DEVELOPING METHODS FOR DETECTING COTTON FIBER IDENTITY THEFT

Except where reference is made to the work of others, the work described in this thesis is my own or was done in collaboration with my advisory committee. This thesis does not include proprietary or classified information.

Yusuf Celikbag

Certificate of Approval:

Gwynedd A. Thomas
Associate Professor
Polymer and Fiber Engineering

Yehia El Mogahzy, Chair
Professor
Polymer and Fiber Engineering

Ann Presley
Associate Professor
Consumer Affairs

George T. Flowers
Dean
Graduate School

DEVELOPING METHODS FOR DETECTING COTTON FIBER IDENTITY THEFT

Yusuf Celikbag

A Thesis

Submitted to

the Graduate Faculty of

Auburn University

in Partial Fulfillment of the

Requirements for the

Degree of

Master of Science

Auburn, Alabama
August 10, 2009

DEVELOPING METHODS FOR DETECTING COTTON FIBER IDENTITY THEFT

Yusuf Celikbag

Permission is granted to Auburn University to make copies of this thesis at its discretion, upon request of individuals or institutions and at their expense. The author reserves all publication rights.

____

Signature of Author

____

Date of Graduation

VITA

Yusuf Celikbag, son of Huseyin and Nahide Celikbag, was born January 01, 1984, in Sivas, Turkey. He attended Uludag University in September 2003, and got his Bachelor of Science degree in Textile Engineering in June, 2007. Yusuf entered the graduate school of Auburn University in August, 2008 to seek the Master of Science in Polymer and Fiber Engineering.

THESIS ABSTRACT

DEVELOPING METHODS FOR DETECTING COTTON FIBER IDENTITY THEFT

Yusuf Celikbag

Master of Science, August 10, 2009
(B.S, Uludag University, 2007)

144 Typed Pages

Directed by Yehia El Mogahzy

This study focused on determining ways to detect identity theft of cotton fibers through developing identification tests from fibers to end products. Cotton types examined in this study include: Extra-Long Staple cotton fibers such as Giza cotton, Supima cotton, and Chinese cotton, and Medium-Staple cotton such as American Upland cotton. Tests used to identify different cotton fiber type in the raw form included (1) standard methods, and (2) non-standard methods. Standard methods were primarily common fiber testing methods using the High-Volume Instrument (HVI) and the Advanced Fiber Information System (AFIS). These two systems were developed by Uster® Technologies and they are widely used all over the world. These systems provide values of common fiber properties such as fiber length, Micronaire, fiber strength, color, maturity, and trash content (HVI), and fiber length, fineness, neps, maturity, and trash (AFIS). Using the values of these properties, one can easily distinguish between major

categories of fiber types. For example, Extra-Long Staple cotton fibers (ELS) will have longer, finer, stronger, and more mature fibers than regular (Upland-like) cotton fibers. Non-standard methods that have never been used for cotton fiber identification were also developed and used. These include: Dyeing Test, Viscosity Test, and Sonic Test. Among these tests, viscosity and sonic modulus seem to provide distinguished differences between different cotton types. The study also dealt with two basic textile end products, namely: bed sheets and knit shirts to examine whether it is possible to identify different cotton fibers through their performances in the end products. This type of analysis showed that different cotton types can indeed have different effects on end product performance through which the identity of fiber can be traced back to its type and sources.

ACKNOWLEDGMENTS

The author would like to express his thanks to his advisor, Dr. Yehia El Mogahzy, for his support, encouragement, patience, and valuable advises and guidance. The author would like to express his gratitude to his committee members, Dr. Gwynedd A. Thomas, and Dr. Ann Pressley for their time and advises. And also, he is thankful for Dr. Ramsis Farag's continuous support and help during the laboratory studies. Thanks to Polymer and Fiber Engineering Department for providing support and welcoming environment.

The author would like to express his most sincere thanks to his mother and his family who support himself in every circumstance and provide motivation all along his life. He would also like to express his appreciation to his friends in Auburn for unforgettable memories. And finally, the author would like to thank God for everything that he has.

Style manual used: The Chicago Manual of Style

Computer software used: Microsoft Word, Microsoft Excel, Microsoft PowerPoint

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Chapter 1. INTRODUCTION

This study aimed at solving a serious problem that in recent years has resulted in major losses to the U.S. economy. This problem is cotton identity theft, represented by enormous claims that cotton textile products sold in the U.S. market and in many areas around the world are made from premium cotton varieties, with the primary target being U.S. medium/long staple cottons, and U.S. Supima Extra Long Staple cottons. In 2007 alone, the claims of U.S. Supima cotton stamped on textile products worldwide reached a record high of 800 million pounds [1]. This is about double the actual amount of Supima cotton produced. Reasons for these false claims include: (1) taking advantage of many trade regulations that give advantages to U.S. cotton-made products, (2) selling products at higher prices using premium U.S. cotton labels and trademarks, and (3) the extreme difficulty in detecting the origin of cotton or its type once a product is in the finished status.

In addition to the losses resulting from tarnishing the famous quality of U.S. cotton, identity theft can ultimately lead to substantial losses resulting from lower demands for U.S. cotton, legal disputes, and overall quality deterioration. Indeed, if one lists the many reasons leading to the fall of the U.S. textile and apparel industry in recent years, cotton identity theft will be among those reasons.

The main objective of this study is to develop verifiable scientific approaches for identity recognition of cotton fiber varieties not only in the raw stage but also in finished end products. Although the main target is the U.S. cotton, which amounts to over 20 million bales of medium staple and nearly a million bales of Extra Long Staple fibers, this work also deal with other non-US cotton varieties such as Egyptian cotton.

Chapter 2. LITERATURE REVIEW

2.1 Fiber Identification

Fiber identification has been a part of textile studies for many years. This can be achieved using many standard tests including [1-4]: microscopic, chemical, burning, and physical tests. Microscopic tests represent the most common technique of fiber identification and they rely on detecting surface and cross-sectional features that are unique for certain fibers. For example, a cotton fiber will have a flat or oval cross-section and convoluted shape along its axis; a wool fiber will have a round or oval cross-section and a scaly shape along its axis; some rayon will have rounded serrated cross section and grooved shape along its axis; and some silk will have a triangular cross section. When synthetic fibers are examined for fiber identification, microscopic tests become limited due to the fact that these fibers can be made in a wide variety of cross sections and longitudinal shapes even within the same fiber type. For example, some nylon fibers may be rounded in cross-section; others can exhibit a square cross-section with voids; and others may have a Trilobal cross-sectional shape. Some acrylic fibers may have a mushroom cross section and others may have dog-bone cross sectional shape. Table 1 lists some fiber types with descriptions of cross-sectional and longitudinal shapes.

Table 1 Comparison of longitudinal and cross-sectional shapes of different fibers [5,6]

Fiber type	Longitudinal appearance	Cross-sectional shape
Cotton	Ribbon-like & convoluted & no significant lengthwise striations	Tubular or collapsed depending on maturity level
Linen	Bamboolike, pronounced cross markings nodes & no significant lengthwise striations	Tubular or collapsed depending on maturity level
Rayon (Regular tenacity)	Very distinct lengthwise striations & no cross markings	Irregular shape & serrated outline
Rayon (High-modulus)	Smooth, rodlike, no irregular stritions	Oval or round
Acetate	Glasslike rod with distinct lengthwise striations	Irregular shape & serrated outline
Triacetate	No cross markings	Irregular shape & serrated outline
Wool	Scaly surface (human-hair like)	Nearly round
Silk	Smooth surface glassrod-like	Triangular, with rounded triangle corners
Nylon (regular tenacity)	Smooth & Glassrod like	Round
Polyester (Regular)-filament	Rod-like with a smooth surface	Round or other shapes (e.g. trilobal)
Polyester (High-tenacity)-filament	Rod-like with a smooth surface	Round or other shapes (e.g. trilobal)
Polyester (Regular)-staple	Rod-like with a smooth surface	Round or other shapes (e.g. trilobal)
Polyester (High-tenacity)-staple	Rod-like with a smooth surface	Round or other shapes (e.g. trilobal)

Table 1 (cont.)

Fiber type	Longitudinal appearance	Cross-sectional shape
Acrylic	Rod-like with a smooth surface	Round or other shapes (e.g. bean or dog bone)
Modacrylic	Rod-like with a smooth surface	Round or other shapes (e.g. bean or dog bone)
Polypropylene	Rod-like with a smooth surface	Round
Spandex	Indistinct lengthwise striations & no cross markings	Dog bone

Chemical tests rely on stimulating the polymeric substance of fibers by dissolving or coloring for the sake of identifying the type of polymer from which the fiber is made. This type of fiber identification is useful particularly when different fiber types such as cotton and polyester are blended together as it can reveal the percent of each fiber in the blend. However, the limitation of this type of identification testing becomes obvious when one attempts to use it in identifying different varieties of the same type of fiber. This limitation is best illustrated in the comparison between different cotton varieties (e.g. American Upland cotton, Supima cotton, Egyptian cotton, etc.). As will be discussed later in this section, the chemical composition of a cotton fiber is a very complex one.

The burn test is a common one as it represents a simple way to identify fibers based on their thermal behavior (burning or melting), and the fiber smell upon burning. Commonly the burn test is used to determine if the fiber is natural, manmade, or a blend of natural and manmade fibers. In other words, it is useful in narrowing the choices down to natural or manmade fibers. This elimination process is not only useful for the sake of identification but also for giving information necessary to decide the care of the fabric. In a burn test, cotton, being a plant fiber, burns when ignited with a steady flame and smells like burning leaves. The ash left is easily crumbled. Linen will exhibit the same behavior as cotton except it will take longer time to ignite. Silk, being a protein fiber, will burn easily, not necessarily with a steady flame, and smells like burning hair. Wool is also a protein fiber but it is typically harder to ignite than silk. Again, the smell of burning wool is like burning human hair. Man-made fibers will behave in many different ways depending on the fiber type. For example, acetate is made from cellulose (wood fibers), technically cellulose acetate. As a result, it will burn readily with a flickering flame that cannot be easily extinguished. The burning cellulose drips and leaves a hard ash. The smell is similar to burning wood chips. Acrylic (acrylonitrile) is made from natural gas and petroleum. As a result, it burns readily due to the fiber content and the lofty, air filled pockets. A match or cigarette dropped on an acrylic blanket can ignite the fabric which will burn rapidly unless extinguished. The ash is hard. The smell is acrid or harsh. Nylon being a polyamide made from petroleum, will melt and then burn rapidly if the flame remains on the melted fiber. If you can keep the flame on the melting nylon, it smells like burning plastic. Polyester is a polymer produced from coal, air, water, and petroleum products. As a result, it melts and burns at the same time, the melting, burning ash can bond quickly to any surface it drips on including skin. The smoke from polyester is black with a sweetish smell. The extinguished ash is hard. Rayon is a regenerated cellulose fiber which is almost pure cellulose. Rayon burns rapidly and leaves only a slight ash. The burning smell is close to burning leaves.

Physical testing is not a common approach of fiber identification although it can be very useful. This is where values of key physical properties are used to identify fiber type and fiber contribution in a blend. Examples of physical properties used to identify fiber types include [5]:

- Fiber length
- Fiber diameter
- Fiber specific gravity
- Fiber strength
- Fiber elongation

Values of physical properties of different fibers are listed in Tables 2, and 3.

Table 2 Comparison of fiber length and fiber fineness of different fiber types [5,6]

Fiber type	Fiber length (mm)	Fineness (millitex/denier)	Specific gravity (g/cm^3)
Cotton	20-44	100-280 (0.9-2.5)	1.54
Linen	300-900	17-22 micron diameter	1.54
Rayon (Regular tenacity)	Cut to different lengths	400-480 (4-4.3)	1.51
Rayon (High-modulus)	Cut to different lengths	400-480 (4-4.3)	1.51
Fiber type	Fiber length (mm)	Fineness (militex/denier)	Specific gravity (g/cm^3)
Acetate	Cut to different lengths	222-333 (2.0-3.0)	1.32
Triacetate	Cut to different lengths	222-333 (2.0-3.0)	1.25
Wool	60-300	400-800 (4.0-8.0)	1.32
Silk	Highly variable (up to 100 feet)	Highly variable (typical diameters 4-10 micon, Spider silk is 14-120 millitex)	1.25

Table 2 (cont.)

Fiber type	Fiber length (mm)	Fineness (millitex/denier)	Specific gravity (g/cm^3)
Nylon (regular tenacity)	Cut to different lengths	Made into various fineness	1.14
Polyester (Regular)-filament	Cut to different lengths	Made into various fineness	1.22 or 1.38
Polyester (High-tenacity)-filament	Cut to different lengths	Made into various fineness	1.22 or 1.38
Polyester (Regular)-staple	Cut to different lengths	Made into various fineness	1.22 or 1.38
Polyester (High-tenacity)-staple	Cut to different lengths	Made into various fineness	1.22 or 1.38
Acrylic	Cut to different lengths	Made into various fineness	1.14-1.19
Modacrylic	Cut to different lengths	Made into various fineness	1.30-1.37
Polypropylene	Cut to different lengths	Made into various fineness	0.92

Table 3 Comparison of strength properties of different fiber types [5, 6]

Fiber type	Tenacity-dry (g/denier)	Tenacity-wet (g/denier)	Breaking extension (%)
Cotton	3.0-5.0	3.3-6.0	5.0-7.2
Linen	5.5-6.5	6.0-7.2	2.5-3.5
Rayon (Regular tenacity)	0.73-3.2	0.7-1.8	15.0-30.0
Rayon (High-modulus)	2.5-5.5	1.8-4.0	5.0-15.0
Acetate	1.2-1.4	0.8-1.0	20.0-25.0
Triacetate	1.1-1.3	0.8-1.0	20.0-25.0
Wool	1.0-1.7	0.8-1.6	30.0-45.0
Silk	2.4-5.1	1.8-4.2	20.0-25.0
Nylon (regular tenacity)	3.0-6.0	2.6-5.4	20.0-30.0
Polyester (Regular) -filament	4.0-5.0	4.0-5.0	20.0-30.0
Polyester (High-tenacity) -filament	6.2-9.4	6.3-9.5 (filament)	6.0-10.0

Table 3 (cont.)

Fiber type	Tenacity-dry (g/denier)	Tenacity-wet (g/denier)	Breaking extension (%)
Polyester (Regular)-staple	2.5-5.0	2.5-5.0	20.0-30.0
Polyester (High-tenacity)-staple	5.0-6.5	5.0-6.4	20.0-25.0
Acrylic	2.0-3.5	1.8-3.3	15.0-25.0
Modacrylic	2.0-3.5	2.0-3.5	10.0-15.0
Polypropylene	4.8-7.0	4.8-7.0	20.0-30.0
Spandex	0.6-0.9	0.6-0.9	500-600

2.2 The Cotton Fiber

This study primarily focuses on cotton fiber identity. For this reason, it is important to review the different aspects associated with this important fiber. Cotton fiber represents a key textile component that has been used in millions of products. The merits of using this fiber are obviously realized by the millions of users of cotton textile products representing all cultures, ages, genders, and religions. They are also realized by the numerous products in which cotton fibers are used from garments to sheets, towels to surgical drapes, and disposable to biodegradable products. This realization is a historical one. Indeed, the popularity of cotton in today's living cannot be separated from the historical evolution of cotton discovery and cotton utilization. Although historians can hardly trace cotton to its true origin, there seems to be an agreement that the use of cotton goes back beyond the records of history. As early as 3000 BC cotton was grown and used in the Indus Valley of India. Ancient Egypt and China also spun and wove it. In the middle Ages, the Arabs brought the cotton plant from India and Spain. They called it "*qutun*", from which comes the name cotton. The most established historical fact about cotton is that the popular status that cotton enjoys today is fully credited to the United States of America. It is in this great country that Eli Whitney is credited with inventing the cotton gin in 1793, which forever revolutionized the whole concept of cotton production. By 1800 cotton production had increased from about 3,000 bales a year to 73,000. History also tells us that cotton was the main reason behind the Civil War initiated by the slavery in the South needed for cotton picking. Shortly after Eli Whitney invented the cotton gin, planters turned from tobacco and rice to cotton. To supply the growing demands of mill owners in England and New England, they imported more slaves to work the cotton fields. The number soared from about 700,000 in 1793 to nearly 4,000,000 by 1860. Plantations sprang up in Alabama, Mississippi, Missouri, Louisiana, Tennessee, and Arkansas. By spreading slavery in the South, cotton helped bring on the Civil War.

Obviously, being a part of history is not the only reason for the huge popularity of cotton. Other commodities such as wool, tobacco and hemp are also associated with historical evolutions but they do not enjoy the popularity that cotton has in today's living.

The structure of a mature cotton fiber may be viewed as consisting of six main parts [7-13]. As shown in Figure 1, the first is the cuticle, or the "skin" of the fiber. This waxy and smooth layer contains pectin and proteinaceous materials. The presence of this layer has a significant impact on the smoothness and the handling of cotton during processing. However, the fact that it is a very thin layer, only a few molecules thick, makes it vulnerable to environmental effects, such as due to heavy rain and high temperature. Upon scouring, this layer is removed, which explains the increase in fiber/fiber friction.

The second part is the primary wall. This is the original thin cell wall and is mainly cellulose made up of a network of fine fibrils. The primary wall may be visualized as a sheath of spiraling fibrils where each layer spirals 20-30^{o} to the fiber axis. The thickness of this wall correlates with the extent of maturity of cotton fiber, the thicker the wall the higher the maturity. The primary wall makes for a well-organized system of continuous very fine capillaries. These fine capillaries "rob" liquids from coarse capillaries; an action that contributes greatly to a cotton material's wipe-dry performance.

The third part is called the winding layer or S1 layer. This is the first layer of secondary thickening and it differs in structure from either the primary wall or the remainder of the secondary wall. It is an open "netting" pattern of fibrils that are aligned at 40-70° angles to the fiber axis. The fourth part is the secondary wall, which consists of concentric layers of cellulose constituting the main portion of the cotton fiber (also called S2 layer). During the growth period, a new layer of cellulose is added to the secondary wall. The fibrils are deposited at angles of 70-80° with points along the length where the angles are reversed. The fibrils are packed close together, again forming small capillaries.

The fifth part is the lumen wall. This wall separates the secondary wall from the lumen, which represents the sixth part. It appears to be more resistant to certain reagents than the secondary wall layers. The lumen is a hollow canal that runs the length of the fiber. It is filled with living protoplasts during the growth period. After the fiber matures and the boll opens, the protoplast dries up and the lumen will naturally collapse.

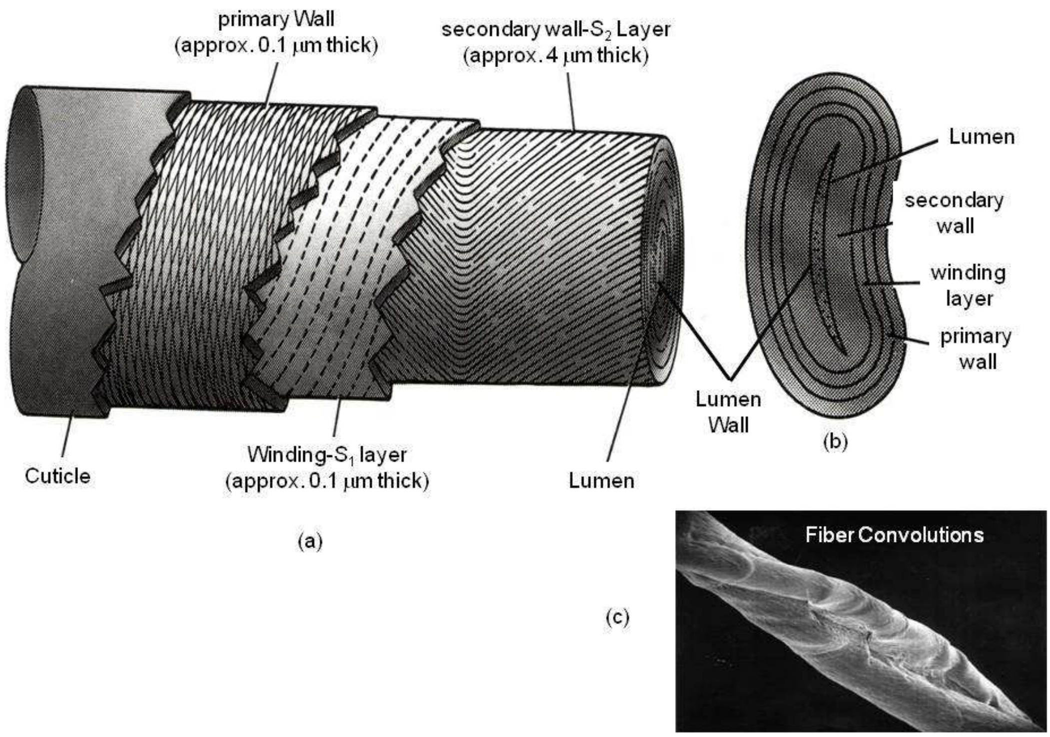


Figure 1 Structural features of cotton fiber [5]

2.3 The Importance of Detecting Cotton Identity Theft

The importance of detecting cotton fiber identity theft stems from the fact that cotton fiber has unique performance characteristics that are uncontested by other fiber types. In addition, different cotton fiber types will exhibit different performance levels. Indeed, the true value of any fiber can only be realized through the benefits of using the fiber in particular textile products. These benefits are determined by a number of performance characteristics that are primarily experienced during the use or the maintenance of the products. In order to understand how cotton compares with other competing fibers with respect to end product performance, it will be important to first define the term performance characteristic. According to Dr. Elmogahzy [6]:

“Performance characteristic is hardly a direct attribute that can be imbedded in the product in a systematic fashion to make the product perform according to its expectation. Instead, it is often a function of carefully assembled elements leading to the end product, associated with a combination of different attributes that collectively result in meeting the required performance of the product assembly. In this regard, it is important that both the assembly elements and their attributes are harmonized so that their integral outcome can lead to an optimum level of the desired performance characteristics. For example, suppose that the desired performance characteristic of a fibrous end product is durability. In this case, the selection of a fiber exhibiting high strength will represent a key element/attribute combination. When the fibers are converted into a yarn, the new fiber assembly should still meet the same level of the desired performance characteristic, enhance it, or at least should not hinder it. The new element/attribute combination to be optimized in this case is yarn structure/yarn strength. Similarly, as the yarn is converted into a fabric, fabric construction/fabric strength combination should be optimized. Finally, fabric finish must be carefully selected and applied in such a way that can enhance durability, or minimize any side effects that can lead to deterioration in this critical performance characteristic.”

Perhaps, no textile performance characteristic is more important than durability. Cotton fiber is typically not the most durable fiber by comparison with other fiber types. However, in the form of a yarn or a fabric it can be truly durable. This aspect will be addressed in this study in the context of comparing the durability of different cotton fibers. In Tables 3 a comparison between the strength properties of cotton fibers and other competing fibers was made. These properties directly influence the durability of a textile product. In general, the stronger the fiber, the stronger the textile product made from this fiber. Within the different varieties of cotton, one can find a wide range of fiber strength. This point was demonstrated in Table 3 by a range of fiber strength from 3.0 to 5.0 g/denier. Typically, extra-long staple cotton fibers (ELS) exhibit significantly higher strength than medium or short-staple cotton varieties. As a result, textile products made from ELS cottons are expected to exhibit more physical durability (e.g. tensile, tear, and bursting strength) than those made from medium or short-staple cottons. Furthermore, ELS cottons exhibit longer lengths and finer diameters than medium and short-staple cottons. These two attributes contribute to the physical durability of textile products particularly when these products are made from fine yarns. Longer and finer fibers result in more fibers per yarn cross section leading to stronger yarns.

When cotton is compared to other fiber types, one will find that cotton fibers are generally stronger or equivalent in strength to all other natural fibers except long-vegetable fibers (e.g. flax or jute). Obviously, synthetic fibers can be made strong by virtue of the control of their molecular orientation, but those that are typically blended with cotton are made to have more or less equivalent strength. The breaking extension of cotton is lower than that of most competing fibers except long-vegetable fibers. The importance of this attribute is realized when a product is subjected to stretching during use. Realizing the poor extension of cotton fibers has resulted in the use of a small quantity of a companion stretchable fiber in many cotton products such as denim, bed sheets, and knit apparels. This fiber is an elastomeric fiber called spandex (trade name

Lycra®). This fiber is added to provide fit and tactile comfort (stretch and recovery) to cotton textile products.

A key point related to breaking extension is that it directly influences the breaking extension of yarn. In other words, fibers of high breaking extension will result in yarns of high breaking extension. This point is critical on the ground that cotton yarns must be sized (coated by a surface film to reduce hairiness and improve abrasion resistance) before it can be woven. Unfortunately, size treatment will inevitably reduce yarn elongation, particularly when size add-on is increased. This leads to undesirable stiffness in the yarn during weaving. It is important, therefore to use fibers of high elongation so that yarns made from these fibers will likely to survive the reduction in elongation upon sizing. It is important to keep in mind that the absolute minimum value of yarn elongation below which the yarn will not weave properly is 4%.

Another key fiber attribute related to durability is fiber toughness, expressed by the so-called “work of rupture”. This is a measure of the energy needed to break the fiber. In this regard, a fiber can be strong but not very tough (e.g. long-vegetable fibers such as linen). This means that although the fiber is strong, it may fail easily under excessive external stress applied in a short period of time (e.g. impact force). When cotton fibers are compared to wool fibers, one will find that cotton is significantly stronger but considerably less tough than wool. Silk on the other hand exhibits the highest toughness among natural fibers.

Another key mechanical parameter, which influences the durability of textile products, is stiffness or flexibility of fibers. This is determined by the initial slope of the stress-strain curve, or the so-called initial modulus; the higher the initial modulus, the higher the fiber stiffness. In practical terms, flexibility is the ease of material to deform or deflect under small forces. This may be in the tension mode or in the bending or twisting mode. The data of initial modulus shown in Table 4 is taken under tensile forces (tension mode). This data indicates that cotton fibers exhibit a wide range of flexibility (range of initial modulus from 390 to 740 g-wt/tex). This means that different cotton varieties may have different levels of flexibility. In general, cotton is more flexible than other long-staple vegetable fibers (e.g. linen and jute) and silk, and stiffer than wool fibers.

Table 4 Non-standard mechanical fiber properties [6]

Fiber type	Work of rupture (g-wt/tex)	Initial modulus (g-wt/tex)
Cotton	0.52-1.52	390-740
Linen	0.82	1830.00
Rayon (Regular tenacity)	3.12	486.00
Rayon (High-modulus)	1.5-2.0	700-1000
Acetate	2.20	370.00
Wool	2.7-3.8	215-310
Silk	6.00	750.00
Nylon (regular tenacity)	7.75	270.00
Polyester (Regular)-Filament	5.40	1080.00
Polyester (High-tenacity)-filament	2.20	1350.00
Polyester (Regular)-Staple	12.00	900.00
Acrylic	4.80	630.00

Durability of textile products can also be measured using parameters that are related to exposure of material to certain environments or chemical treatments during processing or during use. Table 5 provides comparison between different fiber types using some of these parameters. Under prolonged exposure of sunlight, most natural fibers will suffer some form of deterioration either via strength loss or coloration. Cotton fibers are highly resistant to sunlight provided that no rain or wetting condition is involved. Some studies found a slight loss of fiber strength under prolonged exposure of sunlight. The behaviors of other fibers are illustrated in Table 5. Abrasion is a form of rubbing against fiber surface at high speeds that can result in wearing out the fibers. Under abrasion effects, cotton fibers generally perform well. These effects begin during harvesting and continue during ginning and textile manufacturing. During weaving cotton yarns are subjected to excessive abrasion effects and at high speeds, which requires additional protection to yarn surfaces via sizing. Most natural fibers exhibit fair to good abrasion resistance, but silk in particular is known to have poor abrasion resistance. Most synthetic fibers are spin-finished in such a way that allows high abrasion resistance. Unlike long-vegetable fibers, cotton fibers require special care when treated with acid or alkalis during finishing or during washing.

Table 5 Other durability parameters of fibers [6]

Fiber type	Exposure-to-sunlight resistance	Abrasion resistance	Acid resistance	Alkalis resistance
Cotton	Strength loss	Good	Poor	Poor
Linen	Strength loss	Fair	Excellent	Excellent
Rayon (Regular tenacity)	Strength loss	Fair	Poor	Poor
Rayon (High-modulus)	Some strength loss	Fair	Poor	Excellent
Acetate	Some strength loss	Fair	Poor	Strength loss

Table 5 (cont.)

Fiber type	Exposure-to-sunlight resistance	Abrasion resistance	Acid resistance	Alkalis resistance
Triacetate	Moderate	Fair	Poor	Strength loss
Wool	Yellows-strength loss	Good	Moderate	Very poor
Silk	Yellows-degrades	Poor	Poor	Very poor
Nylon (regular tenacity)	Degrades	Good to Excellent	Degrades	Degrades
Polyester (Regular)-filament	Good (if glass protected)	Good to Excellent	Good to weak	Fair to strong
Polyester (High-tenacity)-filament	Good (if glass protected)	Good to Excellent	Good to weak	Fair to strong
Polyester (Regular)-staple	Good (if glass protected)	Good to Excellent	Good to weak	Fair to strong
Polyester (High-tenacity)-staple	Good (if glass protected)	Good to Excellent	Good to weak	Fair to strong
Acrylic	Excellent	Fair to Good	Good except nitric	Good (to weak alkali)
Modacrylic	Excellent	Fair to Good	Good	Good
Polypropylene	Slow strength loss	Fair	Excellent	Excellent
Spandex	High resistant but it yellows	Poor	Good	Fair

2.4 The Challenges of Identifying Different Cotton Fiber Types

The main objective of this study is to develop ways to identify certain variety or cotton type in a raw form or in a textile product. The key challenge associated with this objective is that the methods of fiber identification discussed earlier (microscopic, chemical, and burn tests) seem to fail to distinguish between different types of cotton fibers. Microscopically, most cotton fibers have common features that are not unique to any particular type. As a result, different cotton types may reveal microscopic pictures that are not different enough to segregate them or identify one type from another.

