ABSTRACT

REYNOLDS, KELSEY LAUREN. Wicking Capabilities of Athletic Textiles during Stretch. (Under the direction of Cynthia Istook).

Basic moisture management abilities play a large role in both the competition within athletic apparel manufacturing and performance requirements in athletic and technical clothing. This research aimed to investigate the relationship between garment stretch proportions and their effect on garment wicking capabilities. The production of sweat during exercise is necessary in order for the body to remove extreme heat and should be made possible through garment wicking. If the athlete is not able to wick away moisture during exercise, they become at risk for overheating which compromises performance. Adversely, well-designed athletic wear has the ability to enhance athletic performance and aid in the reduction of injury by way of various moisture management systems.

This research utilizes a test method where fabric wicking capabilities are tested under dynamic percentages of stretch, mimicking realistic garment stretch reductions for the athlete. According to previously existing AATCC Test Methods, wicking tests are conducted under static conditions of 0% stretch or elongation. However, every clothing manufacturer develops their own ratio of garment stretch reductions for body areas, which are unknown to the public and in turn make it nearly impossible to predict fabric performance. As a part of this research, the wicking ability of three athletic fabrics, consisting of commonly used fiber contents, were tested at 0%, 10% and 20% stretch. Results were used to observe the relationship between fabric stretch and wicking capabilities for each fabric. This testing

methodology measured moisture transfer in relation to dynamic stability of sizing ratio to stretch, and the effect of fabric stretch on fabric wicking capabilities.

Testing for this research was conducted using four sample fabrics of athletic fabrics; 1) 90/10 Polyester/Spandex, 32 gauge, 237.3 g/m2, Tricot with an antimicrobial/wicking finish, 2) 100% Polyester, 76 gauge, Plain Weave with no finish, and a 3) 65/35 Polyester/ Rayon, 145.77 g/m2, Jersey with a wicking finish. Knowledge gained through this research can aid in developing an industry wide benchmark method for mapping garment elongation during apparel production. Also, this research can be used for improving clothing moisture management systems, better accommodating the needs of athletes during athletic activity and perspiration.

Wicking Capabilities of Athletic Textiles during Stretch

by
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A thesis submitted to the Graduate Faculty of
North Carolina State University
in partial fulfillment of the
requirements for the degree of
Master of Science
Textile Technology

Raleigh, North Carolina

2015

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BIOGRAPHY

Kelsey Lauren Reynolds was born on April 24, 1991 to Mary and Ronald Reynolds in Hoover, Alabama. She spent her younger years living with her two parents, brother and sister, Kendra and Korey Reynolds. She attended South Shades Crest Elementary School and Bumpus Middle School before graduating from Hoover High School in May of 2009. In August of 2013, she graduated with a Bachelor's of Science in Apparel Merchandising, Design and Production Management from Auburn University. In the fall of 2013 she continued her education at North Carolina State University pursuing a Master's of Science in Textile Technology. She was selected as a graduate teaching assistant and lab manager for the Fashion Textile Design and Fashion Textile Management departments of NCSU. She will graduate with her Master's in May of 2016.

ACKNOWLEDGMENTS

I would like to express my most sincere gratitude to my research advisor, Cynthia Istook for her advice and guidance throughout the journey and process of my research. I would also like to thank Dr. Karla P. Teel, for her encouragement and support, aiding in my enrollment at NCSU and for empowering me to better myself. I would also like to thank the other members of my committee and former professors who have all helped me achieve my goals. I am also grateful for family and friends who have constantly supported me throughout this journey.

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CHAPTER ONE: INTRODUCTION

Moisture management is an important aspect in athletic clothing, enabling the body's ability for temperature regulation and influencing comfort level (Sampath & Senthilkumar, 2009). Thermal comfort and the production of sweat is the most important factor in athletic performance, allowing heat loss from the body and preventing overheating when wearing protective clothing (Smith & Havenith, 2010). During times of exercise in high temperatures environments, evaporation of sweat is the greatest avenue for heat loss from the body and the best for maintaining body temperature.

Moisture in clothing is largely acknowledged as one of the most influential factors contributing to discomfort and fatigue level when exercising (Tang et al., 2014). This supports the idea that during exercise, it is imperative for a clothing moisture management system to be in place in order to avoid drastic change in body temperature. In a study conducted by Galbraith et al. (1962), multiple garments were made from cotton, water-repellent cotton and acrylic fibers and were compared through wearer tests. It was discovered that majority of discomfort was due to the un-evaporated sweat remaining on the skin surface. For this reason, it is important to study the absorption ability of different fabrics and their planar wicking properties.

Sampath and Senthilkumar (2009) reported that water vapor and liquids are transmitted through textiles by diffusion through inter yarn spaces, capillary transfer through fiber bundles, and diffusion through individual fibers. In a garment during wear, water vapor is emitted into the air by passing through the air spaces between the garment and the body. To ensure the movement of moisture through that first textile layer, the garment must lie next to the skin. Form fitted athletic garments are produced from synthetic materials (polyester, nylon, etc.) and are designed to fit the body with no air gap between the skin and the garment under-surface. Absence of the air gap allows the garment material to be in constant contact with the skin and wick away moisture more efficiently.

Because we know moisture management is one of the most imperative qualities for performance and athletic clothing, it is also important to examine other characteristics of athletic garments, i.e. compression and its effect on garment wicking capabilities.

Rationale

One area within the performance apparel sector that has not yet been thoroughly researched is the effect that fabric stretch has on fabric wicking capabilities. Much research has been conducted on fabric wicking and drying capabilities along with known data existing on garment stretch reductions for compression and/or performance garments; however, few studies have combined the two components.

Combination of the two factors are seen to be valuable because of the important role moisture management has in athletic garments and their close-fitting character. During wear, the presence of moisture has been largely linked to discomfort, increasing friction between the fabric and the skin is linked to causing fatigue for the wearer. In a study conducted by Galbraith et al. (1962), the importance of absorption abilities of fabrics was identified as the only way to keep the body dry and provide thermal protection in harsh climates. The normal core temperature of a human should be kept at approximately 37 °C (98.6° F) in order to maintain thermal equilibrium. Thus, it can be concluded that heat transfer to/from the body is the most important ability sport and performance clothing should contain (Oglakcioglu et al., 2015). This can be achieved through thermoregulation along with engineered fiber and fabric selection for manufactured garments.

Considering that performance garments are composed of knitted or woven fabrics, exemplifying two or four way stretch, it is important to also consider the role that stretch has on the garments ability to manage body moisture and heat regulation. Fabrics of two and four-way stretch are suggested to be designed 10% smaller in both directions and rib knit fabrics are suggested to be designed 10% smaller for across measurements. While this theory is a great benchmark for how to design with high stretch materials, it is not an industry standard. The requirement for fibers of high elastic recovery in sport garments is known, but certain garment stretch reduction methodologies, specific to each manufacturer, have not been made available for public knowledge (Ziegert, 1988). We know performance garments are designed with built in stretch reductions, or more commonly known as a compressions factor. This factor is essential to be able to fulfill both comfort and performance needs, but to what degree, is not known. According to Ziegert (1988), most knitted sport garments have different course and whale capabilities; making any generalization of how fabrics will act under stress difficult to conclude.

The results of this study will lead to a better understanding of how fabric stretch affect the role of moisture management in athletic and performance garments. A new development of a flexible system applicable to all stretch fabrics and considering two-dimensional garment pattern systems for body contouring is needed. The need for this system led to the following study which explores the influence of fiber type, fabric construction, fabric modulus, and garment stretch reductions.

Research Question

The purpose of this research was to develop a benchmark method for mapping garment stretch reductions based on percent stretch and fiber type, optimizing moisture management abilities and performance for the athletic clothing industry. To guide this research, the following question was developed related to the impact of garment fit ratios, fiber type and fabric structure. The primary research question guiding this study is:

1. *Does stretch affect a fabric's ability to wick away moisture?*
2. *Can the results gathered by the previous research question help shape a benchmark method for the performance apparel market?*
3. *Can consideration of stretch percentage be implemented into garment construction and be used to improve a garments performance in moisture management?*

Limitations

This study was limited in the following ways:

The tested materials all exemplified some kind of chemical treatment for wicking and antimicrobial finishing. It is important to note that it is not known if the chemical treatments were applied to the fabric or the fiber. If the treatments are not uniform, results gathered can be considered inconclusive or unreliable. Fabrics with any type of performance enhancement finish, i.e. wicking and antimicrobial finishing, do not reflect genuine results of particular fiber type, fabric construction or capillary action.

Data for fabric elongation curves was obtained through use of ASTM Standard Test Method D5034-09, for Breaking Strength and Elongation of Textile Fabrics (Grab Test). This test is suggested for primarily woven fabrics and is not recommended for knitted fabrics having high stretch of more than 11%. Machinery specified for knitted fabrics only, i.e. Ball Burst Test, ASTM D3787-15 and TruBurst Test, ASTM D3786-06, could not meet all three fabrics' breaking points because of limited load potential.

A test method for surface tension utilizing pendant drop method was developed to evaluate the wicking capability of fabric that has not been developed into a standard, as of yet. Limited trials with this test method could also result in less accurate results.

Definition of Terms

Comfort: Interactions between the clothing relationship and the wearer, climate, physiological, and psychological variables (Parsons, 1993).

Conduction: The flow of heat through a medium to an object, which is in direct contact with it (Hepburn, 1998).

Convection: The exchange of heat between hot and cold objects by the physical transfer of heat via the liquid or gas with which the object is in contact (Hepburn, 1998).

Elastomer: Rubber like polymers that can be easily stretched to high extensions and which rapidly recover their original dimensions where the applied stress is released (Banks and Lybeck, 1998).

Evaporation: The conversion of a liquid or solid into a vapor (Tang et al., 2014).

Garment Stretch Ratios: The maximum percentage that a fabric will stretch and applied to a set of garment slopers when designing with knitted fabrics (Richardson, 2008).

Moisture Management: Key performance aspect in today's apparel industry. Defined as the ability of the garment to transport liquid away from the skin to the surface of the garment

Performance Clothing: Classification of clothing type consisting of both sportswear and protective clothing; having the required technical attributes to support needs of the wearer's circumstances.

Radiation: A method of heat transfer that can be defined as an exchange of thermal energy between objects depending on the temperature and the nature of the surface of the radiating object (Hepburn 1998).

Temperature Regulation: A part of the thermoregulation system in which the skin regulates body temperature.

Thermal Comfort: The condition of mind, which expresses satisfaction with the thermal environment (ASHRAE Standard 55-66, 1966).

Thermoregulation: Process that allows the human body to maintain its core internal temperature of roughly 37°C; a requirement for this is he maintenance of heat balance so that the heat lost by the body is equal to the heat produced (Yazdi & Sheikhzadeh, 2014).

Wetability: The initial behavior of a fabric, yarn, or fiber when brought into contact with the water (Ghali, et.al, 1994).

Wicking: The movement of water or liquid through fabrics and fibers (AATCC Test Method 197).

CHAPTER TWO: REVIEW OF LITERATURE

The Importance of Wicking in Sport Clothing

In the review of literature, the following eight topics of research and how they each influence wicking capabilities of athletic textiles during stretch will be reviewed; The Importance of Wicking in Sport Clothing, Thermoregulation, Fundamentals of Wicking, Fiber selection and Fabric Structure, Yarn Structure, Sizing Systems and Garment Stretch Reductions, Fabric Finishes, and Initial Modulus.

According to American Association of Textile Chemists and Colorists (2011), wicking is defined as the movement of water or liquids through fabric, by capillary action. It may be influenced by fiber content, fabric construction, mechanical or chemical processing or a combination of these. Moisture management systems can be seen in applications like sports and performance clothing, disposable materials, and medical products (Tang et al., 2014). The role of such moisture management systems, like liquid absorption and transportation properties, are crucial for necessary performance qualities. During wear, the presence of moisture has been largely linked to discomfort, increasing friction between the fabric and the skin and eventually causing fatigue for the wearer. In a study conducted by Galbraith et al. (1962) , the importance of absorption abilities of fabrics proved to be of great interest because of their influential role in cooling the body, keeping the body dry and providing thermal protection in harsh climates. The normal core temperature of a human should be kept at approximately 37 °C (98.6° F) in order to maintain thermal equilibrium. Thus, it can be concluded that heat transfer to/from the body is one of the most important capabilities sport and performance clothing should contain (Oglakcioglu et al, 2015).

Use of synthetic fibers in performance garments are a newer phenomenon. Because of this, knowledge of how the fibers will react to different testing parameters have been limited. Previous sports garments were created primarily with cotton or natural fibers, with hydrophilic characteristics. These fibers functional properties were limited by inherent liquid absorption. This absorption results in a heavier, wet garment, increasing the coefficient of friction, and could potentially affect athletic performance negatively (Berglund, 1988). Scientists have researched the role of synthetics fibers in performance garments and have discovered the adverse theory proves true; larger denier fibers with no absorptive properties have higher thermo-psychological comfort for athletes during performance (Legerska et al., 2013).

During normal conditions, perspiration is generated between the skin surface and garment layer, thus a steady state of body heat and moisture-vapor changes are maintained (Tang et al., 2014). This is achieved through dissipation of thermal energy; radiation, conduction, convection and evaporation (Liu et al., 2014). If perspiration cannot be dissipated quickly, or is of a high volume, the temperature of the microclimate between the wearer's skin and the garment rises and limits the evaporation of the moisture. This causes the body to then perspire more, attempting to disperse additional thermal energy. During cold conditions, the opposite is true. When additional moisture is trapped between the skin and garment layer, the garment's insulating abilities are reduced, leading to a decrease in body temperature (Ozdil et al., 2009).

Thermoregulation

The relationship between athletic thermoregulation and sweating has been a topic of great interest in the world of athletics and wicking. During thermoregulation, metabolic heat is produced within the body and distributed over various body regions by blood circulation. That heat is then carried to the body's surface where the heat is released by methods of convection, radiation and evaporation (Figure 1). The purpose of human thermoregulation is to maintain a constant body temperature and to avoid overheating or hypothermia . In order for this to be successful, the body must generate as much heat as the body is losing during activity (Yazdi & Sheikhzaded, 2014). The heat balance that the body must maintain can be represented through many different equations. However, all equations are comprised of the same three ideas; heat generation in the body, heat transfer, and heat storage. This balance can be affected by factors like air temperature, radiant temperature, humidity and air movement, metabolic heat and clothing worn by an individual. Over 75% of the energy dissipated through these energy releasing methods (convection, radiation and evaporation) is dissipated through evaporation through the skin of the body. As the skin is normally covered with clothing during physical activity, clothing can inhibit the level of thermal comfort. Clothing can act as a protective barrier to extreme conditions for the skin but can also obstruct the loss of excessive heat production during physical activity (Yazdi & Sheikhzaded, 2014). In normal clothing systems, the body may not be able to maintain a normal thermal balance; therefore the body should dissipate heat to alleviate stress and overheating. This supports the need for developments of clothing systems that can adjust and maintain comfort properties according to body temperature.

Sweat secretion is also a common tool to body uses to achieve thermoregulation. Secretion allows the heat that has been generated from the body to be released through evaporation. When paired with the wearing of clothing, sweat transmission depends on two main factors. The first, is the clothing being able to evaporate sweat from the skin's surface and the second is the removal of moisture (Öner et al., 2012). Clothing must include this capability of removing moisture to provide quick drying times after an athletic activity is finished. If produced sweat can not be removed from the body and it remains on the skin, the feeling of wetness or coldness will be possible because the skin's surface temperature will fall. Because sweat secretion has been proven through previous research to play a vital role in body heat loss (Öner et al., 2012), it is important to understand this concept. In an effort to define the relationship between sweating secretion and body temperature, many researchers have linked sweat secretion as a response to the interaction between the hypothalamus and skin temperature. There has been additional investigation on the input from the skin, but on occasion conflicting data results appear (Nadel et al., 1971). It is known that temperature plays an influential role in thermoregulation, but there are also other factors to take into consideration. Many have studied the variances in sweating responses between athletes and non-athletes and have found that an individual's level of physical fitness and cardiovascular health directly affects the body's ability to regulate a constant body temperature. In a study conducted by Yamauchi (1997), it was discovered that long-term physical training leads to improved circulatory heat transfer to the skin and to a more graded nervous control of sweat expulsion and tends to reduce the rate of sweating.

This research will not explore the physiological stimuli that cause the sweating response in individuals. However, it is important to this research to understand the factors influencing sweat secretion and their relation to wicking capabilities.

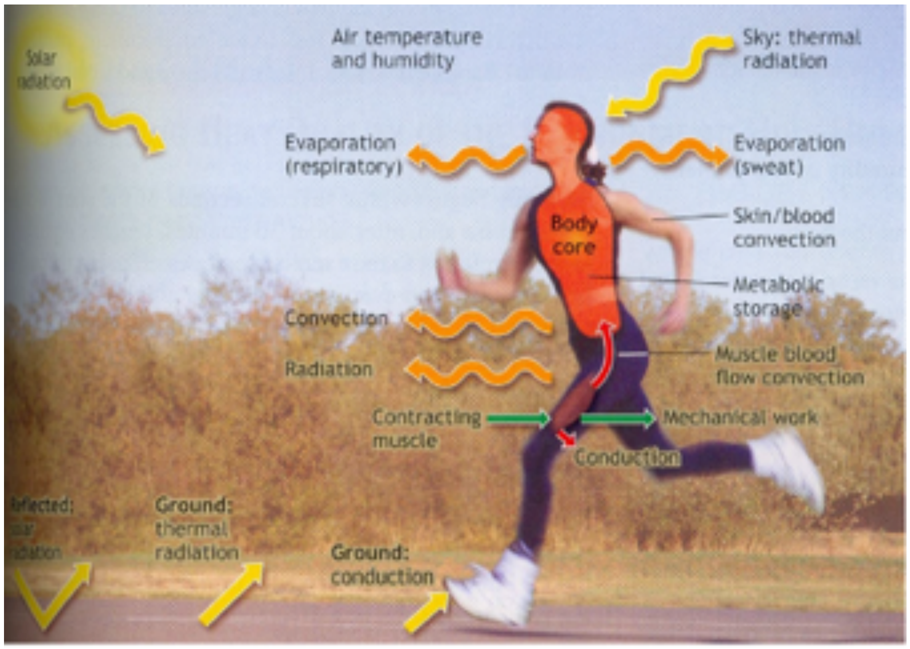


Figure 1: Thermoregulation (McArdle et al., 2001)

Fundamentals of Wicking

In sportswear, comfort level has been recognized as an important aspect of wearer comfort and can be affected by the amount of liquid the fabric is able to move away from the skin's surface and later evaporate into the external environment (Sampath et al., 2011). Thermal senses of comfort tell an individual about their internal and external thermal states, which are necessary to body temperature regulation (Li, 2005). Sense of comfort can be maintained by various moisture management properties in apparel and is dependent on many factors. This can be achieved through fabric construction or applying chemical finishes to a fabric (Sampath et al,. 2011). Higher absorption properties can be attributed by creating capillaries by using different deniers of fibers. A better capillary effect is achieved by the space between the yarns of the fabric being porous enough to breathe and wick away moisture at a faster rate.

Hsieh et al. (1996) reported that distribution of pore sizes is expected in all structures of fabrics including fibrous, woven, non-woven or knitted fabrics. The wicking rate and liquid transportation rate of a fabric depend of the size of the pores and their distribution throughout the fabric. Fangueiro et al.'s (2010) research stated that the wicking behavior of a fabric is determined by the capillary pore distribution and size in conjunction with surface tension. Pause (2001) explains that the movement of water vapor in fabric depends on the micro-porous structure of the material. According to Mecheels (1971), water vapor transmission properties of a fabric is the property of inter yarn pore air and can be varied by fiber type and composition.

Fiber Selection and Fabric Structure

Fiber type is an important factor to consider when evaluating wicking effect and thermal regulation. Selection of fibers can affect nearly every attribute of a final product when developing a sports garment (Legerska et al., 2013). These garments are highly engineered and can require characteristics like strength, durability, moisture management, thermoregulation and increased range of movement.

Wetting and wicking are properties that are of importance to many products like floor coverings, diapers, medical wipes and performance garments; however, each of these industries should have separate fiber selections appropriate for each end use. Form-fitted athletic garments require high levels of moisture transport, to keep the athlete dry and cool. In previous decades, cotton has been the fiber of choice for athletic apparel, but in the last 10 years, the market has drastically shifted. Demands for synthetic fibers have grown because of their excellent ability for moisture transport properties. Without these properties of moisture movement in athletic garments can cause the wearer's to have feelings of wetness and thermal discomfort.

Synthetic fibers have become in high demand because of their ability to be customized at the fiber level. Because the fibers are man-made, fiber cross-section modification possibilities become endless. This permits fabric manufacturers and designers to select fibers dependent on the requirements of garment end use, and allows for greater functional performance (Hatch et al., 1990).

In a study conducted by Li and Zang (Li et al., 2008) it was proven that Coolmax® double faced fabrics exhibit higher comfort properties to athletes and better heat-moisture sensation compared to natural fibers when tested using a MMT (moisture management test) and a Transplanar Water Transport Tester. Theses types of fibers have lower moisture management properties because of their curly fiber structure. The study concludes that,

> "yarn type had a significant effect on thermal characteristics. Among the five fabric types, it was observed that micro-denier polyester fabrics give faster heat transfer, quicker evaporation of sweat from the skin through the fabric, and cooler feeling at initial touch……..Tarakcioglu, et al. investigated the microclimate temperature changes depending on the fiber type used in woven structures at extremely hot

> climates. They concluded that the combination of channeled and hollow polyester fibers provided lower temperature/time curve slopes, thus higher protection capability." (Oglakcioglu et al., 2015, p. 33)

Oglakcioglu's study shows the importance of using synthetic fibers vs. natural fibers, in order to achieve desired technical attributes in performance clothing.

Manipulation of fiber cross-sections allow for increased functionality in fabrics and can be comprised of bicomponent fibers, filament, and staple fibers (Williams, 2009). Each cross section type has inherent qualities that contribute to moisture transport, rigidity and luster. Hollow cross sections are usually round in shape, but are not strictly confined to that shape. They have higher specific surface areas, higher thermal insulation properties and increased rigidity properties. Hollow fiber cross sections are not as well known as other modified cross sections and are not as effective for moisture transport when in comparison. Tri-lobal cross sections are known for attributing characteristics of high levels of resilience and rigidity. The increased surface area of these fibers increases the luster of fabrics. Ribbon cross-sections have even larger flat surfaces that give off high amount of luster. The surfaces of ribbon fibers have a directional bending bias and can be used to alter the bending rigidity of the desired fabric. 4DG™, or deep-grooved fiber (www.fitfibers.com), cross sections are one of the most modified cross sections for fibers, with the primary intent of improved moisture transport capabilities. The modification to this fiber cross section improves capillary action by providing increased surface area in its deep grooves where moisture can be removed. Levels of thermal insulation are also high for 4DG™ cross sections. Figure 2 shows an example of the modified fiber cross sections detailed in this section of research.

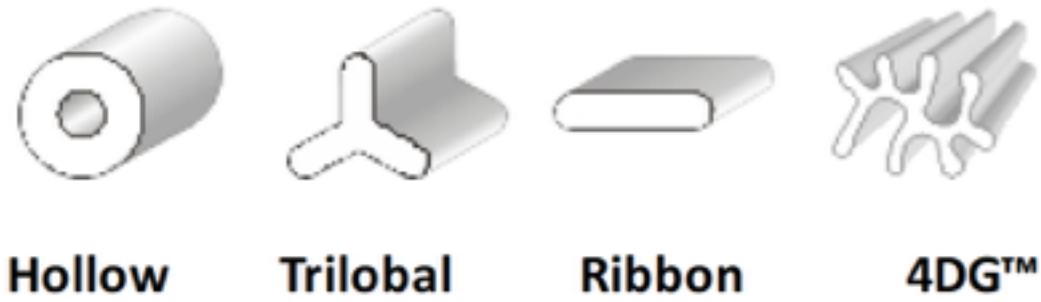


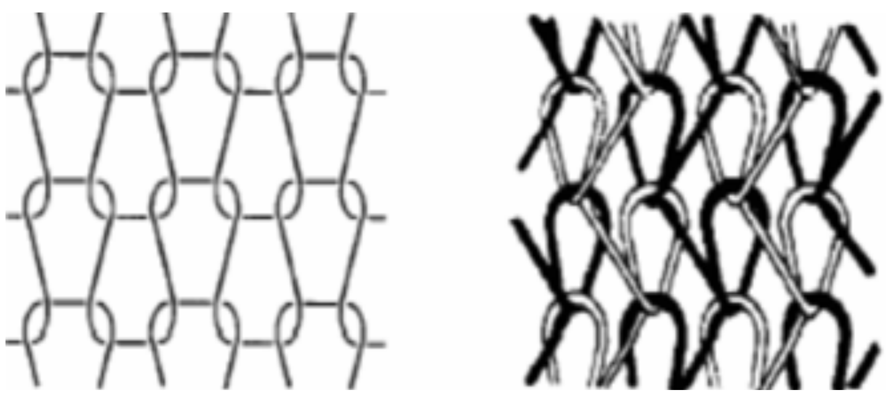
Figure 2: Fiber Cross-Sections (www.fitfibers.com)

There are more options than ever before because of fabric design through fiber selection and content that allow for performance garments that satisfy particular end uses. Garments can also be designed to satisfy specific comfort needs by way of zone placement, embellishment and fabric reinforcement. These features are achieved through focused garment construction and are key factors in providing wearer stimuli to comfort perception.

Fabric Structure

Weaving and knitting are the two most popular methods for fabric production. In weaving, two sets of yarns called the warp and the filling, or weft, are continuously interlaced to form interlocked sections to form the fabric. The warp yarns are the lengthwise yarns and the crosswise yarns are the filling or weft yarns. Fabrics made from weaving generally exhibit low elasticity and high strength, most commonly for furnishings and industrial products. Woven fabrics also are more likely to ravel and fray (Horrocks, 2000).

Knitted fabrics are formed by series of yarn loops producing fabrics that are more flexible and have less stable structures. The most common form of knitted fabric utilized in sportswear garments is single-jersey knitted fabrics, because they are the most cost effective to produce. Knitted fabrics are the preferred structures in athletic wear because of their higher qualities of comfort. They possess high extensibility under low load allowing comfortable fit. Use of knitted structures also allow for a tight fit close to the skin triggering tactile, thermal and moisture related sensations. The process of transferring heat and moisture away from the skin determines the level of comfort to the wearer; porosity is one of the key properties involved in knitted structures influencing such behavior. Pore volume plays an important role in determining the amount of air trapped in a material or the amount of fluid the knitted structure can hold (Karaguzel, 2004). Pore size is also a factor that determines the rate at which liquids are taken in by porous materials, i.e. knitted fabrics. Figures 3 and 4 show the structural differences in knit and woven fabrics.



Weft Knit   Warp Knit

Figure 3: Technical View of Weft and Warp Knit Structure (Karaguzel, 2004)

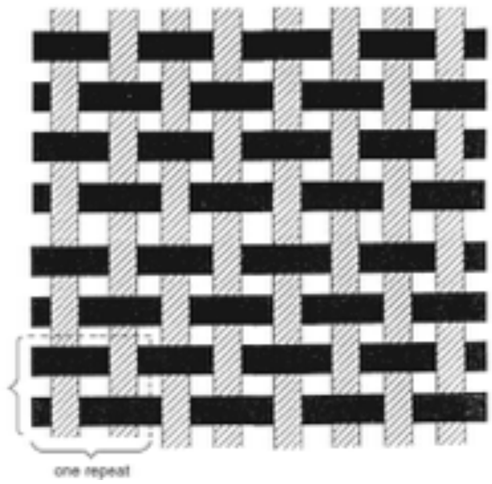


Figure 4: Technical View of Plain Weave (Horrocks, 2000)

Yarn Structure

Differences of yarn structure for various spinning processes are reflected in visual appearance or internal and external technical attributes. Usage of different machines, various spinning processes, diverse machines, twist levels and directions can all affect and attribute differing yarn structures (Li, 2015). These structures, i.e. open or closed; voluminous or compact; smooth or rough or hairy; not only effect the appearance of the yarn, but also contribute to differences in technical properties like wicking, yarn strength, wearing comfort, resistance to abrasion, etc (Table 1). The table below lists the differences attributed to yarn structure from various spinning processes.

Table 1: Difference in yarn structure from the spinning processes (rieters.com)

	Ring-spun Yarn		Open-End Yarn		Airjet Yarn	
	classic	compact	rotor spun	friction spun	jet spun, two nozzles, false twist process	vortex spun, one nozzle
Fiber disposition:						
in the core	parallel, helical	parallel, helical	less parallel, helical	less parallel, helical	parallel without twist	parallel without twist
in the sheath	parallel, helical	parallel, helical	more random, less twisted	less parallel, helical	6% of fibers twisted around core in spirals	20% of fibers twisted around core in spirals
Fiber orientation:						
parallelism:	good	very good	medium	low	medium	good
compactness:	compact	very compact, round	open	compact to open	compact	compact
handle:	soft	soft	hard	hard	hard	medium to hard
hairiness:	noticeable	low	very low	low	some	low to medium
stiffness:	low	low	high	high	high	fairly high

In a study conducted by Erdumlu et al. (2013), the vertical wicking abilities of ring-spun and vortex-spun yarns were compared. These yarns differed in yarn counts (30Nc, 40Ne, 50Ne) and resulted in differences of various heights in vertical wicking tests. The vortex-spun yarns consistently showed lower heights of wicking than the ring-spun samples for each yarn count. According to Patnaik et al. (2006), the consistent results in this study could be a result of an optimum capillary size that will cause fastest entry of water or liquid into the pores of the yarn. Both smaller and larger optimum pores slow down the entry due to low capillary pressure. Therefore, the vortex-spun yarn having a lower fiber-packing density value at both the center and the surface of the yarn might have resulted in lower wicking height in the vortex yarns. Another possible reason for this result may be a result of the tight wrappings along the yarn length in vortex-spun yarns. Ring yarn has a more regular structure along the yarn length, but the crimped yarn axis and tight wrappings in vortex yarn can be attributed to the prevention or retardation of wicking.

Perwuelz *et al.* (2001), also conducted research investigating the role of yarn twist on fabric wicking. The work showed that when the twist of the yarn increases, the yarn heterogeneity decreases, which is indicated by a narrower distribution of capillary diffusion (Li, 2015). Lucas-Washburn created an equation, $h2= D* t$, D being the diffusion coefficient and decreasing with the increasing of twist. This result is consistent with many other individual's work including Nyoni *et al.*'s (2006) and Liu *et al.*'s *(2008)* where the wicking length in a given time and the twist are in inverse proportion.

Ring Spinning

Ring spinning is one of the oldest and most utilized methods of yarn spinning used in the textile industry today. It is also the slowest and most expensive method due to its needed additional processes, i.e. roving and winding (cottonguide.org). Ring spinning also produces the strongest, finest and most soft yarn in comparison to other methods. The image below shows a SEM image of the helix angle of twist responsible for holding the fibers together in a ring spun yarn.

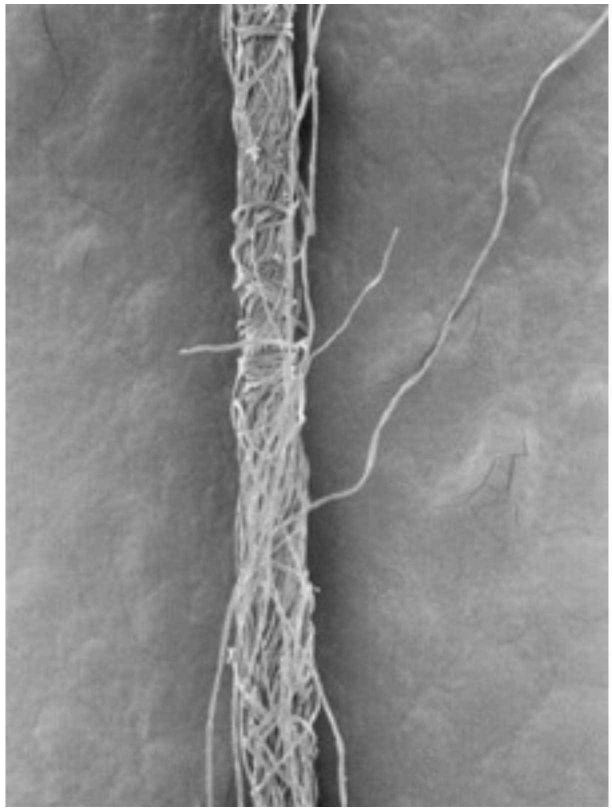
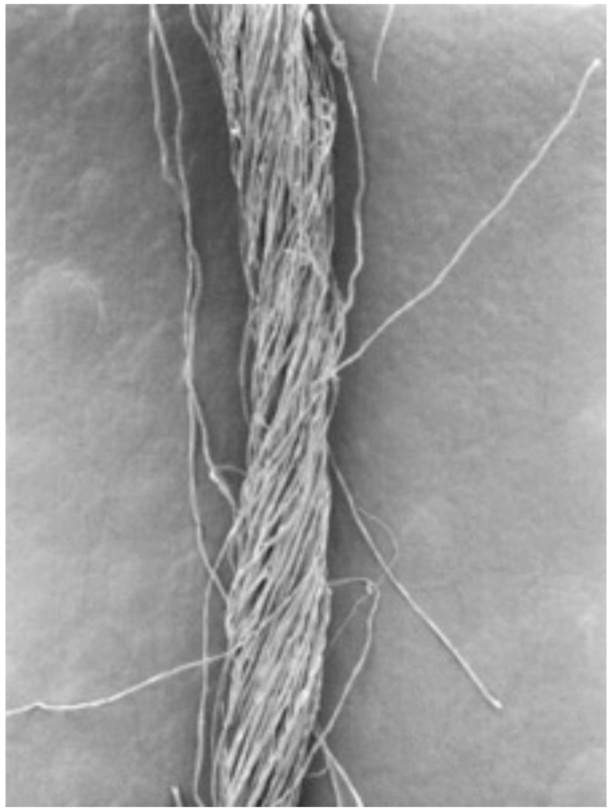


Figure 5: Ring Spun Yarn (cottonguide.org)

Open End Spinning

Open end spinning has a high production capability and as a result, also has a low cost due to this high production rate. This process is able to achieve a higher production rate and a low cost because of the elimination of processing steps. Open end spinning produces a weaker yarn than ring spinning and produces a yarn that is more dry, or harsher in hand when compared to other spinning processes. When looking at the SEM image below of a yarn



produced through open end spinning, the difference in yarn structure is very evident. Particularly, the wrapper fibers are perpendicular to the yarn form.

