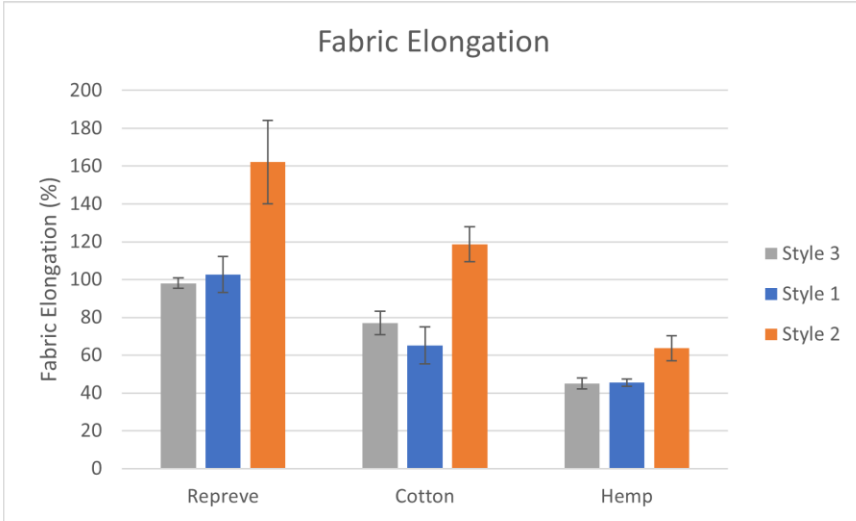


Figure 37. Fabric Elongation

CHAPTER 5: CONCLUSION

The mock mesh fabric performed the best in the weight and thickness categories for the hemp fabric. This is an important consideration for footwear, as footwear, in many cases. Should be light on the foot for physiological and consumer demand purposes. The heaviest fabric was Style 3, but it was also the most robust in the fabric burst strength category due to the inlaid yarn.

Hemp did not perform as well as the other yarn contents in the abrasion resistance or moisture regain tests but was the most air permeable fabric. Air permeability is important for breathability in footwear but may be refuted by the inability of a fabric to expel moisture. Fabric strength is important to consider depending on the application for footwear. Style 3 required the most force to break, therefore it may be well suited for high impact footwear applications. Particularly, the Repreve® fabric performed well in this category due to the polymerization of fibers, crystalline make up of the yarn. Low impact footwear applications would be more suited for the natural yarns in this study.

In conclusion, all three yarn contents performed well in individual categories. While there are many considerations related to footwer uppers in the industry, the results of this study may allow for a more thorough evaluation of yarn content decisions in future developments. The furthering of the hemp market in the United States will allow for future research to be conducted with respect to footwear in particular, and other markets within the textile industry will also undoubtly benefit from this research.

5.1 Future Work

Future work within the realm of this research may include the applications of hemp composites and materials for use in footwear. Another study may be conducted in which certain yarns are slowly integrated into knit structures to evaluate how the integration of such contents affect the physical properties of the fabric. A blended yarn may also be important to study in this situation – gaining certain properties from desired fiber contents. Finally, it will be important to further study and evaluate the comfort and consumer interest in this market with relation to the hemp fiber as the market continues to grow in the United States.

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APPENDICES

Appendix A: Yarn Number by the Skein Method

ASTM D1907 – Yarn Number by the Skein Method

Cone #	Length of Skein (yd)	Wt. of Skein (g)	Denier	Cotton Count
Repreve	120.0	1.9000	156	34.1
cotton	120.0	2.7000	221	24.0
hemp	120.0	5.9600	489	10.9

Appendix B: Yarn Tenacity Raw Data

Hemp

USTER® TENSORAPID 4 2.7.0 UTR4/ 500N Fri 18.09.20 11:37 Operator TJW Page 1

Style Hemp Sample IDSTUDENT 011288 Nom. count Nec 10.9 Nom. twist 0 T/m
Tests 1 / 20 v= 300 mm/min Fv= 27.6 gF Lh= 250 mm Pcl= 30 %

Standard Report

Article Material class Yarn Mach. Nr.
Uster Statistics Name Class
Hemp-Ne=10.9

Subsample 1: 20 Single test(s)

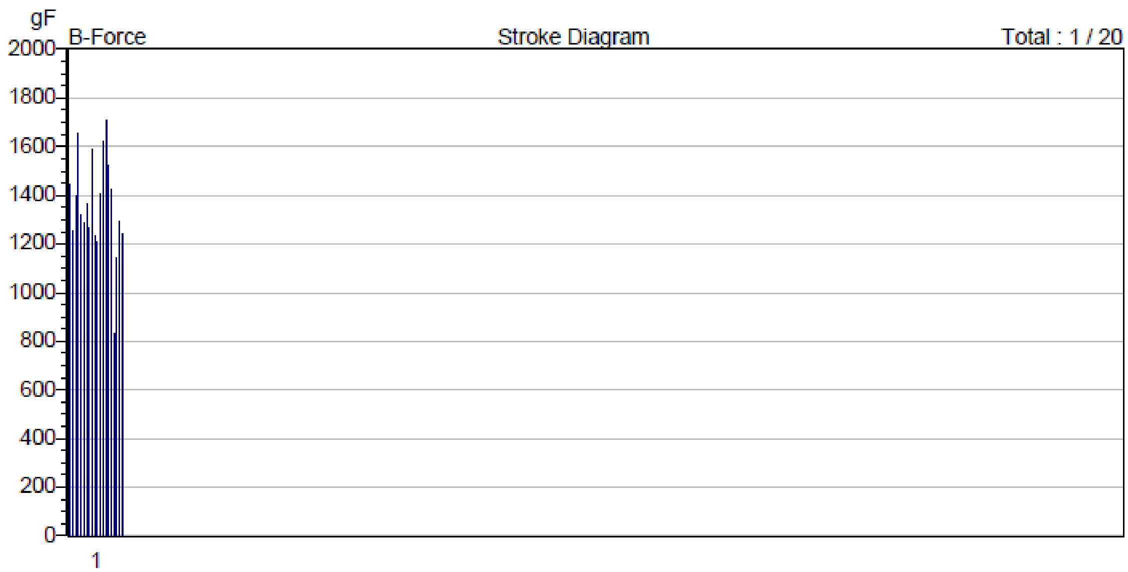
i	Time to break s	B-Force gF	Elong. %	Tenacity gF/den	B-Work gF.cm	Modul 2% N/tex
1	1.13	1442	2.23	2.96	380.3	13.08
2	0.93	1251	1.86	2.57	272.8	
3	1.12	1401	2.22	2.87	363.0	13.29
4	1.16	1651	2.32	3.39	452.8	14.44
5	1.16	1321	2.31	2.71	364.2	11.52
6	0.93	1286	1.85	2.64	290.6	
7	1.02	1366	2.03	2.80	322.8	14.05
8	0.93	1267	1.85	2.60	277.3	
9	1.28	1591	2.55	3.26	481.3	12.36
10	1.11	1230	2.21	2.52	334.8	10.64
11	1.05	1211	2.09	2.48	313.4	10.94
12	0.98	1402	1.95	2.87	323.2	
13	1.33	1621	2.64	3.32	494.1	12.42
14	1.20	1707	2.39	3.50	478.0	14.68
15	1.17	1524	2.32	3.13	415.8	13.22
16	1.03	1422	2.05	2.92	351.2	13.04
17	0.77	834.2	1.53	1.71	161.3	
18	0.85	1140	1.69	2.34	244.5	
19	0.96	1290	1.92	2.65	313.3	
20	0.98	1238	1.95	2.54	286.3	
Mean	1.05	1360	2.10	2.79	346.1	12.81
s	0.14	202.4	0.28	0.42	85.91	1.29
CV	13.55	14.89	13.52	14.89	24.83	10.10
Q95	0.07	94.79	0.13	0.19	40.22	0.82
Min	0.77	834.2	1.53	1.71	161.3	10.64
Max	1.33	1707	2.64	3.50	494.1	14.68
USP™						