Chemical testing is even more challenging. Upon ginning and cleaning, raw cotton fiber is approximately 95% cellulose [4-8]; yet some cotton fibers may have as little as 85% cellulose and others may have as much as 96% depending on the growth rate and the environment in which cotton is planted. Unfortunately, this data does not represent unique identification as this wide range of cellulose content can indeed exist in one type of cotton. A cotton fiber also has protein with a typical value of 1.3 (%N x 6.25) but it may range from 1.1 to 1.9 even within the same type of cotton. Other chemicals presented in cotton include: Pectic substances (typical = 0.9%, range 0.7-1.2), Ash (typical = 1.2%, range 0.7-1.6), natural wax (typical = 0.6%, range 0.4-1.0), Total sugars (typical = 0.3%, range 0.1-1.0), organic acids (typical = 0.8%, range 0.5-1.0). Again, any one of these components can exist over the entire range in the same type of cotton, making it difficult to identify certain cotton types based on the value of chemical composition. Most of the non-cellulosic constituents of the fiber are located principally in the cuticle, in the primary cell wall, and in the lumen.

In the context of fiber identification, it is well known that cotton fibers that have a high ratio of surface area to linear density generally exhibit a relatively higher non-cellulosic content. However, this point is difficult to study unless a huge amount of samples representing different cotton types are available. This was not possible in this study because of the limited samples and the time that could have been taken to test. In addition, within the same cotton type, one can find a substantial range of surface area/linear density ratio, making it difficult to detect on that basis.

It should also be pointed out that variations in non-cellulosic constituents (proteins, amino acids, other nitrogen-containing compounds, wax, pectic substances, organic acids, sugars, inorganic salts, and very small amount of pigments) often arise due to differences in fiber maturity, variety of cotton, and environmental conditions (soils, climate, farming practice, etc.). Thus, an identification by extraction and weighing these non-cellulosic constituents will be subject to a great deal of inconsistency. The non-cellulosic materials are typically removed by selective solvents. The wax constituent can be removed selectively with nonpolar solvents, such as hexane and chloroform, or nonselectively by heating in a 1% sodium hydroxide solution. Hot nonpolar solvents and other water-immiscible organic solvents remove wax but no other impurity, hot ethanol removes wax, sugar, and some ash-producing material but no protein or pectin, and water removes inorganic salts (metals), sugar, amino acids and low-molecular-weight peptides, and proteins. Most of the non-polymeric constituents including sugars, amino acids, organic acids, and inorganic salts may be removed with water. The remaining pectins and high-molecular-weight proteins are removed by heating in a 1% sodium hydroxide solution or by appropriate enzyme treatments. All of the non-cellulosic materials are removed almost completely by boiling the fiber in hot, dilute, aqueous sodium hydroxide (scouring or kier boiling), then washing thoroughly with water. The nitrogen-containing compounds, which constitute the largest percentage of non-cellulosics when expressed as percent protein (1.1-1.9%) largely occurs in the lumen of the fiber, most likely as protoplasmic residue, although a small portion is also extracted from the primary wall [6]. The nitrogen-containing compounds located in the lumen may be removed using water, while those located in the primary cell wall are removed by heating in a 1% sodium hydroxide solution) a mild alkali scour such as that used to prepare cotton fabrics for dyeing and finishing).

In light of the above discussion, it follows that cotton fiber identification to detect different cotton types truly represent a challenge that has to be overcome to prevent identity theft.

In recent years, some attempts to identify cotton types were developed with limited success but great potential for further development. One of these attempts is the so-called "cotton DNA". The idea is to determine genetic roots that can identify different cotton types by developing rapid and simple method to measure expression of a gene of interest in the cotton fiber cell. This type of research was not primarily aimed at identifying cotton types but rather at the evaluation of the phenotype of genes of interest, which is useful in designing transgenic plants with desired characteristics. This type of agricultural research may have good future impacts on cotton identification particularly in the raw form. Cotton is a plant of great commercial importance. One significant product from cotton plants, cotton fiber tissue, is used in the production of textiles. The cotton fiber cells that make up cotton fiber tissue are therefore of great interest. Manipulation of the cotton fiber cell phenotype can produce novel and economically important improvements to cotton fiber tissue and, thus, to textiles. The complexity of cotton fiber development suggests that large numbers of plant genes are involved, especially during initiation, elongation and maturation. However, only about 40 such genes have been reported to date. Searching for these genes can open ideas for cotton fiber identification, a subject that is still under investigation [14-17].

Chapter 3. EXPERIMENTAL

In this study, cotton fiber identity was detected using a complete profiling approach that begins with the end-product (apparel, and bed sheets) and ends with the fiber extracted from the product. The reason for this approach is that the problem of cotton fiber identity theft is commonly discovered in the end-product where it is very difficult to confirm this theft given the different mechanical operations and chemical treatments that a fiber is subject to during spinning, weaving, and dyeing and finishing. Most testing techniques used were standard but few were developed in this study particularly on the raw fibers.

3.1 Fiber Testing

Detecting the identity of cotton fibers in the raw form is relatively easier than in the yarn or fabric form. The methods used for this detection were divided into two classes: (1) standard methods, and (2) non-standard methods.

Standard methods were primarily common fiber testing methods using the High-Volume Instrument (HVI) and the Advanced Fiber Information System (AFIS). These two systems were developed by Uster® Technologies and they are widely used all over the world. These systems provide values of common fiber properties such as fiber length, Micronaire, fiber strength, color, maturity, and trash content (HVI), and fiber length, fineness, neps, maturity, and trash (AFIS). Using the values of these properties, one can easily distinguish between major categories of fiber types. For example, Extra-Long

Staple cotton fibers (ELS) will have longer, finer, stronger, and more mature fibers than regular (Upland-like) cotton fibers.

In this study, some non-standard methods that have never been used for cotton fiber identification were also developed and used. These include:

1. Dying Test
2. Viscosity Test
3. Sonic Test

These methods are described below.

3.1.1 Dyeing Test

Dye absorption behavior of cotton fibers was investigated by using spectrophometer. The following pretreatments were applied to cotton samples before dying.

- **Scouring**

4 grams cotton fiber samples were immersed in the aqueous alkali solution which is prepared according to following receipt;

- 400 CC distilled water
- 0.04g NaOH
- 0.4g AATCC-1993 detergent

Solutions were heated up by heater, and after boiling the cotton fiber samples were immersed in the solutions for 30 minutes. Then the samples were washed with running tap water.

- **Bleaching**

2 grams scoured samples were immersed in the solution which contains 200 CC distilled water and 20 CC sodium hypocloride and suspended for 45 minutes at room temperature. After the treatment, all samples were washed with running tap water and allowed to dry at room temperature.

- **Dyeing**

CI Direct Green#27 dye was used for dyeing. Solutions were prepared according to following receipt;

- 2 CC 1% dye solution (1g dye/100 CC water)
- 100 CC distilled water
- 1 drop NP9 (surfactant) (Nonylphenol Ethoxylate, noniyonic)

When boiling begun, 1g bleached samples were immersed in the solution for 45 minutes. After 45 minutes, all samples were washed with running tap water and dried at room temperature.

- **CIELAB Results**

Shade, color depth and color differences between dyed cotton fibers were determined by CIELAB color coordinates. When a color is expressed in CIELAB;

- L* defines lightness. Maximum L* is 100 which means a perfect reflecting diffuser. Minimum L* is zero which represents black.

- a* means red-green color. Positive a* is red, negative a* is green.

- b* means yellow-blue color. Positive b* is yellow, negative b* is blue

- C* means chroma.

- h defines hue.

ΔE* refers the total color differences between L*, a*, b* of sample and reference.

Calculations are given below;

$$\Delta L^* = L^*_{sample} - L^*_{reference}$$
$$\Delta a^* = a^*_{sample} - a^*_{reference}$$
$$\Delta b^* = b^*_{sample} - a^*_{reference}$$
$$\Delta C^* = C^*_{sample} - C^*_{reference}$$
$$\Delta H^* = \sqrt{\Delta E^{*2} - \Delta L^{*2} - \Delta C^{*2}}$$
$$\Delta E^* = \sqrt{\Delta L^{*2} + \Delta a^{*2} + \Delta b^{*2}}$$
$$K/S = \frac{(1-R)^2}{2R}$$

(R is fraction of light reflected at a wavelength of maximum absorbance or minimum reflectance)

- **Color Strength**

Color strength (K/S) was calculated by Kubelka-Munk equation.

$$\left(\frac{K}{S}\right) = \frac{(1-R)^2}{2R}$$

Where;

K is absorption coefficient

S is scattering coefficient

R is fraction of light reflected at a wavelength of maximum absorbance or minimum reflectance.

Absorption of dye was measured in color strength (K/S) on a spectrophotometer (Chroma Sensor-5 produced by Datacolor International). Higher K/S means higher absorption of dye.

3.1.2 Viscosity Test

In order to measure the viscosity of the cotton fibers, "TAPPI T230 om-89 Viscosity of pulp (capillary viscometer method)" test method was partially followed. This test method shows the techniques to dissolve the pulp and measure the viscosity of the pulp solution.

All the cotton fibers were conditioned under the laboratory condition before test. 0.1616 ±0.0001 g cotton fiber was put into 5 g distilled water and allowed to absorb the water. And then, 15 ml solvent, 0.5M cupriethylenediamine solution $Cu(C_2H_8N_2)_2(OH)_2$, was added and stirred for 1 hour 15 minutes at 25ºC. After that, 10 ml distilled water added and stirred for 1 hour 15 minutes at 25ºC. Finally, solution was filtered, and viscosity of solution was measured by using a viscometer. The viscometer was filled with 10 ml filtered solution, and efflux time was recorded. Viscosity is calculated according to the following formula:

$$V = C \times t \times d$$

Where;

V = viscosity of cupriethylenediamine solution at 25ºC, mPa.s (cP)

C = viscometer constant found by calibration

t = average efflux time, s

d = density of the fiber solution, g/cm^3 (=1.052)

3.1.3 Sonic Test

Sonic test that measures the overall orientation of structure is one of the characterization techniques for polymeric and fibrous structures. When molecular orientation is expressed, what orientation is being measured should be emphasized. Orientation of multiphase or multicomponent materials may refer to overall average orientation or only one phase or component or even one part of the component orientation. For example, X-Ray Diffraction method measures only the orientation of crystalline region dispersed in the amorphous matrix while sonic technique measures the overall orientation of the system.

Sonic test method is based on the measurement of velocity of sound that is related to the orientation of the individual units in a fiber. The magnitude of the velocity depends on the alignment of the individual units along the fiber length. The sound velocity will increase along the axis, when more oriented or aligned units occur along the axis. Basically, more aligned units give greater velocity.

The velocity of sound (V) is equal to $\sqrt{E/d}$ where E is Young's Modulus of Elasticity and d is the density of material. Velocity of sound does not depend on the cross-sectional area. This is an important advantage because biological materials such as cotton have irregular cross-section.

In order to measure the velocity of sound, the sample to be tested is contacted by a transmit transducer and a receive transducer. Recurrent longitudinal mechanical pulses are transmitted through the sample at a certain rate and simultaneously "turn on" a timing circuit. The pulses are converted to electrical energy by the receive transducer, amplified and "turn off" the timing circuit. These recurrent differences between turn on time and turn off time provide continuous elapsed time reading (in microseconds) through the sample as a function of distance along the sample.

3.2 Yarn Testing

Yarn tests used in this study were all standard tests. A list of these tests is given below:

1. YARN COUNT: ASTM D 1059-89 Standard test methods for yarn number based on short-length specimens.

2. YARN TWIST: ASTM D 1423-82 Standard test methods for twist in yarns by the direct-counting method.

3. YARN STRENGTH: ASTM D 2256-97 Standard test methods for tensile properties of yarn by the single strand method.

3.2. Fabric Testing

Fabric tests used in this study were all standard tests. A list of these tests is given below:

1. FABRIC WEIGHT: ASTM D 3776-85 Standard test methods for mass per unit area (weight) of woven fabrics.
2. FABRIC THICKNESS: ASTM D 1777-64 Standard test methods for measuring thickness of textile materials.
3. FABRIC COUNT: ASTM D 3775-85 Standard test methods for fabric count of woven fabrics.
4. FABRIC STRENGTH: ASTM D 5035-95 Standard test methods for breaking force and elongation of textile fabrics (strip method)
5. FABRIC TEAR: ASTM D 2261-96 Standard test methods for tearing strength of fabrics by the tongue (single rip) procedure (constant-rate-of-extension tensile testing machine)
6. TABER ABRASION: ASTM D 3884-80 Standard test methods for abrasion resistance of textile fabrics (rotating platform, double-head method)
7. FLEX ABRASION: ASTM D 3885-80 Standard test methods for abrasion resistance of textile fabrics (flexing and abrasion method)

8. PILLING: ASTM D 3512-96 Standard test methods for pilling resistance and other related surface changes of textile fabrics: Random Tumble Pilling Tester.

9. THERMAL CONDUCTIVITY: ASTM D 1518-85 Standard test methods for thermal transmittance of textile materials.

10. BALL BURST: ASTM D 6797-02 Standard test methods for bursting strength for fabrics. Constant-rate-of-extension (CRE): Ball Burst Test.

11. STIFFNESS: ASTM D 4032-94 Standard test methods for stiffness of fabric by the circular bend procedure.

12. DIMENSIONAL CHANGE: AATCC Test Method 135-2003 Dimensional Change of Fabrics after Home Laundering.

13. SKEWNESS: AATCC Test Method 179-2001 Skewness Change in Fabric and Garment Twist Resulting from Automatic Home Laundering.

14. COLOR CHANGE: AATCC Test Method 61-2003 Colorfastness to Laundering, Home and Commercial: Accelerated.

Chapter 4. RESULTS AND DISCUSSION

4.1 Identification Tests on Raw Fibers

Tables 6 and 7 show values of standard fiber properties measured by HVI and AFIS, respectively, for different types of cottons. These results indicate that Extra-Long Staple cottons (e.g. Giza70, Chinese, Pima) have longer, finer, more mature, and stronger fibers than medium-staple. These results can be used effectively to distinguish these two major categories of cotton type. However, within the same category (e.g. within ELS, or within Upland), they are not very useful in distinguishing one type of fiber from another. It was important therefore to use nonstandard methods of identification. These were the Dying Test, the Viscosity Test, and the Sonic Test described in the experimental section.

Table 6 HVI Fiber Properties of Different Fiber Types

Fiber	Mic	Mat	Len	SFI	Str	Elg	Rd	b+b	Tr Area
GIZA70	4.29	0.92	1.356	6.8	40.7	6.5	78.9	12.4	0.43
CHINESE	4.25	0.93	1.369	6.8	38.1	8.9	84.4	11.6	0.16
PIMA	4.1	0.94	1.513	6.6	41.1	8	76.8	14.3	0.17
ACALA	4.72	0.94	1.348	7	32.3	8.7	82.6	11.5	0.14
LONG-STRONG	4.36	0.92	1.218	8.6	32.9	7.9	83.1	13.7	0.14
SHORT-WEAK	4.56	0.88	0.996	14.6	25.1	9.6	83.4	14.6	0.16
Pima #29947	3.71	0.9	1.346	8.6	37.5	7.9	74.1	15.9	0.16
Pima #29950	3.82	0.9	1.319	8.5	34.8	8.9	74.2	16.1	0.24
Uplands #30699	3.91	0.88	1.205	8.8	32.4	7.6	81.9	13.4	0.12

Table 6 (cont.)

Fiber	Mic	Mat	Len	SFI	Str	Elg	Rd	b+b	Tr Area
Uplands #31907	4.27	0.87	1.085	11.8	26.5	9.8	84	14.4	0.06

* Mic = Micronaire-the higher the Mic, the coarser the fiber, Mat = Maturity ratio Maximum maturity = 1.0), len = Mode Fiber length (inch), SFI = Short Fiber Index (percent of fibers of < 0.5 inch length), Elg = Fiber breaking elongation (%), Rd = color whitness (or light reflection), +b = color yellowness, Tr Area = Trash area.

Table 7 AFIS Fiber Properties of Different Fiber Types

Fiber	**L (w) [in]**	**Fine mTex**	**IFC [%]**	**Mat Ratio**
GIZA70	1.13	148	6.1	0.9
CHINESE	1.11	157	5.9	0.92
PIMA	1.25	158	5.2	0.95
ACALA	1.07	189	4.2	0.98
LONG-STRONG	1.02	170	5.9	0.92
SHORT-WEAK	0.8	182	6.4	0.88
Pima #29947	1.11	154	6.1	0.9
Pima #29950	1.11	155	6.4	0.89
Uplands #30699	1.04	163	6.9	0.88
Uplands #31907	0.89	177	6.6	0.87

* L(w) = mean fiber length (inch), Fine = Fiber fineness (millitex), IFC = Immature Fiber Content (%), Mat = Maturity ratio

Figure 2 shows the results of Viscosity Identification Test for different cotton types. These results clearly indicate that different cotton types even within the same cotton type category (ELS or Upland) can be identified using the viscosity test. As can be seen in this

Figure, Supima® Cotton exhibits the highest Molecular Weight of all Cottons (as measured by Tappi Viscosity Method). This translates to

- High and persistent durability from fiber to finished product
- More homogenous material (uniform dye uptake and low variability in quality parameters)
- Minimum fiber brittleness under hot chemical treatments

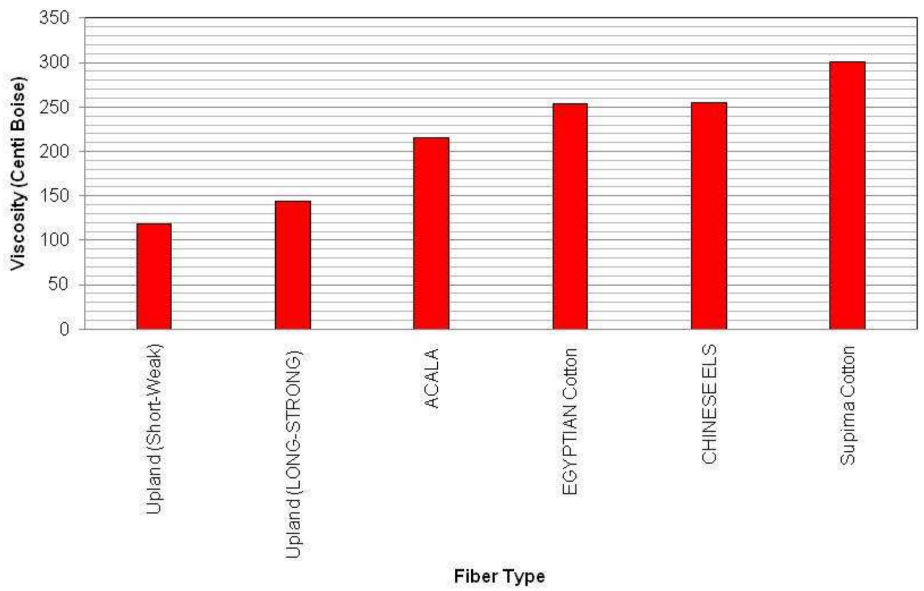


Figure 2 Viscosity Values of Major Cotton Fiber Types

Figure 3 shows the results of molecular orientation reflected by the Sonic test for yarns made from different cotton types. It should be noted that the sonic test is better suited for yarns as cotton fibers are too short to conduct this test. The results indicate that Supima® cotton exhibits the highest Molecular orientation of all Cottons (as measured by the Speed of sound).

This translates to

- A combination of smoothness and durability
- More consistent dye affinity
- High fiber resiliency

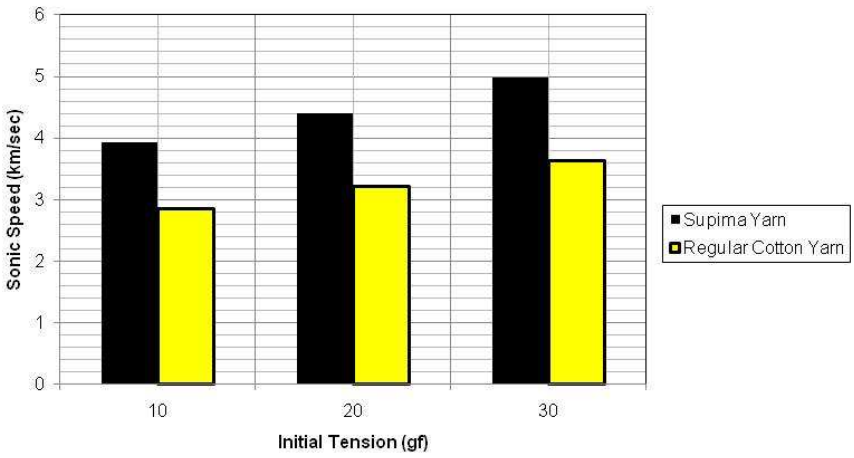


Figure 3 Sonic Speed of Two yarns made from different cotton types

Table 8 shows the results of color parameters revealed by the dye test. These results show that different cotton types can indeed have different levels of color parameters. The problem, however, is that dye uptake can be dependent on many factors including fiber maturity, fiber fineness, and surface morphology. Accordingly, to claim that the dye uptake test is a valid one for identifying different cotton types may not be so accurate unless a large database to support this claim is available, which outside the scope of this study.

Table 8 Color intensity measures of different fiber types

SAMPLE ID	ill. Cond	L*	a*	b*	C*	h	ΔE	K/S
	D65 10˚	69.00	-16.01	-9.41	18.54	210.29	32.50	
Regular-Upland	A 10˚	66.47	-18.85	-14.09	23.54	216.77	37.94	1.422
	F2 10˚	67.41	-11.59	-11.74	16.50	225.36	32.94	
	D65 10˚	62.38	-16.34	-10.29	19.31	212.20	37.86	
Supima Cotton	A 10˚	59.80	-19.57	-15.22	24.80	217.88	43.28	2.295
	F2 10˚	60.67	-11.83	-12.86	17.47	224.67	38.66	
	D65 10˚	65.99	-16.33	-9.60	18.38	210.45	40.99	
CHINESE	A 10˚	63.39	-19.28	-14.45	24.09	216.84	40.38	1.771
	F2 10˚	64.34	-11.83	-12.07	16.90	225.59	35.58	
	D65 10˚	63.85	-16.43	-9.85	19.16	210.95	36.38	
LONG STRONG-Upland	A 10˚	61.22	-19.50	-14.76	24.46	217.11	41.78	2.059
	F2 10˚	62.17	-11.90	-12.38	17.17	226.11	37.08	
	D65 10˚	64.19	-16.59	-10.22	19.49	211.63	36.06	
SHORT WEAK-Upland	A 10˚	61.50	-19.76	-15.20	24.93	217.57	41.63	2.032
	F2 10˚	62.45	-12.03	-12.84	17.60	226.85	36.82	
	D65 10˚	61.82	-16.01	-9.66	18.70	211.11	36.75	
GIZA 70	A 10˚	59.25	-18.96	-14.45	24.44	217.32	41.87	2.280
	F2 10˚	60.51	-11.59	-12.14	16.78	226.33	37.49	

4.2 Identification Tests on Yarns and Fabrics

As indicated earlier, in this study identification was made using a complete profiling from fiber to end-product. In this regard, two types of end product were used: (1) bed sheets, and (2) knit shirts.

In the following sections, results comparing end products made from different cotton types are reported for the three types of end product above.

4.2.1 Bed Sheets

Bed sheets represent a key consumer product used by millions of people and thousands of hotels, hospitals, and care homes on daily basis. Most consumers would like to have bed sheets that are soft, comfortable, easy to maintain, and most importantly durable over time and under repeated handling, washing, and drying. In this study, the key parameter examined was the durability of bed sheets under repeated washing and drying. The main variable of the study was the cotton type. In the initial analysis of the study, many commercial bed sheets were examined and many were disqualified for failure to meet basic requirements particularly pilling rate. Samples that exhibit pilling rates of less than 3.0 were discarded. It was also important to make sure that the selected samples for the study were comparable in every aspect except the fiber type. These include: yarn type, yarn structure (count and twist), fabric pattern, and fabric construction (count, thickness, and weight). Obviously, when commercial products are considered it is typically difficult to obtain samples that are comparable in every aspect. For this reasons, most comparable samples collected were produced by the same companies to minimize variability. Table 9 illustrates a list of the samples used identified by fabric patterns and thread count. Different types of tests performed on fabrics, yarns, and fibers are listed in APPENDIX A. APPENDIX B show the different yarn and fabric dimensional characteristics of the 300 TC bed sheet samples being compared in this study and APPENDIX C show the different yarn and fabric dimensional characteristics of the 500 TC bed sheet samples being compared in this study. We should point out that during testing, all samples were identified and labeled by the sample code and no information about bed sheet type or cotton type was revealed.

Table 9 Bed Sheet Samples

Sample Code	Thread Count	Standard (plain)/Sateen	Fiber
S-300-1	300	Standard (Plain) Weave	100% Egyptian Cotton
S-300-2	300	Standard (Plain) Weave	Regular Cotton
S-300-3	300	Standard (Plain) Weave	60% Egyptian Cotton/40% Polyester
S-300-4	300	Standard (Plain) Weave	100% Supima® Cotton
SA-500-1	500	Sateen Weave	100% Egyptian Cotton
SA-500-2	500	Sateen Weave	Special Cotton Blend
SA-500-3	500	Sateen Weave	100% Supima® Cotton
SA-540-3	540	Sateen Weave	100% Supima® Cotton
SA-778-3	778	Sateen Weave	100% Supima® Cotton

4.2.1.1 Comparison of the Durability of Bed Sheets Made from Different Cotton Types

What is Durability?

One of the key performance characteristics of bed sheets is durability. A durable bed sheet is the one that can withstand the strenuous treatments of bed sheets particularly during washing and drying. Unfortunately, this is one characteristic that consumers are unable to test at the time of purchasing bed sheets as only through use and repeated washing and drying that one can test the durability of the product. Fortunately, this key performance characteristic can be tested even under extreme conditions using standard laboratory testing methods. From a consumer's perspective, using a durable bed sheet could add a great value to the consumer as it could mean longer use of a high-quality bed sheets to the normal consumer and a significant cost saving to institutes using bed sheets in masses such as hotels and hospitals. Such institutes may have to wash and dry bed sheets in the order of hundreds of times every year.

What consumers need to know about the durability of bed sheets is that fiber type is the most critical factor of durable products. Indeed, two bed sheets of the same thread count made from two fiber types of 8 to 10 g/tex strength difference could mean a difference in lifecycle of up to 40%, as weaker fiber will translate into a weaker yarn, and certainly to a less durable fabric. When fibers of high short-fiber content and low maturity are used, the propensity for hairiness, pilling, and severe shrinkage will be some of the common problems witnessed in bed sheets made from these fibers. In this study, we examined many bed sheets starting by extracting fibers from the yarns used to make the bed sheets and testing their different characteristics. What we have discovered was that due to the high price differences between high quality ELS cottons and regular cottons, some spinners tend to blend extreme varieties of cotton for the sake of reducing manufacturing cost. This practice often goes unnoticed until the consumer uses the bed sheets a few times only to discover that they have to be thrown away for excessive pilling, severe shrinkage, or extremely poor appearance.

4.2.1.2 Laboratory Simulation of Bed Sheets Made from Different Cotton Types

The key parameters determining the durability of bed sheet products are:

- Tensile and tear resistance of fabric
- Fabric propensity to pilling
- Fabric resistance to surface abrasion
- Fabric dimensional stability

In this study, these parameters were measured for the bed sheets before and after repeated washing and drying of up to 50 cycles. Tensile, tear, and abrasion tests are considered "accelerated durability tests". They are accelerated because they use extreme external applications to deform the product. In other words, they put the bed sheets to the extreme test of durability or what we may call "pushing effects to the harshest limits". Indeed, bed sheets that are superior in passing these tests will certainly be superior in durability superior. The main reason for these tests is to achieve accelerated effects that otherwise would have only been obtained from many hours, days, or even years of use of products, making them time-consuming and cost prohibited. Pilling, appearance, and dimensional stability simulate effects that are witnessed under the normal use of bed sheets; certainly after washing and drying.