Figure 6: Open End Yarn (cottonguide.org)

Air Jet Spinning

Air jet spinning has a high production capability and a low cost due to its high production rate and the elimination of processing steps. This process inserts twist into a yarn by means of a rotating vortex of compressed air. This spinning method produces yarns that are weaker than ring spinning and has a limited range of yarn counts. In the SEM image below, the vortex yarn shows a high level of similarity to the ring yarn structure. It is important to note that as the yarn count gets finer, the yarn strength improves over open-end spun yarns of the same count. Vortex yarn is more appropriate for medium to fine yarn counts, and the softness from yarns spun by way of vortex spinning methods are similar to open end and ring spun fabrics.

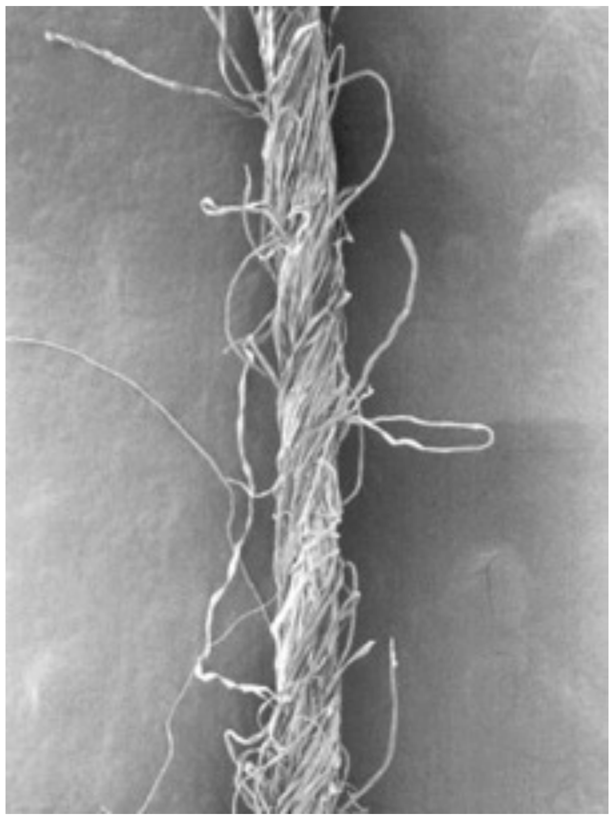


Figure 7: Vortex Yarn (cottonguide.org)

Sizing Systems and Garment Stretch Reductions

The use of knitted elastomers in athletic garments is important to achieve a close fit to the body, stretch-ability and comfort. Close fit eliminates limitation of movement for the wearer and can also aid in comfort enhancement. In woven fabric garment construction, built-in ease is necessary for allowing movement of the wearer. In order to achieve this, garments are designed with a positive ease percentage. Contrary to woven garment design, stretch garments are constructed by using patterns that are cut for smaller dimensions than the actual body measurements (Watkins, 2011). In Richardson's (2008) *Design and Patternmaking for Stretch Fabrics*, fabrics of two and four-way stretch are suggested to be designed 10% smaller in both directions and rib knit fabrics are suggested to be designed 10% smaller for across measurements (Figure 8). While this theory is a great benchmark for how to design with high stretch materials, it is not an industry standard. The demand for fibers of high elongation and high elastic recovery in sport garments is known, but certain garment stretch reduction methodologies, specific to each manufacturer, have not been made available for public knowledge.

Body sizing systems aid manufacturers and designers in how to design for specific end uses depending on desired performance qualities and style. Systems are derived from anthropometric data of the targeted customer population. Measurements that are similar and most relevant to the garment construction are first gathered together, and divided into groups by size intervals so that the members of each size group exhibit similar dimensions. This type of classification of measurements is used to help develop block patterns which serves as the starting pattern when developing a garment pattern. Conventional pattern profiles for stretch fabrics have been developed by modifying the ease allowance and removing darts of woven fabric block patterns (Watkins, 2011). After the pattern has been adjusted in terms of ease and the darts have been removed, the curves are trued and the profile is reduced horizontally and vertically to accommodate a fabric stretch percentage. Watkins (2011) reports that the stretch percentage used for reducing the pattern profile is very subjective and is assigned according to the individual designer. Another approach for producing a pattern that accommodates stretch fabrics is to model the fabric directly onto a dress form. This method is also very subjective and has many areas for error because it is difficult to identify how much force is necessary to achieve the pattern design. Some apparel manufactures simply use smaller sized pattern blocks with the assumption that the garment will stretch in the correct places that will offer and acceptable fit.

According to Richardson (2008), most companies and manufacturers follow traditional methods of sizing including the proportional method, the ray method, and the group method. The proportional method is reported to be most commonly used, where intervals from the body-sizing table are applied to the construction points of a single pattern (Figure 8).

Most sizing systems used in the designing of stretch fabrics are dates back to the 1960's (Watkins, 2011). Pratt and West (2008) suggest a mathematic formula for pattern drafting of with stretch fabrics. In their method, all circumferential measurements are reduced by 20% and length measurements are reduced typically by 20-25% of their total length. They continue to state that applying the formula is not straightforward and needs subjective adjustment based on the chosen fabric and its stretch capabilities.

	Stable knit	Moderate knit	Stretchy	Super-stretch	Two- & Four-way stretch	Rib knit
	0–25% stretch	25–50% stretch	50–75% stretch	75–100% stretch	100% in both directions	over 100% stretch
Reduction for stretch	0% smaller for across measurements	2% smaller for across measurements	3.5% smaller for across measurements	5% smaller for across measurements	10% smaller both directions	10% smaller for across measurements
Multiply your measurement by	*0	*.98	*.96.5	*.95	*.90	*.90 in both directions
Skirt	Yes	Yes	Yes	Yes	Same as super-stretch	Yes
Pant	Yes	Yes	Yes	Yes	Same as super-stretch	Yes
Top	Yes	Yes	Yes	Yes	Same as super-stretch	Yes
Dresses	Yes	Yes	Yes	Yes	Same as super-stretch	Yes
Oversized top	Yes	Yes	Yes	Yes	Yes	Yes
Catsuits	N/A	N/A	N/A	N/A	Yes	N/A
Leotard	N/A	N/A	N/A	N/A	Yes	N/A
Bikini	N/A	N/A	N/A	N/A	Yes	N/A

Figure 8: Professional Sloper Reductions (Richardson, 2008)

Garment Stretch Reductions

The ability to predict how closely stretch fabric should conform to the body is vital in stretch garments and is a known contributing factor for optimum performance and comfort levels (Watkins, 2011). Harada (1982) explored the relationship between the degree of skin stretch and the degree of fabric stretch along with the proximity of the garment to the body. Harada utilized Laplace's law ($P=T/\rho$), where P is the pressure exerted on the body, T is the tension of the fabric, and ρ is the radius of the curved body surface. It is important to note that the T value is dependent upon stretch parameters of the fabric used. If the degree of fabric stretch is maintained at a constant level, the tension in the fabric will remain constant. Therefore, Harada (1982) proved that a key variable affecting the pressure of the fabric exerted on the body is the radius of the body part being covered. The smaller the curve, the higher the exerted pressure is. Taking this principle into consideration, demonstrates that the amount of pressure applied along the leg, or a similarly shaped body part, would not be linear. Sections with smaller radii values (e.g. ankles and wrists) require less reduction in the fabric to achieve the same garment-to-body pressure (Watkins, 2011).

Stretch fabrics are being used across a wide spectrum of clothing applications such as fashion, sportswear, intimate bodywear, medical and functional garments (Watkins, 2011). The most comprehensible application of fabric stretch is seen in manufacturing pressure garments for medical and performance conditions. These fabrics exert pressure over specific body parts and can aid in medical conditions like venous and lymphatic disorders, scar management, and bone and muscle injuries (Chattopadhyay, et al. 2012). The amount of therapeutic pressure exerted by these garments vary depending upon the purpose of the end use garment. Therefore, the properties of engineered stretch within garments must match the requirements of each specific case. Research conducted by Chattopadhyay et al. (2011), investigates the influence of compression garments and their ability to substantially change performance properties is known.

In Chattopadhyay et al.'s (2011) report, Macintyre & Baird (2004) and Yildiz (2007), state that the prescribed amount of pressure in garments required for different medical conditions may vary depending on the patient's requirements. This pressure may need to be more or less than the normal capillary pressure of blood vessels (~25 mmHg). As reported by Liu *et al.* (2008) and Partsch (2005), prescribed amounts of pressure are as follows: light pressure (10-14 mmHg), moderate pressure (18.4-21.2 mmHg), firm pressure (25.1-32.1 mmHg), and strong pressure (36.4-46.5 mmHg). Light pressure is known for relieving pain and fatigue in the legs. In the case of heavily fatigued body parts, or swelling, moderate pressure is needed in garments. Firm pressure could be used in cases like post-traumatic edema, mild lymphedema, and curing moderate varicosities (Chattopadhyay *et al.,* 2012). Strong pressure is applied to control cases of severe venous disease, severe post-traumatic and post-fracture edema, severe edema and leg ulcers, etc.

Pressure garments are manufactured as single seamless tubes and can be warp-knitted as well as weft-knitted fabrics with elastic inlay yarns to provide the required pressure and grip over the body. Exertion of pressure is achieved by manufacturing the garment's circumference smaller than the body circumference so that the inlay yarns stretch and remain under tension while the garment is on the body (Macintyre, 2007; Macintyre & Baird, 2004). The properties of the inlay yarn is a factor in controlling desired pressure, because of their ability to generate radial inward force as they pass over curvature on the body. Size of the garment is also an influential factor for controlling garment pressure.

Two factors are responsible for determining the amount of pressure a garment exerts on a cylindrical body. The first factor is the extension behavior of the fabric used to make up the garment; the second is the reduction factor (RF). Laplace's Law provides the equation for pressure *(P)* exerted on the body:

$$P = \frac{T}{r}$$

where *T* is the tension generated in the fabric and r is the radius of curvature of the cylinder in meters (Chattopadhyay et al., 2012).

Size of the garment is another factor that can determine pressure exertion (Chattopadhyay et al., 2012). Petrova & Ashdown, (2012) report that specific garment dimensions are difficult to define since each group of garments have dimensions particular to the style for which the garment is made. This is also known as the proximal fit, which according to Watkins (2011) can be defined as "the proximity of the garment to the body on a proximal distal fit continue with the body contour as the zero proximal reference point" (p. 374). The term, proximal fit, is also used as a descriptive tool to describe body-contouring garments made from stretch knit fabrics (Watkins, 2011). The amount of negative proximal fit in pattern contouring is in direct relationship with the fabric's ability to exert force on the body, through its modulus or compressive retracting ability. Proximal fit attributes are exemplified in categories of Form Fit, Cling Fit, Action Fit, and Power Fit. Watkins (2011) classifies sport clothing as most commonly belonging to the headings of Action Fit garments, "where the retracting stretch effectively grips the body" (p. 374), or Power Fit garments, "refers to the garment as a whole or to specific areas where the force exerted by the stretch holds and compresses the flesh, changing the body form shape" (p. 374)… These fit classifications support the idea that sport and performance clothing is designed with some kind of built in compression, essential to provide both comfort and performance needs, but to what degree, is not known. It is also important to consider that most knitted sport garments have different course and whale capabilities which aid in producing different stretch characteristics and memory. This makes any generalization of how fabrics will act under stress difficult to conclude (Ziegert et al, 1988).

Fabric Finishes

Before the rise of the chemical industry in the 19th Century, textile companies were very dependent upon mechanical finishing to successfully modify the hand and appearance of textile fabrics. Initially developed for woven fabrics, mechanical finishing became popular to treat warp and weft knitted fabrics in the 20th Century (Holme, 2013). Most mechanical finishing machines were developed to apply only a particular finish, but by the 1970's, manufacturers recognized the growing need for singular machines with the ability to produce various finishes.

Finishes are applied to fabrics for varieties of reasons such as improving flame retardance, or wash and wear qualities. It is also important to recognize that fabric finishes should not negatively effect particular qualities of the finished product like abrasion resistance, comfort or moisture transportation (Chandler & Zeronian, 1979). Fabric finishes are a relatively simple way to make fibers more attractive to consumers and producers and should be considered when working with synthetic fibers.

In performance applications, the use of synthetic fibers create an inherent disadvantage because of their inability to move moisture away from the body. When sweat is produced, it is trapped between the skin and the garment layer causing the wearer to feel hot and potentially overheat. A common example of popular synthetics used in sports garments is polyester. Untreated polyester has natural hydrophobic characteristics, poor soil releasing abilities, and picks up soils from wash water when laundering (American Dyestuff Reporter, 1982). A study conducted by the *American Dyestuff Reporter*, compared wicking, release of oil, soil redeposition, static properties and handle between untreated polyester and treated polyester (Table 2).

Table 2: Comparison of treated and Un-treated Polyester (American Dyestuff Reporter)

Note: Taken from American Dyestuff Reporter

	Untreated	Milease T treated
Wicking (moisture transport	Poor — relatively nonabsorbent	Excellent — readily transports moisture
Release of oily stains	Poor — permanently stained in many cases	Excellent — release most stains in one low temperature wash
Soil redeposition properties	Poor — after 5-10 washes, generally greying is noted	Excellent — resists soil pick-up
Static properties	Poor	Good
Handle	Varies	Always softer to feel than untreated

To improve a fabric's performance characteristics, finishing agents are often applied to the untreated fabric. When treatments are applied to raw fabrics, wicking abilities, durability, hand and static protection improve. Improvement of fabric qualities are demonstrated by application of Milease3 T to polyester fabric. Table 2 (American Dyestuff Reporter, 1982) records the release improvement of stains like motor oil, grass stains and lipstick.

Initial Modulus

Initial modulus of a fabric is a method for measuring fabric strain and indicates how easily the fiber or fabric extends under stress. The first segment of a stress strain curve is a straight line (Figure 9), which indicates the stress is proportional to strain. The slope of the particular section of the line provides the measurement for the fabric or fiber's initial modulus, also called Young's modulus. When the initial modulus segment of the curve rises steeply, a large increase in stress produces a small increase in strain. As the slope decreases and the line becomes more horizontal, the initial modulus of the fiber or fabric becomes lower (Barker, et.al 2000).

Consideration of these details tells us that fibers with low initial modulus are easier to elongate than those with a higher modulus. This means a slight force on a fiber or fabric with low modulus will result in a substantial amount of lengthening. Adversely, a large amount of force must be applied to a fabric or fiber with a high initial modulus in order to result in small amounts of extension (Barker, et.al 2000). Barker and Hamouda give the example in their research of various textile applications needing distinctive characteristics of stretch. In a market like women's hosiery, the fibers need to be able to extend under low stress. In other applications, it is desirable for a fiber or fabric to be able to resist lengthening under small stress. It is also important to note that fibers do not experience slippage during the initial modulus segment of the stress-strain curve (Figure 9).

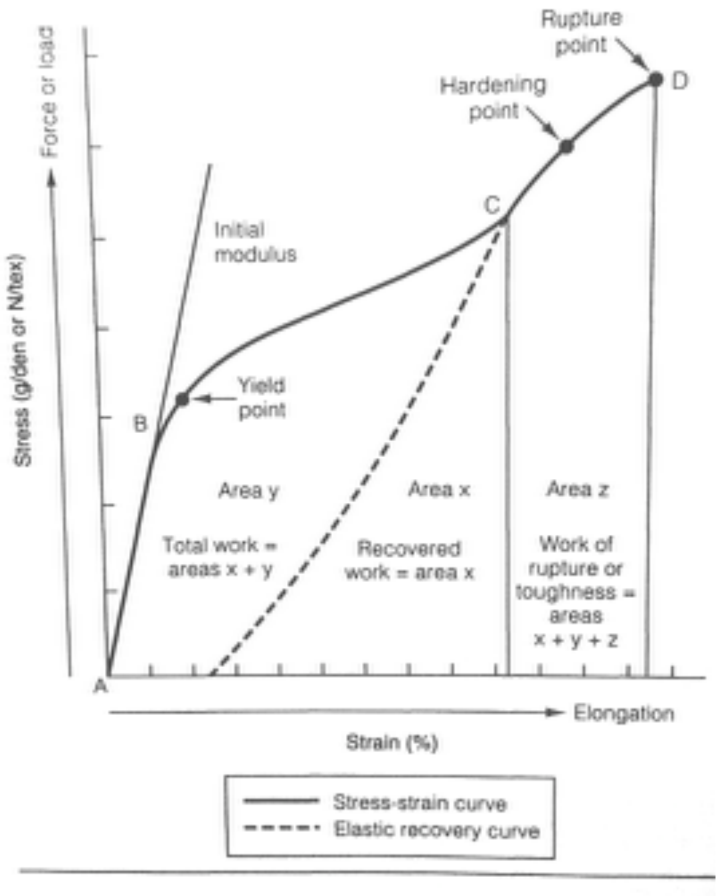


Figure 9: Stress-strain and elastic recovery curves (Barker, et.al 2000)

CHAPTER THREE: METHODOLOGY

In this thesis research, influence of fabric stretch on wicking properties during dynamic situations will be investigated. To accomplish this, several factors need to be researched such as fabric preparation, ASTM Methods, experimental set-up and image processing. The fabrics prepared for these experiments have different structures, exhibit chemical treatments to improve wicking capabilities and/or antimicrobial characteristics, and were chosen based on observations of materials commonly used by athletic and performance textile companies. The fabric samples were tested under 0%, 10% and 20% stretch, 5 times, each on a different fabric sample. These percentage values reflect a neutral state 0%, the maximum stretch according to Richardson (2008) 10% (Figure 8), and a value over the maximum stretch percentage 20%. The liquid drop was consistent for every sample being released at a height of 1 cm and had a volume of 50μL. The liquid shape and size was measured and analyzed using image processing software. In this chapter, the experimental design will be described including the materials used during testing, setup of the equipment, measurement methods and image analysis method.

Fabric Preparation

All fabrics used in the experiments described below were polyester blend performance fabrics provided by Under Armour®. Details of the wicking and antimicrobial finished are not known. Provided fabric details for the samples are as follows:

Fabric 1. 90/10 Polyester/Spandex, 32 gauge, 237.3 g/m2, Tricot with an antimicrobial/wicking finish

Fabric 2. 100% Polyester, 76 gauge, Plain Weave with no finish

Fabric 3. 65/35 Polyester/Rayon, 145.77 g/m2, Jersey with a wicking finish

Figure 10: Close-up Image of Fabric 1

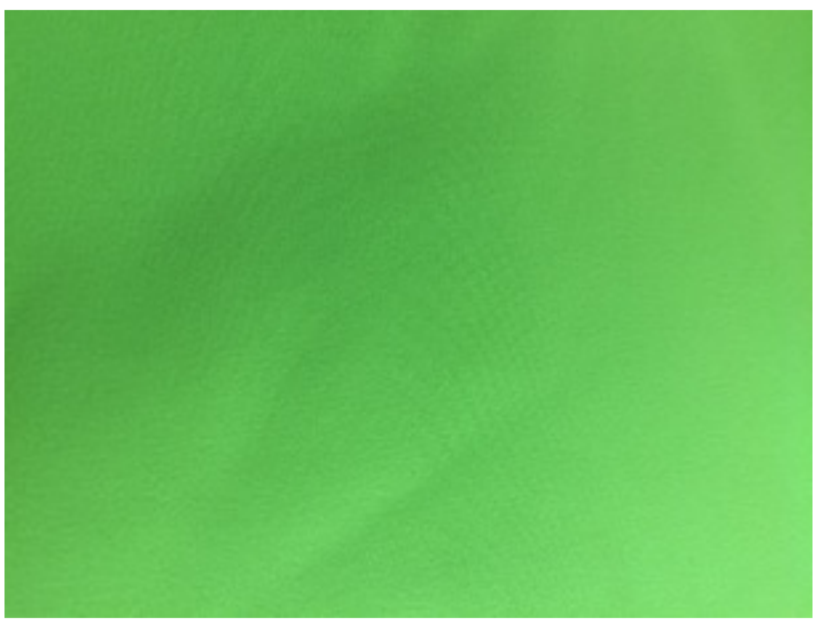


Figure 11: Close-up Image of Fabric 2

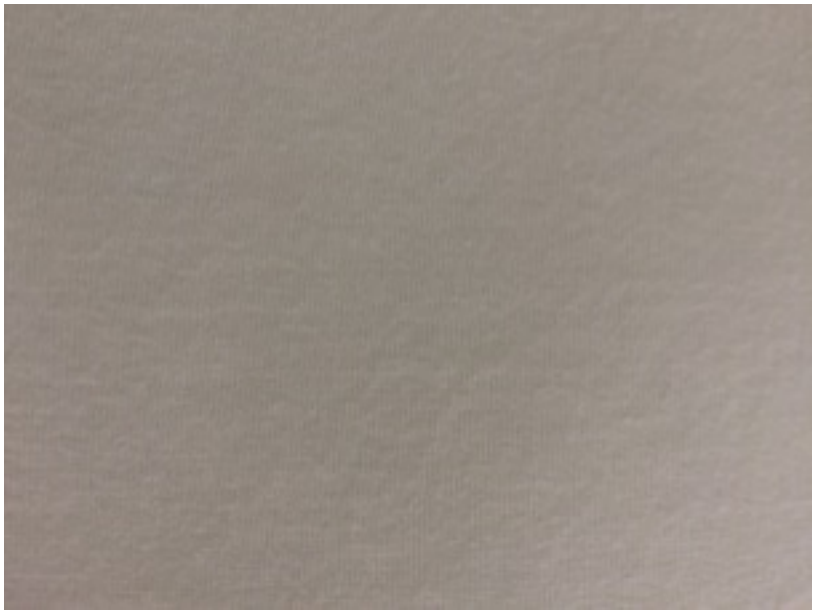


Figure 12: Close-up Image of Fabric 3

ASTM Test Method D5035-11

Test method D5035-11, Standard Test Method for Breaking Force and Elongation of Textile Fabrics (Strip Method), is a test method used for determining the breaking strength and elongation of most textile fabrics. This test is modifiable by means of utilizing the raveled strip test or the cut strip test. The raveled strip test is mainly applicable to woven fabrics while the cut strip test is recommended for nonwoven fabrics, felted fabrics and dipped or coated fabrics. It is not recommended to test knitted fabrics or other textile fabrics that have stretch higher than 11%. Results from this test method provide values in both inch-pound units and SI units (ASTM Test Method D5035-11).

Fabric used in this test was placed in the Physical Testing Lab twenty-four hours in advance to testing in order to allow for conditioning at the standard temperature and percentage of relative humidity; 70° Fahrenheit and 65% Relative Humidity. The three selected fabrics were tested five times each, both in the warp direction and the filling direction. Each sample was prepared according to the ASTM standards, being 25 ± 1mm (1± 0.02 in.) wide by 150 mm (6 in.) long with the long dimension parallel to the direction of testing and force application.

In this study, fabric elongation curves were obtained by using the MTS Q-test tensile tester (Figure 13). The ~1 in. x ~6 in. fabric sample was placed centrally in 1" x 3" jaw faces with equal length of 0.5" of fabric extending beyond the jaw at each end (Figure 13). The tension was uniform across the clamp width for the specimen. Because these fabric samples are considered to be high strength, rubber jaw padding was also used to ensure no slippage or breaks at the end of the jaws (Figure 14). The grip pressure for all three samples was set at 80 psi. Force was then applied until there was a break in the fabric sample. Figure 14 shows a close-up view of a fabric sample correctly set between the jaws of the Q Test™/5 (testing machine) before force is exerted and Figure 15 is the fabric sample after breakage and returned to a neutral state.

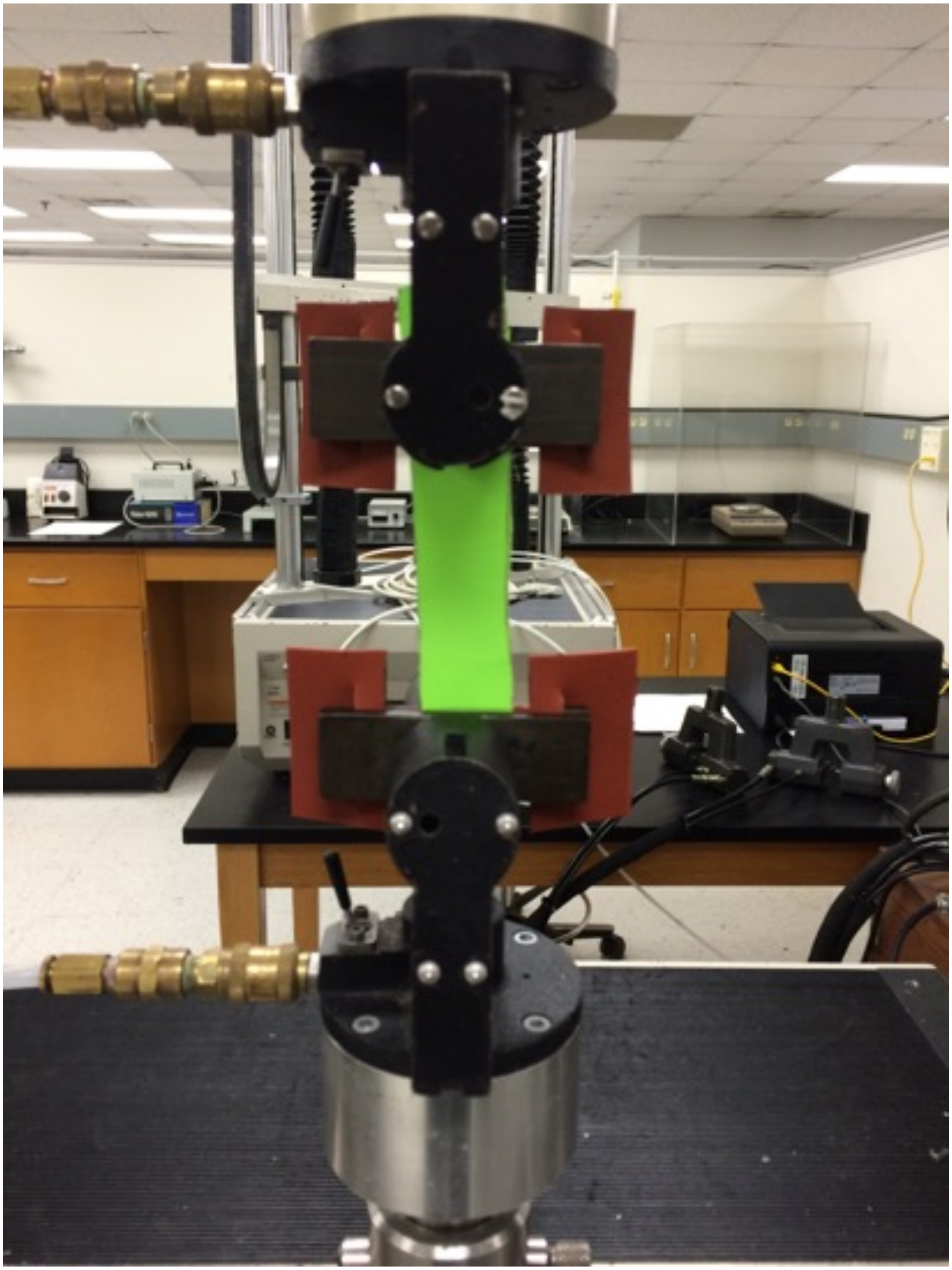


Figure 13: Grab Test (a)

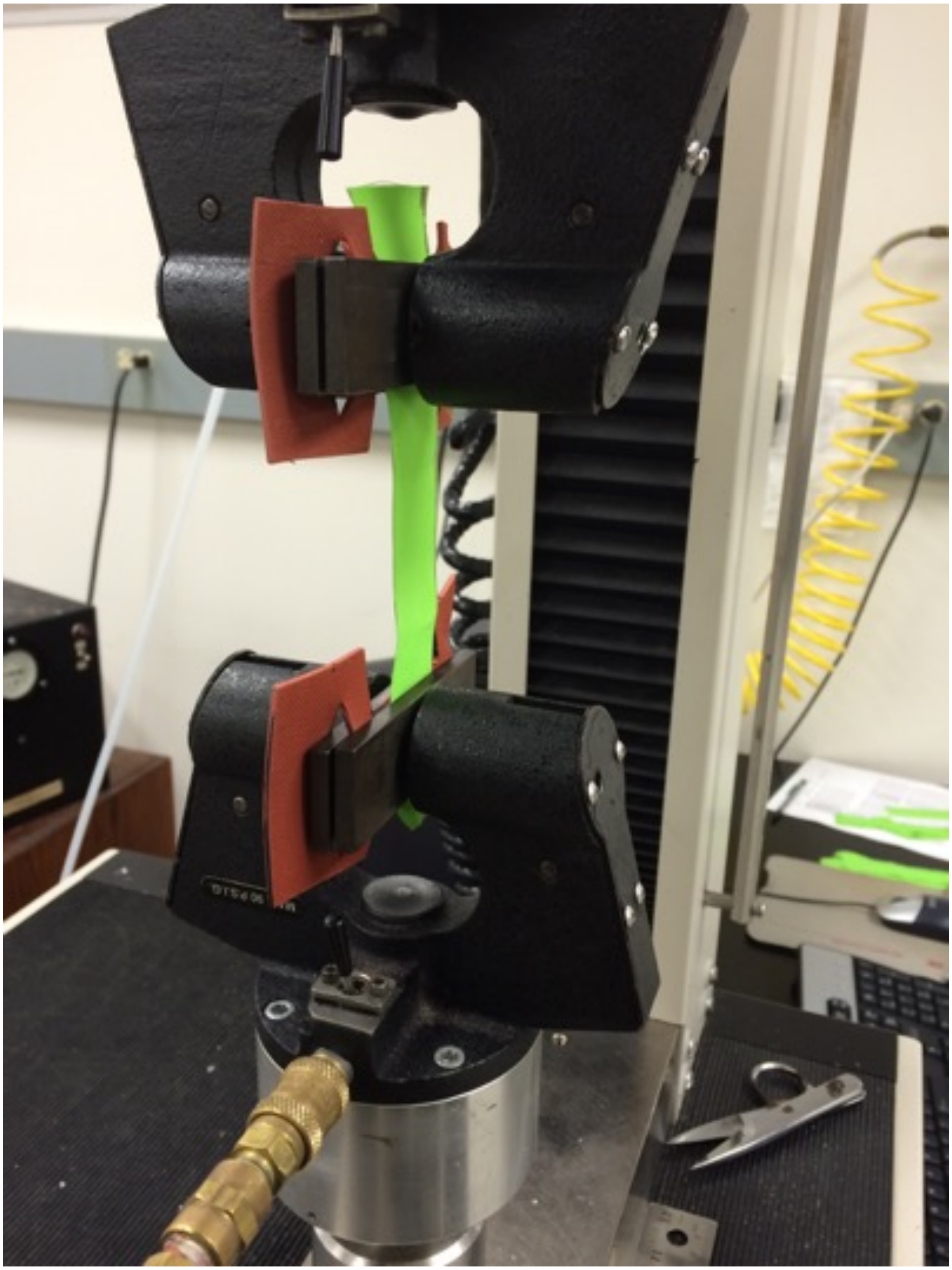


Figure 14: Grab Test (b)

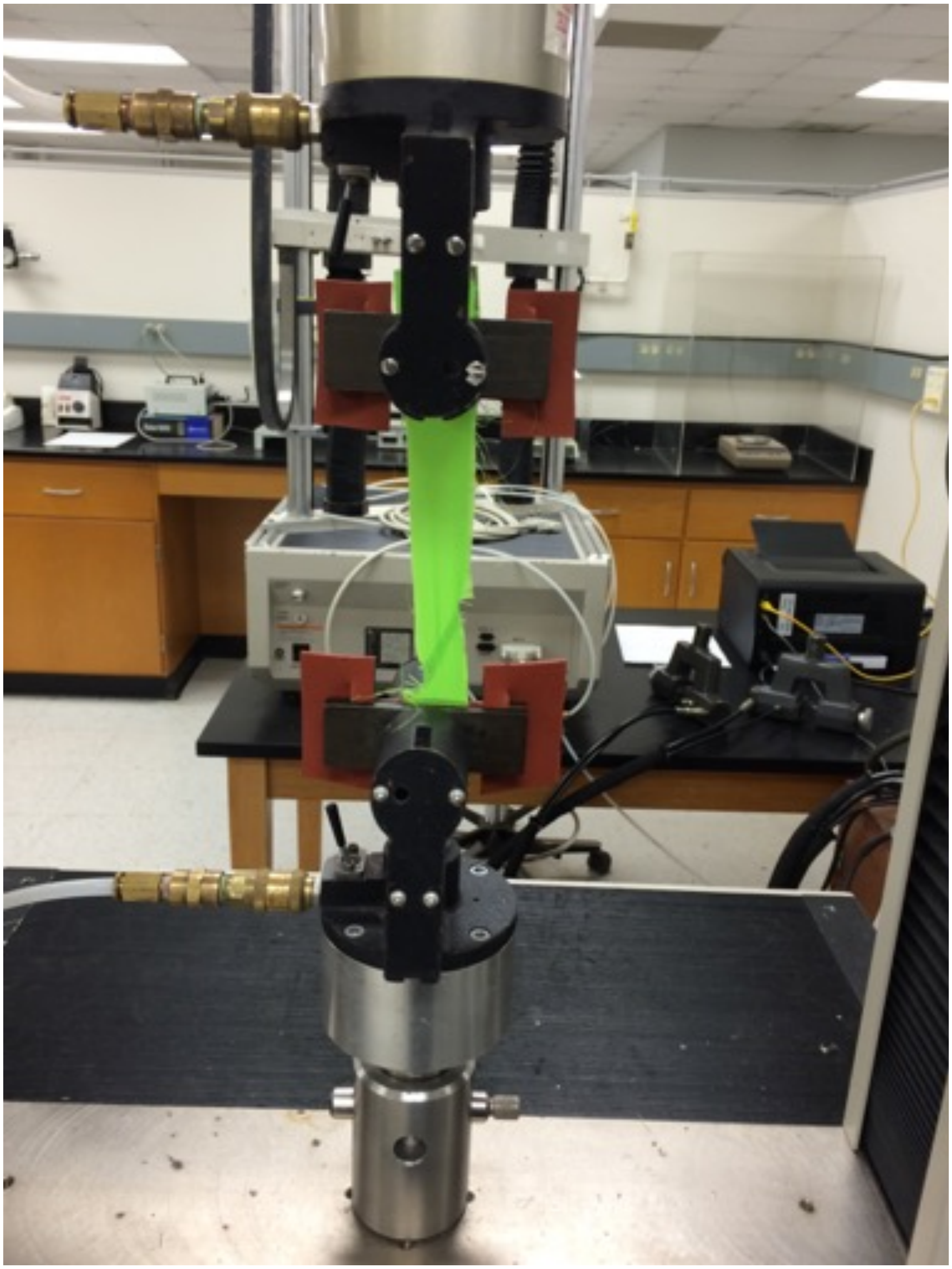


Figure 15: Grab Test (c)

This particular test method was utilized for this experiment because of its ability to break the three fabric samples. Other test methods that were considered did not have the required strength to bring the samples to their breaking point. The available applied force of the Q Test™/5 was 250lbs.