Style Hemp Sample ID STUDENT 011288 Nom. count Nec 10.9 Nom. twist 0 T/m
Tests 1 / 20 v= 300 mm/min Fv= 27.6 gF Lh= 250 mm Pcl= 30 %

Standard Report

Total : 1 / 20 Single test(s)

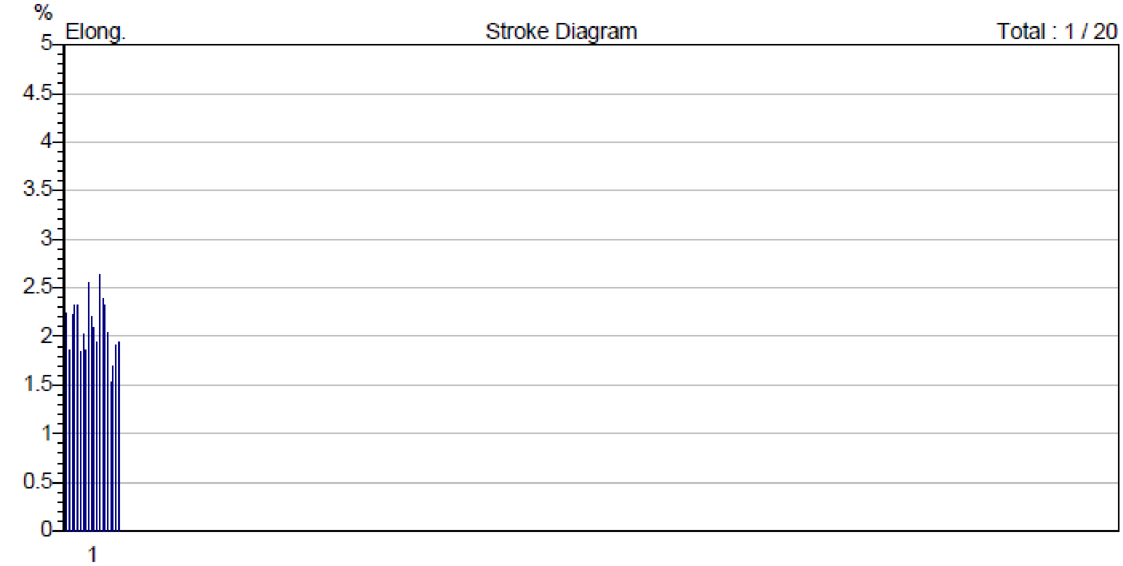
Nr	Time to break s	B-Force gF	Elong. %	Tenacity gF/den	B-Work gF.cm	Modul 2% N/tex
1/20	1.05	1360	2.10	2.79	346.1	12.81
Mean	1.05	1360	2.10	2.79	346.1	12.81
s	0.14	202.4	0.28	0.42	85.91	1.29
CV	13.55	14.89	13.52	14.89	24.83	10.10
Q95	0.07	94.79	0.13	0.19	40.22	0.82
Min	0.77	834.2	1.53	1.71	161.3	10.64
Max	1.33	1707	2.64	3.50	494.1	14.68
USP™						

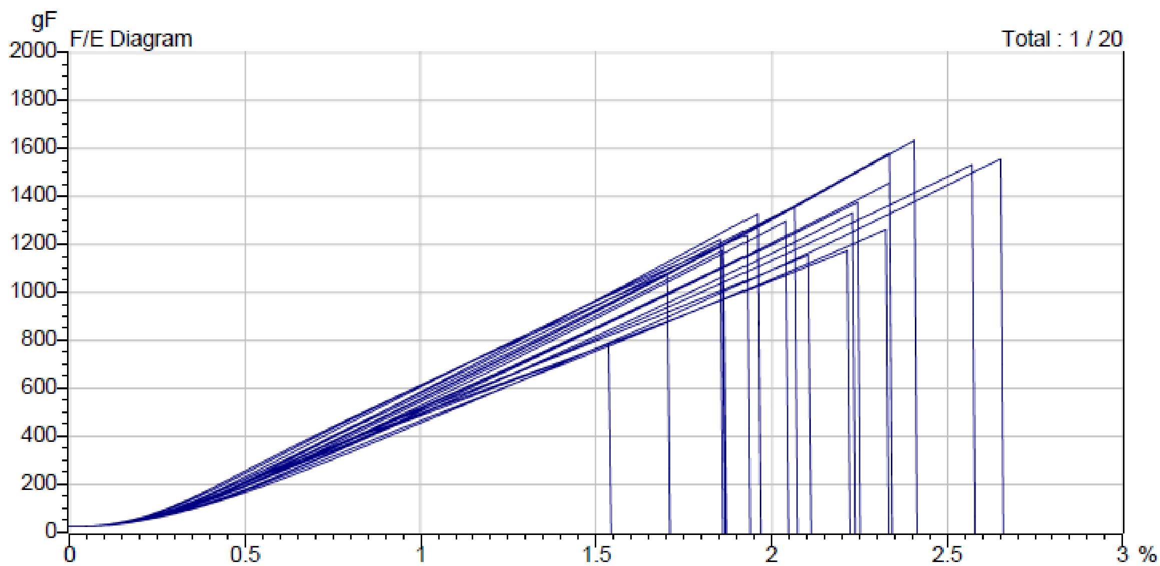


USTER® TENSORAPID 4 2.7.0 UTR4/ 500N Fri 18.09.20 11:37 Operator TJW Page 3

Style	Hemp	Sample ID	STUDENT 011288	Nom. count	Nec 10.9	Nom. twist	0 T/m
Tests	1 / 20	v= 300 mm/min	Fv= 27.6 gF	Lh= 250 mm	Pcl= 30 %		