4.2.1.3 Results of Accelerated Extreme Durability Test

4.2.1.3.1 Tensile and Tear Strength

Figures 4 and 5 illustrate the fabric tensile strength for the 300 TC-Standard bed sheets, and the 500 TC-Sateen bed sheets, respectively. The results illustrated in these Figures can be summarized as follows:

- 300 TC-Standard bed sheets made from Supima® Cotton had higher tensile strength than all other fabrics in both warp and filling directions (Figure 4).
- Regular cotton bed sheets were about 22% to 24% lower in tensile strength than all other 300 TC-Standard bed sheets (Figure 4)
- 500 TC-Sateen bed sheets made from both Supima® Cotton and Egyptian Cotton had approximately the same tensile strength (Figure 5)
- Special cotton blend 500TC-Sateen bed sheets had inferior tensile strength than Supima® or Egyptian bed sheets (45% lower in warp direction and 28% lower in filling direction)

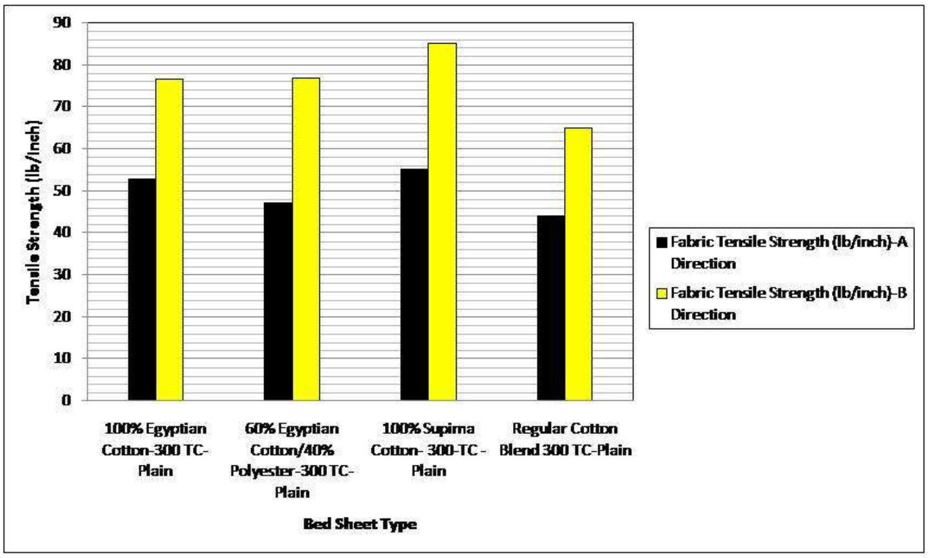


Figure 4 Comparison of Fabric Tensile Strength of Four Comparable 300 TC Standard Bed Sheets made from Different Cotton Types

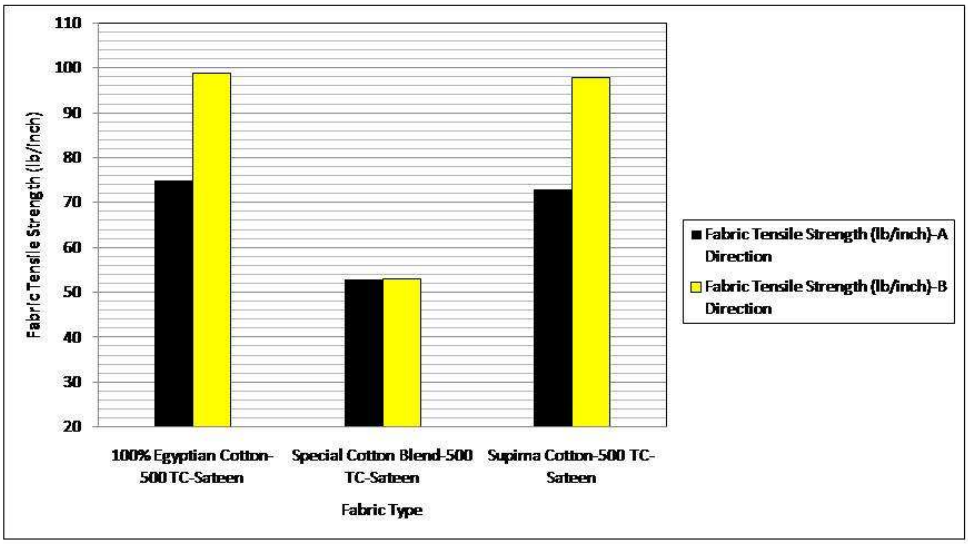


Figure 5 Comparison of Fabric Tensile Strength of Three Comparable 500 TC-Sateen Bed Sheets made from Different Cotton Types

Figures 6 and 7 illustrate the fabric tear strength for the 300 TC-Standard bed sheets, and the 500 TC-Sateen bed sheets, respectively. The results illustrated in these Figures can be summarized as follows:

- 300TC-Standard bed sheets made from Supima® Cotton had higher tear strength than all other bed sheets of this type in both A and B directions (Figure 6)
- 300TC-Standard bed sheets made from Egyptian cotton/Polyester fiber blend had lower tear strength than all other 300TC-Standard bed sheets in both warp and filling directions (Figure 6). This was partially attributed to the abnormally weak yarns produced from this blend as shown in Appendix B.
- 300TC-Standard bed sheets made from regular cotton had lower tear strength than ELS cotton sheets (11% less in warp direction and 25% less in filling direction in comparison with Supima® Cotton 300TC-Standard bed sheet)
- 500TC-Sateen bed sheets made from Supima® Cotton had comparable tear strength to those made from Egyptian cotton. More specifically, in warp direction, fabrics of Supima® Cotton sheets were lower in tear strength than those of Egyptian Cotton Sheets; but in weft direction, fabrics of Supima® Cotton sheets were higher in tear strength than those of Egyptian Cotton Sheets because Supima® Cotton sheets have more yarn in weft direction than other sheets have.
- 500TC-Sateen bed sheets made from the special cotton blend had lower fabric tear strength than the other two fabrics (21%-42% in comparison with Supima® sheet)

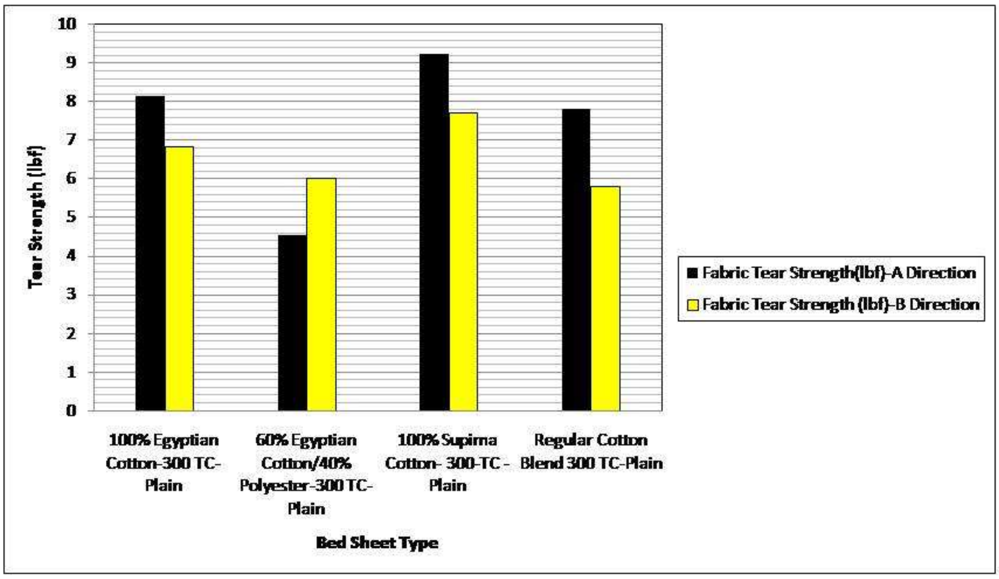


Figure 6 Comparison of Fabric Tear Strength of Four Comparable 300 TC-Standard Bed Sheets made from Different Cotton Types

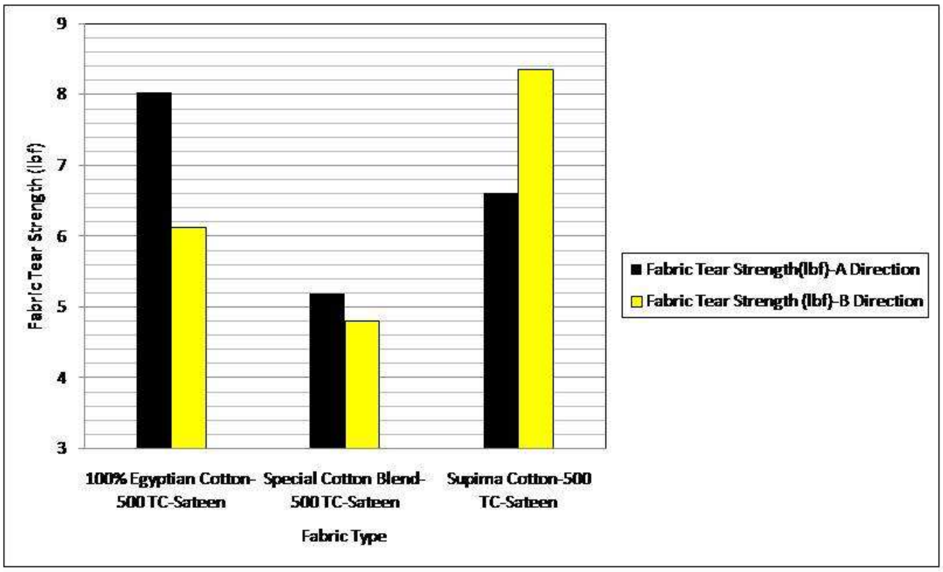


Figure 7 Comparison of Fabric Tear Strength of Three Comparable 500 TC-Sateen Bed Sheets made from Different Cotton Types

4.2.1.3.2 Abrasion Resistance

Two types of abrasion test were performed in this study. The first type is called "Flex Abrasion". This is a common standard abrasion test (**ASTM D 3885-80)** in which a rectangular fabric sample is flexed or bent against a metallic blade while being abraded at high speed to create a combination of flexing and abrasion effects. Flex abrasion resistance is then measured by the number of cycles of flex abrasion to the point at which the fabric totally fails or breaks. The second type of abrasion test performed in this study is the so-called "Taber Abrasion". This is another common standard test (**ASTM D 3884-80**) of abrasion in which a circular fabric sample is mounted on a rotating platform and a harsh-surface roller is rubbed against the fabric in a circular direction. Taber abrasion resistance is then measured by the number of cycles of Taber abrasion to the point at which the fabric totally fails or breaks.

In the context of durability, abrasion resistance represents the ultimate test as it affects both the bulk and the surface integrity of the fabric. Abrasion resistance also reflects the various strenuous effects that a fabric can be subjected to during use and during washing and drying. In relation to fiber type, fabrics made from long, mature, and strong fibers will typically exhibit higher abrasion resistance than fabrics made from short, immature, and weak fibers.

4.2.1.3.2.1 Flex Abrasion

Figures 8 and 9 illustrate the fabric flex-abrasion resistance for the 300 TC-Standard bed sheets, and the 500 TC-Sateen bed sheets, respectively. The results illustrated in these Figures can be summarized as follows:

- Among the 100% Cotton bed sheets, 300TC-Standard bed sheets made from Supima® Cotton exhibited the highest flex abrasion, while those made from regular cotton exhibited the lowest flex abrasion (Figure 8).
- 300 TC-Standard bed sheets made from Egyptian cotton/Polyester had the highest flex-abrasion. This result was expected on the ground that polyester fiber has exceptionally high abrasion resistance (Figure 8).
- 500TC-Sateen bed sheets made from Supima® Cotton exhibited approximately 10% higher Flex-Abrasion Resistance than those made from Egyptian Cotton Sheets (Figure 9)
- 500TC-Sateen bed sheets made from Special cotton blend exhibited lower Flex-Abrasion Resistance than the other two sheets and it was 21% lower in comparison with 500TC-Sateen bed sheets made from Supima® cotton (Figure 9)

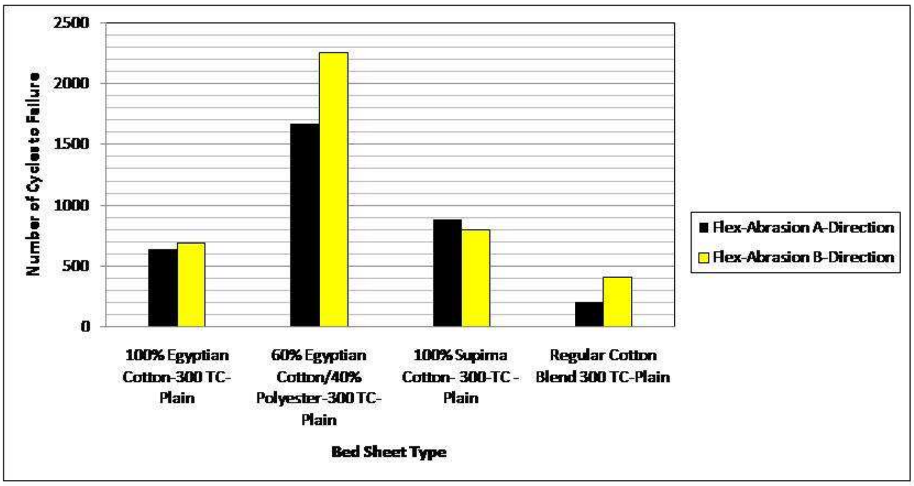


Figure 8 Comparison of Fabric Flex-Abrasion Resistance of Four Comparable 300 TC-Standard Bed Sheets made from Different Cotton Types

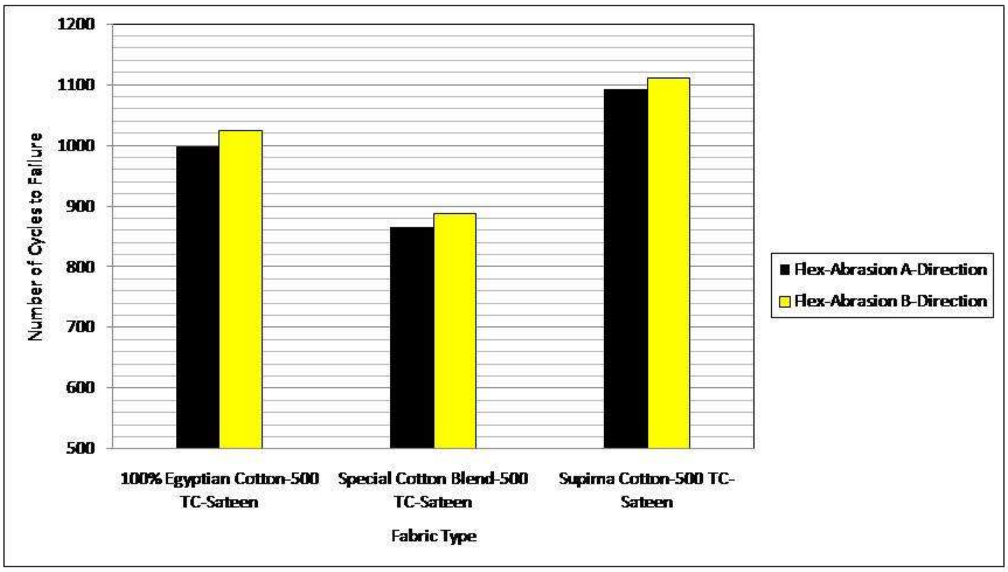


Figure 9 Comparison of Fabric Flex-Abrasion Resistance of Three Comparable 500 TC-Sateen Bed Sheets made from Different Cotton Types

4.2.1.3.2.2 Taber Abrasion

Figures 10 and 11 illustrate the fabric flex-abrasion resistance for the 300 TC-Standard bed sheets, and the 500 TC-Sateen bed sheets, respectively. The results illustrated in these Figures can be summarized as follows:

- Among all the 300 TC-Standard bed sheets, Supima® Cotton sheets exhibited the highest Taber abrasion resistance (Figure 10)
- Both regular cotton sheets and Egyptian cotton/polyester sheets failed approximately at half the same number of Taber abrasion cycles as Supima® Cotton sheets (Figure 10).

- Among all the 500TC-Sateen bed sheets, Supima® Cotton sheets exhibited slightly higher Taber-Abrasion Resistance than Egyptian Cotton Sheets (4%) and Special cotton blend sheets exhibited lower Taber-Abrasion Resistance than the other two sheets (by 14% in comparison with Supima® sheet)-Figure 11

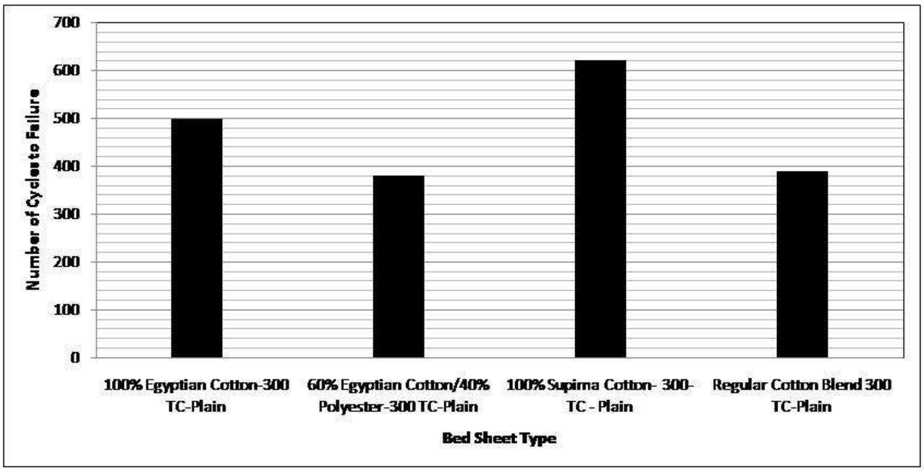


Figure 10 Comparison of Fabric Taber-Abrasion Resistance of Four Comparable 300 TC-Standard Bed Sheets made from Different Cotton Types

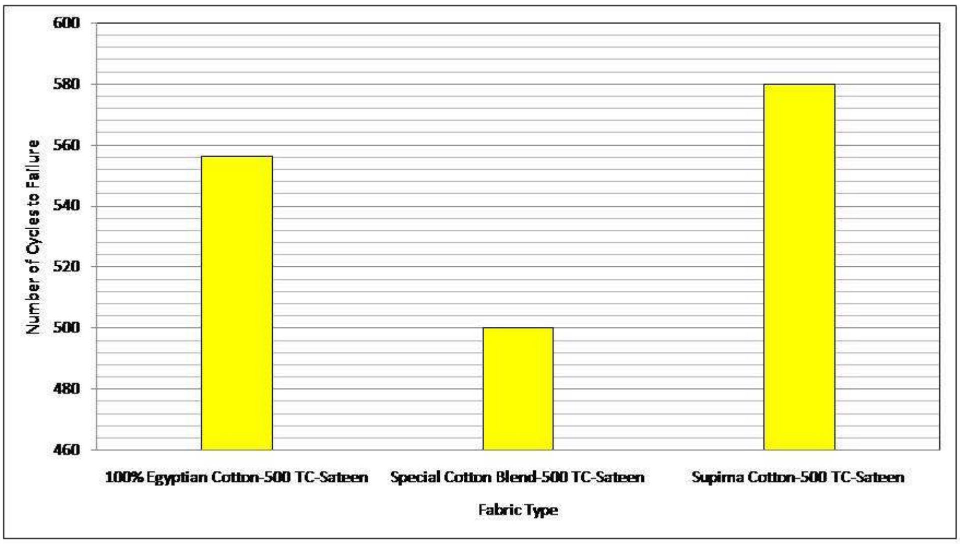


Figure 11 Comparison of Fabric Taber-Abrasion Resistance of Three Comparable 500 TC-Sateen Bed Sheets made from Different Cotton Types

4.2.1.3.2.3 Visual Examination of Taber Abrasion Effects

In order to illustrate how the Taber-Abrasion affects the different bed sheet fabrics, we examined the surfaces of the three 500TC-Sateen bed sheets after 500 cycles by stopping the testing and observing the surface damage on each sample. Figure 12 shows a comparison between the samples. Given the fact that these sheets were made of similar construction and finished more or less equally, the impact of Taber Abrasion becomes directly related to the resistance of fibers to abrasion damage. The results shown in this Figure clearly illustrate significant superiority of the 500TC-Sateen Supima® Cotton sheets over the others as evident by the smaller number of through-damage (holes) and the overall texture of the fabric after 500 abrasion cycles.

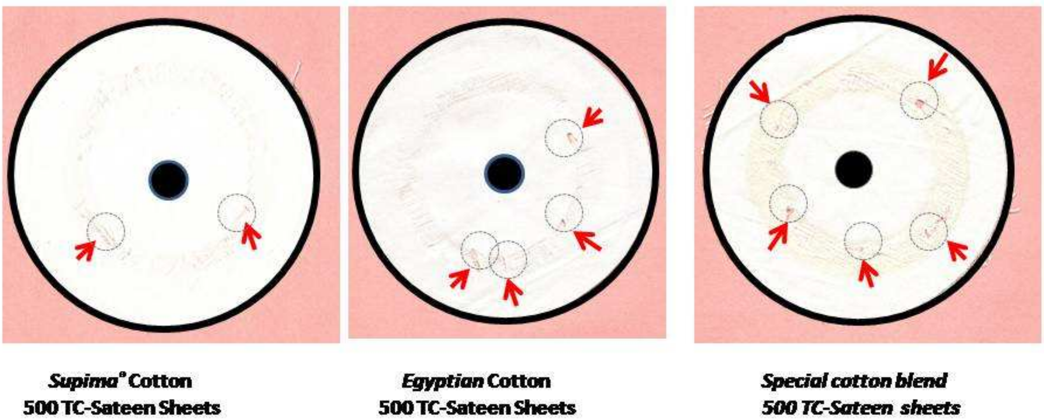


Figure 12 Comparison of the Status of Bed Sheets Samples after 500 Taber-Abrasion Cycles

4.2.1.3.3 Pilling Index

The propensity of fabric to pilling can be considered as perhaps the parameter that most reflect the fiber type used in the bed sheets. Pilling is the formation of balls of fibers presented on the fabric surface which result in a very poor appearance. A fabric of high pilling resistance is a fabric made from a durable fiber that can be spun into yarns leading to fabrics of high surface integrity. Short, immature, and weak fibers typically have greater propensity to pilling. Although some anti-pilling finish treatments can be applied to the fabric during dyeing and finishing, these treatments are typically good for a while as their effects tend to deteriorate over time. In addition, these treatments can add significantly to the cost of fabric manufacturing. In this study, we used **ASTM D 3512-96** Standard Pilling test method for pilling resistance and other related surface changes of textile fabrics. In this test, the fabric sample is subjected to random tumble pilling test in which the sample is rubbed extensively against standard white cotton fabrics and the fabric surface is observed after testing and compared with standard pilling pictures associated with a pilling scale from 1 to 5, with 1 being the worst pilling case and 5 being the best or no pilling case.

Figures 13 and 14 show the pilling indexes of the bed sheet samples examined in this study. As can be seen in Figure 13, for the 300TC-Standard bed sheets, Supima® Cotton sheets showed a superior pilling index in comparison with other bed sheets. For the 500TC-Sateen bed sheets, both Supima® Cotton sheets and Egyptian cotton bed sheets showed equal good pilling performance as shown in Figure 14.

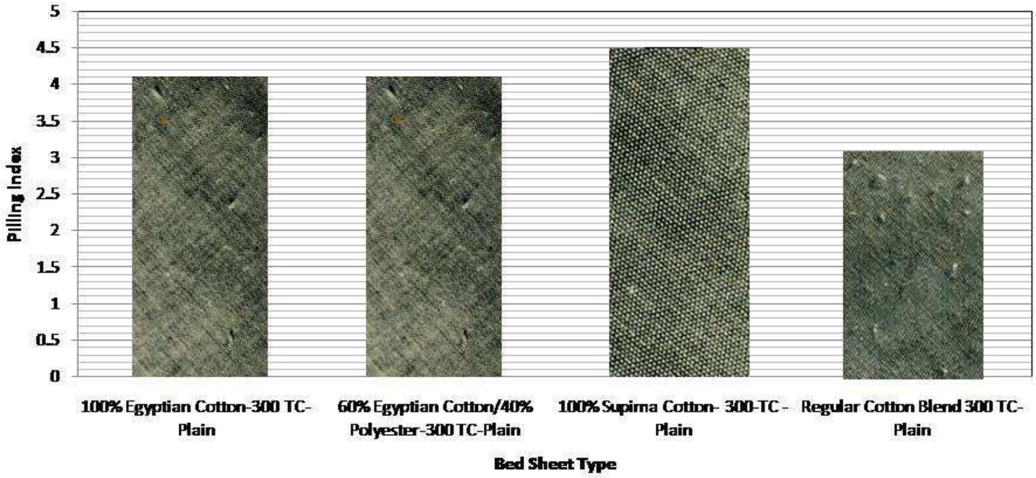


Figure 13 Comparison of Pilling Indexes of 300TC-Standard Bed Sheets Samples

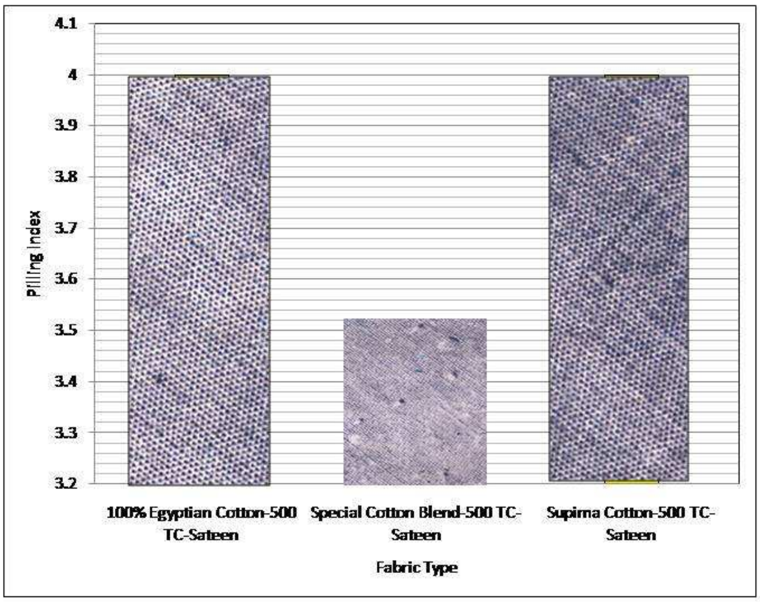


Figure 14Comparison of Pilling Indexes of 500TC-Sateen Bed Sheets Samples

4.2.1.4 Results of Washing – Drying Durability Test

Perhaps the best test that textile products can go through is the evaluation of performance change after repeated washing and drying cycles. Under these conditions, the product is put to the ultimate durability test as many fabrics may undergo adverse changes in dimensions (shrinkage and skew), loss in tensile and tear strength, more vulnerability under abrasion effects, and excessive pilling as a result of the stresses applied during washing and drying. In this section, we report the changes in these characteristics for the bed sheets examined in this study and for up to 50 washing & drying cycles.

4.2.1.4.1 Dimensional Changes of Bed Sheets upon Repeated Washing and Drying

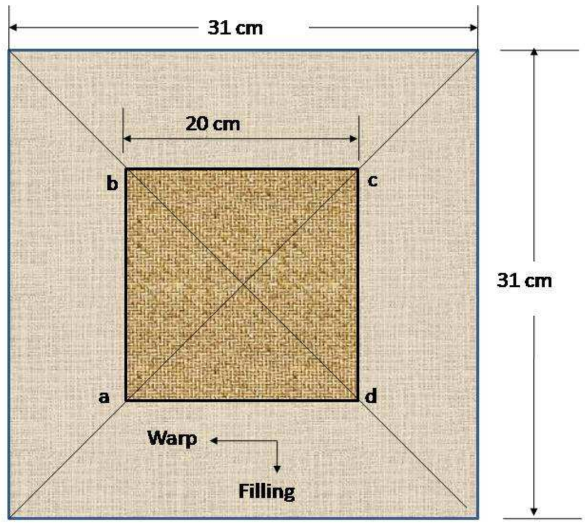
The key dimensional characteristics that are likely to change upon repeated washing and drying are fabric thickness and fabric area. These two parameters undergo changes as a result of fabric shrinkage, which is primarily a fiber-related aspect as different cotton types will shrink at different rates. With bed sheet products these changes can be quite serious since bed sheets must follow standard dimensions depending on the type of beds used.

In this study, we followed **ASTM D 1777-64** Standard test methods for measuring thickness of textile materials and **AATCC Test Method 135-2003** dimensional Change of Fabrics after Home Laundering (Figure 15). In addition, we performed **SKEWNESS test using AATCC Test Method 179-2001** Skewness Change in Fabric and Garment Twist Resulting from Automatic Home Laundering.

4.2.1.4.2 Changes in Fabric Thickness upon Washing and Drying

The results of thickness changes upon repeated washing and drying are shown in Figures 16 and 17. These results can be summarized as follows:

- All bed sheets have a tendency to increase in thickness as a result of washing and drying. This is a natural consequence of the fiber swelling upon water absorption.
- Among all bed sheets tested, Supima® cotton bed sheets exhibited the least amount of shrinkage upon washing and drying followed closely by Egyptian cotton bed sheets (Figures 16 and 17).
- Both regular cotton and special blend bed sheet fabrics encountered significantly greater increase in thickness. Indeed, for these two cotton types, the fabric thickness was almost doubled as a result of washing and drying.
- We also tested Supima® cotton bed sheets of different thread counts as shown in Figure 18. As can be seen in this Figure, the change in fabric thickness tends to dwell off after the first 5 washes.



$$Average\ (DC\%) = 100\frac{A_{after-Laundry} - A_{Before-Laundry}}{A_{Before-Laundry}}$$

Figure 15 Dimensional Changes after Washing & Drying (**AATCC Test Method 135-2003**)

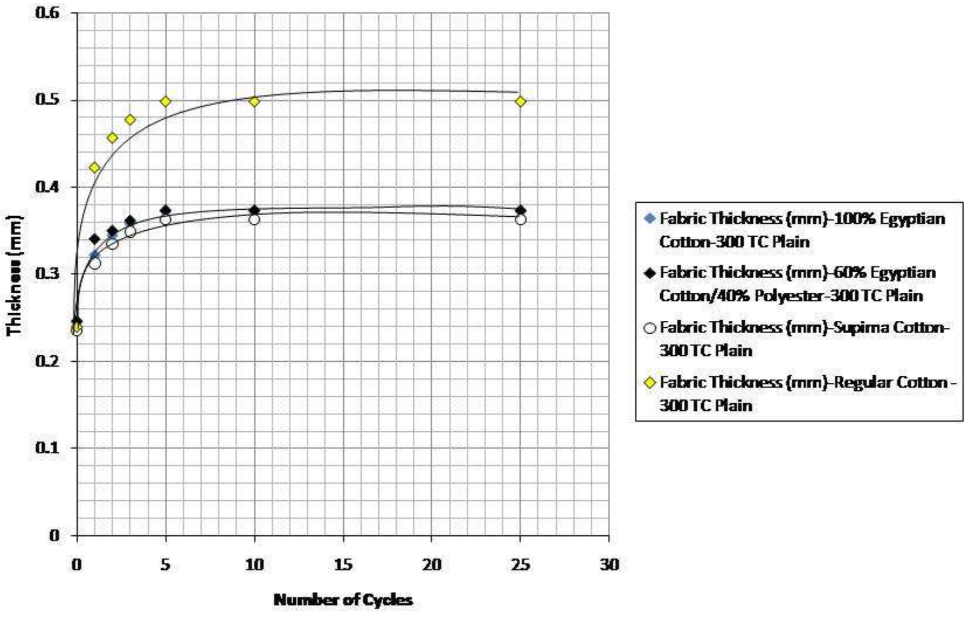


Figure 16 Changes in Fabric Thickness for 300TC-Standard Bed Sheets after Repeated Washing & Drying (AATCC 135)

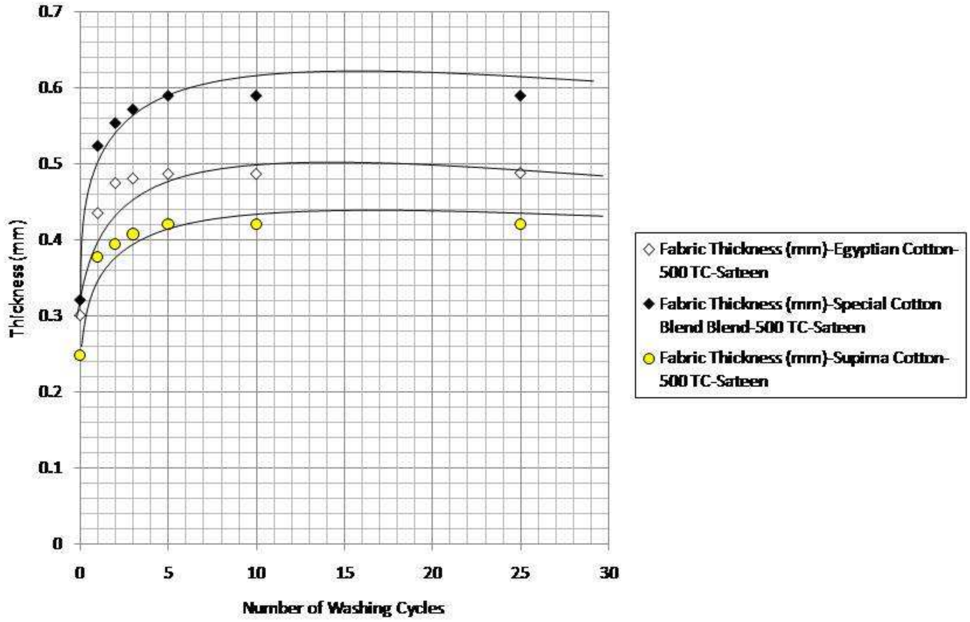


Figure 17 Changes in Fabric Thickness for 500TC-Sateen Bed Sheets after Repeated Washing & Drying (AATCC 135)

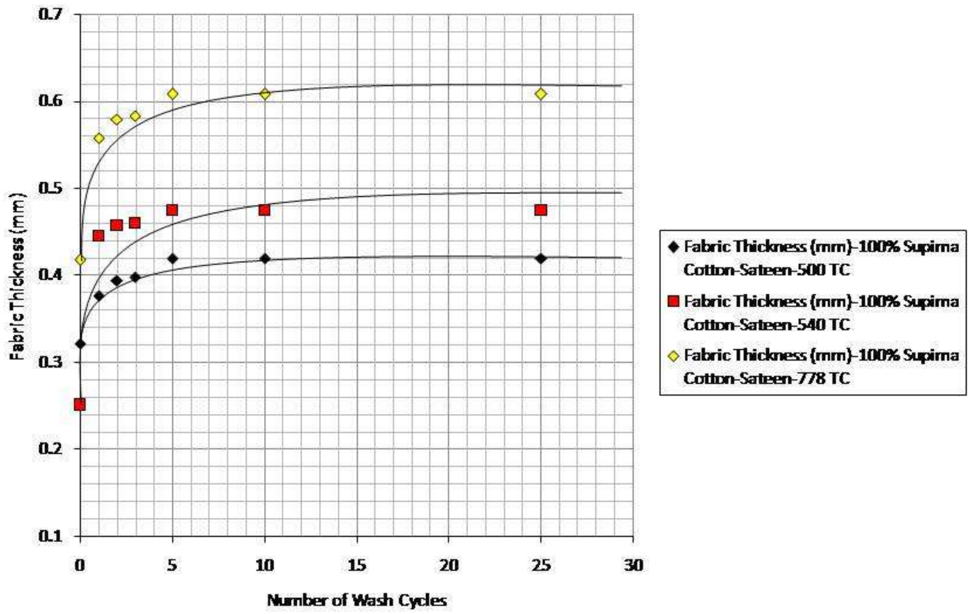


Figure 18 Changes in Fabric Thickness for Supima® Cotton Sateen Bed Sheets of Different Thread Counts after Repeated Washing & Drying (AATCC 135)

4.2.1.4.3 Area Changes of Fabric upon Repeated Washing and Drying

The results of area changes upon repeated washing and drying are shown in Figures 19 and 20. These results can be summarized as follows:

- As a result of the inevitable shrinkage, all bed sheets have a tendency to exhibit a reduction in area upon washing and drying.
- Among all bed sheets tested, Supima® cotton bed sheets exhibited the least area change upon washing and drying followed closely by Egyptian cotton bed sheets (Figures 19 and 20).
- Both regular cotton and special blend bed sheet fabrics encountered significantly greater reduction in area. These bed sheets suffered up to 9% reduction in area with respect to their original dimensions prior to washing.
- It is also important to observe the fabric appearance after many cycles of washing and drying. These observations clearly reveal that Supima® cotton bed sheets have maintained excellent integrity after repeated washing and drying.