ASTM Test Method D1777-96

In order to obtain the modulus value for the three fabric samples tested in this thesis, the fabric thickness was required when conducting the fabric strip test. ASTM standard D1777-96 is used to measure the thickness of most textile materials. This value was gathered by placing the individual specimens on the base of a thickness gauge and lowering a weighted presser foot (Figure 16). The displacement between the base and the presser foot was used as the thickness of the fabric samples in ASTM test method D5035-11, Fabric Strip Test (Figure 17).

The thickness gauge used in this experiment followed the specifications of Testing Option 1, outlined in the test method, and is specified for use of woven, knitted and textured fabrics. Option 1 uses a dead-weight gauge type with a presser foot diameter of 28.7 ± 0.02mm.

Figure 16: Ames Thickness Gauge

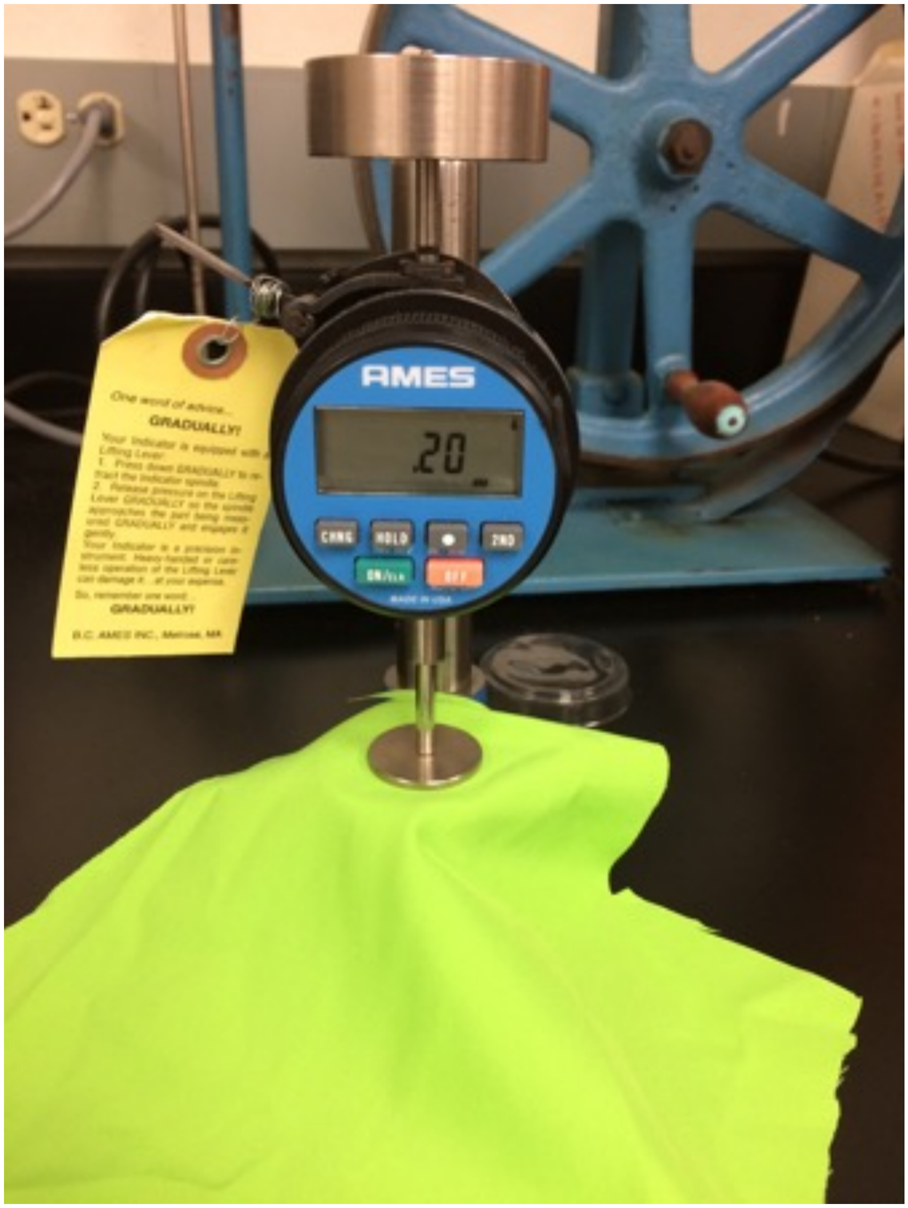


Figure 17: Displacement Value Used as Thickness

ASTM Test Method D3787-15

The first testing standard considered for finding the breaking point of the fabric specimens in this test was ASTM Test Method D3787-15, Bursting Strength of Textiles-Constant-Rate-of-Traverse (CRT) Ball Burst Test (Figure 18). This method describes the measurement for bursting strength with a ball burst strength tester and the values are recorded in either SI units or inch-pound units. A Ball Burst Test primarily tests fabrics of a high degree of ultimate elongation and mainly knitted textiles and has a strength capacity of 250 lbs (ASTM Test Method D3787-15). In this test method, a specimen is securely clamped without tension between grooved, circular plates of the ball burst attachment. These plates are secured to the movable jaw for the CRT testing machine. A force is then exerted against the specimen by a smooth, hardened steel ball. The steel ball is attached to the pendulum-actuating, or fixed clamp of the machine until the rupture takes place. When testing the three fabric samples selected for this research, the Ball Burst Test could not successfully burst fabric 1 because of its high strength, and inability to exceed the maximum elongation of 40 mm.

Figure 18: ASTM Ball Burst Standard (instron.com)

ASTM Test Method D3786/D3786M-13

The next test method considered for testing was ASTM Test Method D3786/ D3786M-13, Bursting Strength of Textile Fabrics- Diaphragm Bursting Strength Tester Method (Figure 19). This test method describes the measurement of the resistance of textile fabrics to bursting using a hydraulic or pneumatic diaphragm bursting center and is applicable to a wide range of textile products (ASTM Standard D3786/3786M-13). Such textile products include stretch-woven and woven industrial fabrics such as inflatable restraints. In this test, a specimen is clamped over an expandable diaphragm and the diaphragm is expanded by fluid pressure. The specimen is expanded to the point of rupture. The difference between the total required pressure to rupture the specimen and the pressure required to inflate the diaphragm is reported as the bursting strength. The values for this test method are recorded in either SI units or inch-pound units. Ability to break fabric #1 was again considered to be a limitation due to the inability to exceed 30mm diameter inflation (ASTM Standard D3786/3786M-13).

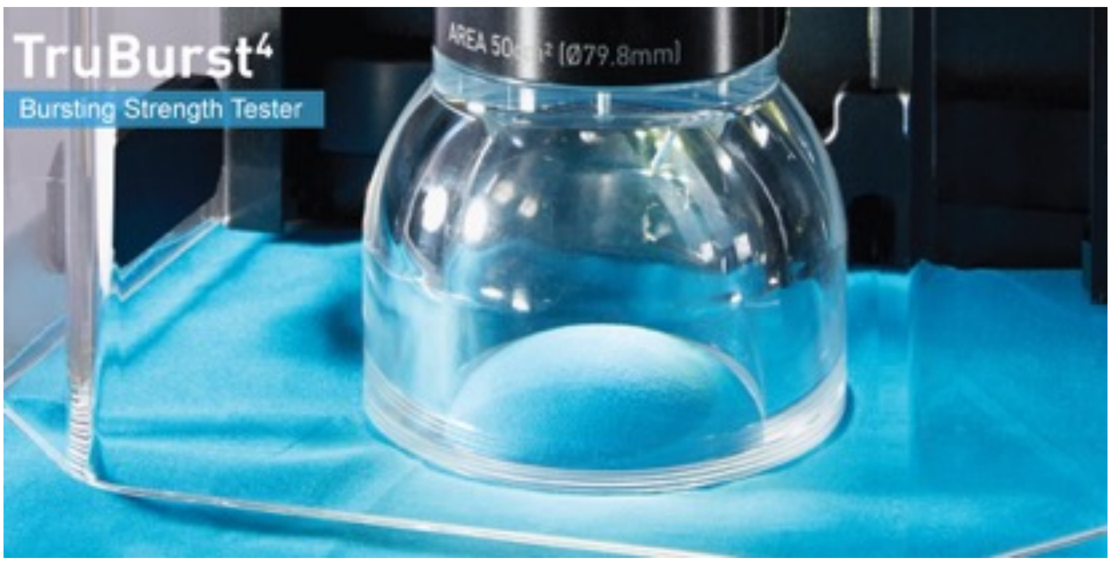


Figure 19: TruBurst (James-Heal.co.uk)

Liquid Preparation

The liquid used for this experiment was a deionized water, direct red 81 dye solution. The dye was purchased from Sigma Aldrich and provided by the Textile Protection and Comfort Center at North Carolina State University. The liquid was used at room temperature for the experiment.

Experimental Setup for Moisture Wicking

This experimental setup sets out to solve the limitations in using traditional vertical wicking test standards when intending to test how moisture moves transversely through a fabric. The utilized method of testing, created by Jingyao Li, was used to determine the transverse wicking rate of textile fabrics. In previous research, measurement of wicking rate by the American Association of Textile Chemists and Colorists (AATCC) standard, Vertical Wicking of Textiles was known to be the most common method of testing. The principle of this test method is to visually observe the rate, being distance per unit of time, at which the liquid travels up the fabric sample and manually record time and rate intervals (AATCC Test Method 197-2013). The AATCC test standard defines vertical wicking as:

“ *in a textile held vertically*, the upward movement of liquid from a cut edge.”

For this experiment, it is important to consider the physiology of sweat when evaluating testing methods. There are between 2 and 4 million sweat glands in the adult skin with a normal rate of secretion ranging from 0.5 to 1 mL/min (Morris, *et al.* 2009). The amounts of sweat produced by sweat glands to naturally cool the body, cover the entire surface of the human body. This distribution of sweat glands shows that production of sweat is for the most part, an even distribution of liquid according to regional variation of body sweat mapping (Smith and Havenith, 2011). This idea of small amounts of sweat in focused areas of the body is in opposition to the principle of the AATCC Vertical Wicking of Textiles test method. When looking at a garment on a human body and its wicking ability, there is no infinite reservoir of liquid where the edge of the fabric is partially immersed. The sweat produced by the body is trapped between the skin's surface and the underneath of the textile garment layer and is transferred based upon contact of the skin and fabric (Li et al., 1993).

To achieve this idea of testing the transverse wicking ability of a fabric, the fabric was mounted onto a 3" embroidery hoop and placed underneath microscope. The microscope used in this experiment was a USB video microscope and was utilized to record the wicking process and gather the data from the top view of the textile (Figure 21). A ruler was placed on the fabric sample along the warp direction and was included in the images captured to aid in later use in the calibration process of the wicking images. The desired volume of 50μL was then placed on the fabric from a constant height of approximately 1 cm using a pipette. The wicking process for each fabric sample was recorded for five minutes.

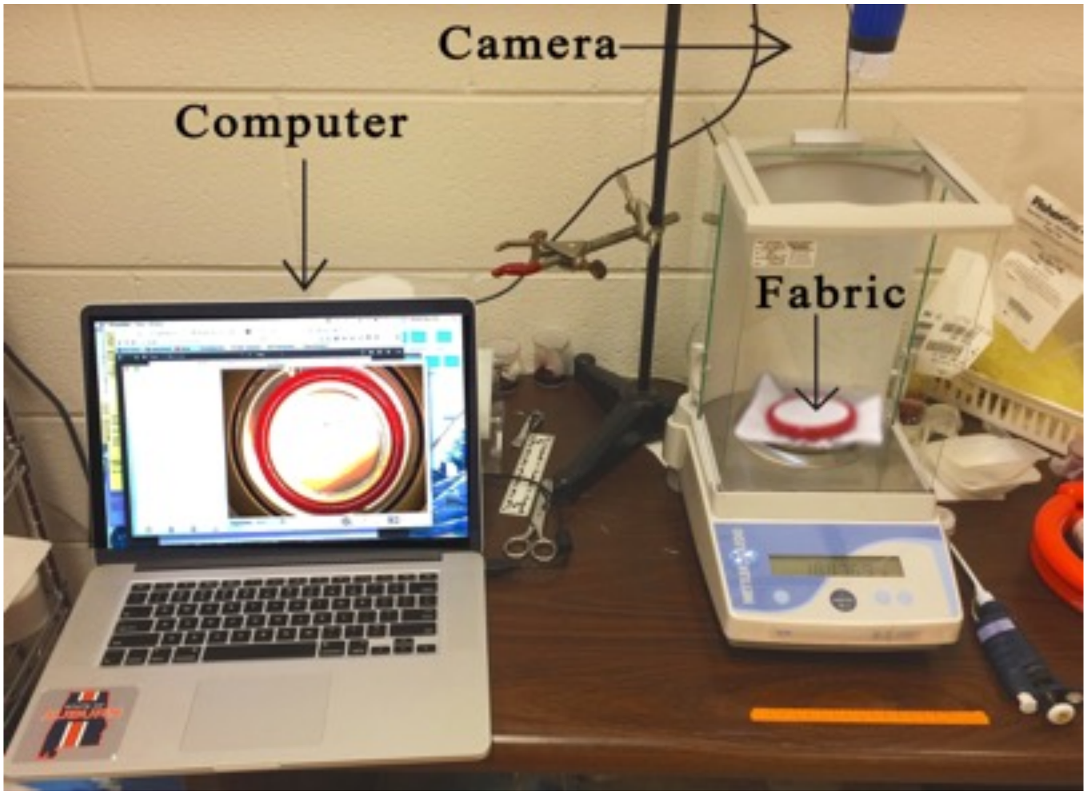


Figure 21: Experimental Setup

Stretch Setup

It is of value to this experimental setup, to take garment stretch reductions into consideration. Referencing earlier research in this thesis, Richardson (2008) states that fabrics of two and four-way stretch are suggested to be designed 10% smaller in both directions. Because of the lack of research available in this area, 10% stretch in both the warp and filling directions of the fabric samples was used as the benchmark percentage for testing. In this experiment, it is of value to observe each fabric sample at a neutral state of 0% stretch, 10% stretch, serving as a benchmark percentage, and 20% stretch to observe the effects of incorrect body-garment stretch ratios. Each fabric type was tested five times each with unused samples each time, at the listed percentages to gather sufficient data about the fabric's wicking behaviors.

In order to correctly calculate the percentages of the stretch that were needed for the experimental setup, the diameter of the embroidery hoop was needed. The diameter was calculated by tracing the inside of the hoop and finding the widest point of the circle. This was measured by hand with a ruler (Figure 22). The inside of the hoop measured to have a diameter of 2.4375 inches (Figure 23).

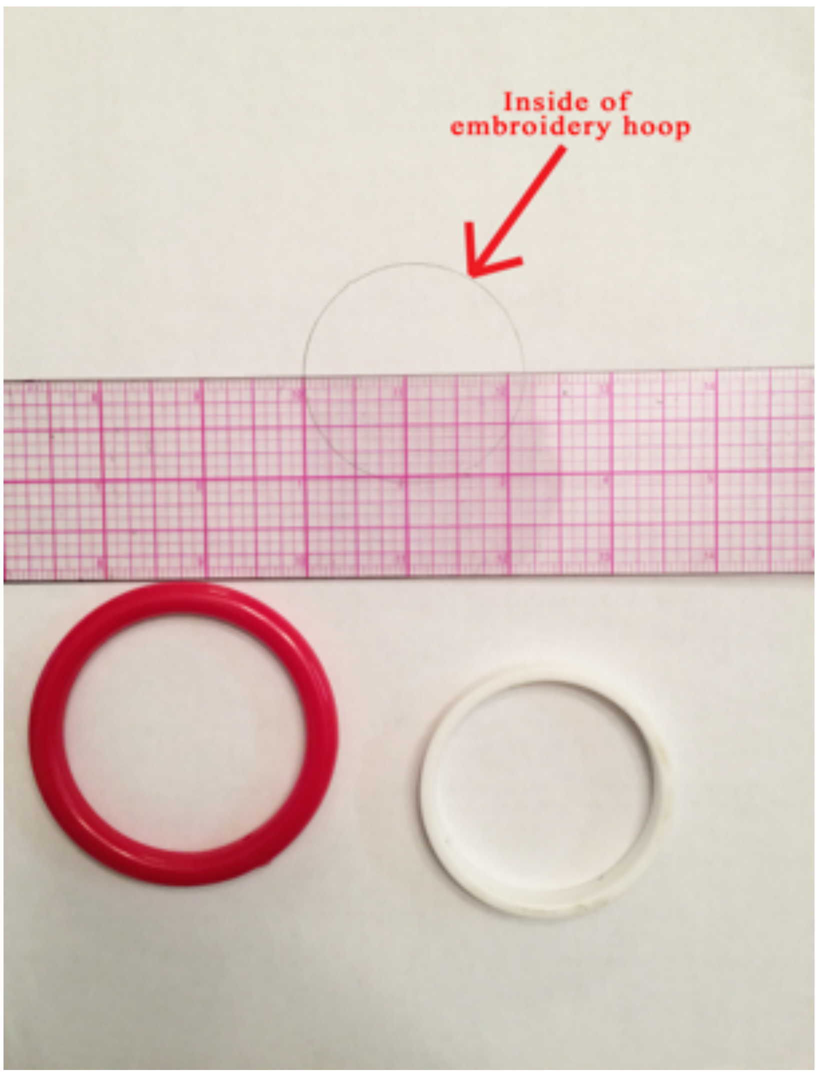


Figure 22: Measuring for Inside of Embroidery Hoop

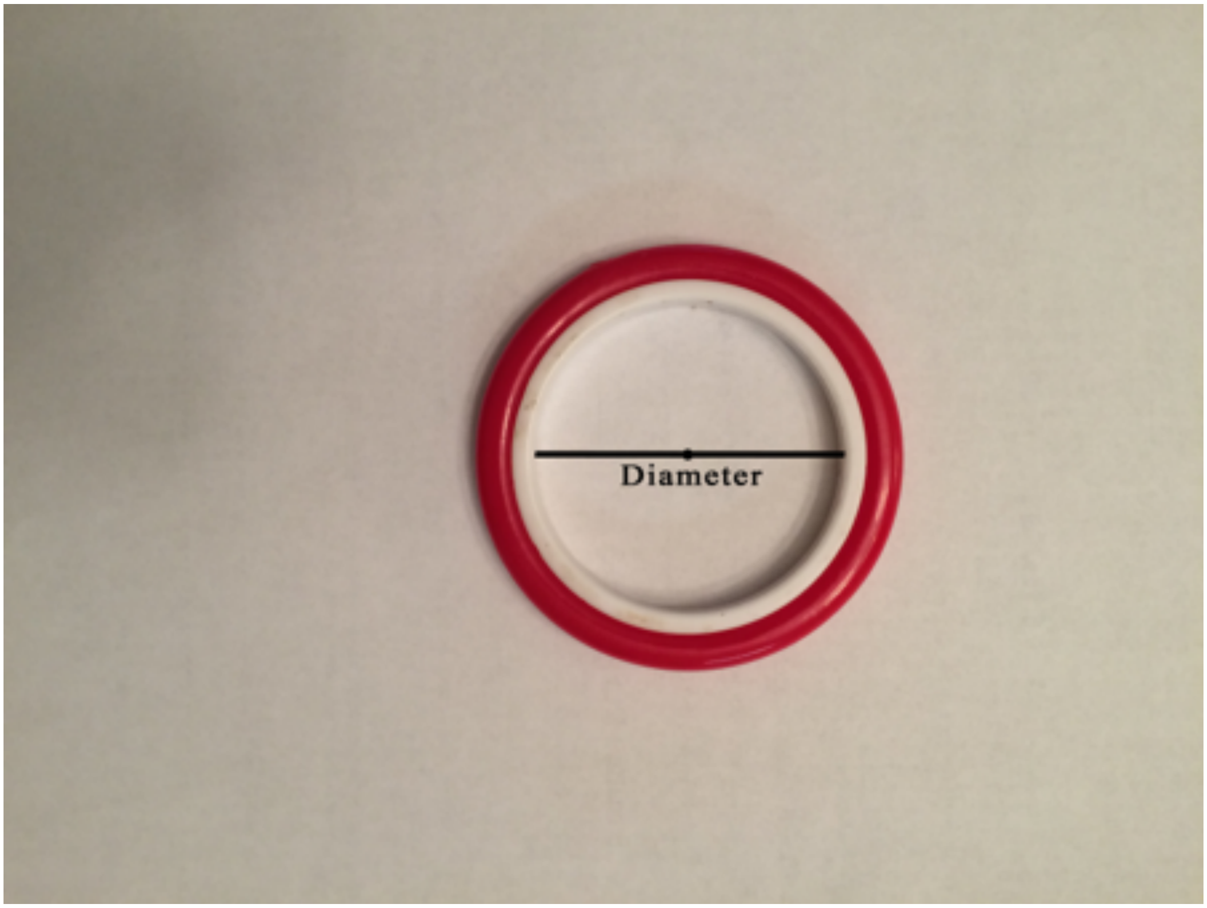


Figure 23: Diameter of Inside of Embroidery Hoop

Because the embroidery hoop is a set diameter and cannot be changed, percentages of stretch were considered by finding the new diameter of the inside of the circle after multiplying it by percentages necessary to produce 10% of the embroidery hoop's diameter and 20% of the embroidery hoop's diameter. This consideration made the size of the circle smaller, allowing the fabric to be stretched to the exact perimeter of the newly calculated circles.

To identify the measurements of the circle at both 10% and 20%, the original diameter of the circle (d_1=2.4375) was multiplied by .9 to find d_2 and .8 to find d_3. Calculations are as follows:

10% stretch: $d_1 * \text{desired } \% = d_2$

$2.4375 * .9 = 2.19375$

20% stretch: $d_1 * \text{desired } \% = d_3$

$2.4375 * .8 = 1.95$

After the preceding values were calculated, the new circles were drawn using Adobe Illustrator CS5 in order to achieve precise measurement of the diameter values. This computer system allows the user to manually choose values for both the height and width of the drawn circles (Figure 24). Using a computer aided design system also allows for the page dimensions to be correctly set to the standard 8.5" x 11" and allows for no scaling to take place, so that when printed, the circle values will remain in proportion to the page size (Figure 26).

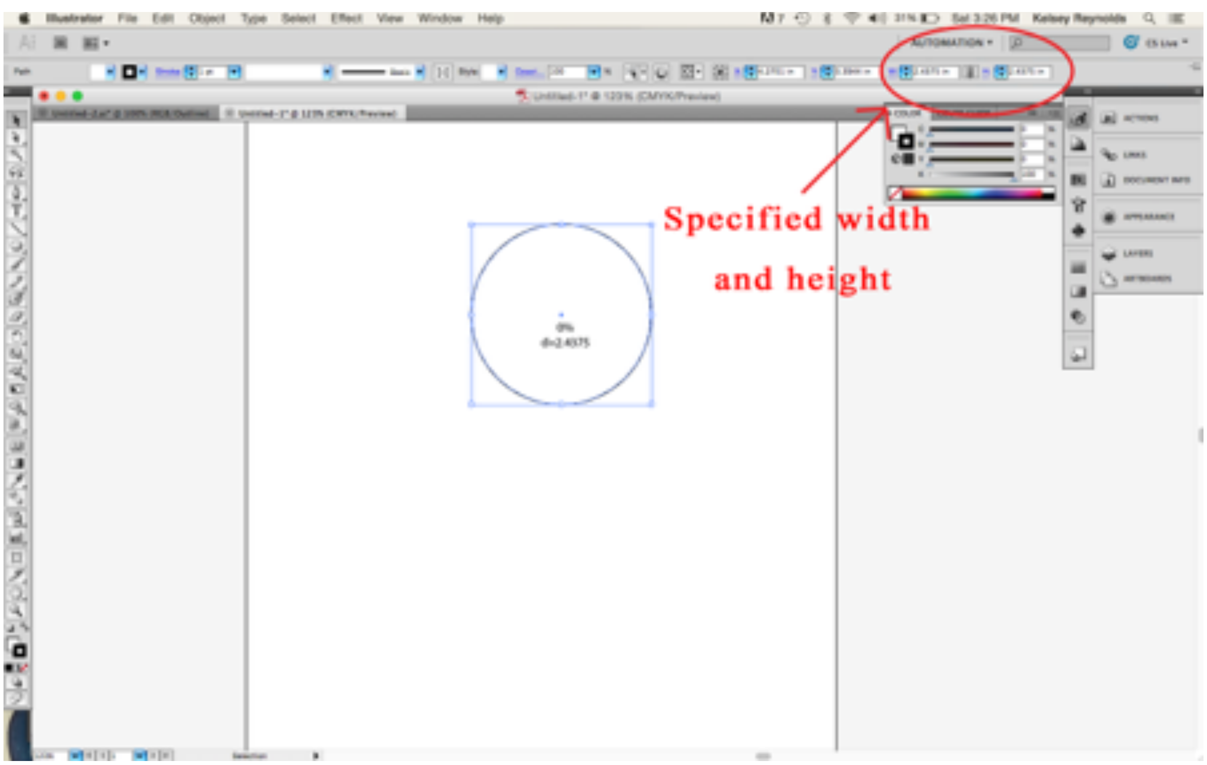


Figure 24: Drawing Circle at 0%

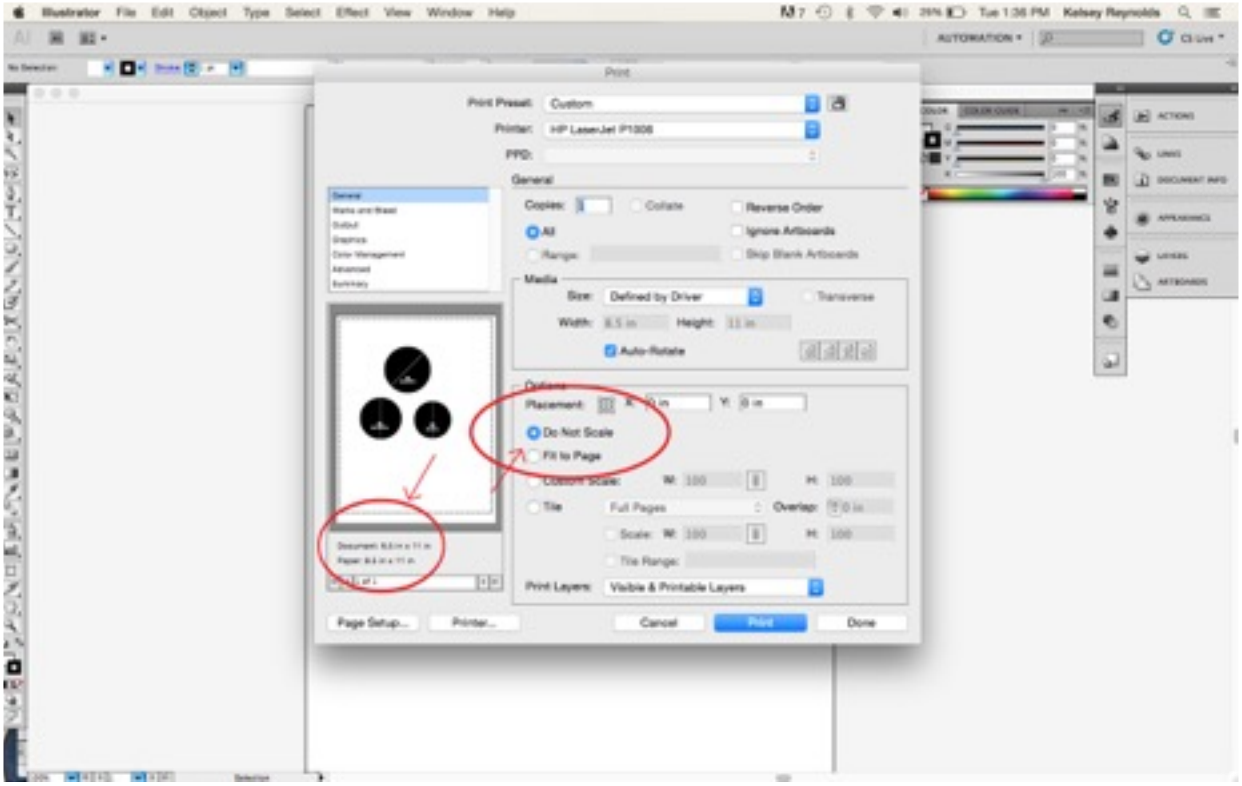


Figure 25: Circle Drawings at final percentages

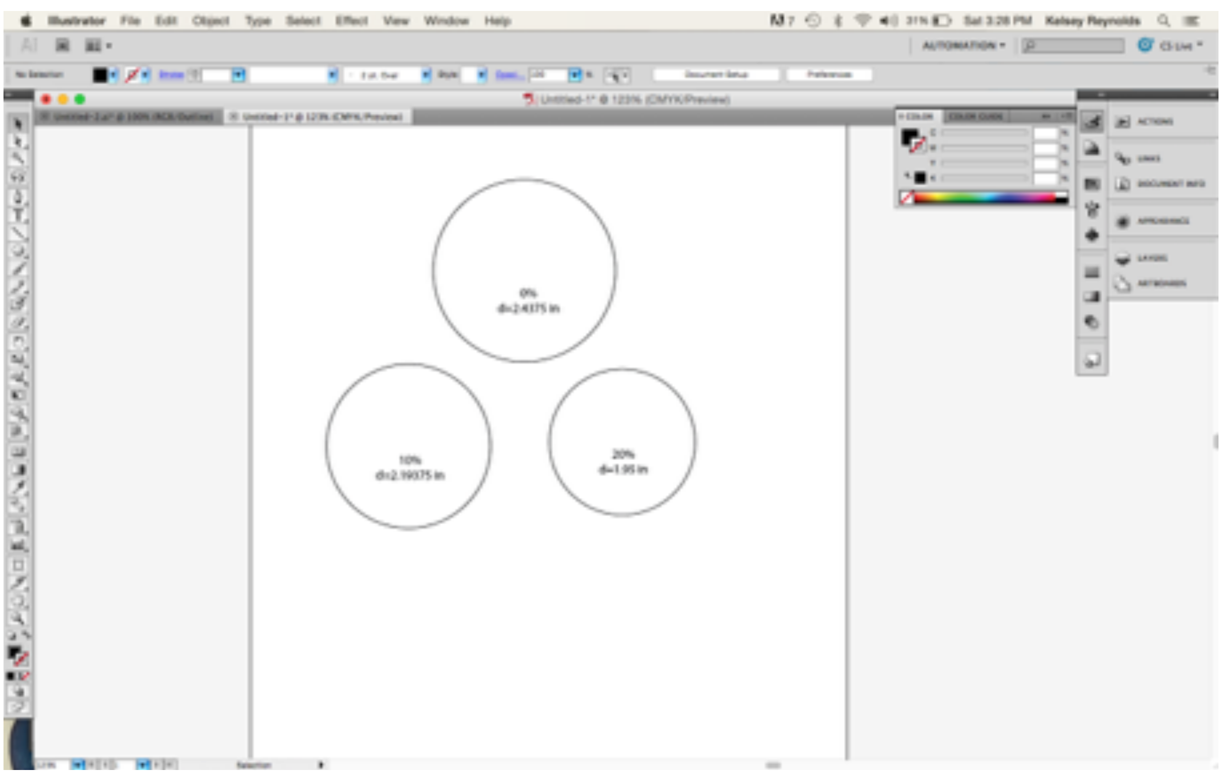


Figure 26: Print Preview Showing Size Ratio

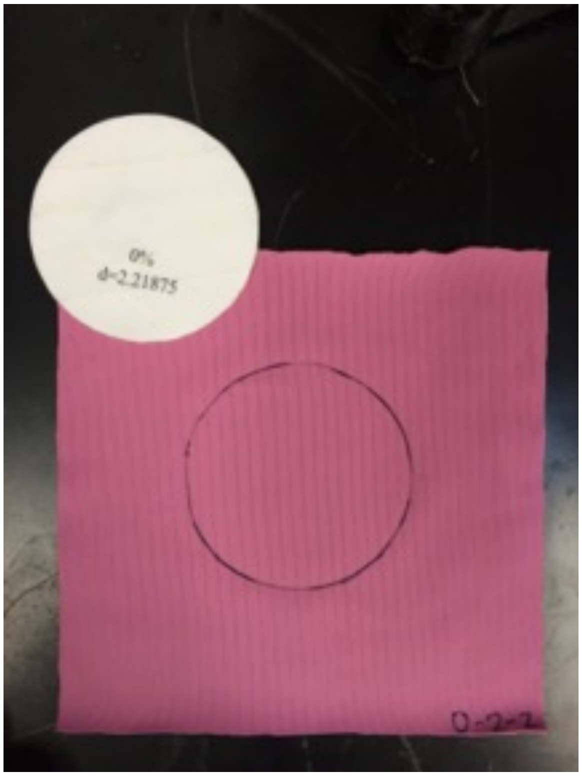


Figure 27: Tracing of Circle Percentage on Fabric Sample

Figure 28: Fabric Stretched to Outside Perimeter of Monogram Hoop

Figure 25 was printed and used as a template for manually controlling the fabric stretch. Each specific percentage circle was used to manually control the stretch by tracing the circles onto the fabric (Figure 27). The perimeter of the traced circle was stretched to meet the outside perimeter of the interior white piece of the monogram circle (Figure 28). Each fabric sample was tested using this method at the required percentages of 0%, 10%, and if possible, 20% stretch. This manual method of stretching allowed for each fabric sample to be accurately tested at the desired stretch percentage.

Image Processing

After recording videos of the wicking process for each fabric samples, the videos were analyzed in the following order. First, the video was converted into image sequences using ImageJ software. The scale was set to centimeters and calibrated based on the ruler placed next to the sample (Figure 29). Then, the area of the liquid stain was selected using the threshold command in the program (Figure 30). The area, perimeter and circulatory of liquid stain were calculated and measured by ImageJ and the profile of the stain was given (Figure 31). The videos have a speed of 30 frames/second and each frame was processed according to the process as described. When the area and perimeter were plotted against time, data resulted in giving the growth trend of the liquid stain and accurately recording the wicking process of the particular fabric (Li, 2015).

