The Effects of Perspiration Application, Weathering Exposures, Washing Action of Automatic Home Clothes Washers, and Repeated Laundering on the Ultraviolet Protection of a Naturally Colored Lightweight Cotton Fabric

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ABSTRACT

Sun protection has gained worldwide attention because repetitive overexposure to ultraviolet radiation can result in harmful effects on human skin, including sunburn, premature skin ageing, and in the worst case, skin cancer (Eckhardt & Rohwer, 2000; Sengupta & Blain, 2001). The diminishing stratospheric ozone layer, due to environmental degradation in the past few decades, combined with the modern outdoor-oriented lifestyles, are leading to unexpected levels of skin cancer (Davis, Capjack, Kerr, & Fedosejevs, 1997). Wearing Ultraviolet protective clothing is a simple way of practicing sun safety; however, regular cotton generally has very low ultraviolet protection and it is one of the most environmentally damaging crops despite of it is commonly used to make summer clothing. With the increased interest of public awareness related to sustainability and environmental issues, naturally colored cotton was recommended as it provides better ultraviolet protection than regular cotton. In addition, the production of naturally colored cotton is more environmentally friendly than regular cotton. Although several studies have been conducted on the UVR protection of naturally colored cotton, many questions regarding the factors that influence the UVR protection of fabrics remain unanswered.

The primary purpose of the study was to examine the effects of perspiration application, weathering exposures, washing action of automatic home clothes washers, and repeated laundering on the UVR protection of a NC lightweight cotton fabric. In addition, five fabric property changes in the test specimen after the treatments of perspiration, weathering exposure, washing action, and repeated laundering (i.e., fabric count change, thickness change, weight change, color change and dimensional change) were included in this study to serve as secondary dependent variables to examine if the four treatment factors (i.e., perspiration application, weathering exposures, washing action of automatic home clothes washers, and repeated laundering) will cause changes in these five fabric properties, and if these changes will lead to changes of UVR protection of NC lightweight cotton fabric.

Based on the purpose and objectives of the study, a split-plot repeated measures experimental design was used for the current study. In this study, the whole plot treatment was the weathering exposure, which contained three levels (i.e., semi-tropical climate without water spray, semi-arid climate, and standard conditioning), and the split plot treatments were the combinations of two treatment factors. In order to understand the effects of repeated laundering on the UVR protection and the five fabric properties, except for the control group, all test specimens were laundered after being treated with the three treatment factors (i.e., perspiration, weathering exposure, and washing action), and this process was repeated 15 times. The UVR protection (i.e., express in UPF value change in current study) and the five fabric properties of these treated test specimens were measured before laundering, and after each laundering cycle.

The results of UPF value change showed that test specimens treated with perspiration had a lower change in UPF value than the specimens without treatment. The test specimens exposed to Florida condition had the most UPF value change, followed by Arizona and Standard textile testing conditions. A significant difference also found in test specimens that laundered in a traditional washer after ninth cycle and the UPF value decreased as the number of laundering cycle increased. However, test specimens that laundered in a front-loading HE washer showed no significant UPF value change. For the five fabric properties that listed in secondary objective, all four treatments significantly influenced fabric count, fabric thickness and fabric weight. However, perspiration treatment had no significant effect on the dimensional change in warp direction of test specimens, and washing action had no significant effect on the dimensional change in filling direction of the test specimen as well as both Delta E and Delta L of color change. For testing the relationship between the changes of the five fabric properties and UPF value change, Delta E and Delta L of color change had the highest correlation coefficient with UPF value change. Therefore, it is possible that the changes of these two properties caused by the four treatments and lead to the UPF value change. Future research is needed to confirm this relationship.

In conclusion, of perspiration application, weathering exposures, washing action of automatic home clothes washers, and repeated laundering do have influence on the ultraviolet protection of the naturally colored cotton. The color change of the test specimens caused by these four treatments possible lead to the change of the ultraviolet protection of the test specimens. More studies are needed to confirm this relationship.

DEDICATION

To my family, wonderful husband, and my lovely daughters for EVERYTHING.

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It has been invaluable experience to complete my doctoral study, and the process of completing this dissertation has been the most significant academic challenges I have ever had. The study would not have been possible without the support and guidance of various individuals. I would like to express my sincere gratitude to all of them.

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TABLE OF CONTENTS

ABSTRACT.......... ii
DEDICATION.......... v
ACKNOWLEDGEMENT.......... vi
TABLE OF CONTENTS.......... vii
LIST OF TABLES.......... xi
LIST OF FIGURES.......... xiii

CHAPTER I INTRODUCTION.......... 1
  Cotton as a Summer Clothing Material.......... 2
  Naturally Colored Cotton.......... 3
    Naturally Colored Cotton – An Environmentally-friendly Fiber.......... 4
    Naturally Colored Cotton – A Fiber that Provides Excellent UVR Protection.......... 5
  Statements of the Problem.......... 6
    Perspiration.......... 6
    Weathering Exposure.......... 7
    Washing Action of Automatic Home Clothes Washers and Repeated Launderings.......... 8
  Research Questions.......... 9
  Purposes and Objectives of the Study.......... 10
    Primary Objectives.......... 12
    Secondary Objectives.......... 12
  Definition of Terms.......... 14
  Assumptions and Limitations of the Study.......... 16

CHAPTER II REVIEW OF LITERATURE.......... 17
  Ultraviolet Radiation Protection.......... 17
    Assessment of Ultraviolet Protection of Textiles.......... 18
      In *Vivo* Approach.......... 19
      In *Vitro* Approach.......... 20
        Radiometric.......... 21
        Spectroradiometric.......... 22
        Spectrophotometric.......... 22
    Test Methods for Textile Ultraviolet Radiation Transmittance.......... 23
      AATCC Test Method 183.......... 23
      ASTM D6544.......... 23
    Standards for Ultraviolet Radiation Protective Textiles.......... 24
      Australia/New Zealand Standard.......... 24
      European Regional Standard.......... 25
      Standard in the United States.......... 26
    Factors that Influence Ultraviolet Radiation Transmission.......... 27

        - Effects of Fiber Type on Ultraviolet Radiation Transmission 27
        - Effects of Fabric Construction on Ultraviolet Radiation Transmission 28
            - Fabric cover 28
            - Fabric weight and thickness 29
        - Effects of Fabric Stretch on Ultraviolet Radiation Transmission 29
        - Effects of Fabric Wetting on Ultraviolet Radiation Transmission 30
        - Effects of Fabric Shrinkage on Ultraviolet Radiation Transmission 31
        - Effects of Dye, Bleach, and Fiber Color on Ultraviolet Radiation Transmission 32
            - Dye 32
            - Conventional cotton, bleached cotton, and naturally colored cotton 33
        - Effects of Additives on Ultraviolet Radiation Transmission 34
            - UV absorbers applied during manufacturing 35
            - UV absorbers applied post fabric manufacturing 36
- Perspiration 37
    - Artificial Perspiration Composition 38
    - Effects of Perspiration on Color Change of Conventional and Naturally Colored Cotton 40
        - Effects of Perspiration on Color Change of Conventional Cotton 41
        - Effects of Perspiration on Color Change of Naturally Colored Cotton 41
- Weather Exposures 42
    - Assessing the Weather Resistance of Textiles 43
        - Natural Weathering Testing 43
        - Accelerated Laboratory Testing 44
            - Carbon arc testers 44
            - Xenon arc testers 45
            - Fluorescent UV testers 47
        - Effects of Weathering Exposures on Color Change of Conventional and Naturally Colored Cotton 48
            - Effects of Weathering Exposure on Conventional Cotton 48
            - Effects of Weathering Exposure on Naturally Colored Cotton 49
- Washing Action of Automatic Home Clothes Washers 50
    - Types of Clothes Washers 51
        - Traditional Vertical Axis Washers 51
        - High-efficiency (HE) Automatic Clothes Washers 52
            - Top-loading high-efficiency (HE) clothes washers. 53
        - Comparisons of Traditional and HE Washers 53
    - Effects of Washing Action on Color Change and Dimensional Change of Conventional and Naturally Colored Cotton 54
        - Effects of Washing Action and Repeated Laundering on Colorfastness or Color Change 55

Effects of washing action on colorfastness of dyed cotton fabrics 55
Effects of repeated laundry on color change of naturally colored cotton. 56
Effects of Washing Action and Repeated Laundering on Dimensional Change 58
Effects of washing action on dimensional change of dyed cotton fabrics 58
Effects of repeated laundering on dimensional change of naturally colored cotton 59
Summary of the Literature Review 59

CHAPTER III MATERIALS AND METHODS 64
Purposes and Objectives of the Study 64
Primary Objectives 65
Secondary Objectives 65
Research Design 67
Primary and Secondary Dependent Variables 68
Independent Variables 68
Perspiration Application 69
Weathering Exposure 70
Washing Action of Automatic Home Clothes Washers 71
Repeated Laundering 71
Hypotheses of the Study 72
Hypothesis 1: Perspiration application, weathering exposure, washing action of automatic home clothes washers, and repeated laundering will influence the UPF value change of the test specimens 72
Hypothesis 2: Perspiration application, weathering exposure, washing action of automatic home clothes washers, and repeated laundering have no effect on the fabric count change of the test specimens 76
Hypothesis 3: Perspiration application, weathering exposure, washing action of automatic home clothes washers, and repeated laundering have no effect on the thickness change of the test specimens. 76
Hypothesis 4: Perspiration application, weathering exposure, washing action of automatic home clothes washers, and repeated laundering have no effect on the weight change of the test specimens. 77
Hypothesis 5: Perspiration application, weathering exposure, washing action of automatic home clothes washers, and repeated laundering have no effect on the color change of the test specimens. 77
Hypothesis 6: Perspiration application, weathering exposure, washing action of automatic home clothes washers, and repeated laundering have no effect on the dimensional change of the test specimens. 78
Materials 79
Fabrics 79
Laundry Detergent 79

Specimen Preparation 80
Whole Plot Fabric Swatch 80
Test Specimens in the Sub-Plot 81
Test Specimen Size 81
Test Specimens Cutting Procedures... 82
Experiment Timeline and Procedures... 87
The Timeline of Experiments for the Three Replicates...................................... 88
Measurements 90
UVR Protection of the Test Fabric and UVR Protection Change of the Test Specimen 91
Fabric Count of the Test Fabric and Fabric Count Change of the Test Specimen 92
Fabric Thickness of the Test Fabric and Thickness Change of the Test Specimen.... 93
Fabric Weight of the Test Fabric and Weight Change of the Test Specimen............ 93
Fabric Initial Color of the Test Fabric and Color Change of the Test Specimen 94
Dimensional Change of the Test Specimens 95
Testing Methods and Procedures.. 95
Perspiration 96
Weathering Exposure.. 97
Laundering 98
Data Analyses 99

CHAPTER IV RESULTS AND DISCUSSION 101
Findings.. 101
Descriptive Statistics... 101
Hypotheses Testing Results 101
Analyses of Primary Purpose – UPF Value Change... 102
Analyses of Secondary Purpose – Fabric Count Change, Thickness Change, Weight Change, Color Change, and Dimensional Change.. 110
Summary and Conclusion of the Study 149
Implications... 151
Recommandation for Future Research.. 151
REFERENCE.. 153
APPENDICES 153
APPENDIX A: Coding System for Whole Plot Treatment Groups 168
APPENDIX B: Random Codes for Specimen Cutting Plans 169
APPENDIX C: The Order of Weathering Exposure in Weathering Chamber......................... 170
APPENDIX D: The Order of Ballast Fabrics Taken from the Washer and Put into the Dryer. 172
APPENDIX E: The Means for UPF values 177

LIST OF TABLES

TABLES

Table 2.1 Australia/New Zealand Standard UPF Ratings and Protection Categories...........25

Table 2.2 ASTM UPF Range, Ratings and Protection Categories.......................................26

Table 2.3 Components of AATCC Standard artificial perspiration.....................................39

Table 2.4 Climate Exposure Procedure in Four Test Cycle Options...................................47

Table 3.1 Levels of Independent Variables..69

Table 3.2 Minimum Hours Required for Specimen Conditioning in Each Test..................90

Table 3.3 Weathering Exposure Procedures in the Three Selected Weather Conditions......98

Table 4.1 Fabric Characteristics……..101

Table 4.2 Repeated Measures Analysis of Variance Testing of Fixed Effects on UPF changes..102

Table 4.3 Means and Standard Deviations for UPF value change by Weathering, Perspiration, and Repeated Cycles............................... 104

Table 4.4 Means and Standard Deviations for UPF value change by Weathering and Washing Action...109

Table 4.5 Repeated Measures Analysis of Variance Testing of Fixed Effects on Fabric Count Change in Warp Direction......................... 111

Table 4.6 Means and Standard Deviations for UPF value change by Weathering and Perspiration..112

Table 4.7 Repeated Measures Analysis of Variance Testing of Fixed Effects on Fabric Count Change in Filling Direction..115

Table 4.8 Means and Standard Deviations for Fabric Count change in Filling Direction by Weathering and Perspiration..116

Table 4.9 Repeated Measures Analysis of Variance Testing of Fixed Effects on Thickness Change.. 120

Table 4.10 Means and Standard Deviations for Thickness change by Perspiration and Washing Action...121

Table 4.11 Means and Standard Deviations for Fabric Count change in Filling Direction by Weathering and Perspiration..123

Table 4.12 Repeated Measures Analysis of Variance Testing of Fixed Effects on Weight changes..125

Table 4.13 Means and Standard Deviations for Weight change by Weathering..................127

Table 4.14 Means and Standard Deviations for Weight Change by Washing and Repeated

Cycles....128

Table 4.15 Repeated Measures Analysis of Variance Testing of Fixed Effects on Color change in Term of Delta E....129

Table 4.16 Means and Standard Deviations Delta E by Weathering, Perspiration, and Repeated Cycles....131

Table 4.17 Means and Standard Deviations for Delta E Change by Washing and Repeated Cycles....134

Table 4.18 Repeated Measures Analysis of Variance Testing of Fixed Effects on Dimensional change in Warp Direction....135

Table 4.19 Means and Standard Deviations for Thickness change by Perspiration and Washing Action....136

Table 4.20 Means and Standard Deviations for Fabric Count change in Filling Direction by Weathering and Perspiration....138

Table 4.21 Repeated Measures Analysis of Variance Testing of Fixed Effects on Dimensional change in Filling Direction....140

Table 4.22 Means and Standard Deviations for Dimensional Change in Filling Direction by Weathering, Perspiration, and Repeated Cycles....141

Table 4.23 Slice Perspiration by Weathering and Washing Action Combinations Results....144

Table 4.24 Slice Perspiration by Weathering and Washing Action Combinations Results....145

Table 4.25 Means and Standard Deviations for Fabric Count change in Filling Direction by Weathering and Perspiration....146

Table 4.26 Correlation coefficient for UPF values change and five fabric properties....148

LIST OF FIGURES

FIGURES

Figure 1.1 Primary Objectives of the Study: Testing the Effects of the Four Treatment Factors on UPF value Change…………………………………………..….11

Figure 1.2 Secondary Objectives of the Study - Testing the Effects of the Four Treatment Factors on the Five Fabric Properties and the Relationship of these Fabric Properties on UPF value Change after Treated with these Four Treatments……11

Figure 3.1 Whole Plot Cutting Plan……………………………………………………81

Figure 3.2 The Weathering Exposure Area of the Test Specimen…………………………82

Figure 3.3 Random Selection of Cutting Locations……………………………………...85

Figure 3.4 The indication of weathering exposure area and the benchmarks for dimensional change test……………………………………………………………………87

Figure 3.5 The Timeline of Experiment for the Three Replicates…………………………..89

Figure 4.1 Plot of Mean UPF Value Change by Weathering and Perspiration Combination after Repeated Laundering……………………………………………………..105

Figure 4.2 Repeated Laundering x Weathering for Fixed Perspiration Interaction Plots....106

Figure 4.3 Repeated Laundering x Perspiration for Fixed Weathering Interaction Plots……………………………………………………………………………108

Figure 4.4 Plot of Mean UPF Value Change Over Weathering by Washing Action…………………………………………………………………………..109

Figure 4.5 Mean Scores of Fabric Count Change in Warp Direction over Weathering by Perspiration……………………………………………………………………..113

Figure 4.6 Mean Scores of Fabric Count Change in Warp Direction over Perspiration by Weathering……………………………………………………………………..114

Figure 4.7 Plot of Fabric Count Change in Warp Direction by Repeated Laundering……115

Figure 4.8 Means and Standard Deviations for Fabric Count change in Filling Direction by Weathering and Perspiration…………………………………………………...117

Figure 4.9 Mean Scores of Fabric Count Change in Warp Direction over Perspiration by Weathering……………………………………………………………………..118

Figure 4.10 Mean Scores of Fabric Count Change in Warp Direction over Perspiration by Weathering……………………………………………………………………..118

Figure 4.11 Mean Scores of Fabric Count Change in Warp Direction over Perspiration by Weathering……………………………………………………………………..119

Figure 4.12 Mean Scores of Thickness Change over Washing Action by Perspiration....…122

Figure 4.12 Mean Scores of Thickness Change over Cycle by Weathering………………..123

Figure 4.14 Mean Scores of Thickness Change over Perspiration by Washing Action…….124
Figure 4.15 Mean Scores of Weight Change on Perspiration………………………………126
Figure 4.16 Mean Scores of Weight Change on Weathering Exposure……….……………127
Figure 4.17 Mean Scores of Thickness Change over Cycle by Washing…………………...128
Figure 4.18 Plot of Mean Delta E by Weathering and Perspiration Combination after Repeated Laundering…………………………………………………………...132
Figure 4.19 Plot of Mean Delta E Over Cycle by Washing Action………………………...134
Figure 4.20 Plot of Mean of Dimensional Change in Warp Direction over Perspiration by Washing Action…………………………………………………………...137
Figure 4.21 Mean Scores of Dimensional Change in Warp Direction over Cycle by Weathering…………………………………………………………………..138
Figure 4.22 Plot of Mean of Dimensional Change in Warp Direction over Washing Action by Perspiration……………………………………………………………………….139
Figure 4.23 Plot of Mean Dimensional Change in Filling Direction Over Perspiration by Weathering …………………………..……………………………………142
Figure 4.24 Plot of Mean Dimensional Change in Filling Direction by Weathering and Perspiration Combination after Repeated Laundering…………………….......143
Figure 4.25 Plot of Mean of Dimensional Change in Filling Direction - Weathering by Perspiration and Washing Action Combinations………………………………144
Figure 4.26 Plot of Mean of Dimensional Change in Filling Direction - Weathering by Perspiration and Washing Action Combinations………………………………145
Figure 4.27 Mean Scores of Dimensional Change in Filling Direction over Cycle by Weathering…………………………………………………………………..147

CHAPTER I
INTRODUCTION

Since ancient times, humans have been aware that sunlight is the ultimate source of energy and life for all living beings on earth (Diffey, 1991). The sunlight wavelength spectrum that reaches the Earth ranges from approximately 10 nm[1] to 3,000 nm. The radiation levels between 100 nm and 400 nm is referred to as ultraviolet radiation (UVR) (Reinert, Fuso, Hilfiker, & Schmidt, 1997). A sufficient dose of UVR is necessary for human well-being because UVR induces the production of vitamin D in the skin, a fundamental component for the formation of healthy bones (Grant, Strange, & Garland, 2003). However, prolonged exposure to UVR can result in harmful effects on human skin, such as sunburn, premature skin aging, and in the worst case, skin cancer (Crews, Kachman, & Beyer, 1999; Eckhardt & Rohwer, 2000; Reinert et al., 1997). Skin cancer is the most common cancer found in the United States, affecting more than two million people annually (Rogers, et al., 2010).

The incidences of skin cancer are mainly contributed to the depletion of the stratospheric ozone layer due to environmental degradation in the last few decades. The ozone depletion leads to increased UVR reaching the Earth, and thus promotes the risks of the skin cancers (Das, 2010). The scenario becomes worse as a change of public interest toward outdoor recreation lifestyles, which has a potential cumulative of UVR exposure, increased in recent years (Davis, Capjack, Kerr, & Fedosejevs, 1997; Cordell, 2008). In addition, the risk of UVR is greatest during the summer because the length of the day is longer and people spend more time in outdoor activities during this period of time.

In order to reduce an individual’s risk of skin cancer, many recommendations have been suggested, which include avoiding the sun when it is at its highest peak, wearing sunscreen, wearing a hat, or covering up with clothing (Lee, Marlenga, & Meich, 1991). However, avoidance of the sun is not practical advice for those who love outdoor activities as well as for people with outdoor occupations. Although sunscreens could offer significant protection from UVR, it does have some disadvantages, such as being uncomfortable because it leaves a greasy

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[1] Nanometer is equal to 10^{-9}m (a billionth of a meter).

residue and it needs to be applied frequently due to continuous sweating of the skin (Truhan, 1991). Thus, wearing UVR protective clothing could be a simpler way to practice sun safety.

Because wearing UVR protective clothing is a simpler way of practicing sun safety, there is a growing public demand in the marketplace for UVR protective clothing. As a result, retailers, manufactures, and textile researchers have paid closer attention to UVR protective clothing. For instance, textile researchers have studied the relationship of the effects of fabric parameters, such as fiber types, fabric construction, fabric stretch, fabric wetting, fabric shrinkage, dye and color, as well as fabric additives, on fabric UVR protection (Dai & Zhang, 2011; Eckhardt & Rohwer, 2000; Hatch & Osterwalder, 2006; Hoffmann, Lapperre, Avermaete, Altmeyer, & Gambichler, 2001; Majumdar, Kothari, & Modal, 2010; Menter & Hatch, 2003; Oda, 2011; Paul et al., 2010; Srinivasan & Gatewood, 2000; Yam et al., 2013).

Cotton as a Summer Clothing Material

Compared to other fibers, cotton is considered more comfortable to wear in the summer months (Kadolph, 2010) because it has excellent moisture absorbency. However, cotton fibers have poor moisture transportation, and moisture, such as perspiration, tends to be retained in the fiber structure and causes it to become heavy (Namiligöz, Çoban, & Bahtiyari, 2010). When a large amount of water or perspiration is absorbed into the fiber, the soaked cotton fabrics will stick to the skin and it leads to discomfort. For these reasons, cotton is considered less favorable for garments worn for activities that cause the wearer to sweat heavily. Although some sportswear manufacturers promote synthetic fibers such as polyester fiber, as more suitable for use in sportswear while exercising due to its excellent wickability (Chinta & Gujar, 2013), regular polyester has low wicking property (Arulkumar & Patil, 2013). Wickability is the ability of a fiber to transport moisture, usually perspiration, away from the skin by capillary action or wicking (Hatch, 1993). Fibers with good wickability can keep the wearer dry, and the wearer will feel comfortable, especially after vigorous exercise. When the wearer does not sweat heavily, the wicking will not happen in regular polyester fibers as there is insufficient amount of water/perspiration to fill the interstices (i.e., capillaries) that formed between fibers of regular polyester (Hatch). In addition, most synthetic fibers are hydrophobic (i.e., fibers that lack of the ability to absorb water), and therefore polyester does not absorb sweat efficiently from the wearer's body. Perspiration is retained or trapped on the skin and will make the wearer feel hot and wet (Tamura, 2010). For these reasons, regular polyester may not be a good choice for high performance sportswear unless modified polyester fibers are used. Modified polyester fibers were introduced to enhance the ability of moisture transportation and release so that even when the water content or perspiration is low, they can have good wickability properties (Arulkumar & Patil, 2013). However, the clothing made of these types of modified fibers usually carries a premium price (Firgo, Suchomel, & Burrow, 2006).

For normal day-to-day activities, in which wearers will not sweat heavily, consumers usually perceive fabrics made of hydrophilic cellulosic fibers, such as cotton, as more comfortable than regular synthetic fibers because this type of fabric absorbs moisture, such as perspiration. By removing perspiration from the skin, a cooling effect is formed (Hatch, 1993). In addition to good absorbency, cotton also has an excellent water vapor transmission rate that allows for good ventilation (i.e., breathable) (Ramkumar, Purushothaman, Hake, & McAlister, 2007). The cooling effect and breathability both provide comfort to the wearer in warm weather. Additionally, cotton's soft hand characteristic (i.e., a soft feeling for skin contact) also helps to account for its comfort (Kadolph, 2010). Cotton is also good for people with allergies or sensitive skin because some synthetic fibers may produce itching and irritation to the skin (Mason, 2008). For these reasons, clothing that is made of light-weight cellulosic fibers, such as cotton, are a common choice for summer clothing.

Naturally Colored Cotton

Throughout history, cotton plants have produced a range of fiber colors (Vreeland, 1999). Therefore, naturally colored (NC) cottons are not new, but have been cultivated for over 5,000 years. However, with the invention of the cotton gin and industrial dyes, creamy white cottons were bred and have been the predominant plant because white fibers are easier to dye than naturally colored cottons. The NC cottons on the other hand were considered genetically inferior in quality to regular cotton because the fiber colors were usually uneven and the fibers were too short and weak to be machine spun compared to regular cottons (Murthy, 2001). In addition, the availability of inexpensive dyes and the need for higher output of cotton production also caused the NC cottons to almost vanish about 50 years ago (Wakelyn & Chaudhry, 2007). As a result, naturally colored cottons only survived in small and traditional communities around the world including Mexico, Peru and Guatemala as well as in seed banks kept by some agriculture departments (Vreeland, 1999).

After being abandoned for about a century, NC cottons revived in the early 1990s (Vreeland, 1999) with the increased public awareness and interest related to sustainability and environmental issues. For instance, selective crossbreeding research in NC cotton has been conducted over the past 30 years in many countries, such as China, India, and Turkey because these fibers were considered to be relatively more environmentally friendly and free from toxic chemicals. Selective crossbreeding research is a technique used to modify and improve plant characteristics, such as growth rate, quality, and seed size by crossing pollinated flowers with selected plants (Kingsbury, 2009). These NC cotton research studies have led to improvements in color range and fiber quality, with increases in length, strength, fineness, color intensity, and yield potential (Yin & Roger, 1996). As a result, commercially available NC cottons with sufficient physical properties for machine spinning were found in the market in 1988 (Yin & Roger). These new hybrids of NC cotton can be spun successfully for many textile applications, including clothing, bedding, and furniture (Katz, Boone, & Vreeland, 1997). NC cottons bring a premium price for growers, with a price of about $4.00 to $100.00 per pound depending on color (J. M. Vreeland, personal communication, June 21, 2014), compared to 74 cents per pound for regular cottons (IndexMundi, July 2, 2014).

Naturally Colored Cotton – An Environmentally-friendly Fiber

Some consumers perceive that cottons are better for the environment because cotton is a natural cellulosic fiber (Watson, 1991). However, regular cotton farming is one of the most environmentally damaging activities in the world as it demands heavy use of fungicides and pesticides as cotton plants are very prone to attack by certain insects and fungi (Chen & Burns, 2006). While regular cotton is grown on only 2.4% of the world’s farmland, regular cotton farming uses more insecticides than any other single crop, and cotton production is responsible for 25% of all agricultural insecticide use worldwide (Myers, 1999). In addition, most of the regular cottons are usually bleached before printing or dyeing to produce a better coloration

(Chen & Burns). Even organically grown cotton does not completely eliminate environmental damage. Although the use of insecticides can be eliminated, the cotton dyeing process still generates environmental problems through the discharge of dyes, pigments, and other chemicals into the water. These toxic chemicals have harmful effects on the environment and cause skin allergies and other health related problems to human beings (Dutt, Wang, Zhu, & Li, 2004).

In contrast to regular cotton, the NC cotton is more environmentally friendly than regular cotton in the processes of cotton plant growing and fabric production. NC cotton plants have better resistance to disease and pests than regular cotton (Myers, 1999), which can eliminate or reduce the use of insecticides during the growth of cotton plants. During fabric production, the harmful and costly bleaching and dyeing process can be virtually eliminated as the NC cotton comes with inherent natural colors (Apodaca, 1990). NC cottons grow in shades of green and brown, and the shades can vary depending on geographic location, climatic and growing conditions, and soil variation (Öktem, Gürel, & Akdemir, 2003) According to Murthy (2001), the pigment development in NC cottons occurs between 30 and 40 days after boll formation. The pigment development patterns in brown and green colored cotton are different. The brown color is derived from the lumen of the fiber cells (i.e., the inner part of the cotton fiber), and it only forms after fibers are exposed to sunlight and oxygen, which occurs when the seed pod opens (Zhang et al., 2011). Therefore, the colors of the naturally brown cottons deepen in the continuous sunshine. Naturally green colored cotton develops its color from caffeic-acid (i.e., a type of acid that is found in the wax layer that is located inside the secondary cellular wall of the fiber). Because the secondary cellular layer is easily peeled off, the naturally green cotton would fade when exposed to continuous sunshine (Wang & Li, 2002; Waghmare & Koranne, 1998; Zhang et al., 2011).

Naturally Colored Cotton – A Fiber that Provides Excellent UVR Protection

Although cotton fiber is popular for summer clothing due to its comfort properties, it generally has very low UVR protection (Davis et al., 1997). According to the study by Smith (1993), a common white cotton T-shirt has an Ultraviolet Protection Factor (UPF) rating of seven when dry and five when wet while a minimum of UPF 15 is required in order for a textile to claim it is sun protective clothing (Gambichler, Laperre, & Hoffmann, 2006). Because of the presence of natural pigments and lignin in the NC cottons acting as UVR absorbers (Pailthorpe, 1994), fabrics made of NC cotton provide better UVR protection than regular cotton in the greige stage (Parmar, Giri, Singh, & Chabbra, 2006) The greige stage refers to the stage after the fabric has been produced by any textile process, such as weaving or knitting, but without going through any manufacturing processes, such as finishing or dyeing (American Society for Testing and Materials, 2012). In the study of Parmar et al. (2006), a brown NC cotton fabric had a UPF rating of 28 and a green NC cotton fabric had a UPF value of 29, which were high enough for a rating of "Very Good Protection" based on the ASTM sun protection label (ASTM, 2012). Değirmenci, Kaynak, and Kireçci (2010) compared the UVR protection of NC cotton, regular white cotton and dyed cotton with both woven and knitted fabric structures, and the results showed that NC cotton fabrics provided excellent UVR protection for both types of fabric structures (i.e., the UPF rating of the knitted fabric was 98.2 and the UPF ratings of two weave fabrics 64.3 and 93.5).

Statements of the Problem

Prolonged exposure to UVR from the sun can cause skin cancer, and a simple way to protect skin from harmful UV rays on a daily basis would be to wear clothing with UVR protection properties. Since summer clothing is subject to be worn and washed on a regular basis, it is important to understand the combination of the effects of perspiration, weathering exposures, washing action of automatic home clothes washers, and repeated laundering on the UVR protection of a NC lightweight cotton fabric that is suitable for wear in summer. The statements of the problem are organized in three parts to discuss the three factors that may influence UVR protection of a NC lightweight cotton fabric and the reasons for selecting these variables. The perspiration is discussed in the first part; weathering exposure is discussed in the second part; washing action of home clothes washers and repeated laundering are discussed in the last section.

Perspiration

Summer weather is hot and humid in many locations, which can cause an increase in perspiration as the human body cool tries to itself. During the summer months, an adult loses an average of 400 ml of perspiration daily (Watkin, 1995). When perspiration is freshly secreted, it is slightly acidic (Perspiration Fastness Subcommittee, 1952). Cotton is widely used for summer clothing due to its ability to absorb moisture, including perspiration, from the human body, which makes it more comfortable to wear. A study by Kantor and Moore (2004) showed that similar to regular cotton, NC cotton also has a good absorbency, but it may lead to fiber degradation too. Because of the good absorbency but poor moisture transportation and release, the perspiration is usually retained in the fiber. This absorption of perspiration may lead to the deterioration of the fabric, shortening the garment's wear life (Collier, Bide, & Tortora, 2009). This degradation disintegrates the cotton fiber and causes a decrease of fabric cover, which may lead to a decrease of fabric UVR protection. Although several studies have been conducted on the effects of perspiration on NC cotton fabrics, they focused on colorfastness and color transfer (Öktem et al., 2003; Wimberley & Roper, 1997). No research study was found investigating the relationship between perspiration and UVR protection. Therefore, studies that examine the effects of perspiration on NC cotton are needed.

Weathering Exposure

All apparel products, especially summer clothes that are regularly worn outdoors, are subjected to the influence of weathering (Howard & McCord, 1960). Weathering is a complex concept which includes the impact of sunlight, rain, humidity, and temperature (heat and cold) on a material, including textiles, and the intensity of these components can vary daily and seasonally as well as by geographic location (Hawkins, 1984). Any combination of these components can cause degradation in textile fibers (Barnett & Slater, 1991). Several studies have provided evidence that weathering is one of the major factors contributing to textile degradation, especially in physical damage, such as loss of color and strength (Guoping & Slater, 1990; Howard & McCord, 1960; Slater, 1986).

In most studies cotton is found to be more resistant to the weathering elements than other natural fibers (e.g. silk) and most manufactured fibers (e.g. rayon, polyester, nylon, and acetate). However, prolonged exposure to weather elements, especially ultraviolet radiation, will still cause deterioration to cotton fabrics (Collier, Bide, & Tortora, 2009) in the form of color loss or fading. For instance, results from several studies had proved that ultraviolet and visible wavelengths of weathering could cause NC cotton fading (i.e., colors become lighter) (Hustvedt

& Crews, 2005; Jahagirdar, Srivastava, & Venkatakrishnan, 2000), and one study has shown that the effect of light exposure caused color fading of NC cottons and led to lower UVR protection (Hustvedt & Crews).

Although moisture is another weathering component that damages the fabric (Hatch, 1993), limited studies have examined the effect of moisture. Evenson and Epps (1999) found that NC cottons showed more color change after exposure to light at high humidity rather than at low humidity. The result of this study suggests that different conditions of weathering exposures with various degrees of humidity, such as hot and humid in Florida climate and hot and dry in Arizona climate (Sleiman, 2011), may have different impacts on fabric UVR protection because fabric color change influences fabric UVR protection (Hustvedt & Crews, 2005). However, no study was found that examined the effects of weathering exposures on UVR protection of NC cotton. Therefore, studies on this area are needed.

Washing Action of Automatic Home Clothes Washers and Repeated Launderings

Summer clothes are usually made of cotton because it's a very absorbent and easy to clean material (Kadolph, 2010). The tendency to soak up perspiration not only creates unpleasant odor but also causes deterioration. Cotton, including NC cotton, can be weakened by chemical damage, such as acidic perspiration. Therefore, it is important to wash summer clothes more often than winter clothing worn in other seasons to keep the clothes clean in appearance and hygienic (Perdue, 1966). Some researchers have examined the effect of laundering on fabric UVR protection, and found that the repeated laundering increased the fabric UVR protection (Clark, Grainger, Agnew, & Driscoll, 2000; Menzies et al., 1991; Osterwalder, Schlenker, Rohwer, Martin, & Schuh, 2000; Standford, Georgouras, & Pailthorpe, 1995a, b; Wang et a1., 2001; Zhou & Crews, 1998). The researchers suggested that the process of laundering led to compaction due to shrinkage, presumably increasing fabric cover and hence resulting in an improvement in UVR protection. Cottons generally exhibit some relaxation shrinkage in the first few launderings; this geometrical change decreases the UVR transmission accordingly, improving UVR protection (Collier et al., 2009). However, all previous studies on the effects of laundering on fabric UVR protection were conducted in traditional washers, and no research was conducted using high-efficiency (HE) washers, which has gradually become more popular with

U.S. consumers due to increased energy and water savings (Association of Home Appliance Manufacturers, 2008).

There are two types of washers in the U.S. market (i.e., traditional washers and HE washers). The washing action of these two types of washers differ due to this different water levels and the mechanical action of the drums during laundering. Several studies compared the effects of the washing action between traditional washers and the front-loading HE washers on fabric durability (i.e., tearing strength, abrasion resistance, and pilling resistance) and maintenance (i.e., appearance smoothness retention, dimensional stability, fabric twist, and stain removal) (Ankeny, Ruoth, Keyes, Quddus, & Higbee, 2006; Chen-Yu, Wong, & Emmel, 2012; Klausing, Maloney, & Easter, 2012; Schlag & Ordonez, 2010; Wong, Chen-Yu, & Emmel, 2012). However, no study was found to compare the effect of the washing action between traditional washers and front-loading HE washers on the UVR protection of NC cotton fabrics. Because the HE washers have gradually become more popular as U.S. consumers become more environmentally conscious (Association of Home Appliance Manufacturers, 2008), it is important to understand whether the differences in washing action will cause dissimilar effects on the UVR protection, especially when consumers use these washers to clean their summer clothes more frequently.

Research Questions

Despite the excellent UVR protection property of NC cotton, no study has been carried out on how consumers' wearing and washing will affect the UVR protection for NC lightweight cotton fabrics. Studies that simulate a typical summer wearing and washing to understand the factors that may affect the UVR protection of NC lightweight cotton fabrics are needed. Therefore, this study will combine perspiration, weathering exposures, washing action, and repeated laundering to simulate a typical summer wearing and washing in a semi-tropical climate such as Florida and a semi-arid climate such as Arizona to examine the UVR protection of a NC cotton fabric. The following research questions are the focus of this study:

1. Do perspiration, weathering exposure, washing action, and repeated laundering affect the UVR protection of a NC lightweight cotton fabric that is suitable for wear in summer?
2. Do perspiration, weathering exposure, washing action, and repeated laundering cause changes in fabric count, thickness, weight, color and dimension of the test specimen? If there are changes caused by these four treatments, is there any relationship between the changes in these five fabric properties and the change in UVR protection of a NC lightweight cotton fabric?

The reason for examining these five fabric property changes is based on the previous studies reviewed in Chapter II. Studies show that these five fabric property changes are important factors affecting the change of fabric UVR protection. For example, a previous study showed that NC cotton fiber had considerable shrinkage after laundering (Dickerson, Lane, & Rodriguez, 1999), and shrinkage increases the compactness of the fabric, and thus usually causes the fabric count to increase (i.e., the number of yarn per square inch within a fabric) (Orzada, Moore, Collier, & Chen, 2009). The increase of fabric count may lead to the increase of fabric cover, which will improve UVR protection (Crews et al., 1999; Hoffmann, Lapperre et al., 2001; Pailthorpe, 1998). Therefore, the fabric count and shrinkage caused by the repeated laundering may significantly influence the UVR protection of the fabric. In addition, fabrics with lighter colors offer less UVR protection (Gies, Roy, McLennan, & Toomey, 1998; Reinert, et al., 1997) and NC cotton fabrics will become lighter after soaked in artificial perspiration (Wimberley & Roper, 1997), as well as after exposure to light for a period of time (Hustvedt & Crews, 2005; Jahagirdar et al., 2000). Therefore, the color change caused by perspiration application or weathering exposure may significantly influence the UVR protection of the fabric.

Purposes and Objectives of the Study

The primary purpose of the study is to examine the effects of perspiration application, weathering exposures, washing action of automatic home clothes washers, and repeated laundering on the UVR protection of a NC lightweight cotton fabric (see Figure 1.1).

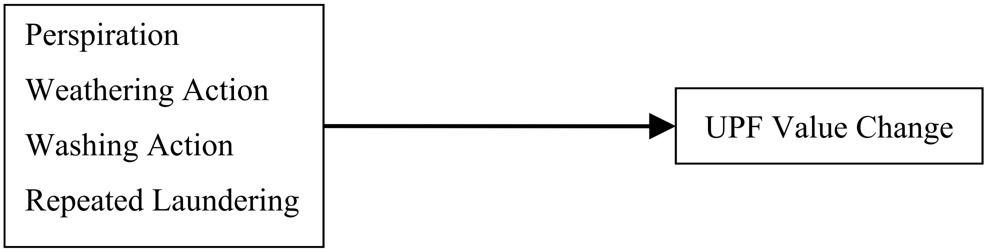

Figure 1.1 Primary Objectives of the Study: Testing the Effects of the Four Treatment Factors on UPF value Change

In addition, five fabric property changes in the test specimen after the treatments of perspiration, weathering exposure, washing action, and repeated laundering (i.e., fabric count change, thickness change, weight change, color change and dimensional change) are included in this study to serve as secondary dependent variables. The purpose of including the examinations of the changes in these five fabric properties is because previous studies have found these properties to be important factors in affecting fabric UVR protection (e.g. Crews et al., 1999; Hustvedt & Crews, 2005; Stanford et al., 1995a; Wong et al., 2000). Therefore, the second purpose of the study is to examine if the four treatment factors (i.e., perspiration application, weathering exposures, washing action of automatic home clothes washers, and repeated laundering) will cause changes in these five fabric properties, and if these changes will lead to changes of UVR protection of NC lightweight cotton fabric (see Figure 1.2).

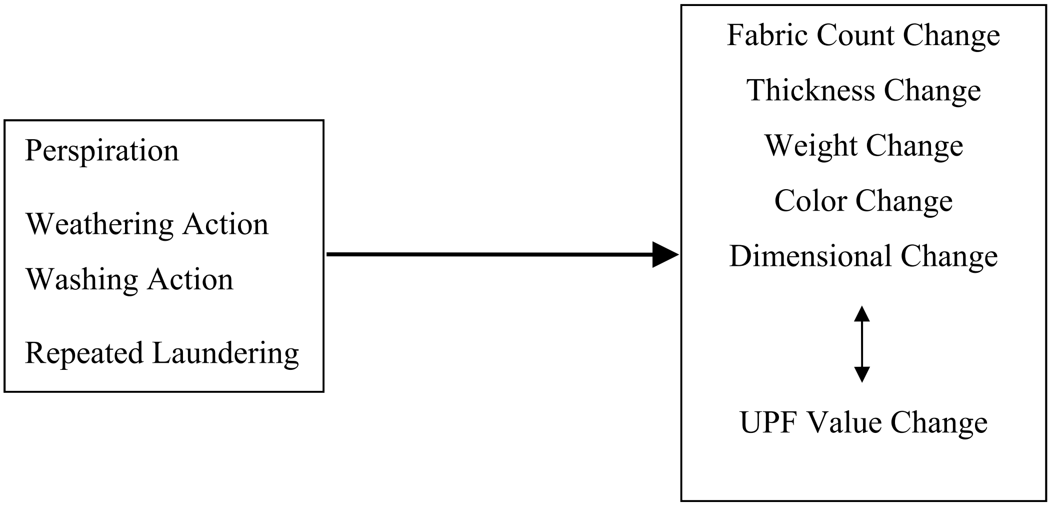

Figure 1.2 Secondary Objectives of the Study - Testing the Effects of the Four Treatment Factors on the Five Fabric Properties and the Relationship of these Fabric Properties on UPF value Change after Treated with these Four Treatments

Based on the purposes of the study, two sets of objectives, primary and secondary objectives are included. These objectives are listed below.

Primary Objectives

The primary objectives are to test if the four treatments (i.e., perspiration application, weathering exposures, washing action of automatic home clothes washers, and repeated laundering) affect the UVR protection of a NC lightweight cotton fabric that is suitable for wear in summer. The primary objectives are listed as the following:

(a) To examine the interaction in the effects of perspiration, weathering exposures, washing action, and repeated laundering on the UVR protection of a NC lightweight cotton fabric;

(b) To examine the UVR protection of a NC lightweight cotton fabric with and without the presence of perspiration;

(c) To examine the UVR protection of a NC lightweight cotton fabric before and after two types of weathering exposures (i.e., semi-tropical climate without water spray and semi-arid climate), and a control (i.e., specimens are stored in the standard textile testing condition without weathering exposure);

(d) To examine the UVR protection of a NC lightweight cotton fabric before and after the washing in the two types of washers (i.e., traditional washer and HE washer);

(e) To examine the UVR protection of a NC lightweight cotton fabric before and after 15 repeated laundering;

(f) To examine the variables (i.e., perspiration, weathering exposure, washing action, and repeated laundering) that best predict the UVR protection of a NC lightweight cotton fabric.

Secondary Objectives

The secondary objective is to examine if the treatments (i.e., perspiration application, weathering exposures, washing action of automatic home clothes washers, and repeated laundering) will cause changes in five fabric properties of the test specimen (i.e., fabric count change, thickness change, weight change, color change and dimensional change). These results may provide insights into understanding if the treatments cause changes in fabric properties and if there are relationships between these five fabric property changes and the change in UVR protection of a NC lightweight cotton fabric. The secondary objectives are listed as the following:

(a) To examine if perspiration application will cause the changes in five fabric properties of the test specimen (i.e., fabric count change, thickness change, weight change, color change and dimensional change). If there are changes to the five fabric properties after the perspiration treatment, then further examinations will be conducted to determine if there is a relationship between the changes in these five fabric properties and the change in UVR protection of a NC lightweight cotton fabric;

(b) To examine if two weathering exposure conditions (i.e., semi-tropical climate without water spray and semi-arid climate), and a standard textile testing condition without weathering exposure (i.e. serving as a control) will cause the changes in five fabric properties of the test specimen (i.e., fabric count change, thickness change, weight change, color change and dimensional change). If there are changes to the five fabric properties after the weathering exposure treatment, then further examinations will be conducted to determine if there is a relationship between the changes in these five fabric properties and the change in UVR protection of a NC lightweight cotton fabric;

(c) To examine if two different types of washing action of automatic home clothes washers (i.e., traditional washer and HE washer) will cause different degrees of changes in five fabric properties of the test specimen (i.e., fabric count change, thickness change, weight change, color change and dimensional change). If there are changes to the five fabric properties after washing in the two types of washers, then further examinations will be conducted to determine if there is a relationship between the changes in these five fabric properties and the change in UVR protection of a NC lightweight cotton fabric;

(d) To examine if repeated launderings, up to 15 laundering cycles, will cause changes in five fabric properties of the test specimen (i.e., fabric count change, thickness change, weight change, color change and dimensional change). If there are changes to the five fabric properties after repeated launderings, then further examinations will be conducted to determine if there is a relationship between the changes in these five fabric properties and the change in UVR protection of a NC lightweight cotton fabric.