Standard Report





Cotton

USTER® TENSORAPID 4 2.7.0 UTR4/ 500N Fri 18.09.20 11:27 Operator TJW Page 1

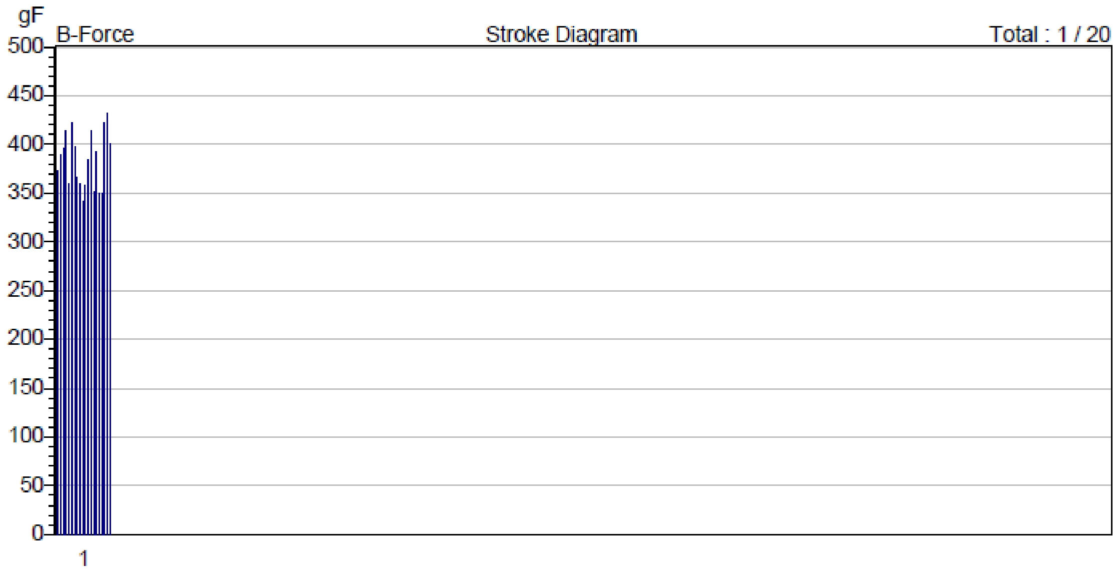
Style Cotton Sample ID STUDENT 011287 Nom. count Nec 24 Nom. twist 0 T/m
Tests 1 / 20 v= 300 mm/min Fv= 12.5 gF Lh= 250 mm Pcl= 30 %

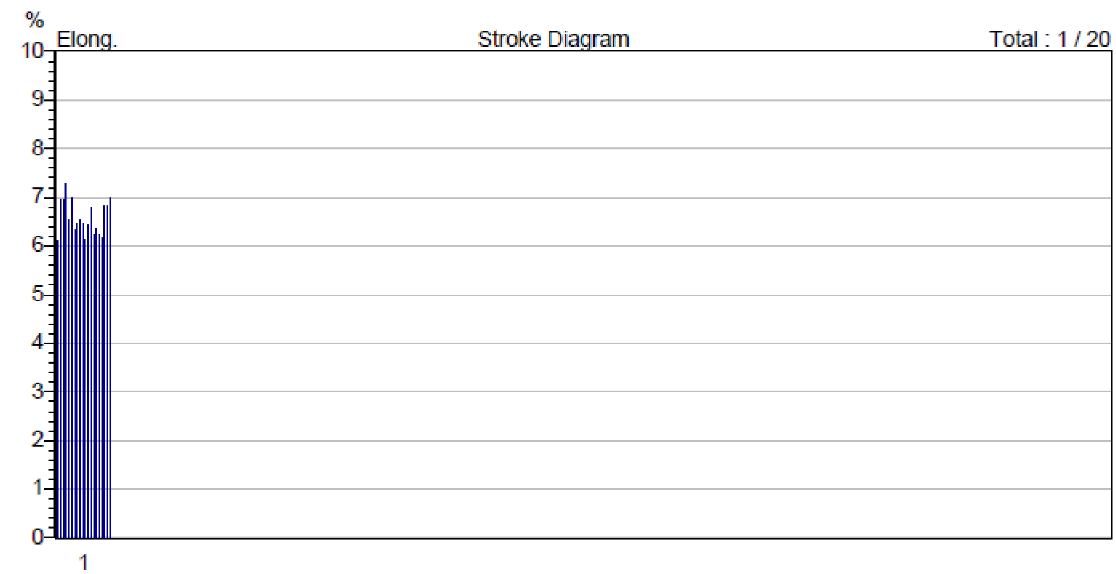
Standard Report

Article Material class Yarn Mach. Nr.
Uster Statistics Name Class
Orange colored cotton - Ne=24/1

Subsample 1: 20 Single test(s)

i	Time to break s	B-Force gF	Elong. %	Tenacity gF/den	B-Work gF.cm	Modul 2% N/tex
1	3.10	373.0	6.11	1.68	274.6	2.447
2	3.51	389.6	6.95	1.76	325.3	2.159
3	3.52	395.8	6.97	1.79	336.9	2.271
4	3.66	414.3	7.27	1.87	355.7	2.159
5	3.30	359.9	6.54	1.63	276.5	2.062
6	3.51	422.4	6.99	1.91	346.7	2.314
7	3.18	398.4	6.32	1.80	303.7	2.490
8	3.25	366.7	6.45	1.66	275.3	2.193
9	3.29	358.9	6.51	1.62	283.6	2.189
10	3.26	342.2	6.47	1.55	268.2	2.053
11	3.09	358.0	6.12	1.62	258.3	2.277
12	3.24	383.9	6.43	1.73	296.4	2.306
13	3.43	414.6	6.80	1.87	335.0	2.311
14	3.15	351.0	6.23	1.59	258.6	2.197
15	3.22	393.0	6.38	1.77	303.0	2.526
16	3.15	350.0	6.23	1.58	259.0	2.247
17	3.10	349.6	6.15	1.58	261.7	2.224
18	3.44	422.9	6.83	1.91	341.4	2.339
19	3.43	431.4	6.81	1.95	342.3	2.385
20	3.52	400.3	6.99	1.81	340.6	2.256
Mean	3.32	383.8	6.58	1.73	302.1	2.270
s	0.17	28.38	0.35	0.13	35.01	0.126
CV	5.20	7.39	5.29	7.39	11.59	5.57
Q95	0.08	13.29	0.16	0.06	16.39	0.059
Min	3.09	342.2	6.11	1.55	258.3	2.053
Max	3.66	431.4	7.27	1.95	355.7	2.526
USP™						