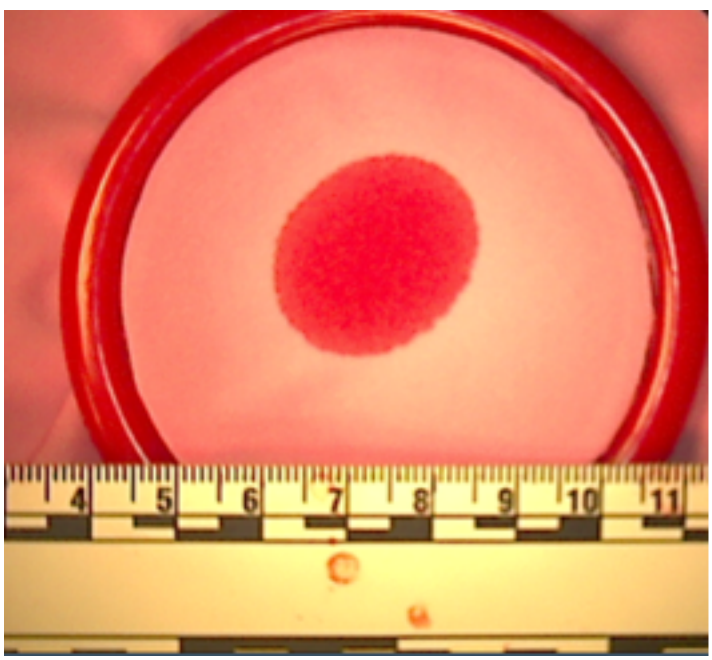


Figure 29: Calibration of Liquid Stain

Figure 30: Area of Stain Selected by

Threshold Command

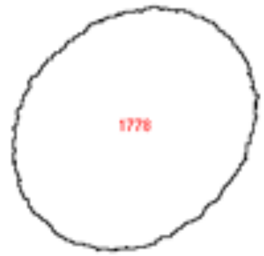


Figure 31: Area Calculated and

Measured by ImageJ

CHAPTER FOUR: FINDINGS

Initial Modulus of Fabric Samples

In this chapter, the findings of how fabric stretch effects liquid wicking on athletic textiles will be reported. Topics include: Fabric thickness, Fabric Modulus, Area of the Liquid Stain, Growth Rate, and Standard Deviation and Coefficient of Variation.

Fabric Thickness

As described in the experimental section, the thickness of each fabric sample was a needed parameter to test the fabric modulus. Thickness value was gathered from testing the three fabric samples 10 times each and averaging the values. Numerical values for fabric samples are as follows:

Fabric 1: 0.680 mm

Fabric 2: 0.200 mm

Fabric 3: 0.490 mm

Fabric Modulus

The initial modulus of each fabric sample was measured using the MTS Q-test tensile tester and followed the specific testing parameters outlined in chapter three. Each fabric sample was tested five times each in both the warp and the filling directions. Tables 3-5 show the modulus values for each sample.

Table 3: Peak Load and Initial Modulus of Fabric 1

	Initial Modulus		**Peak Load**	
Trial #	**Warp Direction (N/m^2)**	**Filling Direction (N/m^2)**	**Warp Direction (N)**	**Filling Direction (N)**
Trial 1:	92,532.22	80,615.25	252.3	286.8
Trial 2:	91,607.85	93,838.01	307.1	285.5
Trial 3:	87,669.42	92246.15	275.5	273.7
Trial 4:	86,259.93	85641.10	293.9	248.7
Trial 5:	85,410.04	84022.48	283.4	275.2
Mean	*88,695.89*	*87,272.60*	*282.4*	*274.0*

Table 4: Peak Load and Initial Modulus of Fabric 2

	Initial Modulus		**Peak Load**	
Trial #	**Warp Direction (N/m^2)**	**Filling Direction (N/m^2)**	**Warp Direction (N)**	**Filling Direction (N)**
Trial 1:	4,354,983.68	2,719,565.91	331.50	275.20
Trial 2:	5,232,016.63	2,453,156.02	292.20	246.10
Trial 3:	3,277,082.63	2,527,875.42	300.20	253.20
Trial 4:	4,893,264.93	2,839,607.85	335.60	275.60
Trial 5:	4,318,594.90	2,198,403.83	322.10	272.20
Mean	*4,415,188.55*	*2,547,721.81*	*316.30*	*264.50*

Table 5: Peak Load and Initial Modulus of Fabric 3

	Initial Modulus		**Peak Load**	
Trial #	**Warp Direction (N/m^2)**	**Filling Direction (N/m^2)**	**Warp Direction (N)**	**Filling Direction (N)**
Trial 1:	235,774.84	104,763.90	166.70	127.90
Trial 2:	194,978.23	122,550.63	142.90	133.00
Trial 3:	179,429.64	104,885.84	156.70	127.30
Trial 4:	213,091.24	106,744.84	142.80	127.80
Trial 5:	376,200.81	99,000.30	190.50	120.70
Mean	*239,894.95*	*107,589.10*	*159.90*	*127.30*

As described in chapter two, the first segment of a stress strain curve depicts the initial modulus of a fabric. This segment is a straight line that indicates how easily the fiber or fabric extends under stress. Each fabric's elongation curve provides the measurement for the initial modulus in the slope of the primary section. When the initial modulus segment of the curve rises steeply, a large increase in stress produces a small increase in strain. As the slope decreases and the line becomes more horizontal, the initial modulus of the fiber or fabric becomes lower. Consideration of these details tells us that the fabric with a lower initial modulus is easier to elongate than the fabric with a higher modulus.

The modulus values for each fabric sample are gathered from tests in both the warp and filling direction with a potential load of 250 lbs (Tables 3-5). As shown above, the modulus increased for fabrics tested in the warp direction when compared to the filling direction. The warp direction tests also required a greater load, expressed in Newtons (N), to bring the fabric samples to their breaking point. Consideration of these details shown in the above tables, tells that fabrics with lower initial modulus are easier to elongate than those with a high modulus. This means, out of the three fabric samples, fabric sample 1 requires the lowest amount of force in order to result in a substantial amount of lengthening.

In performance clothing applications, the fibers making up these garments need to be able to extend under low amounts stress and must have immediate recovery capabilities. When a garment is pulled onto the body, the fibers stretch extending to different percentages according to body type and measurement, and then must have the ability to apply compression to the body through contraction toward their neutral state.

Fabric Stretch and Its Effect on Liquid Wicking Rate

Area of Liquid Stain

The purpose of this experimental set up, as described in chapter three, was to mimic various percentages of stretch that would be seen in performance garments and to observe the effect it has on wicking capacity. The three fabric samples vary in fiber content: Fabric 1, a 90/10 polyester/spandex, tricot with an antimicrobial/wicking finish, Fabric 2, a 100% polyester, plain weave with no finish, and Fabric 3, a 65/35 polyester/rayon, jersey with a wicking finish. Each fabric was chosen because of their distinctive knit or weaving structures, which are commonly used by companies in the performance garment industry. The fabrics also have similar fiber content, all using 65% or more polyester.

The placed drop experiments were repeated five times for the individual fabric types with new samples for each drop test. They were tested at at 0%, 10% and 20% stretch, if the fabric type could reach the desired percentage of stretch. Fabric 1 was the only sample that had the ability to be stretched to 20%. Fabrics 2 and 3 were tested at 0%, a neutral state, and 10% stretch. It was observed for fabric 2 and 3, that as the percentage of stretch increased, a smaller final area of the liquid stain resulted (Table 6). Fabric 1 had a different effect when the percentage of stretch increased, where the final area of the liquid stain grew from 0% to 10% and then decreased by .238 centimeters while under 20% stretch. Fabric 1 verified it's largest value of area under 10% stretch. This result did not follow the trend of the other fabric samples because of its lack of increasing growth rate from 10% to 20% stretch.

Table 6: Final Area of Liquid Stains

Fabric and Stretch %	Area in cm
Fabric 1: 0%	4.494 cm^2
Fabric 1: 10%	5.784 cm^2
Fabric 1: 20%	5.546 cm^2
Fabric 2: 0%	7.624 cm^2
Fabric 2: 10%	6.381 cm^2
Fabric 3: 0%	2.947 cm^2
Fabric 3: 10%	2.673 cm^2

Growth Rate

The growth rate was calculated by observing the growth of the fabric sample area over time:

(ending area value/ beginning area value)^ (1/time)-1

This formula was derived from the Compound Average Growth Rate (CAGR) formula and is used to measure growth that accumulates over time (Table 7). The growth rates for the three fabric samples similarly followed the trend of the final area of the liquid stains by increasing in the rate of growth from 0% to 10% for fabric samples 2 and 3. Fabric sample 1 had a large decrease in growth rate during 10% stretch and then returned to a higher rate while under 20% stretch.

Table 7: Average Exponential Growth Rate of Wicking Samples

	0%	**10%**	**20%**
Fabric 1	0.731%	0.315%	0.677%
Fabric 2	0.412%	0.445%	x
Fabric 3	0.558%	0.692%	x

Standard Deviation and Coefficient of Variation

The resulting calculations and measurements of the wicking rate of the three fabric samples, although believed to be accurate, may not be applicable to larger populations due to the high degree of variability within and between fabric samples. Table 8 and table 9 demonstrate this point. It can be seen from these tables that the graphs of that averaged wicking rates of each fabric sample can be considered highly variable, cv= 23.8%, 32.2%, 24.4%, 27.4% 19.1%, 19.9% and 18.9%. This could possibly be due to the high degree of test method variability.

Figure 29 shows the mean wicking rates of all seven fabric samples combined for reference. The coefficients of variation are all under 27% for fabrics 1 and 2 which reveals that the method is valid for fabric 1 and fabric 2. However, due to accuracy in the experimental setup for observing the wicking rate, the coefficient of variation is larger for fabric 3.

Table 8: Fabric Sample Area Standard Deviation and Coefficient of Variation Value

	Fabric 1: 0%	**Fabric 1: 10%**	**Fabric 1: 20%**	**Fabric 2: 0%**	**Fabric 2: 10%**	**Fabric 3: 0%**	**Fabric 3: 10%**
Mean of Area	3.8027	4.5858	4.4011	6.1729	4.9177	2.3840	2.0647
Standard Deviation	± 0.727	± 0.914	± 0.835	± 1.508	± 1.35	± 0.567	± 0.666
Coefficient of Variation	0.1912	0.1993	0.1898	0.2442	0.2745	0.2380	0.3224

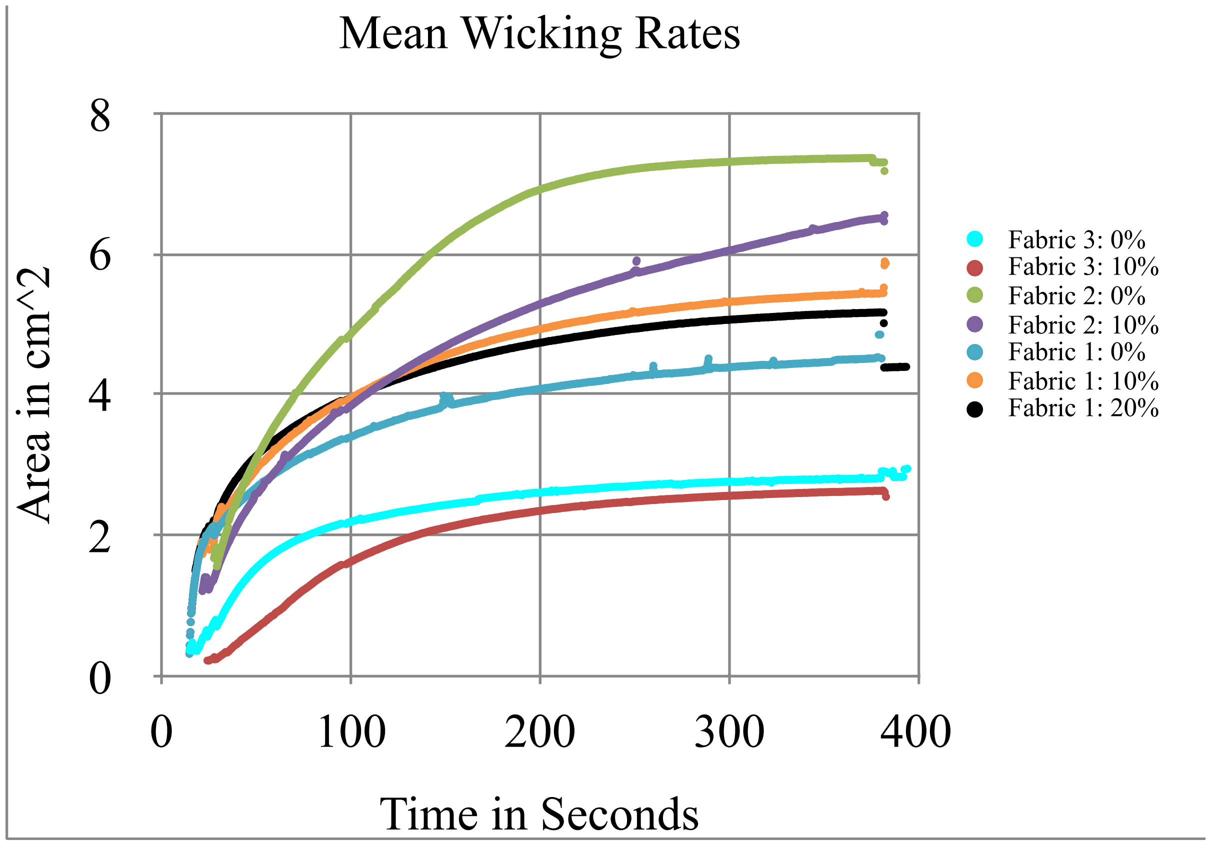


Figure 32: Combined Wicking Rate Means of Fabric Samples

CHAPTER FIVE: CONCLUSION

During this research the wicking rate of a liquid during stretch was studied. Several variables that affect the wicking rate were reviewed: fiber selection and fabric structure, yarn structure, garment stretch reductions, fabric finishes, initial fabric modulus and percentage of stretch. Each group of experiments was repeated five times each on different fabric samples to determine the consistency of the experiments. All 3 fabrics types in this study were made of 65% or more polyester and exhibited different fabric structures. The particular fiber contents and fabric structures were utilized because of their ability to mimic fabrics commonly used in the athletic apparel market. The 3 fabric structures used in the experiment were Fabric 1, a 90/10 polyester/spandex, tricot with an antimicrobial/wicking finish, Fabric 2, a 100% polyester, plain weave with no finish, and Fabric 3, a 65/35 polyester/rayon, jersey with a wicking finish.

It was concluded, that fabrics with a low initial modulus require a lower amount of force to result in substantial amount of elongation and in this study, also have a higher growth rate when wicking. Adversely, results in chapter four show that fabrics with a higher initial modulus have a lower growth rate when wicking. The liquid stain on the woven fabric sample (Fabric 2) has larger area than the stains of both knit fabrics (Fabrics 1 and 3).

With the exception of Fabric 1, the fabric samples followed the trend that as stretch increased, the area of the liquid stain decreased in size and the exponential growth rate increased. These results support the idea that as stretch increases, the wicking ability of an athletic fabric increases, thus improving a fabric's moisture management ability and enhancing the performance aptitude of an athlete wearing the garment.

The goal of this experiment was to investigate the wicking behavior of commonly used fabrics in the industry to create an industry standard. This standard will allow for optimal wicking in garments and in turn enhance performance qualities. It was discovered in previous section's research, that there is no known industry standard for garment stretch ratios when creating garments. The most commonly used rule for fabrics exemplifying four-way stretch, is 10% reduction in all directions. This research shows that wicking rates increase and area of liquid stains decrease when fabrics of higher modulus values are exposed to larger percentages of stretch. This evidence could be used to more effectively design performance garments by considering the effect of compression at higher percentages and their relationship to body type and sizing system ratios. Classification of materials from low to high levels of modulus, paired with their relation to wicking rate could aid in creating more effective garments in the performance garment industry. At large, this research can be accredited with the conclusion that the experimental set-up used in the research allow differentiation between fabric types and specified amount of stretch and their effect on liquid wicking.

CHAPTER SIX: SUGGESTED FUTURE WORK

This study has made the need for several areas of future research evident. It was observed that the area size of a liquid stain after 5 minutes grew heterogeneously in the warp and filling directions of the fabric samples. It would be of great value to further investigate the influence of fabric stretch on wicking by stretching the fabric in only one direction at a time. This concept alone could greatly influence sports performance in means of moisture management for designers and manufacturers.

It was also seen in this research that fabric thickness after applying stretch to a fabric sample was an influential factor for wicking rate and final liquid stain area. Having insight on how fabric thickness changes, after applying a particular percentage, and how it effects capillary action in the pores of the fabric would also be valuable to further understating on this topic.

Utilization of a test standard to measure evaporation rate of a liquid from a textile would be a great tool to pair with the final liquid stain area results from this research. It would allow for the fabric to be classified more accurately by its individual wicking rate. With a more accurate wicking rate, designers would have the ability to reference a benchmarked theory of fabrics' behavior when wicking moisture from the body.

The growth rate portion of this research could also be further investigated to better classify and describe the behavior of each fabric. It is of interest to separate the growth rate into 2 portions of growth; 1 being the initial portion when the liquid is dropped onto the fabric and quickly disperses, and 2 the more linear portion of the graph which could better display the demeanor of the fabric when wicking.

In order to gain a more accurate understating into the mean area of the 3 fabric samples, an increase in the number of trials for each fabric type would be necessary. The values are considered highly variable and the degree of variation could be due to a lack in number of tested samples. In summary, there are infinite possibilities for future research on ways to further and deepen the understanding of fabrics' wicking behavior when exposed to percentages of stretch and use those results to develop an improved system for fabric choice when designing and manufacturing sports garments.

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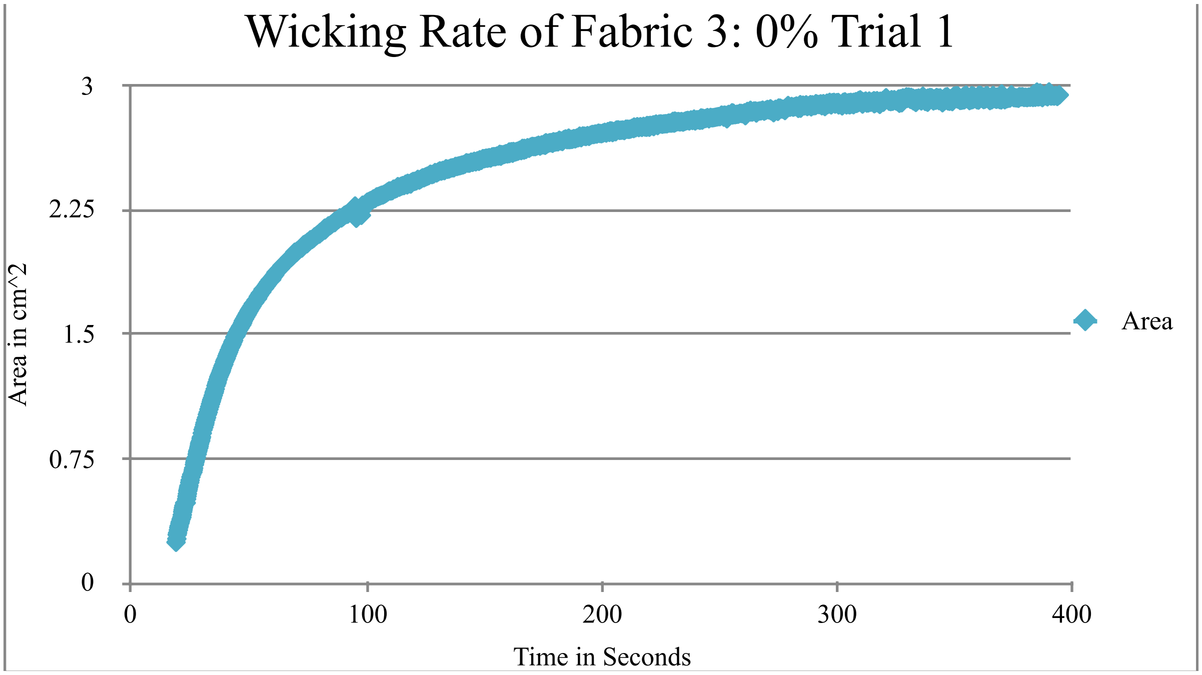
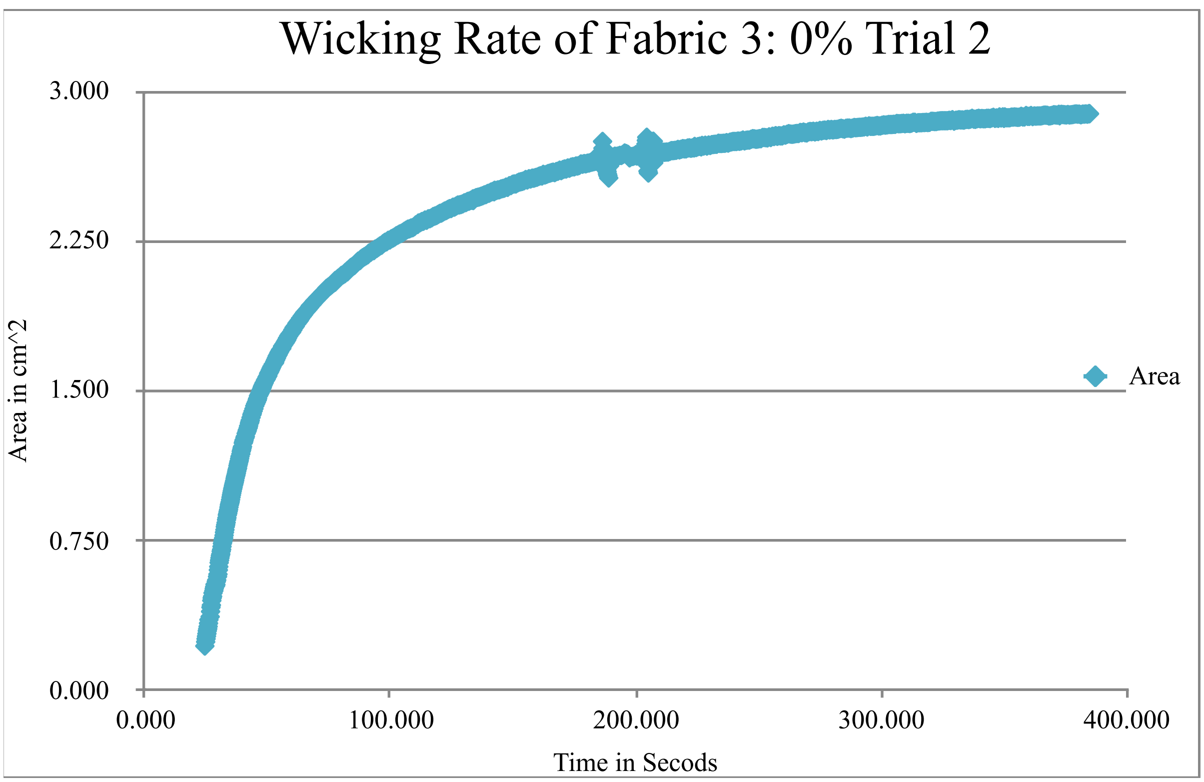
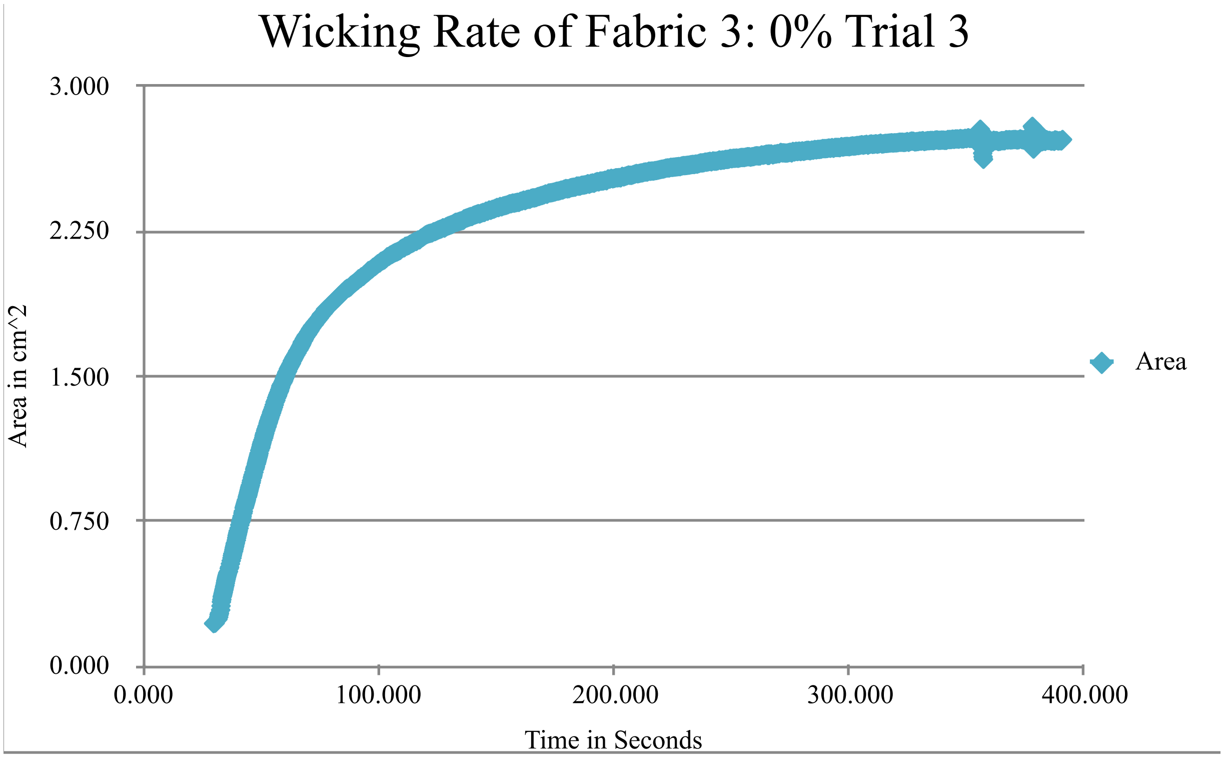
APPENDICIES

Appendix A

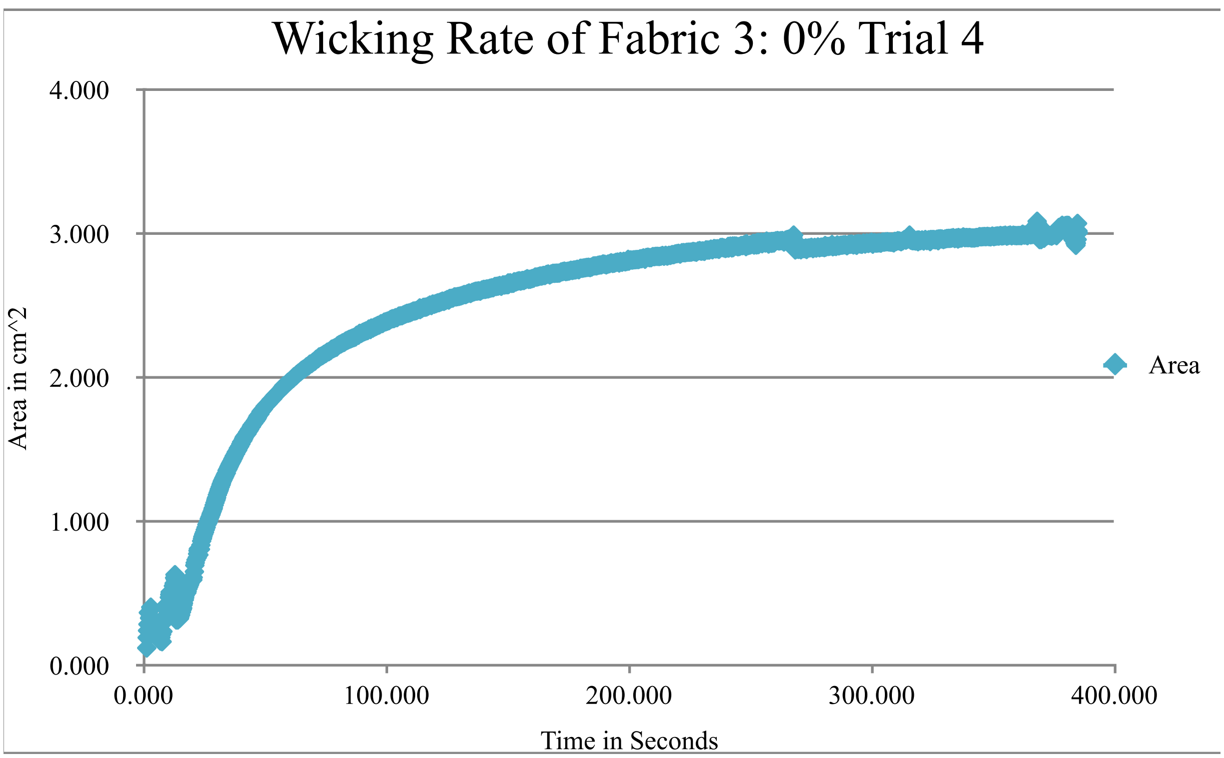
Wicking Rate of Fabric 3: 0% Trial 1-5



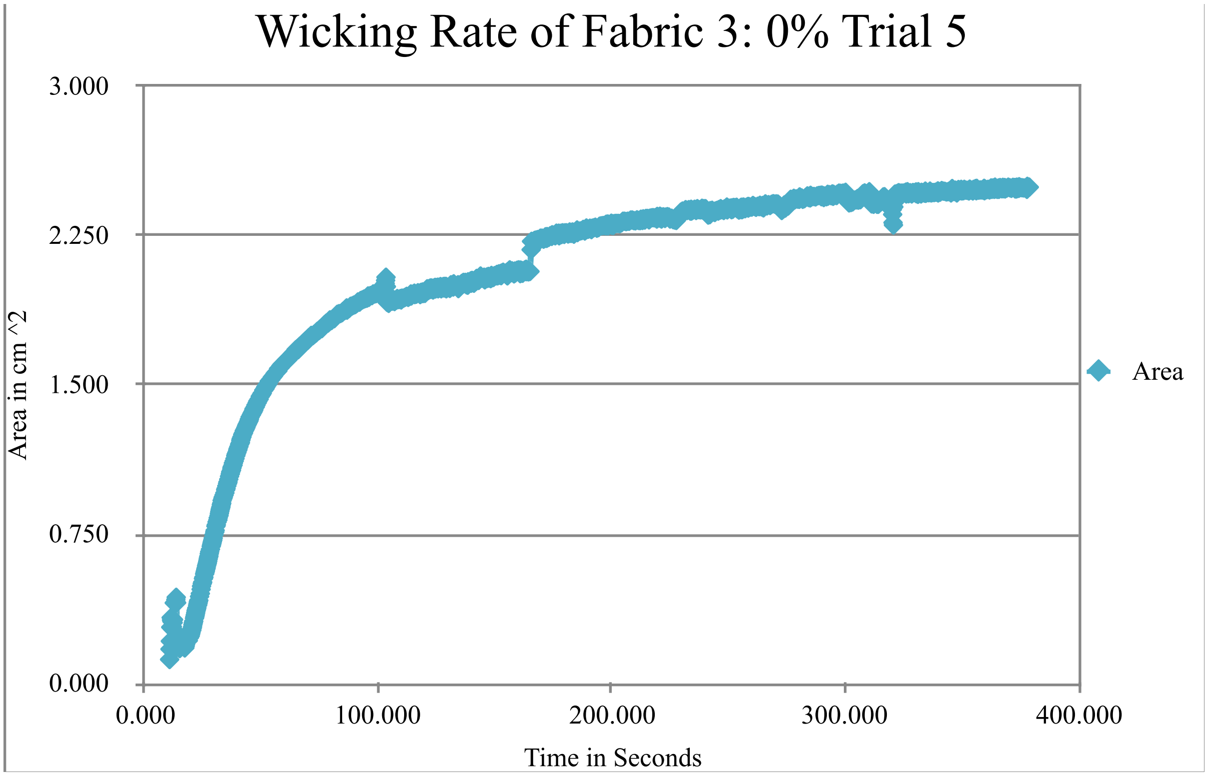




Wicking Rate of Fabric 3: 0% Trial 3
3.000
2.250
1.500
0.750
0.000
Area in cm^2
0.000
100.000
200.000
300.000
400.000
Time in Seconds
Area



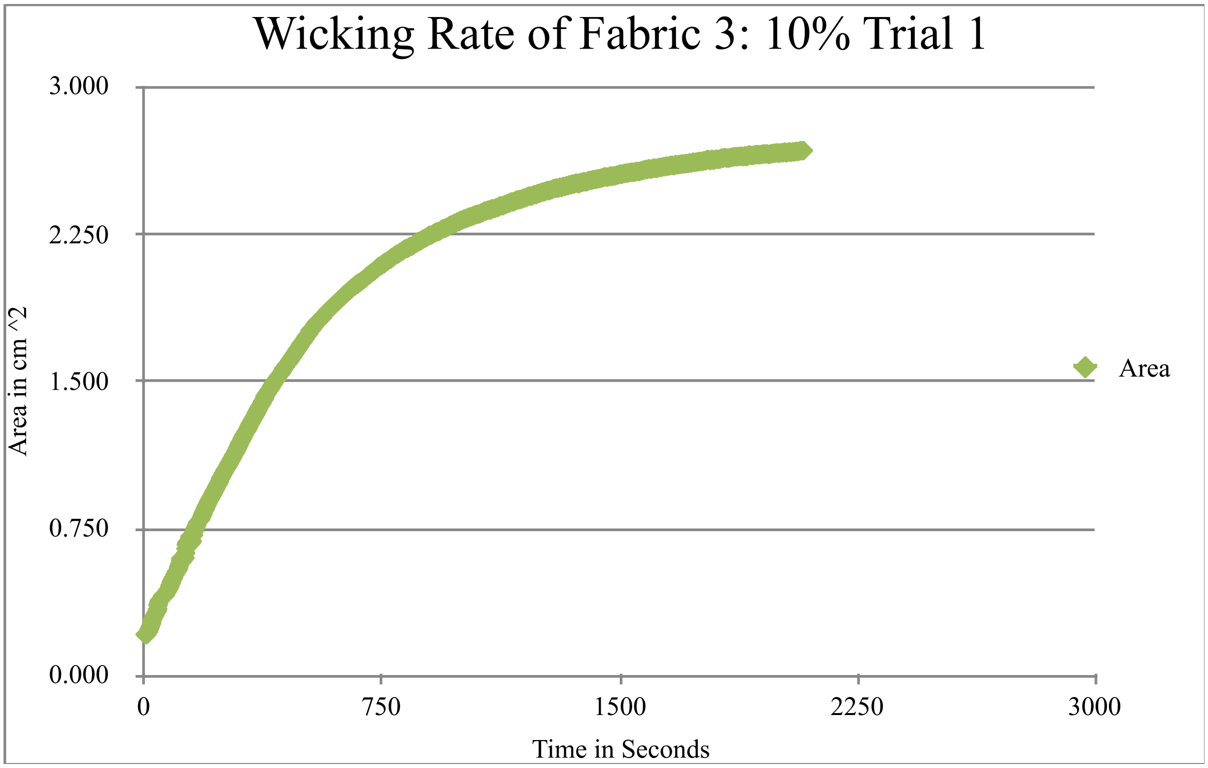
Wicking Rate of Fabric 3: 0% Trial 4
4.000
3.000
2.000
1.000
0.000
Area in cm^2
0.000
100.000
200.000
300.000
400.000
Time in Seconds
Area