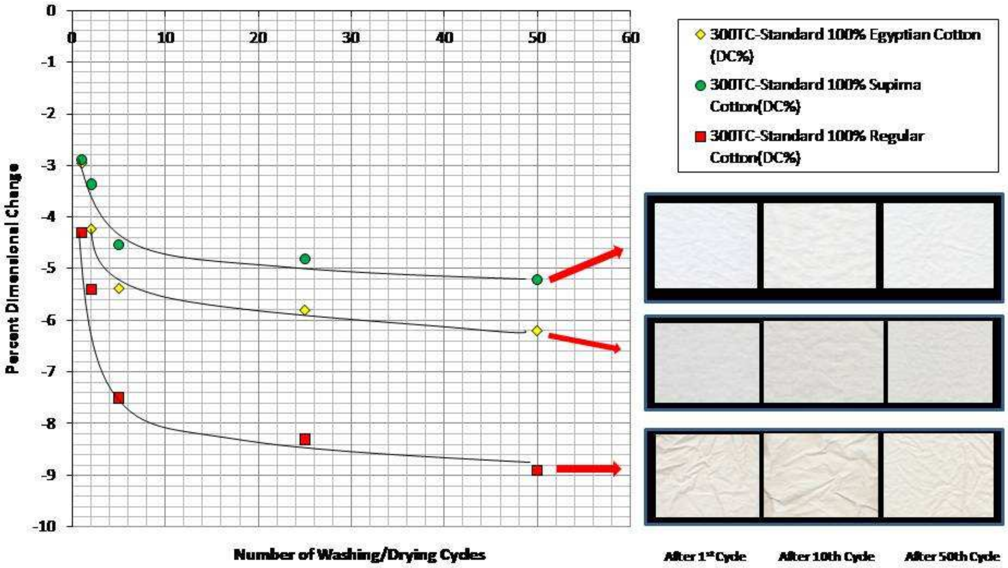


Figure 19 Dimensional Changes in Fabric for 300TC-Standard Bed Sheets after Repeated Washing & Drying (AATCC 135)

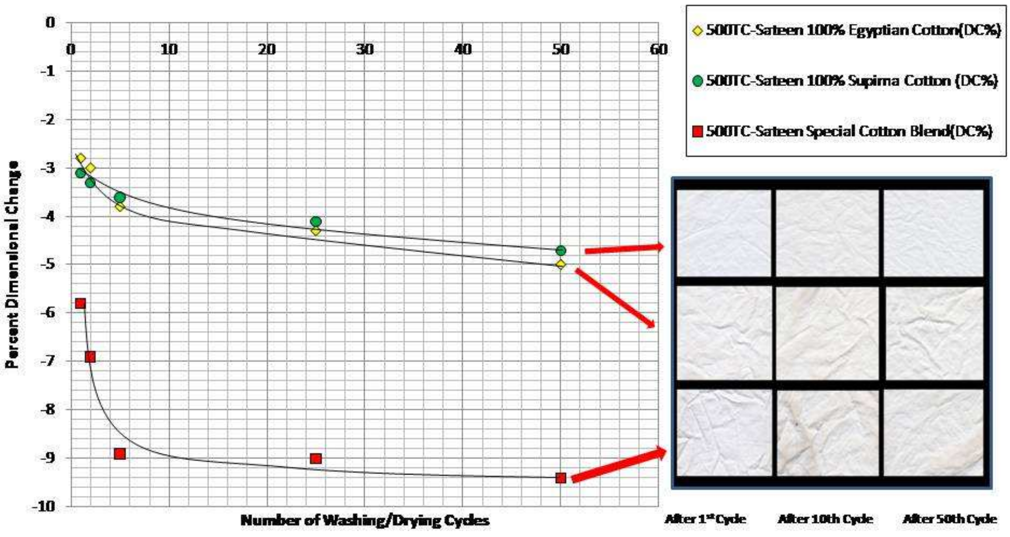


Figure 20 Dimensional Changes in Fabric for 500TC-Sateen Bed Sheets after Repeated Washing & Drying (AATCC 135)

4.2.1.4.4 Fabric Skew or Torquing upon Washing and Drying

Fabric skew is the deviation in weft or warp directions from the expected right angle of yarn crossing. The results of change in percent skew upon repeated washing and drying are shown in Figures 21 and 22. These results can be summarized as follows:

- In general, fabric skew did not represent a significant problem in bed sheets as all sheets examined in this study did not exceed 3% (the maximum acceptable skew level for most fabrics).
- Among all bed sheets, Supima® cotton bed sheets exhibited the least skew upon washing and drying followed closely by Egyptian cotton bed sheets.
- Again, both regular cotton and special blend bed sheet fabrics encountered significantly greater skew. These bed sheets suffered up to 2.5% skew after 50 washing cycles.

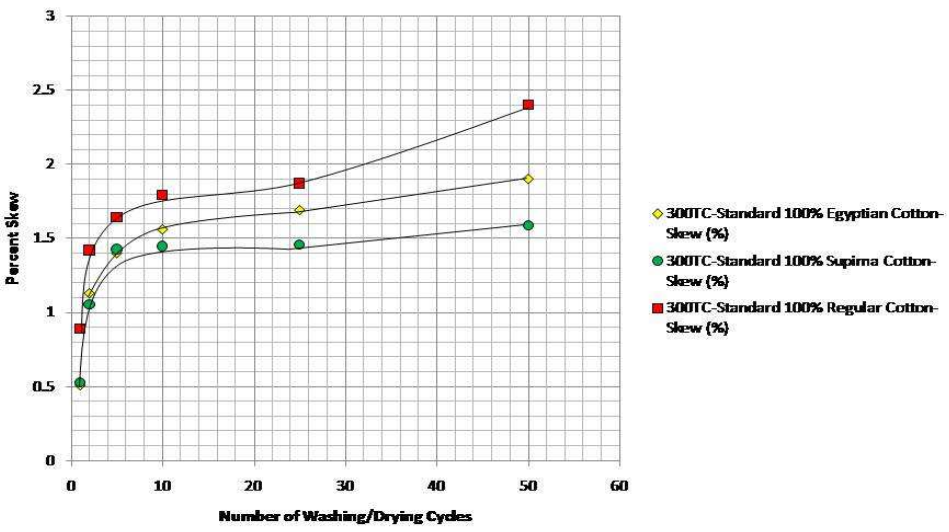


Figure 21 Fabric Skew for 300TC-Standard Bed Sheets after Repeated Washing & Drying (AATCC 135)

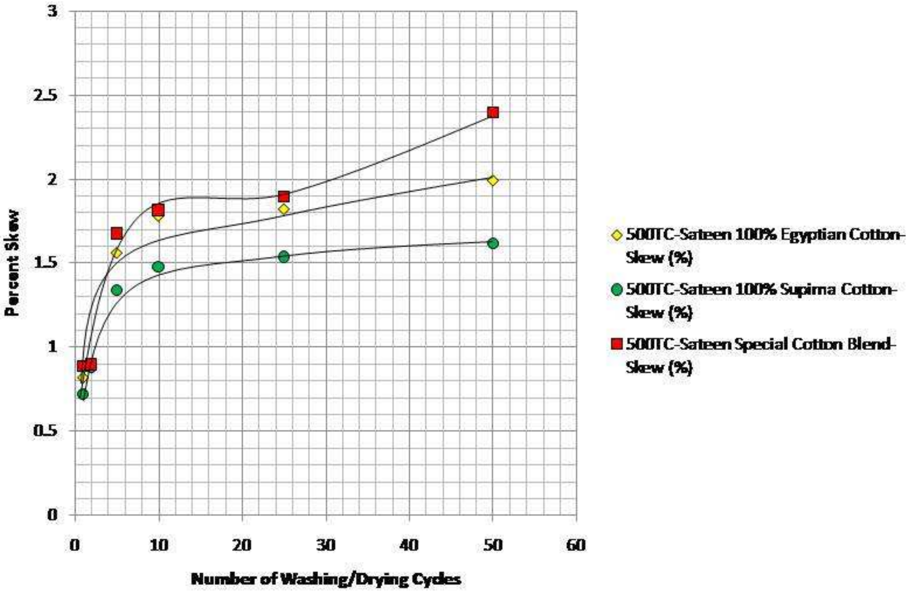


Figure 22 Fabric Skew for 500TC-Sateen Bed Sheets after Repeated Washing & Drying (AATCC 135)

4.2.1.4.5 Physical Changes of Bed Sheets upon Repeated Washing and Drying

In addition to the dimensional changes discussed above, the fabric may undergo changes in its physical properties such as pilling, strength and abrasion resistance. These changes were evaluated by testing fabric samples after each cycle of washing and drying.

4.2.1.4.5.1 Pilling Resistance

The changes in pilling resistance for TC300-Standard bed sheets and 500TC-Sateen bed sheets after repeated washing and drying are shown in Figures 23 and 24, respectively. As can be seen in these Figures, the pilling index for Supima® Cotton bed sheets and Egyptian Cotton bed sheets tend to stay at the same rate after repeated cycles of washing and drying while bed sheets made from regular cotton or special blends tend to deteriorate in pilling resistance.

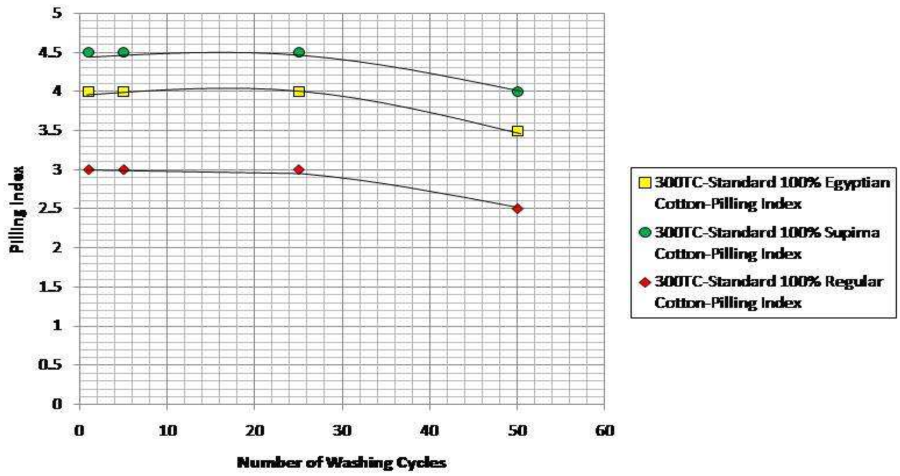


Figure 23 Fabric Pilling Resistance for 300TC-Standard Bed Sheets after Repeated Washing & Drying (ASTM D 3512-96)

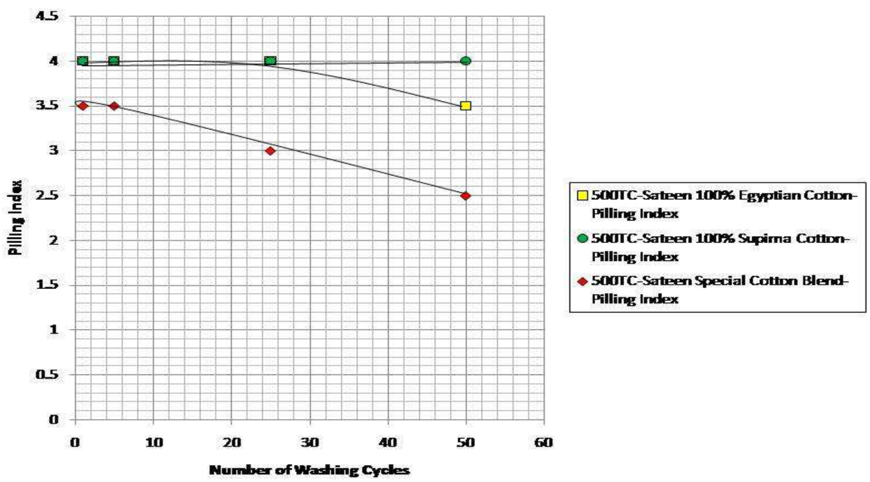


Figure 24 Fabric Pilling Resistance for 500TC-Sateen Bed Sheets after Repeated Washing & Drying (ASTM D 3512-96)

4.2.1.4.5.2 Fabric Strength

Changes in fabric strength for 300TC-Standard, and 500TC-Sateen bed sheets are shown in Figures 25 and 26, respectively. As can be seen in these Figures,

- For 300TC-Standard bed sheets, upon washing and drying, all bed sheets exhibited an increase in tensile strength. Regular Cotton sheets exhibited the least increase in strength and both Supima® Cotton and Egyptian cotton bed sheets exhibited the highest increase
- For 500TC-Sateen bed sheets, similar trends were observed. Upon washing, all bed sheets exhibited an increase in tensile strength. Special Blend Cotton sheets exhibited the least increase in strength and both Supima® Cotton and Egyptian Cotton Sheets exhibited the highest increase

4.2.1.4.5.3 Abrasion Resistance

Changes in Flex-Abrasion Resistance for 300TC-Standard and 500TC-Sateen bed sheets are shown in Figures 27 and 28, respectively. As can be seen in these Figures,

- For 300TC-Standard bed sheets, upon washing, all bed sheets exhibited a decrease in their Flex-Abrasion Resistance (Figure 27). This is typically expected on the basis of wear out of fabric finish providing more exposed surfaces. Supima® Cotton Sheets exhibited one of the least changes in Flex Abrasion
- For 500TC-Sateen bed sheets, Special Blend Cotton sheets exhibited the highest reduction in Flex Abrasion Resistance and Supima® Cotton Sheets exhibited the least change in Flex Abrasion Resistance (Figure 28).

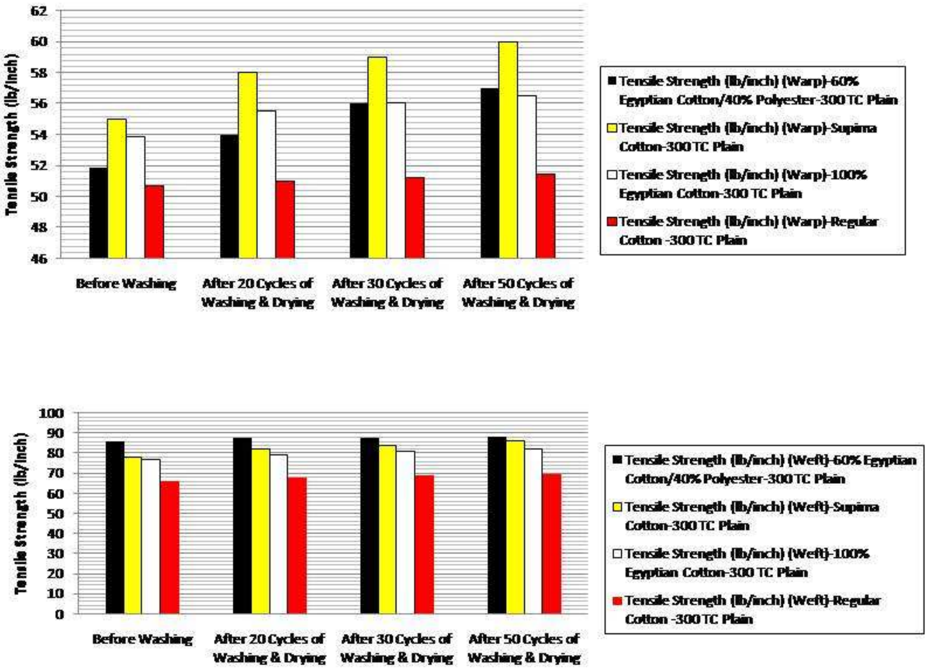


Figure 25 Fabric Tensile Strength for 300TC-Standard Bed Sheets after Repeated Washing & Drying

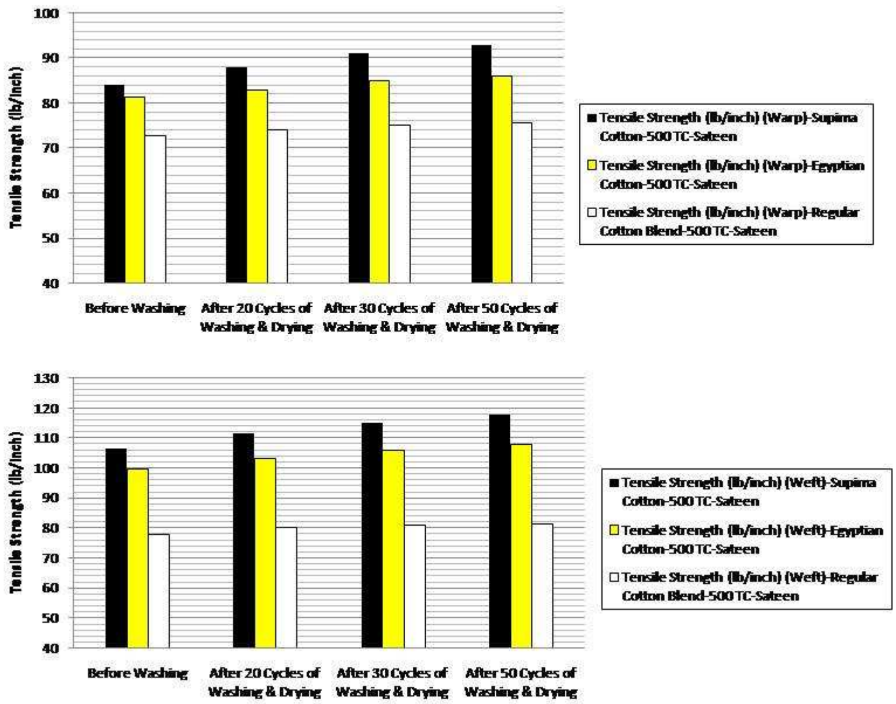


Figure 26 Fabric Tensile Strength for 500TC-Sateen Bed Sheets after Repeated Washing & Drying

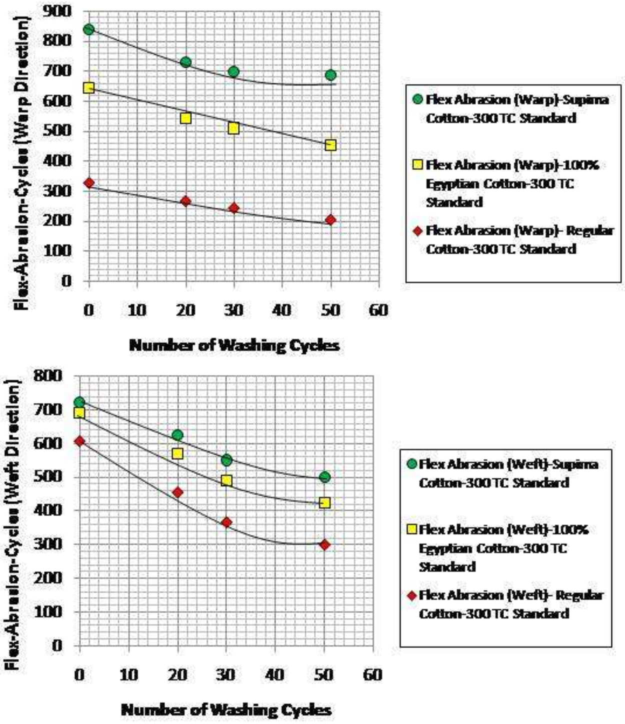


Figure 27 Fabric Flex Abrasion Resistance for 300TC-Standard Bed Sheets after Repeated Washing & Drying

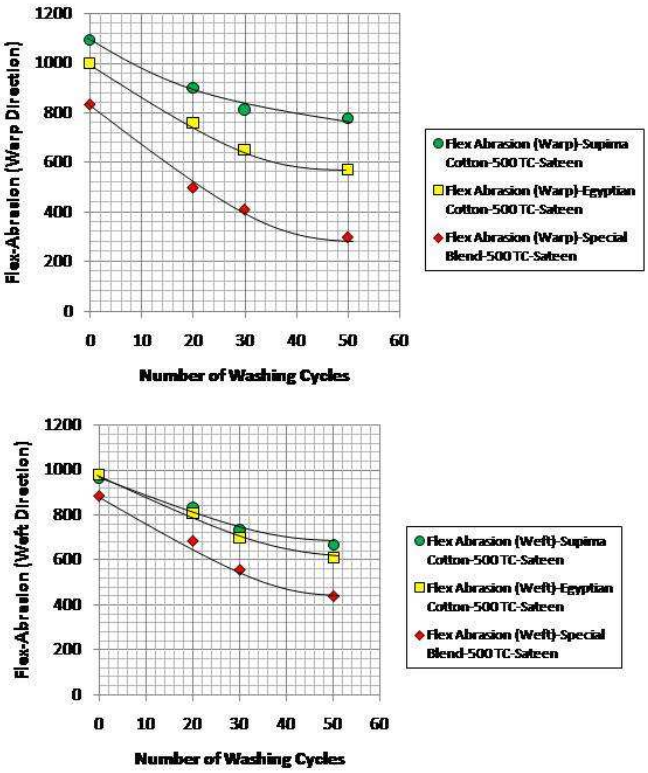


Figure 28 Fabric Flex Abrasion Resistance for 500TC-Sateen Bed Sheets after Repeated Washing & Drying

Changes in Taber-Abrasion Resistance for 300TC-Standard and 500TC-Sateen bed sheets are shown in Figures 29 and 30, respectively. As can be seen in these Figures,

- For 300TC-Standard bed sheets, upon washing, all bed sheets exhibited a decrease in their Tabor-Abrasion Resistance. Again, this is expected on the basis of wear out of fabric finish providing more exposed surfaces. Supima® Cotton Sheets exhibited the least change in Taber Abrasion (Figure 29)
- For 500TC-Sateen bed sheets, similar trends were obtained as shown in Figure 30.

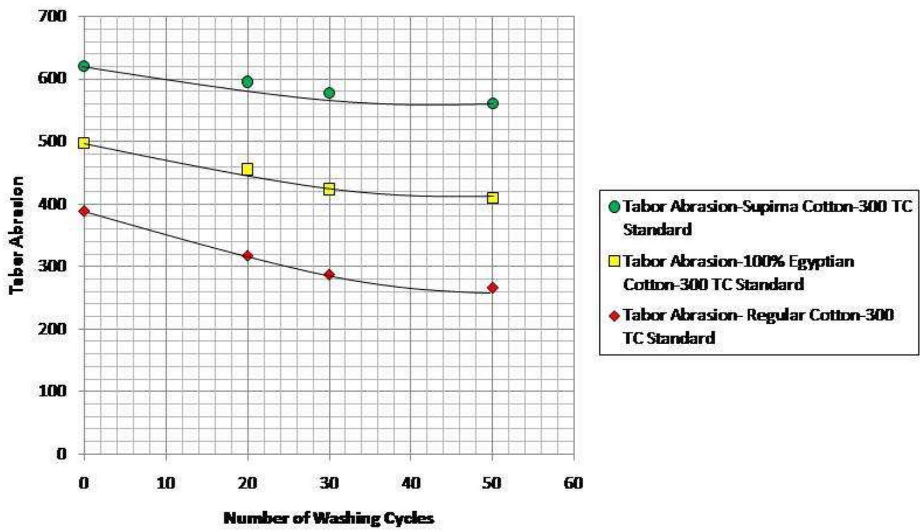


Figure 29 Fabric Taber Abrasion Resistance for 300TC-Standard Bed Sheets after Repeated Washing & Drying

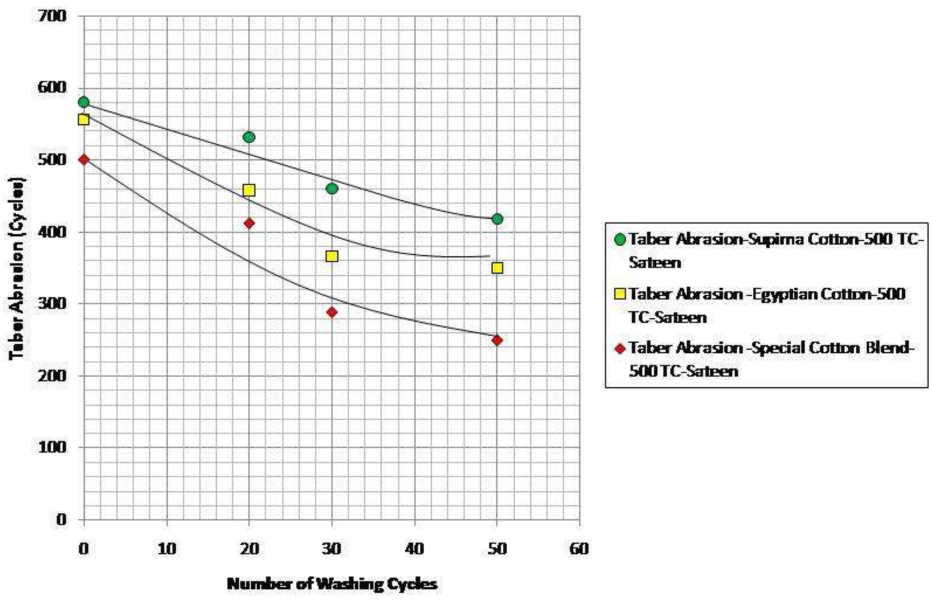


Figure 30 Fabric Taber Abrasion Resistance for 500TC-Sateen Bed Sheets after Repeated Washing & Drying

4.2.1.4.6 Change in Comfort – Related Parameters of Bed Sheets upon Repeated Washing and Drying

In addition to the changes discussed above, we also tested two parameters that are of great importance to consumers as they relate to the comfort characteristics of bed sheets. These are fabric stiffness (**ASTM D 4032-94)** and thermal conductivity (**ASTM D** 1518-85). The first one directly influences the tactile comfort of bed sheets with high stiffness yielding a pronounced discomfort. The second one affects the warm feeling of bed sheets with high thermal conductivity yielding higher warmth.