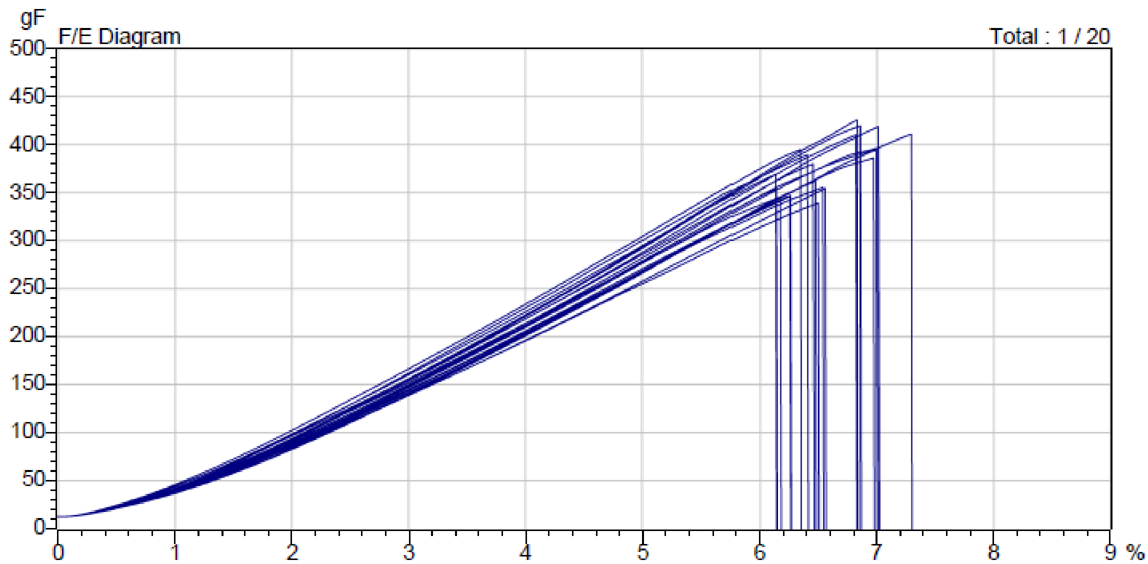

gF
B-Force
Stroke Diagram
Total : 1 / 20
500
450
400
350
300
250
200
150
100
50
0
1


%
Elong.
Stroke Diagram
Total : 1 / 20
10
9
8
7
6
5
4
3
2
1
0
1

USTER® TENSORAPID 4   2.7.0   UTR4/ 500N   Fri 18.09.20 11:27   Operator   TJW   Page   3

Style	Cotton	Sample ID	STUDENT 011287	Nom. count	Nec 24	Nom. twist	0 T/m	
Tests	1 / 20	v= 300 mm/min	Fv= 12.5 gF	Lh= 250 mm	Pcl= 30 %			

Standard Report



Repreve®

USTER® TENSORAPID 4 2.7.0 UTR4/ 500N Fri 18.09.20 11:45 Operator TJW Page 1

Style Repreve Sample IDSTUDENT 011289 Nom. count 156 den Nom. twist 0 T/m
Tests 1 / 20 v= 300 mm/min Fv= 8.8 gF Lh= 250 mm Pcl= 30 %

Standard Report

Article Material class Yarn Mach. Nr.
Uster Statistics Name Class
Neon Yellow Repreve-den=156

Subsample 1: 20 Single test(s)

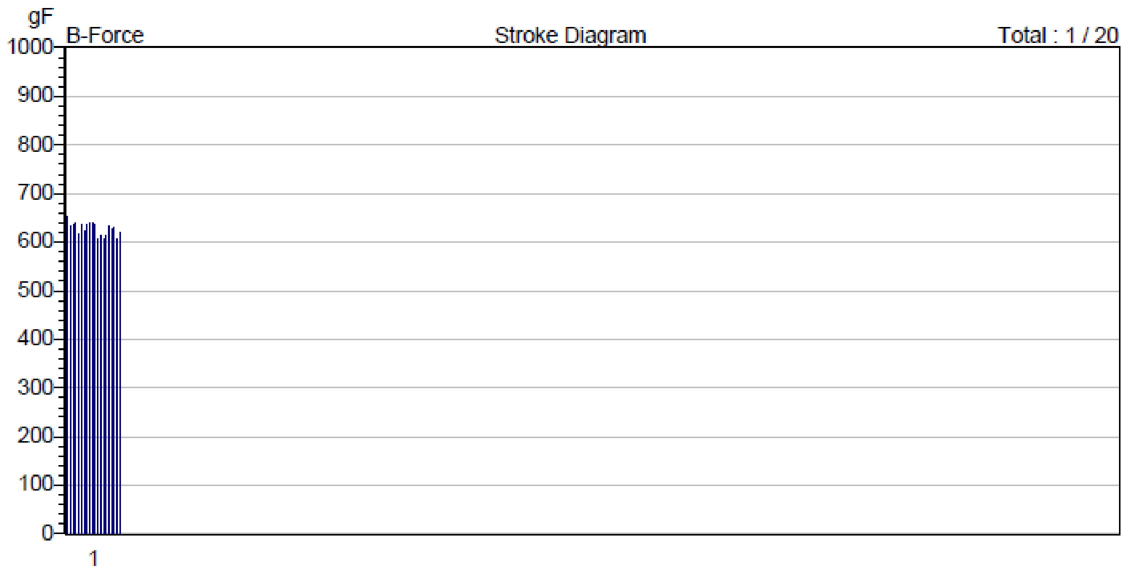
i	Time to break	B-Force	Elong.	Tenacity	B-Work	Modul 2%
	s	gF	%	gF/den	gF.cm	N/tex
1	16.92	653.3	33.28	4.19	3583	2.711
2	15.57	632.4	30.88	4.05	3158	2.498
3	15.48	637.1	30.71	4.08	3150	2.607
4	15.73	639.4	31.22	4.10	3208	2.914
5	14.43	616.6	28.61	3.95	2786	2.706
6	15.15	635.6	30.06	4.07	3068	3.014
7	14.97	624.2	29.69	4.00	2967	2.612
8	15.32	636.8	30.40	4.08	3090	2.624
9	15.94	639.1	31.63	4.10	3272	2.897
10	15.56	639.7	30.86	4.10	3140	2.574
11	15.91	637.8	31.58	4.09	3257	2.669
12	13.71	608.7	27.22	3.90	2605	2.824
13	14.49	613.1	28.75	3.93	2795	2.692
14	14.00	607.7	27.78	3.90	2648	2.733
15	14.34	614.1	28.47	3.94	2761	2.828
16	15.95	632.1	31.67	4.05	3286	2.858
17	15.04	626.4	29.86	4.02	2993	2.829
18	15.54	629.9	30.85	4.04	3155	2.821
19	14.58	606.6	28.80	3.89	2792	2.629
20	14.06	619.7	27.94	3.97	2711	2.908
Mean	15.13	627.5	30.01	4.02	3021	2.747
s	0.81	13.08	1.58	0.08	256.8	0.137
CV	5.36	2.08	5.26	2.08	8.50	4.98
Q95	0.38	6.12	0.74	0.04	120.2	0.064
Min	13.71	606.6	27.22	3.89	2605	2.498
Max	16.92	653.3	33.28	4.19	3583	3.014
USP™						

Style Repreve Sample ID STUDENT 011289 Nom. count 156 den Nom. twist 0 T/m
Tests 1 / 20 v= 300 mm/min Fv= 8.8 gF Lh= 250 mm Pcl= 30 %

Standard Report

Total : 1 / 20 Single test(s)