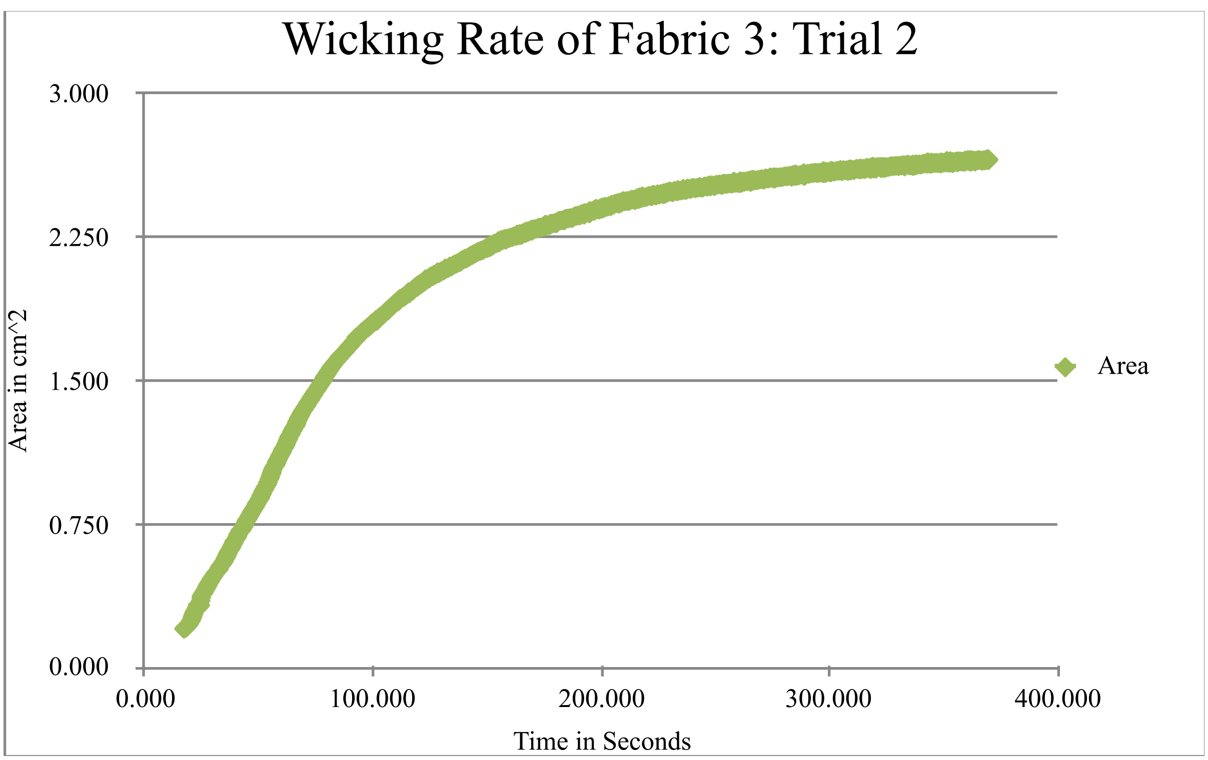


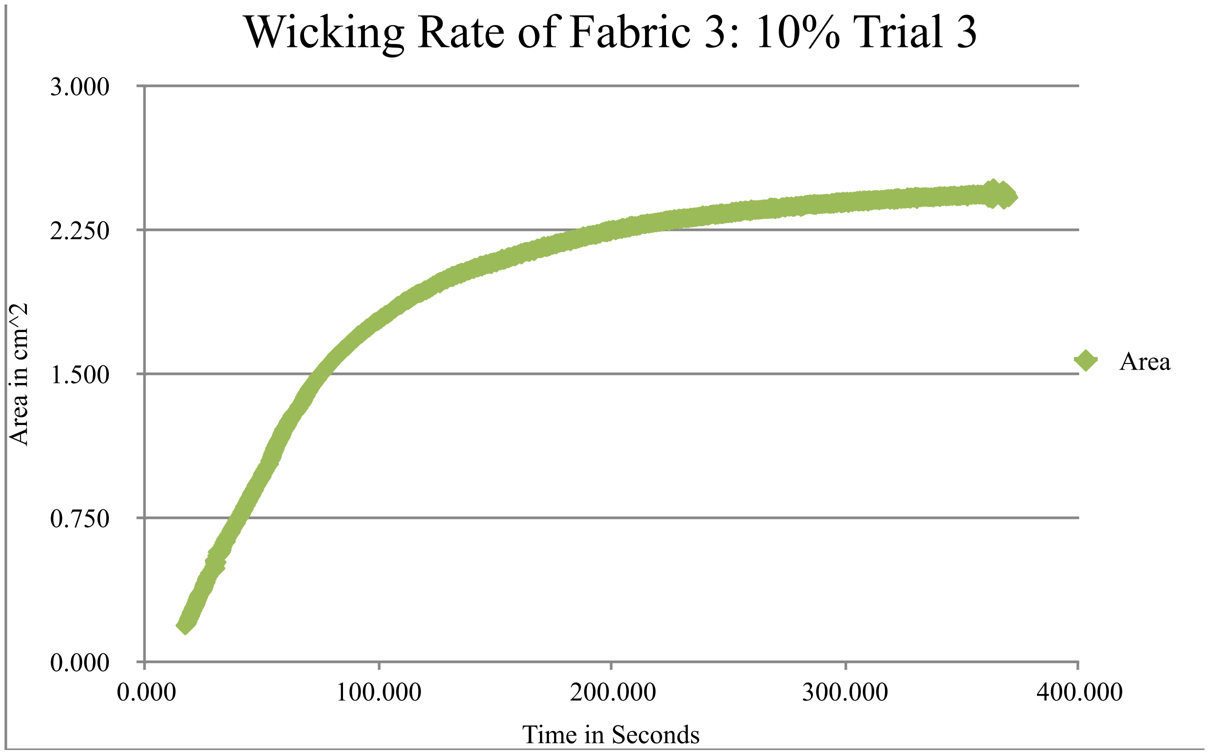
Wicking Rate of Fabric 3: 0% Trial 5
Area in cm ^2
3.000
2.250
1.500
0.750
0.000
0.000
100.000
200.000
300.000
400.000
Time in Seconds
Area

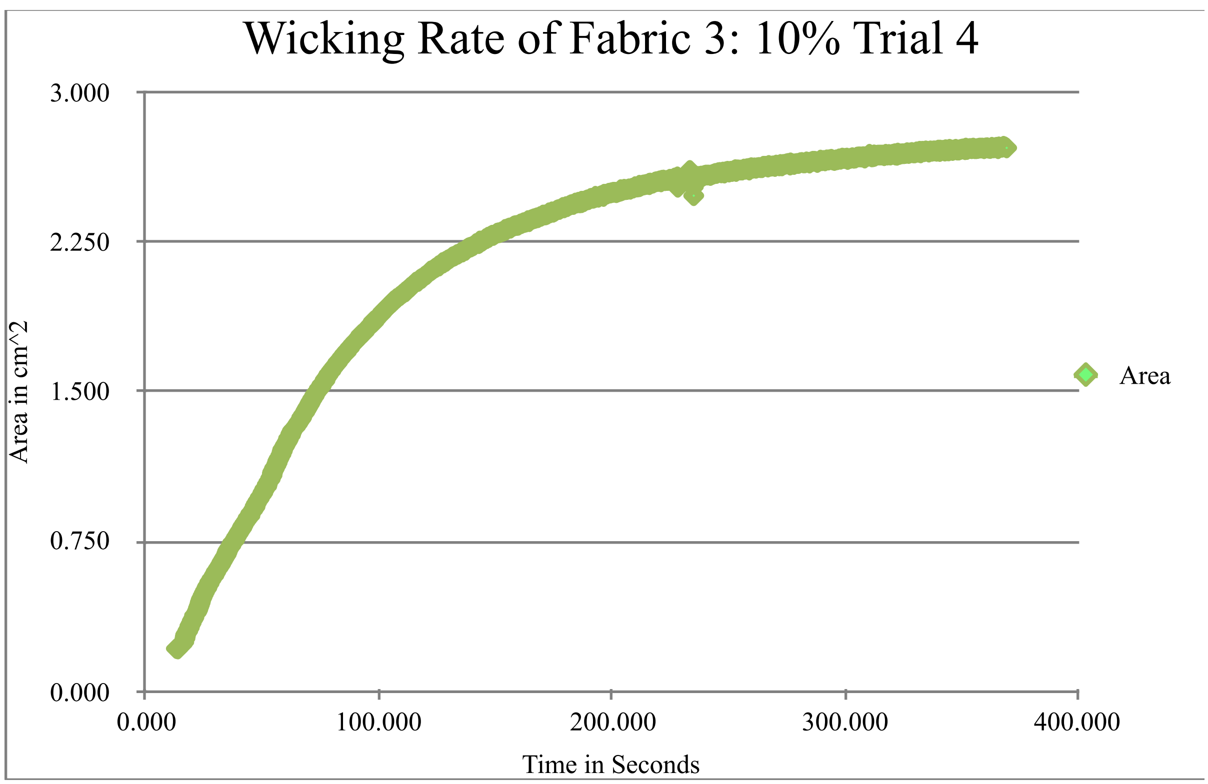
Appendix B

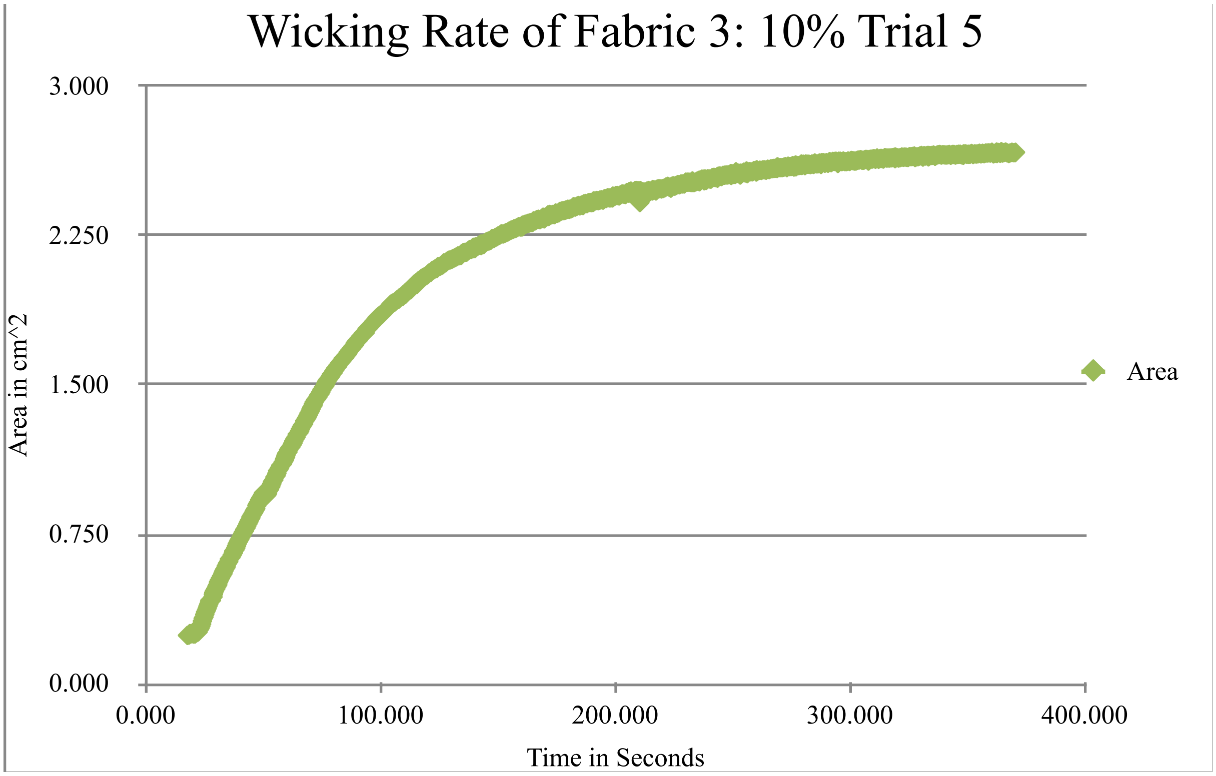
Wicking Rate of Fabric 3: 10% Trial 1-5





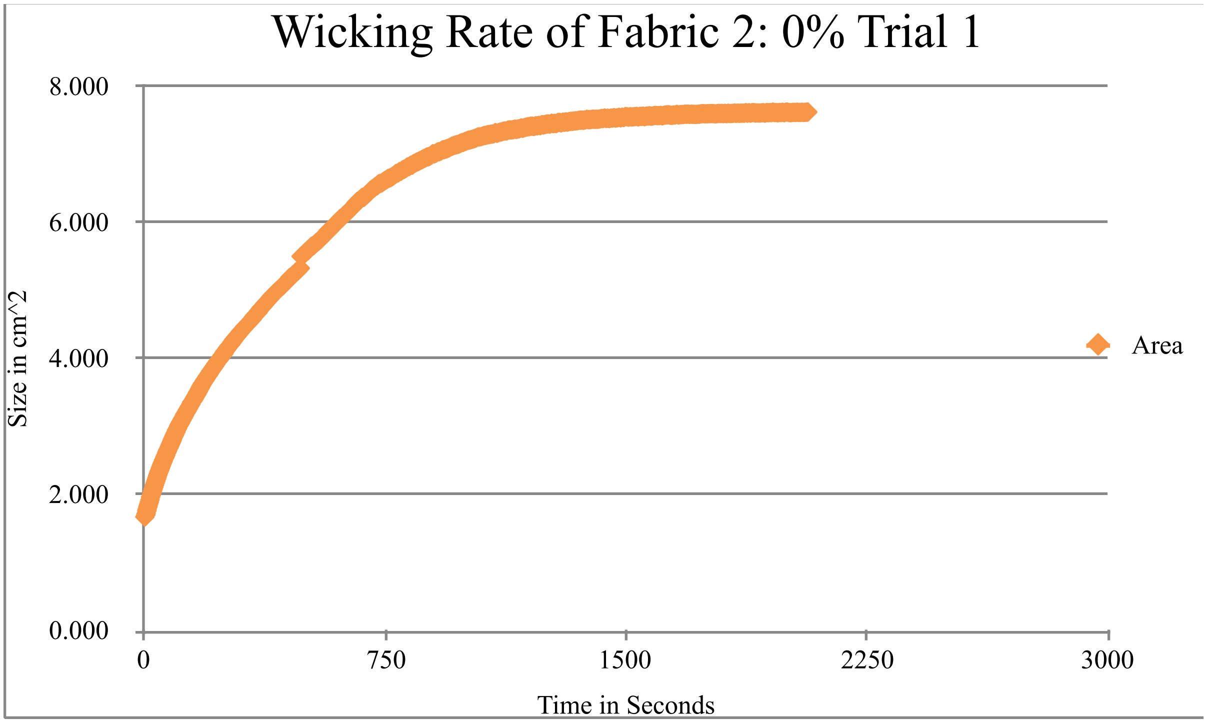

Wicking Rate of Fabric 3: 10% Trial 3
3.000
2.250
1.500
0.750
0.000
Area in cm^2
0.000
100.000
200.000
300.000
400.000
Time in Seconds
Area

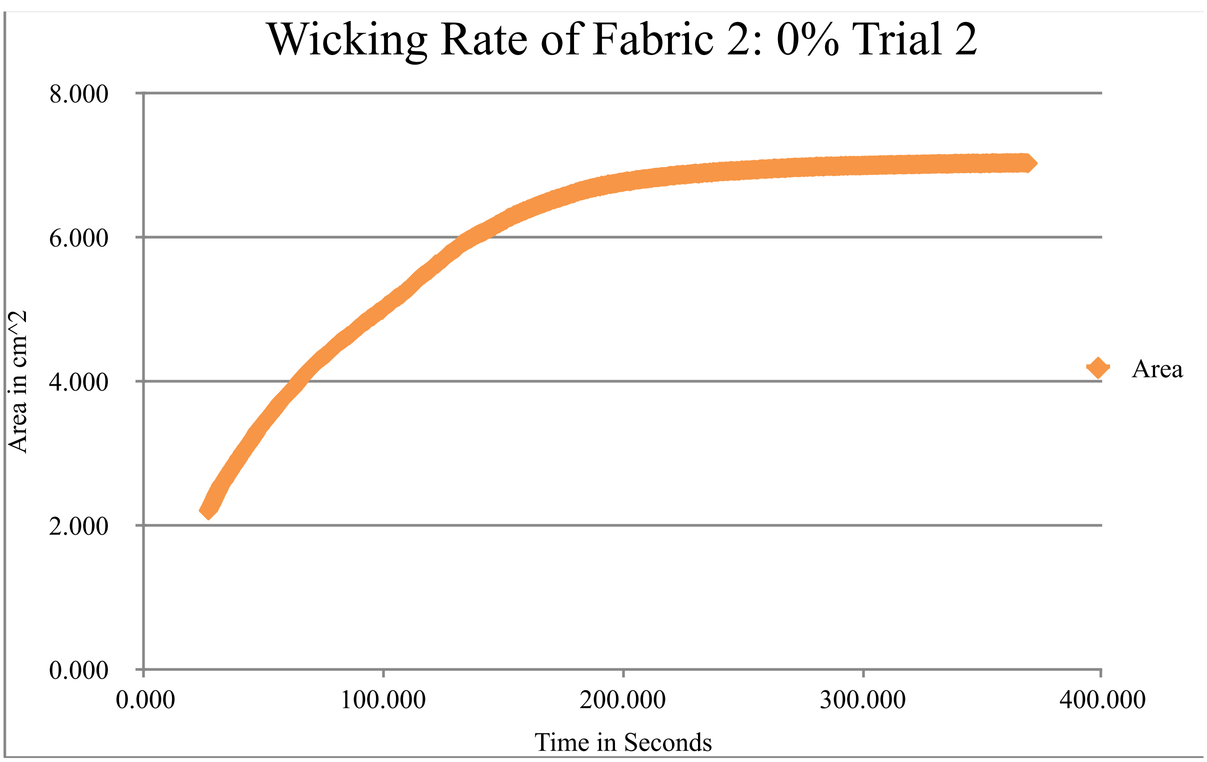

Wicking Rate of Fabric 3: 10% Trial 4
3.000
2.250
1.500
0.750
0.000
Area in cm^2
0.000
100.000
200.000
300.000
400.000
Time in Seconds
Area

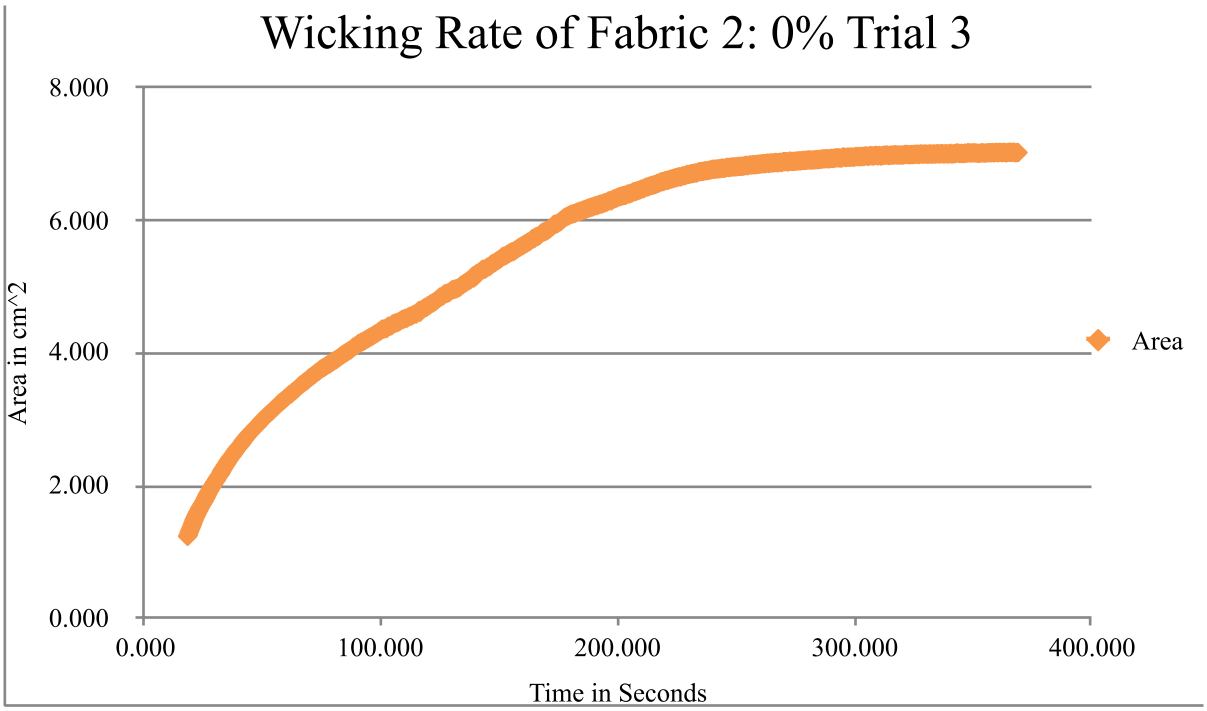

Wicking Rate of Fabric 3: 10% Trial 5
3.000
2.250
1.500
0.750
0.000
Area in cm^2
0.000
100.000
200.000
300.000
400.000
Time in Seconds
Area

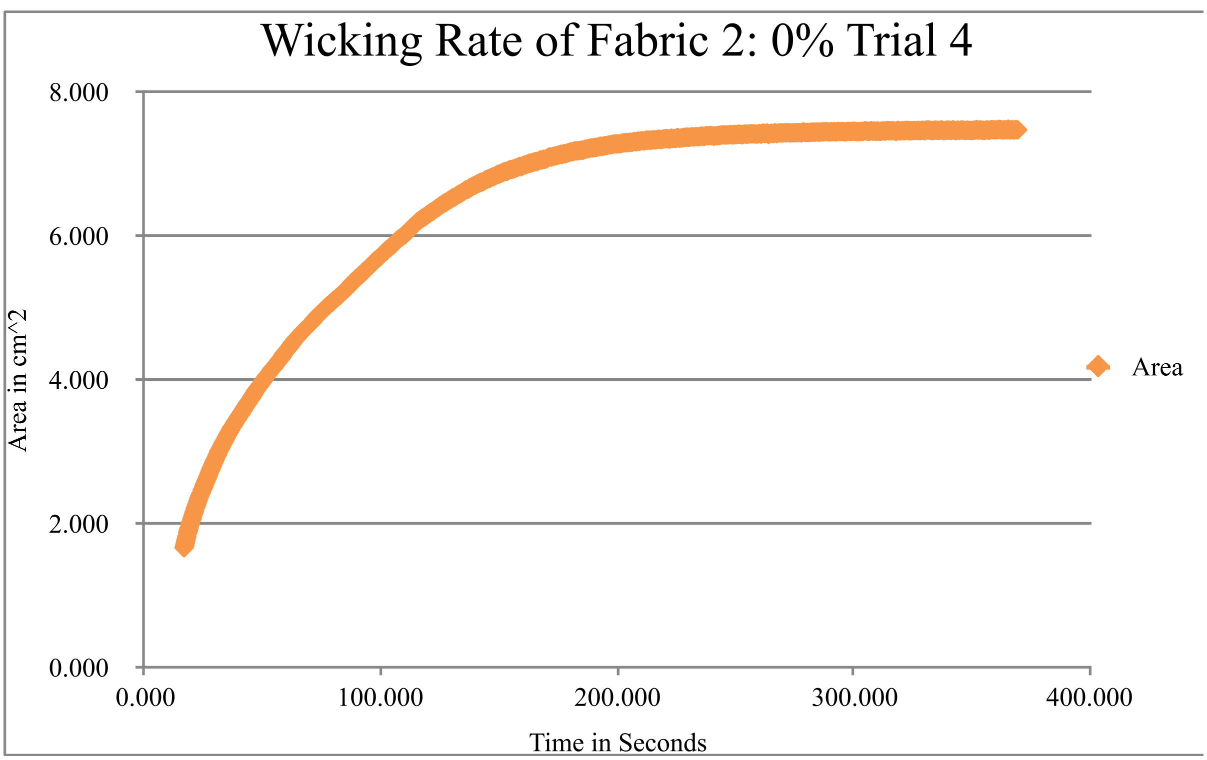
Appendix C

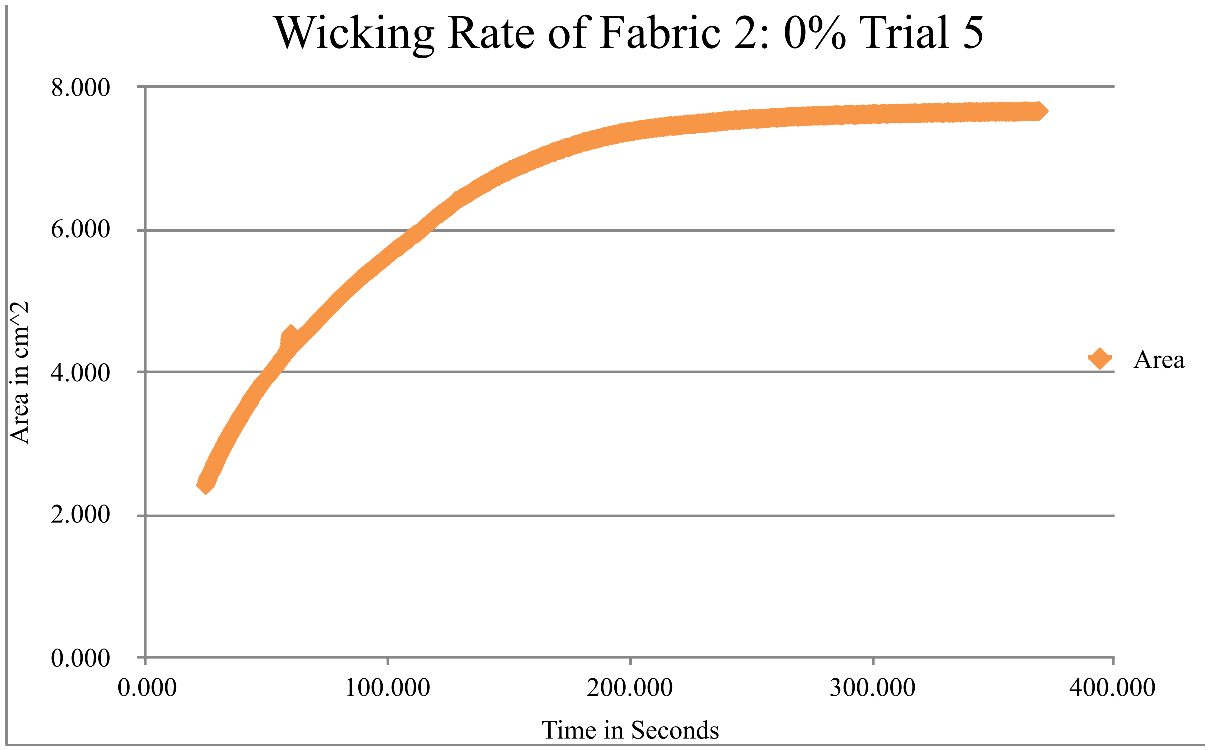
Wicking Rate of Fabric 2: 0% Trial 1-5






Wicking Rate of Fabric 2: 0% Trial 3
8.000
6.000
4.000
2.000
0.000
Area in cm^2
0.000
100.000
200.000
300.000
400.000
Time in Seconds
Area

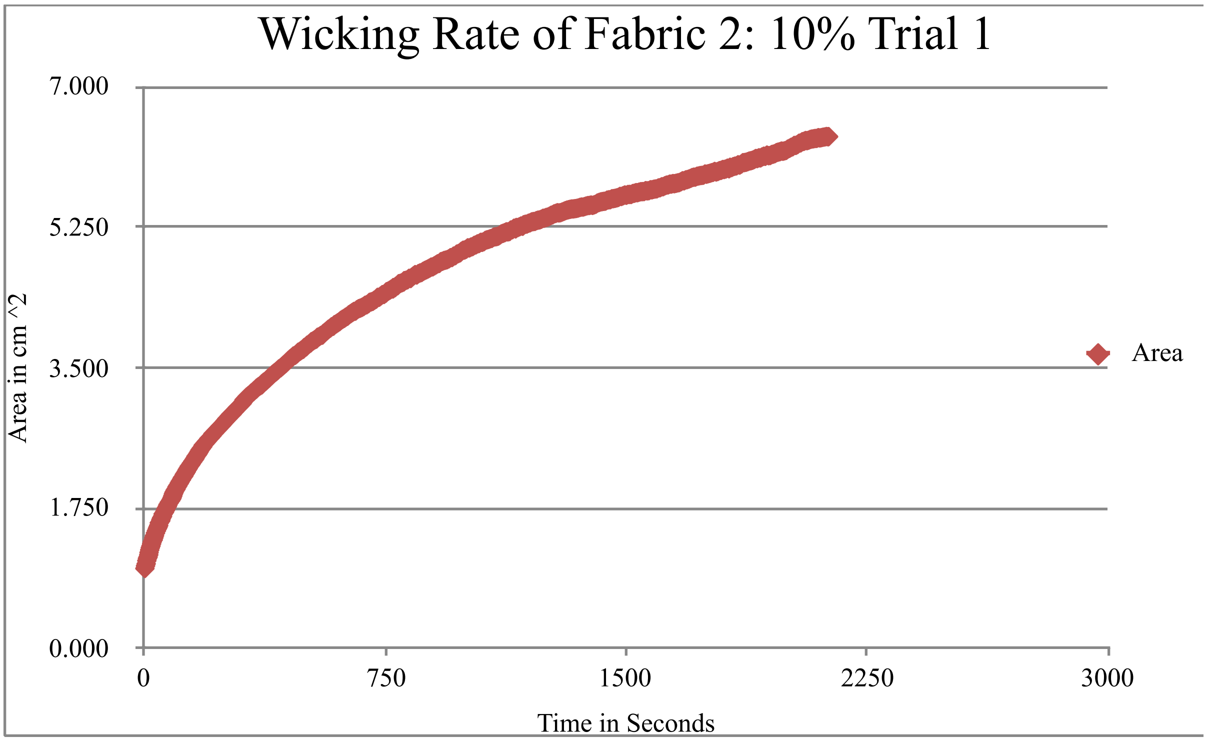

Wicking Rate of Fabric 2: 0% Trial 4
8.000
6.000
4.000
2.000
0.000
Area in cm^2
0.000
100.000
200.000
300.000
400.000
Time in Seconds
Area

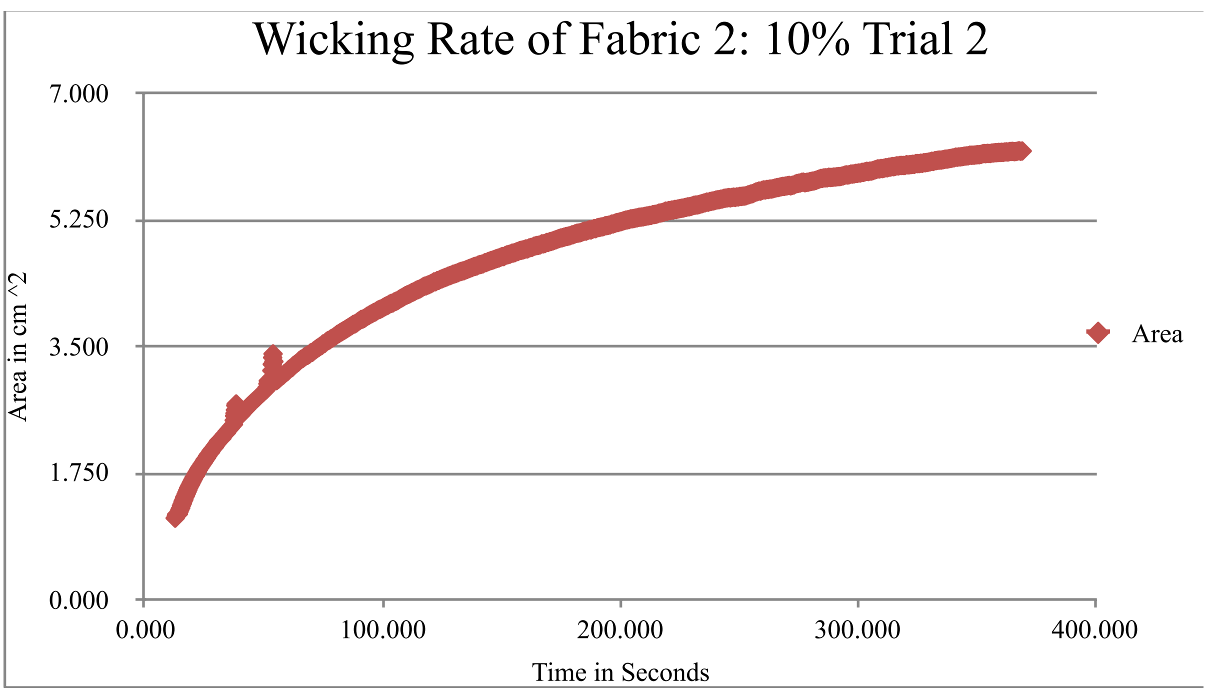


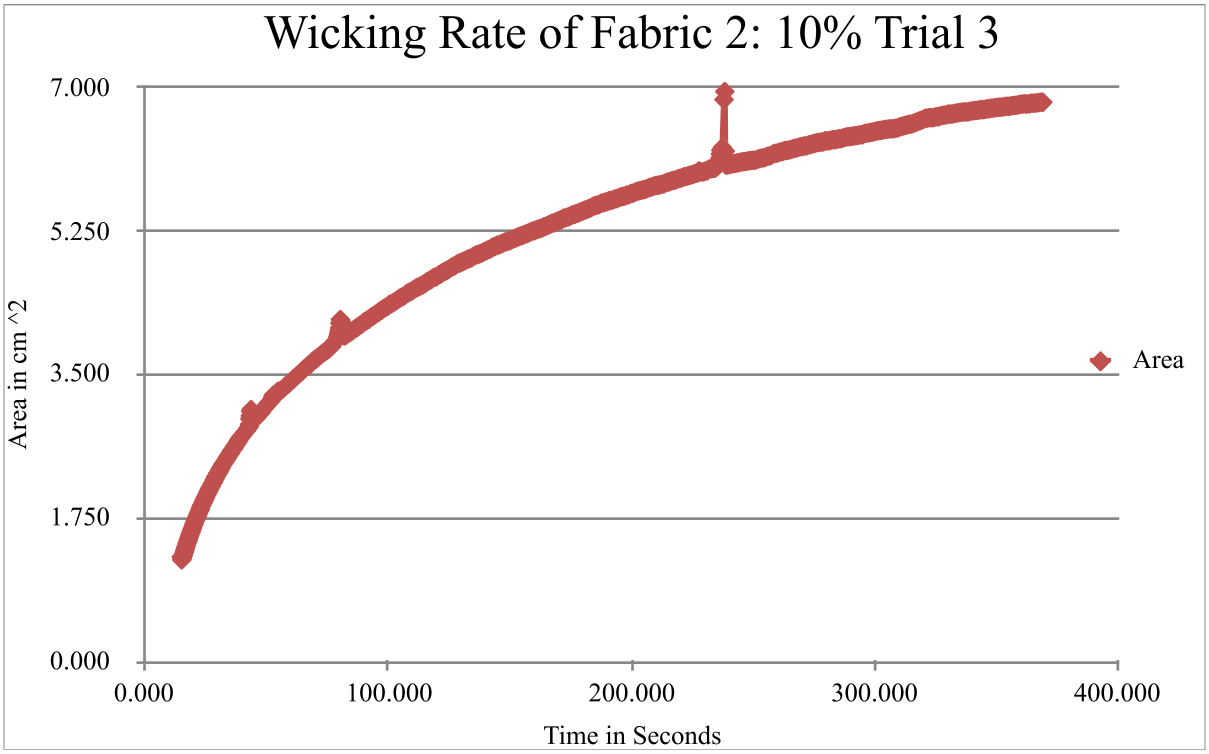
Wicking Rate of Fabric 2: 0% Trial 5
8.000
6.000
4.000
2.000
0.000
0.000
100.000
200.000
300.000
400.000
Area in cm^2
Time in Seconds
Area