Definition of Terms

Ultraviolet Radiation (UVR) – Radiant energy for which the wavelengths of the monochromatic components in the range of 100 to 400 nm (Eckhardt & Rohwer, 2000).

Ultraviolet Protection Factor (UPF) – The ratio of the UVR irradiance transmitted through air to the UVR irradiance transmitted through a fabric (American Association on Textile Chemists and Colorists, 2012). UPF is the number or rating used to indicate the amount of UVR protection provided to skin by a fabric.

Regular and Naturally Colored Cotton – Regular cotton refers to the cotton that is cultivated with the use of synthetic fertilizers, pesticides, and all other plant chemicals (Wakelyn & Gordon, 1995) and most regular cottons are white (Hua et al., 2007). Naturally colored cotton refers to cotton with natural colors other than white (Öktem et al., 2003). In the current study, the naturally colored cotton is a fabric with light brown color, which is purchased from Peru Naturtex Partners, and the test fabric code is Tela Percale with Vicuña color (i.e., tan color).

Lightweight Fabrics Suitable for Wear in Summer – According to Kadoplh (2007), fabrics that weigh less than 135 gm/m^2 (4.0 oz/yd^2) are considered lightweight fabrics that are often used for summer blouses and shirts. In the current study, the test fabric is a fabric with a fabric weight of 130 gm/m^2 (3.8 oz/yd^2).

Artificial Perspiration – The artificial perspiration solution used in the current study was prepared according to AATCC Test Method 15 – Colorfastness to Perspiration. According to this test method, the artificial perspiration solution perspiration solution contained 10g of sodium chloride, 1g lactic acid, 1g disodium hydrogen phosphate, and 0.25g histidsine monohydrochloride per liter of the solution. The solution will be hand-stirred with a glass rod to ensure even distribution, and the pH of this solution is 4.3 ± 0.2.

Weathering – The exposure to climate conditions, including environmental factors of sunlight, rain, humidity, wind, and temperature (heat and cold) (Collier & Epps, 1999). In the current study, a Q-Sun Xenon Test Chambers Xe-3-HS was used to simulate the weather exposure conditions of semi-tropical climate, such as the weathering in Florida, without water spray and semi-arid climate such as the weather in Arizona.

Washing Action of Automatic Home Clothes Washers – Washing action of a traditional washer refers to the mechanical action used to clean the clothes in a clothes washer containing a drum that sits vertically inside a cabinet with a center post agitator (AATCC, 2012; Ankeny et al., 2006). The washing action of a High-efficiency (HE) washer refers to the mechanical action used to clean the clothes in a clothes washer that uses significantly less water and energy than consumed by a traditional washer.

Laundering – A process intended to remove soils and/or stains by washing with a detergent solution and normally includes subsequent rinsing, extracting, and drying (AATCC, 2012).

Fabric Count Change – Fabric count of a test specimen refers to the number of warp and filling yarns per square inch (or centimeter) (Collier et al., 2009). Fabric count change in the current study refers to the change in number of warp and filling yarns per square inch (or centimeter) after each laundering cycle compared to the number of the original test specimen before washing.

Thickness Change – The thickness of a test specimen refers to the distance between the top and bottom surface of a test specimen (Collier & Epps, 1999). Thickness change of a test specimen in the current study refers to the change in distance between the top and bottom surface of a test specimen after each laundering cycle compared to the distance of the original test specimen before washing.

Weight Change – The weight of a test specimen refers to the heaviness of a test specimen (Weight, n.d.). Weight change of a test specimen in the current study refers to the change in weight of a test specimen after each laundering cycle compared to the weight of the original test specimen before washing.

Color Change – Color change refers to the change in hue, lightness, or a combination of these (AATCC, 2012). Color change of a test specimen in the current study refers to the color change of a test specimen is compared to the color of the original test specimen before washing.

Colorfastness – The ability to maintain an originally dyed or printed color and the ability to resist its colorants to transfer to adjacent materials (AATCC, 2012).

Dimensional Change – Dimensional change is defined as the changes of length or width direction of a test specimen subjected to specific conditions, such as after being worn, washed, and/or dry-cleaned (AATCC, 2012). In the current study, the dimensional change is measuring the warp and filling direction distances of the test specimens after each laundering cycle compared to the distances of the original test specimen before washing.

Assumptions and Limitations of the Study

Two assumptions have been made for conducting experiments in this study. It is assumed that all instruments used in this study are accurate and precise after manufacturer's recommended calibration. In addition, it is assumed that the equipment and operator errors are of a random nature and have no significant effect on the test results.

Limitations are recognized for conducting experiments in this study. Firstly, only a 100% plain weave NC cotton in light brown color in 2.84 meters (i.e., 3.11 yards) width with fabric weight of 130 gm/m^2 (3.8 oz/yd^2) will be used in this study. The results of the current study may not generalize to all NC cotton fabrics because only one NC cotton with one color is examined. Secondly, although AATCC Test Method 169 – Weather Resistance of Textiles: Xenon Lamp Exposure includes four different test cycle options, only Option 1 and 3 the modification of Option 1 without water spray are selected to represent the summer weather. Therefore, the results of the current study cannot represent all weather conditions. Thirdly, although many brands of washers are available on the market, only a MAYTAG Automatic Washer of Model A806 will be used to represent traditional top-load vertical axis washers with an agitator, and the Whirlpool® Duet Sport® Front-Loading Washer WFW8300S will be used to represent front-loading HE washers with tumble action. Therefore, the results of the current study cannot represent all traditional and HE washers sold in the U.S. market. Fourthly, although many brands of laundering detergents are available on the market, only "2X Ultra Tide® Free" will be used for the laundry in the traditional washer and "2X Ultra Tide® HE Free" will be used for the front-loading HE. It is unknown that whether using different laundering detergent brands may cause variances in research results. Fifthly, test specimens will be laundered only up to 15 washing cycles, although the UPF values may differ after 15 washing cycles.

CHAPTER II

REVIEW OF LITERATURE

This chapter presents a review of the previous work relevant to this study. This review of literature is organized into five parts. The first part on ultraviolet radiation protection includes four sections (i.e., the assessment of ultraviolet protection provided by textiles, standards for ultraviolet protective textiles, factors that influence ultraviolet radiation transmission, and test methods for evaluating textile ultraviolet radiation protection). The second part on perspiration includes two sections (i.e., artificial perspiration composition and the effects of perspiration on color change of conventional and naturally colored (NC) cotton). The third part on weathering exposure includes two sections (i.e., assessing the weather resistance of textiles and the effects of weathering exposures on color change of conventional and NC cotton). The forth part on the washing action of home clothes washers includes two sections (i.e., types of washers and effects of washing action on color change and dimensional change of conventional and NC cotton). The last part is the summary of the literature review.

Ultraviolet Radiation Protection

Sunlight radiation is a mixture of X-rays, ultraviolet (UV) rays, visible light rays, and infrared rays, and its spectrum extends from 280 nm to 400 nm (Eckhardt & Rohwer, 2000). Radiation measured between 280 nm and 400 nm is referred to as UV radiation (UVR), which has a longer wavelength than X-rays (i.e., between 0.01 nm and 10 nm), and a shorter wavelength than visible rays (i.e., between 400 nm and 800 nm). A low dose of UVR is necessary for human well-being because UVR induces the production of vitamin D in the skin, which is a fundamental component in the formation of healthy bones (Grant et al., 2003). However, overexposure to UVR can result in harmful effects on human skin, such as sunburn, premature skin aging, and in the worst case, skin cancer (Crews et al., 1999; Eckhardt & Rohwer; Reinert et al., 1997).

The UVR band consists of three regions: ultraviolet A (UVA) (between 315 nm to 400 nm), ultraviolet B (UVB) (between 280 nm to 315 nm), and ultraviolet C (UVC) (less than 280 nm) (Diffey, 1991). UVC radiation is completely absorbed by the ozone layer and does not reach the earth, while UVA and UVB are the most significant factors in damaging skin. Although UVA accounts for about 95% of all solar UVR and causes only a little reaction on the skin, it penetrates into human skin deeper than UVB and creates responses that include premature aging of the skin, tanning and photo-toxicity to medicines (Reinert et al., 1997). Alternatively, UVB is shorter in wavelength compared to UVA, but it's responsible for the major cause of skin cancer because it is highly reactive with macromolecules in the skin (Liffrig, 2001).

Garments are usually treated as an effective means to slow the cumulative exposure to UVR (Capjack et al., 1994). Some major health organizations, such as The Skin Cancer Foundation, the World Health Organization, and the European Committee for Standardization recommend that people of all ages wear cover-up clothing when in the sun. The European standard for sun-protective clothing (i.e., EN 13758) includes stringent requirements for the design of UV labeled garments (i.e., clothes for the upper body must provide coverage from the base of the neck down to the hip and across the shoulders, down to three quarters of the upper arm) (Hoffmann, Kesners et al., 2001). In the U.S., the American Academy of Dermatology (2013) has recommended wearing loose woven clothing with maximum surface area coverage. This includes wearing long-sleeved shirts and pants and/or layering clothes as well as wearing a wide-brimmed hat that shades the face and ears. However, different types of fabrics and garment designs consist of different levels of UV protection. For instance, regular cotton T-shirts, which are ideal for summer clothing, give an ultraviolet protection factor (UPF) rating of only seven (Adam, 1998). The UPF rating of regular cotton shows inadequate protection for outdoor wear. Nevertheless, the UV protection of fabrics can be improved in a variety of ways, including using NC cotton, increasing the percentage of fabric cover, and using UV protection additives. The studies related to the causes and influences of fabric's UVR protection are reviewed in the section, "*Factors that influence UVR transmission*."

Assessment of Ultraviolet Protection of Textiles

A variety of quantitative tests have been used to evaluate the ability of a textile to protect against UVR, and there are two distinct approaches to determine the fabric's UVR transmission (i.e., laboratory testing *in vivo* and instrumental measurement *in vitro*). *In vivo* is a Latin word, which means taking place on an organism. *In vitro* refers to the technique of performing a given experiment in a controlled environment outside of a living organism. The two approaches are discussed in the following sections.

In Vivo Approach

The *in vivo* testing is performed by placing fabric swatches on a human subject's skin, and it is analogous to the method for measuring the effectiveness of sunscreen lotions (Hatch & Osterwalder, 2006). The assessment of *in vivo* is the sun protection factor (SPF) (Capjack, Davis et al., 1994). To calculate the SPF value of the fabric, the *in vivo* method measures the minimum amount of radiation energy exposure necessary to cause a uniform erythematous response or skin redness for both protected and unprotected skin. This minimum amount of radiation energy that causes erythematous response is generally called minimum erythema dose (MED). The radiation energy used in this method is generated by a standardized lamp whose spectrum resembles the sunlight spectrum as closely as possible (Hoffmann, Lapperre et al., 2001). To determine MED of unprotected skin, a layer of fabric with several holes is placed over a human skin, and the holes are removed at different time-points to expose the skin to varying durations of UV (Heckman et al., 2013). Changes to the exposed areas of the skin are then evaluated after 24 hours have lapsed. According to The National Tanning Training Institute (2013), the redness that occurs immediately after exposure is mainly caused by heat, which is not comparable with real UV erythema. Therefore, the redness of skin should be evaluated after 24 hours. The redness of skin can be examined by visual evaluation or using a skin color measurement device, such as a spectrophotometer. For a spectrophotometer measurement, the a* (redness) value of exposed skin in each hole, as well as the unexposed skin, were evaluated. To determine a significant redness that is considered a potential burning, the difference in a* values between exposed and unexposed skin must be greater than 2.5 points (Heckman et al.). The minimum exposure time to cause a significant redness can be used to determine the MED to cause the redness of unprotected skin. For a visual evaluation, the same process to determine the MED is used; however, the researcher subjectively determines the significant redness by visual observation instead of using a spectrophotometer. To determine the MED of protected skin, the same process is used by adding a layer of fabrics over the skin. After the MED values for the protected and unprotected skin are determined, the SPF of the fabrics is calculated by the following equation:

$$\text{SPF} = \frac{\text{MED (protected skin)}}{\text{MED (unprotected skin)}}$$

The main advantage of the *in vivo* test method is acquiring a direct response of human skin to UVR (Menzies et al., 1991). However, this test method is difficult to carry out as a standard test method because of the lack of reproducibility due to the human beings involved as test subjects since humans come in varieties of skin tones. According to Fitzpatrick (1988), skin types range from I-VI (very fair to very dark), and fairer skinned humans are more likely to burn. Therefore, the MED of unprotected skin for fairer skinned people will be lower than that of darker skinned people. Several researchers found that cost, impracticality, and time-consumption were also limitations of this test method (Gambichler et al., 2002; Hoffmann, Kesners et al., 2001; Reinert et al., 1997).

In Vitro Approach

The *in vivo* test method measures SPF by observing the redness of protected and unprotected human skin. Since UVB radiation is the main cause of skin redness, the SPF obtained by the *in vivo* test method can only reflect the protection from UVB radiation. Different from the *in vivo* test method, the *in vitro* test method measures the ultraviolet protection factor (UPF), which shows the protection from both UVA and UVB (Edlich, et al., 2004). The *in vitro* test method has been recommended by many researchers as a practical and inexpensive way for routine measurements (Gambichler et al., 2002; Gies, Roy, Elliot, & Wang, 1994; Gies et al., 1997; Hoffmann, Kesners et al., 2001).

The *in vitro* testing is performed by measuring the amount of UV transmittance of both UVA and UVB radiation that passes through the fabric swatches. Similar to *in vivo* testing, an optical radiation source whose spectrum closely resembles the sunlight spectrum is used, but the UV protection is determined based on effective transmittance in the 280-400 nm wavelength regions instead of determining the MED. In order to obtain the UV transmittance data, a fabric specimen is placed in an instrument equipped with an integrating sphere and, a beam of 280 to 400 nm UVR with 2 or 5 mm intervals is applied to the surface of the specimen. The UV transmittance data is collected based on the amount of UVR transmitted through the fabric, and this data is used to calculate the percentage of transmittance and the UPF (Hatch & Osterwalder, 2006).

The UPF of fabrics is calculated by the following equation (Crews et al., 1999; Gies et al., 1997; Hoffmann, Kesners et al., 2001; Menter & Hatch, 2003):

$$\mathrm{UPF} = \frac{\text{Effective irradiance without fabric}}{\text{Effective irradiance through fabric}} = \frac{\sum_{280nm}^{400nm} \mathrm{E}_\lambda * \mathrm{S}_\lambda * \Delta\lambda}{\sum_{280nm}^{400nm} \mathrm{E}_\lambda * \mathrm{S}_\lambda * \mathrm{T}_\lambda * \Delta\lambda}$$

Where

E_λ = erythemal spectral effectiveness

S_λ = solar spectral irradiance in $Wm^{-2}nm^{-1}$

T_λ = average spectral transmittance of the fabric specimen

$\Delta \lambda$ = measured wavelength interval in nanometers (nm)

λ = wavelength of light in nm

The UPF weighs the UVB radiation more heavily than the UVA radiation because UVB radiation is responsible for more biological damage than UVA radiation (Crews et al., 1999; Gies et al., 1997; Hoffmann, Kesners et al., 2001; Menter & Hatch, 2003). Since UPF is the ratio of average effective UV irradiance calculated for unprotected skin to the average UV irradiance calculated for skin protected by the test fabric, the UPF value indicates how much the test fabric allows the UVR to pass through it. For example, a UPF rating of 15 indicates that the fabric allows only one fifteenth of the UVR to pass through it. The higher the UPF values, the better the UV protection of the fabric. This type of measurement is relatively simple compared to the *in vivo* method because it uses a detector to obtain the UV protection instead of a human test subject, which is used by the *in vivo* method.

The three instruments frequently used in the *in vitro* approach to measure UVR transmittance are (a) radiometric, (b) spectroradiometric, and (c) spectrophotometric, which are discussed in the following sections:

Radiometric. This type of measurement uses a broad band UV light source, which can be either filtered for UVB or include a combination of UVA and UVB bands spectral ranges to measure the total UV transmission through a fabric (Hoffmann, Lapperre et al., 2001). The output readings indicate the total radiant energy passing through the test fabrics and reaching the detector surface. The radiometric method alone does not provide a definitive value for the given fabric's protection factor because this measurement is based on the assumption that transmission is independent of wavelength; however, a fabric's UVR absorption varies with different wavelengths (Capjack, Kerr et al., 1994). According to Gies et al. (1994), this method is only reliable if the light source perfectly matches the solar action spectrum and the detectors respond in a manner similar to human skin.

Spectroradiometric. This measurement method uses spectroradiometeris to measure the fabric UVR spectral transmission. In this instrument, an integrating sphere is used to collect both scattered and transmitted radiation to reproduce the actual exposure situation during solar exposure since the skin is subjected to both the scattered and transmitted UVR which pass through the clothing. The radiation transmission of the fabric at each wavelength is then calculated by taking the ratio of the photocurrent with and without the fabric specimen in position (Gies et al., 1997). Gies et al. indicated that spectroradiometers have several advantages compared to other measurement systems in determining fabric UV protection. With the lower stray light levels that contain a very large dynamic range, a spectroradiometer is able to determine very low levels of UVR that pass though the fabric. Thus, the scan results will be accurate and reproducible if the spectroradiometer and light source are stable. Because regular scans of the radiation source are required to provide reference data, the measurements are time consuming and therefore expensive.

Spectrophotometric. Spectrophotometric, which uses a spectrophotometer, is the most commonly used method today to determine the fabric UV transmittance (Gambichler, Laperre, & Hoffmann, 2006). A spectrophotometer is similar to the spectroradiometer, which uses an integrated sphere attachment behind the fabric specimens to collect both scattered and transmitted radiation through a fabric; however, the scanning speeds of the spectrophotometers are greater than the spectroradiometers. In this method, regular scans of the reference light source are not necessary because most spectrophotometers have both sample and reference beams. For measuring and labeling a textile's UPF, the Australia Standards/New Zealand Standards and European Standards suggest that a UVR transmitting filter for wavelengths of less than 400 nm should be equipped with the spectrophotometer to minimize errors caused by fluorescence from optical brightening agents (Gies et al., 1997). One drawback for this measurement method, according to Gies et al. is that the light source radiation goes into its respective wavelength before reaching the sample, and therefore, the detector measures both the transmission through the fabric as well as any fluorescence emission, if any. If this fluorescence emission is present, it will increase the apparent transmission and thus underestimate the UPF. The spectrophotometer is operated in 5 nm intervals or less in the wavelength range from 290 nm to 400 nm. To determine UPF, a minimum of four textile samples must be measured from a textile material with two in the warp direction and two in the filling direction. The spectral transmittances measurement of the textile from a spectrophotometer can be converted and expressed as UPF (Hoffman et al., 1998).

Test Methods for Textile Ultraviolet Radiation Transmittance

In the U.S., two national standard setting organizations (i.e., AATCC and ASTM) have been involved in developing standard methods for textile UV transmission tests. AATCC developed a testing standard, AATCC 183 – Transmittance or Blocking of Erythemally Weighted Ultraviolet Radiation through Fabric and ASTM developed a standard for preparation of fabric specimens prior to transmittance testing (i.e., ASTM D6544 – Standard Practice for Preparation of Textiles Prior to Ultraviolet Transmission Testing).

AATCC Test Method 183

The AATCC TM 183 – Transmittance or Blacking of Erhythemally Weighted Ultraviolet Radiation through Fabric was published in 1998, and this standard describes a procedure for determining the UVR blocked or transmitted through fabric and the calculation of UPF through *in vitro* measurement (AATCC, 2012). Specimens are conditioned prior to testing in the standard test condition (70 ± 2ºF, 65 ± 2% RH). For each test specimen, three sets of UV transmission data are collected including measurements from the warp direction, filling direction, and at 45° to the warp (i.e., bias direction). The mean of UVA and UVB transmittance (%) values are calculated and then the UPF is calculated.

ASTM D6544

The ASTM D6544 – Standard Practice for Preparation of Textiles Prior to Ultraviolet (UV) Transmission Testing focuses on the procedures for sample and preparation of fabric specimens prior to transmittance testing (ASTM, 2012). The purpose of this standard is to simulate UV radiation that the fabric would encounter during two years of wearing and laundering by consumers. This standard is only for the preparation of fabrics used to construct garments or fabrics taken from already constructed garments. It does not cover the preparation of the fabrics used for shade devices such as tents, baby carrier covers, or umbrellas. In order to accomplish this standard, the test fabrics are required to first undergo 40 laundry cycles based on AATCC Test Method 135 – Dimensional Changes of Fabrics after Home Laundering or AATCC TM 172 – Colorfastness to Powdered Non-Chlorine Bleach in Home Laundering. After 40 launderings, the specimens are exposed to 100 AATCC fading units of simulated sunlight based on AATCC Test Method 16 – Colorfastness to Light for about 20 ± 2 hours, where a xenon-arc lamp is used to simulate the UV radiation. For swimsuit fabrics, the test fabrics are required to be exposed to chlorinated water based on AATCC Test Method 162 – Colorfastness to Water: Chlorinated Pool prior to UV transmission testing.

Standards for Ultraviolet Radiation Protective Textiles

There are several national standards for the determination of the UV protection of textile materials (i.e., AS/NZS 4399, prEN 13758-1, prEN 13758-2, ASTM D6544, ASTM D6603, and AATCC Test Method 183). A commonality among these standards is the *in vitro* test method used to calculate the textile UPF. However, the procedures for obtaining the UPF value for these standards differ from each other in relation to scanning interval, position of the test specimen in the instruments, and the erythemal action spectrum designated (ASTM, 2012; European Committee for Standardization, 1999; Standards Australia/New Zealand, 1996). These standards are used voluntarily by fabric and clothing manufacturers who wish to claim that their product provides UV protection in the consumer market (Hatch, 2005).

Australia/New Zealand Standard

The Australia/New Zealand Standard (AS/NZS) 4399 (Standard Australia/Standard New Zealand, 1996), Sun Protective Clothing – Evaluation and Classification was the first published standard developed by the Australian Standardization Institute in 1996 for evaluating and classifying UV protective clothing (Hatch, 2005). This standard includes: (a) a definition of UV protective clothing; (b) a detailed procedure for determining the UV transmittance of fabric; (c) the formulas required to calculate UPF and percent of blocking from UV transmittance data; and (d) directions for using those UPF or blocking percentage numbers to determine a singular UPF or singular blocking percentage value to appear on a label in the consumer marketplace. AS/NZS 4399 also classifies fabrics in three categories of protection – excellent, very good, and good (see Table 2.1). A fabric must have a UPF of 15 to be classified as UV protective (i.e., qualified for "good protection"). A fabric with a UPF above 20 and below 40 is categorized as "very good protection." A fabric with a UPF of 40 or above is categorized as "excellent protection." The Australian Radiation Protection and Nuclear Safety Agency (ARPANSA) issued a UPF rating hang tag featuring the UPF Certification Trade Mark to fabric and clothing manufacturers who test and label their fabrics according to AS/NZS 4399 (ARPANSA, 2004). However, this standard does not take into account the effects of stretching, wetting, wearing, and using, and thus the design characteristics of the garment that affect the UV protection are not addressed (Gambichler et al., 2006; Hatch; Standards Australia/ Standards New Zealand).

Table 2.1 Australia/New Zealand Standard UPF Ratings and Protection Categories

Protection Category	UPF Range	UPF Ratings	UV Blocked
Excellent Protection	40 to 50+	40, 45, 50, 50+	More than 97.5%
Very Good Protection	25 to 39	25, 30, 35	95.9% to 97.4%
Better Protection	15 to 24	15, 20	93.3% to 95.8%

European Regional Standard

The Europeans also adopted UV protection measures after an increased public awareness of sun protection in the United Kingdom (Gambichler et al., 2006). In Europe, 30 professionals from 11 countries, forming the working group of The European Committee for Standardization in 1999 have developed a new standard on test methods and labeling of UV protective clothing (i.e., EN13758) (European Committee for Standardization, 1999). The EN 13758 Standard consists of two parts. The first part covers the test method for textile materials. It requires that the measurement be taken on new, dry, and relaxed fabric (Thiry, 2002). A minimum of UPF 40 is required in order for a textile to claim it is sun protective clothing because a UPF of 40+ will give efficient protection under normal wearing circumstances, considering the effects of stretching, wetting, and wearing (Gambichler et al). The second part of the standard includes the design requirements for the garments, which stated the upper body must at least cover from the base of the neck down to the hip and across the shoulders, down to three quarters of the upper arm. For clothing that is designed to offer UV protection to the lower body, the garment needs to at least cover from the waist to below the patellae (European Committee for Standardization).

Standard in the United States

The ASTM D6603 – Standard Guide for Labeling of UV-Protective Textiles is the standard document that provides directions for specifying UV protection information on labels attached to garments or the fabric itself (ASTM, 2012). This test method provides a uniform system for labeling the UV-protective textile products. The protection classification and calculation of UPF values are similar to those described in the AS/NZS standard (see Table 2.2). The UPF value of the label indicates the least UV protection value to be expected over the life of the garment (i.e., two-year period).

According to the ASTM D6603, to determine the UPF range and rating or protection category that is placed on the label, the test specimens are first prepared according to ASTM D6544 – Standard Practice for Preparation of Textiles Prior to Ultraviolet Transmission Testing procedures (i.e., the specimens are laundered 40 cycles and then exposed to 100 American Association on Textile Chemists and Colorists (AATCC) Fading Units (AFUs) of simulated sunlight with Water-Cooled Xenon Arc according to AATCC Test Method 16 – Colorfastness to Light), and then the UPF value of the test specimen is measured according to AATCC Test Method 183 (ASTM, 2012). The next step is to obtain the UPF value of the original specimen without any treatment. The last step is to compare the UPF values obtained from the specimen after the process indicated in ASTM D6544 and the value of the untreated specimen. The lower UPF value of these two UPF ratings will be used to determine the UV protection category based on the table below. If a product to be labeled “wash once before wearing” is being tested, the UPF rating is determined by comparing the UPF value from the specimens after the process indicated in ASTM D6544 and the value of the specimen laundered once after it is worn.

Table 2.2 ASTM UPF Range, Ratings and Protection Categories

UPF Range	UPF Rating	Protection Category
< 15	N/A	Cannot be labeled as UV Protective
15 – 24	15, 20	Better Protection
25 – 39	25, 30, 35	Very Good Protection
40 – 50+	40, 45, 50, 50+	Excellent Protection

Factors that Influence Ultraviolet Radiation Transmission

Several research studies have been conducted on the UVR transmission of fabrics since the 1960s, and most of these studies were performed by the Australian researchers because Australia has high levels of ambient UVR compared to European countries and the U.S. (Gies et al, 1994). These studies found various fabric parameters affected the performance and efficiency of UVR transmission (i.e., fiber types, fabric constructions, fabric stretch, fabric wetting, fabric shrinkage, dye and color, and additives).

Effects of Fiber Type on Ultraviolet Radiation Transmission

Pailthorpe (1993) indicated that the effects of fiber type on UVR transmission cannot be treated as one group because each fiber has a different manufacturing process that can significantly influence its properties for absorbing UVR, and therefore, the discussion of the effects of fiber type on UVR transmission is based on each type of fiber. Genkov and Atmažov (1968) were the pioneers who conducted research on the UV transmission of different knit fabrics. They compared the UV transmission from a total of 75 various cotton, nylon, and polyester fabrics with different knitting stitches, thicknesses, and colors, which are all suitable for the making of summer shirts and dresses. The results showed that cotton fabric had lower UVR transmission and provided better protection than nylon and polyester fabrics. Consistently, Welsh and Diffey (1981) compared 100% cotton woven fabrics and 100% nylon and 100% polyester in both woven and knit fabrics, and also found that cotton fabrics offered better protection than nylon and polyester.

Many researchers have continued to explore the influence of fiber type on UVR transmission, but the results differed from the two earlier studies (Genkov & Atmažov, 1968; Welsh & Diffey, 1981). Davis et al. (1997) found that cellulose-based fabrics, such as cotton, linen, and rayon, which are commonly used for summer clothing, had a higher UVR transmission. In contrast, polyester provided excellent UV protection. Hilfiker, Kaufmann, Reinert, and Schmidt (1996), Reinert et al. (1997), and Crews et al. (1999) also included a range of natural and synthetic fibers in their research, and the results were in agreement with the study by Davis et al., which showed that polyester had better UVR protection, especially in blocking UVB radiation because polyester contains phenyl ester groups that have a strong absorption for wavelengths below 310 nm, and UVB ranges from 280 nm to 315 nm (Capjack, Kerr, & Fedosejevs, 2001). These studies also reported that wool fiber had good UV transmittance coverage, but it might not be suitable for summer clothing.

Effects of Fabric Construction on Ultraviolet Radiation Transmission

Numerous studies have examined the influence of fabric construction on UVR transmission and concluded that fabric cover, weight, and thickness were important parameters influencing UVR transmission (Berne & Fischer, 1980, Crews et al., 1999; Hoffmann, Lapperre et al., 2001; Pailthorpe, 1998).

Fabric cover. Fabric cover is probably the most important fabric property that affects UVR transmission (Crews et al., 1999; Hoffmann, Lapperre et al., 2001; Pailthorpe, 1998). Fabric cover can be defined as the percentage of fabric surface covered by the warp and filling yarns in a given fabric (Capjack, Kerr et al., 1994). Different fabric structures have different degrees of fabric cover, and therefore, different fabric structures have different UVR transmissions. In general, woven fabrics usually have higher UVR protection than knit fabrics because the spaces between yarns in a knit fabric are usually larger than that in a woven fabric, and plain weave fabrics have a lower UVR transmission (i.e., higher UVR protection) than other weaves (Capjack, Kerr et al.). Several studies found that when the fabric cover was high, the fabric was more opaque to UVR due to more scattering of the UVR transmission. Gies, Roy, and Elliot (1992) conducted a study to investigate the UVR protection in both occupational and recreational situations. They found that an increased tightness of weave in fabrics led to an increase of UVR protection, although there were no details of the fabric construction discussed. These results were consistent with the study conducted by Hilfiker et al. (1996), who stated that the UPF of a fabric was largely dependent on the fabric cover of the fabric. Another consistent result was in the study of Crews et al., who found that the fabric percentage of UVR transmission decreased when the percent of fabric cover increased. A study by Algaba, Riva and Crews (2004) examined the effects of fabric cover on the UPF of summer fabrics and also found a similar result, indicating that the UPF values significantly increased as the percentage of fabric cover decreased. Crews et al. indicated that the primary determinant of fabric cover is the fabric structure (e.g., woven or knit).

Fabric weight and thickness. Besides fabric cover, fabric weight and thickness are the next useful fabric parameters for explaining the differences of fabrics in UVR transmission (Crews et al., 1999). Since heavy fabrics have more fibers and yarn, the UVR is scattered and does not easily penetrate compared to that of lighter fabrics. Berne and Fischer (1980) and Wong, Cowling, and Parisi (2000) both found that the UVR transmission through the fabric was more closely related to the fabric weight than the structure of the material, and heavier fabrics absorbed or blocked UVR more than lightweight ones. Another consistent result was found in the study by Gies et al. (1994) who analyzed UVR transmission data from over 2000 fabrics in the Australian Radiation Laboratory and concluded that heavier fabrics blocked more UVR than lighter clothing, and significantly lowered the UVR transmission.

Thickness is also a useful parameter for understanding the relationship between fabric construction and UVR transmission (Crews et al., 1999). Sliney, Benton, Cole, Epstein, and Morin (1987) found that thicker fabrics transmitted less UVR than thinner fabrics in their study of 45 fabrics. However, inconsistent with the study of Sliney et al. and Crews et al., Welsh and Diffey (1981) found that fabric UVR transmission was not necessarily related to fabric thickness because some of the thinner fabrics with a higher percentage of cover in their study offered lower UVR transmission than other thicker fabrics. Crews et al. suggested that the percentage of cover is a more important factor than the thickness in explaining the results of UVR transmission.

Effects of Fabric Stretch on Ultraviolet Radiation Transmission

Some researchers examined the effects of fabric stretch on UVR transmission. Sayre and Hughes (1993) examined the UPF of 50 garments and found that a polo shirt was reported as having UPF of 31 in the loose tail section, whereas the shoulder area measured only 8.7. The difference was attributed to the degree to which the swatch was stretched. Another experiment by Gies et al. (1994) also found a significant decrease in UPF with stretch, especially in spandex fabrics, which showed a high magnitude of UPF reduction, from 200 to 20, when under significant tension. This result was consistent with the study conducted by Zhang, Thomas, Wong, and Fleming (1997), which showed that UVR transmission of stretched Lycra was up to 20 times higher than that of un-stretched spandex.

Moon and Pailthorpe (1995) conducted an experiment on different brands of UV-protective elastane (spandex) garments and found that the mean UPF was reduced to approximately 50% of the un-stretched value when the elastin fabric was stretched by 10% in both warp and weft direction. Their results also showed that these UV-protective garments were stretched an average of 15% when they were worn; thus, the UPF label on the garment, which was determined in a relaxed state, was significantly higher than the UPF when the garment was worn. The authors concluded that the UV-protective garments in this study should not be considered as UV-protective clothing.

Some researchers examined the UPF of stretch ladies' stockings. Sinclair and Diffey (1997) found that the most popular type of stocking with 15 deniers provided a UPF of less than two. Kimlin, Parisi and Meldrum (1999) found that the unstretched 50 denier stockings provided the greatest amount of UPF. However, the UPF decreased 868% when it was stretched to 30% of their original size. Consistently, Osterwalder et al. (2000) studied the effects of stretched knitwear and found that the increase of the UVR transmission was almost linear with stretch, which means the higher the degree of stretch the higher the increase of the UVR transmission.

Effects of Fabric Wetting on Ultraviolet Radiation Transmission

Wet fabrics are reported to have a higher UVR transmission than dry fabrics. Hydrated fabrics usually, but not always, have decreased UPF values (Crews & Zhou, 2004; Gambichler et al., 2002; Jevtic, 1990; Pailthorpe, 1994). Jevtic reported the first study on the relationship of moisture content to UVR transmission through the fabric. Both the 60% polyester / 40% cotton T-shirt and the 81% polyester / 19% spandex surf shirt in his study showed a significant decrease of 33% in UPF when wet. The author concluded that the water between the spaces of the fabric causes less scattering of the UV light than does air, resulting in more UVR transmission through the fabric. Gies et al. (1994), however, found inconsistent variations of UPF for wet and dry fabrics, with some UVR transmission decreased when fabrics were wet while others increased with wetness. They concluded that the results depended on the absorbency of the test fabrics. Cotton fabrics were more absorbent and transmitted more UVR when wet, and thus had a corresponding decrease in UPF when wet; however, the polyester/cotton blend fabrics showed less consistent in the variation between dry and wet compared to cotton fabrics. Similar results were found in the study conducted by Zhang et al. (1997), which showed that the cotton samples transmitted more UVR when wet (i.e. 4% UVR transmission when dry and 150% when wet) than polyester, polyester/cotton blends, and nylon/spandex blends when wet. Polyester samples had a 13% UVR transmission when dry which changed to 30% when wet; polyester/cotton samples had a13% UVR transmission when dry which changed to 23% when wet; and nylon/spandex samples had a 14% UVR transmission when dry which changed to 29% when wet. However, when Crews and Zhou investigated the effects of wetness on the UVR transmission of 13 fabrics of five different fiber contents (i.e., rayon, nylon, cotton, silk and polyester), they found that all fabrics showed a significant decrease in UPF when wet, except for the three polyester fabrics, which had a significantly higher UPF rating after being wet.

Gambichler et al. (2002) conducted a detailed study that compared the influence of wetness by tap water and salt water on the UV protection provided by summer fabrics. They used both *in vivo* (i.e. measurement in human subjects) and *in vitro* (i.e. instrumental measure) methods. The researchers discovered that there was no significant difference in the degree of UV protection between using tap water and salt water. Crews and Zhou (2004) examined the UVR transmission of woven fabrics in their dry condition and after wetting with different water types (i.e. distilled water, sea water, and chlorinated pool water), and their results also showed that the water type did not significantly affect the UVR transmission of wet fabrics.

Effects of Fabric Shrinkage on Ultraviolet Radiation Transmission

Most fabrics are subject to both relaxation shrinkage and consolidation shrinkage when laundered, and generally, knit cotton fabrics tend to shrink more than woven cotton fabrics (Hatch & Osterwalder, 2006; Kadolph, 2007). Studies have shown that small amounts of shrinkage could lead to significant improvements in the UPF value (Sliney et al., 1987; Stanford et al., 1995a; 1995b). Sliney et al. was the first researcher to study the effects of laundering on UVR transmission. In their study, 11 fabrics were laundered 10 times, and all these fabrics showed a significant decrease in UVR transmission after 10 launderings. The researchers suggested that the process of laundering led to compaction due to shrinkage, presumably increasing fabric cover and hence resulting in an improvement in UVR protection. The hypothesis proposed by Sliney et al. was confirmed by a laundry trial experiment conducted by Stanford et al. (1995a), who investigated the effects of washing and wearing on the sun protection of a summer-weight garment. However, the authors did not provide a definition for “summer-weight garment.” In their study, 20 jersey-knit cotton T-shirts were worn for four to eight hours per week and laundered weekly for 10 weeks, which resulted in an increase of UPF value. However, the authors indicated that further study was required to determine the effects of washing and wearing for a period longer than 10 weeks because longer periods may cause fabric thinning and lead to an increase of UVR transmittance. To investigate if longer periods of washing and wearing would cause fabric thinning and lead to an increase of UVR transmittance, Stanford et al. (1995b) laundered five cotton jersey-knit T-shirts in another study to determine the effects of prolonged laundering (i.e., 36 washing cycles) on UVR transmission and found that the UPF ratings doubled after the first washing, but did not substantially increase in four of the five shirts in the subsequent 35 washings.

Zhou and Crews (1998) also examined the effect of washing on the UPF rating of 100% cotton fabrics and the results showed that the UPF rating did not double until the fifth washing, which differs from the results of Stanford et al. (1995b). Zhou and Crews suggested that the laundry condition and drying time might contribute to the differences between the two studies. They pointed out that Stanford et al. (1995b) only stated that they used a "color-fast" laundry setting as the laundry condition; however, they did not indicate clearly the exact water temperature setting that they used, whereas a permanent press setting with warm water temperature was used in their study. In addition, Stanford et al. tumble dried their cotton knits for 60 minutes after washing, whereas the cotton fabrics in Zhou and Crew's study were dried for only 30 minutes after each wash. As a result, the laundry condition and drying time in Zhou and Crew's study caused less shrinkage in the samples than in Stanford et al.'s study. Therefore, the UPF ratings doubled after the first wash in Stanford et al.'s study, while the UPF ratings of the samples in Zhou and Crew's study did not double until the fifth wash.

Effects of Dye, Bleach, and Fiber Color on Ultraviolet Radiation Transmission

Many studies showed that the dye, bleach, and fiber color affected the clothing UVR transmission. The details are listed in the sections below.

Dye. The dye used to color fabrics may influence the UVR transmission as most dyes have an absorption spectrum extending in the UV region and dyes also absorb visible light rays selectively to achieve a color. Despite the idea that most consumers consider light-colored fabrics more comfortable for summer wear, several research studies have concluded that dark colors generally provide greater UV protection than light colors (Gies et al., 1998; Kim et al., 2004; Pailthorpe, 1993; Reinert et a1., 1997). Gies et al. (1994) conducted a study on cotton and cotton/polyester blend fabrics of identical weight and construction and found that darker-colored fabrics transmitted less UVR than lighter-colored ones. Similar results were found in the study of Stanford, et al., (1995a), who found that darker shades provided more UV protection. Another consistent result was found in the study of Davis et al. (1997), which showed that blue denim transmitted less UVR than white cotton denim although both fabrics had similar fabric weight and thickness. When Dubrovski and Golob (2009) examined the effects of woven fabric construction and color on UPF, they also found consistent results, where all darker-colored fabrics, (i.e., black, blue and red colored fabrics), showed excellent UV protection for twill and satin weave fabrics**.** The study results of Srinivasan and Gatewood (2000), however, showed that the color of a fabric dye was not a reliable indicator of UVR protection. The authors studied the effects of 14 direct dyes on the UVR transmission of a cotton print cloth. They noted that dyes, even in the same hue such as black or red, could have different degrees of UVR transmission due to their individual absorption characteristics. The researchers provided an example of a fabric dyed using Direct Red 80 that had a lower UPF value compared to the fabric dyed using Direct Red 24 and 28 even though three of them were from the same hue.

Conventional cotton, bleached cotton, and naturally colored cotton. Researchers also compared the UVR transmission of unbleached and bleached cotton fabrics. Pailthorpe (1994) stated that bleached cotton had a higher UVR transmittance than unbleached cotton. In other words, the UPF rating of bleached cotton was lower than the rating of unbleached cotton (i.e., UPF 10 for bleached cotton and UPF 19 for unbleached cotton) because bleaching removes the cotton's natural pigments, such as lints and waxes, which serve as natural UV absorbers, and thus reduces the UPF rating. Crews et al. (1999) found that the UV transmission of bleached cotton print cloth was nearly twice as high as unbleached cotton [i.e., 23.7% of UVR transmission (UPF = 4.5) and 14.4% of UVR transmission (UPF = 7.6), respectively), which has supported the claim of Pailthorpe. Research by Hustvedt and Crews (2005) revealed that NC cottons had excellent sun protection properties (i.e. high UPF values), which are far superior to conventional, bleached, or unbleached cottons. NC cotton is cotton that grows with NC fibers, other than white (Öktem, Gürel, & Akdemir, 2003). In Hustvedt and Crews' study, the researchers compared the effects of light exposure and laundering on the UV protection of conventional, bleached cotton to three NC cotton specimens (i.e., green, brown, and tan). The test specimens were exposed to xenon light and accelerated laundering with and without non-chlorine bleach. After exposure to light for 40 and 80 AFUs, the results showed that conventional, bleached cotton exhibited UPF values of 4, unbleached conventional cotton UPF = 8, brown UPF=40~50+, green UPF=30~50+, and tan UPF=20~45. The researchers explained the isolated compound found in the NC cotton is fluorescent which absorbs UVR radiation, and hence provided superior UV blocking properties.

Effects of Additives on Ultraviolet Radiation Transmission

Since textiles do not always have adequate protection, many methods have been used to improve fabric UV protection, including the use of UV absorbers. During the fiber, yarn, and fabric manufacturing processes, UV absorbers can be added as an additive to improve textile UV protection properties (Gies et al., 1994; Hustvedt & Crews, 2005; Srinivasan & Gatewood, 2000; Xin, Daoud, & Kong, 2004). UV absorbers or UV-absorbing agents are colorless compounds that absorb radiation ranging from 290 nm to 400 nm effectively; and the compound also contributes to the fabric’s brightness and whiteness (Pailthorpe, 1998). UV absorbers are capable of taking in UV radiation, and then converting this electronic excitation energy into thermal energy without undergoing any appreciable irreversible chemical change or inducing any chemical change in the textile molecule (Goyal, 2005). By this way, they prevent the light from being absorbed or transferred through textile fibers.

There are two types of UV absorbers: organic and inorganic. Organic UV absorbers are mainly derivatives of o-hydroxy benzophenones, o-hydroxy phenyl triazines, and o-hydroxy phenyl hydrazines (Achwal, 1995; Malik & Arora, 2003; Reinert, Schmidt, & Hilfiker, 1994). The orthohydroxyl group is considered essential for UV absorption. However, these types of UV absorbers have poor stability and are toxic in nature although it is an active ingredient for sunscreen and plastics (Herzog, Quass, Schmidt, Müller, & Luther, 2004). For instance, when the light is converted to heat in the basal layers of the skin, oxybenzone, which is the active ingredient that is used in sunscreen, damages the growing cells during the UV absorption process (Hayden, 1997). Compared to the existing organic UV absorber, the inorganic UV absorbers are preferable because of their unique features including non-toxicity, chemical stability under both high temperature, and UV-ray exposure (Paul et al., 2010; Yang, Zhu, & Pan, 2004). Inorganic UV absorbers are usually containing semiconductor oxides, such as TiO_2, ZnO, Al_2O_3, and SiO_2.

Among these semiconductor oxides, titanium dioxide (TiO_2) and zinc oxide (ZnO) are commonly used (Parthasarathi & Borkar, 2007).