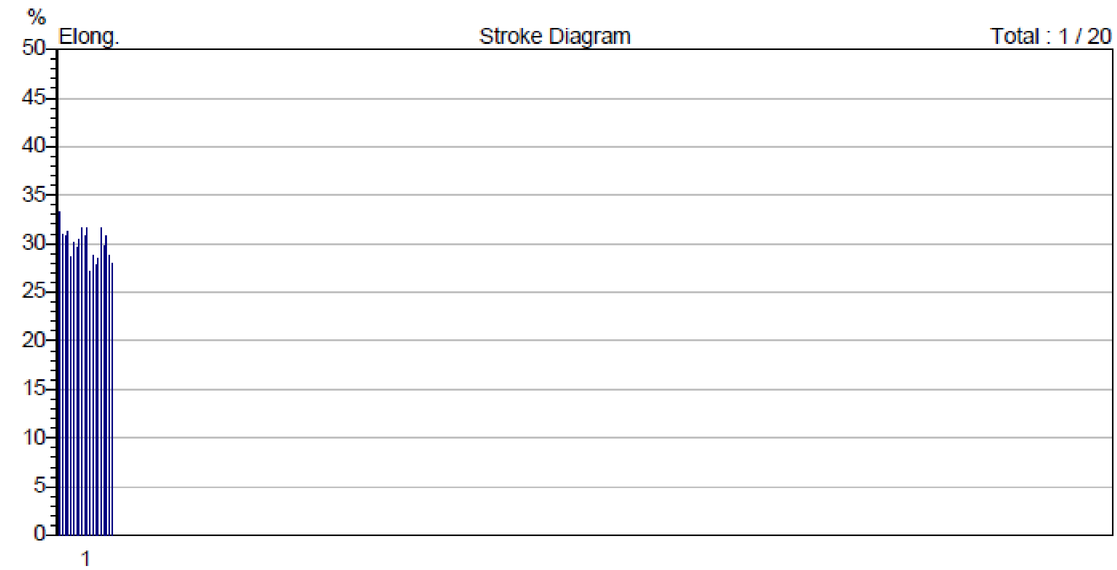
Nr	Time to break s	B-Force gF	Elong. %	Tenacity gF/den	B-Work gF.cm	Modul 2% N/tex
1/20	15.13	627.5	30.01	4.02	3021	2.747
Mean	15.13	627.5	30.01	4.02	3021	2.747
s	0.81	13.08	1.58	0.08	256.8	0.137
CV	5.36	2.08	5.26	2.08	8.50	4.98
Q95	0.38	6.12	0.74	0.04	120.2	0.064
Min	13.71	606.6	27.22	3.89	2605	2.498
Max	16.92	653.3	33.28	4.19	3583	3.014
USP™						

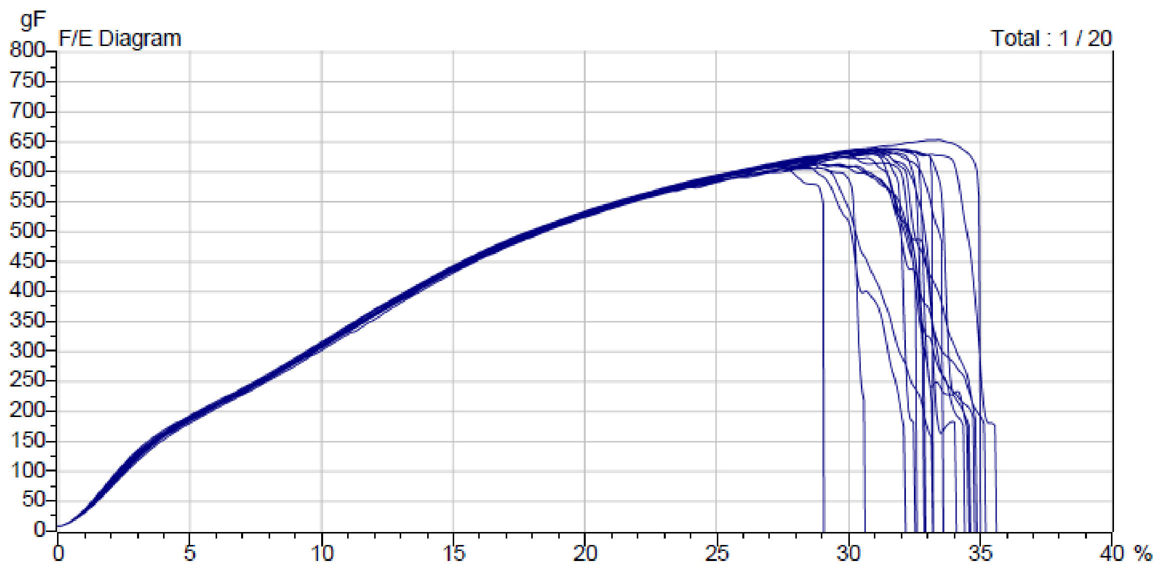


USTER® TENSORAPID 4 2.7.0 UTR4/ 500N Fri 18.09.20 11:45 Operator TJW Page 3

Style	Repreve	Sample ID	STUDENT 011289	Nom. count	156 den	Nom. twist	0 T/m
Tests	1 / 20	v= 300 mm/min	Fv= 8.8 gF	Lh= 250 mm	Pcl= 30 %		

Standard Report





Appendix C: Fabric Tenacity Raw Data

Style 1

100% Hemp

Sample ID:	Zoe-P1H-Hemp--Machine-9-24-20.mss	Test Date:	9/24/2020
Method:	FAB_STRIP_D5035_1000lb_Zoe_9-24-20.msm	Operator:	Teresa

Sample Information:

Name	Value
Client	Zoe-P1H
Date of Test	9-24-20
Grip Pressure	1600 psi
Info 1	Hemp
Jaw Face Size	2" x 3" serrated grips
Lab Conditions	70F, 65% RH
Test Direction	Machine

Specimen Results:

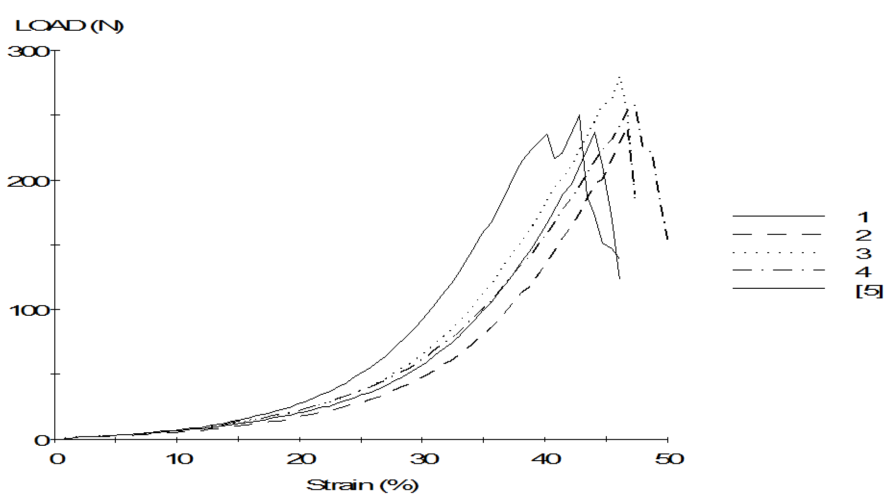
Specimen #	Peak Load lbf	Elong @ Pk Ld mm	%Strn @ Pk Ld %
1	56.2	33	42.8
2	54.1	36	46.7
3	62.9	35	46.1
4	58.0	36	47.4
5	53.1	34	44.1
Mean	56.9	35	45.4
Std. Dev.	3.9	1	1.9