4.2.1.4.6.1 Fabric Stiffness

Changes in Fabric stiffness for 300TC-Standard and 500TC-Sateen bed sheets are shown in Figures 31 and 32, respectively. As can be seen in these Figures,

- For 300TC-Standard bed sheets, upon washing, all bed sheets exhibited an increase in Fabric Bending Stiffness. Regular Cotton sheets exhibited the highest stiffness and Supima® Cotton Sheets exhibited the lowest increase in stiffness (Figure 31)
- For 500TC-Sateen bed sheets, upon washing, all bed sheets also exhibited an increase in Fabric Bending Stiffness. Special Blend Cotton sheets exhibited the highest increase in stiffness and Supima® Cotton Sheets exhibited the lowest increase in stiffness**.**

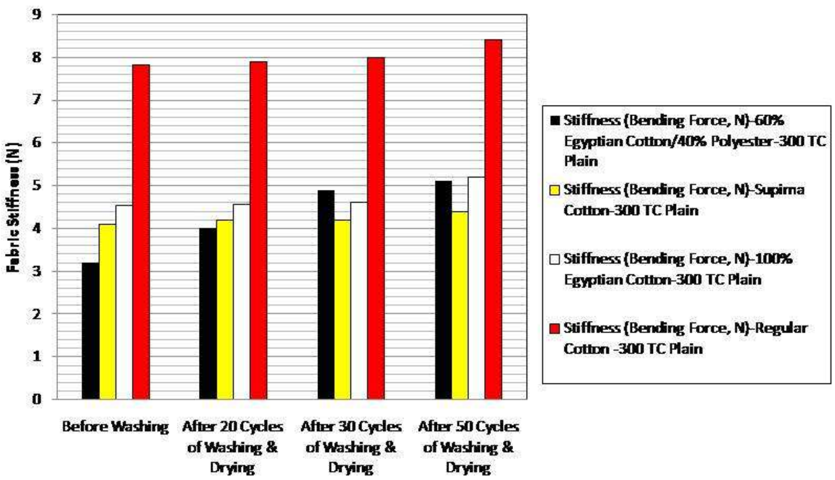


Figure 31 Fabric Stiffness for 300TC-Standard Bed Sheets after Repeated Washing & Drying

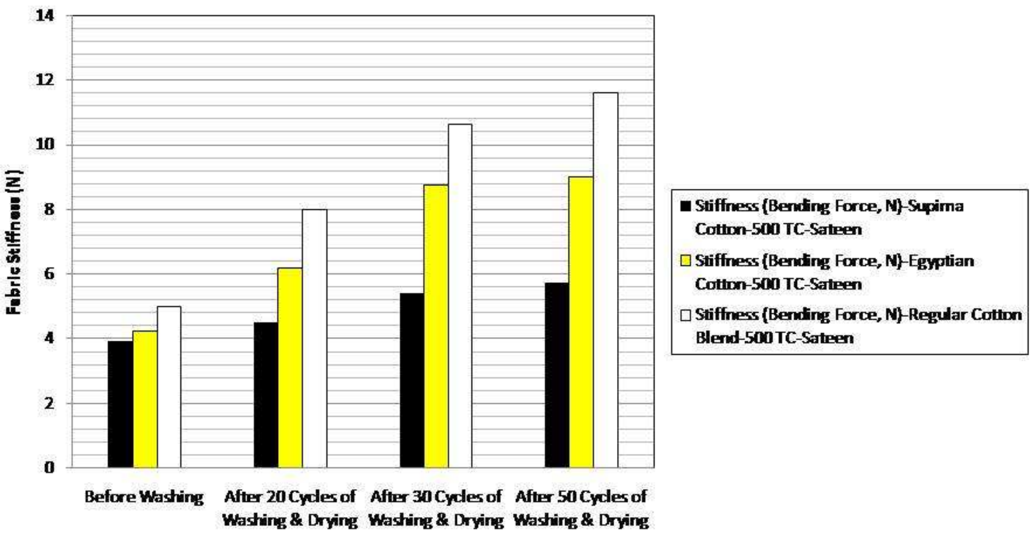


Figure 32 Fabric Stiffness for 500TC-Sateen Bed Sheets after Repeated Washing & Drying

4.2.1.4.6.2 Thermal Conductivity

Changes in thermal conductivity for 300TC-Standard and 500TC-Sateen bed sheets are shown in Figures 33 and 34, respectively. As can be seen in these Figures,

- For 300TC-Standard bed sheets, upon washing, upon washing, all bed sheets exhibited an increase in Thermal Conductivity. Supima® Cotton Sheets exhibited the highest increase in Thermal Conductivity.
- For 500TC-Sateen bed sheets, upon washing all bed sheets exhibited an increase in Thermal Conductivity. Supima® Cotton Sheets exhibited the highest increase in Thermal Conductivity

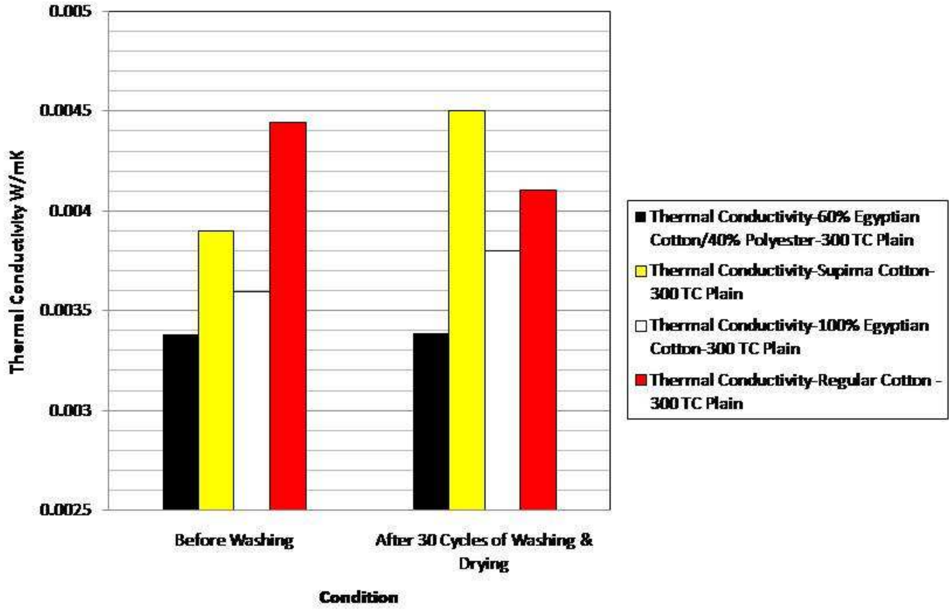


Figure 33 Fabric Thermal Conductivity for 300TC-Standard Bed Sheets after Repeated Washing & Drying

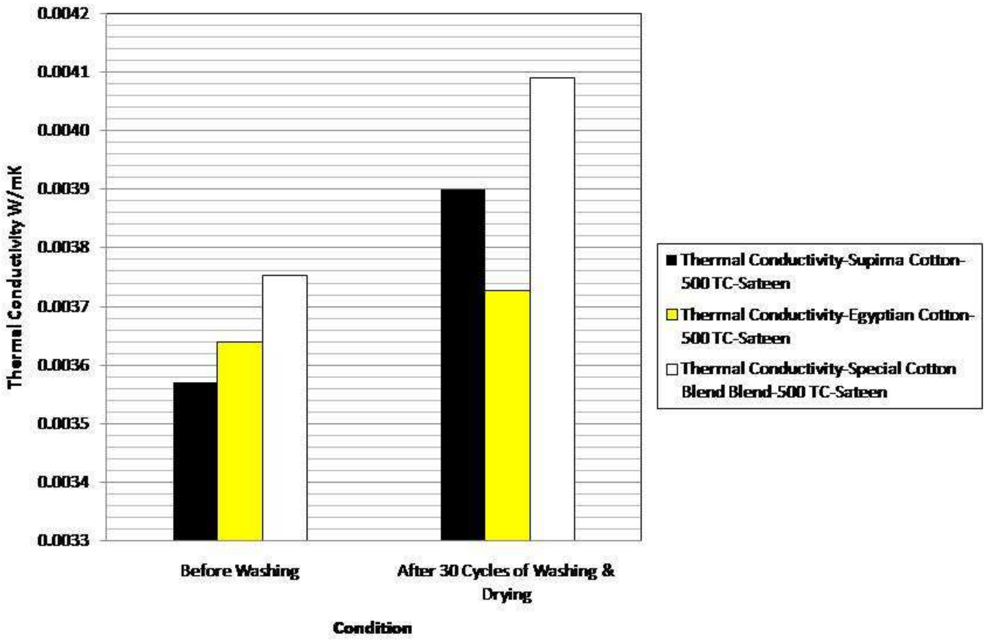


Figure 34 Fabric Thermal Conductivity for 500TC-Sateen Bed Sheets after Repeated Washing & Drying

4.2.2 Knit Shirts

In this part of the study, our focus was on Knit shirts of known brand names that use different cotton types for making approximately the same styles. Knit shirts selected for this study were obtained from famous retail stores to meet the following criteria:

- Same fabric style
- Comparable prices
- Approximately same type of finish

The task to collect these samples was quite difficult as ensuring equality in commercial products particularly of apparel types always represents a challenging issue. We also used samples of women knit shirts that were made by the same company and of the same style using two different types of cotton. Different types of tests performed on fabrics, yarns, and fibers are listed in APPENDIX A. Knit shirts samples used in this study are listed in Table 10. We should point out that during testing, all samples were identified and labeled by the sample code and no information about bed sheet type or cotton type was revealed. Basic information about yarns and fabrics for these samples are listed in Appendix D through Appendix G.

Table 10 Knit Shirts Samples used in this study

Code	Knit Shirt Type
T1	Men-T-Shirt-Single-Jersey-100% Supima Cotton
T2	Men-T-Shirt--Single-Jersey-100% Egyptian Cotton
T3	Men-T-Shirt--Single-Jersey-100% Regular Cotton
T4	Men-T-Shirt-Lacoste knit100% Supima Cotton
T5	Men-T-Shirt-Lacoste knit100% Egyptian Cotton
T6	Men-T-Shirt-Lacoste knit100% Regular Cotton
T7	Women-Shirt-Single Jersey- knit100% Supima Cotton
T8	Women-Shirt-Single Jersey-Knit 100% Egyptian Cotton
T9	Women-Shirt-Single Jersey-Knit 100% Regular Cotton
T10	Women-Under-Shirt-Lacoste knit100% Supima Cotton
T11	Women-Under-Shirt-Lacoste knit100% Egyptian Cotton
T12	Women-Under-Shirt-Lacoste knit100% Regular Cotton

4.2.2.1 Comparison of the Durability of Knit Shirts made from Different Cotton Types

The concept of durability of knit shirts is quite different from that of bed sheets. Typically, the tensile or tear strength of knits shirts do not represent major concerns by virtue of the stretchy nature of these products. As a result, key durability measures of knit shirts are:

- Fabric Pilling
- Bursting strength
- Dimensional changes (Shrinkage and skew)

4.2.2.1.1 Knit Shirts Fabric Pilling

Figures 35 through 38 show the differences in pilling indexes for the various comparable knit shirts used in this study. As can be clearly seen from these Figures tumble pilling tests reveal superior performance for Supima® Cotton knit shirts of different types. Egyptian cotton knit shirts was largely equal in performance except for women's Single-Jersey shirts. In all cases, knit shirts made from regular cotton were inferior in pilling propensity.

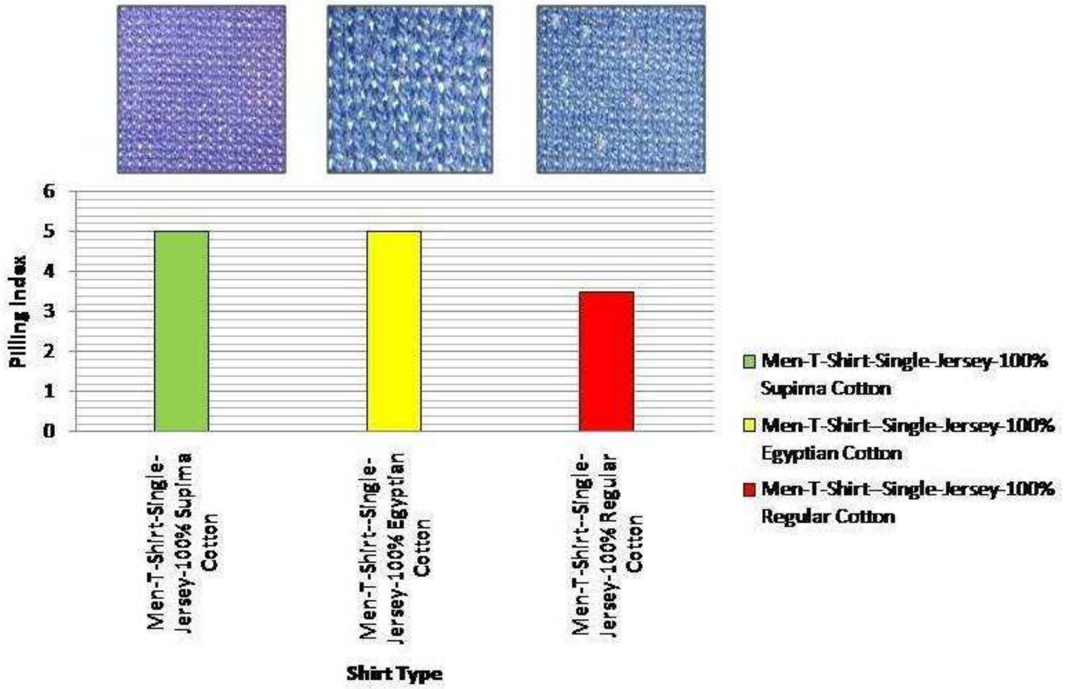


Figure 35 Fabric Pilling for Men's Single-Jersey Knits made from Different Cotton Types

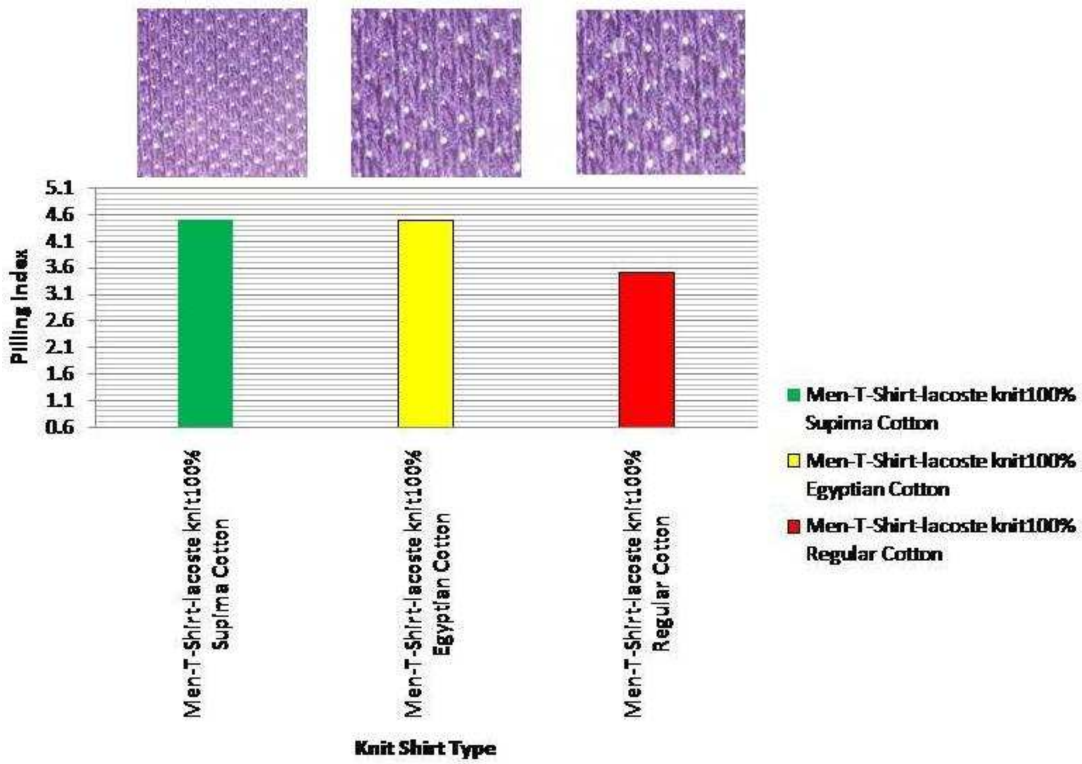


Figure 36 Fabric Pilling for Men's Lacoste Knits made from Different Cotton Types

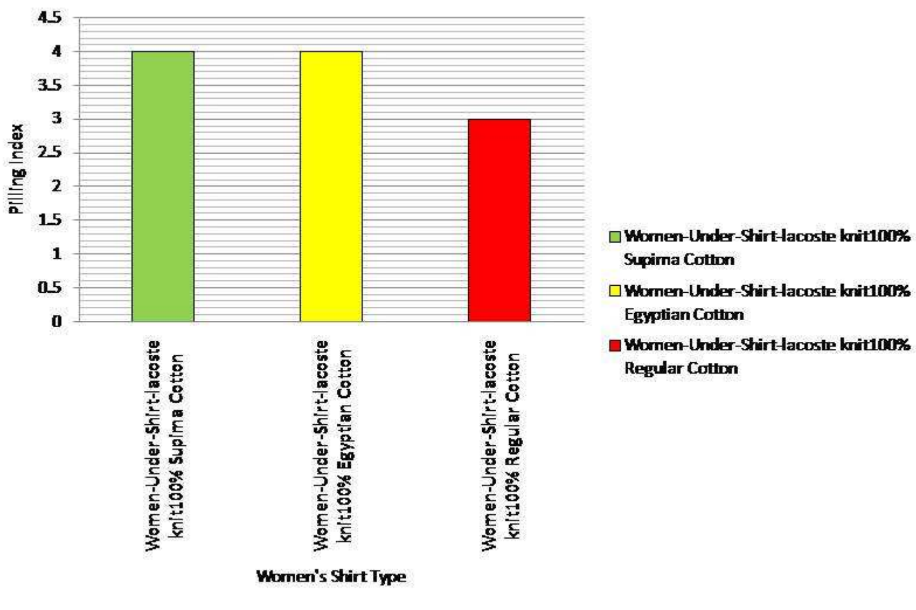


Figure 37 Fabric Pilling for women's Lacoste Undershirts Knits made from Different Cotton Types

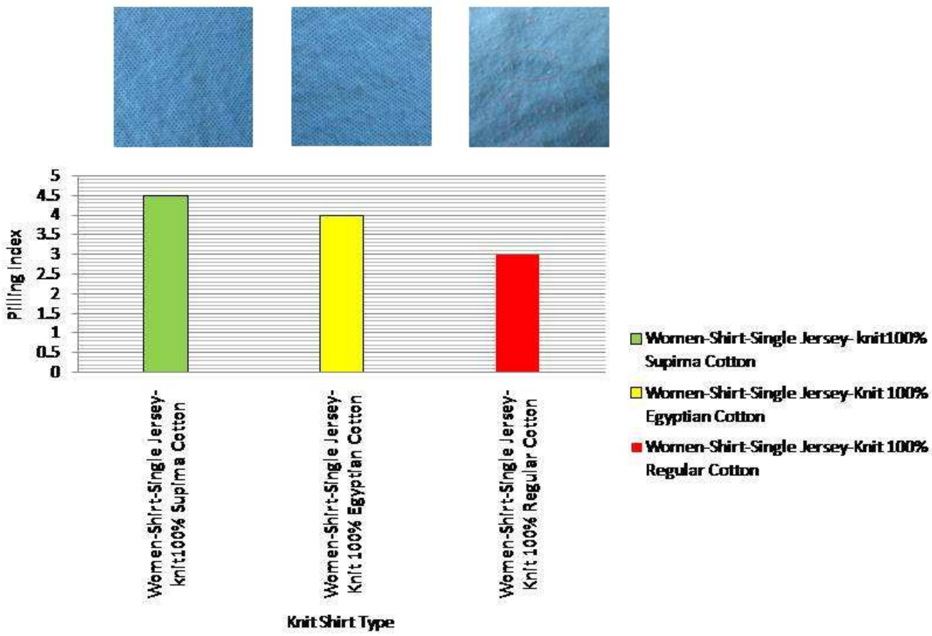


Figure 38 Fabric Pilling for Women;s Single-Jersey Knits made from Different Cotton Types

4.2.2.1.2 Knit Shirts Fabric Bursting Strength

Ball burst strength is defined as the ability of material to resist rupture by pressure. It is basically the force required to rupture a fabric by distending it with a force applied at right angles to the plane of the fabric under specified conditions. This type of strength measures is widely used for knit fabrics, nonwoven fabrics, and felts where the constructions do not lend themselves to tensile tests. The two basic types of burst tests are the inflated diaphragm method and the ball-burst method. In this study, we tested the ball-burst strength using ASTM D 6797-02 at a constant-rate of elongation (Figure 39).

Figures 39 through 42 show bursting strength of the different knit shirts examined in this study. These Figures clearly indicate superior performance for both Supima®

Cotton and Egyptian cotton knit shirts. Again, in all cases, knit shirts made from regular cotton were inferior in ball-burst strength. Percent differences between Supima® Cotton knit shirts and regular cotton knit shirts were mostly up to 40%, which is a substantial difference imposed solely by the fiber type used. This result makes it undutiful that the use of Supima® Cotton knit shirts provides an immense advantage from a durability viewpoint.

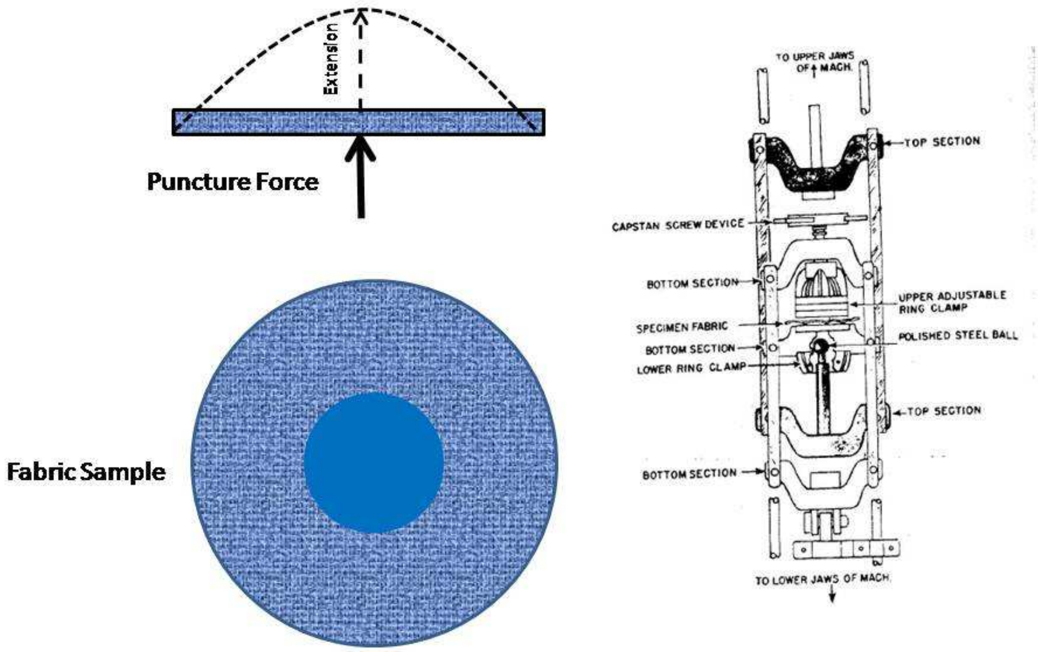


Figure 39 Ball Bursting Strength (ASTM D 6797-02)

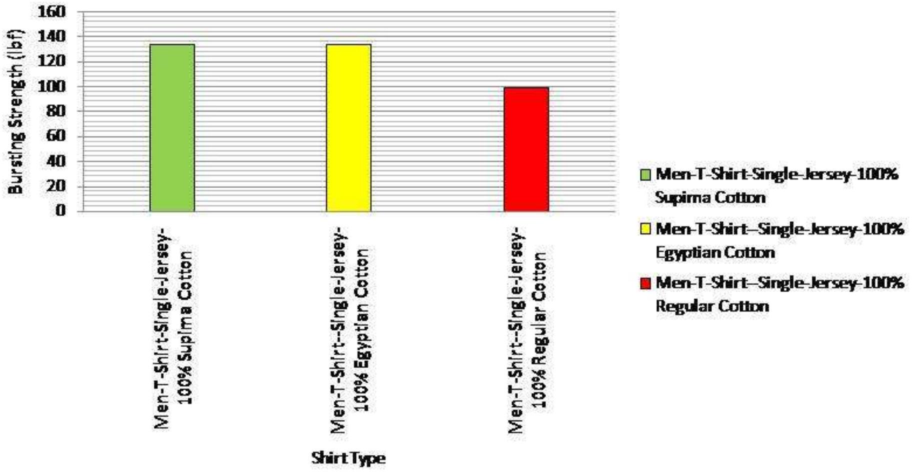


Figure 40. Fabric Bursting Strength for Men's Single-Jersey Knit Shirts made from Different Cotton Types

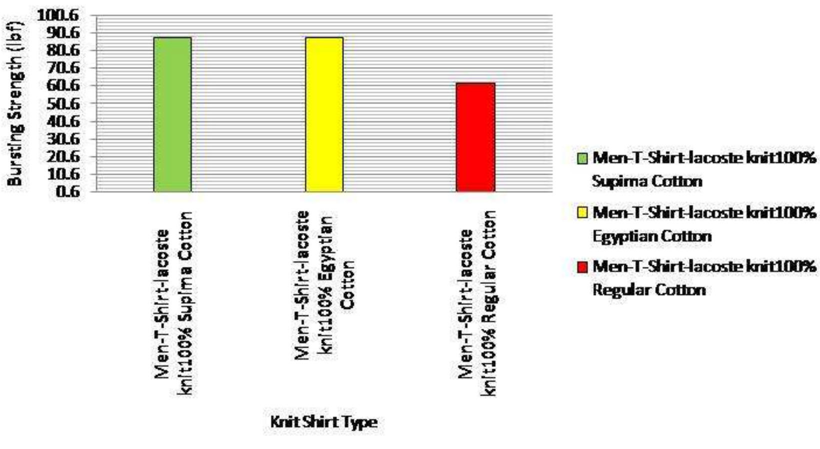


Figure 41. Fabric Bursting Strength for Men's Lacoste Knit Shirts made from Different Cotton Types

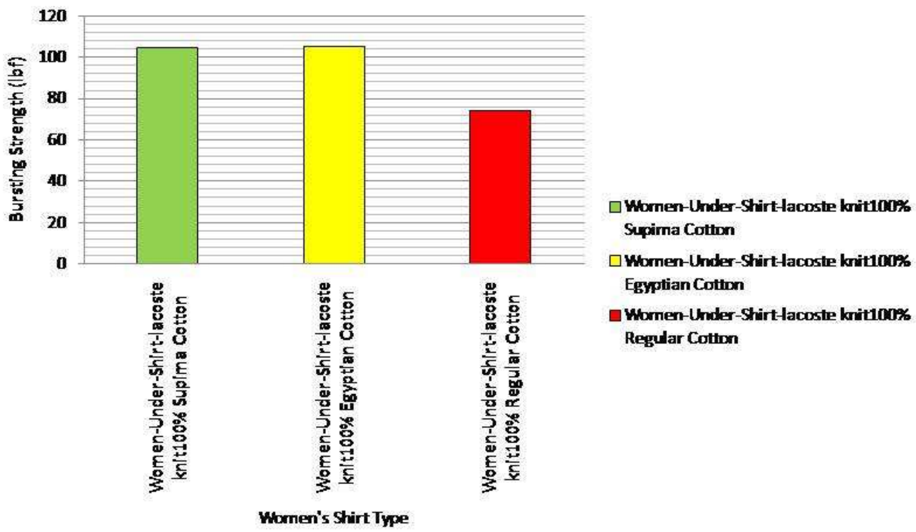


Figure 42. Fabric Bursting Strength for women's Lacoste Knit Undershirts made from Different Cotton Types

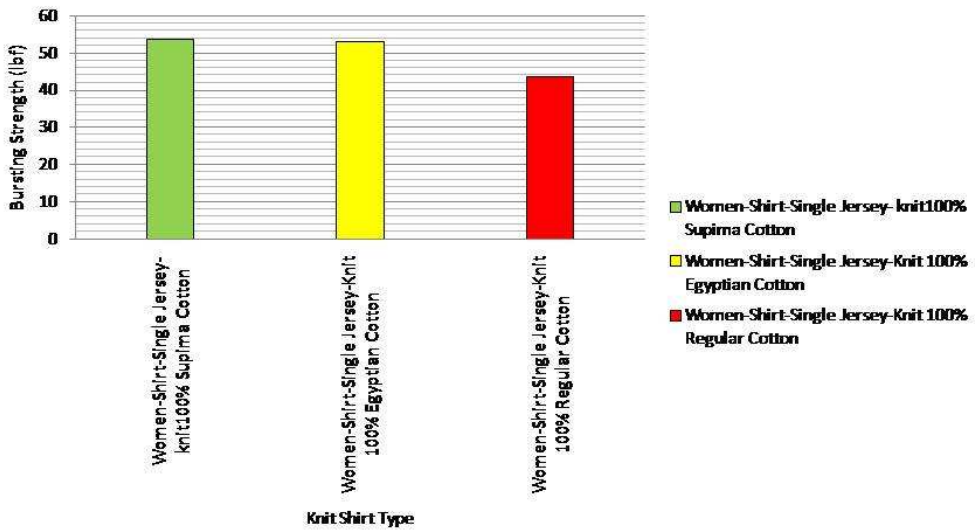
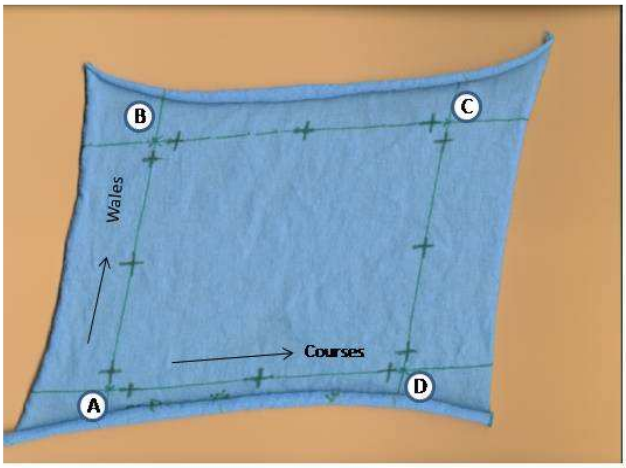


Figure 43 Fabric Bursting Strength for Women;s Single-Jersey Knits made from Different Cotton Types

4.2.2.1.3 Performance of Knit Shirt Fabrics after Repeated Washing and Drying

The key index of knit products performance is their behavior after repeated washing and drying. Most cotton knit fabrics tend to shrink significantly after washing by virtue of their construction and the fiber type used. Some knits tend to skew where wales lines deviate from the right angle (or perpendicular arrangement) with respect to the course line. In addition, knit fabrics tend to pill and lose strength upon washing and drying. In this study, we washed knit shirts of different types up to 50 times to examine the changes in their performances. Key performance characteristics examined in this regard include:

- Thickness change
- Weight change
- Area change (See Figure 44)
- Skew or torquing in fabric (see Figure 44)
- Bursting strength
- Pilling performance



Area = Wale Length (cm) x Course length (cm)
Skewness Calculation:

X = 100 x (2x(AC-BD) / (AC+BD)) —AATCC Test Method 179-2001
Where:
X = % change in skewness
positive percent change indicates skewness to the left, negative percent change indicates skewness to the right.