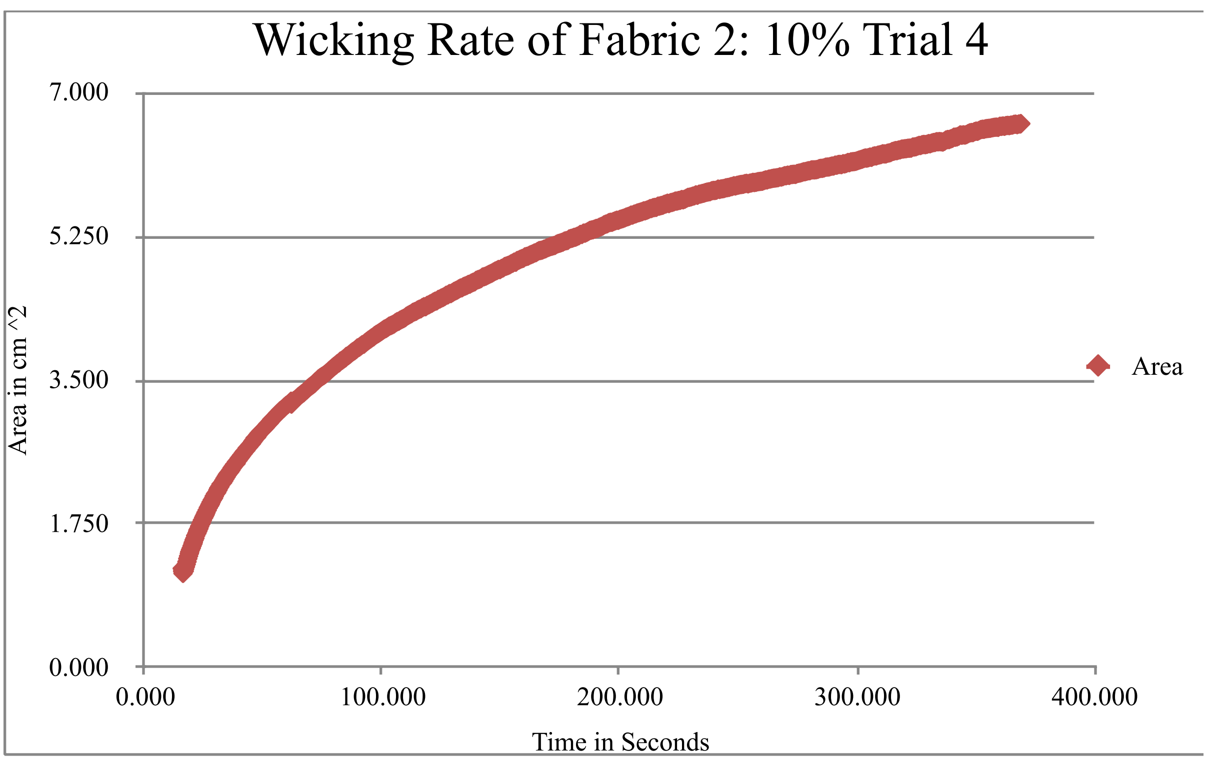
Appendix D

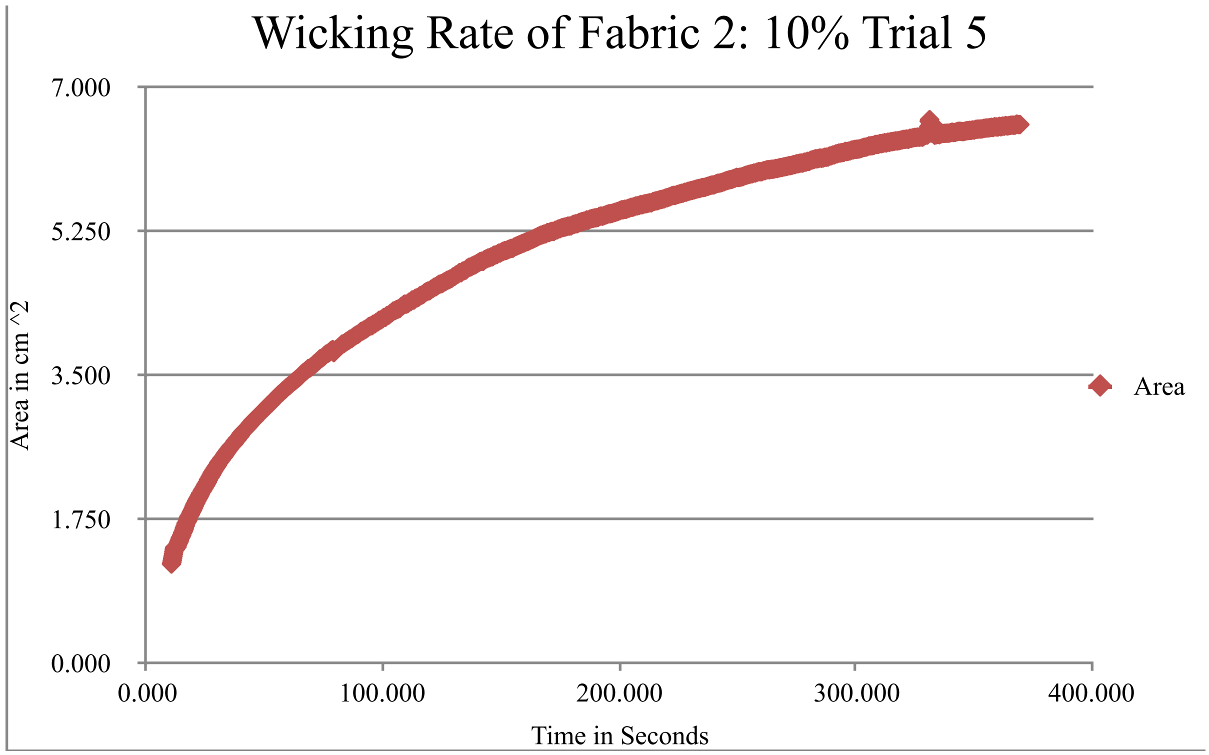
Wicking Rate of Fabric 2: 10% Trials 1-5






Wicking Rate of Fabric 2: 10% Trial 3
7.000
5.250
3.500
1.750
0.000
Area in cm ^2
0.000
100.000
200.000
300.000
400.000
Time in Seconds
Area

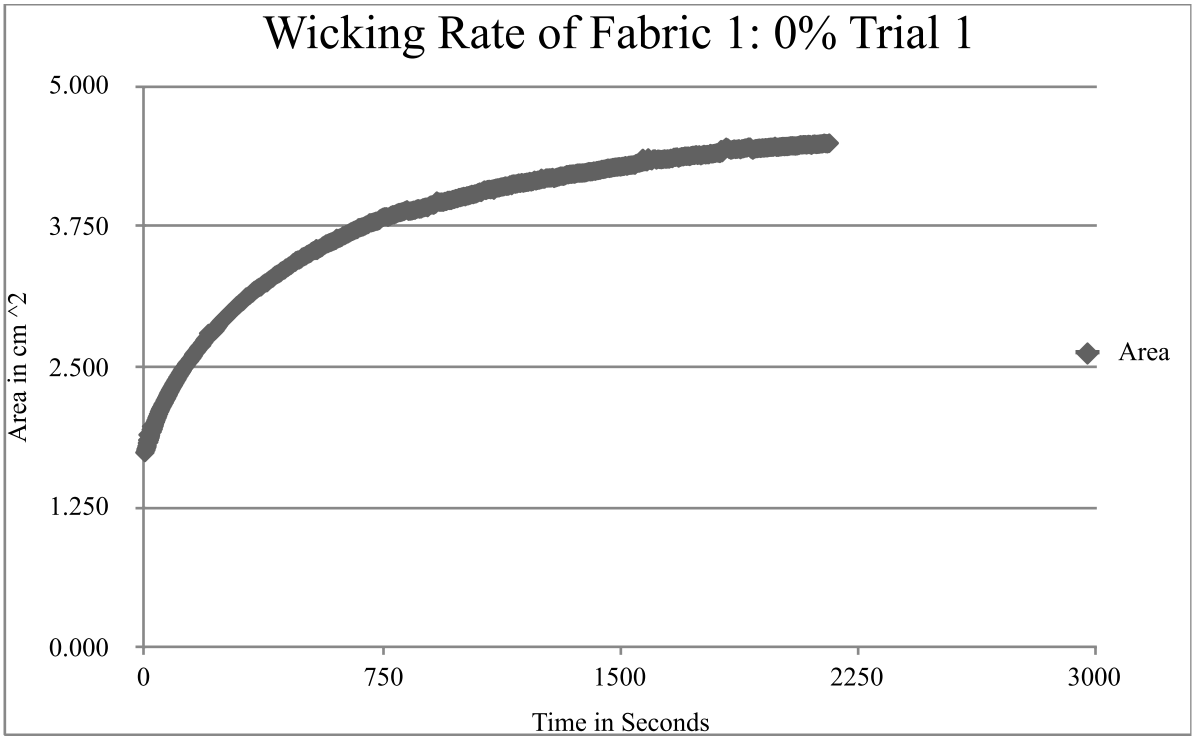

Wicking Rate of Fabric 2: 10% Trial 4
7.000
5.250
3.500
1.750
0.000
Area in cm ^2
0.000
100.000
200.000
300.000
400.000
Time in Seconds
Area

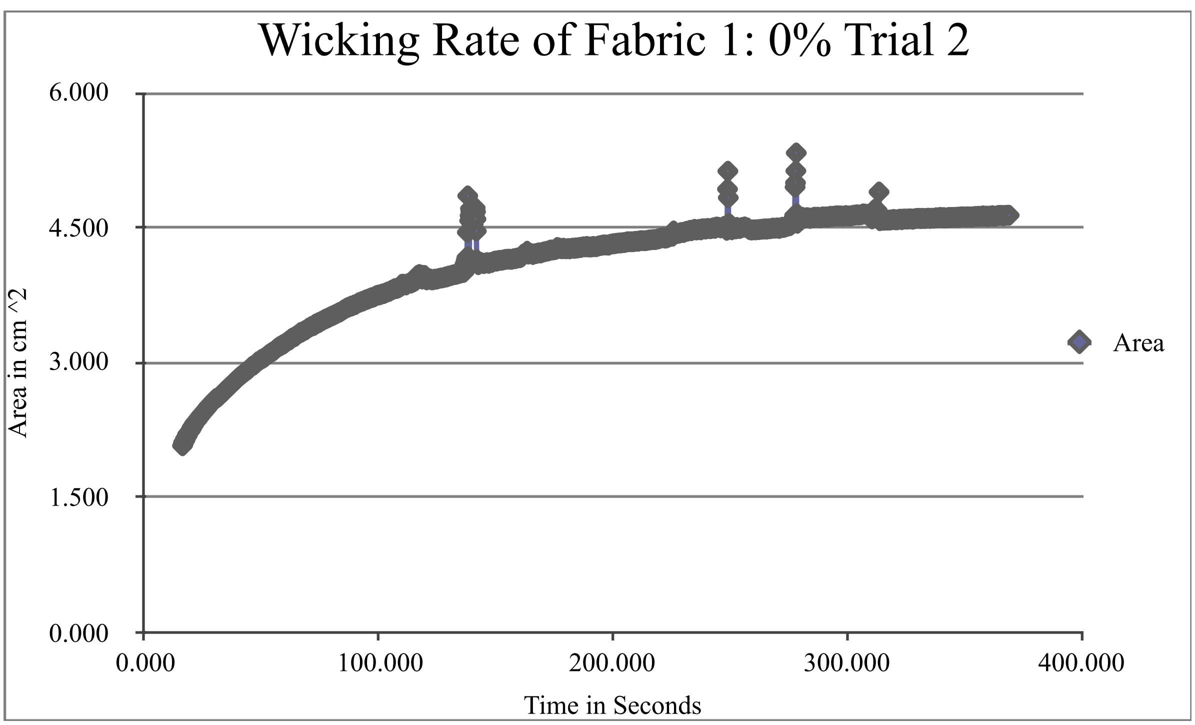


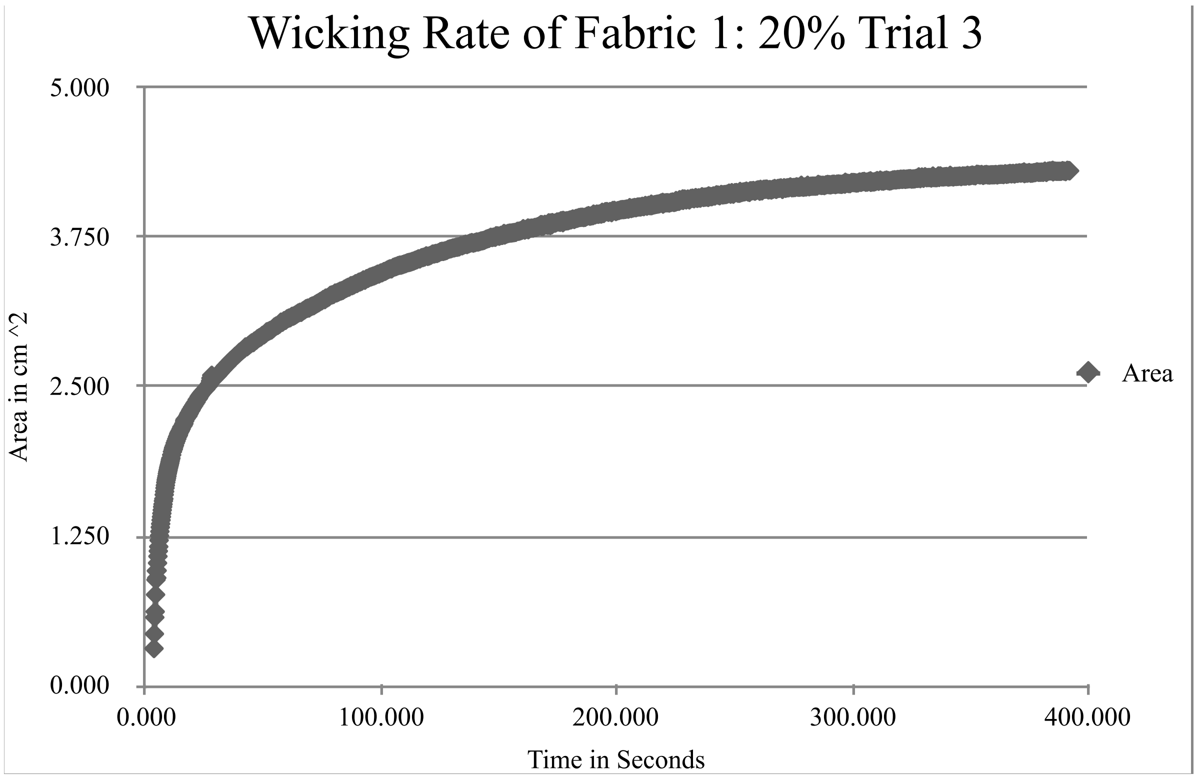
Wicking Rate of Fabric 2: 10% Trial 5
7.000
5.250
3.500
1.750
0.000
Area in cm ^2
0.000
100.000
200.000
300.000
400.000
Time in Seconds
Area

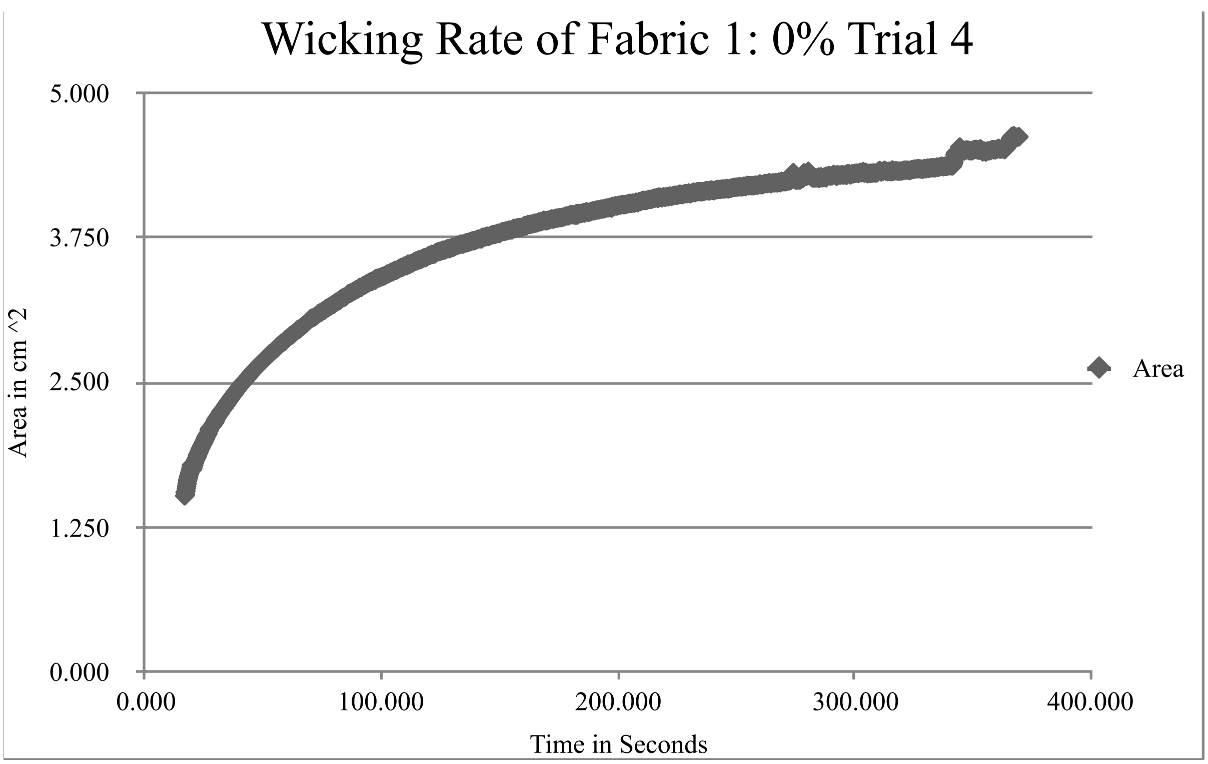
Appendix E

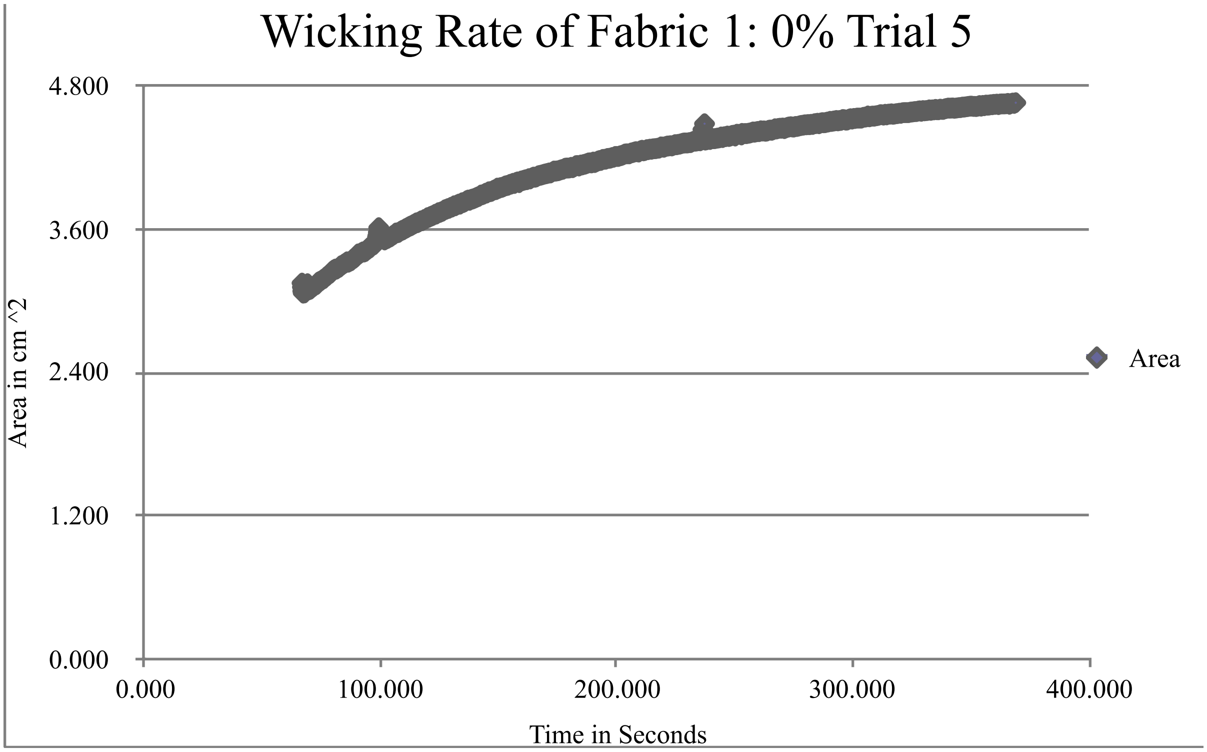
Wicking Rate of Fabric 1: 0% Trials 1-5






Wicking Rate of Fabric 1: 20% Trial 3
5.000
3.750
2.500
1.250
0.000
0.000
100.000
200.000
300.000
400.000
Time in Seconds
Area in cm ^2
Area

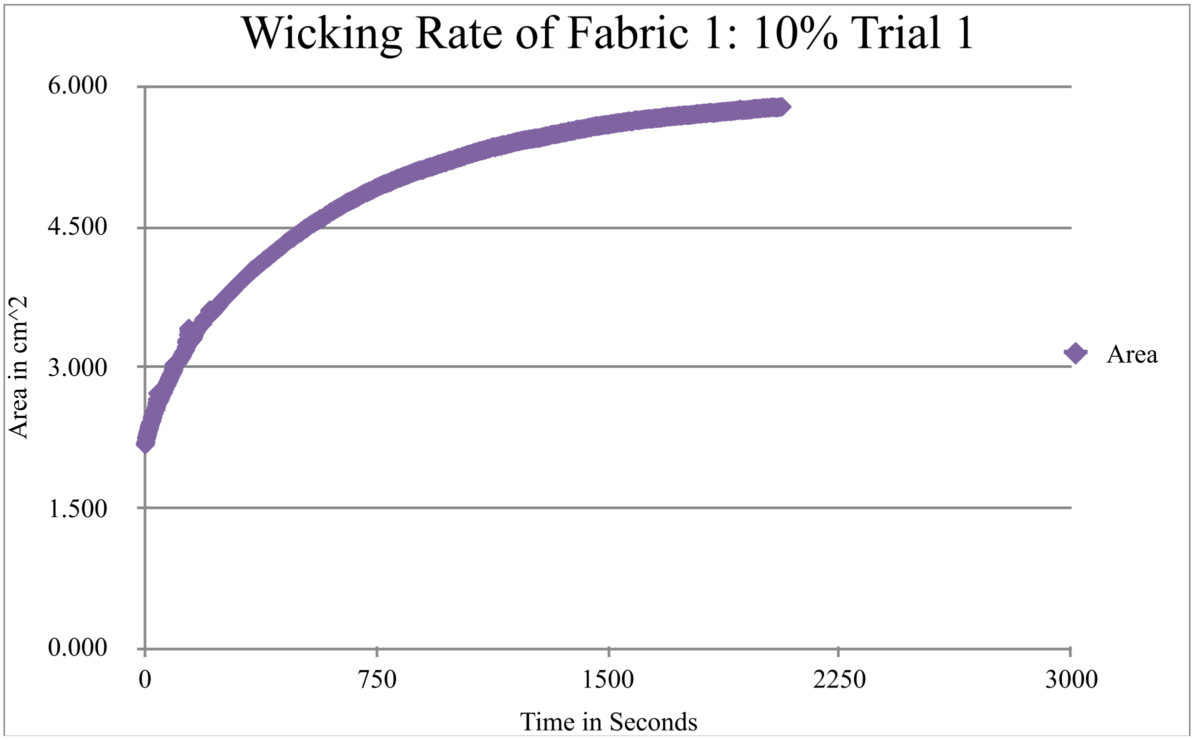

Wicking Rate of Fabric 1: 0% Trial 4
5.000
3.750
2.500
1.250
0.000
0.000
100.000
200.000
300.000
400.000
Time in Seconds
Area in cm ^2
Area

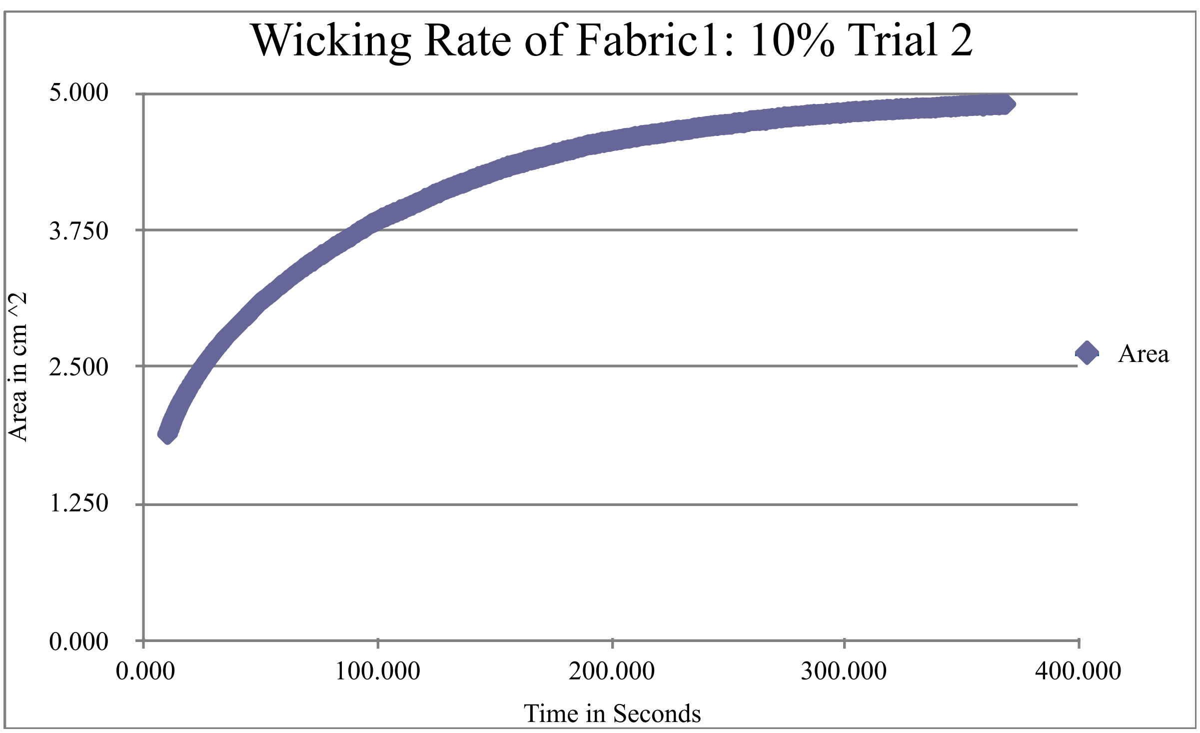


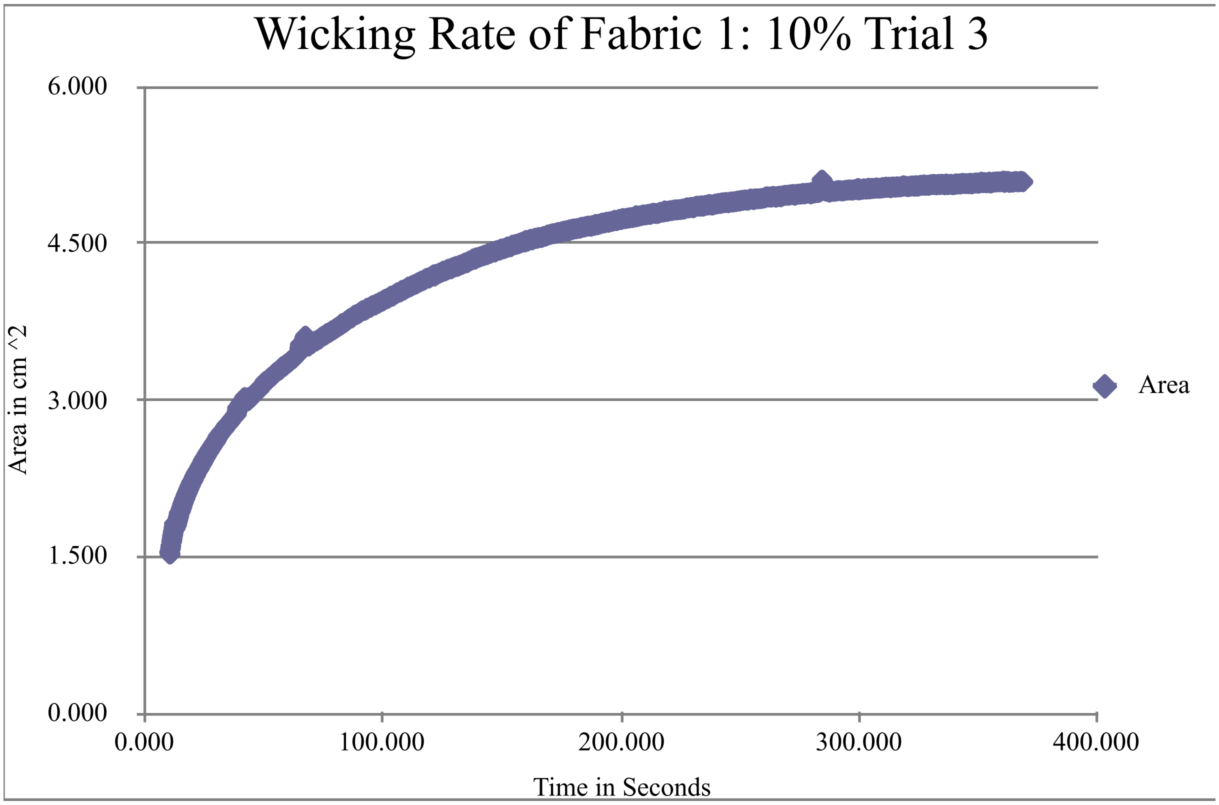
Wicking Rate of Fabric 1: 0% Trial 5
4.800
3.600
2.400
1.200
0.000
Area in cm ^2
0.000
100.000
200.000
300.000
400.000
Time in Seconds
Area

Appendix F

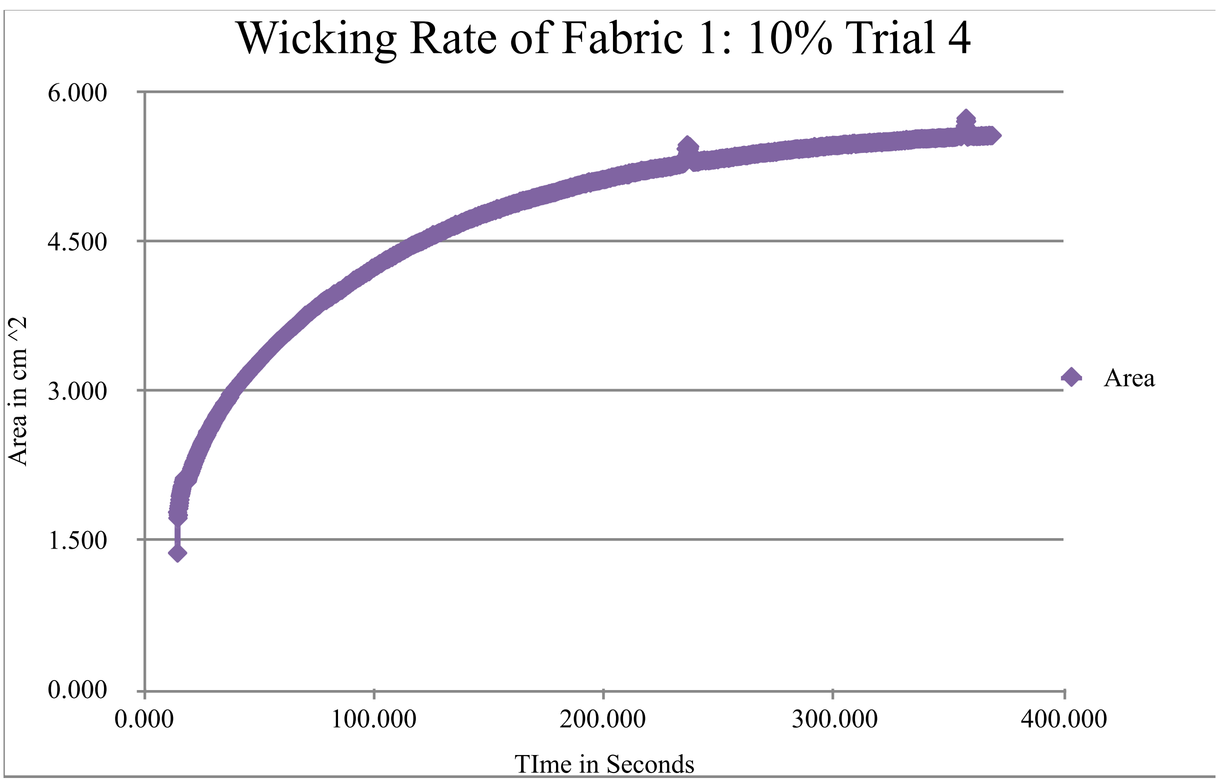
Wicking Rate of Fabric 1: 10% Trials 1-5