UV absorbers applied during manufacturing. During the fiber, yarn, and fabric manufacturing UV absorbers can be added as an additive to improve textile UV protection properties (Gies et al., 1994; Hustvedt & Crews, 2005; Srinivasan & Gatewood, 2000; Xin et al., 2004). UV absorbers can be applied into the spinning solution prior to fiber extrusion for manufactured fibers (Achwal, 1995; Haerri, Haerri & Donze, 2001). When manufactured fibers are made, the UV absorbers are added into the solution prepared for fiber extrusion. Fiber extrusion is the process of forcing the solution through the tiny holes of a spinneret to form filament fibers. During the preparation of fabric dyeing for fabrics made of natural fibers, the UV absorbers can be added into the dye bath using padding methods. Padding is a common method to apply a paste or liquor to textiles for dyeing or finishing by passing fabrics through a dye or chemical bath and then through squeeze rollers to squeeze out the excess liquor.

A new area has developed in the area of textile finishing called nano finishing, and this new technology is also used to apply UV absorbers to textiles. Nano technology is defined as the utilization of structures with at least one dimension of nano-meter size for the construction of functional materials, devices, or systems with novel or significantly improved properties due to their nano-size (The National Nanotechnolgy Initiative, 2013). In general, a nano finish is more efficient in absorbing and scattering UV radiation than a normal pigment finish (Vigneshwaran, Kumar, Kathe,Varadarajan, & Prasad, 2006). This occurs because UV absorber particles have a larger surface area per unit mass and volume, and thus leads to an increase in the effectiveness of UV protection compared to bulk materials (Gokarneshan & Jeyathy, 2009; Mankodi & Agarwal, 2011; Yadav et al., 2006).

Various research studies were conducted on the applications of UV protection treatment on fabrics using nano technology (Kathirvelu, D’Souza, & Dhurai, 2009; Mankodi &Agarwal, 2011; Xin et al., 2004; Yadav et al., 2006). Mankodi and Agarwal examined the effect of an application of TiO_2 nano finish onto apparel fabrics. The application of a homogeneous mixture of TiO_2 nanoparticles and acrylic binder had been done at the yarn stage of cotton, cotton/viscose rayon and polyester/cotton, and subsequently these yarns were converted to a garment. The results showed that an increase in absorption of UV light over the investigated UV spectrum (i.e., 290 – 400 nm), and a significant decrease in UV transmittance of TiO_2 treated fabrics compared with the untreated fabrics. Kathirvelu et al. examined the fabric UV protection finishing using ZnO nano particles on four types of fabric (cotton and 45/55 polyester/cotton) with both woven and knit structures. The fabric samples were soaked for 10 minutes in 2-propanol dispersion of ZnO nano-particles, and then dried in an oven for 15 minutes under atmospheric pressure. In order to evaluate the nano-particles adhesion to the textile fibers, the treated samples were laundered 25 times. The results indicated a significant improvement of the UV absorbing activity of the ZnO treated fabrics and the UV protection ratings remained excellent after 25 washes. In another study conducted by Paul et al. (2010) on the UV protection of cotton fabrics by coating with TiO_2 and ZnO nano particles, the results showed that TiO_2 performed much better than the ZnO.

UV absorbers applied post fabric manufacturing. UV absorbers in laundry detergents and rinse cycle fabric softeners have also been developed for consumers to improve UV protection. The UV absorber in laundry detergents or fabric softeners is bound on to the fibers and these effects are accumulated through repeated launderings (Eckhardt & Osterwalder, 1998; Eckhardt & Rohwer, 2000; Schaumann & Rohwer, 2003). Scientists concluded that the UV absorber was superior to the fluorescent whitening agents for increasing the UV protection (Eckhardt & Osterwalder, 1998). Several UV absorbers can be found on the market. For example, Rit ® SunGuard™ from Ciba Specialty Chemicals is a laundry additive that contains TINOSORB®, a colorless UV absorber that exhibits two absorption maxima in the UVA and UVB ranges, resulting in very effective UV blocking properties for cotton fibers (Phoenix Brands LLC, 2005). TINOSORB® FD is used in laundry detergents, while the TINOSORB® FR is used in rinse-cycle fabric softeners.

Rohwer and Eckhardt (1998) applied a UV absorber (TINOSORB® FD) in the wash cycle and the rinse cycle and found that regardless of when the UV absorber was applied, the UV absorber did bind onto the laundered fibers and accumulated during repeated wash and rinse cycles, leading to a significant increase in UPF. According to their study, this UV absorber worked best on cotton and cotton blends. After five wash cycles with the UV absorber, the UPF rating was substantially increased from 17 before washing to 22 after five wash cycles. After 10 wash cycles, the UPF rating increased even more and led to an UPF rating of 30. A similar result was also found in the study conducted by Eckhardt and Osterwalder (1998) who found that repeated laundering caused an accumulation of the UV absorber, and thus, led to an increase in

UV protection. The UPF ratings were increased from 16 before wash to 22 after five washing cycles, and then to 30 after 10 washing cycles. The researchers indicated that this improvement of UV protection could be achieved after five wash cycles, despite the use of a low concentration UV absorber.

Eckhardt and Rohwer (2000) investigated the effects of both optical brightening agents and UV absorbers on the improvement of UVR transmission in cotton fabrics (i.e. two knit cottons and two woven cottons). The fabric specimens were laundered 1, 5, 10, and 20 wash cycles, with and without an optical brightener, and used a detergent with 0.1% and 0.2 % of the UV absorber TINOSORB® FD. The results showed that the UV absorber was superior to the optical brightening agent in the reduction of UVR transmission. The UV absorber, TINOSORB® FD, provided very good (UPF > 15) to excellent (UPF > 40) UV protection with fewer than 10 wash cycles, while the optical brightening agent reached comparable values after 20 washings. Similar results were also found in the study by Wang et al. (2001). The researchers evaluated various treatments (i.e. laundering with water-only, detergent only, and detergent with UV absorber, TINOSORB® FD) on two types of white cotton fabric (i.e. cotton T-shirt and mercerized cotton print cloth). The results showed that the fabrics washed with the UV absorber had significantly higher UPFs than those treated with water and detergent. Kim et al., (2004) also tested the effects of an UV absorber (i.e., Rit® SunGuard™) and an optical brightener (i.e., Rit® Whitener-and-Brightener) on the improvement of UVR transmission. Two types of knit fabric (i.e. 100% cotton jersey and cotton/polyester blend) were laundered, and the results showed that a more rapid achievement of UPF values could be obtained by adding an UV absorber, Rit® SunGuard™, into the laundry water. After only one wash cycle, the UPF values of the specimens were increased to 30 and above. After five wash cycles, an ordinary detergent with optical brightening agents also achieved an improvement in UV protection (i.e., increasing UPF values to 30+).

Perspiration

Perspiration is an important mechanism for the human body in order to maintain heat balance. A human body generally produces water loss at the same rate as heat is produced (Hatch, 1993). When the human body's temperature rises, the perspiration assists in regulating human body temperature by increasing the heat lost, and transforms the sweat that is present on the skin surface into water vapor. By moisture evaporating from the skin into the atmosphere, the human body is cooling down. According to Hatch, about 0.6 kilograms calories of cooling is produced by every gram of sweat at the skin temperature.

There are two forms of perspiration: insensible perspiration and sensible perspiration. Insensible perspiration is a form of perspiration that evaporates within skin layers in the form of emitting moisture vapor unconsciously (Hatch, 1993; Saville, 1999). For sensible perspiration, as the surrounding temperature rises, the human body becomes overheated under these hot or strenuous conditions (Watkins, 1995). High blood pressure causes the hypothalamus to activate the sweat glands where sensible perspiration is produced in the form of liquid sweat on the skin (Watkins).

Artificial Perspiration Composition

Human perspiration is composed of water, urea, lactic acid, amino acids, sugar, alkali sulfates/phosphates, inorganic salts, and uric acids (McSwiney, 1934). According to Vass (1931) and the Perspiration Fastness Subcommittee in AATCC (1952), fresh perspiration is slightly acidic; however, it later turns alkaline due to bacteriological contamination. Testing for damage by perspiration has been difficult in the past because it is almost impossible to collect large amounts of perspiration for use in laboratory research. As a result, artificial perspiration solutions have been developed to simulate the action of normalized perspiration on the textile product being tested.

There are several national standards for the determination of the artificial perspiration tests of textile materials (i.e., AATCC Test Method 15, ASTM D2322, Japanese industrial standard – JIS L0888, and ISO test method – ISO 105-E04, Canadian CGSB4-GP-2 Method 23). According to Sievenpiper (1974), the initial perspiration test developed by AATCC was involved with one acid based on lactic acid and one alkaline based on ammonium carbonate. However, the alkaline solution was questioned by some researchers (Gobeil & Mueller, 1974). Furthermore, alkaline perspiration can only be found in people suffering from certain diseases or under conditions of extremely poor personal hygiene (Barail, 1946). For this reason, Gobeil and Mueller conducted a study to examine the effects of acid and alkaline in artificial perspiration by evaluating colorfastness to perspiration in both laboratory and actual wear tests. Ten fabrics (i.e., three 100% wool in color green, red, and maroon; a 100% wool crepe in color green; a 65% wool with nylon and acrylic blend; two 100% acetate tricot in color red and navy; and two 100% nylon tricot in color red and black) were used in the investigation, and the fabrics were later made into T-shirts for 30 wearers. For the actual wear test, the T-shirts were worn for two consecutive days in the hottest areas and returned unwashed to researchers. For the laboratory test, the test fabrics were processed according to AATCC Test Method 15. Both test specimens were evaluated for staining and shade changes. The results showed no significant differences in staining or color changes under acidic conditions for both the laboratory and actual wear tests. The results showed consistent results in the acidic phase between laboratory and actual wear tests, indicating that the acidic phase of perspiration successfully simulates actual sweat and can be used to examine the effects of perspiration on fabric color change. However, all wool fabrics (i.e., 100% wool and wool blend fabrics) under the alkaline laboratory method showed more severe staining than those in actual wear tests, and all acetate fabrics showed less severe staining in the alkaline laboratory method than the actual wear tests although all nylon fabrics showed consistent results in both laboratory and actual wear tests. Since the alkaline phase did not provide reliability on the staining due to perspiration, the portion of alkaline in artificial perspiration was removed. Table 2.3 shows the components for the current AATCC Test Method 15 used in the artificial perspiration solution.

Table 2.3 Components of AATCC Standard artificial perspiration

Component	Concentration (g/L)
ℓ-Histidine Mono Hydrochloride ($C_6H_9N_3O_2 \cdot HCl \cdot H_2O$)	0.25
Lactic acid, USP 85%	1.00
Disodium hydrogen phosphate (Na_2HPO_4)	1.00
Sodium chloride (NaCl)	10.00

Effects of Perspiration on Color Change of Conventional and Naturally Colored Cotton

During the summer, human perspiration will occur more frequently due to hot temperatures and increased physical activity. The process of perspiration from the human body is complex. Fresh perspiration is always acidic, but may change into an alkaline due to bacterial contamination (Saville, 1999). Therefore, perspiration can stain, discolor, or deteriorate some of the fabrics of the garment, especially in the underarm area (Lyle, 1977). Thus, resistance to perspiration is an important factor, especially in summer clothes.

The studies on the effects of perspiration have been focused on fabric durability (Bhat, Benjamin, Buch, Wani, & Dharmadhikari, 1989; Bhat, Dharmadhikari, Wani, & Kulkarni, 1990), dyes, and colors (Bhat et al., 1990; Bredereck & Schumacher, 1993; Srivastava, 1992). According to the studies reviewed in the section of "*Effects of Dye, Bleach and Fiber Color on Ultraviolet Radiation Transmission,*" colors are relevant to fabric UV protection. Therefore, studies related to color change were reviewed to examine if perspiration has a significant effect on fabric colors. If perspiration does cause damage to textile colors, perspiration may affect fabric UV protection. These studies are discussed in the following two sections: effects of perspiration on color change of conventional cotton and the effects of perspiration on color change of NC cotton.

Effects of Perspiration on Color Change of Conventional Cotton

Fabric color fading and alteration can be caused by the constituents of human perspiration (Lyle, 1977). Bhat et al. (1990) investigated the effects of perspiration on the fine structure of cotton cellulose. An unbleached cotton cloth with a fabric count of 87 x 58 and synthetic perspiration were used in this study. Two groups of test specimens were subjected to repeated treatments in the perspiration solution for one group with a cycle of five-hours and another group with a cycle of 18 hours. After a cycle of treatment, the test specimens were removed from the perspiration solution, washed in distilled water, and dried before being subjected to the next cycles. The processes were repeated for a total of 640 hours. The results of both groups showed that yellowing increased with an increase in treatment time, and specimens treated for the five-hour cycles showed a larger color difference in ΔE[2]. The yellowing in the fabrics in the 18-hour cycle group was less severe than the yellowing in the 5-hour cycle group. The researchers explained that they found a marginal increase of pH of the artificial perspiration from 3.5 to slightly 3.7 in the treatment group of 18 hours, while the pH of the solution in treatment group of five hours remained unchanged (i.e., 3.5). The increase of pH values will

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[2] The overall color difference between two samples measured by the CIELAB Color System is called Delta E (ΔE). In this color system, each color is computed by measuring the three dimensions (i.e., L, a, and b) of the color space. L is the lightness-darkness dimension*)*; *a* is the redness-greenness dimension; and *b* is the yellowness-blueness dimension. ΔE is calculated by the formula: $\Delta \mathrm{E} = \sqrt{(\Delta \mathrm{L})^2 + (\Delta a)^2 + (\Delta b)^2}$

cause a reduction of acid in the solution. As a result, the perspiration has less of an effect in the fabric in the treatment group of 18 hours, and thus, the yellowing is less than the treatment group of five hours. Similar results were found in the study conducted by Srivastava (1992), who examined the colorfastness to perspiration in 10 types of fabrics (i.e., cotton, polyester/cotton blends, rayon, silk, wool/nylon blends, and wool/polyester blends in plain or twill weaves). In this study, the test specimens were placed in the under-arm portion of dresses and in shoes for 12, 24, and 36 hours. The results showed a positive correlation between time of exposure to perspiration and colorfastness. Polyester/cotton and wool/nylon blends had better colorfastness, while cotton, rayon, and silk were the most susceptible to color loss. The researcher explained that fiber's absorbency was the main reason for variation of colorfastness with different fiber contents.

Effects of Perspiration on Color Change of Naturally Colored Cotton

Several studies examined the effects of perspiration on NC cottons. Wimberley and Roper (1997) examined the effects of perspiration on color transfer and color change of four woven and five knitted NC fabrics of various colors (e.g., beige, brown, brown-green) and mixed colors (e.g., mixing light beige, green and brown colors). To determine if the color of the NC cotton would transfer or stain another fiber, each specimen was assembled with a multi-fiber stripe (i.e., a strip contains narrow fiber stripes made of different fiber contents) according to the AATCC Test Method 15 – Colorfastness to Perspiration. The specimens were soaked in the artificial perspiration solution for 30 minutes. Color transfer and color change were measured instrumentally in CIELab readings and visually in AATCC Gray Scale readings. The results showed that no color transfer occurred for all test fabrics because the fabric coloration was a genetic component. However, all fabrics did undergo color change according to the CIELab reading. The researchers did not report the findings from the Gray Scale reading. For the woven fabrics, two fabrics with a single color (i.e., beige and brown) showed greater color changes (i.e., $\Delta E = 7.07$ for beige color and 6.95 for brown) than the other two fabrics with mixed colors (i.e., ΔE ranged from 0.9 to 1.2). Both beige and brown NC cottons had greater lightness change (i.e., $\Delta L = 7.0$ for beige color and 5.0 for brown; positive number indicates that the color becomes lighter.) than the other two fabrics with mixed colors (i.e., $\Delta L = -0.1$ and -1.0; negative sign indicates that the color becomes darker.). The results showed that both beige and brown NC cottons became lighter after being soaked in the artificial perspiration solution for 30 minutes. The brown woven fabric also showed changes in hues ($\Delta a = 2.0$, $\Delta b = 3.8$). However, the beige woven fabric showed almost no changes ($\Delta a = 0.1$, $\Delta b = 0.5$) in hues.

Among the five knit fabrics, (i.e., two brown, two light brown, and one green), one brown knit fabric had the greatest color changes (i.e., $\Delta E = 5.3$). Both lightness and hue had some changes ($\Delta L = -3.2$, $\Delta a = 2.0$, $\Delta b = 3.8$). Another brown knit fabric had a similar degree of color change as the green knit fabrics (i.e., $\Delta E = 3.2$ and 2.9, respectively). Different from the woven fabrics, the two brown knit fabrics became darker instead of lighter ($\Delta L = -3.5$ and -2.8). The green knit fabric, however, became lighter (i.e., $\Delta L = 2.0$). In terms of the two light brown fabrics, they showed only small color changes (i.e., $\Delta E = 1.3$ and 1.9).

Öktem et al. (2003) investigated the colorfastness to perspiration of six types of NC cotton fibers (i.e., one light brown, three dark brown, and two green colored fibers) and they found a different result from Wimberley and Roper (1997). The researchers used a HunterLab ColorQuest II spectrophotometer to measure the color change according to ISO 105-E04 – Colorfastness to Perspiration (Acid and Alkaline). The results showed that all fibers had a color change rating of a step 4-5 (i.e., slight color change). However, the artificial perspiration solutions used in the two studies were different. The artificial perspiration solution in ISO standard contains both acid and alkaline while the AATCC one only contains acid.

Weather Exposures

Most textiles, during normal use, are exposed to sunlight, rain, humidity, and various temperatures, and these environmental factors have a degradation effect on fabric properties, including durability and colorfastness. The term “weathering” refers to exposure to climate conditions (Collier & Epps, 1999). Sunlight (especially the UV rays), high temperature, and moisture (in the form of rain, dew, and high humidity) are the main weathering forces responsible for textile degradation (Wall & Frank, 1971). Degradation of textiles from weathering involves both chemical and physical changes. The chemical deterioration, caused by sunlight and moisture, may change the water, air, and moisture vapor permeability as well as the flammability of the textile; while the physical deterioration, caused by wind, dust abrasion, and the alternate freezing and thawing, may change its tensile strength, stiffness, or elasticity and cause color fading and yellowing (Collier & Epps, 1999; Howard & McCord, 1960; Slater, 1986).

Assessing the Weather Resistance of Textiles

The weather resistance of textile products refers to its ability to resist degradation of its properties when exposed to real or simulated climatic conditions (Kadolph, 2007). Several standard test methods are used to evaluate the weather resistance of textiles. The tests can be classified as either natural weathering testing or accelerated laboratory testing.

Natural Weathering Testing

The most realistic way to test the weather resistance of a textile product is to expose it to natural weather conditions (i.e., outdoor exposure) or to natural sunlight behind glass (i.e., indoor exposure). Florida and Arizona have long been benchmarks for real-time, outdoor exposure testing due to their extreme climates that accelerate the degradation of materials (Lucas, 2001). For instance, Florida is known for high density sunlight, high annual UVR, high humidity, and high temperatures, which together produce a subtropical environment; while Arizona has high levels of UVR, high temperatures, and extreme dryness that combine to produce a semi-arid environment (Lucas; Marques, 2002). The instability of weather makes outdoor degradation exposure difficult to perform precisely. For instance, solar radiation is not available during the night time. Seasonal and climatic conditions also affect natural sunlight, and thus affect the textile degradation. In addition, factors such as humidity, rain, wind, and time of day are subjected to daily, seasonal, and geographical variations. Consequently, all these factors have caused the natural weathering exposure tests to be very time consuming, which cannot be easily adapted to the analysis of individual variables (Hawkins, 1984).

The AATCC Test Method 111 – Weather Resistance of Textiles: Exposure to Daylight and Weather, is the only test method that measures the natural outdoor weather resistance of textiles (AATCC, 2012). Two test options have been offered by this test method. Option A is direct exposure to natural light and weather, and Option B is exposure to natural sunlight, indoor, behind glass where wetting is not a factor. In either case, fabric specimens are mounted on the exposure rack that is placed in an exposure cabinet. In Option A, the cabinet is exposed, which allows wetting by natural rainfall; while in Option B, the cabinet is covered by glass to protect against wetting by natural rainfall. The exposure can be timed for calendar days, months, or years depending on the end-use of the fabrics to be exposed. Following the exposure, the weather resistance of the fabrics is then determined by comparing the exposed portion of the test specimens to an unexposed counterpart related to selected physical properties such as tensile strength or colorfastness.

Accelerated Laboratory Testing

Due to the difficulty of controlling natural weather conditions and the time consuming nature of the natural weathering test, accelerated weathering tests were developed. The advantages of having a laboratory accelerated test include: the use of controlled test conditions, which leads to better reproducibility and repeatability of exposure results, cost effectiveness, and possible estimation of exposure time (Lucas, 2001). The testers may also be equipped with a water spray mechanism to stimulate wet conditions (i.e., rain) during testing. One major disadvantage of accelerated weathering is none of the instrumental methods can precisely reproduce the sunlight (Collier & Epps, 1999). These types of accelerated weathering tests generally employ a variety of light sources, which produce different UV spectra to simulate sunlight. Three types of illumination light sources have been widely used to study the weathering effects of textiles that are the carbon arc lamp, xenon lamp, and fluorescent UV lamp (Lucas).

Carbon arc testers. The first carbon arc tester, also called fadeometer, was introduced in 1918. With this tester, a pair of carbon rods was used to produce light, and test samples are mounted vertically on a carousel that revolves around the rods (Lucas, 2001). This carbon arc fadeometer is not widely used due to the deficiency of short UV wavelength (such as UVB) that it produces. The short UV wavelength contains more harmful radiation that mainly produces melanin in the skin. Because of this reason, the lack of UVB creates a milder effect on products damaged. Consequently, this type of tester is often criticized for its lack of reproducible and realistic results, and thus the carbon arc fadeometer is generally considered outdated (Lucas).

A later version of the instrument is the open flame or sunshine carbon arc weatherometer, which was introduced in 1930 as an improvement of the carbon arc fadeometer (Lucas, 2001). The main difference between the fadeometer and the weatherometer are in their light source. The carbon arc fadeometer uses an enclosed carbon arc light source whereas the sunshine carbon arc weatherometer uses a sunshine carbon arc light source. The weatherometer instrument also has a water spray option to simulate rain and dry conditions, while the fadeometer can only simulate dry conditions (Collier & Epps, 1999). Different from the enclosed carbon arc light source, the sunshine carbon arc weatherometer produces an extremely short wave of UV light (<300 nm), which represents an overly severe and unnatural condition. This instrument provides a function when researchers intentionally expose test specimens to spectral energies beyond the limits of their intended service exposures although these unrealistic conditions do not correlate with actual outdoor exposures (Lucas). Although carbon arc instruments continue to be used in the American Society for Testing and Materials (ASTM) standard test method (2012), the reproducibility of the test is often limited due to the aging of the filters, resulting in variability in output (Collier & Epps).

The AATCC Test Method 192 – Weather Resistance of Textiles: Sunshine-Arc Lamp Exposure with and without Wetting provides two options to evaluate weather resistance of textile (i.e., Option A: Sunshine-Arc Lamp Exposure with Wetting, and Option B: Sunshine-Arc Lamp Exposure without Wetting) (AATCC, 2012). The main purpose of Option A is to evaluate the weather resistance of a fabric or related material, including coated fabrics when subjected to artificial weathering using light and wetting. The purpose of Option B is to evaluate the weather resistance of a fabric when subject to weathering and sunlight exposure conditions where wetting is not a factor. In both options, the fabric specimens are mounted on the specimen rack and exposed to the radiance source. Assessment of the resistance of degradation is evaluated as percent of strength loss and colorfastness.

Xenon arc testers. The xenon arc tester was introduced in the 1950s, and it provides the most realistic simulation of full spectrum light in the same way the sun does, which includes UV, visible light, and infrared wavelength. Therefore, it can provide very accurate and realistic testing data. In this instrument, different types of filters can be used to simulate different conditions, such as full spectrum sunlight or filtered sunlight (i.e., indoor exposures) (Lucas, 2001). The tester can also be equipped with a water spray mechanism to simulate rain conditions (Lucas; Marques, 2002). Because full spectrum testing is particularly useful for testing colorfastness, the xenon arc testers are more widely used than the carbon arc testers (Collier & Epps, 1999). The major drawback of xenon arc instruments is that they are more costly than other weathering testers or natural outdoor testing (Lucas; Marques).

Researchers had found that the results of the experiments using xenon arc testers had a good correlation with natural weathering tests (Ranby & Rabek, 1975). Norton, Stone, Ofjord and Hemphill (1975) and Stone, Hardegree, Norton and Smith (1977) examined the correlation between accelerated weathering tests and the natural weathering tests. They found that machine weather exposures in xenon arc testers more closely simulated subtropical weathering conditions (e.g., the climate of Florida) than exposures in carbon arc testers.

In the AATCC Test Method 169 – Weather Resistance of Textiles: Xenon Lamp Exposure, specimens are exposed to conditions specified as humidity, irradiance level, chamber air temperature, and black panel temperature (AATCC, 2012). The test method includes four different test cycle options that specify different climate conditions in terms of the timing of cycles of light and dark (i.e., turning the light on and off to imitate day and night), water spray, temperature, and relative humidity. Option 1 and Option 2 cycles simulate the semi-tropical climate found in South Florida but with differences in timing of the light and dark cycle, and with and without water spray (see Table 2.4). Option 3 simulates the semi-arid climate found in Phoenix, Arizona. In this option, the specimen is exposed to a continuous light cycle and a no-water-spray climate condition. Option 4 simulates a temperate climate likes that of Columbus, Ohio, with a different timing for light and dark, low relative humidity, and low black panel temperature. In all cases, fabric specimens are mounted on the exposure rack, placed into the xenon arc testers, and exposed to the selected conditions. The specimens are exposed for a minimum time cycle of seven days. Upon completion, the specimens are removed from the exposure rack, conditioned (i.e., bringing the test specimens to moisture equilibrium in an environment controlled at 21 ± 1°C (70 ± 2°F) and 65 ± 2% RH as recommended by ASTM D 1776, Standard Practice for Conditioning and Testing Textiles), and evaluated for the rate of weather degradation by either percent loss in strength and/or colorfastness.

Table 2.4 Climate Exposure Procedure in Four Test Cycle Options

Climate Condition	Cycle duration	Light Duration per cycle	Relative Humidity (RH)	Water Spray	Black panel / Black Standard Thermometer temperature
Option 1 (Florida)	120 min	90 min light	70 ± 5%	Alternating with 30 min light and water spray	77 ± 3 °C (170 ± 5 °F)
Option 2 (Florida)	120 min	60 min light 60 min dark	70 ± 5%	No water spray	77 ± 3 °C (170 ± 5 °F)
Option 3 (Arizona)	120 min	Continuous light	27 ± 5%	No water spray	77 ± 3 °C (170 ± 5 °F)
Option 4 (Ohio)	120 min	102 min light 18 min dark	50 ± 5%	Alternating with 18 min light and water spray	63 ± 3 °C (145 ± 5 °F)

Fluorescent UV testers. Fluorescent UV testers use fluorescent lamps that are similar to the lamps used in general lighting, but they only reproduce the UV portion of the spectrum. This approach is very effective since UVR causes almost all of the sunlight damage to textile products that are typically used outdoors, such as tents and awnings (Lucas, 2001; Marques, 2002; Roberts, 1999). Fluorescent UV testers also simulate the effects of outdoor moisture through a condensation mechanism. In general, studies on outdoor materials have shown that the condensation of dew caused more wetness than rain does. Because fluorescent UV testers offer the best simulation of UV wavelength and are less expensive compared to carbon arc and xenon arc testers, fluorescent UV testers are very useful for testing the physical degradation of textiles, such as tensile strength and elasticity (Lucas). Since the spectrum distribution of fluorescent UV testers does not extend into the visible range, these testers are not as useful as the xenon arc tester for evaluating material colorfastness and fading, which often occurs due to exposure to longer wavelength light.

In the AATCC Test Method 186 – Weather Resistance: UV Light and Moisture Exposure", fluorescent UV lamps are used as a light source and condensing humidity and/or water spray are used for wetting (AATCC, 2012). Three test cycle options are offered by this test method (i.e., Option 1: General Applications, Option 2: Thermal Shock Applications, and Option 3: Automotive Exterior). Option 1 is mainly used for testing outdoor materials, such as tent and outdoor furniture fabrics. Option 2 has been widely used for architectural and other applications where thermal shock (i.e., sudden change in temperature) may be an issue. Option 3 is used for testing automotive exterior materials. This test is performed similarly to the AATCC Test Method 192, where the specimens are mounted on the special racks with the test surfaces facing the lamp. The resistance of the degradation will be reported as either percent loss in strength and/or colorfastness.

Effects of Weathering Exposures on Color Change of Conventional and Naturally Colored Cotton

All apparel products are subjected to the influence of weathering (Howard & McCord, 1960). Overexposure to weathering affects the fabric's strength and colors. Other fabric properties, such as abrasion resistance, can also be compromised by weathering (Collier & Epps, 1999). Several studies examined the effects of weathering exposure on fabric strength (Barnett & Slater, 1991; Little & Parsons, 1967), abrasion resistance (Barnett & Slater), and colors (Grimes, 1933). According to the studies reviewed in the section of "*Effects of Dye, Bleach and Fiber Color on Ultraviolet Radiation Transmission,*" colors are relevant to fabric UV protection. Therefore, studies related to color change were reviewed to examine if weathering exposure has a significant effect on colors. If weathering exposure does cause damage to fabric colors, weathering exposure may affect fabric UV protection. These studies are discussed in the following two sections: effects of weathering exposure on color change of conventional cotton and the effects of weathering exposure on color change of NC cotton.

Effects of Weathering Exposure on Conventional Cotton

Conventional cotton fabrics usually oxidize from prolonged exposure to sunlight, especially UV light, which causes white and pastel color cottons to yellow (Kadolph, 2010). Yellowing is one of the degradations that occur from exposure to weathering, especially from the light of a wavelength shorter than 380 nm (Grimes, 1933). A few studies have examined the effect of weathering on fabric yellowing. Morris (1966) studied the effects of weathering on cotton fabrics and found that fabric samples exposed to sunlight during the summer months, especially June, in California, Nevada, New Mexico, and Oregon resulted in greater yellowing than in other seasons.

Effects of Weathering Exposure on Naturally Colored Cotton

A study was found that examined the effects of weathering on NC cotton. Evenson and Epps (1999) investigated how the instrumental weathering influenced the colorfastness of three naturally NC fabrics (i.e., brown, green, and white). The researchers used a water-cooled xenon-arc weatherometer to simulate outdoor weathering. The test specimens were exposed to a continuous light cycle, with two different humidity levels (i.e., 30% Relative Humidity (RH) and 90% RH) for durations of 20, 40, 60, and 80 hours. Spectral reflectance and CIELAB color measurements were taken before and after exposure. The results showed that all test specimens became increasingly lighter as the exposure duration increased, and all test specimens showed more color change after exposure to light at a high humidity rather than at a low humidity. The green fabrics showed the greatest color change at both humidity levels (mean ΔE values of 5.1 at low humidity and 8.7 at high humidity), while the brown had the least overall color change (i.e., mean ΔE values of 3.34 at low humidity; the researchers did not report the rating of brown cotton at high humidity, and they did not indicate at which hours of exposure these ratings occurred).

Two other studies also examined the color change of NC cotton (Hustvedt & Crews, 2005; Jahagirdar, Srivastava, & Venkatakrishnan, 2000). However, they only examined the effects of light on color change, while other weathering factors (such as rain and temperature) were not put into consideration. In a study that examined color change in lightness (i.e., color becomes lighter or darker) due to light exposure of 11 NC cottons (i.e., two green cottons and nine brown cottons), Jahagirdar et al. exposed the specimens to light from 400 watt mercury vapor filament phosphor coated fluorescent lamps for 500 hours. The researchers found that all nine brown cottons showed no significant change after being exposed to light for up to 250 hours. The change of lightness (ΔL) in the nine brown colored cottons ranged from 0.18 to 1.24 after 250 hours of exposure. However, after 250 hours and up to 400 hours of exposure, the lightness of these brown colored cottons all became gradually lighter (i.e., ΔL ranged from 2.99 to 10.52). After 400 hours of exposure, the color stayed constant with no further significant change in lightness. Hustvedt and Crews also investigated the color change of green, brown, and tan NC cotton following light exposure. The specimens were exposed to lights of 40 and 80 AFUs according to AATCC test method 16. The results showed that the majority of the degree of color change in the NC cotton occurred during the 40 AFUs of light exposure, and no significant difference was found in color change between 40 and 80 AFUs for all NC cottons. After 40 AFUS, the color difference (ΔE) for green NC cotton changed from 2.1 with no exposure to 7.1; for tan cotton it changed from 0.2 to 7.4; for brown cotton it changed from 0.2 to 4.5. After 80 AFUs, the color difference increased only slightly more with no statistical significance. Among the green, brown, and tan color cotton, the green color changed color the most, followed by tan and lastly brown. The research explained that the color change indicated that some damage occurred to the chromophores (i.e., molecules that absorb light resulting in the coloration).

Washing Action of Automatic Home Clothes Washers

The automatic home clothes washer was introduced to the United States (U.S.) market in the 1930s, and only three manufacturing companies had models on the market and in homes before 1941 (Association of Home Appliance Manufacturers, 2008). The automatic home clothes washer machine allows the washing of clothes by filling the machine with water, washing the clothes, rinsing the clothes, and automatically spinning the clothes to a damp-dry state (Wilson, 1976). Now, many companies are producing automatic clothes washers, and there are over 80 million washers in U.S. homes. For the past three decades, the traditional top-loading vertical axis washer has been dominating the U.S. market. Because large amounts of water and energy are used with each load of clothing being washed and dried in these traditional machines, there has been an increased concern for water and energy conservation in the area of the home laundry process (Kadolph, 2010). Consequently, the high-efficiency (HE) washer, which operates with a lower consumption of electric power and water as well as labeled as an Energy Star appliance, was reintroduced into the market in 1997 (“New Generation,” 1997). The Energy Star label is a voluntary program that the Environmental Protection Agency (EPA) and the Department of Energy (DOE) created in 1992 to help consumers save energy and money by identifying energy-efficient products and services (Energy Star, 2013).

Types of Clothes Washers

In this section, the two main types of washers found in the U.S. (i.e., the traditional vertical axis washer and the HE washer) are discussed in the first and second subsections. The comparison of these two types of washers is discussed in the last section.

Traditional Vertical Axis Washers

From the 1930s, until recently, most clothes washers sold in the U.S. were traditional vertical axis washers (Association of Home Appliance Manufacturers, 2008). A 2010 Association of Home Appliance Manufacturers survey of 8082 households also showed that traditional washers were the most commonly owned (70%). Most U.S. consumers prefer a top-loading washer because it does not require bending to load the machine (Clothes Care Research Center, 2007). They are also sold for a more reasonable price and the total washing time is shorter compared to HE washers ("Washer & Dryer," 2012). However, the traditional washer uses more water as well as energy, which is used to heat the water to the appropriate temperatures ("New Generation," 1997).

Traditional washers have a vertically-mounted tub that contains an agitator in the center of the drum (Collier et al., 2009). During the laundry cycle, the tub will fill with water and the agitator will rotate, alternating between a clockwise and counterclockwise motion to clean the clothes. The traditional top-loading washers use approximately 40 gallons of water per load, which allows the clothes to easily float and move in the detergent solution (Tomlinson & Rizy, 1998).

Ross, Taube, and Greene (1954) used three types of washers (i.e., automatic, semi-automatic, and non-automatic) found on the market at that time, to study the effects of four different types of washing actions (i.e., cylinder, agitator, agitating basket, and modified agitator) on the breaking strength and soil removal of three lingerie fabrics (i.e., acetate-rayon satin, acetate-rayon crepe, and nylon crepe) after 50 washing cycles. The findings showed that these washers were not significantly different in fabric strength and soil removal, and no one type was greatly superior to the other.

High-efficiency (HE) Automatic Clothes Washers

Since 1992, as the result of the U.S. Department of Energy's (USDOE) effort to enact a set of standards to increase appliance energy-efficiency and water-efficiency, the HE clothes washers were brought back into the market and received the Energy Star label ("New Generation," 1997). Although their growth has been slow, the HE clothes washer has gradually become more popular with U.S. consumers due to increased energy and water savings (Association of Home Appliance Manufacturers, 2008). The one major drawback of HE washers is that they generally cost more than traditional washers, although HE washers may save money in the long run because of the savings of water, energy, and detergent. A survey conducted by Bellomy Research (2010) showed that HE washers were owned by 30% of the households in the U.S., while traditional washers made up the remaining 70%.

There are two types of HE washers in the U.S. market (i.e., the front-loading HE washer and the top-loading HE washer). Despite their differences in mechanical methods, they both use significantly less water and energy than the traditional washers. Because HE washers use less water than traditional washers, detergents specifically designed for HE washers were introduced (The Soap and Detergent Association (SDA), 2008). Traditional detergents are formulated for the high water volumes used in traditional top-loading washers to remove stains and soils. HE detergents are formulated not only to remove stains and soils, but also to be low-sudsing and quick-dispersing because over-sudsing may cause problems in the HE washer washing process. The HE washer's tumble action usually creates more suds than a traditional agitator action, due to the interaction of the tumbling water and detergent (AATCC, 2012). The amount of water used by HE washers does not sufficiently dilute the higher sudsing action of traditional detergent, thus, leaving more soap residue in the clothes which impacts proper cleaning.

Front-loading high-efficiency (HE) clothes washers. The market research survey conducted by Bellomy Research (2010) indicated that approximately 21% of the U.S. households with a clothes washer in the house reported having a front-loading HE washer**.** In contrast to traditional washers, front-loading HE washers use a tumbling action similar to a dryer, tumbling items back and forth through a small amount of water (Association of Home Appliance Manufacturers, 2008). By rotating the tub clockwise and then counterclockwise, the motion flexes the weave of the fabrics and forces water and detergent through each garment, removing soils. Since front-loading HE washers hold water only in the bottom of the tub to moisten the fabric (typically only one-third full of water), less water is required (Tomlinson & Rizy, 1998). If garments are washed in either hot or warm water, using less water means that less energy is needed to heat the water ("New Generation," 1997). Another energy saving benefit is the shorter drying time. Since front-loading HE washers have a significantly faster spin speed than traditional top-loading washers, the water can be extracted more effectively. With less water remaining in the fabrics, less energy is needed to dry laundry after washing ("New Generation"). The other advantage of using a front-loading HE washer is that it requires less detergent since less water is required for the laundry process. The SDA (2008) claims that the tumbling motion used in the HE washer treats clothing more gently and also provides efficient cleaning and rinsing. However, SDA did not indicate any studies to support this claim.

Top-loading high-efficiency (HE) clothes washers. Similar to the front-loading HE washers, top-loading HE washers also offer gentle cleaning action (AATCC, 2012). Instead of cleaning the clothes by rotating the tub clockwise and counterclockwise as in the front-loading HE washers, the top-loading HE washers use a smaller-sized impeller shaped wash-plate (i.e., a low-post agitator) or an impeller with no agitator to clean clothes. The wash-plate or impeller in the bottom of the tub uses a wobbling motion to shake, bounce, and toss the laundry around. With this type of washing action, the clothes are moved through the water against each other to loosen and lift dirt and stains rather than just simple agitation as in traditional washers. Similar to the front-loading HE washers, top-loading HE washers also spin at a very high speed, and thus, reduce drying time and energy consumption ("Washers & Dryer," 2007). The costs of top-loading HE washers and front-loading HE washers are also similar ("Washers & Dryer," 2006). However, compared to the front-loading HE washers, top-loading HE washers are less energy and water-efficient, but they use less water than traditional washers ("Washers & Dryer," 2007). These types of top-loading HE washers comprise only 10% of the HE washer market (AATCC, 2012).

Comparisons of Traditional and HE Washers

In general, front-loading HE machines can reduce water usage by 30% and energy usage by 50% compared to traditional top-loading washers (Kadolph, 2010). Tomlinson and Rizy (1998) conducted a study in comparing the water consumption and energy efficiency of traditional top-loading and front-loading HE washers. One hundred and four participants, who were comprised of households and professional cleaners, were involved in this five-month study. The study was divided into two phases. In Phase I, participants used their traditional top-loading washers to wash their laundry for two months. In Phase II, participants replaced their washers with the front-loading HE washers to wash their laundry for three months. Both water and energy consumptions of the two phases were recorded by the participants after each load. Load dampness, detergent use and consumption, and satisfaction with cleaning performance were also measured. After a visual inspection of the washed clothes, participants rated their satisfaction of the cleaning performance on a scale from "completely satisfied" to "not at all satisfied." The researchers found that the front-loading HE washers produced better energy and water savings than the traditional top-loading washers. A higher percentage of "completely satisfied" ratings were also recorded when participants used the front-loading HE washers to wash their laundry.

Effects of Washing Action on Color Change and Dimensional Change of Conventional and Naturally Colored Cotton

The effects of washing action on clothes washers has been studied in various areas, such as colorfastness (Ankeny et al., 2006; Wong, Chen-Yu, & Emmel, 2012), durability (i.e., fabric strength, abrasion resistance, and pilling resistance) (Schlag & Ordonez, 2010), and maintenance (i.e., appearance retention, dimensional change, fabric twist and stain removal) (Ankeny et al.; Chen-Yu, Wong, & Emmel, 2012; Schlag & Ordonez). However, no study was found in examining the effects of washing action on fabric UV protection.

According to the studies reviewed in the section of "*Effects of Dye, Bleach and Fiber Color on Ultraviolet Radiation Transmission,*" and "*Effects of Fabric Shrinkage on Ultraviolet Radiation Transmission*," colors and dimensional change are relevant to fabric UV protection. Therefore, studies related to color change and dimensional change were reviewed to examine if washing action has a significant effect on colors and shrinkage. If washing action does cause color change or shrinkage, washing action may also affect fabric UV protection.

After thorough searching of literature, no studies were found that examined the effects of washing action on color change of conventional or NC cottons. However, several studies have investigated the effects of washing action on colorfastness of dyed cotton fabrics and the effects of repeated laundering on conventional and NC cottons. These studies are reviewed in the first sub-section (i.e., effects of washing action and repeated laundering on colorfastness or color change).

Regarding the effects of washing action on dimensional change of conventional and NC cottons, no studies were found after a detailed exploration of literature. However, several studies have examined the effects of washing action on dimension change of dyed cotton fabrics, and one study was found investigating the effects of repeated laundering on dimensional change of NC cotton. These studies are reviewed in the second section (i.e., effects of washing action and repeated laundering on dimensional change).

Effects of Washing Action and Repeated Laundering on Colorfastness or Color Change

To differentiate the change of dyed or printed color from the change of natural fiber color, different terms (i.e., colorfastness and color change resistance) are used in this study. Colorfastness is defined as the ability to maintain an original dyed or printed color and the ability to resist its colorants to adjacent materials (AATCC, 2012). Color change resistance is defined as the ability to resist the color change of any kind, whether in chroma[3], hue, and lightness, or any combination of these (AATCC). Colorfastness or color change resistance to laundering is important in textiles and garments that undergo frequent laundering (Collier et al., 2009). Consumers have consistently cited color loss in home laundering as one of the major problems associated with cotton products (Cotton Incorporated, 2004). No study was found on examining the effects of washing action on color change of conventional and NC cottons. However, several studies have investigated the effects of washing action on colorfastness of dyed cotton fabrics, and these studies are reviewed in the first sub-section (i.e., effects of washing action on colorfastness of dyed cotton fabrics). As mentioned in the above paragraph, several studies on the effects of repeated laundering on conventional and NC cottons were found, and these studies are reviewed in the second-sub section (i.e., effects of repeated laundry on color change of NC cotton).

Effects of washing action on colorfastness of dyed cotton fabrics. Ankeny et al. (2006) investigated the effects of various washers on the colorfastness to laundering of black cotton knit fabrics after 20 laundering cycles. In this study, the researchers used three types of washers (i.e.,

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[3] Chroma is the strength of a color, and is sometimes substituted for terms like "intensity," "saturation," or "purity" (Collier & Epps, 1999). A low chroma may be referred to as a dull color and a high chroma may be described as a bright color.

a top-loading HE washer, a front-loading HE washer, and a traditional washer) but only one type of dryer was used for drying the test specimens. The test specimens were labeled, initial color readings taken from Cotton Incorporated, and then shipped to the Whirlpool Corporation for laundering. Test specimens were laundered with different repeated laundering cycles (i.e., 1, 5, 10, 15 and 20). After laundering, the Whirlpool Corporation measured the colorfastness of laundered samples using a HunterLab™ ColorQuest spectrophotometer with Universal software. The laundered samples were then sent back to Cotton Incorporated. Cotton Incorporated used three types of measurements to measure colorfastness (i.e., ΔE values where a HunterLab™ UltrascanXE spectrophotometer equipped with SliForm™ software was used to take the color readings, percent of color strength, and the ratings of the AATCC Gray Scale for color change). According to the results from the color readings by the HunterLab™, Cotton Incorporated found that the top- loading HE washer imparted more color change than traditional and front-loading washers after 10 cycles and beyond, but no significant differences were found between the front-loading and traditional washers. After the 10 cycles, the mean ΔE value is 1.08 for a top-loading HE washer and 0.88 for both traditional and front-loading HE washers. After 20 cycles, the mean ΔE value changed to 1.98 for a top-loading HE washer, 1.65 for a front-loading HE washer, and 1.48 for a traditional washer. Another study conducted by Wong et al. (2012), comparing a traditional washer and a front-loading HE washer also found no significant differences in colorfastness before washing and after 1, 5, 10, 15, and 20 laundering cycles. However, a significant difference was found related to the number of laundering cycles, where the color had faded most significantly after the first laundering. Significant differences were also found between the 1 and 5, 5 and 10, and 10 and 20 cycles; however, no significant differences were found in between the 10 and 15 cycles, or the 15 and 20 cycles.