Figure 44 Dimensional Characteristics of Knit fabric after washing and drying (AATCC Test Method 135-2003 & AATCC Test Method 179-2001)

4.2.2.1.3.1 Thickness Change upon Washing and Drying

The changes in fabric thickness upon washing and drying for men's single-jeresy knit shirts, men's lacoste knit shirts, and women's single-jersey knit shirts are illustrated in Figures 45, 46, and 47, respectively. In general, an increase in fabric thickness is expected upon washing as a result of the inevitable fabric shrinkage. These results indicate that at the first few washing cycles both Supima® cotton knit shirts and Egyptian cotton knit shirts were very similar in their performance as they both exhibited low thickness changes, and they were both superior to knit shirts made from regular cotton. After many washing and drying cycles, Supima® cotton knit shirts remained the lowest in thickness changes after washing and drying.

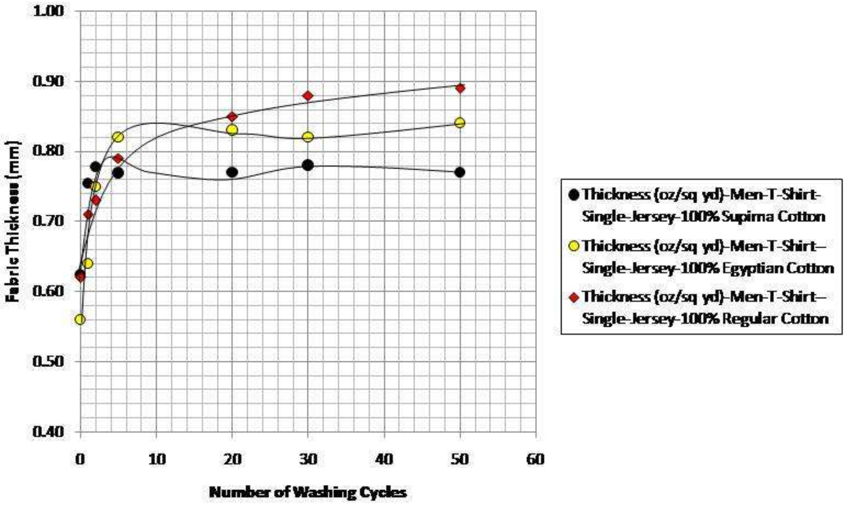


Figure 45 Fabric Thickness change of Men's Single-Jersey Knits made from Different Cotton Types after repeated washing and drying

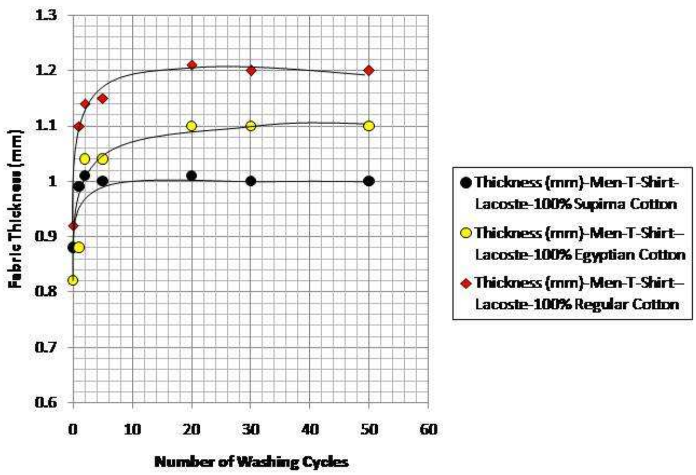


Figure 46 Fabric Thickness change of Men's Lacoste Knits made from Different Cotton Types after repeated washing and drying

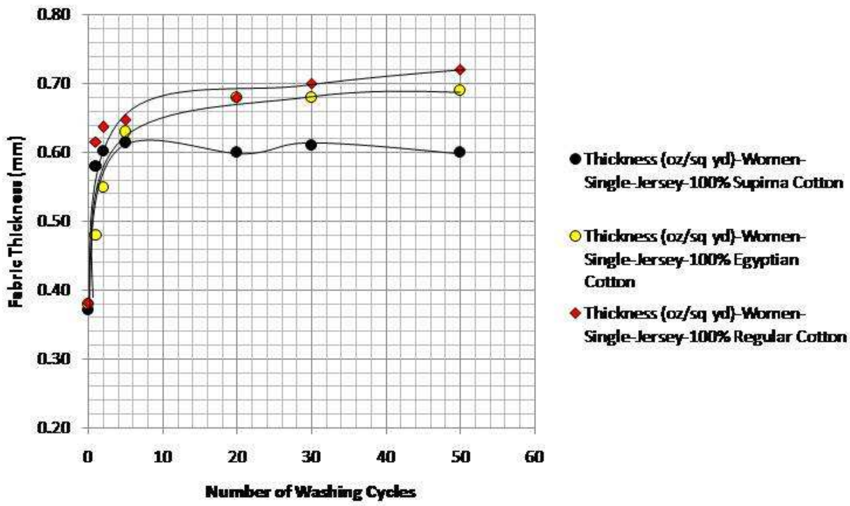


Figure 47 Fabric Thickness change of Women's Single-Jersey Knits made from Different Cotton Types after repeated washing and drying

4.2.2.1.3.2 Weight Change upon Washing and Drying

The changes in fabric weight upon washing and drying for men's single-jeresy knit shirts, men's lacoste knit shirts, and women's single-jersey knit shirts are illustrated in Figures 48, 49, and 50, respectively. In general, an increase in fabric weight is expected upon washing as a result of the inevitable fabric shrinkage. These results indicate that at the first few washing cycles both Supima® cotton knit shirts and Egyptian cotton knit shirts were very similar in their performance as they both exhibited low weight changes, with slight improvement in the Egyptian cotton knit shirts. Both types of shirts were superior to knit shirts made from regular cotton. After many washing and drying cycles, Supima® cotton knit shirts remained the lowest in weight changes after washing and drying particularly for men's single-jeresy knit shirts and women's single-jersey knit shirts. For men's lacoste construction knit shirts, Egyptian cotton shirts were superior.

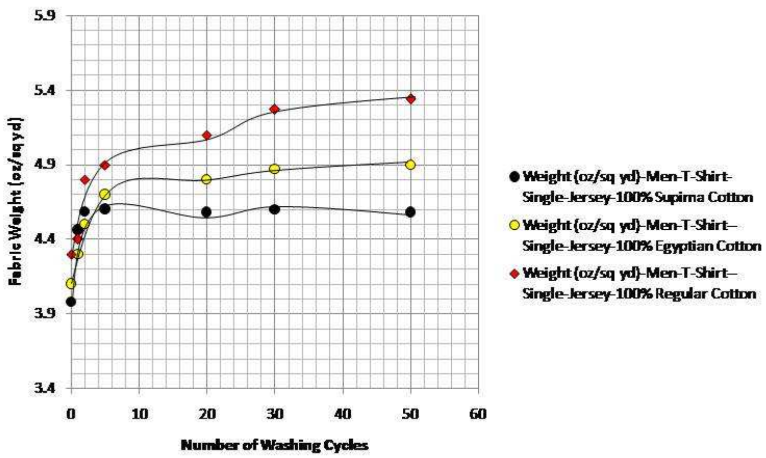


Figure 48 Fabric Weight change of Men's Single-Jersey Knits made from Different Cotton Types after repeated washing and drying

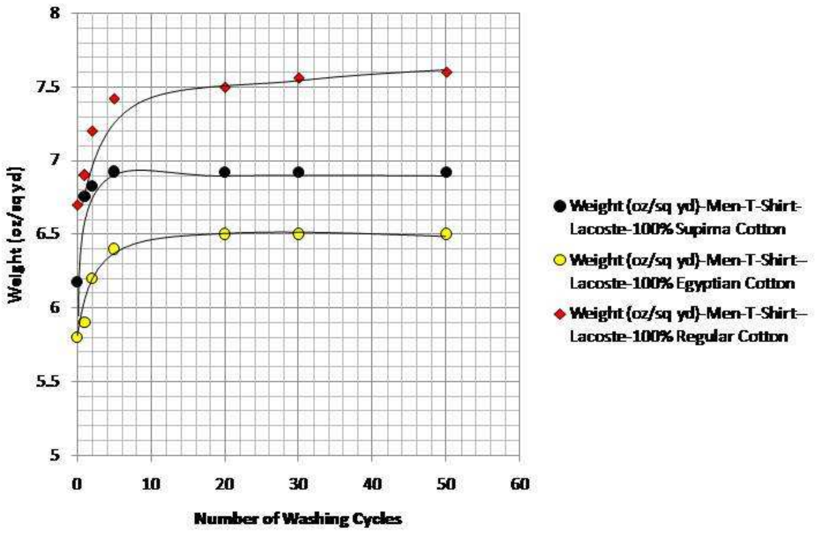


Figure 49 Fabric Weight change of Men's Lacoste Knits made from Different Cotton Types after repeated washing and drying

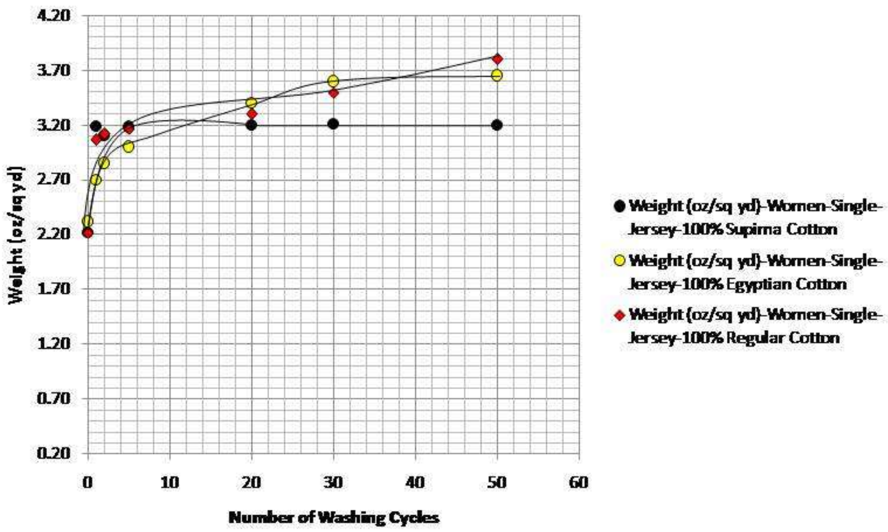


Figure 50 Fabric Weight change of Women's Single-Jersey Knits made from Different Cotton Types after repeated washing and drying

4.2.2.1.3.3 Area Change upon Washing and Drying

Area change was determined according to the **AATCC Test Method 135-2003** & **AATCC Test Method 179-2001** methods illustrated in Figure 44. The changes in fabric area upon washing and drying for men's single-jeresy knit shirts, men's lacoste knit shirts, and women's single-jersey knit shirts are illustrated in Figures 51, 52, and 53, respectively. In general, a reduction in fabric area is expected upon washing as a result of the inevitable fabric shrinkage. Note that in this experiment all fabrics were marked at the same original area; the change in area was then measured after each washing-drying cycle. These results indicate that Supima® cotton knit shirts exhibited the least area change among all shirts followed closely by Egyptian cotton knit shirts. Regular-cotton knit shirts exhibited a substantial area change indicating severe shrinkage upon washing and shrinkage that can amount to a significant reduction in shirt sizes.

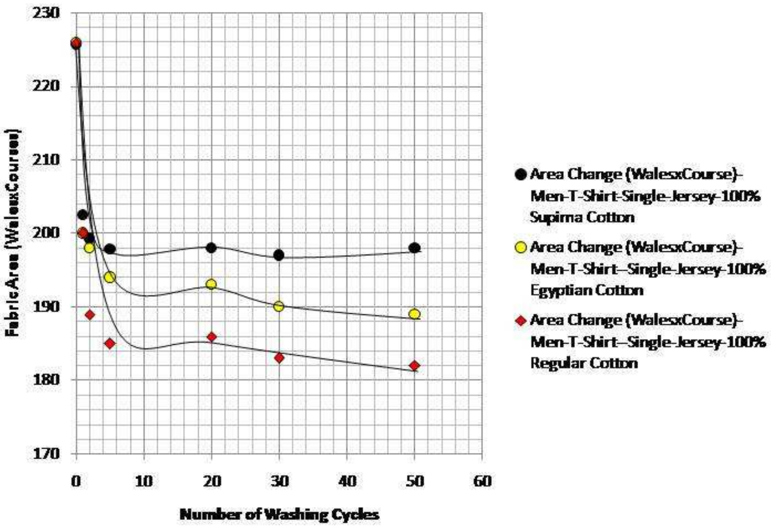


Figure 51 Fabric Area change of Men's Single-Jersey Knits made from Different Cotton Types after repeated washing and drying

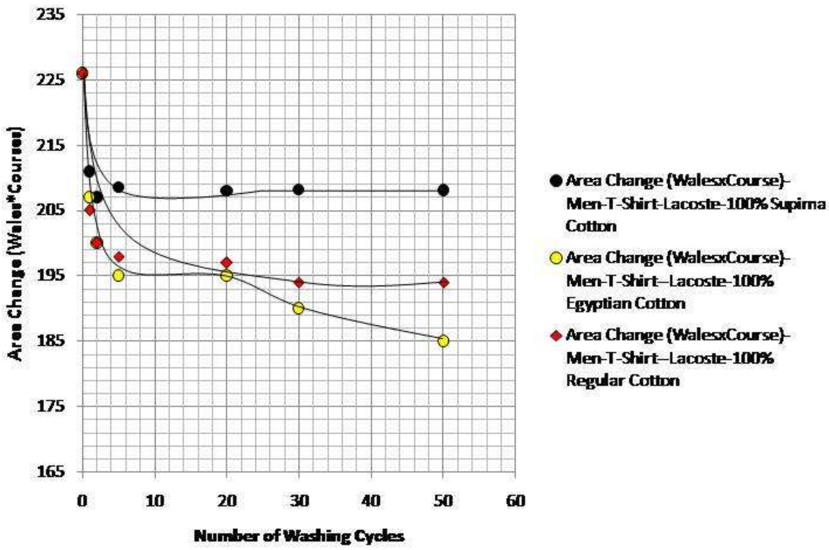


Figure 52 Fabric Area change of Men's Lacoste Knits made from Different Cotton Types after repeated washing and drying

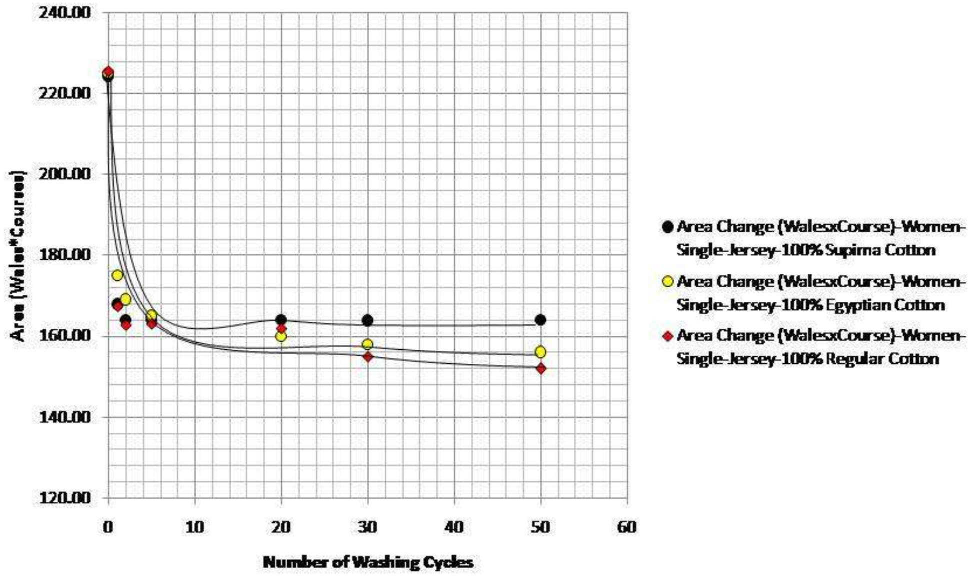


Figure 53 Fabric Area change of Women's Single-Jersey Knits made from Different Cotton Types after repeated washing and drying

4.2.2.1.3.4 Skewness Change upon Washing and Drying

Skewness was determined according to the **AATCC Test Method 135-2003** & **AATCC Test Method 179-2001** methods illustrated in Figure 44. Fabric skewness is known to be a direct result of excessive yarn twist and the tendency of the yarn to untwist in the knit structure. When different fiber types are used, yarns made from longer, stronger, and finer fibers can be spun at lower twist than those made from shorter, weaker, and coarser fibers. The changes in fabric skewness upon washing and drying for men's single-jeresy knit shirts, men's lacoste knit shirts, and women's single-jersey knit shirts are illustrated in Figures 54, 55, and 56, respectively. In general, an increase in fabric skew to the right (positive) or the left (negative) is expected upon washing as a result of the inevitable fabric shrinkage. These results indicate that Supima® cotton knit shirts exhibited the least skewness among all shirts followed closely by Egyptian cotton knit shirts. Regular-cotton knit shirts exhibited a substantial increase in fabric skew indicating severe dimensional instability upon washing and drying. Note that the women's single-Jersey shirts exhibited an exceptionally higher skew than other types of shirts. This is because those shirts were made experimentally at relatively much lighter and thinner dimensions than other commercial shirt types.

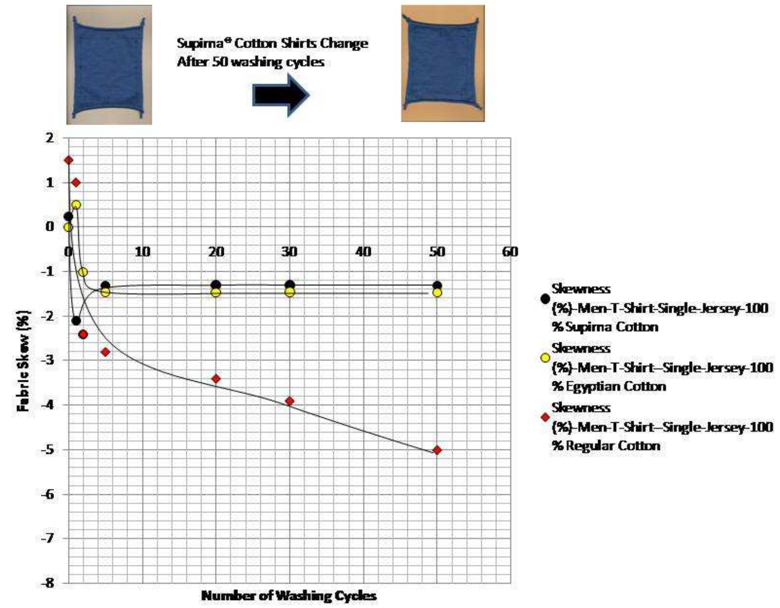


Figure 54 Fabric Skew change of Men's Single-Jersey Knits made from Different Cotton Types after repeated washing and drying

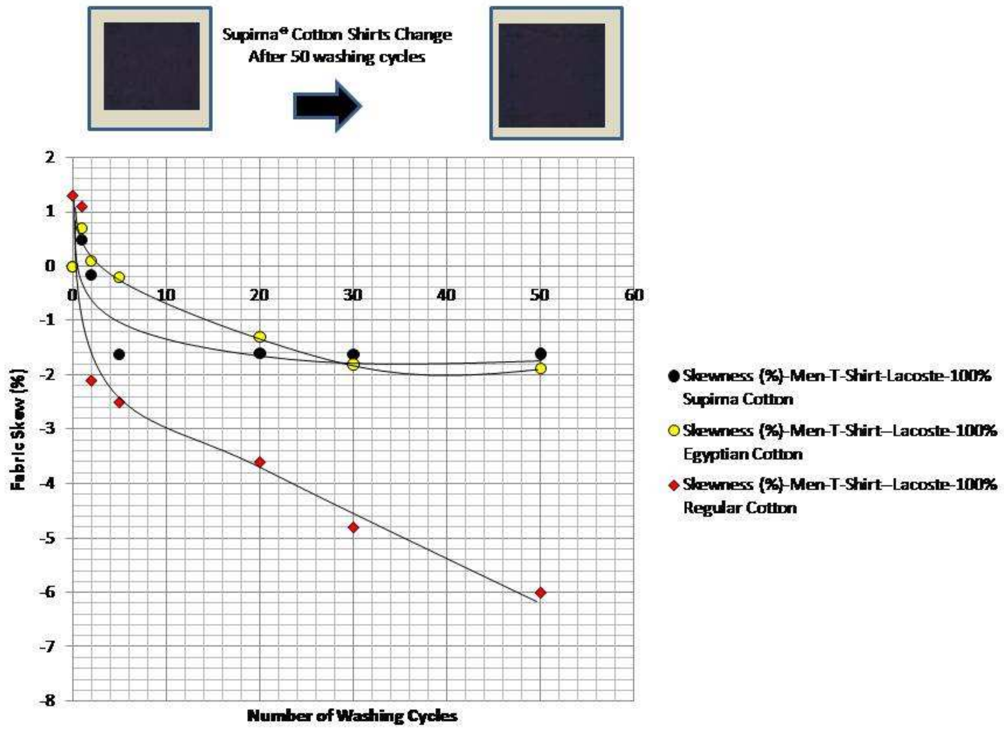


Figure 55 Fabric Skew change of Men's Lacoste Knits made from Different Cotton Types after repeated washing and drying

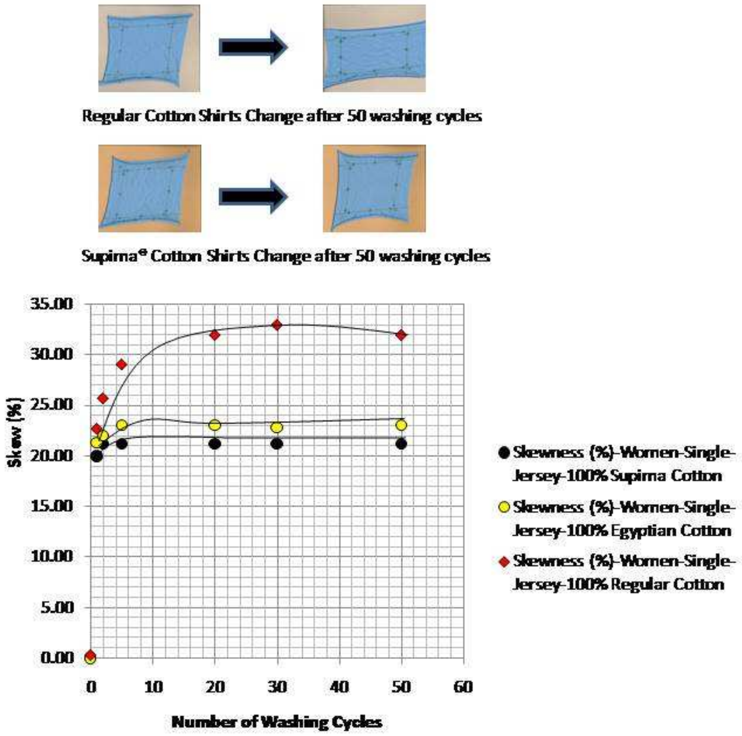


Figure 56 Fabric Skew change of Women's Single-Jersey Knits made from Different Cotton Types after repeated washing and drying

4.2.2.1.3.5 Bursting Strength Change upon Washing and Drying

Bursting strength was determined according to the **ASTM D 6797-02** method illustrated in Figure 39. It was important to measure this performance characteristic to determine whether repeated washing and drying has resulted in any deterioration in knit fabric strength. The changes in fabric bursting strength upon washing and drying for men's single-jeresy knit shirts, men's lacoste knit shirts, and women's single-jersey knit shirts are illustrated in Figures 57, 59, and 59, respectively. Corresponding changes in burst elongation are illustrated in Figures 60, 61, and 62, respectively. In general, a reduction in burst strength and an increase in burst elongation are expected upon washing and drying. The results indicate that Supima® cotton knit shirts suffered the least change in burst strength and elongation, followed closely by Egyptian cotton sheets. Regular-cotton knit shirts exhibited a substantial reduction in ball-burst strength upon washing and drying.

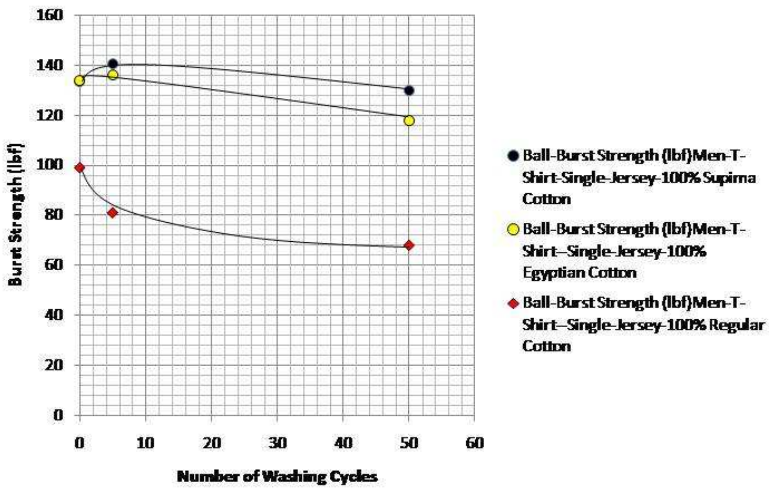


Figure 57 Fabric Bursting Strength of Men's Single-Jersey Knits made from Different Cotton Types after repeated washing and drying

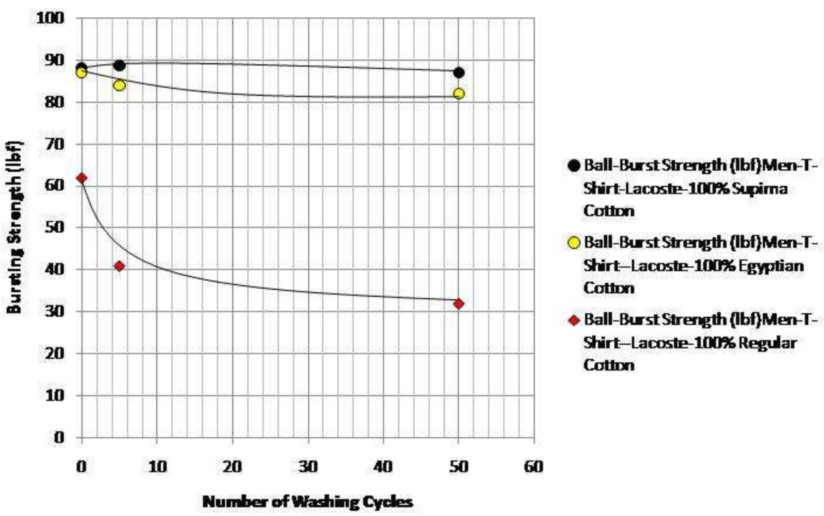


Figure 58 Fabric Bursting Strength of Men's Lacoste Knits made from Different Cotton Types after repeated washing and drying

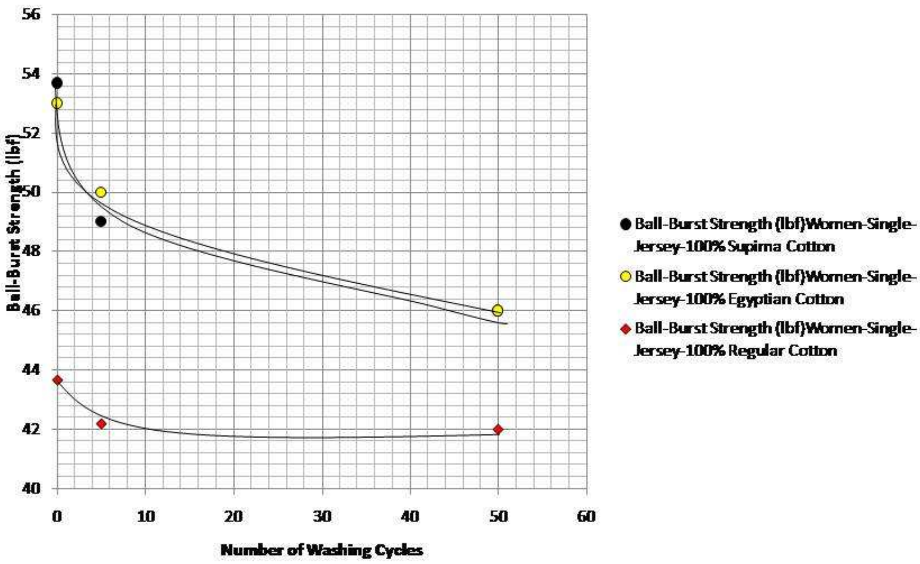


Figure 59 Fabric Bursting Strength of Women's Single-Jersey Knits made from Different Cotton Types after repeated washing and drying

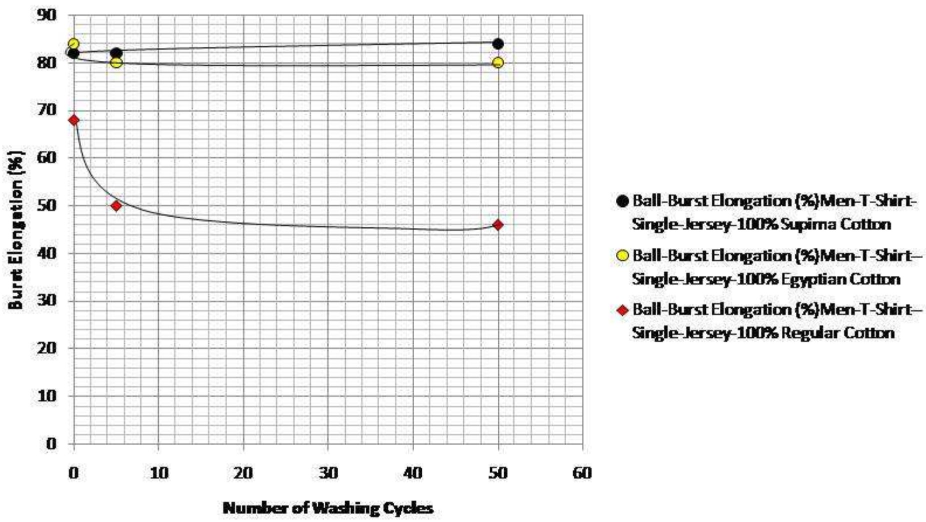


Figure 60 Fabric Bursting Elongation of Men's Single-Jersey Knits made from Different Cotton Types after repeated washing and drying

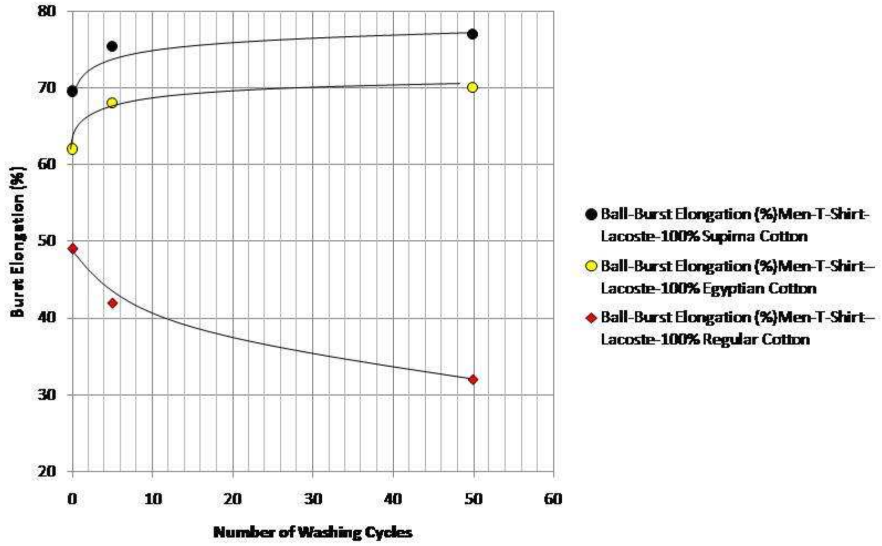


Figure 61 Fabric Bursting Elongation of Men's Lacoste Knits made from Different Cotton Types after repeated washing and drying

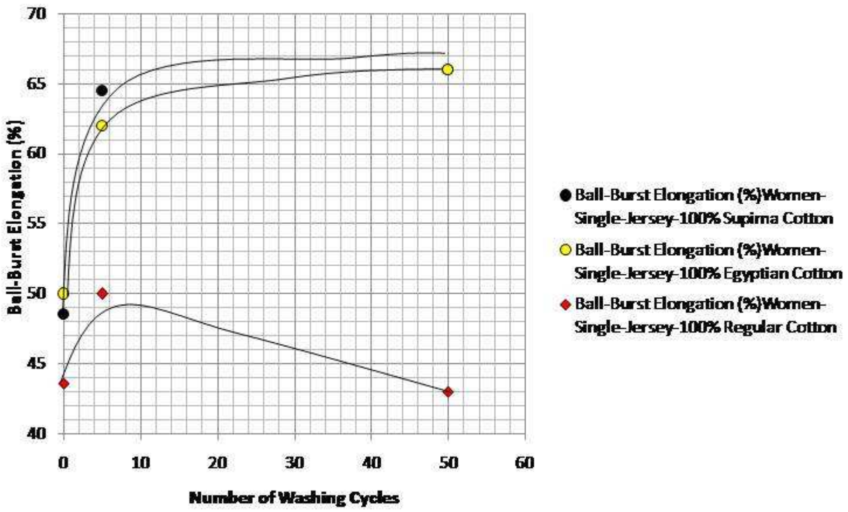


Figure 62 Fabric Bursting Elongation of Women's Single-Jersey Knits made from Different Cotton Types after repeated washing and drying

4.2.2.1.3.6 Pilling Performance upon Washing and Drying

The changes in fabric pilling upon washing and drying for men's single-jeresy knit shirts, men's lacoste knit shirts, and women's single-jersey knit shirts are illustrated in Figures 63, 64, and 65, respectively. In general, an increase in pilling is expected upon washing and drying. The results indicate that Supima® cotton knit shirts suffered no change in pilling propensity followed closely by Egyptian cotton sheets. Regular-cotton knit shirts exhibited a substantial increase in pilling propensity upon washing and drying.