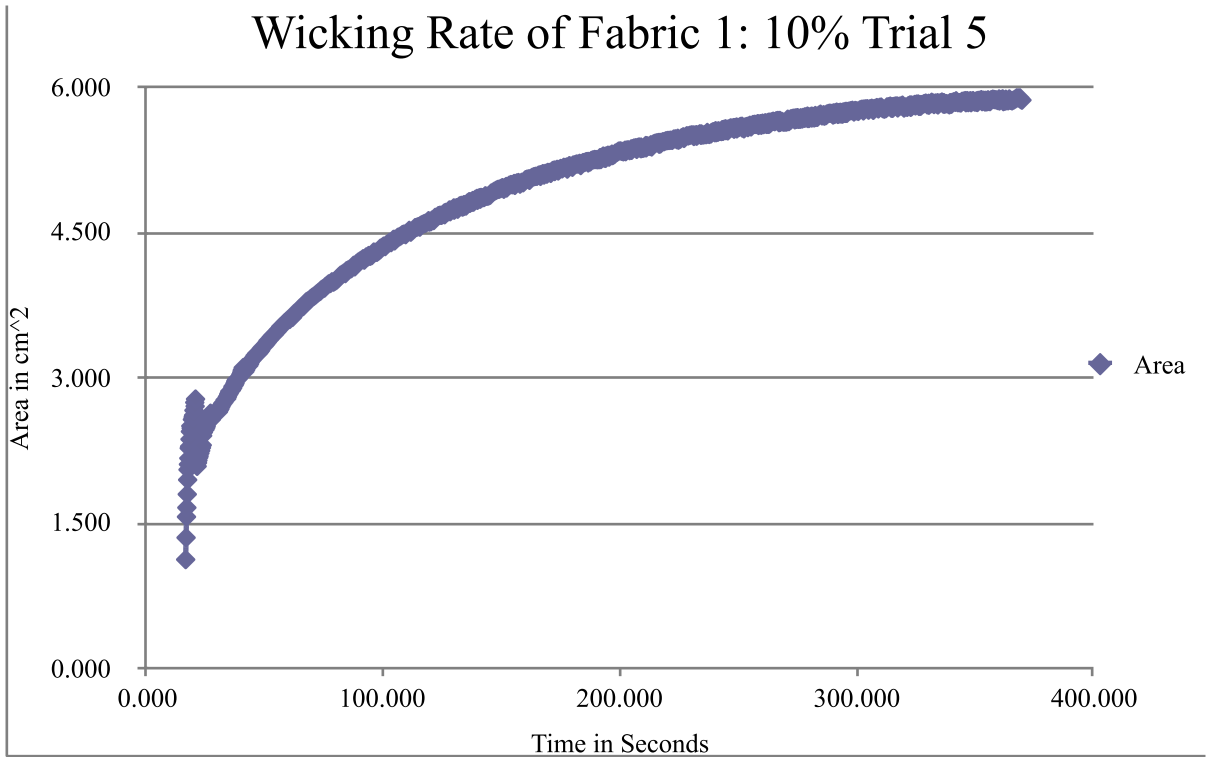




Wicking Rate of Fabric 1: 10% Trial 3
6.000
4.500
3.000
1.500
0.000
0.000
100.000
200.000
300.000
400.000
Area in cm ^2
Time in Seconds
Area



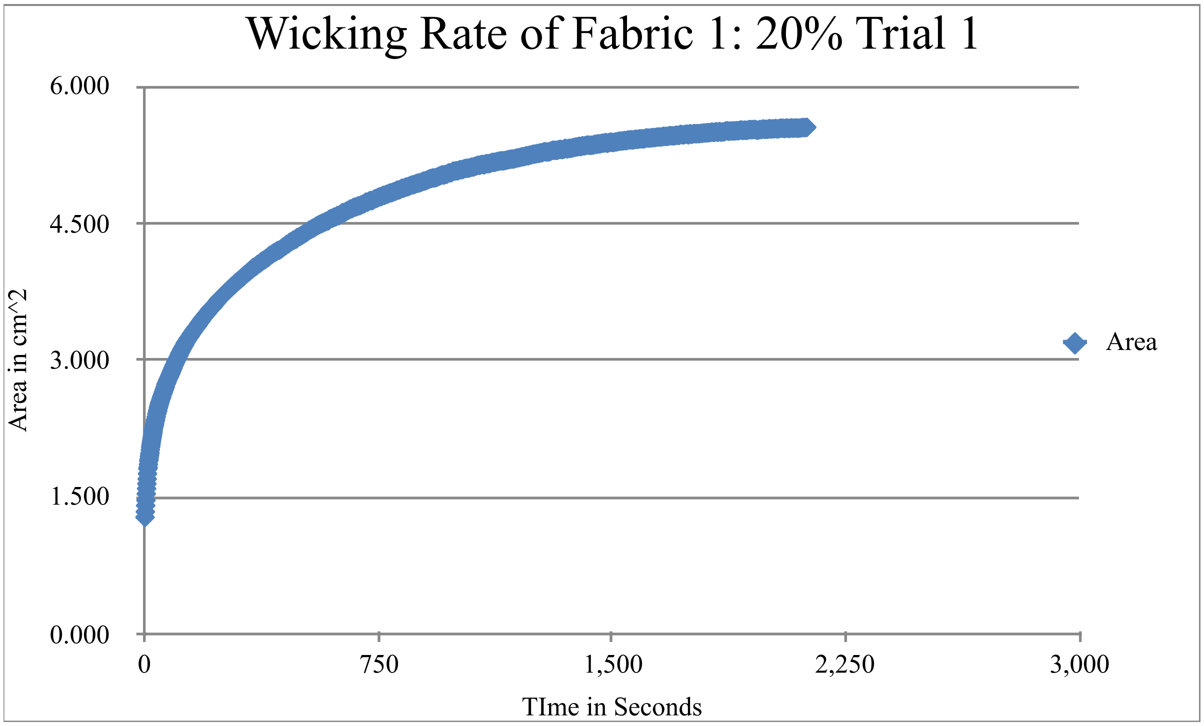
Wicking Rate of Fabric 1: 10% Trial 4
6.000
4.500
3.000
1.500
0.000
0.000
100.000
200.000
300.000
400.000
Area in cm ^2
TIme in Seconds
Area

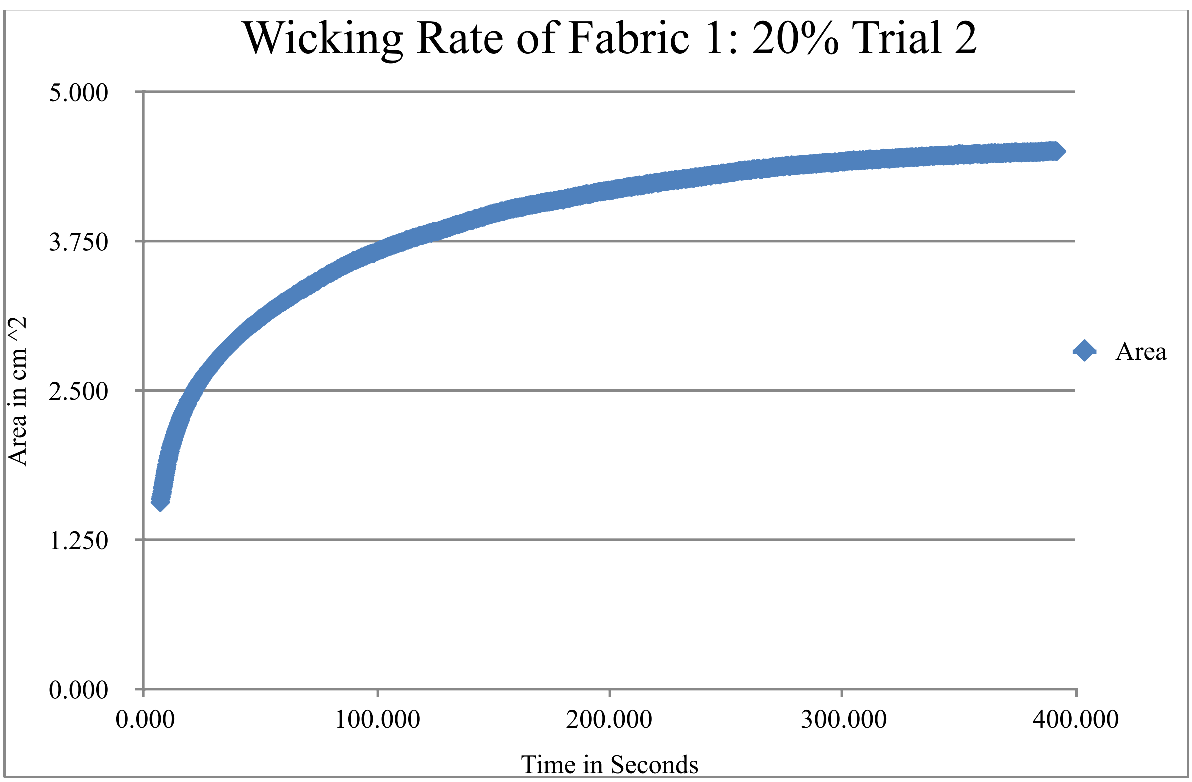


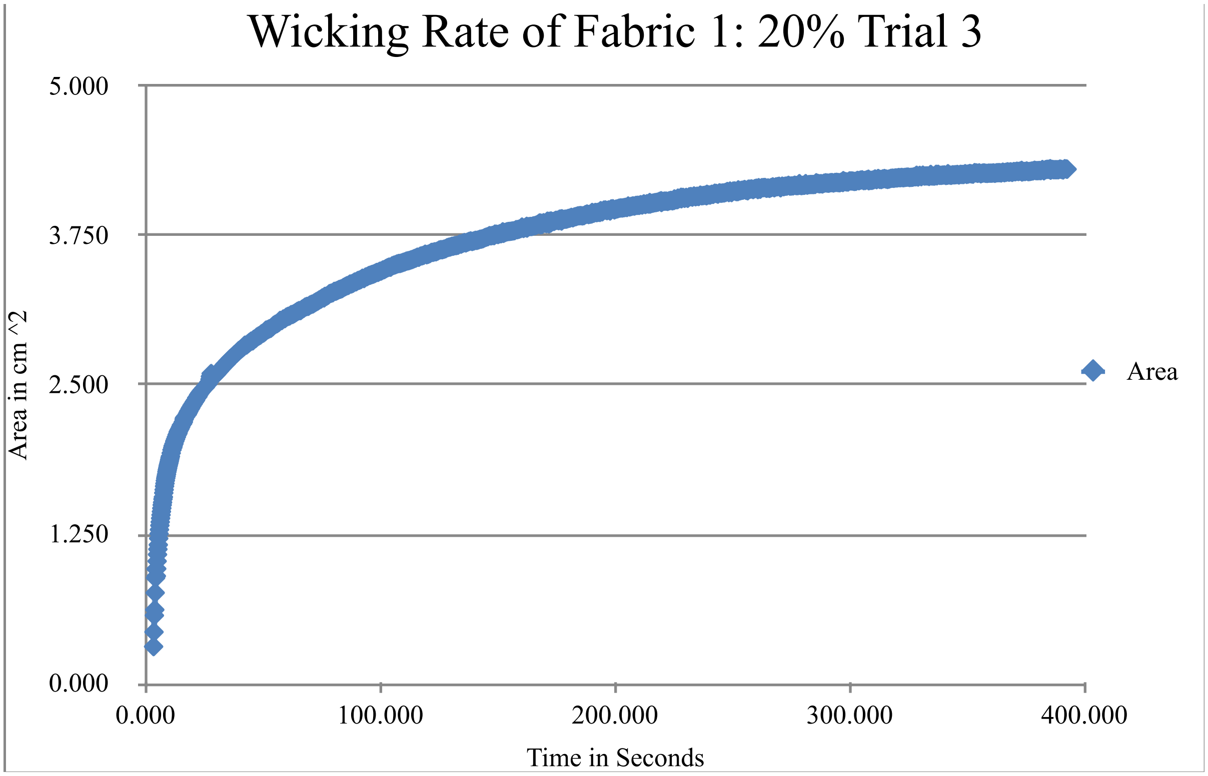
Wicking Rate of Fabric 1: 10% Trial 5
6.000
4.500
3.000
1.500
0.000
Area in cm^2
0.000
100.000
200.000
300.000
400.000
Time in Seconds
Area

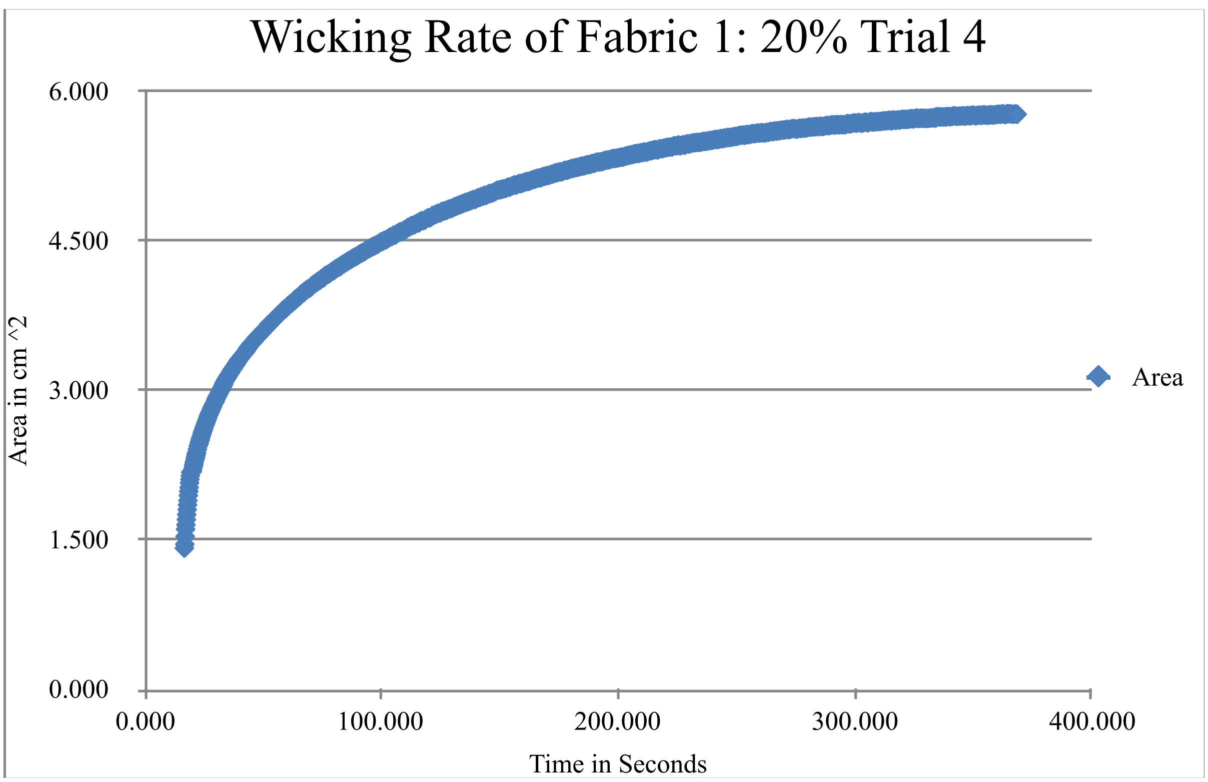
Appendix G

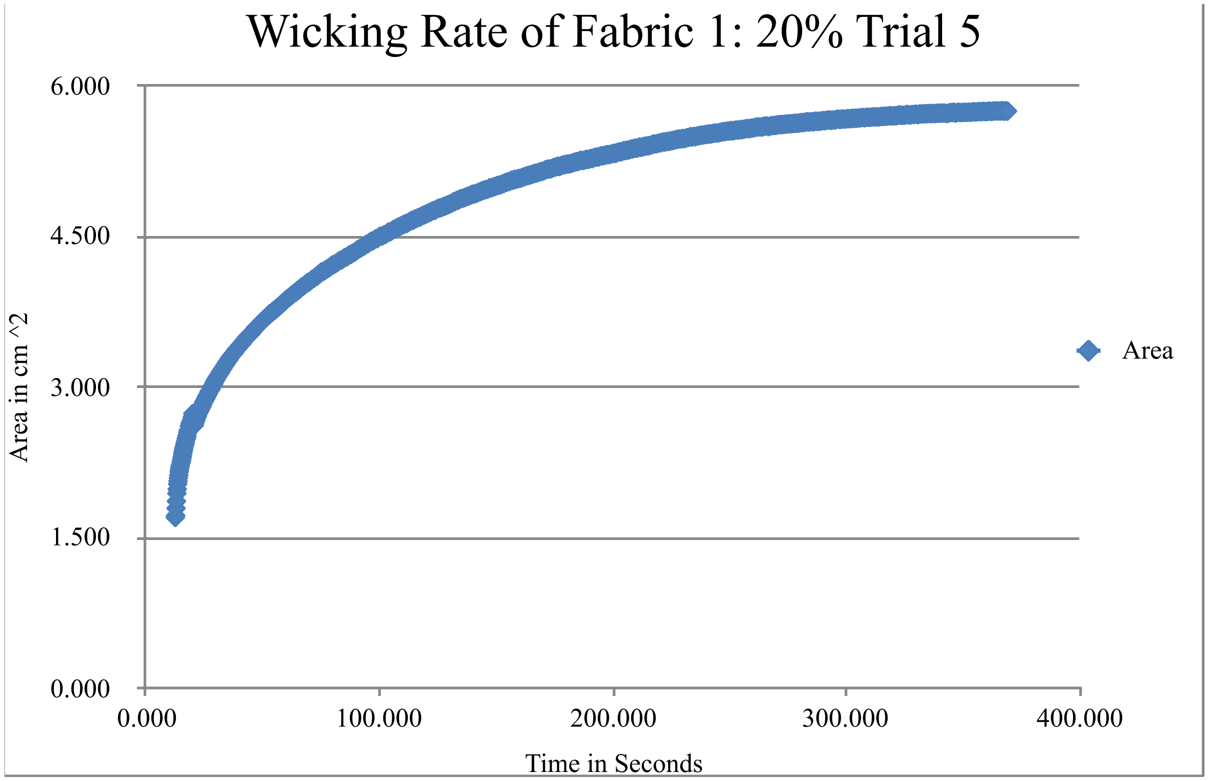
Wicking Rate of Fabric 1: 20% Trials 1-5





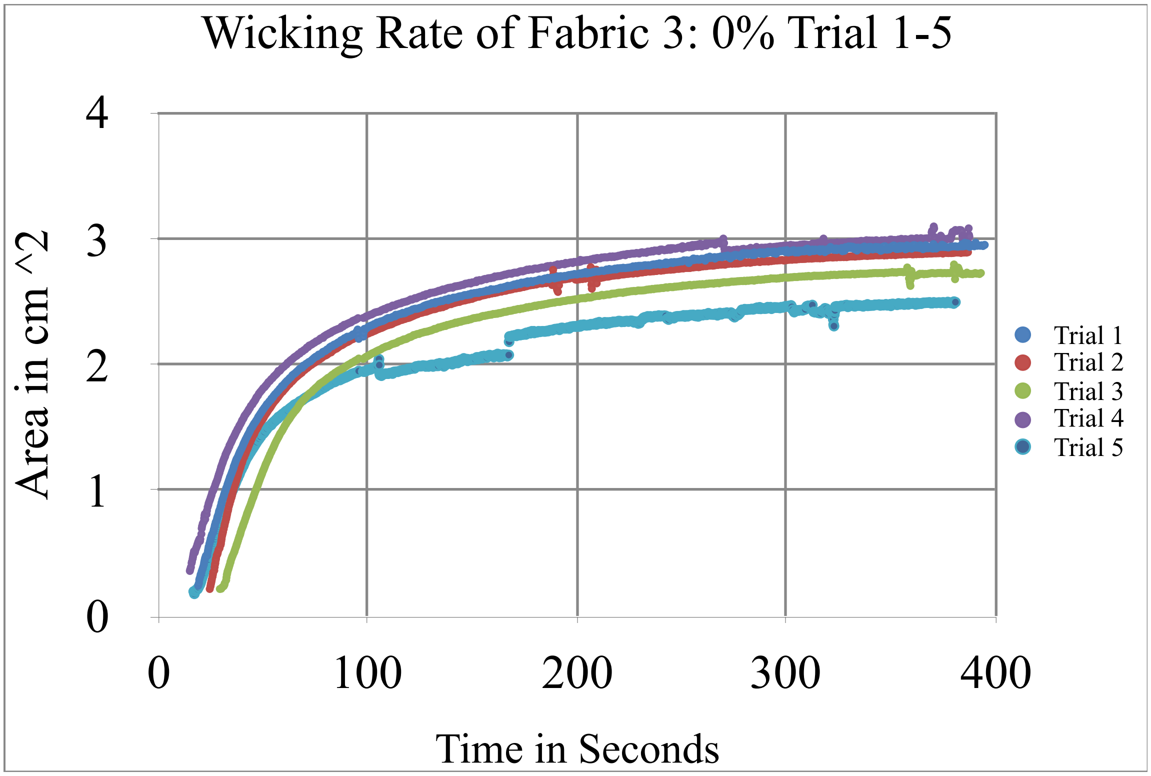

Wicking Rate of Fabric 1: 20% Trial 3
5.000
3.750
2.500
1.250
0.000
Area in cm ^2
0.000
100.000
200.000
300.000
400.000
Time in Seconds
Area

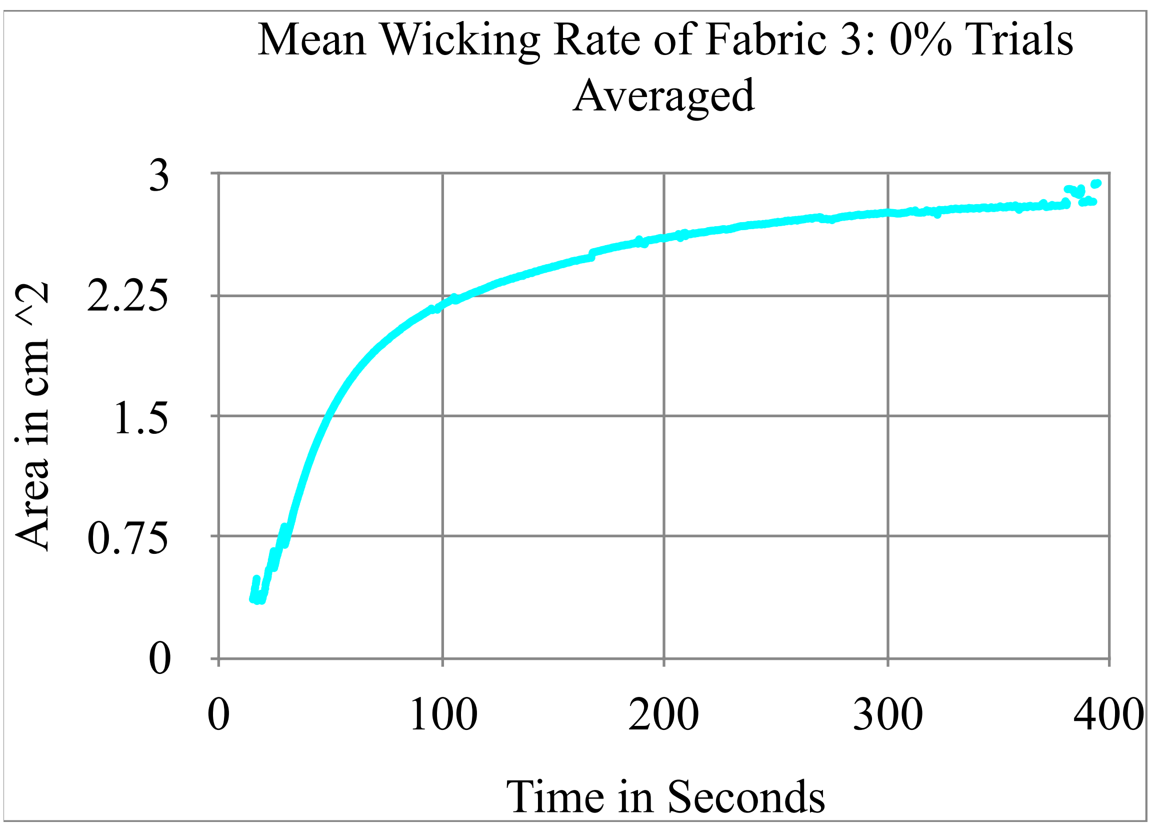

Wicking Rate of Fabric 1: 20% Trial 4
6.000
4.500
3.000
1.500
0.000
Area in cm ^2
0.000
100.000
200.000
300.000
400.000
Time in Seconds
Area

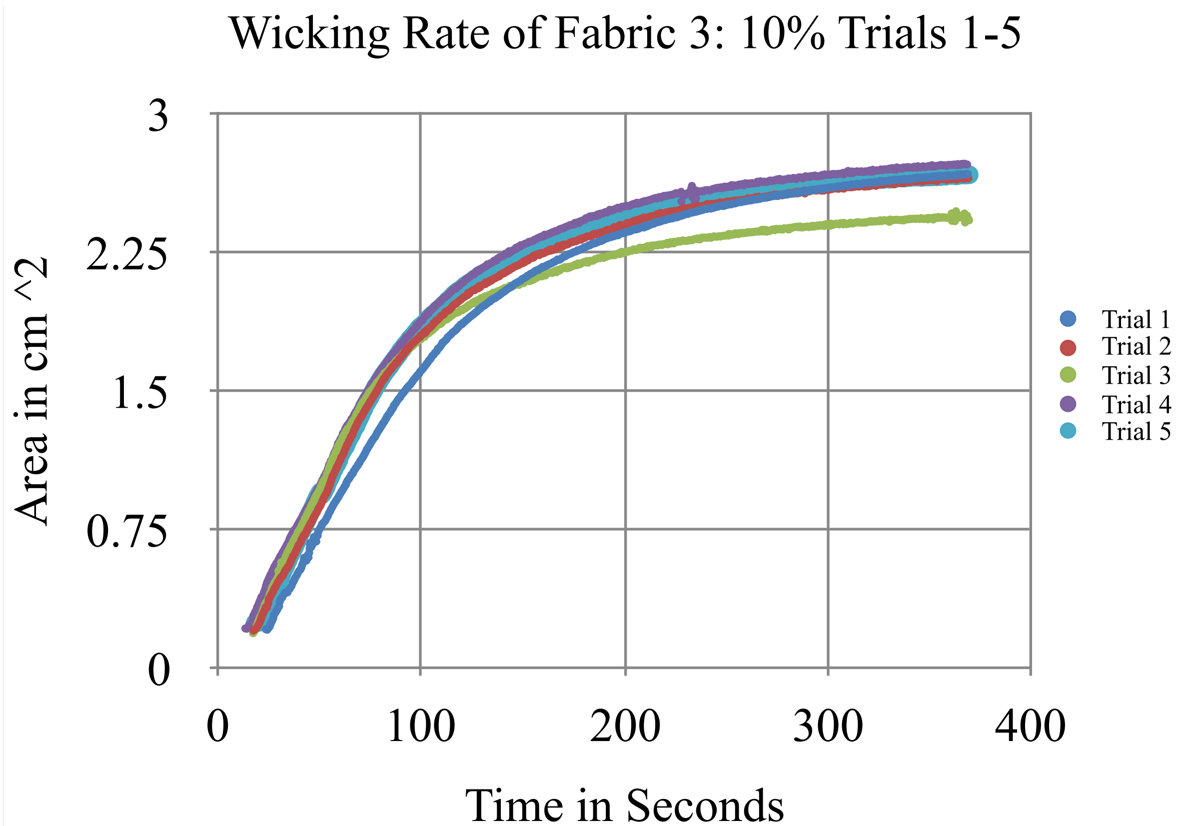

Wicking Rate of Fabric 1: 20% Trial 5
6.000
4.500
3.000
1.500
0.000
Area in cm ^2
0.000
100.000
200.000
300.000
400.000
Time in Seconds
Area