Effects of repeated laundry on color change of naturally colored cotton. No study was found in comparing the washing action on the color change of NC cotton. However, many studies reported NC cotton became darker after repeated launderings (Dickerson et al., 1999; Elesini, Richards, & Rowe, 1996; Kantor & Moore, 2004; Williams & Horridge, 1996). Elesini et al. examined the effects of washing on a brown and a green NC cotton, and a white conventional cotton was also included to serve as a control. All specimens were knit fabrics. The test samples were laundered for 50 laundry cycles, and a Datacolor Spectra flash 300 Reflectance Spectrophotometer was used to measure color change. The results showed that there was a significant darkening for both brown and green cotton with the increase of laundry cycles, while white cotton displayed no significant change. After 5 laundry cycles, the lightness change (Δ*L*) was -2.5 for brown NC cotton and -3.0 for green. After 25 laundry cycles, the Δ*L* was -5.5 for both brown and green cottons, and after 50 laundry cycles, the Δ*L* was -6.5 for brown cotton and -8.3 for green cotton. Another consistent result was found in the study of Williams and Horridge, who also studied the color changes of a brown and a green NC cottons, and a white conventional cotton. The color changes were measured after 15 laundering cycles by two types of measurements (i.e., MacBeth Series 1500 Color Measurement System and Gray Scale for color change); however, the researcher only reported the results measured by the MacBeth Series 1500 Color Measurement System. The researchers indicated that both brown and green NC cottons became darker after repeated laundering cycles while the control (i.e., white conventional cotton) became lighter. However, the researchers did not provide information regarding the lightness change values. Considering the color change, the green cotton was affected most by repeated launderings among the three colors (i.e., ΔE = 7.39 for green, 4.17 for brown, and 0.75 for white).

Dickerson et al. (1999) also examined the color change of three NC cottons (i.e., brown, green, and red), and a white conventional cotton was also included to serve as a control. All specimens were also knit fabrics, and the color changes were measured after 5, 10, 15, and 20 laundering cycles. Consistently, the results showed that all NC cotton fabrics became darker after laundering, especially during the first 5 laundering cycles (i.e., Δ*L* = -4 for brown, -8 for red, and -10 for green). However, different from the study of Elesini et al. (1996), the darkness of NC cottons did not increase with the increase in number of laundering cycles after 5 laundering cycles. For the white conventional cotton, the results were consistent with the study of Elesini et al. (1996) with no noticeable color change. Consistent results were also shown in the study conducted by Kantor and Moore (2004), who investigated the effects of laundering on buffalo NC cotton knit fabrics with three different constructions (i.e., rib, fleece, and terry). The color changes were measured after 5, 10, and 20 laundering cycles using the Gray Scale for Color Change. In the Gray Scale method, the color change of the test specimen is evaluated by comparing the test specimen with a corresponding untested sample, where 5 corresponds to no change and 1 indicates that the color has changed most severely (AATCC, 2012). The findings showed that the color changes more with an increase of laundry cycles in all fabrics despite different fabric structures. After 5 laundry cycles, the color changes were 3.11 for rib and 2.83

for both fleece and terry. After 20 laundering cycles, all fabrics showed further color changes of 2.61 for rib, 2.56 for fleece, and 2.67 for terry.

Effects of Washing Action and Repeated Laundering on Dimensional Change

Dimensional change is defined as the changes of length or width of a fabric subjected to specific conditions, such as after being worn, washed, and/or dry-cleaned (AATCC, 2012). A fabric may shrink (decrease), grow (increase), or have no change in size. Dimension retention is very important because a garment can become unusable if it shrinks or grows out of shape. In the apparel industry, the acceptable dimensional change is generally recognized as no more than 3% of the shrinkage values (Lyle, 1977).

No study was found in examining the effects of washing action on dimensional change of un-dyed and NC cottons, but several studies were found in investigating the washing action on dimensional change of dyed cotton, and these studies are reviewed in the first sub-section (i.e., effects of washing action on dimensional change of dyed cotton fabrics). Studies were also found in the examination of the effects of repeated laundering on the dimensional change of NC cotton, and these studies are discussed in the second sub-section (i.e., effects of repeated laundry on dimensional change of NC cotton).

Effects of washing action on dimensional change of dyed cotton fabrics. Ankeny et al. (2006) investigated the effects of various washers on the shrinkage of cotton knit fabrics after 20 laundering cycles. In this study, the researchers used three different types of washers (i.e., top-loading HE washer, front-loading HE washer, and traditional washer) but only one type of dryer was used for drying the test specimens. The results showed that no significant difference in dimensional change among these three types of washers was found. Schlag and Ordonez (2010) studied the effects of washing action on the fabric dimensional change of white 100% cotton plain woven and knit fabrics in traditional and front-loading HE washers. The results also showed no significant difference between the two washers for both woven and knit ballast fabrics after 30 laundering cycles. Wong et al. (2012) compared the effects of traditional and front-loading HE washers and dryers on the dimensional change of a 100% cotton woven fabric and consistently found no significance between the two types of washers but was significant between selected laundering cycles. Shrinkage significantly increased after first wash, and also between 1 and 5, and 5 and 10 cycles. No significant differences were found between 10 and 15 cycles, and between 15 and 20 cycles.

Effects of repeated laundering on dimensional change of naturally colored cotton. Dickerson et al. (1999) examined the dimensional change of three NC cottons (i.e., brown, green, and red). All specimens were knit fabrics. The findings showed that all fabrics had considerable shrinkage after laundering and the most change occurred after the first laundering. The researchers did not provide the information about the percentage of shrinkage.

Summary of the Literature Review

UVR is the radiation between 280 nm and 400 nm (Eckhardt & Rohwer, 2000), and the UVR band consists of three regions: UVA (between 315 nm to 400 nm), UVB (between 280 nm to 315 nm), and UVC (less than 280 nm) (Diffey, 1991). A small dose of UVR is necessary for human well-being; however, overexposure to UVR can result in harmful effects on human skin (Grant et al., 2003). Textiles have been used to reduce health risks related to UVR exposure, and garments are usually treated as an effective means to slow the cumulative exposure to UVR (Capjack et al., 1994).

There are two distinct approaches to determine the fabric’s UVR transmission (i.e., laboratory testing *in vivo* and instrumental measurement *in vitro*). The main advantages of the *in vivo* test method are acquiring a direct response of human skin to UVR (Menzies, et al., 1991). However, the disadvantages of this test method are that it is difficult to carry out as a standard test method because humans are involved as the test subject. Different from the *in vivo* test method, the UPF obtained in the *in vitro* test method measures the protection blocked from both UVA and UVB (Edlich, et al., 2004). The main advantage of this test method is that it is a relatively economical and practical way to measure UVR transmission (Gambichler et al., 2002). The three instruments frequently used in the *in vitro* approach to measure UVR transmittance are radiometric, spectroradiometric, and spectrophotometric. Among the three instruments, the spectrophotometric is the most commonly used method today to determine fabric UVR transmittance (Gambichler et al., 2006). UPF is the instrumental evaluation value for *in vitro* of a textile with UVR protection. It is calculated by the ratio of the average effective UVR irradiance transmitted without fabric to the average effective UVR irradiance transmitted through the fabric (AATCC, 2012).

In the U.S., two national standard setting organizations (i.e., AATCC and ASTM) have been involved in developing test methods for textile UV transmission tests (i.e., AATCC 183 and ASTM D 6544). There are several national standards for the determination of the UV protection of textile materials [i.e., AS/NZS 4399 (Australia/New Zealand), prEN 13758-1and prEN 13758-2 (The European Committee for Standardization), ASTM D6544 (United States)]. The standard that is used in the U.S. is ASTM D6544, in which fabrics are classified into three categories of UVR protection [i.e., better (UPF between 15 and 24), very good (UPF between 25 and 39), and excellent (UPF of 40 and above)]. Fabrics with UPF less than 15 cannot be labeled as UV protective.

Inconsistent studies were found that showed the effects of fiber types on UVR transmission, where two old studies stated that cottons had a lower UVR transmission (Genkov & Atmažov, 1968; Welsh & Diffey, 1981), while other studies stated that cellulose-based fabrics like cotton, linen, and rayon had a higher UVR transmission, and polyester has better UVR protection, especially in blocking UVB radiation (Crews et al., 1999; Davis et al., 1997; Hilfiker et al., 1996; Reinert et al., 1997). Fabric cover is the most important fabric property that affects UVR transmission (Crews et al.; Hoffmann, Lapperre et al., 2001; Pailthorpe, 1998). Fabric cover can be defined as the percentage of fabric surface covered by the warp and filling yarn (Capjack, Kerr et al., 1994), and when the fabric cover is high, the UVR transmission decreases, providing better protection. Heavy and thicker fabrics also blocked more UVR (Berne & Fischer, 1980; Crews et al., 1999; Wong et al., 2000), and even small amounts of shrinkage could increase fabric cover and lead to significant improvements in the UVR protection (Gies et al., 1994; Sliney et al., 1987; Stanford et al., 1995a; 1995b). Studies also found a significant decrease in UPF with fabric stretch (Moon & Pailthorpe, 1995; Sayre & Hughes, 1993; Sinclair & Diffey, 1997) and when textiles are wet (Crews & Zhou, 2004; Gambichler et al., 2002; Gies et al., 1994; Jevtic, 1990; Pailthorpe, 1994; Zhang et. al., 1997). Furthermore, darker colors and NC fabrics offer better UV protection (Gies et. al., 1998; Pailthorpe, 1993; Reinert et a1., 1997). In contrast, bleached fabrics offer lower UV protection (Crews et al., 1999). The use of UV absorber during fabric manufacturing or during home laundering leads to good UV protection (Eckhardt &

Osterwalder, 1998; Eckhardt & Rohwer, 2000; Gies et al., 1994; Hustvedt & Crews, 2005; Schaumann & Rohwer, 2003; Srinivasan & Gatewood, 2000; Xin et. al., 2004).

Perspiration is an important mechanism for the human body to maintain heat balance, which assists the human body in cooling down (Hatch, 1993). Human perspiration will occur more frequently due to hot temperatures and increased physical activities during the summer. Human perspiration is composed of water, urea, lactic acid, amino acids, sugar, alkali sulfates/phosphates, inorganic salts, and uric acids (McSwiney, 1934). It can cause fabric color fading and alteration (Lyle, 1977). Artificial perspiration solutions have been developed to simulate the action of normalized perspiration on the textile product because it is almost impossible to collect large amounts of perspiration for use in laboratory research (McSwiney). Bhat et. al. (1990) studied the effect of perspiration on greige cotton clothes, and the results showed that yellowing occurred with an increase in treatment time. Other studies examined the colorfastness to perspiration of 10 types of fabrics, and found that polyester/cotton and wool/nylon blends had the least color loss, while cotton, rayon, and silk were the most susceptible to color loss (Bhat et. al., 1990; Srivastava, 1992). Wimberley and Roper (1997) examined the effects of perspiration on NC cotton in color transfer (i.e., color stains or transfers to another fiber) and found that no color transfer occurred for all the test fabrics because the fabric coloration was a genetic component. Öktem et al. (2003) and Wimberley and Roper (1997) used two different types of artificial perspiration solutions (i.e., AATCC standard solution contains only acid vs. ISO standard solution both acid and alkaline) and color measurement [CIELAB reading vs. Gray Scale readings] to measure the effects of perspiration on NC cottons. Different results were found where Wimberley and Roper found that all fabrics became lighter after soaked in the artificial perspiration solution while Öktem et al. only found slight color change.

During normal use, most textiles are exposed to sunlight, rain, humidity, and various temperatures, and these environmental factors have a degradation effect on fabric properties, including durability and colorfastness (Collier & Epps, 1999; Howard & McCord, 1960; Slater, 1986; Wall & Frank, 1971). Several standard test methods are used to evaluate the weather resistance of textiles, and these test methods can be classified as either natural weathering testing or accelerated laboratory testing. Natural weathering testing is the most realistic way to test the weather resistance of a textile product, in which the textile product is exposed to natural weather conditions (i.e., outdoor exposure) or to natural sunlight behind glass (i.e., to imitate indoor exposure) (AATCC, 2012). The unpredictability of weather makes outdoor degradation exposure difficult to perform precisely because solar radiation is not available during the nighttime, and seasonal conditions also affect natural sunlight, thus affecting the textile degradation (Hawkins, 1984). Consequently, accelerated weathering tests were developed. There are several advantages of accelerated weathering tests: the use of controlled test conditions, cost effectiveness, and possible estimation of exposure time (Lucas, 2001). One major drawback of accelerated weathering is none of the instrumental methods can precisely reproduce sunlight (Collier & Epps, 1999). Three types of illumination light sources have been widely used to study the weathering effects of textiles, including the carbon arc lamp, xenon lamp, and fluorescent UV lamp (Lucas). Studies have shown that overexposure to weathering affected the fabric's strength and colors (Collier & Epps, 1999). Yellowing is one of the degradations that occur from exposure to weathering (Grimes, 1933), and Morris (1966) studied the effects of weathering on cotton fabrics and found that fabric samples exposed in summer months had greater yellowing than in other seasons. Evenson and Epps (1999) found that NC cottons became increasingly lighter as exposure duration increased (i.e, 20, 40, 60, and 80 hours) and also showed more color change after exposure to light at high humidity than at low humidity. Two studies also examined the color change of NC cotton (Hustvedt & Crews, 2005; Jahagirdar et al., 2000), but only investigated the effects of light on color change, while other weathering factors (such as rain and temperature) have not been put into consideration. The findings of these studies showed that the majority of the test specimens showed color change after exposure to light for a period of time (i.e., after 250 hours or after 40 AFUs), and then the color stayed constant between 400 and 500 hours or between 40 and 80 AFUs (Hustvedt & Crews; Jahagirdar et al.).

The traditional top-loading vertical axis washer has been dominating the U.S. market for the past three decades (Association of Home Appliance Manufacturers, 2008). Most U.S. consumers prefer a top-loading washer because it does not require bending to load the machine (Clothes Care Research Center, 2007). Traditional washers are also sold for a more reasonable price and the total washing time is shorter compared to HE washer ("Washer & Dryer," 2012). However, the large amounts of water and energy that are used with each load of clothing being washed and dried in the traditional washer lead to the increased concern for water and energy conservation of the home laundry process. As a result, the HE washer, which operates with a lower consumption of electric power and water, was introduced into the market in 1997 and labeled as an Energy Star (“New Generation,” 1997). There are two types of HE washers in the U.S. market (i.e., the front-loading HE washer and the top-loading HE washer). Although their growth has been slow, they have gradually become more popular as U.S. consumers become more environmentally conscious (Association of Home Appliance Manufacturers, 2008). The one major drawback of HE washers is that they generally cost more than traditional washers, although HE washers may save money in the long run because of the savings of water, energy, and detergent. In general, front-loading HE machines can reduce water usage by 30% and energy usage by 50% compared to traditional top-loading washers (Kadolph, 2010). Previous studies showed that washing action of traditional and front-loading HE washers do not affect colorfastness and dimensional change of dyed cotton fabrics (Ankeny et al., 2006; Wong et al., 2012). The color of all NC cottons, regardless of what kind of color (i.e., brown, green, or buffalo), would change after repeated laundering (Dickerson et al., 1999; Elesini et al., 1996; Kantor & Moore, 2004; Williams & Horridge, 1996). The study by Elesini et al. indicated clearly that both green and brown NC cottons became darker after repeated laundering, but the green NC cotton became much darker than the brown color. Besides, the NC cotton fabrics in the study of Dickerson et al. showed a considerable dimensional change after laundering.

CHAPTER III

MATERIALS AND METHODS

This chapter includes eight sections to provide an explanation of methods and procedures for this study. The first section, purpose and objectives of the study, lists the purpose, the primary objectives, and secondary objectives of the study. The second section, research design, lists the dependent variables of the study and explains the level in each independent variable. The third section, hypotheses of the study, lists the hypotheses generated from the objectives of the study. The fourth section, materials, discusses the fabrics and detergents used in this study. The fifth section, specimen preparation, explains the procedures of preparing and cutting the test specimens. The sixth section, experiment timeline and testing procedures, discusses the timeline of experiments for the three replicates, the measurements of UVR protection and the five additional dependent variables, and the testing method and procedures of each treatment. The data analyses are addressed in the last section.

Purposes and Objectives of the Study

The primary purpose of the study was to examine the effects of perspiration application, weathering exposures, washing action of automatic home clothes washers, and repeated laundering on the UVR protection of a NC lightweight cotton fabric. In addition, five fabric property changes in the test specimen after the treatments of perspiration, weathering exposure, washing action, and repeated laundering (i.e., fabric count change, thickness change, weight change, color change and dimensional change) were included in this study to serve as secondary dependent variables to examine if the four treatment factors (i.e., perspiration application, weathering exposures, washing action of automatic home clothes washers, and repeated laundering) will cause changes in these five fabric properties, and if these changes will lead to changes of UVR protection of NC lightweight cotton fabric. Based on the purposes of the study, two sets of objectives, primary and secondary objectives were included and these objectives are listed below.

Primary Objectives

The primary objectives were to test if the four treatments (i.e., perspiration application, weathering exposures, washing action of automatic home clothes washers, and repeated laundering) affected the UVR protection of a NC lightweight cotton fabric. The primary objectives are listed as the following:

(g) To examine the interaction in the effects of perspiration, weathering exposures, washing action, and repeated laundering on the UVR protection of a NC lightweight cotton fabric;

(h) To examine the UVR protection of a NC lightweight cotton fabric with and without the presence of perspiration;

(i) To examine the UVR protection of a NC lightweight cotton fabric before and after two types of weathering exposures (i.e., semi-tropical climate without water spray and semi-arid climate), and a control (i.e., specimens are stored in the standard textile testing condition without weathering exposure);

(j) To examine the UVR protection of a NC lightweight cotton fabric before and after the washing in the two types of washers (i.e., traditional washer and HE washer);

(k) To examine the UVR protection of a NC lightweight cotton fabric before and after 15 repeated laundering;

(l) To examine the variables (i.e., perspiration, weathering exposure, washing action, and repeated laundering) that best predict the UVR protection of a NC lightweight cotton fabric.

Secondary Objectives

The secondary objective was to examine if the treatments (i.e., perspiration application, weathering exposures, washing action of automatic home clothes washers, and repeated laundering) would cause changes in five fabric properties of the test specimen (i.e., fabric count change, thickness change, weight change, color change and dimensional change). The secondary objectives are listed as the following:

(e) To examine if perspiration application will cause the changes in five fabric properties of the test specimen (i.e., fabric count change, thickness change, weight change, color change and dimensional change). If there are changes to the five fabric properties after the perspiration treatment, then further examinations will be conducted to determine if there is a relationship between the changes in these five fabric properties and the change in UVR protection of a NC lightweight cotton fabric;

(f) To examine if two weathering exposure conditions (i.e., semi-tropical climate without water spray and semi-arid climate), and a standard textile testing condition without weathering exposure (i.e. serving as a control) will cause the changes in five fabric properties of the test specimen (i.e., fabric count change, thickness change, weight change, color change and dimensional change). If there are changes to the five fabric properties after the weathering exposure treatment, then further examinations will be conducted to determine if there is a relationship between the changes in these five fabric properties and the change in UVR protection of a NC lightweight cotton fabric;

(g) To examine if two different types of washing action of automatic home clothes washers (i.e., traditional washer and HE washer) will cause different degrees of changes in five fabric properties of the test specimen (i.e., fabric count change, thickness change, weight change, color change and dimensional change). If there are changes to the five fabric properties after washing in the two types of washers, then further examinations will be conducted to determine if there is a relationship between the changes in these five fabric properties and the change in UVR protection of a NC lightweight cotton fabric;

(h) To examine if repeated launderings up to 15 laundering cycles will cause changes in five fabric properties of the test specimen (i.e., fabric count change, thickness change, weight change, color change and dimensional change). If there are changes to the five fabric properties after repeated launderings, then further examinations will be conducted to determine if there is a relationship between the changes in these five fabric properties and the change in UVR protection of a NC lightweight cotton fabric.

Research Design

Based on the purpose and objectives of the study, a split-plot repeated measures experimental design was used for the current study. The split-spot experimental repeated measures design was selected for this study mainly due to three reasons. Firstly, the split-plot experimental design contains two levels of experimental units (i.e., whole plots and sub-plots), where the sub-plots are the experimental units within the whole plots. In this study, the whole-plot experimental units were the swatches sized 880 mm x 2840 mm (34.5 x 111 inches). The whole plot treatment was the weathering exposure, which contained three levels (i.e., semi-tropical climate without water spray, semi-arid climate, and standard conditioning). Because there were three levels, the number of whole-plot experimental units for one replicate was three. In other words, there was a total of three fabric swatches sized 880 mm x 2840 mm for each trial, one fabric swatch for one type of weathering condition. These three fabric swatches were cut randomly from the same roll of fabric and the details of these fabric swatches' preparations are explained in the section "*Specimen Preparation*." These three fabric swatches were randomly assigned to receive one of the three weathering conditions, and therefore the whole-plot was considered a completely randomized design.

Another level of experimental units was needed for the combinations of two treatment factors (i.e., 2 levels of perspiration x 2 levels of washing action = 4 combinations of the two treatment factors). In addition, the fabric UVR protection in this study was expressed as an ultraviolet protection factor (UPF), which was calculated as the ratio of UVR without fabric present over the irradiance with a fabric present (AATCC, 2012). According to the AATCC Test Method 183, two test specimens from each swatch are required to determine the UPF value. Thus, eight test specimens were needed to cut from each swatch to serve as sub-plot experimental units (2 test specimens x 4 treatment combinations = 8 test specimens). All test specimens cut from the same whole plot unit were exposed to the weathering condition together. The sub-plots in the current study thus form a generalized randomized complete block design. A generalized randomized complete block design is a design in which each treatment is replicated the same number of times in each block (i.e., each whole plot). In this study, treatments of perspiration and washing action were repeated twice because two test specimens were needed to measure the UPF value.

Secondly, in order to understand the effects of repeated laundering on the UVR protection, except for the control group, all test specimens were laundered after being treated with the three treatment factors (i.e., perspiration, weathering exposure, and washing action), and this process was repeated 15 times. The UVR protection of these treated test specimens was measured before laundering, and after each laundering cycle. In other words, the outcomes of the laundering effects were measured on the same test specimen over time. One main advantage of repeatedly measuring the same test specimen after each treatment is that the measurement taken from the test specimen in a repeated measures design has less variability due to the elimination of the sampling error (Stevens, 2009). For this reason, the repeated measures design was incorporated into this research design.

Primary and Secondary Dependent Variables

The main objective of this study was to understand the effects of the four treatment factors (i.e., perspiration application, weathering exposures, washing action of automatic home clothes washers, and repeated laundering) on the UVR protection of a NC lightweight cotton fabric. The fabric UVR protection in the current study was expressed as an UPF value. The higher the UPF value, the better the fabric UVR protection; consequently, UPF can be interpreted as how much the test fabric inhibits the UVR to pass through it. Because NC colored cottons usually have high UPF values (Hustvedt & Crews, 2005), it is important to understand any UPF value change before and after the four treatments application. For this reason, the primary dependent variable in this study was the UPF value change.

The secondary objective was to examine the effects of perspiration application, weathering exposures, washing action of automatic home clothes washers, and repeated laundering on five fabric properties (i.e., fabric count change, thickness change, weight change, color change, and dimensional change). Thus, these five fabric properties were measured and serve as “secondary dependent variables.”

Independent Variables

Based on the objectives of the study, four independent variables were selected (i.e., perspiration application, weathering exposure, washing action of automatic home clothes washers, and repeated laundering). In this section, the reasons for selecting these independent variables and the levels in each variable are discussed in the following sections.

Perspiration Application

The first independent variable was perspiration application, which includes two levels (i.e., with perspiration and without perspiration). Hot and humid summer weather can cause an increase in perspiration. The perspiration assists in regulating human body temperature by increasing the heat lost, and transforms the sweat that is present on the skin surface into water vapor (Hatch, 1993). The human body cools down by the moisture evaporating into the atmosphere. Cotton fibers are commonly used for lightweight clothing due to its excellent ability to absorb moisture, including perspiration from the human body (Kadolph, 2010). However, previous studies showed that NC cottons became lighter after application of perspiration (Wimberley & Roper, 1997). Because lighter color offers less fabric UVR protection, the application of perspiration may affect the UVR protection. Therefore, perspiration application was included in this study to examine its effects on the UVR protection of a NC lightweight cotton fabric. Furthermore, a control group (i.e., without perspiration treatment) was also included in the study to serve as a standard to compare to the perspiration treatment group (Oehlert, 2010). By comparing the treatment group with the control group, the researchers can understand whether the treatment factors have any effect on the study (see Table 3.1).

Table 3.1 Levels of Independent Variables

	1	**2**	**3**
Perspiration	Control (No treatment)	With treatment	
Weathering Exposure Conditions	Control (Standard conditioning)	Semi-tropical climate with the modification of removing water spray (Florida)	Semi-arid climate (Arizona)
Washing Action of automatic home clothes washers	Washing action of a traditional washer: Top-load vertical axis washer with an agitator	Washing action of a front-loading HE washer with tumble action	
Repeated Laundering	0, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14 and 15 laundering cycles		

Weathering Exposure

The second independent variable was weathering exposure. Clothing made of lightweight fabrics is usually worn during the summer season and are subjected to the effects of weathering. The combination of weathering elements, which includes sunlight, rain, humidity, and temperature (heat and cold), can cause degradation in fibers (Barnett & Slater, 1991). Previous studies showed that NC cottons became lighter after prolonged exposure to light (Hustvedt & Crews, 2005; Jahagirdar et al., 2000) or exposure to light and humidity (Evenson & Epps, 1999). Because lighter colors offer less fabric UVR protection, weathering exposure may affect the UVR protection. For these reasons, this variable was included in this study to examine the effects of weathering exposure on the UVR protection of a NC lightweight cotton fabric.

Two conditions were selected among the four conditions listed in the AATCC Test Method 169 – Weather Resistance of Textiles: Xenon Lamp Exposure (AATCC, 2012). The two weathering conditions were Option 1 – a semi-tropical climate option found in South Florida and Option 3 – a semi-arid climate found in Phoenix, Arizona (see Table 3.1). The reason to select these two weathering conditions was because Florida and Arizona have long been benchmarks for real-time, outdoor exposure testing due to their extreme climates that accelerate the degradation of materials (Lucas, 2001). However, a modification of omitting water spray for Option 1 – a semi-tropical climate option found in South Florida was made to better simulate a weathering condition that a fabric in summer clothing is usually exposed to. The fabric tested in this study is not an outdoor textile, which may be exposed to rain for a long period of time. It is unusual for a person to frequently stay in the rain for a long period of time, unlike outdoor furniture, and thus the setting with water spray will be omitted. The other two conditions that were not tested in the current study were: Option 2 – semi-tropical climate with restricted water supply and light and dark alternate light cycles, and Option 4 – temperate climate. Due to the weathering chamber limitation, the Option 2 condition cannot be conducted. Option 4 - the temperate climate commonly found in Ohio was not selected because the geographical location of such weather condition has lower levels of solar UVR in comparison with Florida and Arizona. The setting of this option was less extreme than the other three options; therefore, it may have less effect on the fabric properties and UPF value change. For this reason, this option was not selected.

In addition to the two selected weathering conditions (i.e., a modified semi-tropical climate and a semi-arid climate), the specimens in the control experimental group were conditioned in the standard atmospheric condition for textile testing (i.e., 21 ± 1 °C or 70 ± 2 °F, 65 ± 2% Relative Humidity, and no light exposure) according to the ASTM D1776 – 08e11: Standard Practice for Conditioning Textiles for Testing (ASTM, 2013).

Washing Action of Automatic Home Clothes Washers

The third independent variable was washing action of automatic home clothes washers. There are a wide variety of automatic home clothes washers being introduced to the consumer market, such as the traditional washer and HE washer, to accommodate the consumers' needs. The effects of washing action of clothes washers have been studied in various areas, such as colorfastness (Ankeny et al., 2006; Wong et al., 2012), durability (i.e., fabric strength, abrasion resistance, and pilling resistance) (Schlag & Ordonez, 2010), and maintenance (i.e., appearance retention, dimensional change, fabric twist and stain removal) (Ankeny et al.; Chen-Yu et al., 2012; Schlag & Ordonez). These studies showed that HE washers had better performance in abrasion and pilling resistance, as well as less wrinkle and skewness than a traditional washer. These results suggest that the washing action of HE washers may be gentler than the washing action of traditional washers, and thus may have different effects on fabric UVR protection. Therefore, an HE washer and a traditional washer were selected to examine whether different types of washing action would have different effects on fabric UVR protection. The two types of washing action of automatic home clothes washers were: (a) washing action of a traditional washer (i.e., a top-load vertical axis washer with an agitator) and (b) washing action of a front-loading HE washer (i.e., a front-loading HE horizontal axis washer with tumble action).

Repeated Laundering

The forth independent variable was the number of repeated laundering cycles, which includes 16 laundering cycles (i.e., 0, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14 and 15). The zero laundering cycle was treated as a control group, in which the fabric specimens were not laundered. During the summer season, clothing is usually laundered more often than clothing worn in other seasons in order for them to be clean and hygienic because human perspiration increases during the hot summer. The increase of perspiration can discolor, stain, or deteriorate some of the fabrics of the garment, especially in the underarm area (Lyle, 1977). Dickerson et al. (1999) found that NC cotton showed considerable dimensional changes after laundering and previous studies have shown that small amounts of shrinkage could lead to significant improvements in the fabric UVR protection because shrinkage caused the fabric cover to increase (Sliney et al., 1987; Stanford et al., 1995a; 1995b). For these reasons, repeated laundering was included in this study.

In the current study, the total washing cycles was 15 cycles. The selection of the number of laundering cycles was based on a previous study investigating the effects of repeated laundering on NC cotton and the results of a pilot test. Williams and Horridge (1996) examined the effect of washing on a brown NC cotton fabric and a green NC cotton fabric after 15 cycles. Their results showed that the NC cottons became significantly darker after 15 repeated laundering cycles. In addition, in a wear study of Stanford et al. (1995a), the authors assumed that consumers would wash their clothes once a week. The same assumption was used in the current study. Because the summer season has the duration of three months, about 13 weeks, 15 laundering cycles were assumed to be similar to the total number of washings of a certain garment in the summer season.

Hypotheses of the Study

The purpose of the study was to examine the factors that may significantly influence the UVR protection of a NC lightweight fabric. Based on the purpose of the study, seven hypotheses were formed and organized by the dependent variables (i.e., UPF value change, fabric count change, thickness change, weight change, color change and dimensional change). To simplify the statement of hypotheses, the term “NC lightweight cotton fabric specimens” is shortened to “test specimens.”

Hypothesis 1: Perspiration application, weathering exposure, washing action of automatic home clothes washers, and repeated laundering will influence the UPF value change of the test specimens.

Because four independent variables with multiple levels were used in this study, some interactions might exist among independent variables. For instance, the test specimens treated with perspiration were expected to have lower UVR protection because perspiration causes textile colors to lighten (Öktem et al., 2003; Wimberley & Roper, 1997), and thus the UVR protection of the treated textile was expected to become lower (i.e., larger UPF). Meanwhile, NC cotton fabric was expected to have better UVR protection after repeated launderings because the fabric becomes darker after washing (Dickerson et al., 1999; Elesini et al., 1996; Kantor & Moore, 2004; Williams & Horridge, 1996), and darker color fabrics offer better UVR protection (i.e., higher UPF) (Gies et al., 1998; Kim et al., 2004; Pailthorpe, 1993; Reinert et a1., 1997). In this case, a non-constancy of simple effect might occur (i.e., an interaction) between perspiration application and repeated launderings. Based on these reasons, Hypothesis 1a was formed.

H1a: There is an interaction among the effects of the application of four treatment factors (i.e., perspiration application, weathering exposure, washing action of automatic home clothes washers, and repeated laundering) on the UPF value change of test specimens.

Studies found that fabrics with lighter colors generally provide lower UVR protection (i.e., smaller UPF values) than those with darker colors (Gies et al., 1998; Pailthorpe, 1993; Reinert et a1., 1997). Furthermore, Wimberley and Roper (1997) and Öktem et al. (2003) found that both NC woven and knitted cotton fabrics became lighter after being treated with artificial perspiration. If perspiration causes the colors of NC cotton fabrics to lighten, then the UVR protection of the treated fabrics will become lower (i.e., smaller UPF values) or have a greater change in UPF value. Based on the results from the studies above, Hypothesis 1b was formed.

H1b: There is a difference in UPF values between the test specimens treated with and without perspiration. The test specimens treated with perspiration will have a greater change in UPF value than the specimens without treatment.

Studies investigating color change in NC cotton fabrics due to light exposure found that all NC cottons in these studies became lighter after exposure to light for a period of time (i.e., after 300 hours or after 40 AFUs) (Hustvedt & Crews, 2005; Jahagirdar et al., 2000). If light exposure causes the color of NC cotton fabrics to become lighter, then the UVR protection of the light-treated fabrics may become lower (i.e., smaller UPF values) because fabrics with a lighter color generally provide less UVR protection (Gies et al., 1998; Pailthorpe, 1993; Reinert et a1., 1997). Therefore, those test specimens exposed to the two weathering conditions (i.e., semi-tropical and semi-arid climates) were expected to have lower UVR protection (i.e., smaller UPF value) or a greater change in UPF value than those in the control group because specimens in the control group had not been exposed to light. Evenson and Epps (1999) found that the colors of NC cotton fabrics exposed to weathering with high humidity changed more than those exposed to weathering with low humidity. For this reason, those test specimens exposed to the semi-tropical climate were expected to have more color changes than those exposed to the semi-arid climate because the semi-tropical climate has a higher relative humidity setting than the semi-arid climate (i.e., 70% versus 27%), although both weathering conditions have the same temperature setting (77 ± 3 °C or 170 ± 5 °F). Thus, Hypothesis 1c was formed.

H1c: There is a difference in the UPF values among the test specimens exposed to the following three weathering conditions - (a) semi-tropical climates without water spray, (b) semi-arid climates, and (c) control (i.e., standard conditioning). The test specimens exposed to a semi-tropical climate condition will have the most UPF value change, followed by the test specimens exposed to a semi-arid climate condition, and then the test specimens maintained in the standard textile testing condition.

According to SDA (2008), the tumbling motion used in the HE washer treats clothing more gently than a traditional washer. Furthermore, past research results showed that a front-loading HE washer had better abrasion and pilling resistance, less wrinkles, and less skewness changes than a traditional washer (Schlag &

Ordonez, 2010; “Washers & Dryers,” 2012), suggesting that the washing action of HE washers are gentler than the washing action of traditional washers. If the washing action of the HE washer is gentler, then the fabric deterioration, such as abrasion, was less. For instance, Schlag & Ordonez had found that HE washer caused less abrasion than the traditional washer. Because abrasion may cause fabric weight loss, fabrics with lighter weight have less UVR protection (Berne & Fischer, 1980; Gies et al., 1994), test specimens that laundered in the HE washer were expected to have better UVR protection (i.e., less change in UPF values). For these reasons, Hypothesis 1d was formed.

H1d: There is a difference in UPF values between the test specimens laundered in a traditional washer and the test specimens laundered in a front-loading HE washer. The test specimens laundered in the front-loading HE washer will have less UPF values change than those laundered in the traditional washer.

Cotton fabrics are subject to both relaxation shrinkage and consolidation shrinkage when laundered (Hatch & Osterwalder, 2006; Kadolph, 2007). Studies have found that shrinkage causes the fabrics to become denser, and thus reduces fabric cover. Study results showed that the increase of fabric cover significantly improves UVR protection (i.e., higher UPF value) (Crews et al., 1999; Gies et al., 1994; Stanford et al., 1995a; 1995b; Wong et al., 2000). Many studies also reported NC cotton became darker after repeated launderings (Dickerson et al., 1999; Elesini et al., 1996; Kantor & Moore, 2004; Williams & Horridge, 1996). Because darker color fabrics offer better UVR protection (Gies et. al., 1998; Pailthorpe, 1993; Reinert et a1., 1997), fabrics after repeated launderings were expected to provide better UVR protection. Based on these reasons, Hypothesis 1e was formed.

H1e: There is a difference in UPF values between the test specimens before and after repeated laundering cycles. The UPF value change of the test specimens will increase with the increase of laundering cycles, up to 15 laundry cycles.

***Hypothesis 2**:* Perspiration application, weathering exposure, washing action of automatic home clothes washers, and repeated laundering have no effect on the fabric count change of the test specimens.

H2a: There is no interaction among the effects of the application of four treatment factors (i.e., perspiration application, weathering exposure, washing action of automatic home clothes washers, and repeated laundering) on the fabric count change of the test specimens.

H2b: There is no difference in fabric count change between the test specimens treated with and without perspiration.

H2c: There is no difference in the fabric count change among the test specimens exposed to the following three weathering conditions - (a) semi-tropical climates without water spray, (b) semi-arid climates, and (c) control (i.e., standard conditioning).

H2d: There is no difference in fabric count change between the test specimens laundered in a traditional washer and the test specimens laundered in a front-loading HE washer.

H2e: There is no difference in fabric count change between the test specimens before and after repeated laundering cycles, up to 15 laundering cycles.

***Hypothesis 3**:* Perspiration application, weathering exposure, washing action of automatic home clothes washers, and repeated laundering have no effect on the thickness change of the test specimens.

H3a: There is no interaction among the effects of the application of four treatment factors (i.e., perspiration application, weathering exposure, washing action of automatic home clothes washers, and repeated laundering) on the thickness change of the test specimens.

H3b: There is no difference in thickness change between the test specimens treated with and without perspiration.

H3c: There is no difference in the thickness change among the test specimens exposed to the following three weathering conditions - (a) semi-tropical climates without water spray, (b) semi-arid climates, and (c) control (i.e., standard conditioning).

H3d: There is no difference in thickness change between the test specimens laundered in a traditional washer and the test specimens laundered in a front-loading HE washer.

H3e: There is no difference in thickness change between the test specimens before and after repeated laundering cycles, up to 15 laundering cycles.

Hypothesis 4*:* Perspiration application, weathering exposure, washing action of automatic home clothes washers, and repeated laundering have no effect on the weight change of the test specimens.

H4a: There is no interaction among the effects of the application of four treatment factors (i.e., perspiration application, weathering exposure, washing action of automatic home clothes washers, and repeated laundering) on the weight change of the test specimens.

H4b: There is no difference in weight change between the test specimens treated with and without perspiration.

H4c: There is no difference in the weight change among the test specimens exposed to the following three weathering conditions - (a) semi-tropical climates without water spray, (b) semi-arid climates, and (c) control (i.e., standard conditioning).

H4d: There is no difference in weight change between the test specimens laundered in a traditional washer and the test specimens laundered in a front-loading HE washer.

H4e: There is no difference in weight change between the test specimens before and after repeated laundering cycles, up to 15 laundering cycles.

Hypothesis 5*:* Perspiration application, weathering exposure, washing action of automatic home clothes washers, and repeated laundering have no effect on the color change of the test specimens.

H5a: There is no interaction among the effects of the application of four treatment factors (i.e., perspiration application, weathering exposure, washing action of automatic home clothes washers, and repeated laundering) on the color change of the test specimens.

H5b: There is no difference in color change between the test specimens treated with and without perspiration.

H5c: There is no difference in the color change among the test specimens exposed to the following three weathering conditions - (a) semi-tropical climates without water spray, (b) semi-arid climates, and (c) control (i.e., standard conditioning).

H5d: There is no difference in color change between the test specimens laundered in a traditional washer and the test specimens laundered in a front-loading HE washer.

H5e: There is no difference in color change between the test specimens before and after repeated laundering cycles, up to 15 laundering cycles.

Hypothesis 6*:* Perspiration application, weathering exposure, washing action of automatic home clothes washers, and repeated laundering have no effect on the dimensional change of the test specimens.

H6a: There is no interaction among the effects of the application of four treatment factors (i.e., perspiration application, weathering exposure, washing action of automatic home clothes washers, and repeated laundering) on the dimensional change of the test specimens.

H6b: There is no difference in dimensional change between the test specimens treated with and without perspiration.

H6c: There is no difference in the dimensional change among the test specimens exposed to the following three weathering conditions - (a) semi-tropical climates without water spray, (b) semi-arid climates, and (c) control (i.e., standard conditioning).

H6d: There is no difference in dimensional change between the test specimens laundered in a traditional washer and the test specimens laundered in a front-loading HE washer.

H6e: There is no difference in dimensional change between the test specimens before and after repeated laundering cycles, up to 15 laundering cycles.

Materials

Fabrics

The fabric selection for the current study was limited to lightweight fabrics because the purpose of the study was to examine the effects of perspiration application, weathering exposures, washing action of automatic home clothes washers, and repeated laundering on the UVR protection of a NC lightweight cotton fabric. According to Kadoplh (2007), fabrics that weigh less than 135 gm/m^2 (4.0 oz/yd^2) are considered lightweight fabrics that are often used for summer blouses and shirts. In this study, the light brown color was selected because consumers consider light colored fabrics more comfortable for summer clothing (Gies et al., 1998; Pailthorpe, 1993; Reinert et a1., 1997).

The fabric with a light brown color used in the study was purchased from Peru Naturtex Partners, and the test fabric code was Tela Percale with Vicuña color (i.e., tan color). According to the information provided by the Peru Naturtex Partners, the test fabric was a 100% NC plain weave cotton sheeting with a width of 2.84 meters (3.11 yards), and a fabric weight of 130 gm/m^2 (3.8 oz/yd^2). Sheeting is made of a plain weave fabric, which usually comes in various weights (i.e., light, medium, and heavy weights), and widths appropriate for all sizes of beds (Picken, 2010). Lightweight cotton sheeting is suitable to be used for apparel (Tortora & Johnson, 2014). The reasons for purchasing the fabric from this company were because their fabrics were commercially viable and were used in a previous study investigating the UPF of NC cotton (Hustvedt & Crews, 2005). Fabric weight, fabric thickness, and fabric count were measured before conducting the tests to verify the information given by the fabric company and provide more descriptive information about the test fabric.

Laundry Detergent

A “Tide® 2X Ultra Free” regular liquid laundry detergent was used in the traditional washer. The reasons for choosing Tide as the detergent were because according to the most current record of the sales of the leading 10 liquid laundry detergent brands of the United States, Tide® has the largest market share (*Sales of the Leading 10 Liquid Laundry Detergent Brands,* 2013) and was the most commonly used laundry detergent in previous studies (Ankeny et al., 2006; Chen-Yu, Guo & Kemp-Gatterson, 2009; Kim et al., 2004; Schlag & Ordonez, 2010).

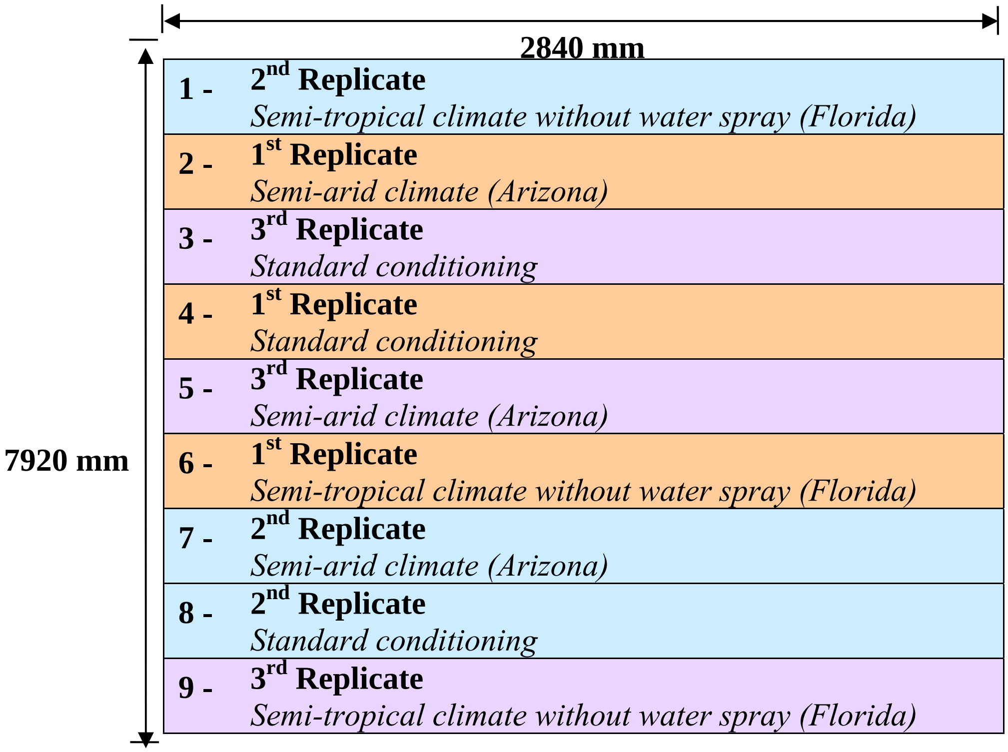
Another reason for choosing Tide® “2X Ultra Free” was because it was a dye-free and unscented detergent, and was available for both traditional washing machines and HE washers. In this study, regular Tide® “2X Ultra Free” laundry detergent was used in the traditional washer while HE laundry detergent was used in the HE washer. According to SDA (2008), if a regular laundry detergent was used in a HE washer, it would produce too many suds which would make rinsing clothes more difficult (SDA, 2008); therefore, a Tide® “2X Ultra Free” HE laundry detergent was used in the HE washer.