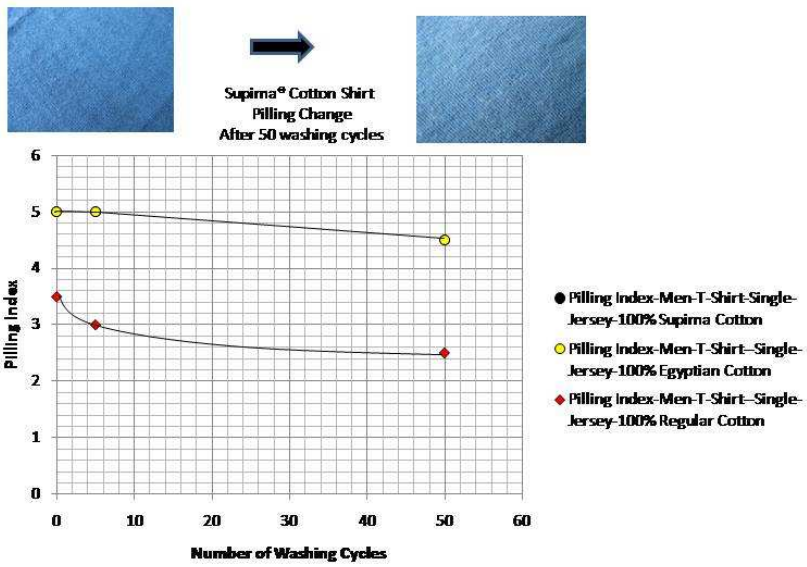


Figure 63 Fabric Pilling of Men's Single-Jersey Knits made from Different Cotton Types after repeated washing and drying

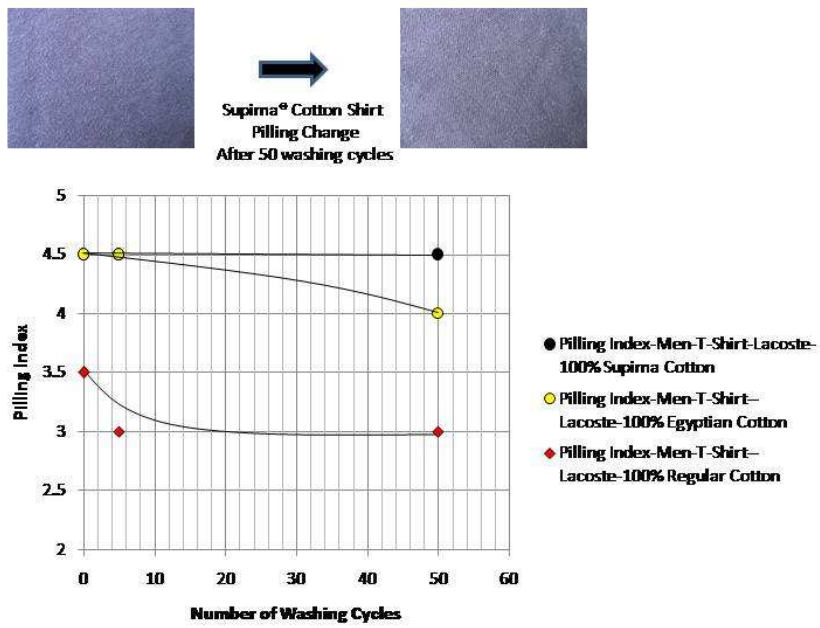


Figure 64 Fabric Pilling of Men's Lacoste Knits made from Different Cotton Types after repeated washing and drying

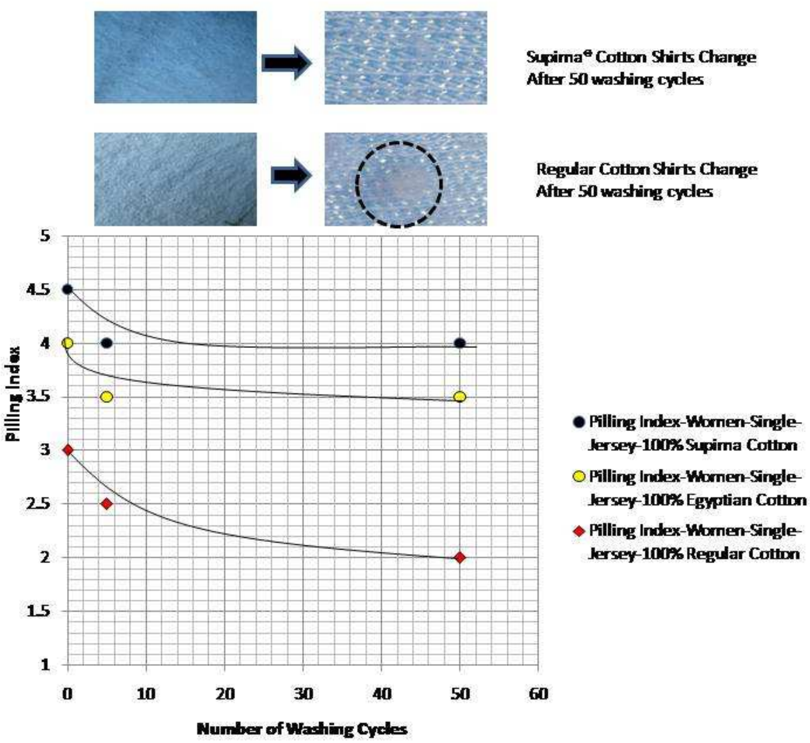


Figure 65 Fabric Pilling of Women's Single-Jersey Knits made from Different Cotton Types after repeated washing and drying

Chapter 5. CONCLUSION

5.1 Summary of Comparative Analysis of Fiber Identification

In the early part of this study, we examined different raw fibers using both standard and non-standard methods. The results of this examination can be summarized as follows:

These results indicate that Extra-Long Staple cottons (e.g. Giza70, Chinese, Pima) have longer, finer, more mature, and stronger fibers than medium-staple. These results can be used effectively to distinguish these two major categories of cotton type. However, within the same category (e.g. within ELS, or within Upland), they are not very useful in distinguishing one type of fiber from another. It was important therefore to use nonstandard methods of identification. These were the DYING TEST, the Viscosity Test, and the Sonic Test described in the experimental section.

The results of Viscosity Identification Test for different cotton types clearly indicate that different cotton types even within the same cotton type category (ELS or Upland) can be identified using the viscosity test. As can be see in this Figure, Supima® Cotton exhibits the highest Molecular Weight of all Cottons (as measured by Tappi Viscosity Method). This translates to

- High and persistent durability from fiber to finished product

- More homogenous material (uniform dye uptake and low variability in quality parameters)
- Minimum fiber brittleness under hot chemical treatments

The results of molecular orientation reflected by the Sonic test for yarns made from different cotton types indicate that Supima® cotton exhibits the highest Molecular orientation of all Cottons (as measured by the Speed of sound). This translates to

- A combination of smoothness and durability
- More consistent dye affinity
- High fiber resiliency

The results of color parameters revealed by the dye test show that different cotton types can indeed have different levels of color parameters. The problem, however, is that dye uptake can be dependent on many factors including fiber maturity, fiber fineness, and surface morphology. Accordingly, to claim that the dye uptake test is a valid one for identifying different cotton types may not be so accurate unless a large database to support this claim is available, which outside the scope of this study.

5.2 Summary of Comparative Analysis of Durability between Different Bed Sheets

In this study, we examined many bed sheets with the primary goal being to investigate whether fiber type makes a difference in the type of bed sheets consumers should purchase and use. The investigation was made in two phases:

- Comparative analysis of different bed sheets that are largely comparable in all characteristics (yarn properties, thread count, and fabric construction) but differ only in cotton fiber type
- Comparison of the same samples of bed sheets after many cycles of washing and drying

The results of the first phase of this study can be summarized in the following points:

- The results of accelerated extreme durability tests clearly indicate that Supima® Cotton bed sheets are superior to bed sheets made from other cotton types in all durability aspects.
- Obviously, a direct correlation between these results and real-life usage and applications has to be made very carefully as many external factors may play significant roles in determining a product performance over time. What we can say is that bed sheets that fail at lower levels of loading under tear or tension and fewer cycles under harsh abrasion actions is likely to fail under typical real-life usage much faster than those that fail at higher tensile and tear stress or high number of abrasion cycles. In addition, fabrics of low pilling propensity will maintain better appearance upon use than those of high pilling propensity.
- Supima® Cotton bed sheets have passed the accelerated extreme durability tests with superior performance to bed sheets made from other fiber types.
- Under tension, Supima® Cotton bed sheets were able to withstand up to 10 pounds per inch more than its close competitor, the Egyptian cotton bed sheets, and up to 50 pounds per inch more than bed sheets made from regular or specially blended cottons.

- Under tear, Supima® Cotton bed sheets were able to withstand up to 2 pounds more than the Egyptian cotton bed sheets and up to 3 pounds more than bed sheets made from regular or specially blended cottons.
- Under Flex Abrasion, Supima® Cotton bed sheets were able to withstand up to 200 abrasion cycles more than the Egyptian cotton bed sheets and up to 400 abrasion cycles more than bed sheets made from regular or specially blended cottons.
- Under Taber Abrasion, Supima® Cotton bed sheets were able to withstand up to 100 abrasion cycles more than the Egyptian cotton bed sheets and up to 200 abrasion cycles more than bed sheets made from regular or specially blended cottons.

The results of the second phase of this study can be summarized in the following points:

- Upon washing and drying, bed sheets undergo inevitable dimensional and physical changes. Common inevitable trends include: (1) a reduction in fabric thickness and fabric area as a result of shrinkage, (2) an increase in fabric torquing or skew, (3) potential increase in pilling as a result of possible fiber damage caused by repeated washing and tumble drying, (4) an increase in fabric strength as a natural consequence of the effect of wetting on cotton fibers, (5) a reduction in abrasion resistance as a consequence of fading of fabric finish and possible fiber damage, and an increase in fabric stiffness.

With the above trends being inevitable, the best bed sheet is the one that can survive these effects at a minimum deterioration of its appearance and durability. In this regard, Supima® cotton bed sheets have proven to be on the top followed closely by Egyptian cotton bed sheets. Bed sheets made from special blends or regular cottons have failed the durability tests to such an extent that any saving in their prices will certainly be outweighed by their poor performance.

5.3 Summary of Comparative Analysis of Durability between Different Knit Shirts

In this study, we examined many knit shirts as discussed in this report with the primary goal being to investigate whether fiber type makes a difference in the type of knit shirts consumers should purchase and use. The investigation was made in two phases:

- Comparative analysis of different knit shirts that are largely comparable in all characteristics (yarn properties, thread count, and fabric construction) but differ only in cotton fiber type
- Comparison of the same samples of knit shirts after many cycles of washing and drying

The results of the study can be summarized in the following points:

- Supima® Cotton knit shirts provides a range of 25% to 50% advantage in pilling resistance in comparison with regular-cotton knit shirts.
- Supima® Cotton knit shirts provides a range of 20% to 42% advantage in bursting strength in comparison with regular-cotton knit shirts.
- Upon washing and drying of 50 cycles, Supima® Cotton knit shirts suffered the least thickness change and the best dimensional stability while regular-cotton knit shirts suffered substantial shrinkage.

- Upon washing and drying of 50 cycles, Supima® Cotton knit shirts maintained an excellent pilling performance while regular-cotton knit shirts suffered substantial pilling.
- Upon washing and drying of 50 cycles, Supima® Cotton knit shirts suffered the least change in burst strength while regular-cotton knit shirts suffered substantial reduction in burst strength.

REFERENCES

1. Cotton Production and Consumption Statistics-2005/2006, http://www.qualitybc.com/

2. Luniak, B., The Identification of Textile Fibres, London 1953

3. Mauersberger, R., editor, Matthew's Textile Fibers, sixth edition, New York 1954

4. Stoves, J. L., Fibre Microscopy, Princeton 1958.

5. Yehia Elmogahzy, and Charles Chewning, Jr., Cotton Fiber To Yarn Manufacturing Technology", Published by Cotton Incorporated, 2002

6. Yehia Elmogahzy, "Engineering textiles: Integrating the design and manufacture of textile products", Woodhead Publishing, *UK, 2009*

7. Morton, W. S., and Hearle, J. W. S., Physical Properties of Textile Fibers, The Textile Institute-Butterworths, Manchester and London, 1962.

8. El Mogahzy Y E, Broughton R, Guo H and Taylor R A, ‘Evaluating staple fiber processing propensity. Part I: Processing propensity of cotton fibers’, *Textile Res. J.*, 1998, 68(11), 835-840.

9. Allen H C Jr., ‘The cotton fiber process and fiber characteristics’, *Cotton Incorporated Technical Reports*, 1, 1993.

10. Duckett K E, ‘Surface properties of cotton fibers’, Fiber science series, in M.J. Schick, Ed., *Surface Characteristics of Fibers and Textiles*, Part I, Marcel Dekker, Inc. NY and Basel, 64-70, 1975.

11. El Gaiar M N, Cusick G E, ‘A study of the morphology of cotton-fiber fracture in abrasion tests in relation to coefficient of friction between the fabric tested and the abradant’, *J. Tex. Inst.*, 1976, 67(4), 141-145.

12. Seshan K N, ‘An investigation of the taper of cotton fibers. Part V: Differential friction in cotton fibers’, J. *Text. Inst.*, 1978, 69(7), 214-219.

13. Zhukov V I, Yakovlev V V and Kharitonova N F, ‘The relation between the birefringence and ripeness of cotton fibers’, *Tech. of Textile Industry*, U.S.S.R., 1971, 5(3), 26-28.

14. Ausubel FM, Brent R, Kingston RE, More DD, Seidman JG, Smith JA, Struhl K (eds), Current protocols in molecular biology, supplement 27, p. 2.4.1. J. Wiley and Sons, New York, 1987.

15. Dabo MS,Mitchell DE,Melcher U. A method for isolation of nuclear DNA from cotton (*Gossypium*) leaves. Anal Biochem 210: 34–38, 1993.

16. Dellaporta SJ, Wood J, Hicks JB. A plant DNA mini preparation: version II. Plant Mol Biol Reptr 1: 19–21, 1983.

17. Katterman FRH, Shattuck VI. An effective method of DNA isolation from the mature leaves of gossypium species that contain large amounts of phenolic terpenoids and tannins. Prep Biochem 13(4): 347–359, 1983.

18. Booth J. E., Principles of Textile Testing, Newnes-Butterworth, London/Boston, 1968.

19. KŮS, Z., GLOMBÍKOVÁ, V., HALASOVÁ, A. KES detects interesting fabric parameter change, 10th international conference STRUTEX, Liberec, 8. – 9. december 2003 (proceedings), s. 367-369, ISBN 80-7083-769-1.

20. Hearle, J. W. S., and Peters, R. H., Moisture in Textiles, Textile Institute. Manchester, England, 1960.

21. Munden, D., L., Geometry of Knitted Structures, Textile Institute, review of Text. Progress, Vol. 14, pp 250-56, 1963.

22. Munden, D., L., Geometry of Knitted Structures, Textile Institute, review of Text. Progress, Vol.17, pp 266-69, 1967.

23. Zurek, W., The Structure of Yarn, Translated from Polish, Published by the USDA and the National Science Foundation, 1975.

24. KRYŠTŮFEK, J., WIENER, J. Změna intenzity odstínu vlivem fyzikálních vlastností vláken barviv – praktické důsledky, Část I. (Influence of Physical Parameters on Color of Textiles –Practical Conclusions, Part I.), Textil plus 6, 2/2001, s. 17.

25. NECKÁŘ, B., IBRAHIM, S. Structural theory of fibrous assemblies and yarns. Part 1 Structure of fibrous assemblies. TU Liberec 2003. (167 stran).

26. BRZEZINA, M., MILITKÝ, J. Complex characterization of textile surface profile. Sborník konference Robust 2002, Hejnice, 21. - 25. ledna 2002, 50-68, ISBN 80-7015-900-6.

27. Hearle, J. W. S, Grosberg, P., and Backer, S., The Structural Mechanics of Fibers, Yarns, and Fabrics. Wiley-Interscience, NY, 1969.

28. El Mogahzy, Y. E., Applied Statistics & Quality Control for Engineers and Manufacturers, Quality Tech Press, AL, 2001

29. DeJesus, S.T., Wang, Q., Development of a Near Infrared based fiber identification system for carpet recycling, NFS, 6, A259-A263, 1998.

30. Gupta, B.S., and EL Mogahzy, Y. E., Friction in Fibrous Materials, Part I: Structural Model. Textile Research Journal, Vol. 61, No. 9, 547-555, 1991

31. EL Mogahzy, Y.E., Gupta, B.S, Friction in Fibrous Materials, Part II: Experimental Study of the Effects of Structural and Morphological Factors, Textile Research Journal,Vol. 63, No. 4, 219-230, 1993.

APPENDICES

APPANDIX A: Different Tests Performed in the Study

A. 1. Fabric

15. **FABRIC WEIGHT: ASTM D 3776-85** Standard test methods for mass per unit area (weight) of woven fabrics.
16. **FABRIC THICKNESS**: **ASTM D 1777-64** Standard test methods for measuring thickness of textile materials.
17. **FABRIC COUNT: ASTM D 3775-85** Standard test methods for fabric count of woven fabrics.
18. **FABRIC STRENGTH: ASTM D 5035-95** Standard test methods for breaking force and elongation of textile fabrics (strip method)
19. **FABRIC TEAR: ASTM D 2261-96** Standard test methods for tearing strength of fabrics by the tongue (single rip) procedure (constant-rate-of-extension tensile testing machine)
20. **TABER ABRASION: ASTM D 3884-80** Standard test methods for abrasion resistance of textile fabrics (rotating platform, double-head method)
21. **FLEX ABRASION: ASTM D 3885-80** Standard test methods for abrasion resistance of textile fabrics (flexing and abrasion method)
22. **PILLING: ASTM D 3512-96** Standard test methods for pilling resistance and other related surface changes of textile fabrics: Random Tumble Pilling Tester.

23. **THERMAL CONDUCTIVITY: ASTM D** 1518-85 Standard test methods for thermal transmittance of textile materials.
24. **BALL BURST: ASTM D 6797-02** Standard test methods for bursting strength for fabrics. Constant-rate-of-extension (CRE): Ball Burst Test.
25. **STIFFNESS: ASTM D 4032-94** Standard test methods for stiffness of fabric by the circular bend procedure.
26. **DIMENSIONAL CHANGE: AATCC Test Method 135-2003** Dimensional Change of Fabrics after Home Laundering.
27. **SKEWNESS: AATCC Test Method 179-2001** Skewness Change in Fabric and Garment Twist Resulting from Automatic Home Laundering.
28. **COLOR CHANGE: AATCC Test Method 61-2003** Colorfastness to Laundering, Home and Commercial: Accelerated.
    - For evaluation:
    - **AATCC Evaluation Procedure 7:** Instrumental Assessment of the Change in Color of a test Specimen
    - **AATCC Evaluation Procedure 2:** Gray Scale for Staining.

A. 2. Yarn

4. **YARN COUNT: ASTM D 1059-89** Standard test methods for yarn number based on short-length specimens.
5. **YARN TWIST: ASTM D 1423-82** Standard test methods for twist in yarns by the direct-counting method.
6. **YARN STRENGTH: ASTM D 2256-97** Standard test methods for tensile properties of yarn by the single strand method.

A. 3. Fiber

1. **DYING: ASTM D 1464-90** Standard test methods for differential dying behavior of cotton.
2. **STRENGTH: ASTM D 3822-01** Standard test methods for tensile properties of single textile fibers.
3. Fiber Length Analysis-By Yarn and Fiber Extraction

APPANDIX B: Basic Yarn and Fabric Properties of Bed Sheets (Standard 300 TC)

B. 1. The 300 -TC Plain Bed Sheets are made from:

- Four Cotton Types: ELS Egyptian Giza Cotton, 60% Egyptian/40% Polyester, Supima® Cotton, and Regular Cotton
- Same thread count
- Approximately Same yarn counts in both directions
- Approximately Same yarn twist in both direction

B. 2. The 300 -TC Plain Bed Sheets are made from:

- Thread counts followed the same patterns in A and B directions of fabrics

.

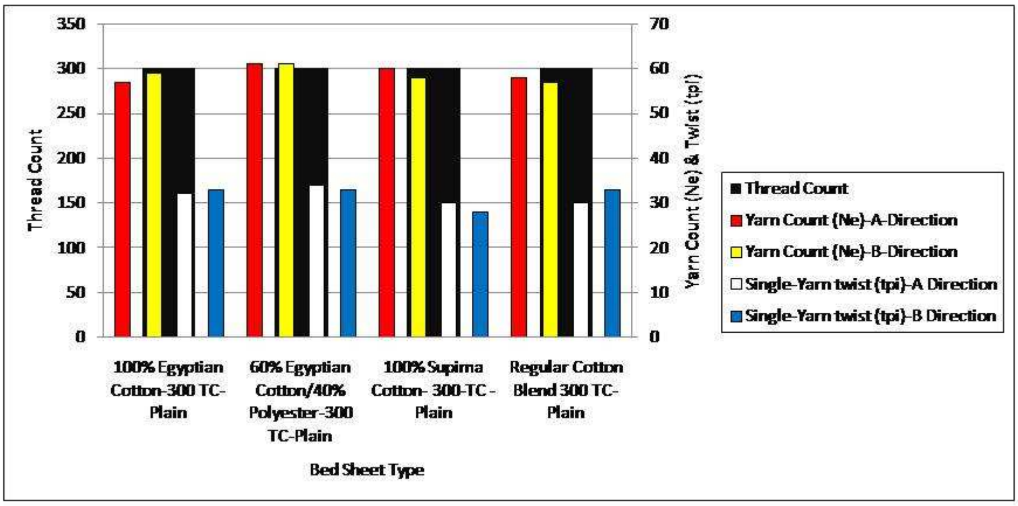


Figure B.1 Comparison of Fabric Thread Count, Yarn Count, and Yarn Twist of 300 TC Bed Sheet Fabrics

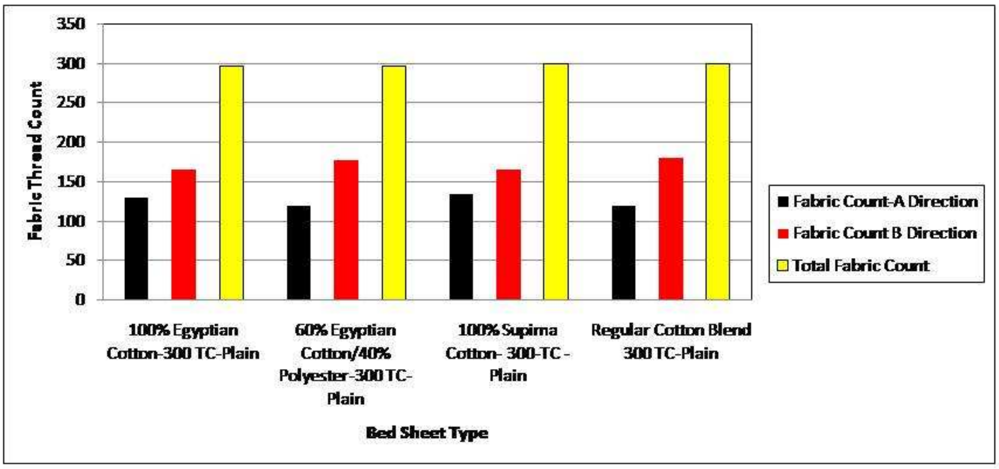


Figure B.2 Comparison of Fabric Thread Count in Warp and Filling Directions of 300 TC Bed Sheet Fabrics

B. 3. Yarn Strength and Elongation:

- Yarns of ELS cotton sheets (ELS Egyptian Giza Cotton , Supima® Cotton) are approximately similar in yarn strength (on average 18 cN/tex in A-Direction and 23 cN/tex in B-Direction) .
- Yarns of Egyptian cotton/Polyester bed sheets have comparable strength to those of 100% ELS cottons (on average 19 cN/tex in A-Direction and 20 cN/tex in B-Direction)
- Yarns of regular cotton sheets are significantly weaker than those of ELS cottons (14 cN/tex)
- Yarns of ELS cotton sheets (ELS Egyptian Giza Cotton , Supima® Cotton) are approximately similar in yarn elongation (on average 8.5% in A-Direction and 8% in B-Direction)
- Yarns of Egyptian cotton/Polyester bed sheets have 7.3% elongation in A-Direction and 11% elongation in B-Direction)
- Yarns of regular cotton sheets have significantly lower elongation than those of ELS cottons (5.7 to 6%)

B. 4. Fabric Weight and Thickness:

- All cotton fabrics have approximately the same weight
- Egyptian cotton/Polyester bed sheets were slightly thicker than ELS cotton sheets.
- Regular cotton sheets were 4% thinner than ELS cotton sheets

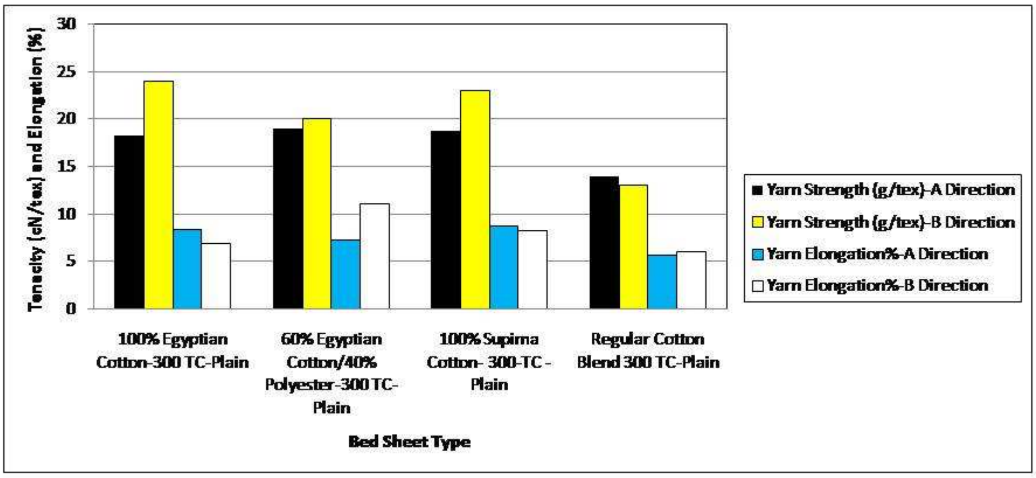


Figure B.3 Comparison of Yarn Strength and Elongation in Warp and Filling Directions of 300 TC Bed Sheet Fabrics