Calculation Inputs:

Name	Value	Units
Gage Length 1	3.00	in

Test Inputs:

Name	Value	Units
Brk Sensitivity	50	%
Crosshead Speed	300.00	mm/min
Initial Speed	300.00	mm/min
Load Limit HI	1000	lbf



100% Cotton

Sample ID:	Zoe-P1C-Cotton--Machine-9-24-20.mss	Test Date:	9/24/2020
Method:	FAB_STRIP_D5035_1000lb_Zoe_9-24-20.msm	Operator:	Teresa

Sample Information:

Name	Value
Client	Zoe-P1C
Date of Test	9-24-20
Grip Pressure	1600 psi
Info 1	Cotton
Jaw Face Size	2" x 3" serrated grips
Lab Conditions	70F, 65% RH
Test Direction	Machine

Specimen Results:

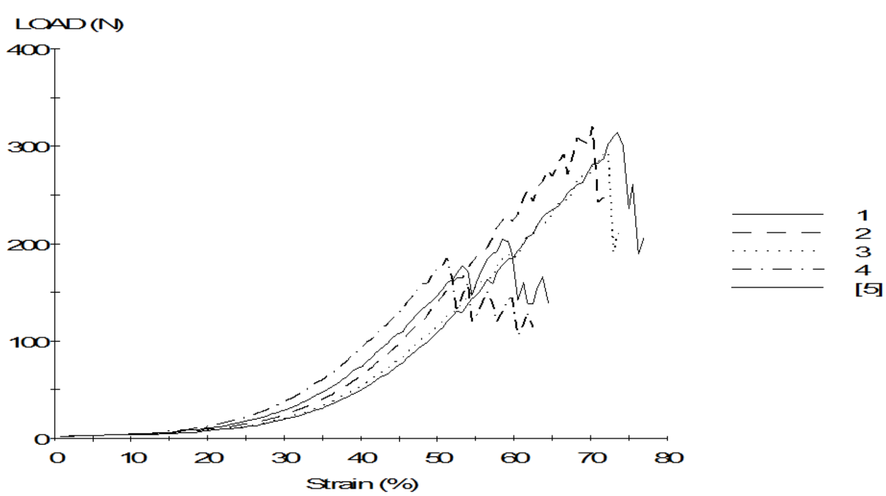
Specimen #	Peak Load lbf	Elong @ Pk Ld mm	%Strn @ Pk Ld %
1	70.7	56	73.6
2	72.0	54	70.3
3	66.9	55	72.3
4	41.7	39	51.3
5	45.8	45	58.5
Mean	59.4	50	65.2
Std. Dev.	14.5	7	9.8

Calculation Inputs:

Name	Value	Units
Gage Length 1	3.00	in

Test Inputs:

Name	Value	Units
Brk Sensitivity	50	%
Crosshead Speed	300.00	mm/min
Initial Speed	300.00	mm/min
Load Limit HI	1000	lbf



Repreve®

Sample ID: Zoe-P1R-Reprieve--Machine-9-24-20.mss Test Date: 9/24/2020
Method: FAB_STRIP_D5035_1000lb_Zoe_9-24-20.msmOperator: Teresa

Sample Information:

Name	Value
Client	Zoe-P1R
Date of Test	9-24-20
Grip Pressure	1600 psi
Info 1	Repreve
Jaw Face Size	2" x 3" serrated grips
Lab Conditions	70F, 65% RH
Test Direction	Machine

Specimen Results:

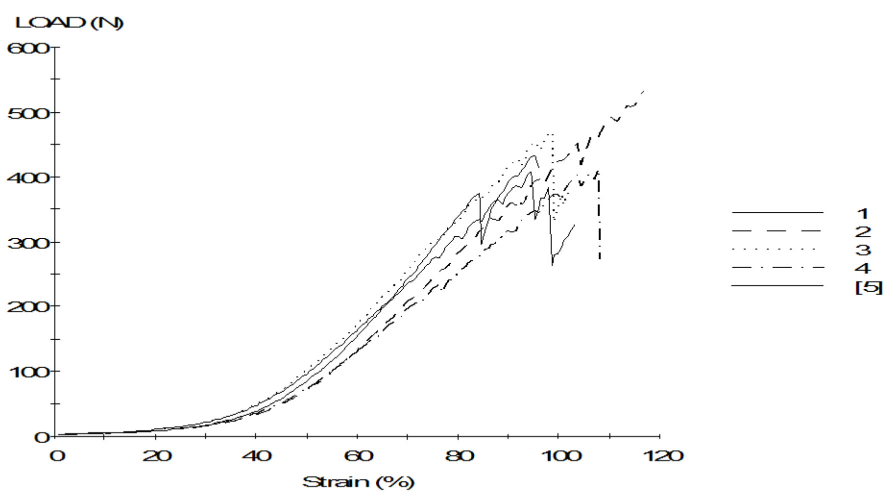
Specimen #	Peak Load lbf	Elong @ Pk Ld mm	%Strn @ Pk Ld %
1	97.4	73	95.3
2	119.9	89	116.9
3	105.4	75	98.6
4	92.5	82	107.7
5	91.7	72	94.6
Mean	101.4	78	102.6
Std. Dev.	11.7	7	9.6

Calculation Inputs:

Name	Value	Units
Gage Length 1	3.00	in

Test Inputs:

Name	Value	Units
Brk Sensitivity	50	%
Crosshead Speed	300.00	mm/min
Initial Speed	300.00	mm/min
Load Limit HI	1000	lbf



Style 2

100% Hemp

Sample ID:	Zoe-P2H-Hemp--Machine-9-24-20.mss	Test Date:	9/24/2020
Method:	FAB_STRIP_D5035_1000lb_Zoe_9-24-20.msm	Operator:	Teresa

Sample Information:

Name	Value
Client	Zoe-P2H
Date of Test	9-24-20
Grip Pressure	1600 psi
Info 1	Hemp
Jaw Face Size	2" x 3" serrated grips
Lab Conditions	70F, 65% RH
Test Direction	Machine

Specimen Results:

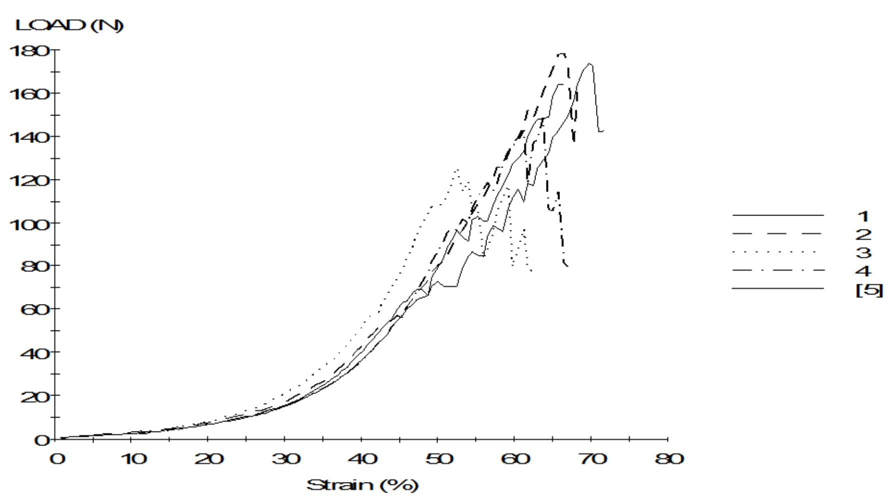
Specimen #	Peak Load lbf	Elong @ Pk Ld mm	%Strn @ Pk Ld %
1	39.1	53	69.7
2	40.1	51	66.4
3	28.3	40	52.6
4	33.3	49	63.8
5	36.9	50	65.7
Mean	35.5	48	63.6
Std. Dev.	4.8	5	6.5