Specimen Preparation

In this study, the whole plot fabric swatches were first prepared and then the sub-plot test specimens were cut from these whole plot swatches. Therefore, the organization of this section is listed with the whole plot in the first section, and the sub-plot specimen preparation listed in the second section.

Whole Plot Fabric Swatch

In this study, the whole-plot experimental units were swatches sized 880 mm x 2840 mm (34.5 x 111 inches). The number of whole plot experimental units was three for each replicate (i.e., 3 weathering exposure conditions), and the total number of fabric swatches was nine because all the tests had three replicates (3 units x 3 = 9 units). Before preparing the sub-plot test specimens, each swatch was coded from one to nine by using a permanent marker pen (see Figure 3.1). These nine swatches were randomly divided into three groups, one for each replicate with random numbers generated by the Microsoft Excel software. Each group for one replicate contained three swatches, and these three swatches were randomly assigned to three different weathering conditions. The three random codes for the weathering conditions of each replicate are shown in Appendix A, “Coding System for Whole Plot Treatment Groups.”



1 -	**2nd Replicate** *Semi-tropical climate without water spray (Florida)*
2 -	**1st Replicate** *Semi-arid climate (Arizona)*
3 -	**3rd Replicate** *Standard conditioning*
4 -	**1st Replicate** *Standard conditioning*
5 -	**3rd Replicate** *Semi-arid climate (Arizona)*
6 -	**1st Replicate** *Semi-tropical climate without water spray (Florida)*
7 -	**2nd Replicate** *Semi-arid climate (Arizona)*
8 -	**2nd Replicate** *Standard conditioning*
9 -	**3rd Replicate** *Semi-tropical climate without water spray (Florida)*

Figure 3.1 Whole Plot Cutting Plan

Test Specimens in the Sub-Plot

As mentioned in the section of "*Research Design*," eight test specimens were cut from each whole plot fabric swatch (i.e. 2 test specimens for UVR value measurement x 4 combinations of the treatment factors of perspiration and washing action = 8 test specimens). A total of 24 test specimens were cut out from three fabric swatches for each replicate. Because three replicates were needed, a total of 72 test specimens were cut from the fabric swatches.

Test Specimen Size

During the weathering exposure process, specimen holders were used to secure the test specimens to prevent it blowing away by the high air flow. The exposure area in the specimen holder used in the weathering chamber was 97 mm x 44 mm (3.75 x 1.75 inches). To prevent the edges of the fabric from becoming distorted or frayed during laundering, 15 mm (i.e., 0.6 inch) of allowance was added to the four sides of the test specimens. According to the pilot test, this 15 mm allowance for each side was sufficient to endure distortions and protect the testing area of the specimen. Therefore, the actual test specimen was cut into a size of 127 x 74 mm (5 x 2.9 inches) (see Figure 3.2).

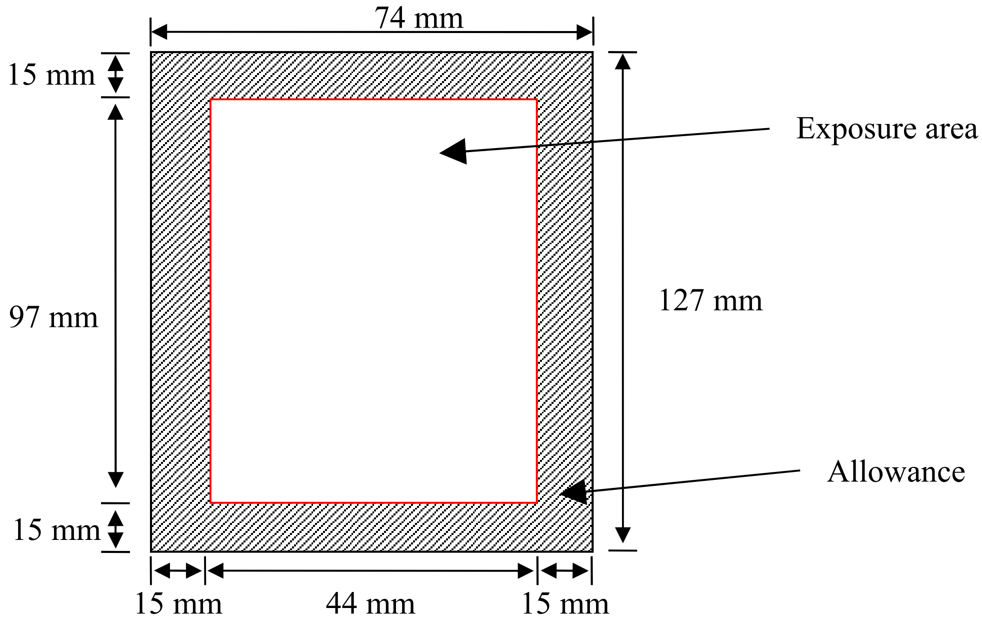


Figure 3.2 The Weathering Exposure Area of the Test Specimen

Test Specimens Cutting Procedures

According to Merkel (1991), when conducting repeated tests, the test specimens for the same test should not contain exactly the same warp or filling yarns. In general, different warp yarns used in a fabric are spun from a different piece of sliver on a different spindle, which may cause dissimilarity in the warp yarns. In order to best represent the full variability of the fabric, each test specimen should contain different warp and filling yarns. For this reason, three cutting plans, one for each replicate, were prepared to cut test specimens for the same test in different locations (see Figure 3.3).

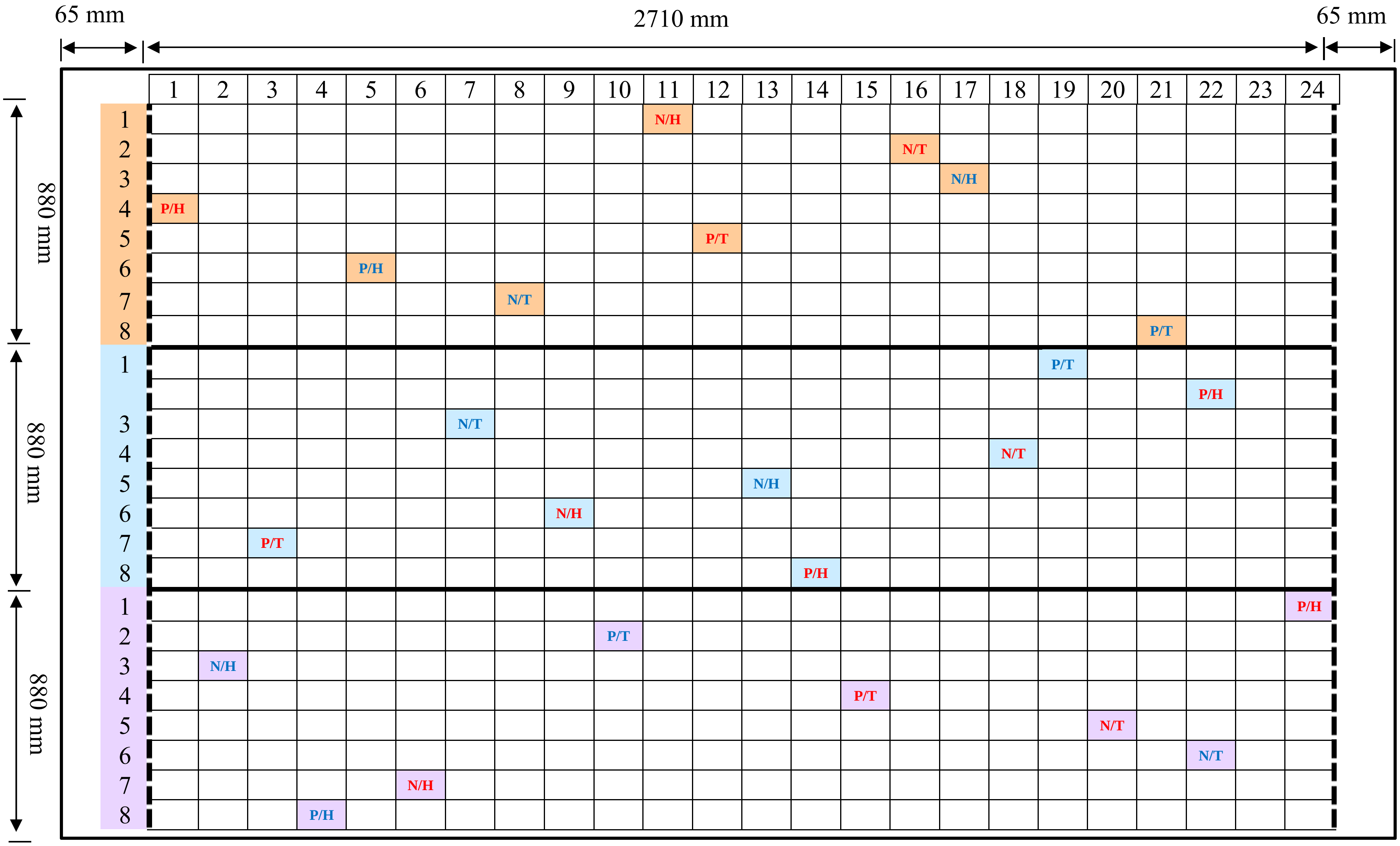
The processes for preparing the three cutting plans are listed below:

(a) The selvages of the fabrics are usually constructed in a different way from its body (i.e., the selvages are usually heavier to protect the fabric from damage in handling) (Merkel, 1991); therefore, no specimen was taken nearer than 65 mm (2.5 inches) on the fabric selvage edge. Based on this restriction, eight test specimens for each replicate were cut from the fabric with widths of 2710 mm (i.e., original fabric width was 2840 mm subtract two 65 mm from the two fabric selvages: 2840 mm – (2 x 65 mm) = 2710 mm).

(b) As mentioned above, eight test specimens for each replicate were cut from the fabric with full width. In order to avoid the test specimens for the three replicates sharing the same warp and filling yarns, all 24 test specimens from these three groups were included to determine the cutting locations (8 test specimens per replicate x 3 replicates = 24 test specimens). The remaining fabric width (i.e., 2710 mm) of the fabric swatch was divided into 24 columns, and the 24 test specimens were randomly assigned to one of these 24 columns. A random list, from number 1 to 24, was prepared to determine the locations of the 24 test specimens for three replicates in the horizontal direction (see Appendix B, "Column Number"). By this way, none of these test specimens will share the same warp yarns (see Figure 3.3). Similar procedures were applied to select the locations of the test specimens in the vertical direction, where the fabric length will be divided into eight rows for each replicate because there were eight test specimens for each replicate. Three random lists, from number 1 to 8, were prepared to determine the locations of the eight test specimens for each replicate in the vertical direction (see Appendix B, "*Row Number*").

(c) Based on the row number and column number, the location of each of the 24 test specimens for three replicates was randomly determined. For example, the test specimen for the first replicate, treated with perspiration and laundered in HE washer, and the first test specimen used to measure UVR value was located on row number 4 and column number 1. Orange background color was used to indicate the first replicate; blue background color was used to indicate the second replicate; and purple background color was used to indicate the third replicate.

(d) To show the perspiration and washing action treatment combination that were applied to each test specimen, 'P" was used to show the treatment of perspiration; "N" was used to show no perspiration treatment; "T" was used to show traditional washer; and "H" was used to show HE washer. In addition, the first test specimen used to measure UVR value was shown as red color and blue color for the second test specimen. For example, in Figure 3.3, the cell located in the third replicate, on row number 8 and column number 4 was labeled with “P/H” in a blue color, which indicated that this test specimen was treated with perspiration and washed in HE washer as well as it was the second duplicate for the measure of UVR value.



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
1											N/H													
2																N/T								
3																	N/H							
4	P/H																							
5												P/T												
6					P/H																			
7								N/T																
8																					P/T			
1																			P/T					
																						P/H		
3							N/T																	
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1																								P/H
2										P/T														
3		N/H																						
4															P/T									
5																				N/T				
6																						N/T		
7						N/H																		
8				P/H																				

Figure 3.3 Random Selection of Cutting Locations

1st Repeat Group

2nd Repeat Group

3rd Repeat Group

As mentioned in the section of "Research Design," each replicate contained three fabric swatches (i.e., whole plot experimental unit), one for each weathering condition, and these three fabric swatches shared the same cutting plan. In other words, for the same replicate, the eight test specimens were cut in the same locations from the three fabric swatches (i.e., one for each weathering condition). The test specimens cut from the same location and different swatches were treated with the same treatment combinations of perspiration and washing action but with different weathering exposure conditions. The reason for cutting the eight test specimens at the same locations was to reduce the discrepancy among the test fabrics because these test specimens shared the same warp yarns. The results measured from these test specimens can better determine whether the changes were caused by the perspiration and/or washing action treatment, instead of the differences among the test specimens.

After using each cutting plan to cut test specimens from three fabric swatches for the same replicate, a total of 72 test specimens were cut out from the nine whole plot units (i.e., 8 test specimens from each whole plot unit x 3 whole plot units for each replicate x 3 replicates = 72 test specimens). Before cutting out the test specimens, each test specimen was coded using a permanent marker to show the number of the fabric swatch that the test specimen cut from and the treatment factors that were applied to the specimen. The treatment of perspiration was coded as yes (P) and no treatment (N); weathering exposure was coded as – semi-tropical climate without water spray such as the climate in Florida (F), semi-arid climate such as the climate in Arizona (A), and standard conditioning (S); washing action was coded as traditional washer (T) and HE washer (H); and the number of the test specimens used to measure UVR value was shown as 01 and 02. For example, a specimen cut from the first fabric swatch (1), for the 2nd replicate (2), treated with perspiration (P), exposed to the semi-tropical climate without water spray weather condition (Florida), washed in a traditional washer (T), and for the second test specimen used to measure UVR value (02) was coded as 12PFT02.

After cutting out these 72 specimens, three pairs of benchmarks in the length direction with a length of 97 mm in each pair and three pairs of benchmarks in the width direction with a length of 44 mm in each pair were marked by using a permanent marker pen to indicate the weathering exposure area as well as to determine dimensional change (see Figure 3.4). In addition, the edges of each test specimens were pinked with a pinking scissor to help prevent the fabric from unraveling during laundering.

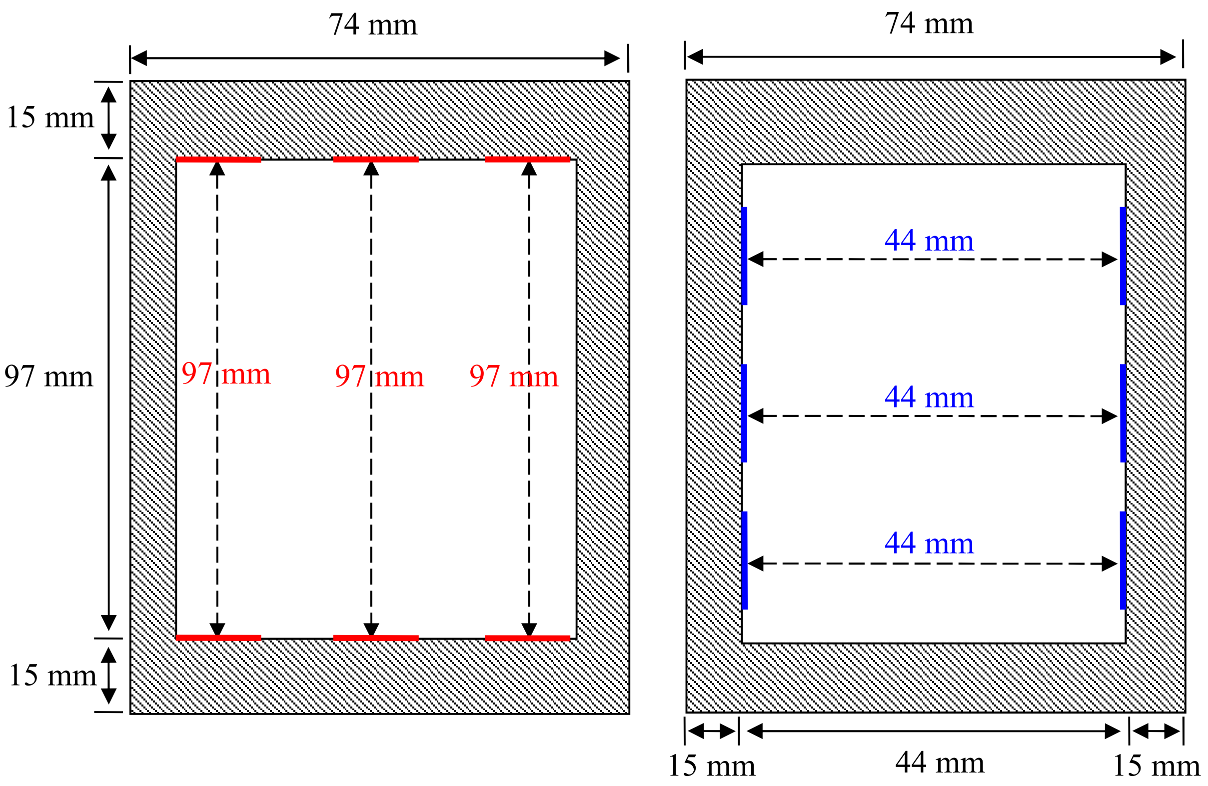

Figure 3.4 **The indication of weathering exposure area and the benchmarks for dimensional change test**

Experiment Timeline and Procedures

There were three sub-sections for the section of Experiment Timeline and Procedures. The first section discusses the timeline of experiments for the three replicates. The second section discusses measurements, which explains the test methods and procedures of measurements for the primary dependent variable, UPF value change, and the additional five dependent variables (i.e., fabric count change, thickness change, weight change, color change, and dimensional change). The last section is testing procedures addressing the methods and procedures of each treatment (i.e., perspiration application, weathering exposures, washing action of automatic home clothes washers, and repeated laundering).

The Timeline of Experiments for the Three Replicates

In this study, all test specimens were treated in the sequence of perspiration application (i.e., with or without the application), followed by weathering exposure (i.e., semi-tropical climate without water spray as the climate in Florida, semi-arid as the climate in Arizona, or standard conditioning), and ending with laundering (i.e., washed in a traditional or a HE washer). For each replicate, this sequence of treatments was conducted, once for each type of weathering exposure conditions. In order to efficiently use the weathering chamber, as well as shortening the entire experimental time, three replicate repeat groups were handled at the same time. Because only one weathering chamber was available to be used in this study and there were two weathering exposure conditions, the test specimens of one type of weathering exposure condition were treated first and then the second type of weathering exposure treatment followed. In order to reduce all unknown extraneous variables caused by the order of the weathering, the order of running the weathering conditions was randomized so that all test specimens had an equal chance to receive the nuisance variables. The random code for weathering exposure order for each replicate was shown in Appendix C.

For the first replicate, after the first set of test specimens were treated with perspiration and put in the weathering chamber to be exposed to a condition similar to semi-tropical climate (Florida), the perspiration was applied to the test specimens used for the standard conditioning. Instead of being exposed in the weathering chamber, the test specimens for this standard conditioning were put into the conditioning chamber. For the test specimens used for the second type of weathering exposure (i.e., semi-arid as the climate in Arizona), the perspiration was applied about three hours before the first type of weathering exposure treatment ends. Before the second type of weathering exposure starts, there was a 15-minute break to make sure that the temperature of the weathering chamber goes back to room temperature (see Figure 3.5). After the completion of the three types of weathering exposure for the first replicate and after a 15-minute break, the weathering exposure for the second replicate was started. Similarly, after the completion of the three types of weathering exposure for the second replicate and after a 15-minute break, the third replicate started to be exposed in the weathering chamber. Because there were 15 laundering cycles, the same procedures, including perspiration treatment, weathering exposure, and laundering, were repeated for 15 times for each replicate. Figure 3.5 shows an example of the timeline of experiments for the three replicates.

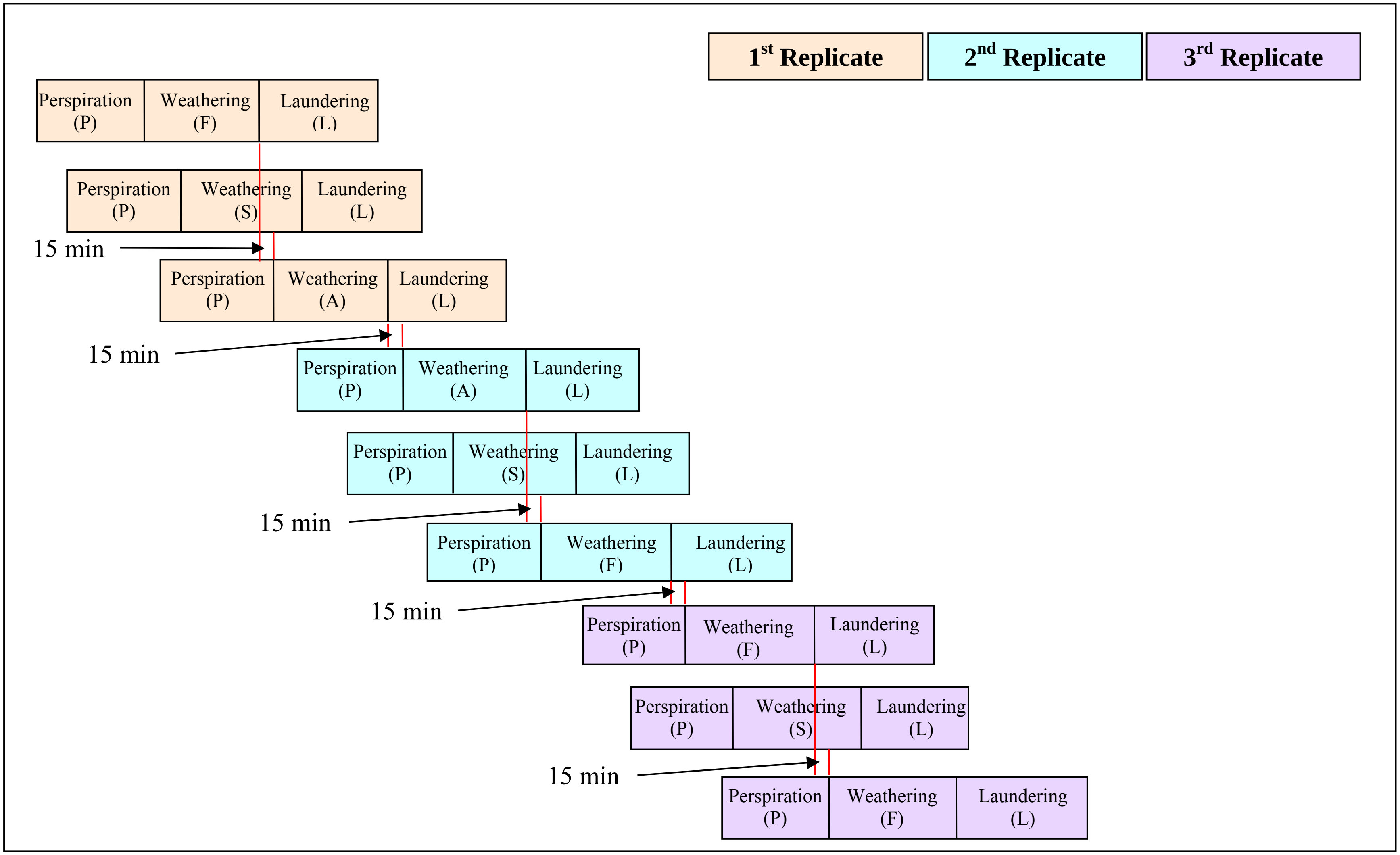

Figure 3.5 The Timeline of Experiment for the Three Replicates

Measurements

In order to understand how the four treatment factors (i.e., perspiration application, weathering exposures, washing action of automatic home clothes washers, and repeated laundering) affect the UPF value change and the addition five fabric properties (i.e., fabric count change, thickness change, weight change, color change, and dimensional change), the changes of UPF value and the other five fabric properties were calculated based on the measurements from the same test specimen, sized 127 x 74 mm (4.5 x 2.9 inches), before and after each sequence of the four treatments. The results of comparing the before and after treatment measurements can indicate whether the treatment factors have any effect on the UVR protection or the five fabric properties.

Before conducting any measurements or tests, the test specimens were conditioned in a laboratory conditioning chamber of model G212D1-D6 according to the ASTM D1776 – 08e1: Standard Practice for Conditioning Textiles for Testing, in which, a relative humidity of 65 ± 2% and a temperature of 21 ± 1 °C (70 ± 2 °F) were specified as the conditioning situation for the test specimens. Table 3.2 lists the minimum hours required for specimen conditioning in each test. Based on this table, all specimens were conditioned for at least six hours before conducting any tests as well as for data collection.

Table 3.2 Minimum Hours Required for Specimen Conditioning in Each Test

Test	Test Method	Minimum Conditioned Hours
Fabric Count	ASTM D3775	6 hours
Fabric Weight	ASTM D3776	6 hours
Fabric Thickness	ASTM D1777	6 hours
UVR Protection	AATCC TM 183	4 hours
Color Change	AATCC TM 61	4 hours
Dimensional change	AATCC TM 135	4 hours (lay flat after wash)

After all the cutting, labeling codes, and marking of benchmarks, all 72 test specimens were sorted into three replicates (i.e., 24 test specimens each group) and then put into the conditioning chamber. When the experiment for the first replicate starts, 24 test specimens for this group were removed from the conditioning chamber after at least six hours of conditioning for the pre-measurement of UPF value, fabric count, fabric thickness, fabric weight, initial color, and original dimension of each specimen. After recording the pre-measurement, these test specimens were ready for the treatments. Upon completion of each sequence of the four treatments, these test specimens were conditioned for another six hours, and then the six fabric properties of these test specimens were measured again. For each replicate, the test specimens were treated for 15 times of the sequence of the four treatment factors, and measurements were taken after each sequence. Therefore, each test specimen was measured 15 times after the treatments. Similarly, the same procedures were applied for the second and third replicates. The descriptions of the test methods and procedures of measuring each of the six dependent variables (i.e., UPF value change, fabric count change, thickness change, weight change, color change, and dimensional change) are listed in the following sections:

UVR Protection of the Test Fabric and UVR Protection Change of the Test Specimen

In this study, UPF value change was used to indicate the change of UVR protection. A Labsphere's UV-1000F series Ultraviolet Transmittance Analyzers was used to determine the UPF values in accordance with the AATCC Test Method 183 – 2010: Transmittance or Blocking of Erythemally Weighted Ultraviolet Radiation Through Fabrics. A minimum of two specimens from each swatch was required to measure the UPF values. According to the test method, the required specimen size is 50 x 50 mm (2.0 x 2.0 inches). However, all the tests in this study were conducted on the test specimens with the size of 127 mm x 74 mm (5 x 2.9 inches). To measure the UPF value, the weathering exposure area was placed between the UV source and a sensor to measure the UV transmittance of the test specimen. For each specimen, three measurements of the UV transmittance were measured in the warp, filling, and bias (45° diagonal) directions (i.e., one measurement per direction). The UPF values of each specimen will be automatically calculated by the UV-1000F software, which will be based on the formula provided below. In the current study, the initial UPF value of the test fabric was the average of the UPF values of all 72 test specimens.

$$UPF = \frac{\sum_{280\,nm}^{400\,nm} E_\lambda * S_\lambda * \Delta\lambda}{\sum_{280\,nm}^{400\,nm} E_\lambda * S_\lambda * T_\lambda * \Delta\lambda}$$

where

E_λ = erythemal spectral effectiveness
S_λ = solar spectral irradiance in $Wm^{-2}nm^{-1}$
T_λ = average spectral transmittance of the fabric specimen
$\Delta \lambda$ = measured wavelength interval in nanometers (nm)
λ = wavelength of light in nm

To understand the effects of the four treatments on UPF value change of each test specimen, the UPF value change was calculated by subtracting the fabric count pre-treatment measurement of the test specimen (i.e., the UPF value of the test specimen before any treatment has been applied) from the measurement of the test specimen after each laundering cycle (UPF value change = UPF value measurement after each laundering cycle – UPF value pre-treatment measurement).

Fabric Count of the Test Fabric and Fabric Count Change of the Test Specimen

Fabric count of the test fabric was measured using the ASTM D3775 – 12: Standard Test Method for Fabric Count of Woven Fabric. A document camera was used to take a picture that shows an enlarged fabric structure picture of each test specimen on a white board. These enlarged fabric structure pictures were used to count the number of yarns per 25 mm (i.e., fabric count). For each test specimen, the number of warp and filling yarns in 25 mm of fabric were counted separately. When stating the count of a fabric count, the warp yarn count is indicated first, followed by the filling yarn count. For example, if a warp yarn count is 100 and a filling yarn count is 40, the fabric count will be shown as 100 X 40. In the current study, the fabric count of the test fabric was the average of the warp yarn count of the 72 test specimens and the average of the filling yarn count of the 72 test specimens.

To understand the effects of the four treatments on fabric count change in warp and filling directions of each test specimen, the fabric count change for each direction was calculated by subtracting the fabric count pre-treatment measurement of the test specimen (i.e., the fabric count of the test specimen before any treatment has been applied) from the measurement of the test specimen after each laundering cycle (Fabric count change = Fabric count measurement after each laundering cycle – Fabric count pre-treatment measurement).

Fabric Thickness of the Test Fabric and Thickness Change of the Test Specimen

Fabric thickness of the test fabric was measured using the ASTM D1777 – 96 (2011)e1[4]: Standard Method for Thickness of Textile Materials. A ProGage Thickness Tester was used to measure the thickness of the fabric. The test specimens were handled carefully by placing them face side up on the anvil of the dual speed pressure foot, to avoid altering the natural state of the fabric. The pressure foot was gradually lowered into contact with the swatch, and it took five to six seconds to apply full pressure. Testing Option 1 for woven, knitted, and textured fabrics was selected, and the applied pressure for this section was 4.14 ± 0.21 kPa (0.06 ± 0.03 psi). The distance between two pressure foots was the fabric thickness of the specimen, and the thickness of the test specimens was reported in millimeters to the nearest 0.02 mm. For the current study, the fabric thickness of the test fabric was the average reading from all the 72 test specimens.

To understand the effects of the four treatments on thickness change of each test specimen, the thickness change was calculated by subtracting the pre-treatment measurement of the test specimen (i.e., the thickness of the test specimen before any treatment has been applied) from the measurement of the test specimen after each laundering cycle (Thickness change = Thickness measurement after each laundering cycle – Thickness pre-treatment measurement).

Fabric Weight of the Test Fabric and Weight Change of the Test Specimen

Fabric weight of the test fabric was measured using the ASTM D3776/D3776M – 09a (2013)[5]: Standard Test Method for Mass Per Unit Area (Weight) of Fabric, Option C – Small Swatch of Fabric. For small swatches of fabrics, the size of the specimen in the test method requires an area of at least 13,000 mm^2 (20 inch^2); however, in this study, all tests were conducted on the test specimen, sized 127 mm x 74 mm (5 x 2.9 inches). A Denver Mettler balance was used to measure the weight of the test specimens to the nearest 0.001g for each test specimen. The formula for calculating fabric weight was listed on the next page, and the fabric weight was reported in grams per meter squared (g/m^2). For the current study, the fabric weight of the test fabric was the average reading from all the 72 test specimens.

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[4] 96 = year of original or the year of last revision; (2001) = year of last re-approval; e1 = indicates editorial change

[5] M = SI units; 09 = year of original adoption or the year of last revision; a = indicates subsequent revision in same year; (2013) = year of last re-approval.

$$W\ (g/m^2) = G\ (g)\ /\ A\ (m^2)$$

where

W = Fabric Weight
G = Weight of Specimen
A = Area of Specimen

To understand the effects of the four treatments on weight change of each test specimen, the weight change was calculated by subtracting the weight pre-treatment measurement of the test specimen (i.e., the fabric weight of the test specimen before any treatment has been applied) from the measurement of the test specimen after each laundering cycle (Weight change = Weight measurement after each laundering cycle – Weight pre-treatment measurement).

Fabric Initial Color of the Test Fabric and Color Change of the Test Specimen

The initial color of the test fabric was measured using the AATCC Evaluation Procedure 7-2009: Instrumental assessment of the change in color of a test specimen. A Hunter LabScan LS5100 spectrophotometer was used to measure the initial color and the color after each sequence of four treatments. In this study, an instrumental measurement method was selected to be used to evaluate color change instead of a subjective visual assessment method. A prior study examining the relationship between color and UVR protection showed that the instrumental CIE measurements successfully differentiated the color from each other (Wilson et al., 2008). However, the visual assessment failed to identify the difference between colors. To understand if the color change after the four treatments has a relationship with the UVR protection of a NC lightweight cotton fabric, it is important to precisely measure the color change. For this reason, an instrumental measurement method will be used.

According to the CIELAB Color System, each color can be described by using L, a, and b. L is the lightness-darkness dimension; *a* is the redness-greenness dimension; and *b* is the yellowness-blueness dimension. Therefore, the initial color of the test specimen was shown by using L, a, and b. The color change between two test specimens or before and after treatments measured is called Delta E (ΔE), and the color change of each specimen was calculated based on the following formula:

$$\Delta E = \sqrt{(\Delta L)^2 + (\Delta a)^2 + (\Delta b)^2}$$

where

$\Delta L = L_{\text{after each laundering cycle}} - I_{\text{initial color}}$ (L: lightness or darkness)

$\Delta a = a_{\text{after each laundering cycle}} - a_{\text{initial color}}$ (a: Redness or greenness)

$\Delta b = b_{\text{after each laundering cycle}} - b_{\text{initial color}}$ (b: yellowness or blueness)

Dimensional Change of the Test Specimens

The dimensional change of the test specimen was measured and calculated using the AATCC Test Method 135 – 2012: Dimensional Changes of Fabrics after Home Laundering. Originally, the size of the specimen in the test method requires an area of 380 × 380 mm (15 × 15 inches). However, in this study, all tests were conducted on the test specimen sized 127 mm x 74 mm (5 x 2.9 inches). The distances between the benchmarks in the length and width direction were measured separately before and after the tests (see Figure 3.4), and the dimensional changes of length and width of the test specimens were calculated by the formula below and were reported separately to the nearest 0.1%. A negative number in the dimensional change implies shrinkage, and a positive number in the dimensional change implies growth.

$$\%\ \text{Dimension al Change} = 100\ \text{x}\ \frac{\text{Dimension after laundering - Dimension of pre - treatment measuremen t}}{\text{Idimension of pre - treatment measuremen t}}$$

Testing Methods and Procedures

After the pre-treatment measurements of 24 test specimens for the first replicate, they were sorted into three weathering exposure treatment groups, and each group had eight test specimens. According to Appendix C: the order of weathering exposure in the weathering chamber, for the first replicate, the eight test specimens for the semi-tropical climate without water spray weathering condition (i.e., Florida) were exposed first. While these test specimens were exposed in the weathering chamber, the rest of 16 test specimens, eight for the standard conditioning (i.e., control) and eight for the semi-arid weathering condition (i.e., Arizona) were put into the conditioning chamber right after the pre-treatment measurement (see Appendix C).

For the eight test specimens that were exposed to the semi-tropical climate without water spray weathering condition (i.e., Florida), four specimens were treated with perspiration and the other four specimens were served as a control group, which were stored in the conditioning chamber. The test method and the procedures of perspiration treatment for these four test specimens are described in the following section.

Perspiration

Perspiration treatment for the four test specimens was applied using the following procedures based on the AATCC TM 125 – Colorfastness to Perspiration and Light:

1) The artificial perspiration was prepared according to the AATCC TM 125 – Colorfastness to Perspiration and Light. According to this test method, the artificial perspiration solution perspiration solution contained 10 g of sodium chloride, 1 g lactic acid, 1 g disodium hydrogen phosphate, and 0.25 g histidsine monohydrochloride per liter of the solution. The solution was hand-stirred with a glass rod to ensure even distribution. A pH meter was used to ensure the solution is 4.3 ± 0.2. Because artificial perspiration turns alkaline due to bacteriological contamination (Vass, 1931; the Perspiration Fastness Subcommittee in AATCC, 1952), the artificial perspiration solution was prepared fresh for each perspiration treatment.
2) The test specimens were placed in a petri dish that was 20 mm deep and 90 mm in diameter. A prepared artificial perspiration solution was added to a depth of 15 mm in the petri dish, and the four test specimens were soaked in the solution for 30 ± 2 min with occasional agitation and squeezing to ensure complete wetting.
3) After 30 ± 2 min, the test specimens were removed from the solution and each specimen was passed through a laboratory wringer to remove excess solution. The test specimens were weighed again to ensure it weights double its original weight.

The same perspiration procedures were applied to all the test specimens before they were exposed to any type of weathering exposure treatment.

Weathering Exposure

For the first replicate, after four test specimens treated with perspiration and four test specimens without the perspiration treatment, these eight test specimens were exposed to the semi-tropical climate without water spray weathering condition (i.e., Florida) condition. The test methods and the detailed procedures of the weathering exposure treatment are listed in the following:

1) The AATCC Test Method 169 – Weather Resistance of Textiles, Xenon lamp exposure was followed for the weathering exposure test. A Q-Sun Xenon Test Chambers Xe-3-HS was used to simulate the weather exposure conditions. Before the first test is performed, the Q-Sun Xenon Test Chamber was calibrated and operated for 20 hours to ensure the equipment was fully operational.
2) The eight test specimens were mounted in the exposure frame, and the face sides of the test specimens were directly exposed to the radiant source.
3) Based on the AATCC Test Method 169 – Weather Resistance of Textiles, Xenon lamp exposure, the conditions of light durations, relative humidity, black panel temperatures, and level of irradiance for the three selected weathering exposure conditions are listed in Table 3.3. Each exposure cycle is 120 minutes (2 hours). The test method does not give a certain cycle that a specimen should be exposed to, only suggesting at least seven days of exposure time (i.e. 7 x 24 hours = 168 hours). Based on the pilot test result, the UPF values did not show significant change after 300 hours. Therefore, 20 hours (10 cycles) of exposure time was used to fulfill the minimum requirement of 168 hours of exposure (20 hours x 15 laundering cycles = 300 hours).

Table 3.3 Weathering Exposure Procedures in the Three Selected Weather Conditions

Weather Condition	**Light Durations per cycle**	**Water Spray**	**Relative Humidity (RH)**	**Black panel / Black Standard Thermometer temperature**
Control (*Standard conditioning*)	Continuous dark (120 min)	No water sprays	65 ± 2%	21 ± 1 °C (70 ± 2 °F)
Semi-tropical climate without water spray (*Florida*)	Continuous light (120 min)	No water sprays	70 ± 5%	77 ± 3 °C (170 ± 5 °F)
Semi-arid climate (*Arizona*)	Continuous light (120 min)	No water sprays	27 ± 5%	77 ± 3 °C (170 ± 5 °F)

Laundering

Once after all the eight test specimens had been exposed to the designated weathering condition, they were put into two different washers (i.e., traditional washer and HE washer) separately. The test specimens will be washed based on AATCC Test Method 135 – Dimensional Changes of Fabrics after Home Laundering. The laundering procedures are as follows:

1) A Maytag Automatic Washer of Model A806, which is qualified for AATCC standard laundering conditions for traditional washers, was used to represent the traditional washer, and a Whirlpool® Duet Sport® Front-Loading Washer Model WFW8300SW was used to represent the front-loading HE washer.
2) Plain-woven fabrics were used as ballast and were added to the washer with the test specimens to make a 4.00 ± 0.13-pound (lb) (1.8 ± 0.06 kg) wash load.
3) Similar washer settings were used for the traditional washer and front-loading HE washer. The traditional washer was set on regular wash, regular spin, warm wash, warm rinse, and normal water level. In the case of the front-loading HE washer, the washer was set on normal/casual wash, medium speed spin, and warm wash conditions.
4) "2X Ultra Tide® Free" regular liquid laundry detergent was used for the laundering in the traditional washer. For the front-loading HE washer, "2X Ultra Tide® HE" HE liquid laundry detergent was used for the laundering. The amount of detergent used

was determined by the manufacturer recommendation (i.e., fill the detergent to the lower line of the cup for a medium load, for all washers).

5) After the four test specimens were washed in the traditional washer and the other four test specimens were washed in the HE washer, these eight test specimens were gathered together and placed in a MAYTAG Automatic Tumble Dryer of Model DE806 with the dialing set on a regular setting. The ballast fabrics in one of the wash loads were dried together with the eight test specimens because if the ballast fabrics in both loads were added into the dryer, the load sizes would be more than 4.00 ± 0.13 pound (lb), exceeding the test method requirement. For this reason, a random list was prepared to show the ballast fabrics of which wash load was taken into the dryer (see Appendix D). The total drying time was approximately 40 minutes. The wash load was promptly removed from the dryer to avoid over-drying.
6) After one laundering and drying cycle, all these eight test specimens were removed and immediately put in the conditioning chamber. After a minimum of six hours of conditioning, these test specimens were gathered and measured in order to determine the six fabric properties after one wash. The same laundering procedures were repeated for up to 15 laundering cycles.

Data Analyses

The Statistical Analysis System (SAS) software was used to analyze the UPF rating of each specimen. Two types of statistical analysis were used for the data analysis in this study. In descriptive statistics analyses, mean was used to show the UPF value, fabric count, fabric thickness, and fabric weight of the test fabric. In addition, mean was also used to show the UPF value change, fabric count change, thickness change, weight change and color change of the test specimens due to the four treatment factors (perspiration application, weathering exposures, washing action of automatic home clothes washers, and repeated laundering). Percentage was used to show the dimensional change of the test specimens after each treatment cycle. In the inference statistics analyses, three factors, repeated measured ANOVA were used to test Hypotheses 1 and 3 to 7 to examine the effects of the four treatment factors on the UPF value change as well as the five secondary dependent variables. A Multiple regression analysis was used to test Hypothesis 2, and a model of the four treatment factors was developed to predict the UPF value change. A confidence level of $p < .01$ was used to establish significance. The Tukey's Honestly Significant Difference Test (THSDT) was used to perform multiple comparisons between group means.

CHAPTER IV

RESULTS AND DISCUSSION

This chapter is organized into three parts. The first part lists all the findings, analyses of the results and tests of hypotheses, which are organized based on the purposes of this study [i.e., the findings and analyses of the results of the primary purpose (i.e., UPF value change) are listed first and the findings and analyses of the results of the secondary purpose (i.e., five fabric properties) are listed in the second]. The second part lists the summary, and recommendations are listed in the last part.

Findings

Descriptive Statistics

As explained in the measurement section in Chapter 3, the fabric characteristics components are the average results of the total of 72 test specimens. The results are listed in the table on the next page:

Table 4.1 Fabric Characteristics

UPF value	**Fabric count** (warp x filling)	**Fabric thickness** (mm)	**Fabric weight** (g/m^2)
44.66 (Excellent UVR Protection)	107 x 70	0.248	130

Hypotheses Testing Results

In this section, the results of the study are presented based on the purposes of the study, where the hypotheses related to the primary purpose (i.e., UPF value changes testing) are listed in the first sub-section and the hypotheses related to the secondary purpose (i.e., the five fabric properties) are listed in the second sub-section. Under the hypotheses in each section, the SAS codes used to analyze the particular hypotheses are also included, and the results of the hypotheses are listed at the end of each sub-section separately.

Analyses of Primary Purpose – UPF Value Change

Hypothesis 1: Perspiration application, weathering exposure, washing action of automatic home clothes washers, and repeated laundering will influence the UPF value change of the test specimens.