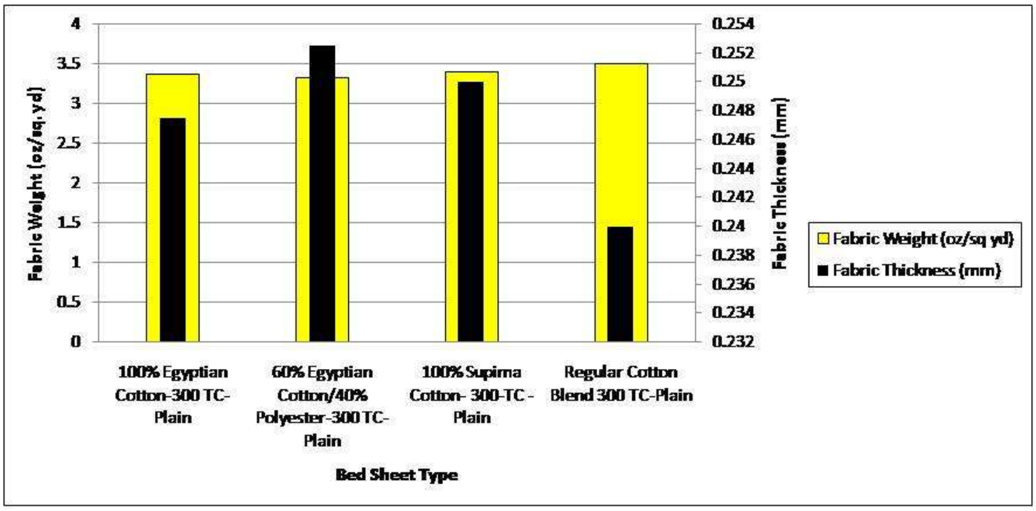


Figure B.4 Comparison of Fabric Weight and Fabric Thickness of 300 TC Bed Sheet Fabrics

APPANDIX C: Basic Yarn and Fabric Properties of Bed Sheets (Sateen 500 TC)

C. 1. The 500 -TC Sateen Bed Sheets are made from:

- Three Cotton Types: ELS Egyptian Giza Cotton, Special Blend Cotton, and Supima® Cotton
- The Special Cotton Blend was not fully identified in the label. Our testing revealed that it is more of a regular and Upland-like cotton and some Unknown ELS model. This was revealed by a clear bi-modality in fiber length distribution
- Same thread count
- Same yarn count
- Same yarn twist

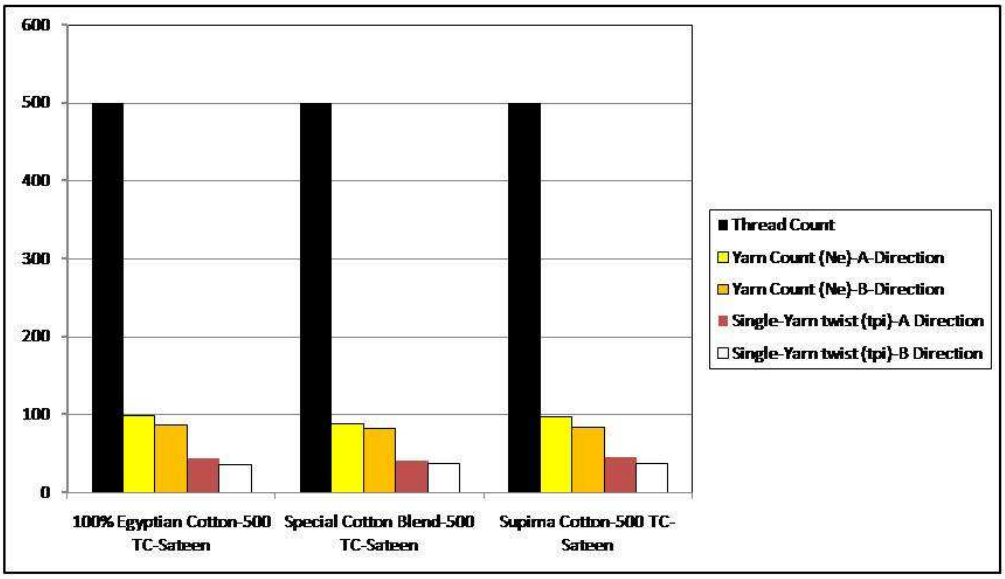


Figure C.1 Comparison of Fabric Thread Count, Yarn Count, and Yarn Twist of 500 TC Sateen Bed Sheet Fabrics

C. 2. Yarn Strength:

- Yarns in both Supima® Cotton sheets and Egyptian Cotton Sheets had approximately the same yarn strength
- Special cotton blend sheets had lower yarn strength than the other two fabrics (20%-23% in comparison with Supima® sheet yarn)

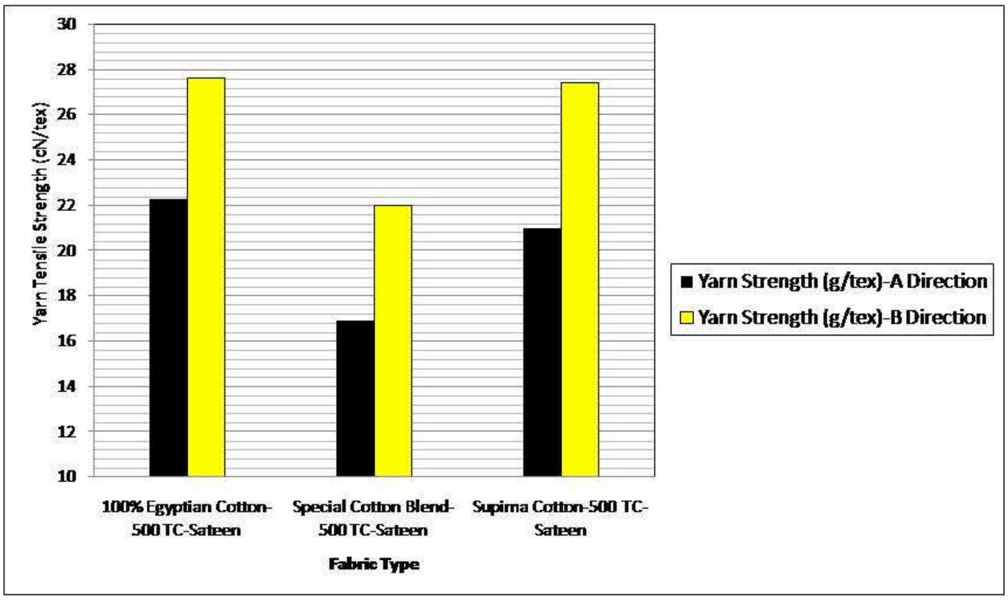


Figure C.2 Comparison of Yarn Strength in Warp and Filling Directions of Fabric of 500 TC Sateen Bed Sheets

C. 3. Yarn Elongation:

- In Warp direction, yarns in Supima® Cotton sheets had higher breaking elongation than yarns in Egyptian Cotton Sheets
- In Weft direction, yarns in both Supima® Cotton sheets and in Egyptian Cotton Sheets had approximately the same yarn breaking elongation

- Special cotton blend sheets had lower yarn elongation than the other two fabrics (23%-30% in comparison with Supima® sheet yarn)

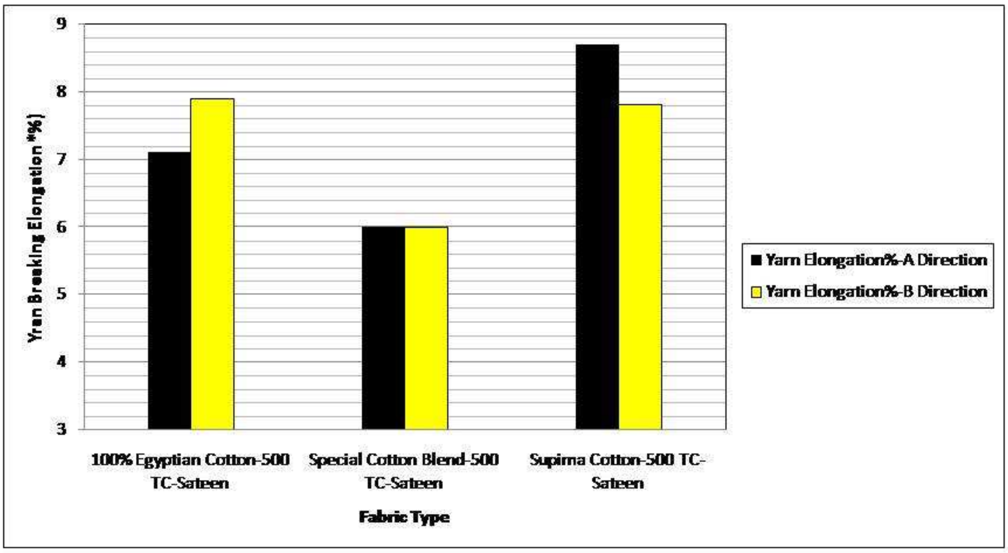


Figure C.3 Comparison of Yarn Elongation in Warp and Filling Directions of Fabric of 500 TC Sateen Bed Sheets

C. 4. Fabric Weight & Thickness:

- The Three Fabrics exhibited approximately the same weight
- Supima® Cotton sheets had slightly lower thickness than the other two types

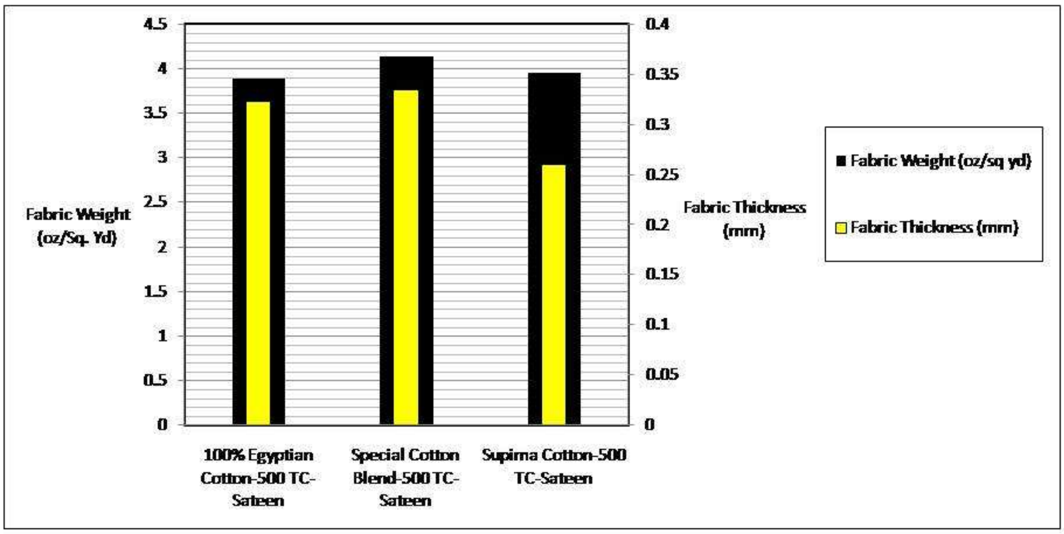


Figure C.4 Comparison of Fabric Weight and Thickness of Fabrics of 500 TC Sateen Bed Sheets

APPANDIX D: Basic Yarn and Fabric Properties of Men's Single-Jersey Knits

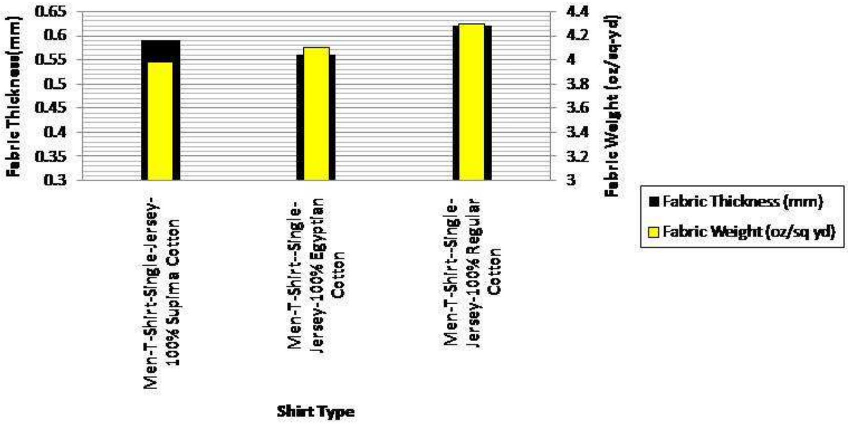


Figure D.1 Fabric Thickness and Weight-Single Jersey Men's Knit Shirts

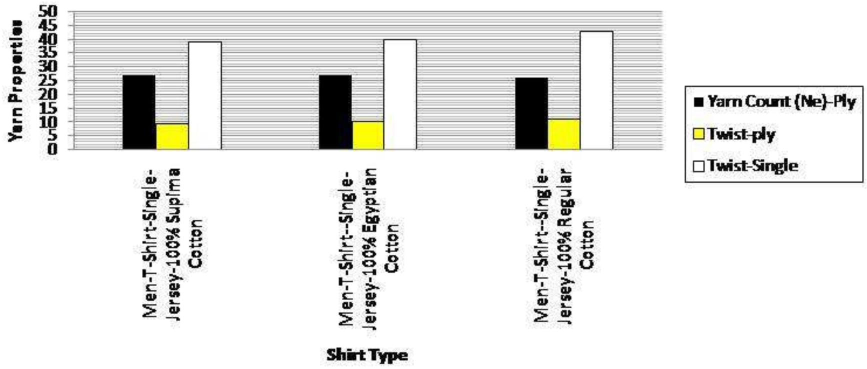


Figure D.2 Yarn Count, and Yarn Twist for Single Jersey Men's Knit Shirts

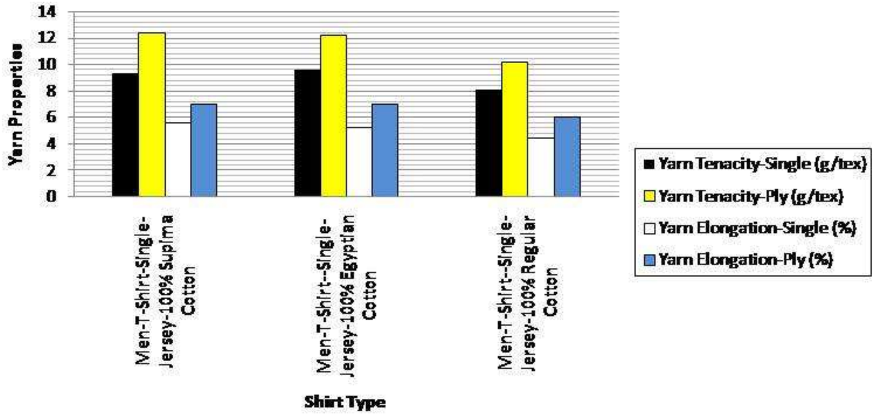


Figure D.3 Yarn Tenacity and Elongation for Single Jersey Men's Knit Shirts

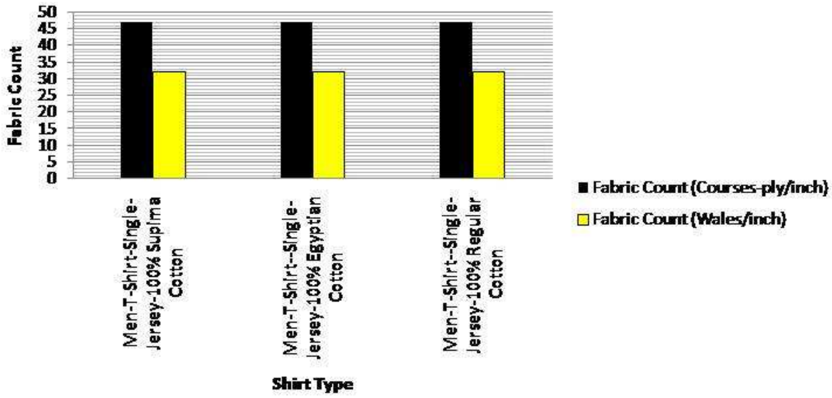


Figure D.4 Fabric Count for Single Jersey Men's Knit Shirts

APPANDIX E: Basic Yarn and Fabric Properties of Men's Lacoste Knits

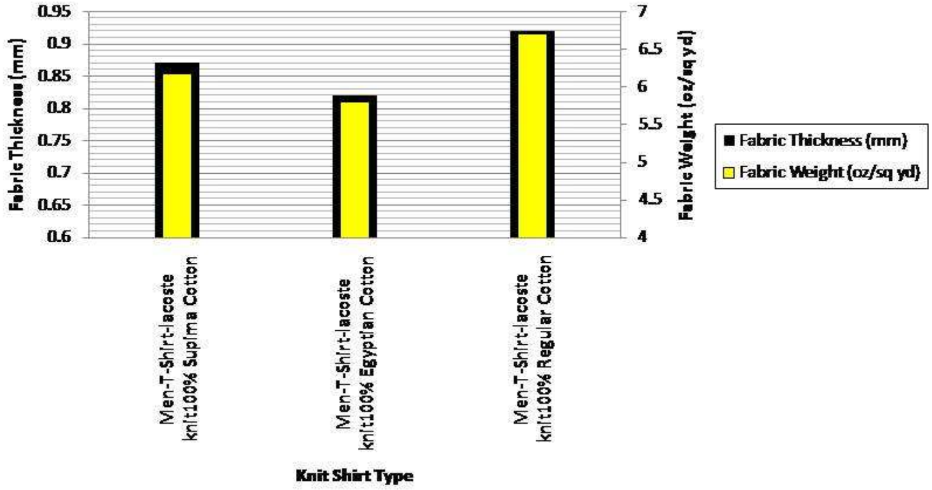


Figure E.1 Fabric Count for Lacoste Men's Knit Shirts

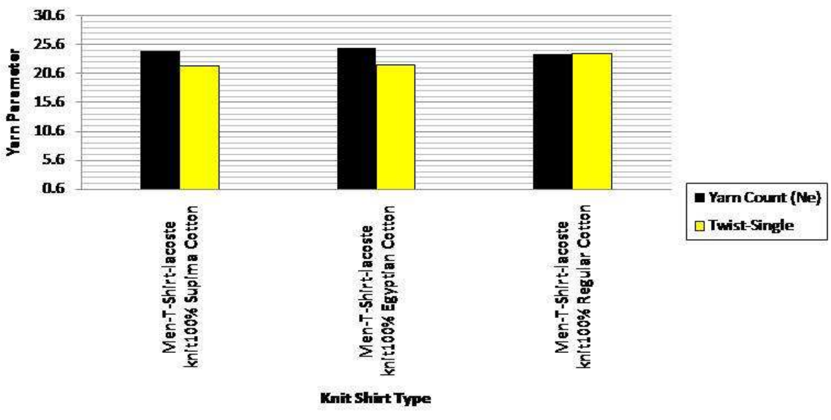


Figure E.2 Yarn Count and Twist for Lacoste Men's Knit Shirts

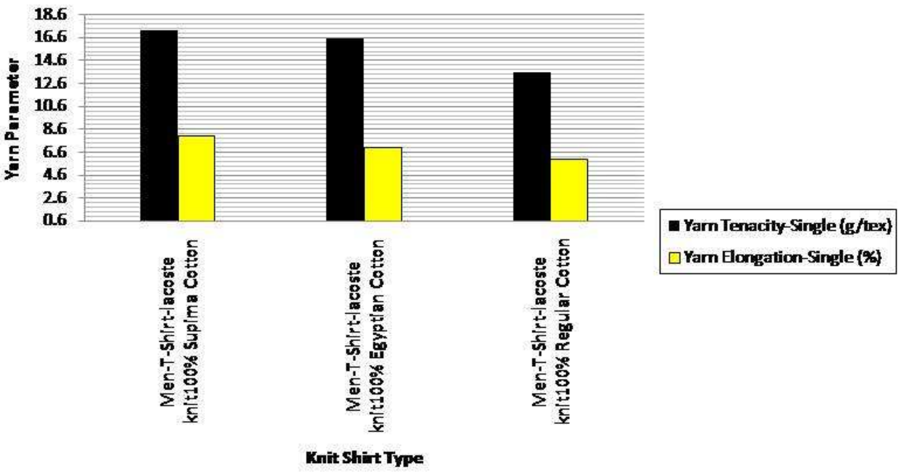


Figure E.3 Yarn Count and Twist for Lacoste Men's Knit Shirts

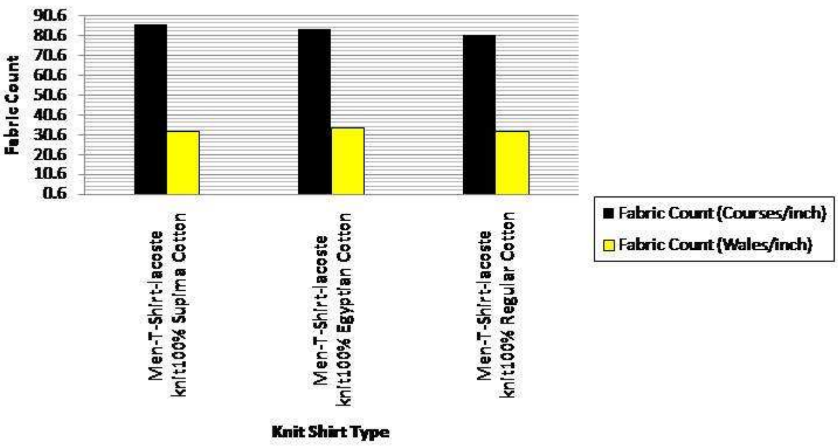


Figure E.4 Yarn Count and Twist for Lacoste Men's Knit Shirts

APPANDIX F: Basic Yarn and Fabric Properties of Women's Lacoste under Knits

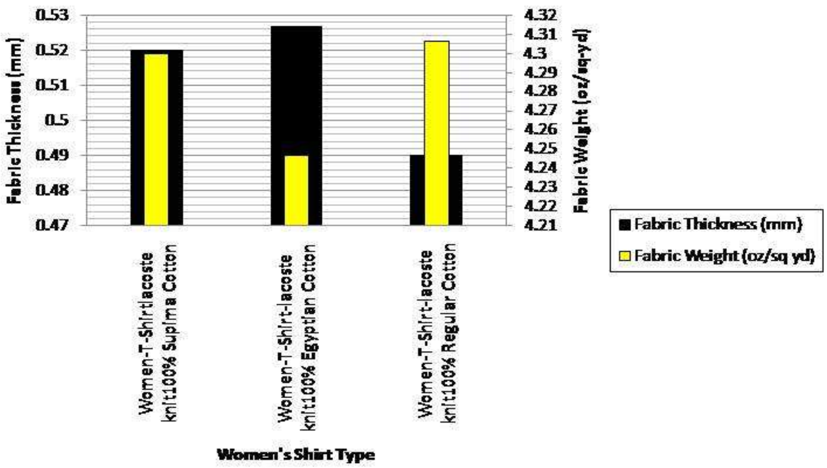


Figure F.1 Fabric thickness and Weight for Lacoste Women's Knit Shirts

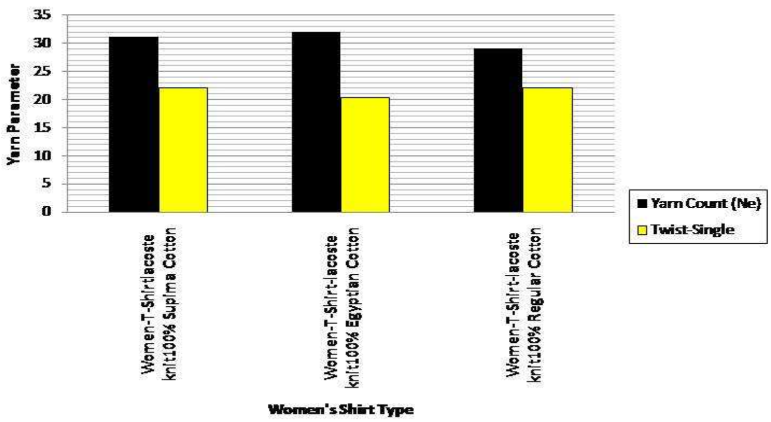


Figure F.2 Yarn Count and Twist for Lacoste Women's Knit Shirts

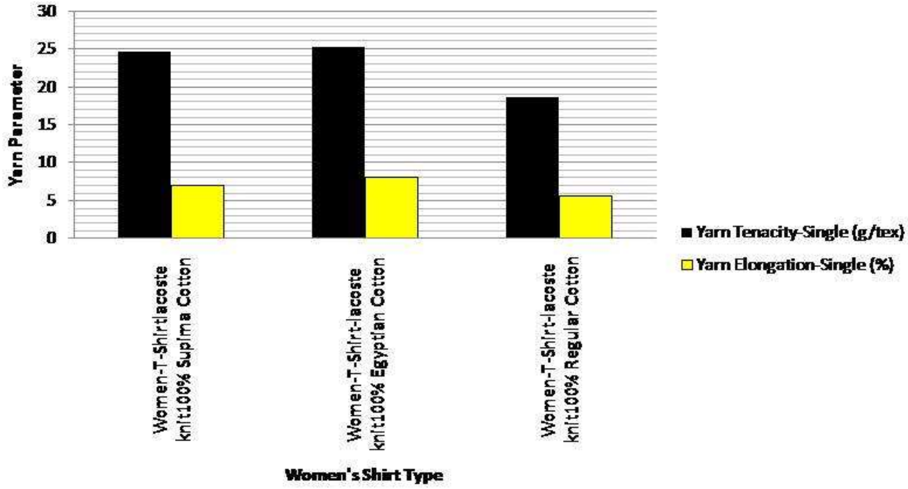


Figure F.3 Yarn Tenacity and Elongation for Lacoste Women's Knit Shirts

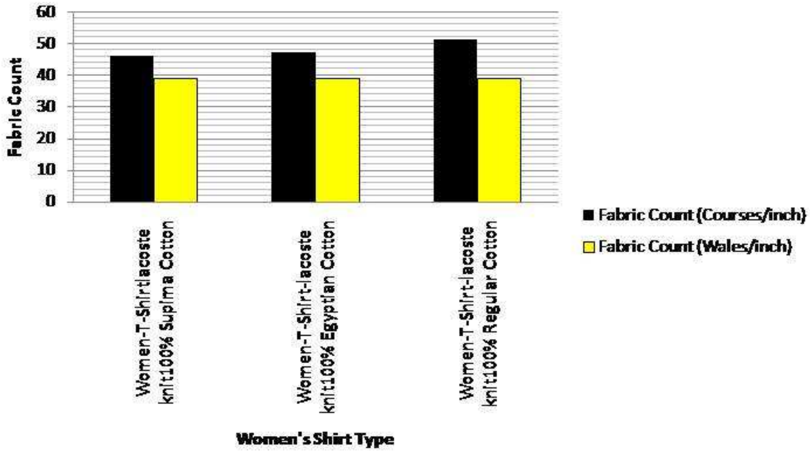


Figure F.4 Fabric Count for Lacoste Women's Knit Shirts

APPENDIX G: Basic Yarn and Fabric Properties of Women's Single-Jersey under Knits

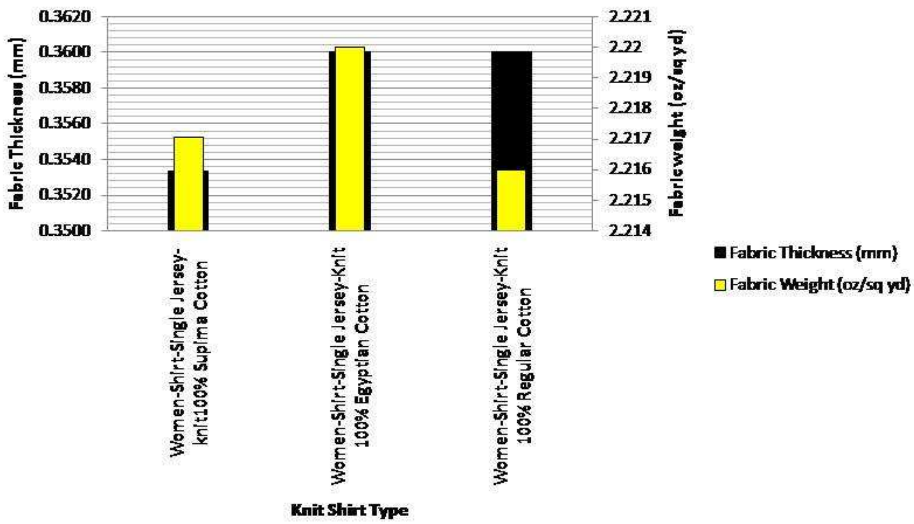


Figure G.1 Fabric Thickness and Weight for Single-Jersey Women's Knit Shirts

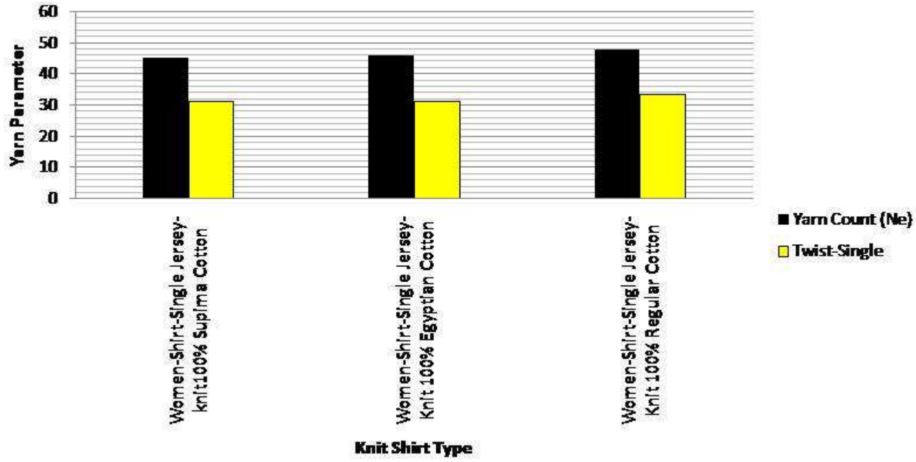


Figure G.2 Yarn Count and Twist for Single-Jersey Women's Knit Shirts