Appendix H

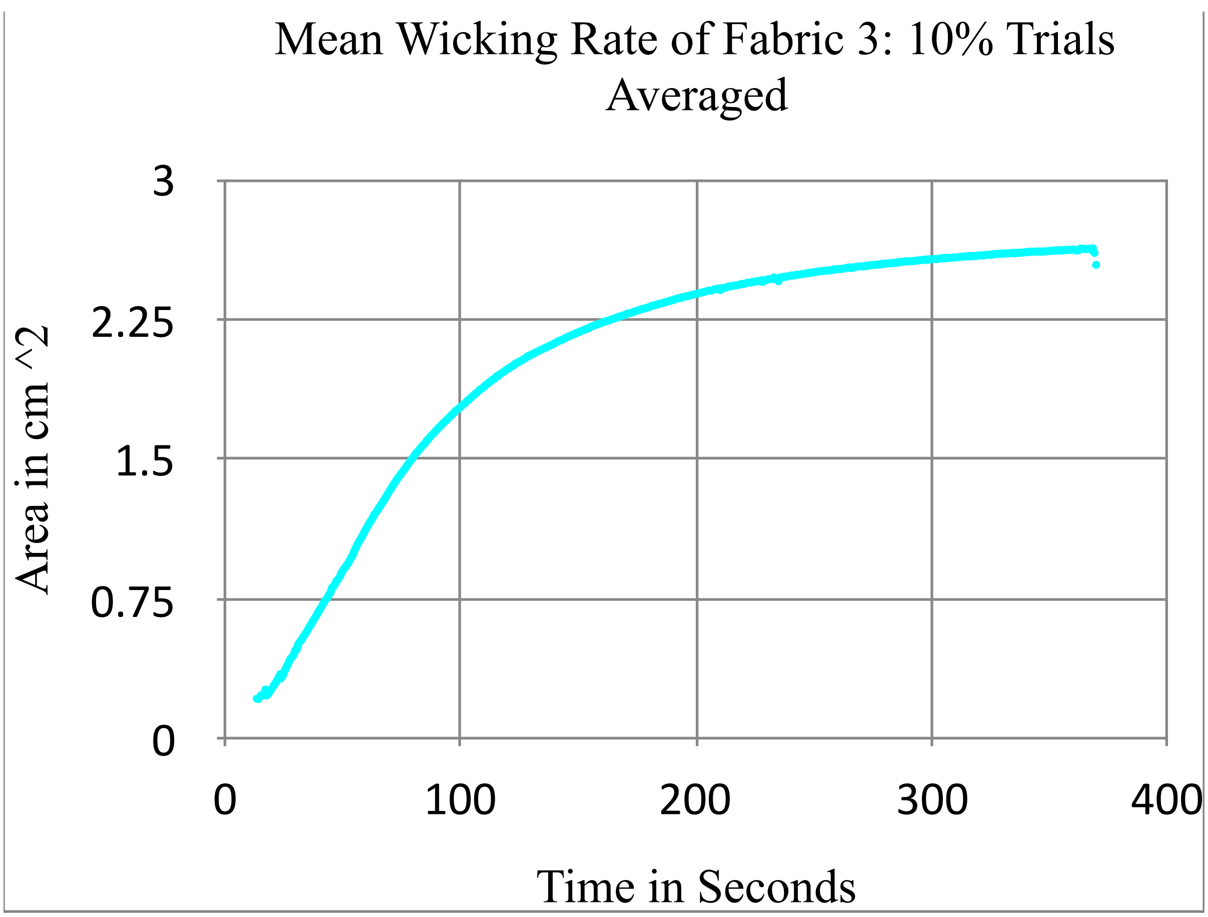
Mean Wicking Rate of Fabric Samples



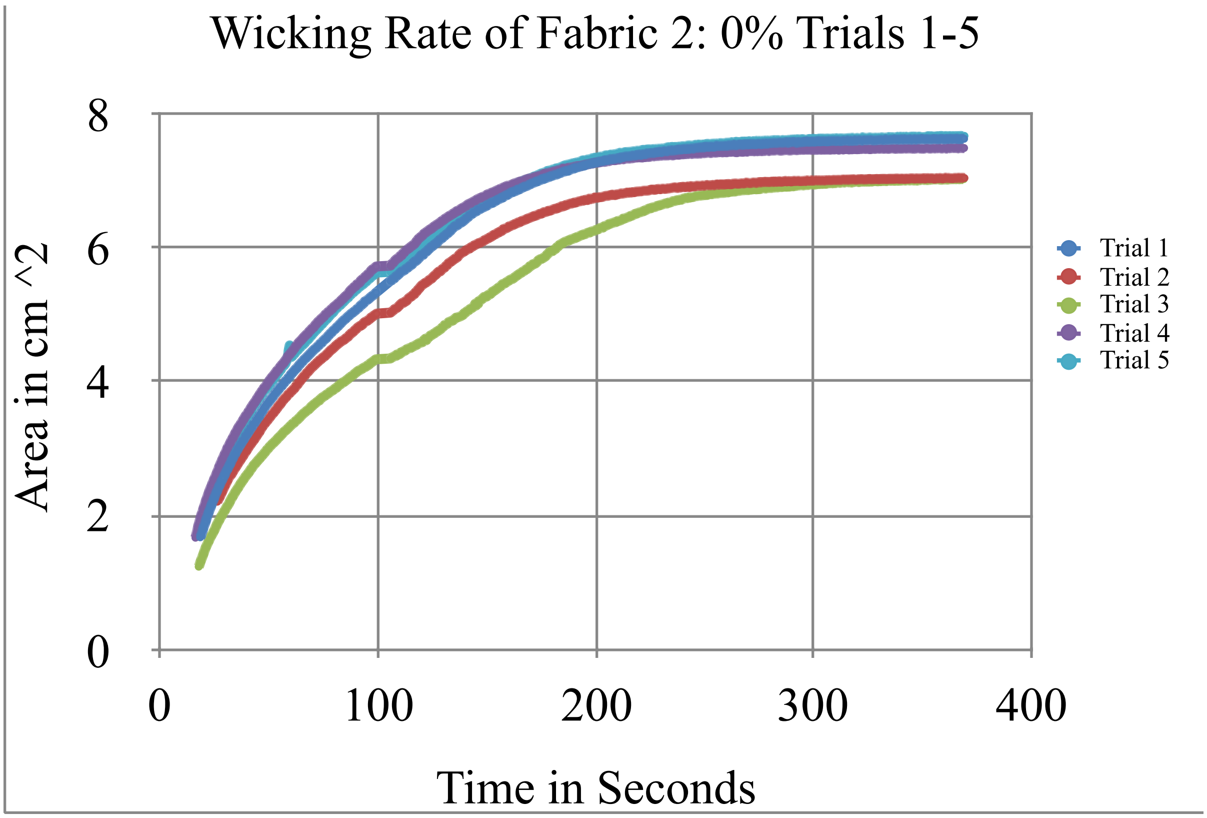


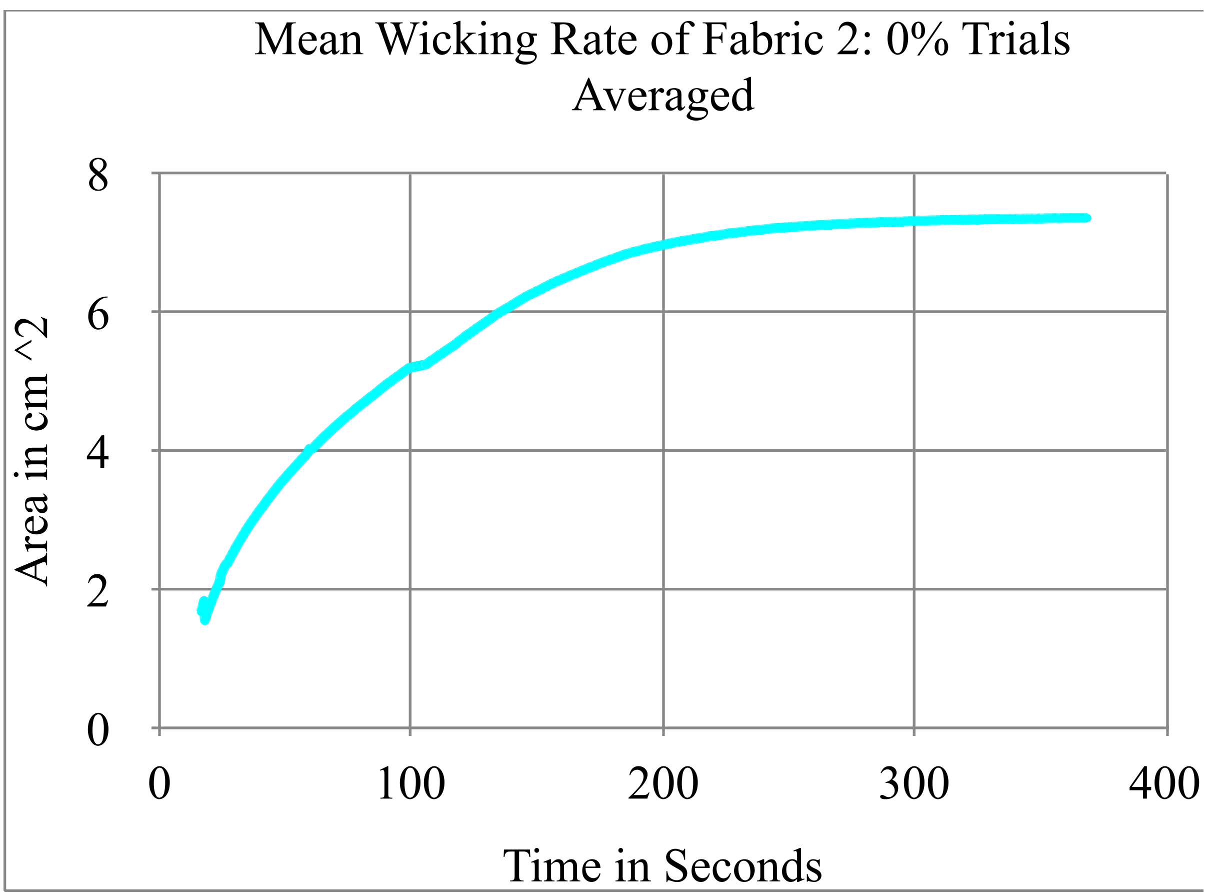


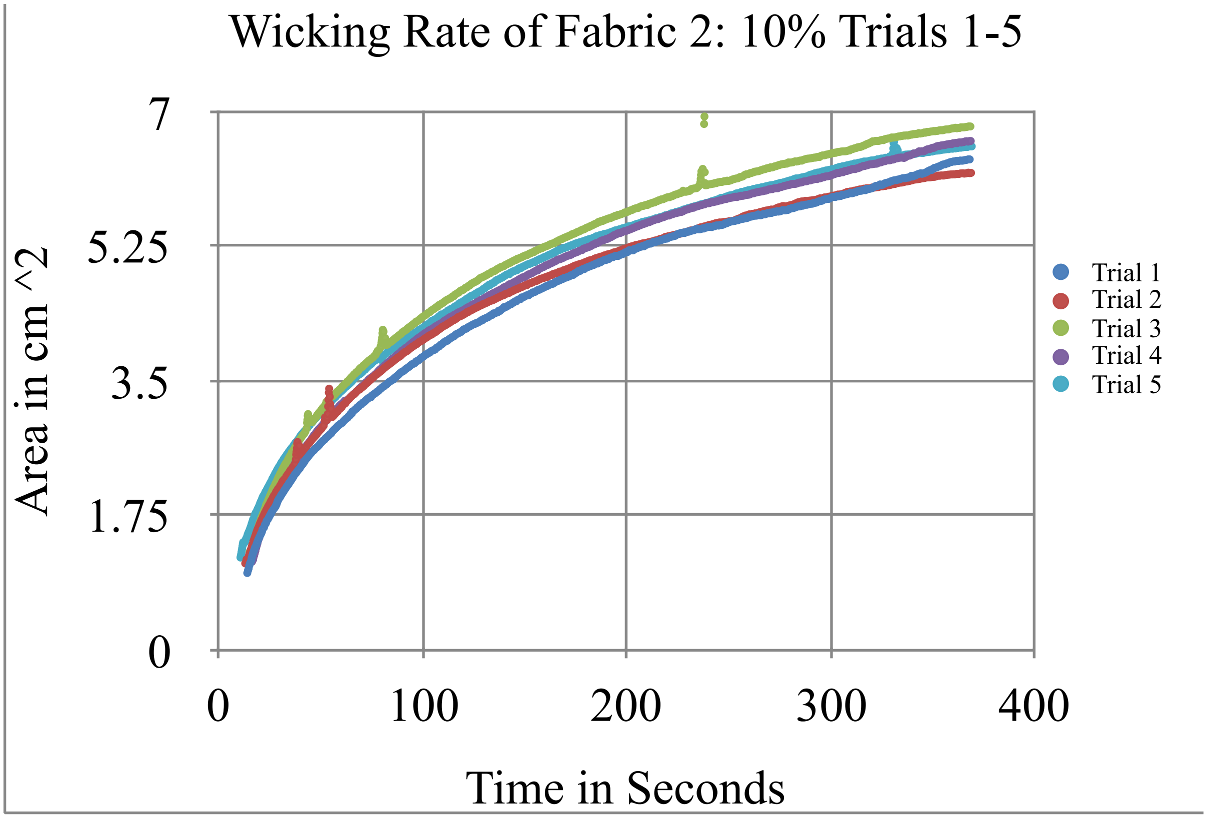
Wicking Rate of Fabric 3: 10% Trials 1-5
3
2.25
1.5
0.75
0
Area in cm ^2
0
100
200
300
400
Time in Seconds
Trial 1
Trial 2
Trial 3
Trial 4
Trial 5

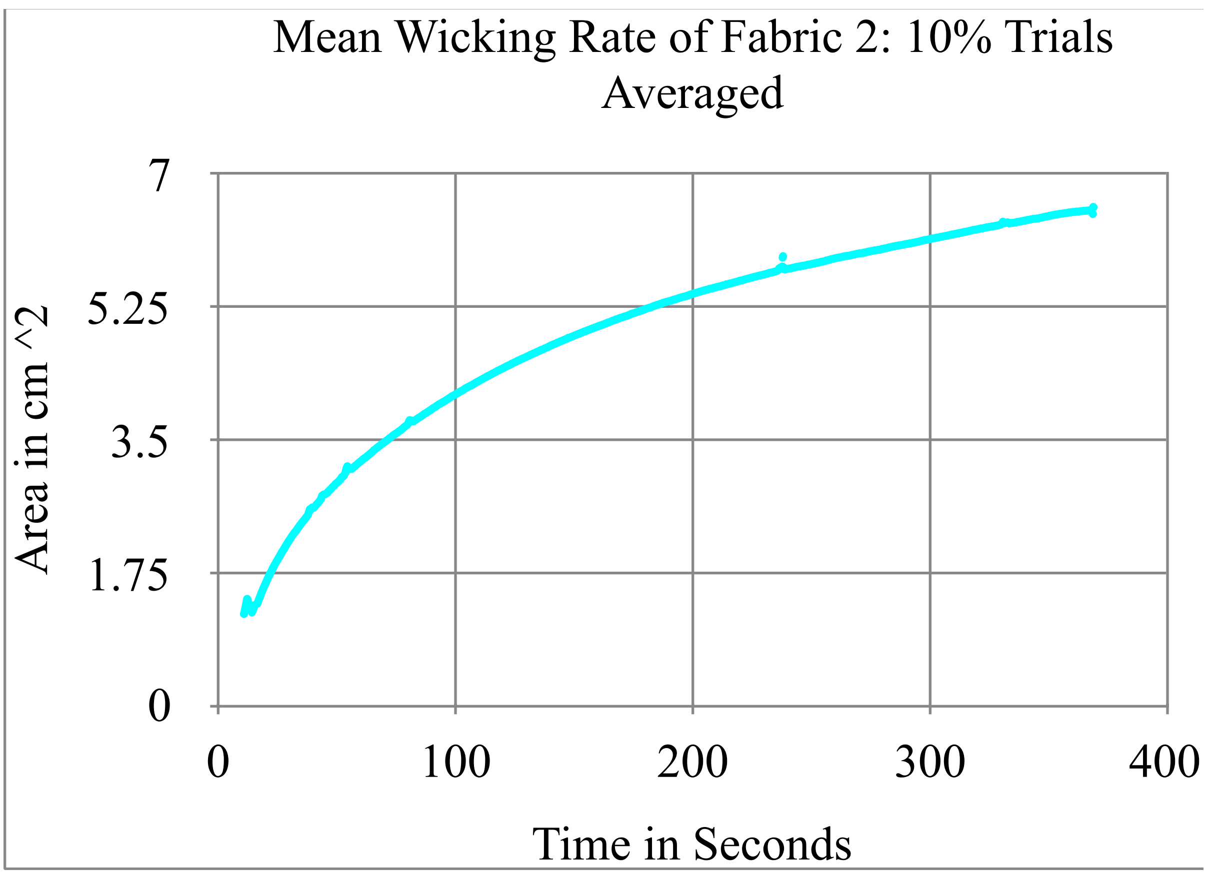


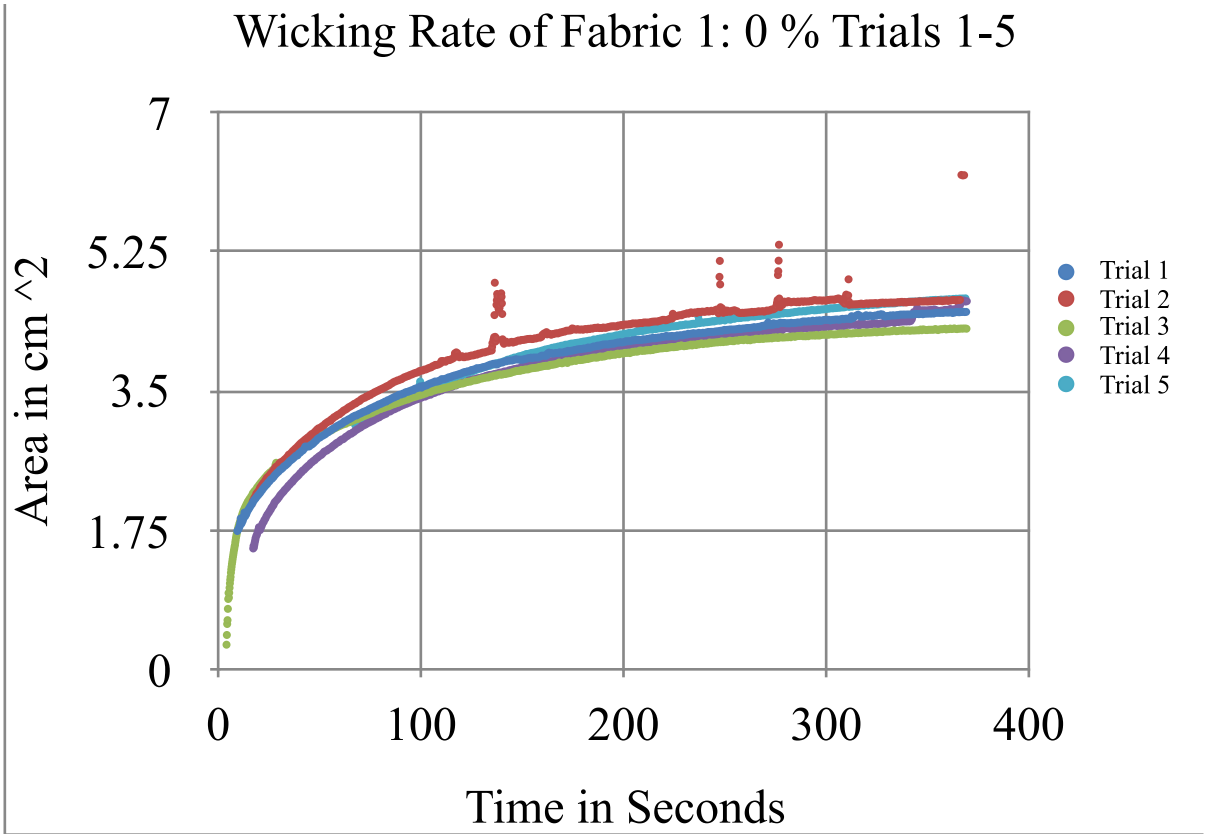
Mean Wicking Rate of Fabric 3: 10% Trials Averaged
3
2.25
1.5
0.75
0
Area in cm ^2
0
100
200
300
400
Time in Seconds

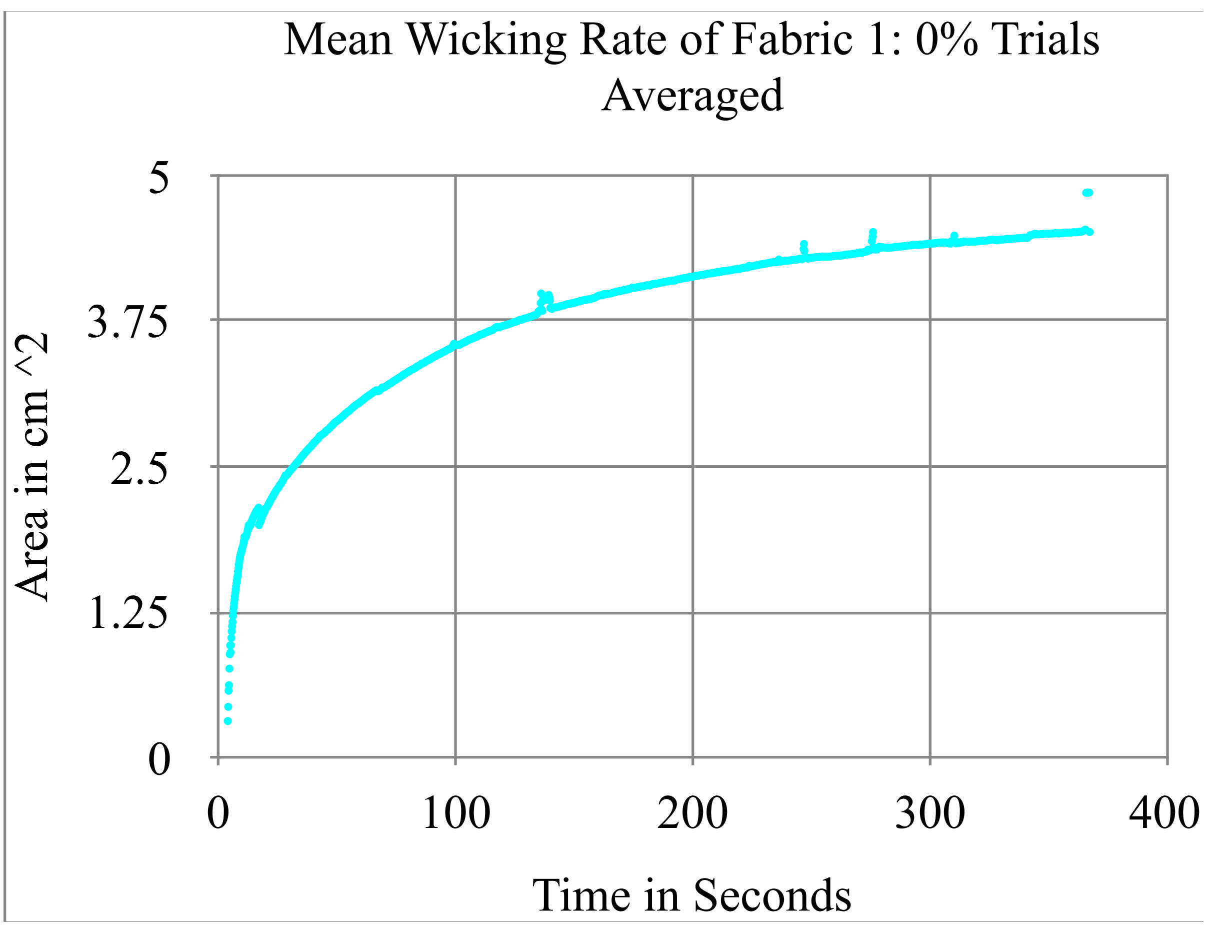

Wicking Rate of Fabric 2: 0% Trials 1-5
Area in cm ^2
Time in Seconds
0
2
4
6
8
0
100
200
300
400
Trial 1
Trial 2
Trial 3
Trial 4
Trial 5

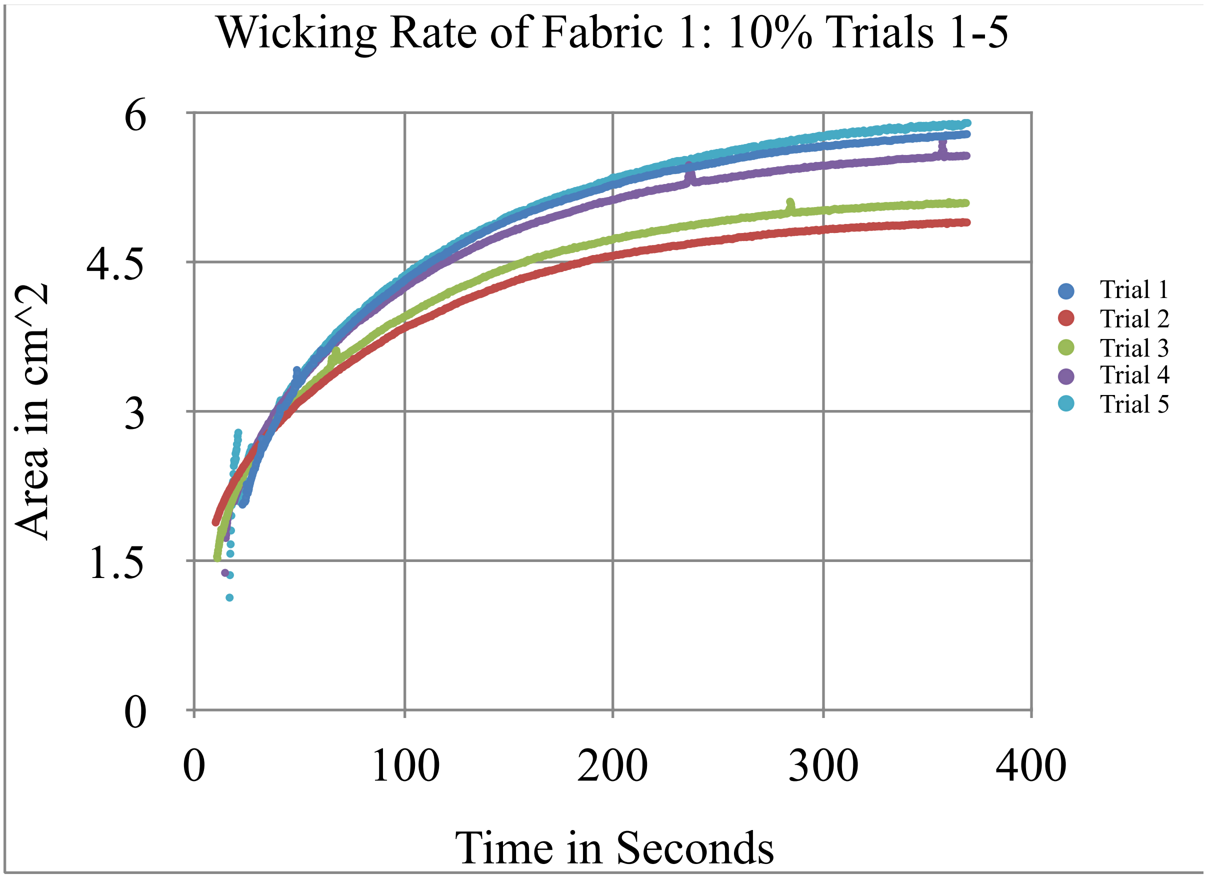

Mean Wicking Rate of Fabric 2: 0% Trials Averaged
Area in cm ^2
Time in Seconds
0
2
4
6
8
0
100
200
300
400


Wicking Rate of Fabric 2: 10% Trials 1-5
Area in cm ^2
7
5.25
3.5
1.75
0
0
100
200
300
400
Time in Seconds
Trial 1
Trial 2
Trial 3
Trial 4
Trial 5

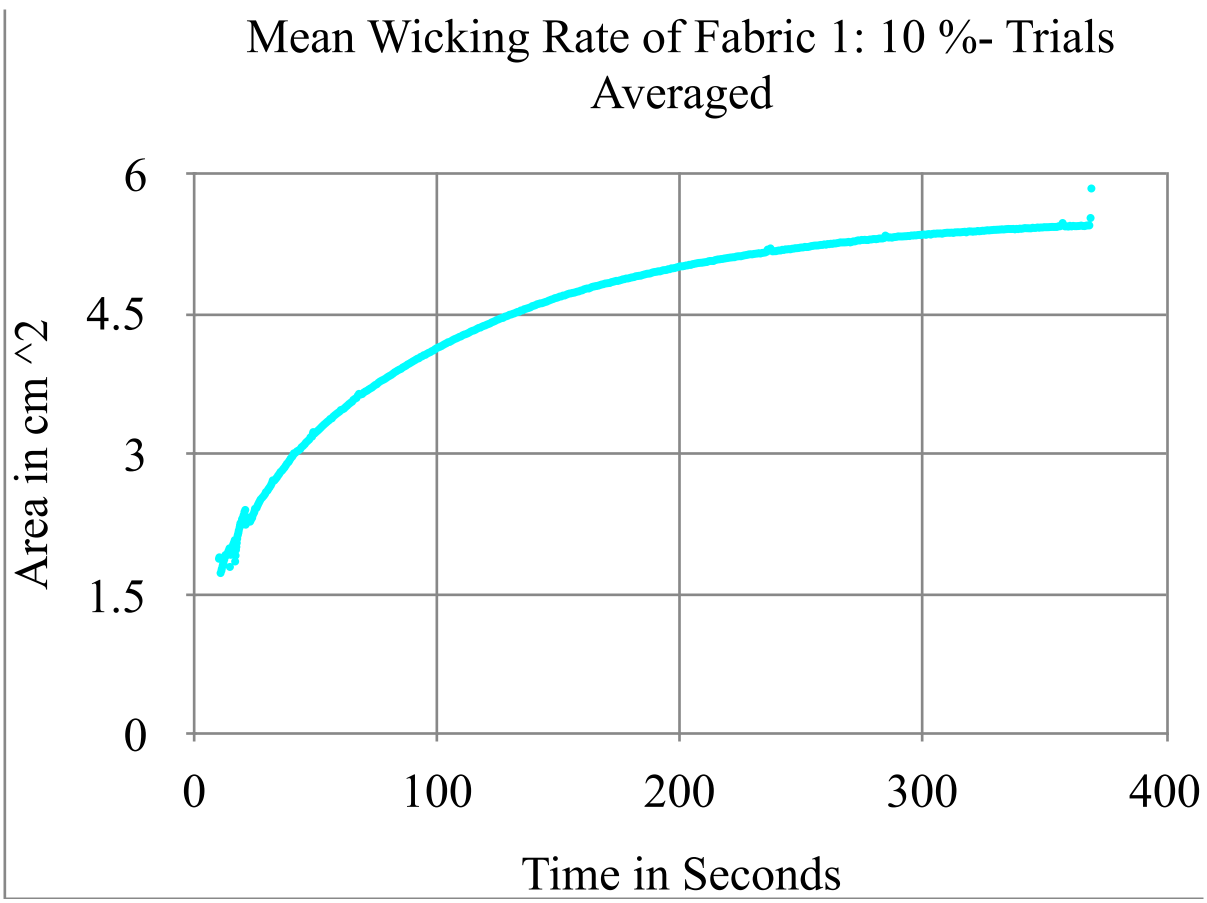

Mean Wicking Rate of Fabric 2: 10% Trials Averaged
Area in cm ^2
7
5.25
3.5
1.75
0
0
100
200
300
400
Time in Seconds


Wicking Rate of Fabric 1: 0 % Trials 1-5
Area in cm ^2
7
5.25
3.5
1.75
0
0
100
200
300
400
Time in Seconds
Trial 1
Trial 2
Trial 3
Trial 4
Trial 5

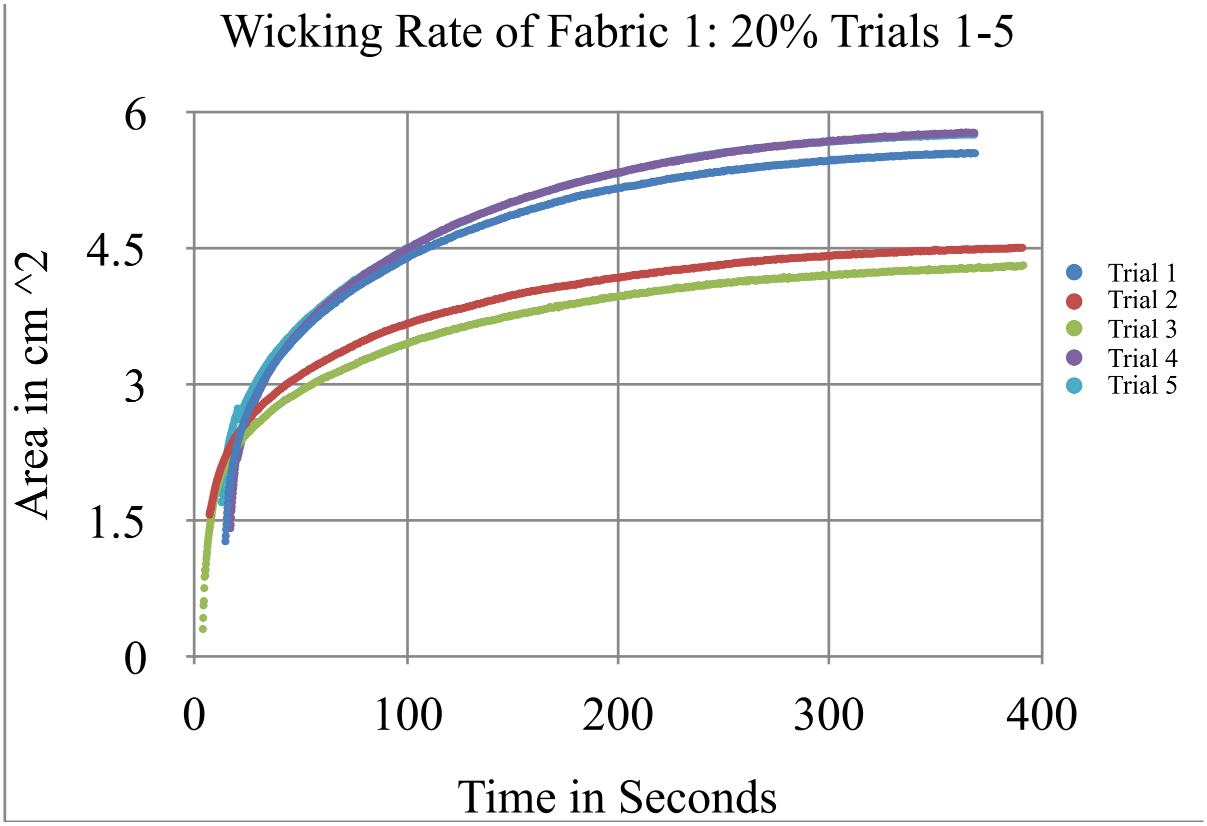

Mean Wicking Rate of Fabric 1: 0% Trials Averaged
Area in cm ^2
5
3.75
2.5
1.25
0
0
100
200
300
400
Time in Seconds

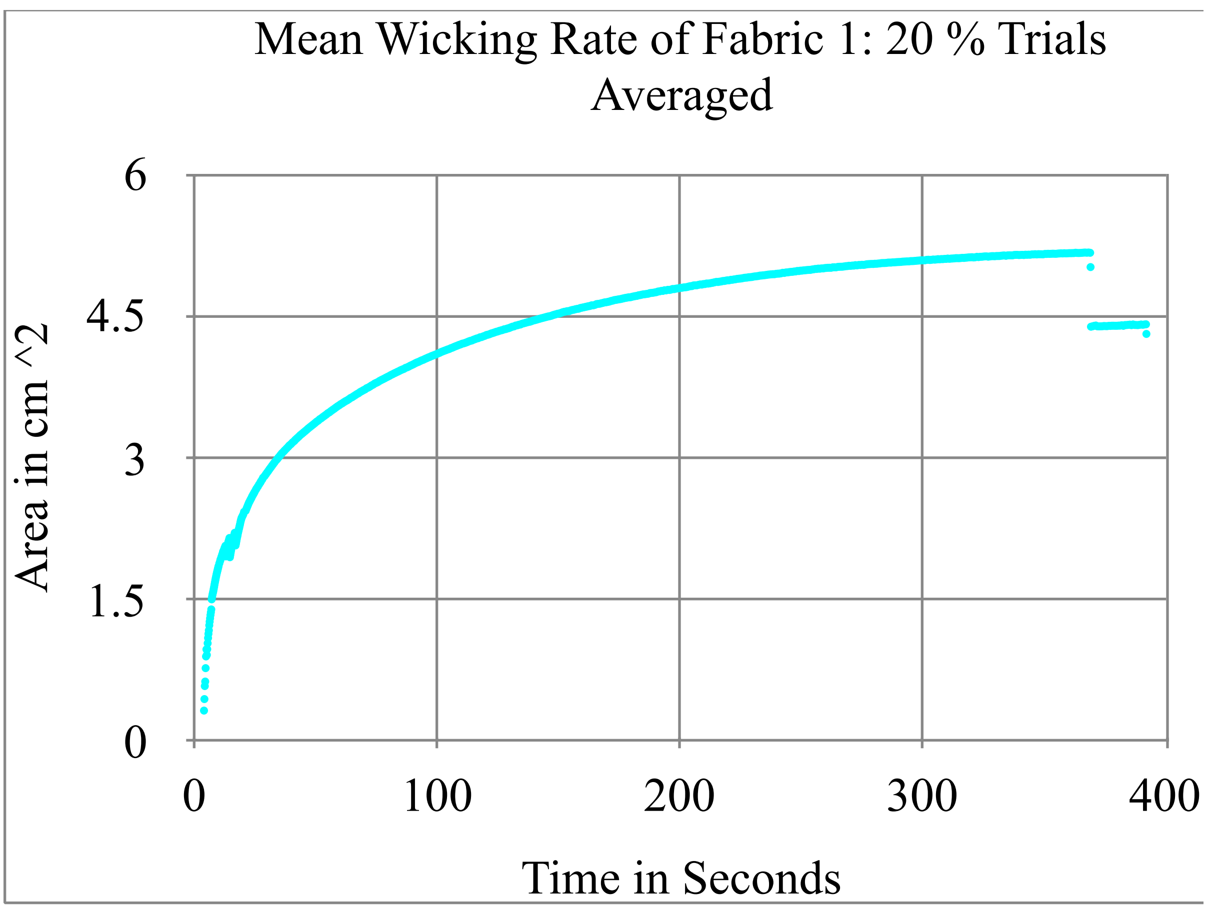


Wicking Rate of Fabric 1: 10% Trials 1-5
Area in cm^2
Time in Seconds
6
4.5
3
1.5
0
0
100
200
300
400
Trial 1
Trial 2
Trial 3
Trial 4
Trial 5



Mean Wicking Rate of Fabric 1: 10 %- Trials Averaged
Area in cm ^2
Time in Seconds
6
4.5
3
1.5
0
0
100
200
300
400


Wicking Rate of Fabric 1: 20% Trials 1-5
6
4.5
3
1.5
0
Area in cm ^2
0
100
200
300
400
Time in Seconds
Trial 1
Trial 2
Trial 3
Trial 4
Trial 5


Mean Wicking Rate of Fabric 1: 20 % Trials Averaged
6
4.5
3
1.5
0
Area in cm ^2
0
100
200
300
400
Time in Seconds