Table 4.2 Repeated Measures Analysis of Variance Testing of Fixed Effects on UPF changes

Source	**df**	***F***
Weathering main effects (***Whole plot***)	2	679.57**
Perspiration main effects (***Split- plot***)	1	604.43**
Washing Action main effects	1	128.01**
Weathering x *Perspiration* interaction	2	230.71**
Weathering x *Washing Action* interaction	2	7.89*
Perspiration x *Washing Action* interaction	1	9.58*
Weathering x *Perspiration* x *Washing Action* interaction	2	0.60
Repeated Laundering (Cycle) main effects (***Repeated Measures***)	15	32.05**
Repeated Laundering x *Weathering* interaction	30	119.03**
Repeated Laundering x *Perspiration* interaction	15	5.32**
Repeated Laundering x *Washing* interaction	15	1.57
Repeated Laundering x *Weathering* x *Perspiration* interaction	30	2.77**
Repeated Laundering x *Weathering* x *Washing Action* interaction	30	0.55
Repeated Laundering x *Perspiration* x *Washing Action* interaction	15	0.38
Repeated Laundering x *Weathering* x *Perspiration* x *Washing Action* interaction	30	0.41

******p* value < 0.01;** *p* value < 0.0001

H1a: There is an interaction among the effects of the application of four treatment factors (i.e., perspiration application, weathering exposure, washing action of automatic home clothes washers, and repeated laundering) on the UPF value change of test specimens.

When the interactions among perspiration, weathering exposure, washing action of automatic home clothes washers, and repeated laundering on the UPF value change were examined, the four-factor interaction (i.e., *Repeated Laundering* x *Weathering* x *Perspiration* x *Washing Action* interaction) was not significant ($F = 0.41$, $p = 0.9976$) (see Table 4.1). However, one of the three-way interactions was found significant (i.e., *Repeated Laundering* x *Weathering* x *Perspiration* interaction with $F = 2.77$, $p < 0.0001$) although the other three three-way interactions [i.e., *Weathering* x *Perspiration* x *Washing Action* interaction ($F = 0.60$, $p = 0.5512$), *Repeated Laundering* x *Weathering* x *Washing Action* interaction ($F = 0.55$, $p = 0.9714$) and *Repeated Laundering* x *Perspiration* x *Washing Action* interaction ($F = 0.38$, $p = 0.9804$)] were not significant. These results indicated that the influences of perspiration and weathering on UPF value change were different in various laundering cycles. To further confirm this finding, a three-way interaction figure was plotted and a significant interaction was found (see Figure 4.1). The means and standard deviations for UPF value change as a function of the weathering, perspiration, and repeated cycles are presented in Table 4.3. Therefore, H1a is supported.

Table 4.3 Means and Standard Deviations for UPF value change by Weathering, Perspiration, and Repeated Cycles

		Weathering Conditions						
Cycle	Perspiration	Standard Conditioning		Florida		Arizona		
		Mean	SD	Mean	SD	Mean	SD	*F*
1	No Perspiration	-1.04 ^{ax}	2.70	-9.63 ^{bx}	1.75	-10.19 ^{bx}	3.07	31.17*
	With Perspiration	-0.67 ^{ax}	1.76	-8.56 ^{bx}	2.92	-9.35 ^{bx}	3.09	27.93*
2	No Perspiration	2.08 ^{ax}	2.15	-13.74 ^{bx}	1.91	-13.14 ^{bx}	1.92	97.62*
	With Perspiration	2.50 ^{bx}	3.14	-10.30 ^{by}	1.67	-10.41 ^{by}	2.93	66.92*
3	No Perspiration	2.71 ^{bx}	3.30	-17.08 ^{bx}	2.03	-15.43 ^{bx}	2.35	146.32*
	With Perspiration	2.94 ^{bx}	1.77	-12.31 ^{by}	2.30	-12.81 ^{by}	3.28	97.40*
4	No Perspiration	3.94 ^{bx}	2.90	-18.48 ^{bx}	1.29	-16.32 ^{bx}	2.47	185.72*
	With Perspiration	4.17 ^{bx}	1.95	-13.31 ^{by}	2.47	-13.69 ^{by}	2.92	126.43*
5	No Perspiration	5.84 ^{bx}	2.71	-21.39 ^{bx}	1.72	-18.17 ^{bx}	2.99	268.69*
	With Perspiration	4.89 ^{bx}	2.30	-13.94 ^{by}	3.13	-14.31 ^{by}	3.62	146.37*
6	No Perspiration	5.88 ^{bx}	2.21	-23.71 ^{bx}	1.86	-20.15 ^{bx}	2.43	317.03*
	With Perspiration	5.38 ^{bx}	1.55	-16.20 ^{by}	2.45	-15.86 ^{by}	3.33	185.60*
7	No Perspiration	8.03 ^{bx}	2.04	-25.50 ^{bx}	1.48	-21.27 ^{bx}	2.97	404.95*
	With Perspiration	5.64 ^{by}	1.72	-16.72 ^{by}	3.50	-17.24 ^{by}	3.37	207.12*
8	No Perspiration	9.31 ^{bx}	2.53	-26.69 ^{bx}	1.69	-23.42 ^{bx}	2.67	481.53*
	With Perspiration	8.71 ^{by}	2.96	-17.80 ^{by}	3.55	-18.21 ^{by}	2.94	288.90*
9	No Perspiration	11.79 ^{bx}	3.18	-24.06 ^{bx}	4.41	-23.28 ^{bx}	3.22	509.33*
	With Perspiration	10.21 ^{bx}	2.75	-18.16 ^{by}	3.07	-18.11 ^{by}	3.10	325.13*
10	No Perspiration	11.81 ^{bx}	2.95	-27.86 ^{bx}	1.75	-23.78 ^{bx}	2.81	578.12*
	With Perspiration	12.24 ^{bx}	3.56	-18.45 ^{by}	3.35	-18.17 ^{by}	3.04	377.82*
11	No Perspiration	13.33 ^{bx}	4.91	-28.94 ^{bx}	1.71	-25.31 ^{bx}	3.25	666.54*
	With Perspiration	13.53 ^{bx}	3.03	-19.61 ^{by}	2.75	-19.89 ^{by}	3.42	448.15*
12	No Perspiration	13.57 ^{bx}	3.25	-29.14 ^{bx}	1.94	-25.52 ^{bx}	3.38	681.11*
	With Perspiration	11.53 ^{bx}	2.06	-20.05 ^{by}	3.54	-19.99 ^{by}	2.99	402.74*
13	No Perspiration	14.80 ^{bx}	4.91	-29.69 ^{bx}	1.78	-26.92 ^{bx}	3.26	754.57*
	With Perspiration	13.27 ^{bx}	2.43	-20.02 ^{by}	2.92	-20.87 ^{by}	3.06	460.13*
14	No Perspiration	12.99 ^{bx}	3.25	-30.05 ^{bx}	1.84	-26.98 ^{bx}	3.16	700.12*
	With Perspiration	13.12 ^{bx}	2.21	-18.98 ^{by}	4.33	-20.55 ^{by}	3.41	438.50*
15	No Perspiration	14.58 ^{bx}	3.29	-30.77 ^{bx}	1.92	-27.51 ^{bx}	3.55	776.99*
	With Perspiration	13.74 ^{bx}	2.51	-20.75 ^{by}	3.26	-20.96 ^{by}	3.24	484.46*

$^{a, b}$ In the same column, means with different superscript letters are significantly different at 0.01 level by THSDT. $^{x, y}$ In the same row, means with different superscript letters are significantly different at 0.01 level by THSDT. * $p < 0.0001$

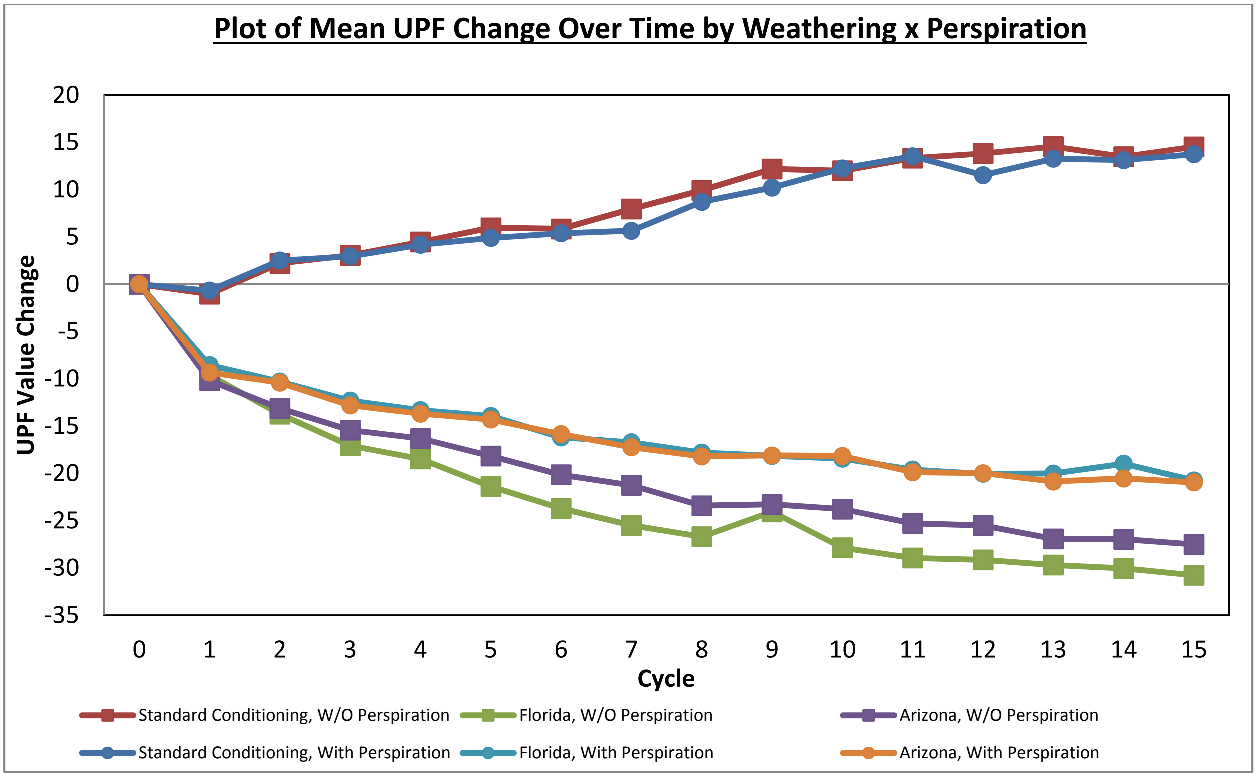


Figure 4.1 Plot of Mean UPF Value Change by Weathering and Perspiration Combination after Repeated Laundering

***H1b**:* There is a difference in UPF values between the test specimens treated with and without perspiration. The test specimens treated with perspiration will have a greater change in UPF value than the specimens without treatment.

According to Maxwell and Delaney (2003), a significant three-way indicates that the two-way interaction is not similar at each level of the third factor. Because three-way interaction was found, a series of follow-up tests of using two-way ANOVA were performed to examine the two-way interactions separately at each individual level of the third factor (i.e., the *Repeated Laundering* x *Weathering* under the condition of with and without perspiration application, *Repeated Laundering* x *Perspiration* at three levels of the *Weathering Exposure*, and *Weathering* x *Perspiration* at 16 levels of *Repeated Laundering*). In order to understand the effect of perspiration application, the *Weathering* x *Repeated Cycle* interaction was examined separately for each level of perspiration application (i.e., with or without perspiration). The results showed that significant differences were found. For test specimens stored in the Standard conditioning, regardless of being treated with or without perspiration, no significant differences in UPF value change were found between 1st and 6th cycle as well as from 8th cycle to 15th cycle. A significant difference was found after seventh cycle. For all the test specimens, regardless of being exposed to any of the weathering conditions (i.e., Florida and Arizona) and treated with or without perspiration, significant differences in UPF value change were found after the second cycle (see Figure 4.2). Those test specimens stored in the Standard conditioning showed positive changes in UPF values as the number of laundering cycles increased, while those exposed to Florida and Arizona conditions showed negative changes in UPF values as the number of laundering cycles increased. A positive number of UPF value change indicates the UPF value has increased (i.e., UVR protection increase), while a negative number indicates that the UPF value has decreased (i.e., UVR protection decreased). The proposed hypothesis stated that test specimens treated with perspiration were expected to have greater UPF value change, and different results were found, where test specimens treated with perspiration had a lower UPF value change. Based on these results, Hypothesis H1b was rejected despite significant differences found between test specimens treated with and without perspiration.

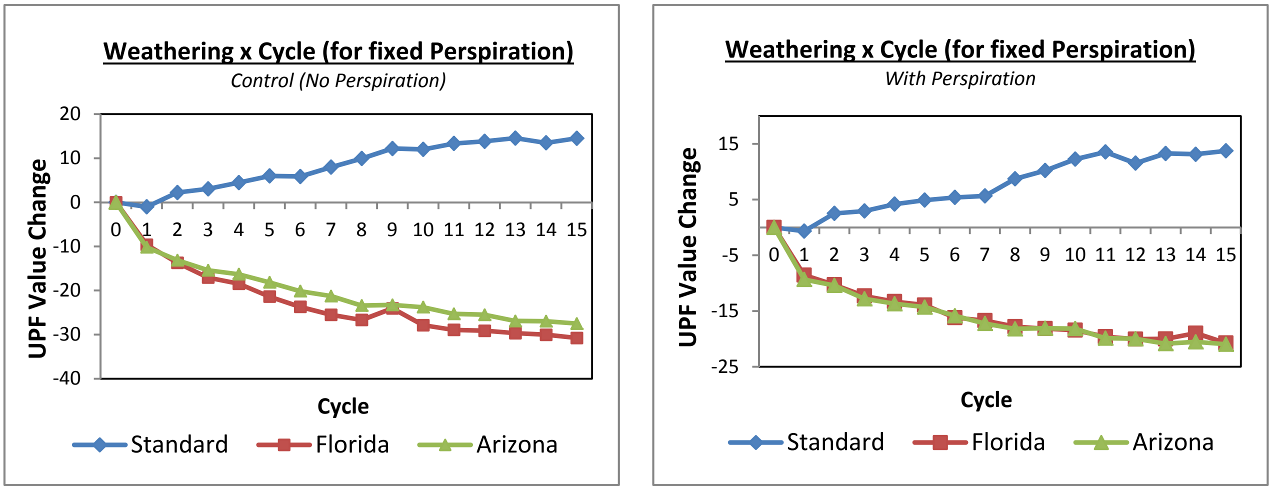
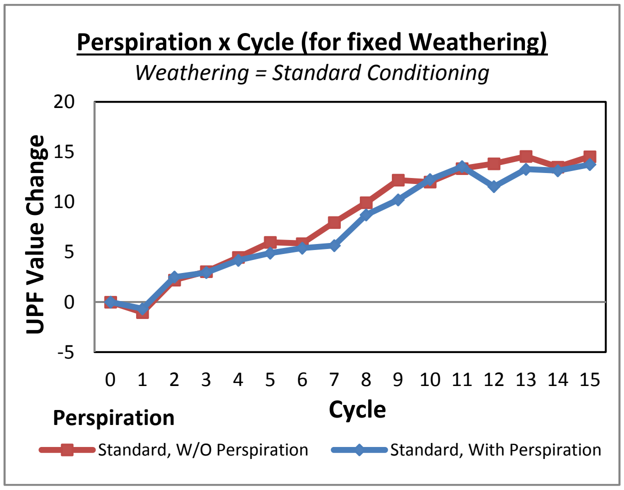
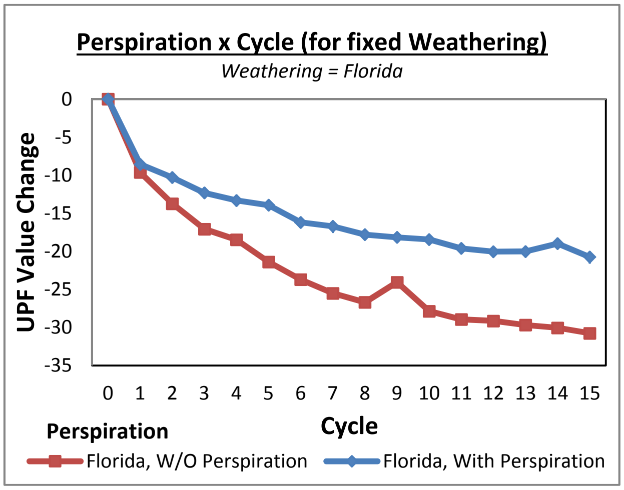


Figure 4.2 ***Repeated Laundering*** **x** ***Weathering*** **for Fixed** ***Perspiration*** **Interaction Plots**

H1c: There is a difference in the UPF values among the test specimens exposed to the following three weathering conditions - (a) semi-tropical climates without water spray, (b) semi-arid climates, and (c) control (i.e., standard conditioning). The test specimens exposed to a semi-tropical climate condition will have the most UPF value change, followed by the test specimens exposed to a semi-arid climate condition, and then the test specimens maintained in the standard textile testing condition.

Similar to Hypothesis H1b, a series of follow-up tests of using two-way ANOVA were performed to examine the *Perspiration* x *Repeated Cycle* interaction and were examined separately for each level of weathering exposure conditions (i.e., Standard, Florida, and Arizona conditions). The results of THSDT showed that there was a significant difference in UPF value change of test specimens exposed to different weathering conditions (see Figure 4.3). For those test specimens stored in the Standard conditioning, regardless of being treated with and without perspiration, the UPF value change showed significant increase after the first cycle (i.e., UPF value increased as the number of repeated laundering cycle increased). For those test specimens treated without perspiration, a significant difference between Florida and Arizona conditions was found after fifth cycle. For those treated with perspiration, a significant difference was found after second cycle. For test specimens that exposed to both weathering conditions (i.e., Florida and Arizona), the UPF value change all showed significant increase as the number of cycle increased (i.e., UPF value decreased as the number of repeated laundering cycle increased). In addition, the test specimen treated without perspiration had a greatest change in UPF value compared to those with perspiration treatment. For instance, for those test specimens exposed to the Florida condition, the UPF value decreased the most compared to other groups. Based on these results, H1c is supported.





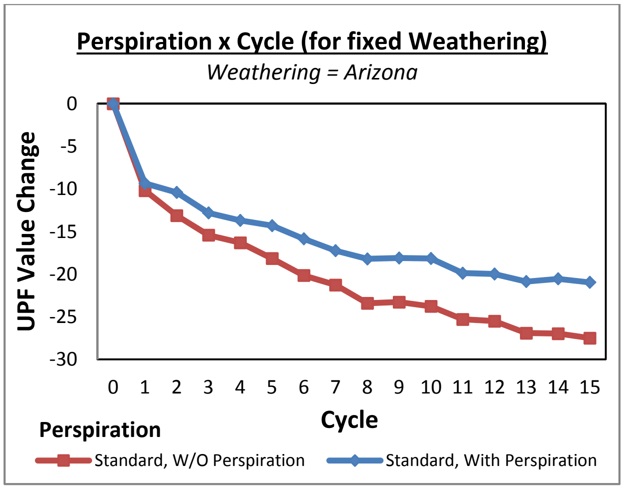


Figure 4.3 *Repeated Laundering* x *Perspiration* for Fixed Weathering Interaction Plots

H1d: There is a difference in UPF values between the test specimens laundered in a traditional washer and the test specimens laundered in a front-loading HE washer. The test specimens laundered in the front-loading HE washer will have less UPF values change than those laundered in the traditional washer.

When the effects of washing cycles on UPF value change was examined, two significant interactions related to washing were found (i.e., *Weathering* x *Washing Action* interaction and *Perspiration* x *Washing Action* interaction). These results indicated the effect of washing action depends on the level of weathering and perspiration separately. For the reason, the effect of washing action is discussed based on its interaction effects with perspiration and weathering separately. For the interaction between *Weathering* and *Washing action* in the influence on UPF value change, the means and standard deviations for UPF value change as a function of washing action and weathering are presented in Table 4.4 and Figure 4.4. Because the interaction was significant between washing action and weathering, a series of one-way ANOVA and THSDT were performed to examine the differences between the two types of washing action. The results showed that there was a significant difference in the UPF value change between the test specimens laundered in a traditional washer and the test specimens laundered in a front-loading HE washer for those that exposed to standard conditioning and Arizona, but there was no significant difference for those that exposed to Florida. Similar analysis also conducted for the *Perspiration* and *Washing action* interaction; however, no significant result was found in the one-way ANOVA and THSDT. Despite of no significant difference was found in the *Perspiration* and *Washing action* interaction, the effect of washing action on UPF value change was significant found under different weathering conditions. Based on these results, H1d was supported.

Table 4.4 Means and Standard Deviations for UPF value change by Weathering and Washing Action

Washing Action	Weathering Conditions						
	Standard Conditioning		Florida		Arizona		
	Mean	SD	Mean	SD	Mean	SD	*F*
Traditional Washer	7.44 [a]	4.88	-20.54 [a]	6.94	-20.14 [a]	6.14	643.53*
HE Washer	9.27 [b]	5.92	-19.59 [a]	6.69	-17.71 [b]	5.27	652.38*

[a, b] In the same column, means with different superscript letters are significant different at 0.05 level by THSDT. **p* value < 0.0001

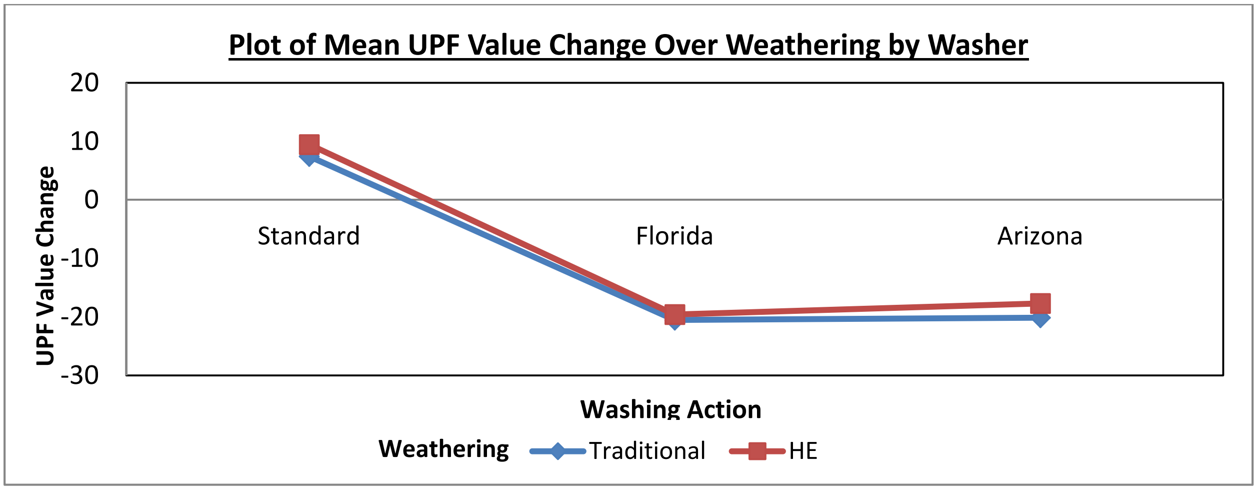


Figure 4.4 Plot of Mean UPF Value Change Over Weathering by Washing Action

H1e: There is a difference in UPF values between the test specimens before and after repeated laundering cycles. The UPF value change of the test specimens will increase with the increase of laundering cycles, up to 15 laundry cycles.

When the effects of repeated laundering cycles on UPF value change was examined, the results showed that a significant three-way interaction among weathering, perspiration, and repeated laundering was present ($F = 2.77$, $p < 0.0001$) (see Table 4.2). Subsequent analyses demonstrated that there was a simple effect for repeated laundering, where all UPF value change showed a significant difference among different cycles after the first laundering cycle. The UPF value change decreased with the increase of the number of laundering cycles. In other words, the UVR protection of the test specimens decreased with the increase of the number of laundering cycles. Using THSDT multiple comparisons, significant differences in UPF value change were found before and after each repeated laundering. Therefore, H1e is supported.

Analyses of Secondary Purpose – Fabric Count Change, Thickness Change, Weight Change, Color Change, and Dimensional Change

Hypothesis 2: Perspiration application, weathering exposure, washing action of automatic home clothes washers, and repeated laundering have no effect on the fabric count change of the test specimens.

In textile studies, the fabric counts (i.e., the number of warp and filling yarns) of a fabric are usually recorded separately. For this reason, the results of the fabric count are analyzed and reported separately, where warp direction for fabric count change are discussed first, followed by filling direction.

Analysis of Fabric Count Change in Warp Direction

Table 4.5 Repeated Measures Analysis of Variance Testing of Fixed Effects on Fabric Count Change in Warp Direction

Source	**df**	***F***
Weathering main effects **(*Whole plot*)**	2	7.93
Perspiration main effects **(*Split- plot*)**	1	7.13*
Washing Action main effects	1	17.34**
Weathering x *Perspiration* interaction	2	39.58**
Weathering x *Washing Action* interaction	2	2.93
Perspiration x *Washing Action* interaction	1	5.35
Weathering x *Perspiration* x *Washing Action* interaction	2	0.57
Repeated Laundering (Cycle) main effects **(*Repeated Measures*)**	15	13.31**
Repeated Laundering x *Weathering* interaction	30	0.74
Repeated Laundering x *Perspiration* interaction	15	0.73
Repeated Laundering x *Washing* interaction	15	0.78
Repeated Laundering x *Weathering* x *Perspiration* interaction	30	0.63
Repeated Laundering x *Weathering* x *Washing Action* interaction	30	0.41
Repeated Laundering x *Perspiration* x *Washing Action* interaction	15	0.50
Repeated Laundering x *Weathering* x *Perspiration* x *Washing Action* interaction	30	0.55

***p* value < 0.01;** *p* value < 0.0001

***H2a1*:** There is no interaction among the effects of the application of four treatment factors (i.e., perspiration application, weathering exposure, washing action of automatic home clothes washers, and repeated laundering) on the fabric count change of the test specimens.

When the effects of four treatments on fabric count change in warp direction were examined, the interaction between perspiration application and weathering exposure was significant ($F = 34.58$, $p < 0.0001$) (see Table 4.5). This result indicated that the influences of the perspiration application on fabric count change in warp direction were different in three weathering conditions. Based on this result, H2a1 is rejected.

.

H2b1: There is no difference in fabric count change between the test specimens treated with and without perspiration.

Because a significant interaction between perspiration and weathering was found, a series of one-way ANOVA were conducted to examine the effect of perspiration separately in each weathering condition. The simple effect of perspiration showed that the fabric count change in warp direction between the test specimens treated with and without perspiration were significantly different at different weathering conditions (see Table 4.6 and Figure 4.5). For those test specimens treated without perspiration, the THSDT results showed that significant differences were found between standard conditioning and Florida, and between Florida and Arizona (F = 115.36, $p < 0.0001$); however, no significant difference was found between standard conditioning and Arizona. A different result was found for those test specimens treated with perspiration. The THSDT results showed that significant differences were found between standard conditioning and Florida, and between standard conditioning and Arizona (F = 14.71, $p < 0.0001$); however, no significant difference was found between Florida and Arizona. Based on these results, the H2b1 is rejected.

Table 4.6 Means and Standard Deviations for UPF value change by Weathering and Perspiration

Perspiration	**Weathering Conditions**						
	Standard Conditioning		**Florida**		**Arizona**		
	Mean	**SD**	**Mean**	**SD**	**Mean**	**SD**	***F***
No Perspiration	-2.07^{a}	1.09	-0.87^{b}	1.11	-2.25^{a}	1.07	115.36*
With Perspiration	-1.79^{a}	1.08	-1.65^{b}	1.09	-2.17^{b}	1.08	14.71*

$^{a, b}$ In the same column, means with different superscript letters are significant different at 0.05 level by THSDT. *p value < 0.0001.

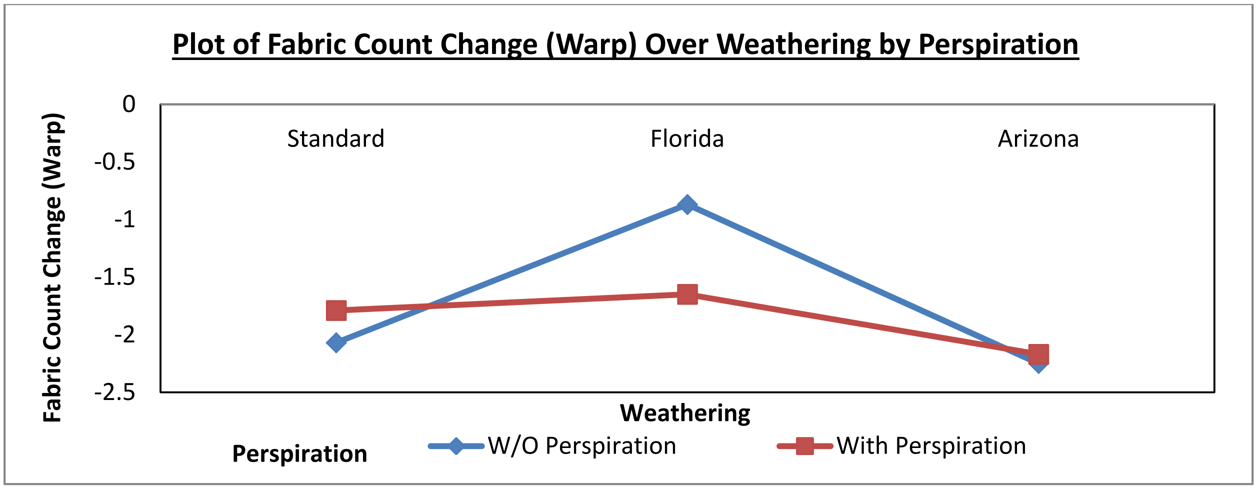


Figure 4.5 Mean Scores of Fabric Count Change in Warp Direction over Weathering by Perspiration

H2c1: There is no difference in the fabric count change among the test specimens exposed to the following three weathering conditions - (a) semi-tropical climates without water spray, (b) semi-arid climates, and (c) control (i.e., standard conditioning).

The simple effect of perspiration showed that the fabric count change in warp direction between the test specimens exposed in three weathering conditions were significantly different with and without perspiration application (see Table 4.6 and Figure 4.6). As explained in the previous section, when the perspiration was absent, the fabric count in warp direction exposed to Florida had significantly changed the least and those exposed to Arizona had significantly changed the most. Therefore, H2c1 is rejected.

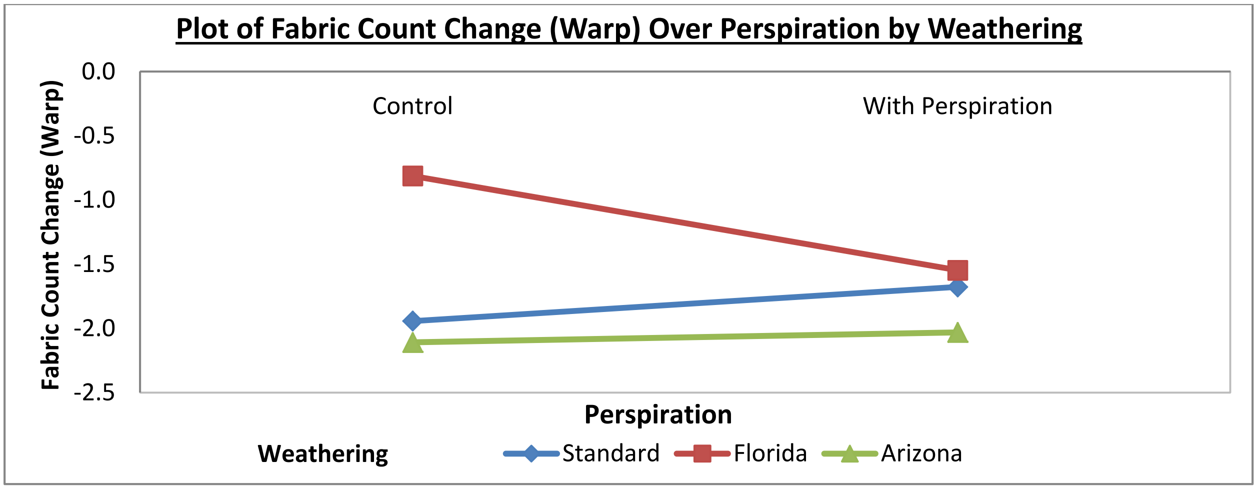


Figure 4.6 Mean Scores of Fabric Count Change in Warp Direction over Perspiration by Weathering

H2d1: There is no difference in fabric count change between the test specimens laundered in a traditional washer and the test specimens laundered in a front-loading HE washer.

When the effect of washing action on fabric count change in warp direction was examined, a significant difference was found (*F* = 17.34, $p < 0.0001$) (see Table 4.5). The results showed that those test specimens laundered in traditional washers had less fabric count change in warp direction (*M* = -1.69) compared to those test specimens laundered in HE washer (*M* = -1.91). Therefore, H2d1 is rejected.

H2e1: There is no difference in fabric count change between the test specimens before and after repeated laundering cycles, up to 15 laundering cycles.

When the effect of repeated laundering on fabric count change in warp direction was examined, a significant difference was found (*F* = 13.31, $p < 0.0001$) (see Table 4.5). When examining the plot of Mean Fabric Count Change in Warp direction over cycle (see Figure 4.7), it also showed that the trend of the fabric count change in warp direction fluctuated as the number of laundering cycles increased, and the results are shown in Table 4.8. These results indicated a significant difference found in fabric count change in warp direction after the second and third cycle. However, no significant difference was found between the first cycle, after the fourth cycle and up to the 15th cycle. Therefore, H2e1 is rejected.

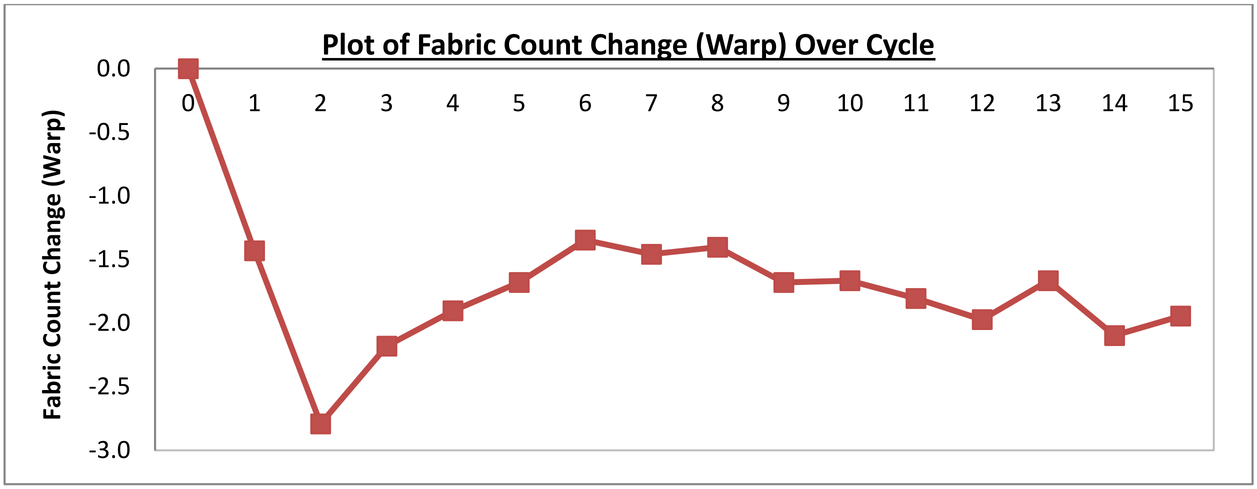


Figure 4.7 Plot of Fabric Count Change in Warp Direction by Repeated Laundering

Analysis of Fabric Count Change in Filling Direction

Table 4.7 Repeated Measures Analysis of Variance Testing of Fixed Effects on Fabric Count Change in Filling Direction

Source	**df**	***F***
Weathering main effects (***Whole plot***)	2	2.81
Perspiration main effects (***Split- plot***)	1	0.81
Washing Action main effects	1	68.53**
Weathering x *Perspiration* interaction	2	5.67*
Weathering x *Washing Action* interaction	2	1.74
Perspiration x *Washing Action* interaction	1	3.57
Weathering x *Perspiration* x *Washing Action* interaction	2	2.42
Repeated Laundering (Cycle) main effects (***Repeated Measures***)	15	195.85**
Repeated Laundering x *Weathering* interaction	30	1.67
Repeated Laundering x *Perspiration* interaction	15	0.56
Repeated Laundering x *Washing* interaction	15	1.97
Repeated Laundering x *Weathering* x *Perspiration* interaction	30	1.12
Repeated Laundering x *Weathering* x *Washing Action* interaction	30	0.75
Repeated Laundering x *Perspiration* x *Washing Action* interaction	15	0.57
Repeated Laundering x *Weathering* x *Perspiration* x *Washing Action* interaction	30	0.66

*****p value < 0.01;** p value < 0.0001

***H2a2*:** There is no interaction among the effects of the application of four treatment factors (i.e., perspiration application, weathering exposure, washing action of automatic home clothes washers, and repeated laundering) on the fabric count change of the test specimens.

When the effects of four treatments on fabric count change in filling direction were examined, the interaction between perspiration application and weathering exposure ($F = 5.67$, $p < 0.01$) was significant (see Table 4.7). These results indicated that the influences of the perspiration application on fabric count change in filling direction were different in three weathering conditions. Based on these results, H2a2 is rejected.

H2b2: There is no difference in fabric count change between the test specimens treated with and without perspiration.

Because an interaction between perspiration and weathering exposure was found ($F = 5.67$, $p < 0.01$), a one-way ANOVA was conducted to examine the simple effect of perspiration. The result showed that no significance was found ($F = 0.11$, $p = 0.7393$). However, a different scenario was found when plotting the fabric count change in filling over weathering by perspiration (see Figure 4.8). The fabric count in filling direction of test specimens treated with perspiration changed the most under the standard conditioning, and those test specimens exposed to Arizona had the lowest fabric count change in filling direction. Based on these results, H2b2 is rejected.

Table 4.8 Means and Standard Deviations for Fabric Count change in Filling Direction by Weathering and Perspiration

	Weathering Conditions						
Perspiration	**Standard Conditioning**		**Florida**		**Arizona**		
	Mean	**SD**	**Mean**	**SD**	**Mean**	**SD**	***F***
No Perspiration	5.27	1.43	5.16	1.22	5.09	1.30	0.83
With Perspiration	5.40^{a}	1.38	5.11^{b}	1.19	4.89^{b}	1.22	7.52*

$^{a, b}$ In the same column, means with different superscript letters are significant different at 0.05 level by THSDT. *****p value < 0.01.

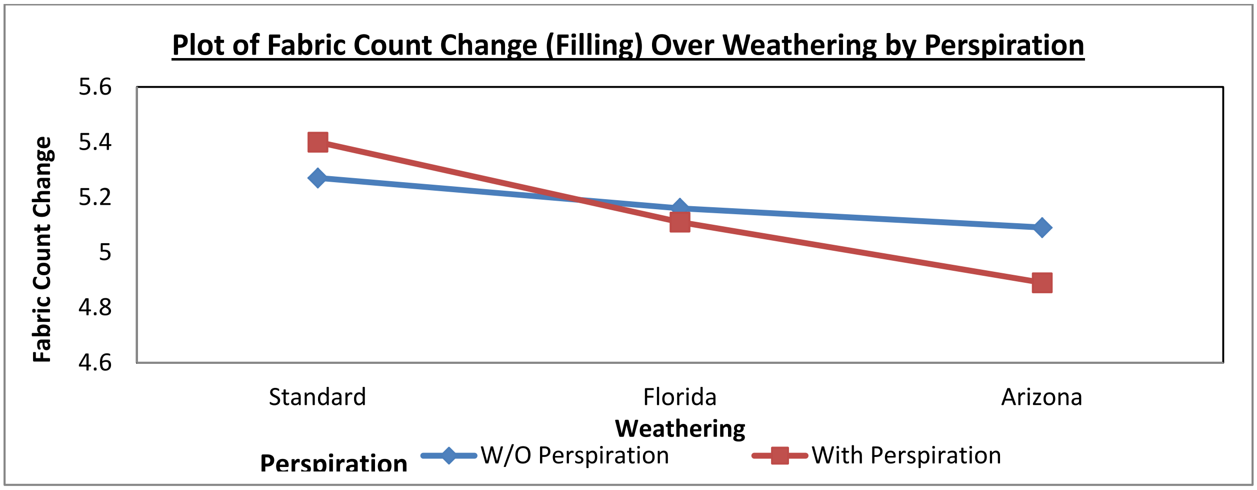


Figure 4.8 **Mean Scores of Fabric Count Change in Warp Direction over Perspiration by Weathering**

H2c2: There is no difference in the fabric count change among the test specimens exposed to the following three weathering conditions - (a) semi-tropical climates without water spray, (b) semi-arid climates, and (c) control (i.e., standard conditioning).

The ANOVA results and plots confirmed that no significant difference was found in weathering for fabric count change in filling direction at alpha level of 0.01. However, an interaction was found when examining the interaction plot (i.e., all three lines were not parallel) (see Figure 4.9). For instance, test specimens that were stored in the standard conditioning, regardless of being treated with or without perspiration, had the most fabric count change in filling direction, while test specimens exposed to Arizona had the lowest fabric count change. Therefore, H2c2 is rejected.

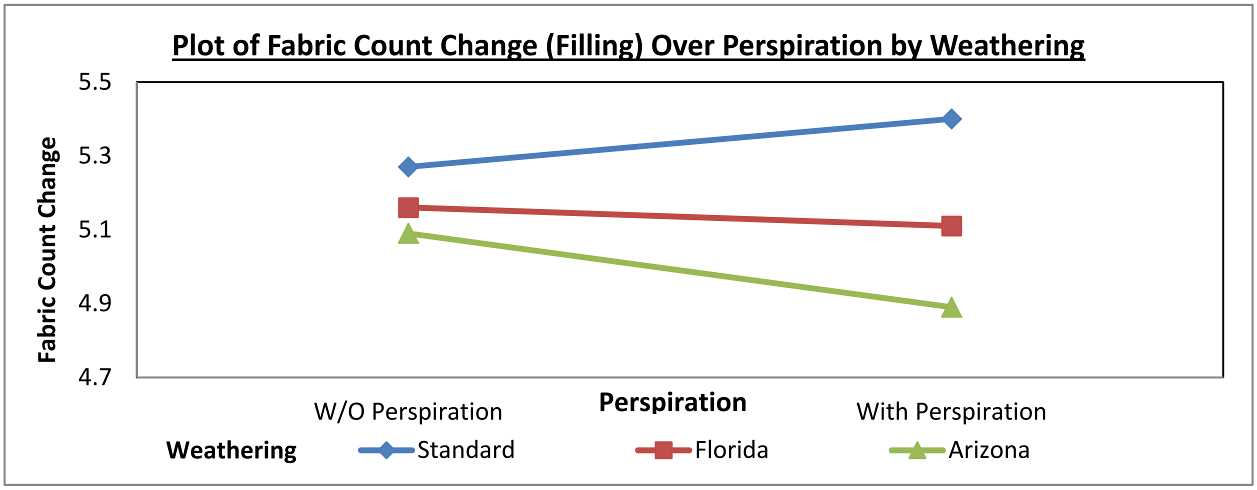


Figure 4.9 **Mean Scores of Fabric Count Change in Warp Direction over Perspiration by Weathering**

H2d2: There is no difference in fabric count change between the test specimens laundered in a traditional washer and the test specimens laundered in a front-loading HE washer.

When the effect of washing action on fabric count change in filling direction was examined, a significant difference was found ($F = 68.53$, $p < 0.0001$) (see Table 4.7). The results showed that those test specimens laundered in traditional washers had less fabric count change in warp direction ($M = 5.32$) compared to those test specimens laundered in HE washer ($M = 4.98$) (see Figure 4.10). Therefore, H2d2 is rejected.

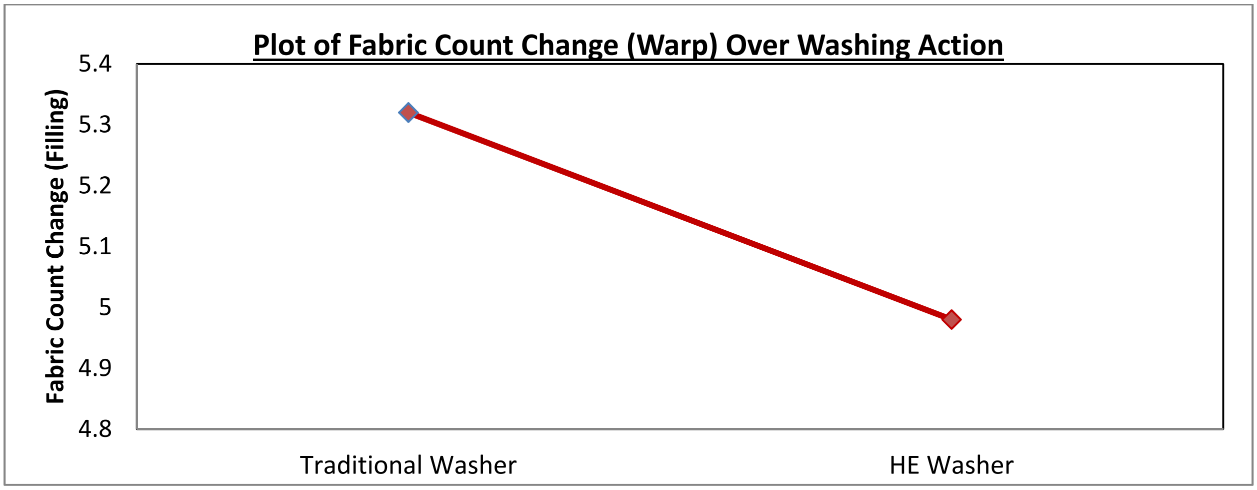


Figure 4.10 **Mean Scores of Fabric Count Change in Warp Direction over Perspiration by Weathering**

H2e2: There is no difference in fabric count change between the test specimens before and after repeated laundering cycles, up to 15 laundering cycles.