Calculation Inputs:

Name	Value	Units
Gage Length 1	3.00	in

Test Inputs:

Name	Value	Units
Brk Sensitivity	50	%
Crosshead Speed	300.00	mm/min
Initial Speed	300.00	mm/min
Load Limit HI	1000	lbf



100% Cotton

Sample ID:	Zoe-P2C-Cotton--Machine-9-24-20.mss	Test Date:	9/24/2020
Method:	FAB_STRIP_D5035_1000lb_Zoe_9-24-20.msm	Operator:	Teresa

Sample Information:

Name	Value
Client	Zoe-P2C
Date of Test	9-24-20
Grip Pressure	1600 psi
Info 1	Cotton
Jaw Face Size	2" x 3" serrated grips
Lab Conditions	70F, 65% RH
Test Direction	Machine

Specimen Results:

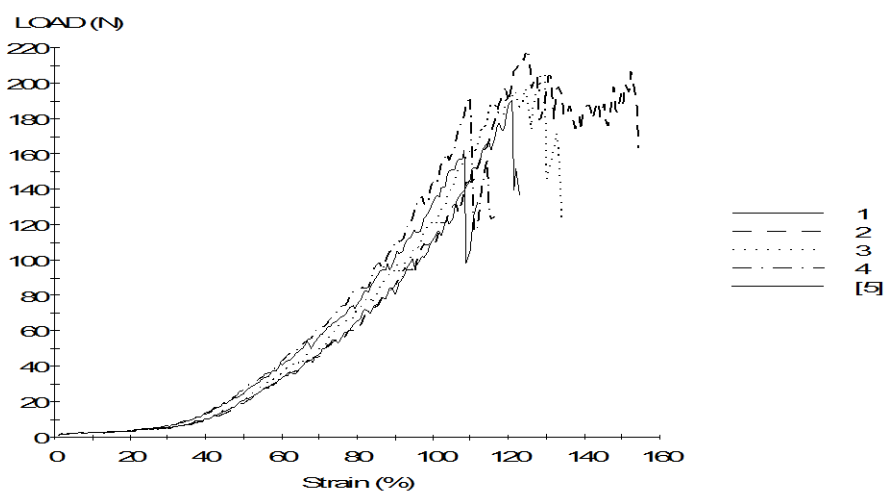
Specimen #	Peak Load lbf	Elong @ Pk Ld mm	%Strn @ Pk Ld %
1	42.7	92	120.9
2	48.8	95	124.8
3	46.1	99	129.4
4	43.2	84	109.7
5	36.5	83	108.4
Mean	43.5	90	118.6
Std. Dev.	4.6	7	9.3

Calculation Inputs:

Name	Value	Units
Gage Length 1	3.00	in

Test Inputs:

Name	Value	Units
Brk Sensitivity	50	%
Crosshead Speed	300.00	mm/min
Initial Speed	300.00	mm/min
Load Limit HI	1000	lbf



Repreve®

Sample ID: Zoe-P2R-Reprieve--Machine-9-24-20.mss Test Date: 9/24/2020
Method: FAB_STRIP_D5035_1000lb_Zoe_9-24-20.msmOperator: Teresa

Sample Information:

Name	Value
Client	Zoe-P2R
Date of Test	9-24-20
Grip Pressure	1600 psi
Info 1	Repreve
Jaw Face Size	2" x 3" serrated grips
Lab Conditions	70F, 65% RH
Test Direction	Machine

Specimen Results:

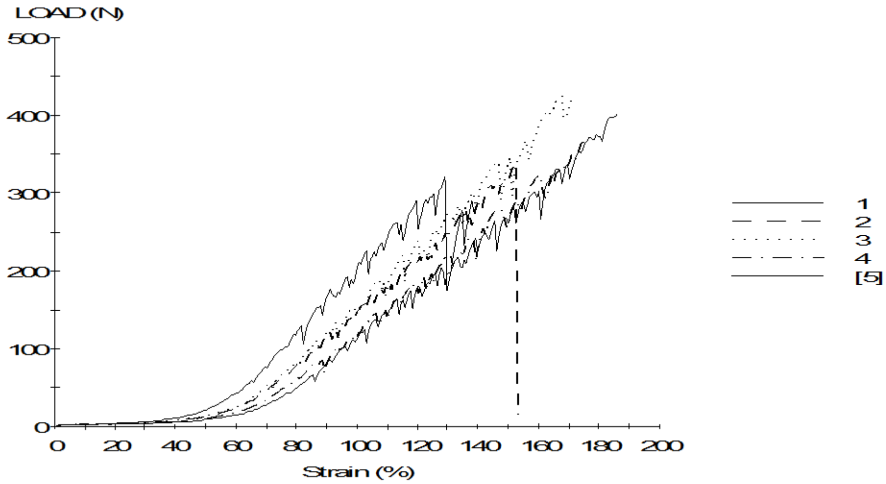
Specimen #	Peak Load lbf	Elong @ Pk Ld mm	%Strn @ Pk Ld %
1	72.3	99	129.4
2	76.2	116	152.4
3	95.5	128	167.5
4	83.3	134	175.3
5	90.2	142	185.8
Mean	83.5	123	162.1
Std. Dev.	9.6	17	22.0

Calculation Inputs:

Name	Value	Units
Gage Length 1	3.00	in

Test Inputs:

Name	Value	Units
Brk Sensitivity	50	%
Crosshead Speed	300.00	mm/min
Initial Speed	300.00	mm/min
Load Limit HI	1000	lbf



Style 3

100% Hemp

Sample ID:	Zoe-P3H-Hemp--Machine-9-24-20.mss	Test Date:	9/24/2020
Method:	FAB_STRIP_D5035_1000lb_Zoe_9-24-20.msm	Operator:	Teresa

Sample Information:

Name	Value
Client	Zoe-P3H
Date of Test	9-24-20
Grip Pressure	1600 psi
Info 1	Hemp
Jaw Face Size	2" x 3" serrated grips
Lab Conditions	70F, 65% RH
Test Direction	Machine

Specimen Results:

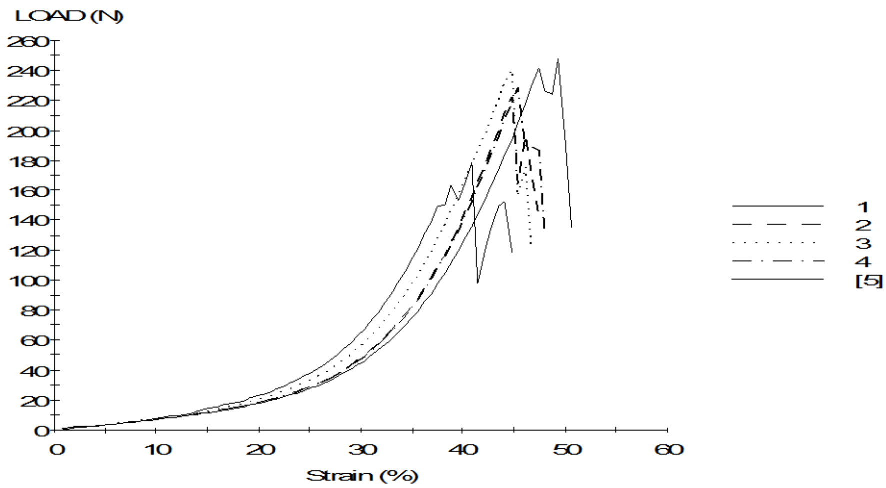
Specimen #	Peak Load lbf	Elong @ Pk Ld mm	%Strn @ Pk Ld %
1	40.1	31	40.8
2	50.1	34	44.7
3	54.0	34	44.7
4	51.5	35	45.4
5	55.6	38	49.3
Mean	50.3	34	45.0
Std. Dev.	6.1	2	3.0

Calculation Inputs:

Name	Value	Units
Gage Length 1	3.00	in

Test Inputs:

Name	Value	Units
Brk Sensitivity	50	%
Crosshead Speed	300.00	mm/min
Initial Speed	300.00	mm/min
Load Limit HI	1000	lbf



100% Cotton

Sample ID: Zoe-P3C-Cotton--Machine-9-24-20.mss Test Date: 9/24/2020
Method: FAB_STRIP_D5035_1000lb_Zoe_9-24-20.msmOperator: Teresa

Sample Information:

Name	Value
Client	Zoe-P3C
Date of Test	9-24-20
Grip Pressure	1600 psi
Info 1	Cotton
Jaw Face Size	2" x 3" serrated grips
Lab Conditions	70F, 65% RH
Test Direction	Machine

Specimen Results:

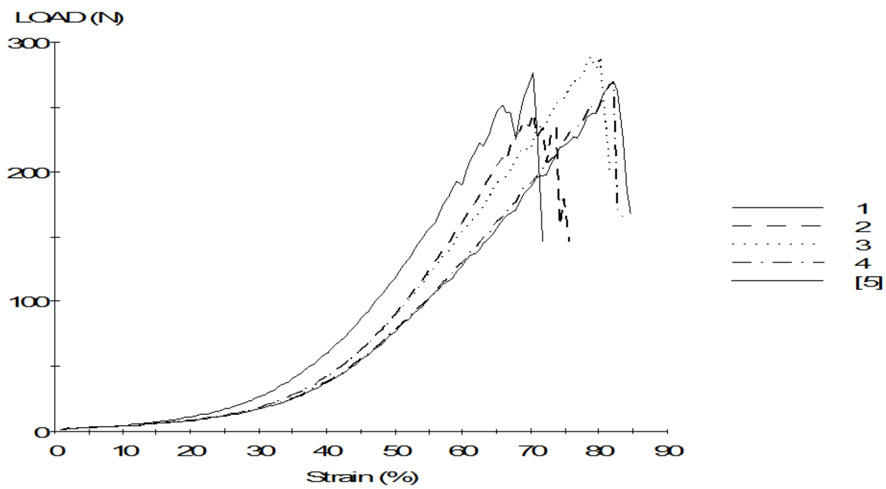
Specimen #	Peak Load lbf	Elong @ Pk Ld mm	%Strn @ Pk Ld %
1	62.1	54	70.3
2	55.3	54	70.3
3	64.9	61	80.2
4	60.7	63	82.1
5	60.5	63	82.1
Mean	60.7	59	77.0
Std. Dev.	3.5	5	6.2

Calculation Inputs:

Name	Value	Units
Gage Length 1	3.00	in

Test Inputs:

Name	Value	Units
Brk Sensitivity	50	%
Crosshead Speed	300.00	mm/min
Initial Speed	300.00	mm/min
Load Limit HI	1000	lbf



Repreve®

Sample ID: Zoe-P3R-Reprieve--Machine-9-24-20.mss Test Date: 9/24/2020
Method: FAB_STRIP_D5035_1000lb_Zoe_9-24-20.msmOperator: Teresa

Sample Information:

Name	Value
Client	Zoe-P3R
Date of Test	9-24-20
Grip Pressure	1600 psi
Info 1	Repreve
Jaw Face Size	2" x 3" serrated grips
Lab Conditions	70F, 65% RH
Test Direction	Machine
Type of Test	

Specimen Results:

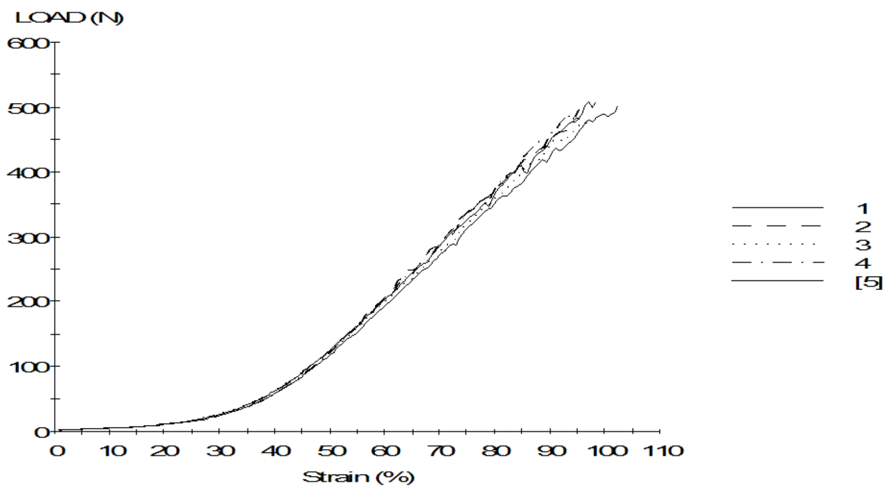
Specimen #	Peak Load lbf	Elong @ Pk Ld mm	%Strn @ Pk Ld %
1	114.4	75	98.5
2	108.9	73	95.3
3	108.8	75	97.9
4	113.3	73	95.9
5	112.6	78	102.5
Mean	111.6	75	98.0
Std. Dev.	2.6	2	2.8

Calculation Inputs:

Name	Value	Units
Gage Length 1	3.00	in

Test Inputs:

Name	Value	Units
Brk Sensitivity	50	%
Crosshead Speed	300.00	mm/min
Initial Speed	300.00	mm/min
Load Limit HI	1000	lbf


LOAD (N)
600
500
400
300
200
100
0
0 10 20 30 40 50 60 70 80 90 100 110
Strain (%)
1
2
3
4
[5]