When the effect of repeated laundering on fabric count change in filling direction was examined, a significant difference was found ($F = 195.85$, $p < 0.0001$) (see Table 4.7). The results showed that the fabric count change in filling direction significantly increased as the number of laundering cycles increased. Therefore, H2e2 is rejected.

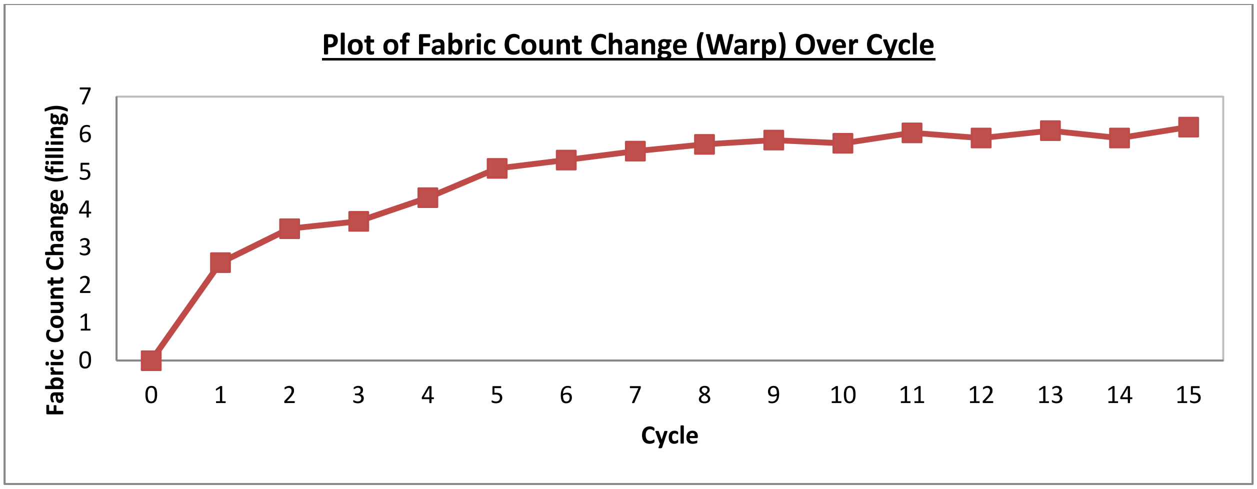


Figure 4.11 Mean Scores of Fabric Count Change in Warp Direction over Perspiration by Weathering

Hypothesis 3: Perspiration application, weathering exposure, washing action of automatic home clothes washers, and repeated laundering have no effect on the thickness change of the test specimens.

Table 4.9 Repeated Measures Analysis of Variance Testing of Fixed Effects on Thickness Change

Source	**df**	***F***
Weathering main effects **(*Whole plot*)**	2	8.14
Perspiration main effects **(*Split- plot*)**	1	4.12
Washing Action main effects	1	201.65**
Weathering x *Perspiration* interaction	2	0.47
Weathering x *Washing Action* interaction	2	3.40
Perspiration x *Washing Action* interaction	1	17.18**
Weathering x *Perspiration* x *Washing Action* interaction	2	4.38
Repeated Laundering (Cycle) main effects **(*Repeated Measures*)**	15	9.21**
Repeated Laundering x *Weathering* interaction	30	3.45**
Repeated Laundering x *Perspiration* interaction	15	1.49
Repeated Laundering x *Washing* interaction	15	2.55*
Repeated Laundering x *Weathering* x *Perspiration* interaction	30	0.96
Repeated Laundering x *Weathering* x *Washing Action* interaction	30	0.98
Repeated Laundering x *Perspiration* x *Washing Action* interaction	15	1.02
Repeated Laundering x *Weathering* x *Perspiration* x *Washing Action* interaction	30	0.61

*****p value < 0.001;** p value < 0.0001

***H3a**:* There is no interaction among the effects of the application of four treatment factors (i.e., perspiration application, weathering exposure, washing action of automatic home clothes washers, and repeated laundering) on the thickness change of the test specimens.

When the effects of four treatments on fabric thickness change were examined, the interaction between *Perspiration application* and *Washing action* ($F = 17.18, p < 0.0001$), the interaction between *Repeated laundering* and *Weathering* ($F = 3.45, p < 0.0001$), as well as the interaction between *Repeated laundering* and *Washing action* ($F = 2.55, p < 0.01$) were found (see Table 4.90). This result indicated that the influences of the perspiration application on thickness change were different in three weathering conditions. Based on this result, H3a is rejected.

***H3b**:* There is no difference in thickness change between the test specimens treated with and without perspiration.

Because a significant interaction between perspiration and washing action was found (F = 17.18, $p < 0.0001$) (see Table 4.9), a series of one-way ANOVA were conducted to examine the effect of perspiration had on each level of washing action. The simple effect of perspiration showed that the thickness change between the test specimens treated with and without perspiration were significantly different at different levels of washing action (see Table 4.10 and Figure 4.12). The THSDT results showed that for those test specimens treated with perspiration, the thickness of test specimens that were laundered in a traditional washer were significantly changed more than those laundered in a front-loading HE washer (F = 7.15, $p < 0.01$). However, no significant change was found in test specimens that were without the perspiration application and laundered in a traditional washer. Based on these results, the H3b is rejected.

Table 4.10 Means and Standard Deviations for Thickness change by Perspiration and Washing Action

Perspiration	Washing Action of automatic home clothes washers				
	Traditional Washer		HE Washer		
	Mean	SD	Mean	SD	*F*
No Perspiration	0.08 ^{a}	0.03	0.07 ^{b}	0.02	1.27
With Perspiration	0.08 ^{a}	0.03	0.06 ^{b}	0.02	16.58*

$^{a,\,b}$ In the same column, means with different superscript letters are significant different at 0.01 level by THSDT. ***p** value < 0.0001.

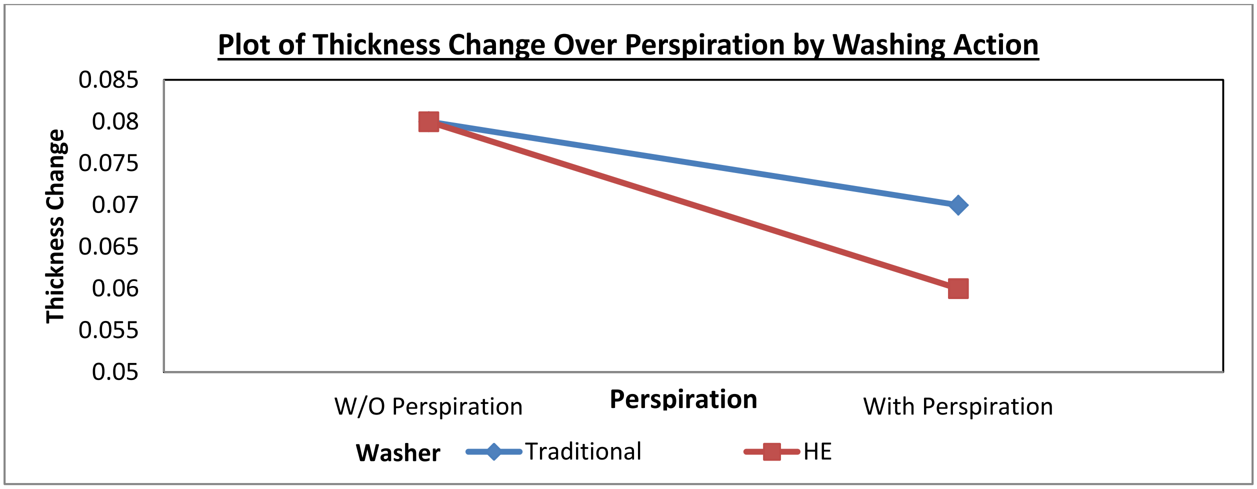


Figure 4.12 Mean Scores of Thickness Change over Washing Action by Perspiration

H3c: There is no difference in the thickness change among the test specimens exposed to the following three weathering conditions - (a) semi-tropical climates without water spray, (b) semi-arid climates, and (c) control (i.e., standard conditioning).

Because an interaction between weathering and repeated laundering was found ($F = 3.42$, $p < 0.0001$), a one-way ANOVA was conducted to examine the weathering effects separately for each repeated laundering cycle. The result of the simple effects showed that the mean scores of thickness change were significantly different among different weathering conditions after the first cycle (see Table 4.11 and Figure 4.13). Test specimens that were exposed to Florida condition had the lowest thickness change while those test specimens stored in the standard conditioning had the highest thickness change. Based on these results, H3c is rejected.

Table 4.11 Means and Standard Deviations for Fabric Count change in Filling Direction by Weathering and Perspiration

Cycle	Weathering Conditions						
	Standard Conditioning		Florida		Arizona		
	Mean	SD	Mean	SD	Mean	SD	*F*
1	0.07	0.02	0.06	0.02	0.07	0.02	2.91
2	0.08^{a}	0.03	0.06^{b}	0.02	0.07^{b}	0.02	3.24
3	0.08	0.02	0.08	0.03	0.08	0.02	0.65
4	0.09	0.02	0.08	0.01	0.08	0.01	1.41
5	0.10	0.02	0.08	0.01	0.09	0.01	3.36
6	0.08	0.02	0.07	0.01	0.08	0.02	2.74
7	0.08^{a}	0.03	0.07^{b}	0.03	0.06^{a}	0.02	3.98
8	0.09^{a}	0.02	0.07^{b}	0.01	0.07^{b}	0.02	8.21*
9	0.09^{a}	0.02	0.07^{b}	0.02	0.07^{b}	0.01	7.64*
10	0.09^{a}	0.02	0.07^{b}	0.01	0.08^{b}	0.01	14.10**
11	0.09^{b}	0.02	0.06^{b}	0.01	0.07^{c}	0.02	30.10**
12	0.08^{a}	0.02	0.06^{b}	0.01	0.07^{b}	0.02	11.77**
13	0.09^{a}	0.01	0.06^{b}	0.01	0.07^{b}	0.01	38.10**
14	0.08^{a}	0.02	0.06^{b}	0.01	0.06^{b}	0.01	21.48**
15	0.08^{a}	0.02	0.06^{a}	0.01	0.06^{a}	0.01	27.00**

$^{a, b}$ In the same column, means with different superscript letters are significant different at 0.05 level by THSDT. ***p** value < 0.001;** *p* value < 0.0001

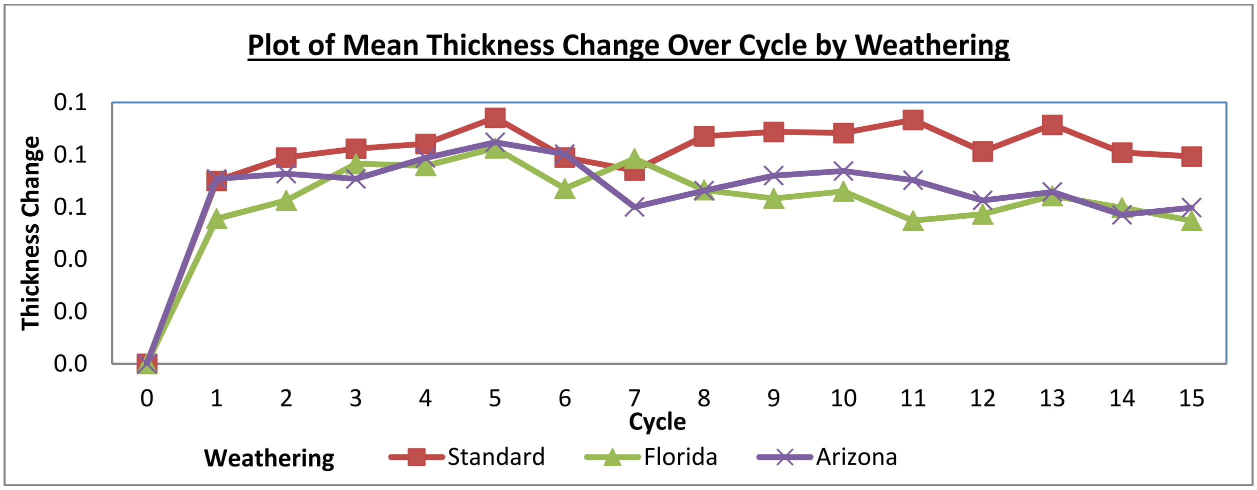


Figure 4.13 Mean Scores of Thickness Change over Cycle by Weathering

H3d: There is no difference in thickness change between the test specimens laundered in a traditional washer and the test specimens laundered in a front-loading HE washer.

Because a significant interaction between perspiration and washing action was found ($F = 17.18$, $p < 0.0001$), a series of one-way ANOVA were conducted to examine the effect of the washing action separately in each level of perspiration. The simple effect of washing action showed that the thickness change between the test specimens laundered in a traditional washer and a front-loading HE washer was significantly different at different levels of perspiration (see Table 4.10 and Figure 4.14). The THSDT results showed that for test specimens that were laundered in a traditional washer, those treated with perspiration had a higher thickness change than those without perspiration treatment. However, a different scenario was found in test specimens that were laundered in a front-loading HE washer, where test specimens treated with perspiration had a lower thickness change than those without perspiration. Based on these results, the H3d is rejected.

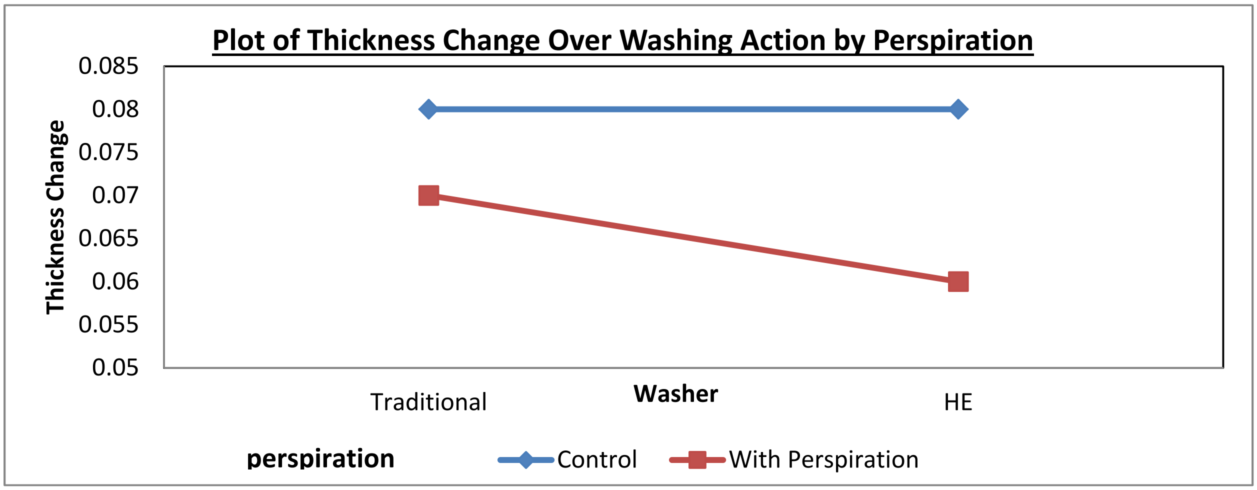


Figure 4.14 Mean Scores of Thickness Change over Perspiration by Washing Action

H3e: There is no difference in thickness change between the test specimens before and after repeated laundering cycles, up to 15 laundering cycles.

Because an interaction between weathering and repeated laundering was found ($F = 3.45$, $p < 0.0001$), a one-way ANOVA was conducted to examine the weathering effects separately for each repeated laundering cycle. The result of the simple effects showed that a significant difference was found after eighth cycle among three weathering conditions (see Table 4.10 and Figure 4.11). Based on these results, H3e is rejected.

Hypothesis 4: Perspiration application, weathering exposure, washing action of automatic home clothes washers, and repeated laundering have no effect on the weight change of the test specimens.

Table 4.12 Repeated Measures Analysis of Variance Testing of Fixed Effects on Weight changes

Source	**df**	***F***
Weathering main effects (***Whole plot***)	2	28.27*
Perspiration main effects (***Split- plot***)	1	8.29*
Washing Action main effects	1	231.40**
Weathering x *Perspiration* interaction	2	1.75
Weathering x *Washing Action* interaction	2	2.75
Perspiration x *Washing Action* interaction	1	0.22
Weathering x *Perspiration* x *Washing Action* interaction	2	0.43
Repeated Laundering (Cycle) main effects (***Repeated Measures***)	15	32.81**
Repeated Laundering x *Weathering* interaction	30	1.12
Repeated Laundering x *Perspiration* interaction	15	0.85
Repeated Laundering x *Washing* interaction	15	2.39*
Repeated Laundering x *Weathering* x *Perspiration* interaction	30	1.06
Repeated Laundering x *Weathering* x *Washing Action* interaction	30	0.85
Repeated Laundering x *Perspiration* x *Washing Action* interaction	15	0.92
Repeated Laundering x *Weathering* x *Perspiration* x *Washing Action* interaction	30	0.98

p value < 0.01;** *p* value < 0.0001

***H4a**:* There is no interaction among the effects of the application of four treatment factors (i.e., perspiration application, weathering exposure, washing action of automatic home clothes washers, and repeated laundering) on the weight change of the test specimens.

When the effects of four treatments on fabric weight change were examined, an interaction between repeated laundering and washing action was significant ($F = 2.39$, $p < 0.01$) (see Table 4.12). This result indicated that the influences of the washing action on fabric weight change of the test specimens were different in various laundering cycles. Based on this result, H4a is rejected.

***H4b**:* There is no difference in weight change between the test specimens treated with and without perspiration.

When the effect of perspiration on weight change was examined, a significant difference was found ($F = 8.29$, $p < 0.01$) (see Table 4.12). The results showed that test specimens treated without perspiration had less weight change than those treated with perspiration. They were -0.074 for the non-perspiration group and -0.079 for the perspiration treated group (see Figure 4.15). Therefore, H4b is rejected.

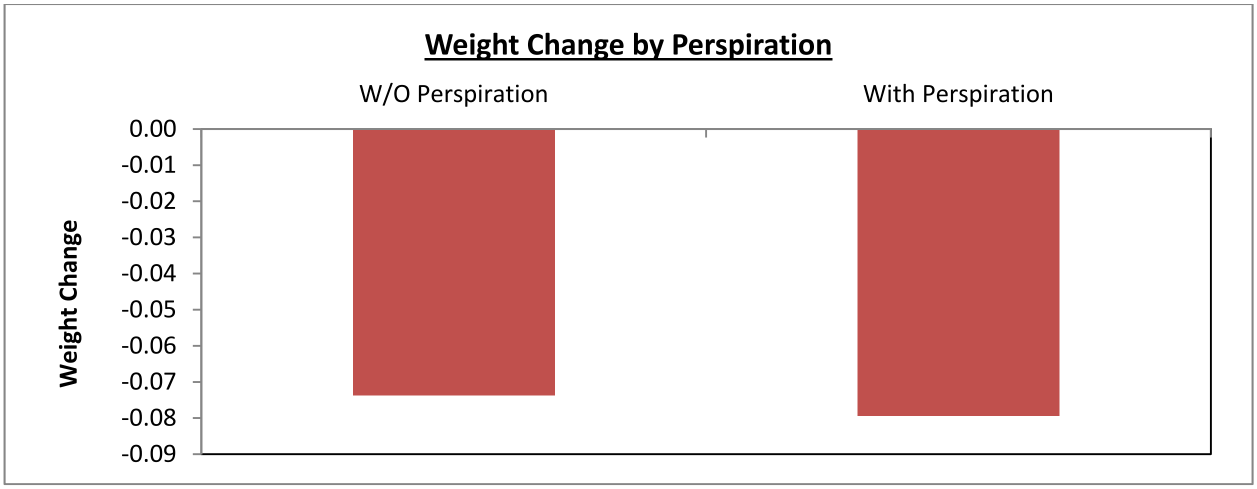


Figure 4.15 Mean Scores of Weight Change on Perspiration

***H4c**:* There is no difference in the weight change among the test specimens exposed to the following three weathering conditions - (a) semi-tropical climates without water spray, (b) semi-arid climates, and (c) control (i.e., standard conditioning).

When the effect of weathering exposure on weight change was examined, a significant difference was found ($F = 27.36$, $p < 0.001$) (see Table 4.13 and Figure 4.16). The results showed that test specimens stored in the standard conditioning had the smallest weight change, and test specimens exposed to Florida conditions had the most weight change. The means and standard deviations for weight change as a function of weathering exposure are presented in Table 4.13. Therefore, H4c is rejected.

Table 4.13 Means and Standard Deviations for Weight change by Weathering

Weathering Exposure	Mean	SD
Standard	-0.064 [a]	0.059
Florida	-0.087 [b]	0.029
Arizona	-0.078 [c]	0.029

[a, b, c] In the same column, means with different superscript letters are significant different at 0.05 level by THSDT

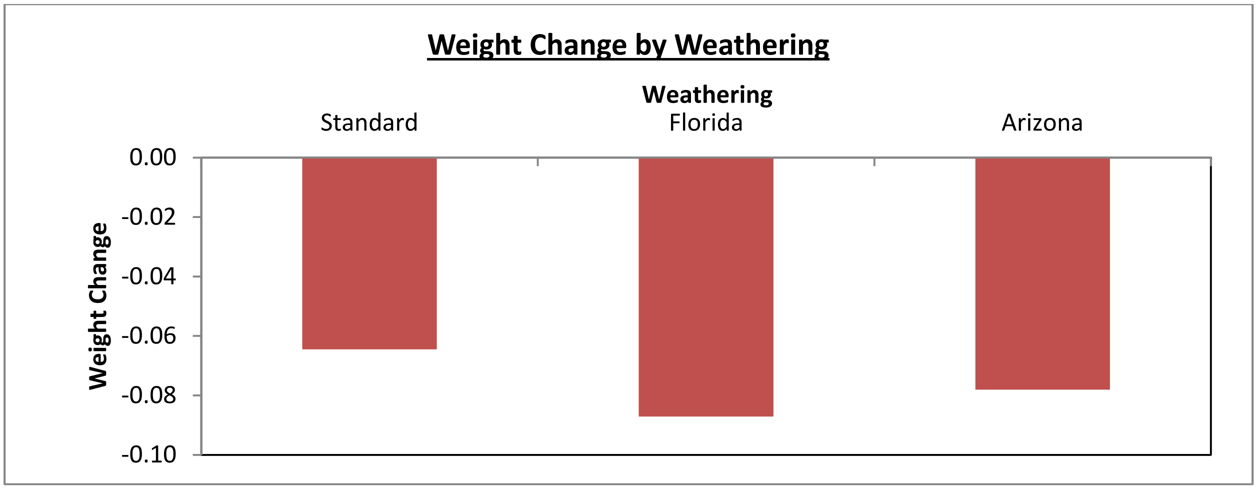


Figure 4.16 Mean Scores of Weight Change on Weathering Exposure

***H4d**:* There is no difference in weight change between the test specimens laundered in a traditional washer and the test specimens laundered in a front-loading HE washer.

Because an interaction between weathering and repeated laundering was found (F = 32.81, $p < 0.0001$), a one-way ANOVA was conducted to examine the weathering effects separately for each repeated laundering cycle. The result of the simple effects showed that the mean scores of weight change were significantly different among different weathering conditions after the first cycle (see Table 4.14 and Figure 4.17). Test specimens that were laundered in a front-loading HE washer had a lower weight change than those laundered in a traditional washer. Based on these results, H4d is rejected.

Table 4.14 Means and Standard Deviations for Weight Change by Washing and Repeated Cycles

Cycles	Washing Action of automatic home clothes washers				
	Traditional Washer		HE Washer		
	Mean	SD	Mean	SD	*F*
1	-0.039 ^{a}	0.011	-0.027 ^{b}	0.009	23.84*
2	-0.052 ^{a}	0.010	-0.037 ^{b}	0.010	69.10*
3	-0.067 ^{a}	0.011	-0.048 ^{b}	0.012	51.59*
4	-0.072 ^{a}	0.011	-0.048 ^{b}	0.012	71.21*
5	-0.078 ^{a}	0.010	-0.053 ^{b}	0.013	86.00*
6	-0.085 ^{a}	0.012	-0.057 ^{b}	0.014	85.00*
7	-0.092 ^{a}	0.015	-0.063 ^{b}	0.014	66.11*
8	-0.096 ^{a}	0.014	-0.068 ^{b}	0.015	70.49*
9	-0.102 ^{a}	0.016	-0.071 ^{b}	0.016	71.44*
10	-0.104 ^{a}	0.016	-0.072 ^{b}	0.015	73.48*
11	-0.104 ^{a}	0.020	-0.072 ^{b}	0.019	47.48*
12	-0.109 ^{a}	0.018	-0.074 ^{b}	0.018	65.24*
13	-0.109 ^{a}	0.020	-0.074 ^{b}	0.019	57.79*
14	-0.113 ^{a}	0.027	-0.082 ^{b}	0.020	31.09*
15	-0.148 ^{a}	0.163	-0.083 ^{b}	0.022	5.60*

[a, b] In the same column, means with different superscript letters are significantly different at 0.0001 level by THSDT. * $p < 0.01$, ** $p < 0.0001$

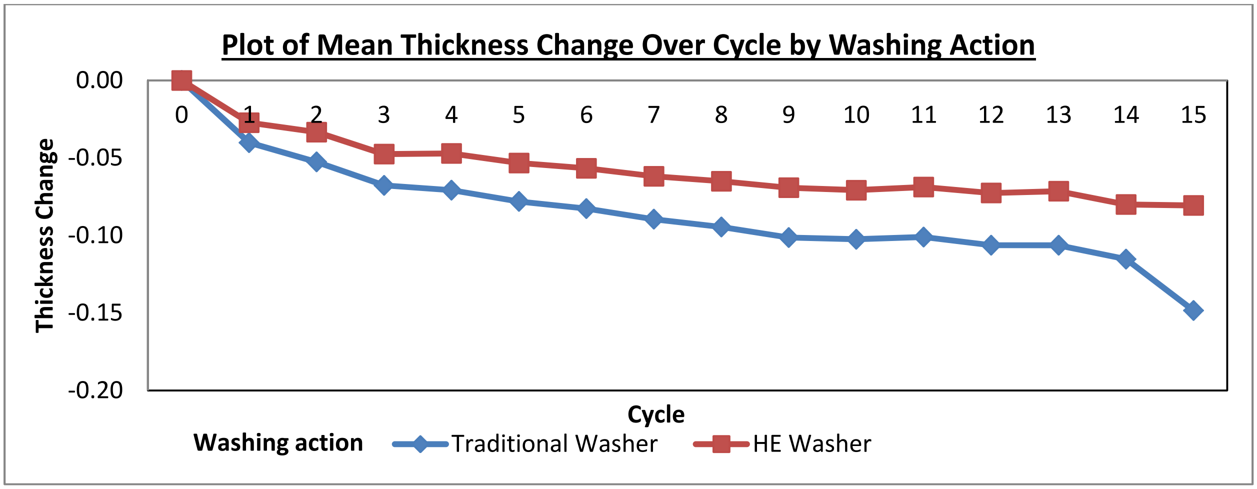


Figure 4.17 Mean Scores of Thickness Change over Cycle by Washing

***H4e**:* There is no difference in weight change between the test specimens before and after repeated laundering cycles, up to 15 laundering cycles.

Because an interaction between weathering and repeated laundering was found ($F = 3.42$, $p < 0.0001$), a one-way ANOVA was conducted to examine the repeated laundering effects on weight change separately for each type of washing action. The result of the simple effects showed that, regardless of being laundered in either washer, the mean scores of thickness change were significantly different between two types of washer after the fourth repeated laundering cycle (see Table 4.14 and Figure 4.17). Based on these results, H4e is rejected.

Hypothesis 5: Perspiration application, weathering exposure, washing action of automatic home clothes washers, and repeated laundering have no effect on the color change of the test specimens.

Table 4.15 Repeated Measures Analysis of Variance Testing of Fixed Effects on Color change in Term of Delta E

Source	**df**	***F***
Weathering main effects (***Whole plot***)	2	1880.54**
Perspiration main effects (***Split- plot***)	1	5706.91**
Washing Action main effects	1	174.13**
Weathering x *Perspiration* interaction	2	1498.47**
Weathering x *Washing Action* interaction	2	80.36**
Perspiration x *Washing Action* interaction	1	2.76
Weathering x *Perspiration* x *Washing Action* interaction	2	1.68
Repeated Laundering (Cycle) main effects (***Repeated Measures***)	15	4794.69**
Repeated Laundering x *Weathering* interaction	30	597.37**
Repeated Laundering x *Perspiration* interaction	15	52.22**
Repeated Laundering x *Washing* interaction	15	5.74**
Repeated Laundering x *Weathering* x *Perspiration* interaction	30	23.94**
Repeated Laundering x *Weathering* x *Washing Action* interaction	30	1.65
Repeated Laundering x *Perspiration* x *Washing Action* interaction	15	0.65
Repeated Laundering x *Weathering* x *Perspiration* x *Washing Action* interaction	30	0.41

***p** value < 0.01;** *p* value < 0.0001

***H5a**:* There is no interaction among the effects of the application of four treatment factors (i.e., perspiration application, weathering exposure, washing action of automatic home clothes washers, and repeated laundering) on the color change of the test specimens.

When the effects of four treatments on the color change of Delta E were examined, a three-way interactions [i.e., *Repeated Laundering* x *Weathering* x *Perspiration* interaction (F = 30.22, $p < 0.0001$)] was significant (see Table 4.16). This result indicated that the influences of perspiration and weathering on UPF value change were different in various laundering cycles. To further confirm these findings, the three-way interaction figure was plotted (see Figure 4.18), and significant interactions were found. Therefore, H5a is rejected.

Table 4.16 Means and Standard Deviations Delta E by Weathering, Perspiration, and Repeated Cycles

Cycle	Perspiration	Weathering Conditions						
		Standard Conditioning		Florida		Arizona		
		Mean	**SD**	**Mean**	**SD**	**Mean**	**SD**	***F***
1	**No Perspiration**	1.80^{ax}	0.43	3.07^{bx}	0.31	2.57^{cx}	0.29	39.81*
	With Perspiration	1.51^{ax}	0.40	2.43^{by}	0.27	2.28^{by}	0.31	26.70*
2	**No Perspiration**	2.42^{ax}	0.27	5.88^{bx}	0.38	4.55^{cx}	0.31	345.79*
	With Perspiration	1.88^{ay}	0.41	4.47^{by}	0.35	3.90^{cy}	0.39	150.62*
3	**No Perspiration**	2.72^{ax}	0.39	8.08^{bx}	0.23	6.04^{cx}	0.24	994.59*
	With Perspiration	2.22^{ay}	0.41	6.19^{by}	0.39	4.95^{cy}	0.37	320.06*
4	**No Perspiration**	3.10^{ax}	0.49	10.12^{bx}	0.37	7.39^{cx}	0.29	981.86*
	With Perspiration	2.74^{ax}	0.51	7.74^{by}	0.43	5.82^{cy}	0.44	356.21*
5	**No Perspiration**	3.40^{ax}	0.39	11.81^{bx}	0.30	8.50^{cx}	0.27	2046.50*
	With Perspiration	3.00^{ay}	0.32	8.80^{by}	0.62	6.81^{cy}	0.29	549.80*
6	**No Perspiration**	3.58^{ax}	0.38	13.68^{bx}	0.38	10.22^{cx}	0.37	2218.24*
	With Perspiration	3.20^{ay}	0.40	10.08^{by}	0.48	8.36^{cy}	0.32	939.84*
7	**No Perspiration**	3.91^{ax}	0.45	15.02^{bx}	0.36	11.21^{cx}	0.35	2532.34*
	With Perspiration	3.62^{ax}	0.41	10.76^{by}	0.92	9.12^{cy}	0.26	461.81*
8	**No Perspiration**	4.21^{ax}	0.51	16.43^{bx}	0.38	12.08^{cx}	0.39	2460.07*
	With Perspiration	3.94^{ax}	0.51	12.12^{by}	0.79	9.81^{cy}	0.25	679.70*
9	**No Perspiration**	4.45^{ax}	0.69	18.24^{bx}	0.84	13.28^{cx}	0.27	1394.35*
	With Perspiration	7.43^{ax}	1.11	13.40^{by}	1.19	10.77^{cy}	0.43	270.74*
10	**No Perspiration**	4.53^{ax}	0.64	18.97^{bx}	0.47	14.00^{cx}	0.35	2589.99*
	With Perspiration	4.46^{ax}	0.88	14.05^{by}	0.92	11.33^{cy}	0.37	501.35*
11	**No Perspiration**	4.91^{ax}	0.83	19.78^{bx}	0.42	14.94^{cx}	044	1956.06*
	With Perspiration	4.75^{ax}	0.82	14.84^{by}	0.73	12.24^{cy}	0.32	760.16*
12	**No Perspiration**	4.84^{ax}	0.75	20.59^{bx}	0.42	15.61^{cx}	0.39	2587.89*
	With Perspiration	7.79^{ax}	0.73	15.63^{by}	0.49	12.83^{cy}	0.28	1327.42*
13	**No Perspiration**	4.96^{ax}	0.63	21.32^{bx}	0.35	16.14^{cx}	0.46	3434.51*
	With Perspiration	4.91^{ax}	0.75	16.12^{by}	0.54	13.41^{cy}	0.31	1279.75*
14	**No Perspiration**	5.03^{ax}	0.69	21.58^{bx}	0.48	16.84^{cx}	0.44	2904.68*
	With Perspiration	5.07^{ax}	0.66	15.77^{by}	1.54	13.93^{cy}	0.23	410.86*
15	**No Perspiration**	5.20^{ax}	0.71	22.17^{bx}	0.52	17.45^{cx}	0.57	2510.36*
	With Perspiration	5.25^{ax}	0.71	17.16^{by}	0.93	14.63^{cy}	0.40	1048.39*

$^{a, b, c}$ In the same column, means with different superscript letters are significantly different at 0.01 level by THSDT. $^{x, y}$ In the same row, means with different superscript letters are significantly different at 0.01 level by THSDT. * $p < 0.0001$

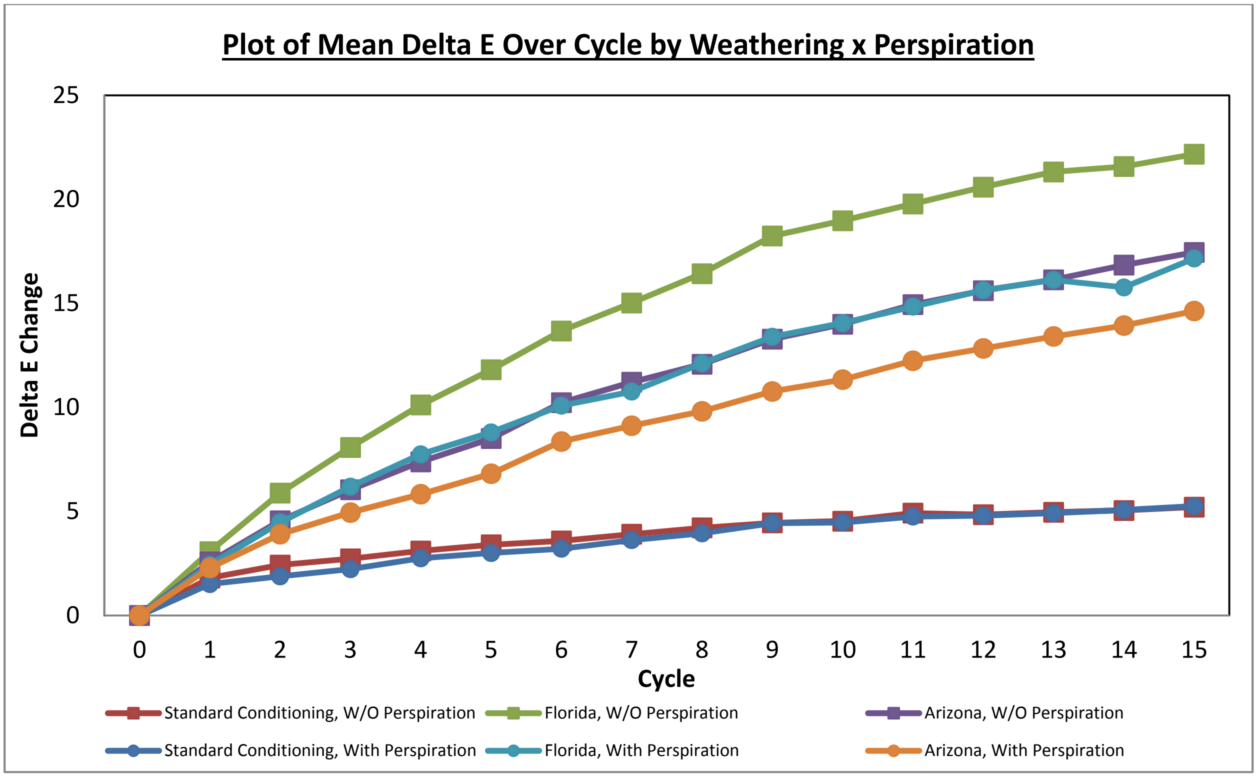


Figure 4.18 Plot of Mean Delta E by Weathering and Perspiration Combination after Repeated Laundering

H5b: There is no difference in color change between the test specimens treated with and without perspiration.

Because three-way interaction was found (i.e., *Perspiration* x *Weathering* x *Cycle*), a series of follow-up tests using two-way ANOVA were performed to examine the two-way interactions separately at each individual level of the third factor (i.e., *Weathering* x *Cycle* under the condition of with and without perspiration application) (see Table 4.16). The results showed that test specimens stored in the standard conditioning, regardless of being treated with or without perspiration, no significant difference was found before and after repeated laundering. For test specimens exposed to Florida condition, a significant difference was found after the first laundering cycle, and test specimens treated with perspiration had a higher Delta E change than those without perspiration. However, a different scenario was found in those exposed to the Arizona condition, where a significance was only found after the second laundering cycle, and test specimens treated with perspiration had a higher Delta E change than those without perspiration (see Figure 4.18). Based on these results, H5b is rejected.

H5c: There is no difference in the color change among the test specimens exposed to the following three weathering conditions - (a) semi-tropical climates without water spray, (b) semi-arid climates, and (c) control (i.e., standard conditioning).

A series of follow-up tests using two-way ANOVA were also performed to examine the two-way interactions separately at each individual level of the third factor (i.e., *Perspiration* x *Washing Action*) under the exposure to three weathering conditions. The results showed that significant differences were found in all test specimens that included treated and non-treated perspiration treatment, regardless of being exposed to any weathering condition, all showed a significant difference after the first cycle. In general, test specimens exposed to Florida condition had the highest Delta E followed by those exposed to Arizona condition. Those test specimens stored in the standard conditioning had the lowest Delta E (see Figure 4.18). Based on these results, H5c is rejected.

H5d*:* There is no difference in color change between the test specimens laundered in a traditional washer and the test specimens laundered in a front-loading HE washer.

Because two-way interaction was found (i.e., *Repeated Laundering* x *Washing Action*), a series of follow-up tests using two-way ANOVA were performed. The results showed that no significance was found between the test specimens laundered in a traditional washer and the test specimens laundered in a front-loading HE washer as the number of cycle increased. This can be confirmed by looking at Figure 4.19. Based on these results, H5d is failed to reject.

Table 4.17 Means and Standard Deviations for Delta E Change by Washing and Repeated Cycles

Cycles	Washing Action of automatic home clothes washers				
	Traditional Washer		HE Washer		
	Mean	SD	Mean	SD	*F*
1	2.16	0.61	2.39	0.59	5.09
2	3.74	1.44	3.97	1.38	5.01
3	4.95	2.15	5.12	2.03	2.76
4	6.07	2.77	6.24	2.58	2.62
5	7.02	3.24	7.09	3.08	0.47
6	8.17	3.94	8.20	3.68	0.07
7	8.87	4.30	9.00	3.99	1.57
8	9.67	4.76	9.86	4.35	3.17
9	10.34	5.15	11.18	5.05	66.00**
10	10.94	5.49	11.51	5.24	30.16**
11	11.59	5.76	12.24	5.38	39.46**
12	12.08	6.10	12.69	5.72	34.95**
13	12.62	6.33	13.00	5.95	14.05*
14	12.82	6.44	13.25	6.02	16.67**
15	13.35	6.66	13.94	6.28	32.44**

* $p < 0.01$, ** $p < 0.0001$

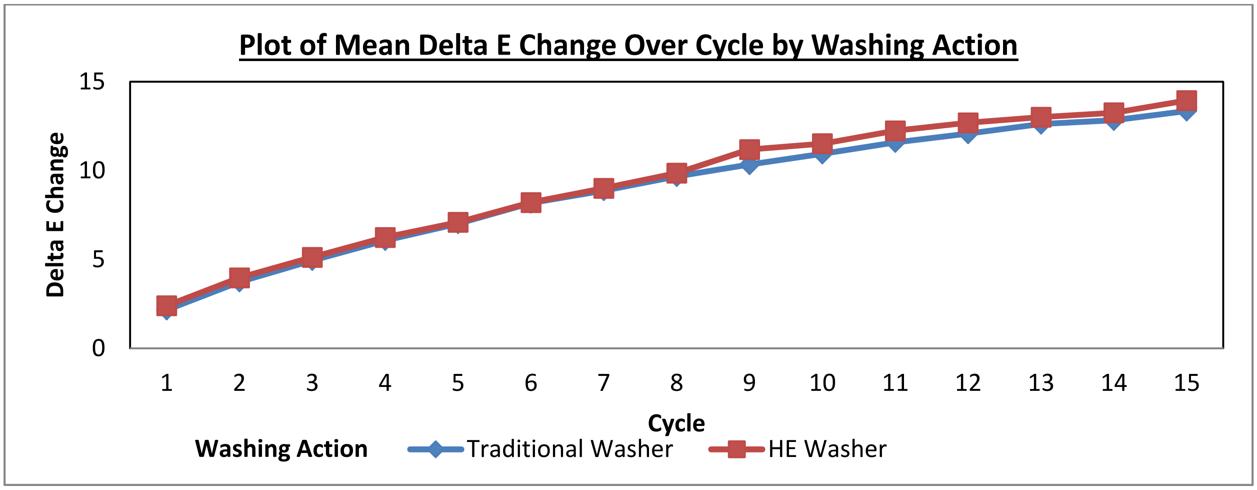


Figure 4.19 Plot of Mean Delta E Over Cycle by Washing Action

H5e: There is no difference in color change between the test specimens before and after repeated laundering cycles, up to 15 laundering cycles.

Because an interaction between washing action and repeated laundering was found ($F = 5.74$, $p < 0.0001$), a one-way ANOVA was conducted to examine the repeated laundering effects on Delta E change separately for each type of washing action. The result showed that the significant differences between two washers were found after ninth cycle (see Figure 4.19). Based on these results, H5e is rejected.

Hypothesis 6: Perspiration application, weathering exposure, washing action of automatic home clothes washers, and repeated laundering have no effect on the dimensional change of the test specimens.

Analysis of Dimensional Change in Warp Direction

Table 4.18 Repeated Measures Analysis of Variance Testing of Fixed Effects on Dimensional change in Warp Direction

Source	**df**	***F***
Weathering main effects (***Whole plot***)	2	3.40
Perspiration main effects (***Split- plot***)	1	0.28
Washing Action main effects	1	193.53**
Weathering x *Perspiration* interaction	2	7.25*
Weathering x *Washing Action* interaction	2	2.06
Perspiration x *Washing Action* interaction	1	7.24*
Weathering x *Perspiration* x *Washing Action* interaction	2	0.33
Repeated Laundering main effects (***Repeated Measures***)	15	753.37**
Repeated Laundering x *Weathering* interaction	30	3.55**
Repeated Laundering x *Perspiration* interaction	15	2.48*
Repeated Laundering x *Washing* interaction	15	1.98*
Repeated Laundering x *Weathering* x *Perspiration* interaction	30	1.10
Repeated Laundering x *Weathering* x *Washing Action* interaction	30	1.01
Repeated Laundering x *Perspiration* x *Washing Action* interaction	15	0.65
Repeated Laundering x *Weathering* x *Perspiration* x *Washing Action* interaction	30	1.00

*****p value < 0.001;** p value < 0.0001

H6a1: There is no interaction among the effects of the application of four treatment factors (i.e., perspiration application, weathering exposure, washing action of automatic home clothes washers, and repeated laundering) on the dimensional change of the test specimens.

When the effects of four treatments on the dimensional change in warp direction were examined, four two-way interactions [i.e., *Perspiration* x *Washing Action* ($F = 7.24$, $p < 0.01$), *Repeated Laundering* x *Weathering* interaction ($F = 3.55$, $p < 0.0001$), *Repeated Laundering* x *Perspiration* interaction ($F = 2.48$, $p < 0.01$), and *Repeated Laundering* x *Washing Action* interaction ($F = 1.98$, $p < 0.01$)] were significant. These results indicated that the influences of weathering, perspiration, and washing action on the dimensional change in warp direction were different in various laundering cycles. Therefore, H6a1 is rejected.

H6b1: There is no difference in dimensional change between the test specimens treated with and without perspiration.

Because a significant interaction between perspiration and washing action was found ($F = 7.24$, $p = 0.0074$), a series of one-way ANOVA were conducted to examine the effect of perspiration separately in each type of washing action. The simple effect of perspiration showed that dimensional change in warp direction between the test specimens treated with and without perspiration were not significantly different at different washing action conditions (see Table 4.22 and Figure 4.21). When examine the interaction plot, both lines were almost parallel, which indicated little or no interaction found. Based on this reason, H6b1 is failed to reject.

Table 4.19 Means and Standard Deviations for Thickness change by Perspiration and Washing Action

Perspiration	Washing Action of automatic home clothes washers				
	Traditional Washer		HE Washer		
	Mean	SD	Mean	SD	*F*
No Perspiration	-8.10 ^{a}	1.16	-7.75 ^{b}	1.24	3.14*
With Perspiration	-8.03 ^{a}	1.07	-7.79 ^{b}	1.13	1.43

$^{a, b}$ In the same column, means with different superscript letters are significant different at 0.01 level by THSDT. ***p** value < 0.01.

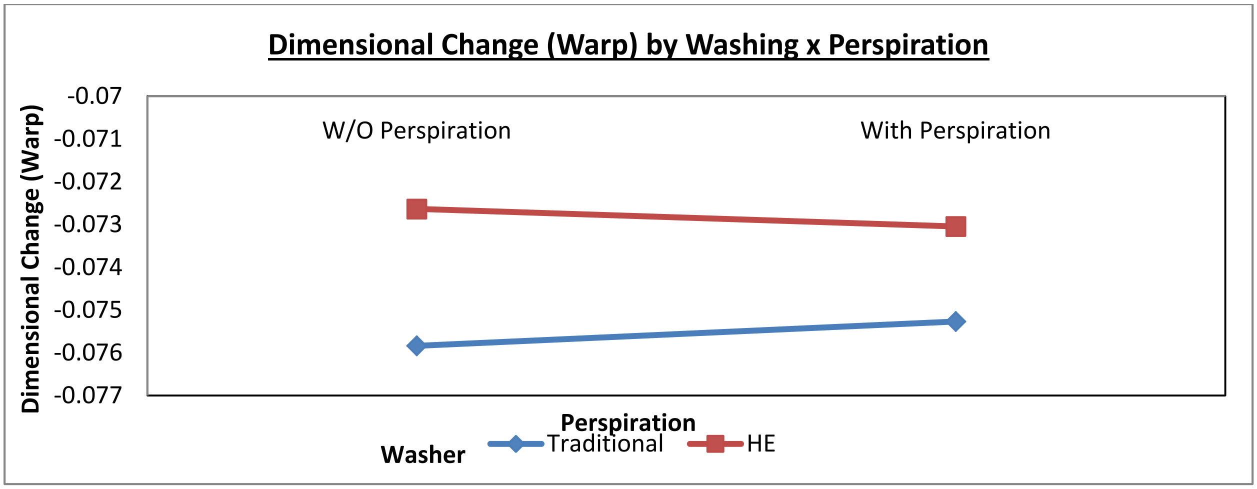


Figure 4.20 Plot of Mean of Dimensional Change in Warp Direction over Perspiration by Washing Action

H6c1: There is no difference in the dimensional change among the test specimens exposed to the following three weathering conditions - (a) semi-tropical climates without water spray, (b) semi-arid climates, and (c) control (i.e., standard conditioning).

Because an interaction between weathering and repeated laundering was found (F = 3.75, $p < 0.0001$), a one-way ANOVA was conducted to examine the weathering effects separately for each repeated laundering cycle. The result of the simple effects showed that the mean scores of thickness change were significantly different among different weathering conditions after the 5th, 6th, 9th, 10th, 11th, 13th, 14th and 15th cycles (see Table 4.20 and Figure 4.21). Based on these results, H6c1 is rejected.

Table 4.20 Means and Standard Deviations for Fabric Count change in Filling Direction by Weathering and Perspiration

Cycle	Weathering Conditions						*F*
	Standard Conditioning		Florida		Arizona		
	Mean	SD	Mean	SD	Mean	SD	*F*
1	-5.05	0.36	-5.02	0.42	-5.17	0.29	15.97*
2	-6.34	0.62	-6.21	0.57	-6.44	0.39	120.88**
3	-6.67	0.53	-6.65	0.49	-6.83	0.49	281.49**
4	-7.19	0.42	-7.30	0.48	-7.25	0.31	462.51**
5	-7.89^{a}	0.42	-7.55^{b}	0.41	-7.74^{b}	0.34	650.15**
6	-7.97^{a}	0.41	-7.75^{b}	0.36	-8.11^{a}	0.46	953.78**
7	-8.42	0.46	-8.25	0.40	-8.25	0.33	1106.69**
8	-8.49	0.45	-8.32	0.29	-8.24	0.45	1363.15**
9	-8.62^{a}	0.47	-8.25^{b}	0.33	-8.59^{a}	0.37	1691.20**
10	-8.86^{a}	0.31	-8.40^{b}	0.27	-8.66^{a}	0.36	1898.12**
11	-9.02^{a}	0.33	-8.21^{b}	0.37	-8.54^{c}	0.34	2067.79**
12	-8.66	0.45	-8.44	0.22	-8.67	0.42	2355.00**
13	-9.02^{a}	0.25	-8.78^{b}	0.40	-8.83^{a}	0.36	2540.59**
14	-9.12^{a}	0.30	-8.74^{b}	0.39	-8.80^{b}	0.41	2548.00**
15	-9.19^{a}	0.33	-8.72^{b}	0.26	-8.97^{a}	0.36	2843.68**

$^{a, b, c}$ In the same column, means with different superscript letters are significantly different at 0.01 level by THSDT. * $p < 0.01$, ** $p < 0.0001$

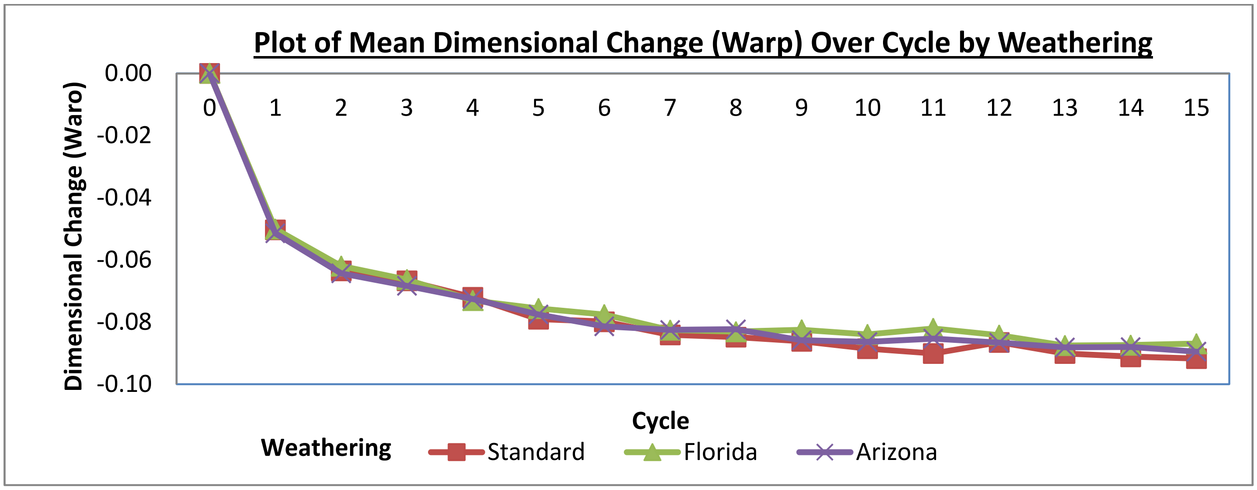


Figure 4.21 Mean Scores of Dimensional Change in Warp Direction over Cycle by Weathering

H6d1: There is no difference in dimensional change between the test specimens laundered in a traditional washer and the test specimens laundered in a front-loading HE washer.

Because a significant interaction between perspiration and washing action was found ($F = 7.24$, $p = 0.0074$), a series of one-way ANOVA were conducted to examine the effect of washing action separately in each level of perspiration. The simple effect of washing action showed that dimensional change in warp direction between the test specimens treated with and without perspiration were not significantly different at different type of washing action (see Table 4.19). When examining the interaction plot, a significant difference was found. For test specimens laundered in a traditional washer, those treated with perspiration had a lower dimensional change in warp direction than those without perspiration. However, a different scenario was found in those test specimens laundered in a front-loading HE washer, where the perspiration control group had a smaller change than those treated with perspiration. In addition, test specimens laundered in the HE washer, regardless of being treated with or without perspiration, had less dimensional change. Based on this reason, H6d1 is failed to reject.

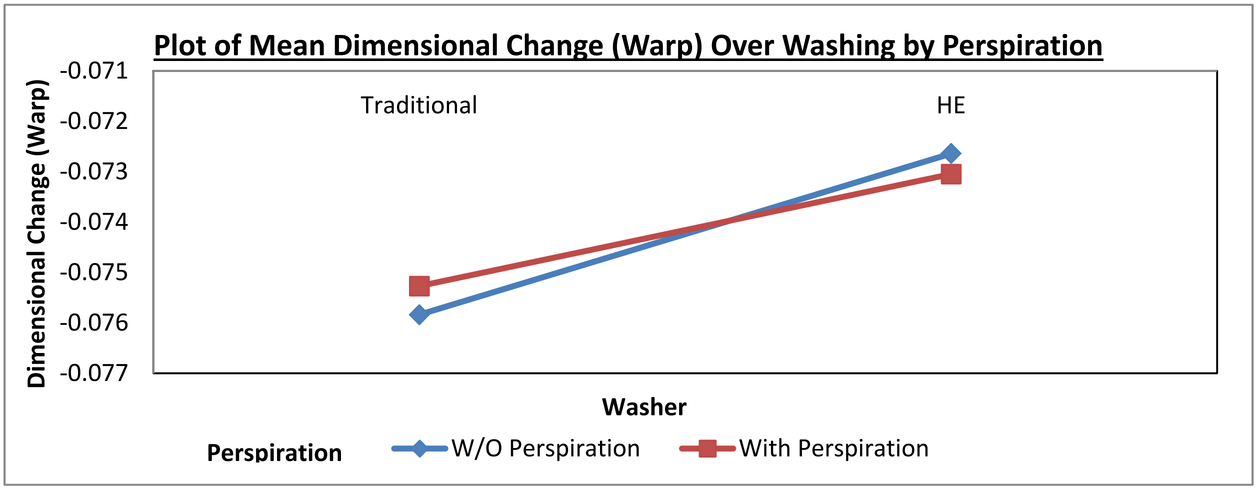


Figure 4.22 Plot of Mean of Dimensional Change in Warp Direction over Washing Action by Perspiration

H6e1: There is no difference in dimensional change between the test specimens before and after repeated laundering cycles, up to 15 laundering cycles.

Because an interaction between weathering and repeated laundering was found ($F = 3.55$, $p < 0.0001$), a one-way ANOVA was conducted to examine the repeated laundering effects on the dimensional change in warp direction separately for each level of weathering condition. The result of the simple effects showed that, no matter if laundered in either washer, the mean scores of dimensional change in warp direction were significantly different among different weathering conditions after 5th, 6th, 9th, 10th, 11th, 13th, 14th, and 15th repeated laundering cycles (see Table 4.20 and Figure 4.21). Based on these results, H6e1 is rejected.

Analysis of Dimensional Change in Filling Direction

Table 4.21 Repeated Measures Analysis of Variance Testing of Fixed Effects on Dimensional change in Filling Direction

Source	**df**	***F***
Weathering main effects (***Whole plot***)	2	0.75
Perspiration main effects (***Split- plot***)	1	18.41**
Washing Action main effects	1	5.19
Weathering x *Perspiration* interaction	2	15.22*
Weathering x *Washing Action* interaction	2	4.86*
Perspiration x *Washing Action* interaction	1	1.55
Weathering x *Perspiration* x *Washing Action* interaction	2	6.50*
Repeated Laundering (Cycle) main effects (***Repeated Measures***)	15	15.61**
Repeated Laundering x *Weathering* interaction	30	3.23**
Repeated Laundering x *Perspiration* interaction	15	1.73
Repeated Laundering x *Washing* interaction	15	0.90
Repeated Laundering x *Weathering* x *Perspiration* interaction	30	1.57
Repeated Laundering x *Weathering* x *Washing Action* interaction	30	0.92
Repeated Laundering x *Perspiration* x *Washing Action* interaction	15	0.49
Repeated Laundering x *Weathering* x *Perspiration* x *Washing Action* interaction	30	0.93

*****p value < 0.01;** p value < 0.0001

H6a2: There is no interaction among the effects of the application of four treatment factors (i.e., perspiration application, weathering exposure, washing action of automatic home clothes washers, and repeated laundering) on the dimensional change of the test specimens.

When the effects of four treatments on the dimensional change in filling direction were examined, a three-way interaction (i.e., *Weathering* x *Perspiration* x *Washing Action* interaction ($F = 6.50$, $p < 0.01$), and a two-way interaction (*Repeated Laundering* x *Weathering* interaction ($F = 3.23$, $p < 0.0001$) were significant (see Table 4.21). To further confirm this finding, one two-way interaction figure was plotted and a significant interaction was found (see Figure 4.23). Therefore, H6a2 is rejected.

Table 4.22 Means and Standard Deviations for Dimensional Change in Filling Direction by Weathering, Perspiration, and Repeated Cycles

		Weathering Conditions						
Perspiration	**Washing Action**	**Standard Conditioning**		**Florida**		**Arizona**		
		Mean	**SD**	**Mean**	**SD**	**Mean**	**SD**	***F***
Without Perspiration	**Traditional**	0.46^{ax}	0.46	0.33^{b}	0.52	0.44^{c}	0.38	0.08
	HE	0.41^{ay}	0.37	0.12^{b}	0.43	0.36^{c}	0.34	0.97
With Perspiration	**Traditional**	0.69^{ax}	0.40	0.50^{b}	0.47	0.71^{c}	0.48	3.66
	HE	0.52^{ay}	0.35	0.57^{b}	0.47	0.58^{c}	0.37	0.53

$^{a,\,b}$ In the same column, means with different superscript letters are significantly different at 0.01 level by THSDT. $^{x,\,y}$ In the same row, means with different superscript letters are significantly different at 0.01 level by THSDT.

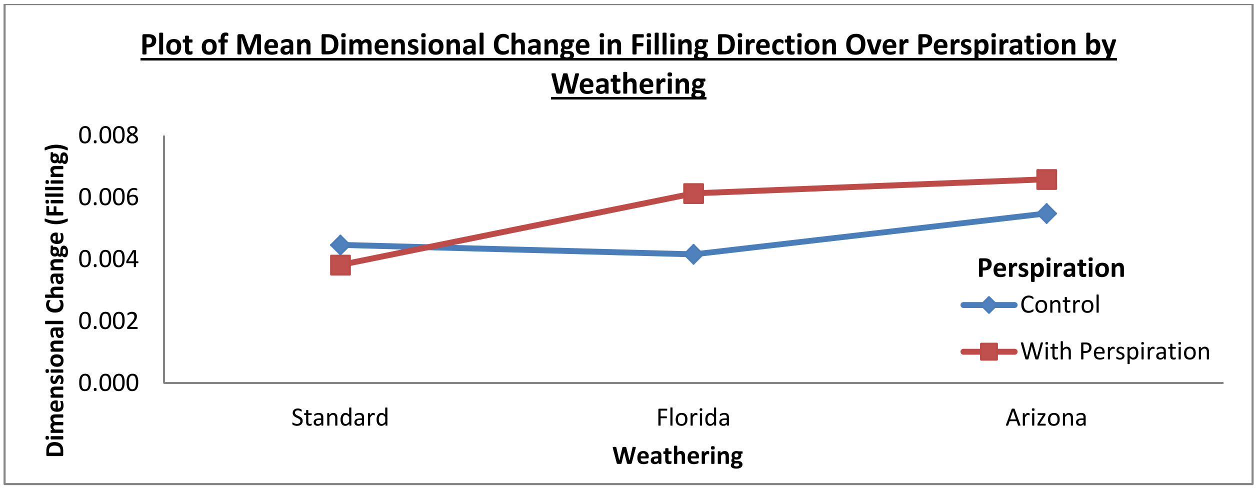


Figure 4.23 Plot of Mean Dimensional Change in Filling Direction Over Perspiration by Weathering

H6b2: There is no difference in dimensional change between the test specimens treated with and without perspiration.

Because three-way interaction was found (i.e., *Perspiration* x *Weathering* x *Washing Action*), a series of follow-up tests of using two-way ANOVA were performed to examine the two-way interactions separately at each individual levels of the third factor (i.e., *Weathering* x *Washing Action* under the condition of with and without perspiration application). In the case to understand the effect of perspiration application, the *Weathering* x *Washing Action* interaction was examined separately for each level of perspiration application (i.e., with or without perspiration). The results showed that significant differences were found in all weathering and washing action combination conditions except for those test specimens that stored in the standard conditioning and laundered in a HE washer, regardless of being treated with or without perspiration, which showed no significant difference (see Figure 4.24). Based on these results, the H6b2 is rejected.

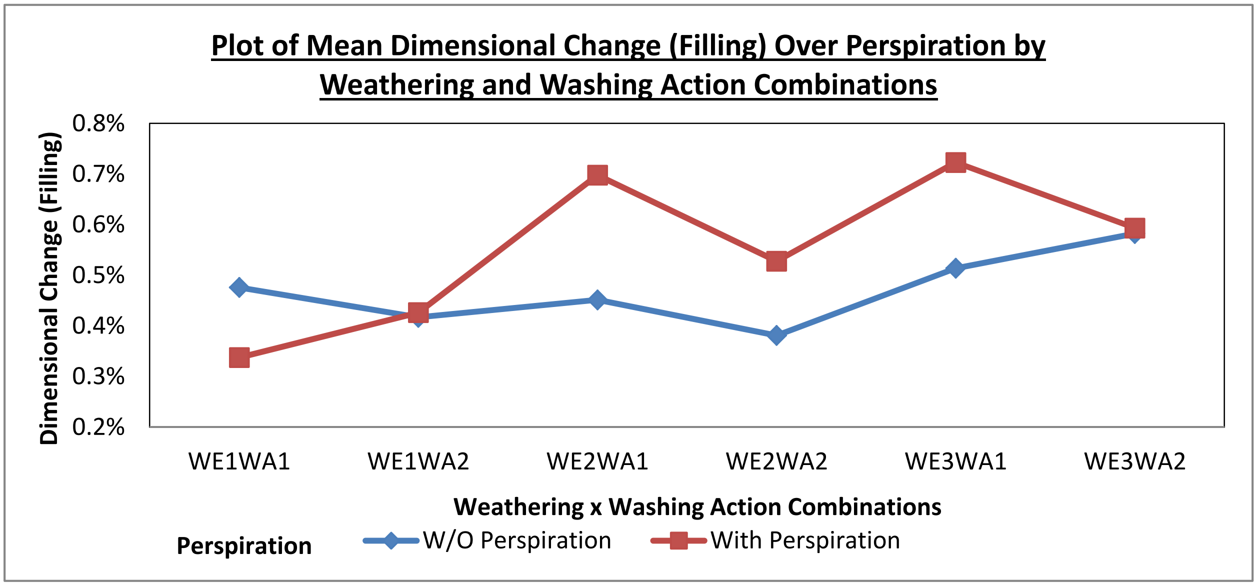


Figure 4.24 Plot of Mean Dimensional Change in Filling Direction by Weathering and Perspiration Combination after Repeated Laundering

H6c2: There is no difference in the dimensional change among the test specimens exposed to the following three weathering conditions - (a) semi-tropical climates without water spray, (b) semi-arid climates, and (c) control (i.e., standard conditioning).

Because three-way interaction was found (i.e., *Perspiration* x *Weathering* x *Washing Action*), a series of follow-up tests of using two-way ANOVA were performed to examine the two-way interactions separately at each individual levels of the third factor (i.e., *Perspiration* x *Washing Action*) under the exposure to three weathering conditions. The results showed that significant differences were found in those test specimens that treated with perspiration and laundered in a traditional washer, regardless of exposed to either Florida or Arizona condition, had a higher dimensional change in filling direction compared to those stored in the standard conditioning (see Table 4.23 and Figure 4.25). Based on these results, the H6c2 is rejected.

Table 4.23 Slice Perspiration by Weathering and Washing Action Combinations Results

	Perspiration	Washing Action	df	SS	MS	*F*
Weathering	**Without Perspiration**	**Traditional**	1	0.19	0.09	0.50
		HE	1	2.30	1.15	6.39*
	With Perspiration	**Traditional**	1	8.66	4.33	24.04**
		HE	1	1.25	0.63	3.48

*p value < 0.01;** p value < 0.0001

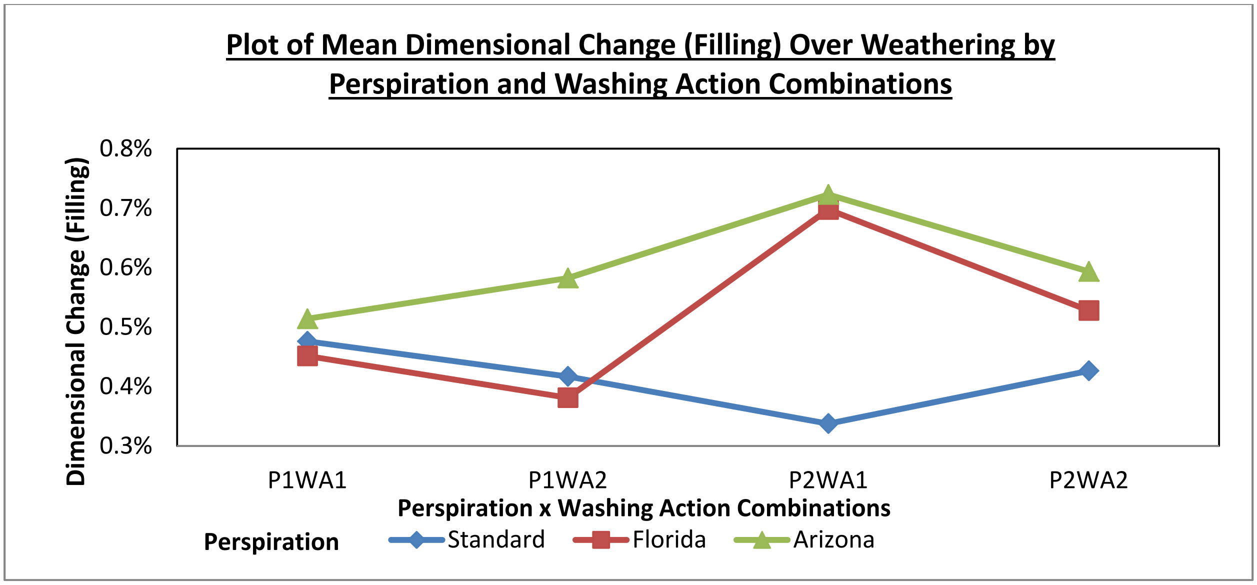


Figure 4.25 Plot of Mean of Dimensional Change in Filling Direction - Weathering by Perspiration and Washing Action Combinations

H6d2: There is no difference in dimensional change between the test specimens laundered in a traditional washer and the test specimens laundered in a front-loading HE washer.

Because three-way interaction was found (i.e., *Perspiration* x *Weathering* x *Washing Action*), a series of follow-up tests of using two-way ANOVA were performed to examine the two-way interactions separately at each individual levels of the third factor (i.e., *Weathering* x *Perspiration*) under the exposure to three weathering conditions. The results showed that significant differences were found in those test specimens treated with perspiration, exposed to Florida and laundered in a traditional washer had a higher dimensional change than those test specimens that received the same treatments (i.e., treated with perspiration and exposed to

Florida) but laundered in a front-loading HE washer (see Table 4.24 and Figure 4.26). Based on these results, the H6d2 is rejected.

Table 4.24 Slice Perspiration by Weathering and Washing Action Combinations Results

	Weathering	Washing Action	df	SS	MS	*F*
Perspiration	**Standard Conditioning**	**Traditional**	1	0.12	0.12	0.69
		HE	1	0.39	0.39	2.19
	Florida	**Traditional**	1	0.30	0.30	1.67
		HE	1	0.43	0.43	7.97*
	Arizona	**Traditional**	1	0.23	0.23	1.30
		HE	1	0.74	0.74	4.09

***p** value < 0.01

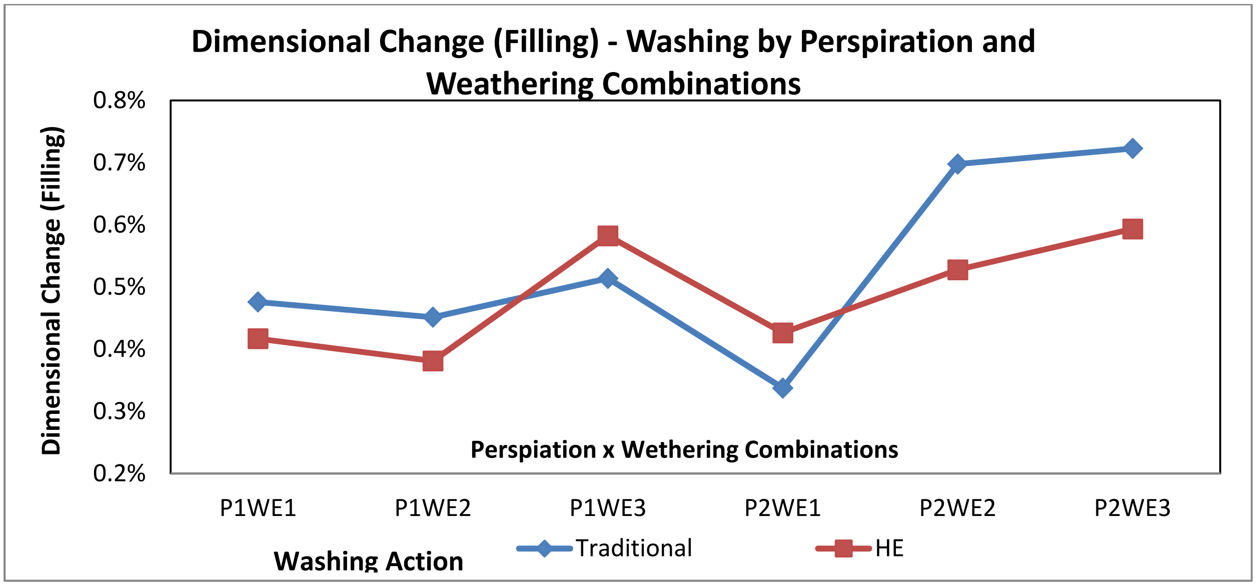


Figure 4.26 Plot of Mean of Dimensional Change in Filling Direction - Weathering by Perspiration and Washing Action Combinations

H6e2: There is no difference in dimensional change between the test specimens before and after repeated laundering cycles, up to 15 laundering cycles.

Because an interaction between weathering and repeated laundering was found (F = 3.23, $p < 0.0001$), a one-way ANOVA was conducted to examine the repeated laundering effects on the dimensional change in filling direction separately for the each level of weathering condition.

The result of the simple effects showed that, no matter laundered in which washer; the mean scores of dimensional change in warp direction were significantly different among different weathering conditions after 8, 10, 11, 13, 14, and 15 repeated laundering cycle (see Table 4.26 and Figure 4.27). Based on these results, H6e2 is rejected.

Table 4.25 Means and Standard Deviations for Fabric Count change in Filling Direction by Weathering and Perspiration

Cycle	Weathering Conditions						
	Standard Conditioning		Florida		Arizona		
	Mean	SD	Mean	SD	Mean	SD	*F*
1	0.27	0.13	0.23	0.10	0.23	0.11	0.11
2	0.31	0.11	0.31	0.15	0.29[c]	0.10	0.02
3	0.47[a]	0.16	0.44[b]	0.13	0.47[c]	0.16	0.03
4	1.01[a]	0.25	0.93[b]	0.33	0.83[c]	0.46	1.29
5	0.49[a]	0.41	0.59[b]	0.41	0.45[c]	0.29	0.89
6	0.30	0.54	0.60[b]	0.26	0.45[c]	0.47	3.67
7	0.49[a]	0.53	0.50[b]	0.37	0.67[c]	0.44	1.72
8	0.41[a]	0.51	0.42[b]	0.39	0.90[c]	0.53	13.28**
9	0.40[a]	0.43	0.60[b]	0.39	0.67[c]	0.55	3.12
10	0.34	0.53	0.39	0.50	0.66[c]	0.47	5.10*
11	0.45[a]	0.42	0.67[b]	0.35	0.81[c]	0.45	5.61*
12	0.55[a]	0.42	0.68[b]	0.33	0.78[c]	0.41	2.14
13	0.33	0.52	0.54[b]	0.34	0.87[c]	0.36	12.52**
14	0.27	0.49	0.46[b]	0.48	0.66[c]	0.47	6.16*
15	0.40[a]	0.50	0.72[b]	0.23	0.72[c]	0.40	5.75*

[a, b, c] In the same column, means with different superscript letters are significant different at 0.01 level by THSDT. * $p < 0.01$, ** $p < 0.0001$

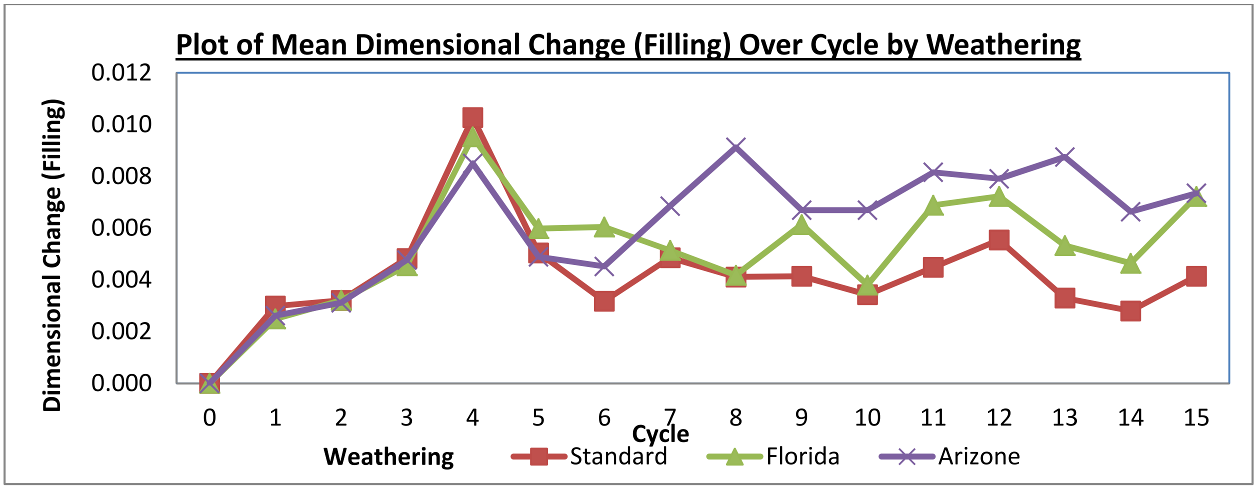


Figure 4.27 **Mean Scores of Dimensional Change in Filling Direction over Cycle by Weathering**

<u>The relationship between the changes in five fabric properties and the change in UPF value</u>

Based on the results of the correlation test, all fabric properties showed significant correlation with UPF values change except for fabric count change for warp direction (see Table 4.30). Fabric count change for warp direction, Delta E, and Dimensional change in filling direction showed a negative relationship with UPF value change. In addition, fabric thickness changes and fabric weight change showed a positive relationship with UPF value change. In particular, the Delta E showed a strong linear relationship with UPF values change, there is a possibility that changes of Delta E after the treatments application lead to the changes of UPF values. Because strong correlation does not imply causation and this study could not confirm the relationship between these variables, further research is needed in this area.

Table 4.26 Correlation coefficient for UPF values change and five fabric properties

	UPF	**FC_W**	**FC_F**	**Thickness**	**Weight**	**Delta E**	**DC_W**	**DC_F**
UPF	1.00000	-0.1268	0.0007	0.3342	0.2745	-0.7998	0.16020	-0.24707
p-value		<.0001	0.9776	<.0001	<.0001	<.0001	0.4963	<.0001
FC_W		1.00000	0.0952	0.0933	-0.0661	0.1799	-0.0704	-0.0321
p-value			0.0017	0.0021	0.0298	<.0001	0.0208	0.2913
FC_F			1.00000	0.1179	-0.4122	0.4163	-0.8198	0.1221
p-value				0.0001	<.0001	<.0001	<.0001	<.0001
Thickness				1.00000	0.00145	-0.3232	-0.1528	-0.0828
p-value					0.9621	<.0001	<.0001	0.0065
Weight					1.00000	-0.4384	0.4605	-0.1325
p-value						<.0001	<.0001	<.0001
Delta E						1.00000	-0.4734	0.1656
p-value							<.0001	<.0001
DC_W							1.00000	-0.0962
p-value								0.0015
DC_F								1.00000
p-value								

Note: FC_W = Fabric count change in warp direction; FC_F = Fabric count change in filling direction; DC_W = Dimensional change in warp direction; DC_F = Dimensional change in filling direction.

Summary and Conclusion of the Study

There are two purposes in this study. The primary purpose is to examine the effects of perspiration application, weathering exposures, washing action of automatic home clothes washers, and repeated laundering on the UVR protection of a NC lightweight cotton fabric. The secondary purpose of the study is to test the effects of the four treatment factors on the five fabric properties (i.e., fabric count change, thickness change, weight change, color change and dimensional change), and the relationship of these fabric properties on UPF value change after being treated with these four treatments. Based on the purpose and objectives of the study, a split-plot repeated measures experimental design was used, where the whole plot treatment was the weathering exposure and the combination of perspiration and washing action comprised the sub-plot treatments in order to understand the effects of repeated laundering on the UVR protection. Except for the control group, all test specimens were laundered after being treated with the three treatment factors (i.e., perspiration, weathering exposure, and washing action), and this process was repeated 15 times. The UPF value change and the changes of the five fabric properties of these treated test specimens were measured before laundering, and after each laundering cycle.

The results showed perspiration, weathering exposure, washing action, and repeated laundering significantly influenced UVR protection of a NC lightweight cotton fabric. The effects of perspiration on UPF value change depended on the levels of weathering conditions and the number of laundering cycles. Under the Standard textile testing condition, regardless of being treated with or without perspiration, no significant difference in UPF value change was found as the number of laundering cycles increased. For test specimens that were exposed to Florida and Arizona conditions, a significant difference in UPF value change was found. Test specimens that were treated with perspiration, regardless of being exposed to Florida or Arizona condition, had a greater change in UPF value than those treated without perspiration. The fabric exposed to weather, such as Florida and Arizona, showed significant differences in UVR protection depending on the levels of perspiration application and the number of laundering cycles. Test specimens stored in the Standard conditioning, regardless of being treat with or without perspiration, had a significant difference than those exposed to Florida and Arizona conditions as the number of laundering cycles increased. However, for test specimens that were exposed to Florida and Arizona conditions, the UPF value change was decreased as the number of laundering cycles increased. In addition, test specimens exposed to Florida conditions and treated without perspiration, had a greater change in UPF value than those exposed to Arizona condition and without perspiration as the number of laundering cycles increased. Repeated laundering increased the fabric UVR protection and fabric laundered in a traditional washer showed significant increase in UVR protection than those laundered in a traditional washer as the number of laundering cycles increased. Finally, the effects of repeated laundering on UPF value change depended on the levels of weathering conditions and perspiration application. All test specimens, regardless of being treated with or without perspiration and exposed to any type of weathering conditions, showed a significant difference after 1st cycle. For those stored in the Standard conditioning, regardless of being treated with or without perspiration, showed a significant increase in UPF value change as the number of laundering cycles increased (i.e., the UVR protection increased). However, for those exposed to either Florida or Arizona conditions, regardless of being treated with or without perspiration, showed a significant decreased in UPF value change as the number of laundering cycles increased (i.e., the UVR protection decreased).

For the results from the secondary purpose, perspiration, weathering exposure, washing action, and repeated laundering significantly influenced fabric count, fabric thickness and fabric weight. However, perspiration treatment had no significant effect on the dimensional change in warp direction of test specimens, and washing action had no significant effect on the dimensional change in filling direction of the test specimens, as well as both Delta E and Delta L of color change. Because the changes of fabric count, fabric thickness, fabric weight, and dimensional change did not have a strong relationship (i.e., low correlation) with fabric UPF value, it can be inferred that the changes of these fabric properties might not lead to the changes of UVR protection of a NC lightweight cotton fabric. In addition, perspiration, weathering exposure, and repeated laundering significantly influenced Delta E (-0.79) of color change. Because this Delta E had a strong relationship (i.e., high correlation) with fabric UPF value change, it can be inferred that the changes of this fabric property might lead to the changes of UVR protection of a NC lightweight cotton fabric.

Implications

The findings of the current study have implications for the consumers, apparel and textile industry. It means that NC cotton has a better UVR protection than conventional cotton. The worst UPF value change of the current study was found in the fabric exposed to Florida weathering without perspiration treatment and laundered in a traditional washer, where the UPF value was about 13 after 15 repeated laundering cycles. Despite having a minimum number, UPF 15 is required for a textile to claim it is sun protective clothing; this result of this study is far beyond that a common white cotton T-shirt, which only has a UPF 7 when dry and a UPF 5 when wet. In this study, the details means for UPF values of the test specimen by perspiration, weathering exposure, washing action of automatic home clothes washers, and number of laundering cycles are listed in Appendix E.

The implications to the apparel and textile industry are also suggested from the findings of this study. Apparel and textile industries, which include retailers and manufacturers, should become aware of the importance of the UVR protection provided by the NC cotton. NC cottons bring a premium to growers as the raw NC cottons have a higher price than conventional cottons. The environmental friendly charatetistic of the fiber also helps in lowering the production cost. By providing lower cost products to the retailers, the retailers could promote specially designed UPF label clothings to the market at a reasonable price. With the increase of public awareness related to the environmental issue and sun protection, the incidence of UVR related illness, such as skin cancer, may eventually be reduced.

Recommandation for Future Research

Based on the results of the past literatures and the experiment presented in current study, several recommendations are suggested for future studies:

1) Many prior studies compared the effects of perspiration, weathering exposure, washing action, and number of laundering cycles on various fabric properties. The current study extends the understanding of the influence of perspiration, weathering exposure, washing action, and number of laundering cycles on UVR protection of NC

cotton. The results showed that all independent variables had a significant effect on UPF. However, a conclusion regarding the effect of all these variables cannot be made based solely on one study. Further studies are needed in this area. In this study, only one color of NC cotton was tested. The effects of treatments may or may not be the same as the result of this study for NC cotton with other colors, such as dark brown and green. In future research, NC cotton with other colors, such as green and dark brown, may need to be included to examine whether the results are consistent with the current study. In addition, other fabric types, such as polyester blend, which is commonly used for summer clothing, should be examined in future study.

2) Household fabric softeners have been commonly applied to textile products in home laundering (Consumer Reports, 1999). Kim, Stone, Crews, Shelley, and Hatch (2004) and Rohwer and Eckhardt (1998) had examined the effect of laundry detergents on the UVR protection of fabrics. Previous research also demonstrated that fabric porosity can affect fabric UPF. Cotton fabric usually shrinks on repeated laundering, which might affect porosity, thickness, and consequently UPF. However, no study has examined the effect of household fabric softeners on the UVR protection. Furthermore, no study was found in examining the effect of fabric softener on NC cotton, and therefore, it would be interesting to study the UVR protection performance of NC cotton to fabric softener. If the overall UVR protection of NC cotton could be further improved via fabric softener treatments, the NC cotton might be preferable to regular cotton for summer clothing as it is more environmentally friendly in the processes of cotton plant growing and fabric production. Apparel and textile firms could include sun-protective clothing made of NC cotton in their merchandise assortment to accommodate the increased interest of public awareness related to sustainability and environmental issues.

REFERENCE

Achwal, W. B. (1995). Use of UV absorbers in textiles. *Colorage, 42*(10), 44-45.

Adam, J. (1998). Sun-protective clothing. *Journal of Cutaneous Medicine and Surgery, 3*(1), 50-53.

Algaba, I., Riva, A., & Crews, P.C. (2004). Influence of fiber type and fabric porosity on the UPF of summer fabrics. *AATCC Review, 4*(2), 26-31.

American Academy of Dermatology. (2013). *Protect yourself from the sun*. Retrieved from http://www.aad.org/public/News/DermInfo/DInfoProtectYourself.htm.

American Association on Textile Chemists and Colorists (AATCC). (2012). *AATCC Technical Manual.* Research Triangle Park, NC: AATCC.

American Society for Testing and Materials (ASTM). (2012). *Annual Book of ASTM Standards*. Philadelphia, PA: ASTM.

Ankeny, M., Ruoth, B., Keyes, N., Quddus, M., & Higbee, L. (2006). Evaluation of various laundering platforms on the color retention and surface appearance of 100% cotton knit fabric. *Proceedings of the Annual International Conference & Exhibition of AATCC,* 240-250.

Apodaca, J. K. (1990). *Naturally colored cotton: A new niche in the Texas natural fibers market*. Austin, TX: Bureau of Business Research.

Arulkumar, S., & Patil, U. J. (2013). Modified polyester with better water absorption, wickability. *The Indian Textile Journal, 123*(7), 32-44.

Association of Home Appliance Manufacturers (AHAM). (2008). *Clothes washer history*. Retrieved from http://www.aham.org/ht/a/GetDocumentAction/i/1407.

Australian Radiation Protection and Nuclear Safety Agency (ARPANSA). (2004). *Clothing and solar UV protection*. Retrieved from http://www.arpansa.gov.au/radiationprotection/FactSheets/is_UVProtection.cfm.

Barail, L. C. (1946). Perspiration: What do textile men know about it? *Rayon Textile Monthly, 27*(12), 93-95.

Barnett, R. B., & Slater, K. (1991). The progressive deterioration of textile materials. Part V: The effects of weathering on fabrics durability. *Journal of the Textile Institute, 82*(4), 417-425. doi: 10.1080/00405009108659228.

Bellomy Research (2010). *2010 major appliance consumer research webinar presentation*. Unpublished webinar presentation, Association of Home Appliance Manufacturers (AHAM), Washington, DC.

Berne, B., & Fischer, T. (1980). Protective effects of various types of clothes against UV radiation. *Acta Dermato-Venereologica, 60*(5), 459-460.

Bhat, N. V., Benjamin, Y. N., Buch, V. H., Wani, S. N., & Dharmadhikari, A. R. (1989). Effect of sunlight on cotton fabric in presence of perspiration. *Indian journal of textile research, 14*(3), 138-140.

Bhat, N. V., Dharmadhikari, A. R., Wani, S. N., & Kulkarni, S. D. (1990). Effect of perspiration on the fine structure of cotton fabrics. *Textile Research Journal, 60*(4), 240-244.

Bredereck, K. & Schumacher, C. (1993). Structure reactivity correlations of azo reactive dyes based on H-acid. IV. Investigations into the light fastness in dry state, in the wet state, and in presence of perspiration. *Dyes and Pigments, 23*(2), 135-147. doi: 10.1016/0143-7208(93)80031-U.

Capjack, L., Davis, S., & Kerr, N. (1994). Textiles and UV (ultraviolet) radiation. *Canadian Textile Journal, 111*(3), 14-15.

Capjack, L., Kerr, N., Davis, S., Fedosejevs, R., Hatch, K. L., & Markee, N. L. (1994). Protection of humans from ultraviolet radiation through the use of textiles: A Review. *Family and Consumer Sciences Research Journal, 23*(2), 198-218. doi: 10.1177/1077727X94232007.

Capjack, L., Kerr, N., & Fedosejevs, R. (2001). Fabric characteristics affecting transmission of ultraviolet radiation. *Canadian Home Economics Journal, 51*(1), 19-23.

Chen, H-L., & Burns, D. L. (2006). Environmental analysis of textile products. *Clothing and Textiles Research Journal, 24*(3), 248-261. doi: 10.1177/0887302X06293065.

Chen-Yu, J. H., Guo, J., & Kemp-Gatterson, B. (2009), Effects of Household Fabric Softeners on Thermal Comfort of Cotton and Polyester Fabrics After Repeated Launderings. *Family and Consumer Sciences Research Journal, 37*(4), 535–549. doi: 10.1177/ 1077727X09333277.

Chen-Yu, J., Wong, S. W., & Emmel, J. (2012, November). Comparisons of traditional and high-efficieny washers and dryers in the performance of stain removal, appearance smoothness, and fabric hand. *Proceedings of International Textile and Apparel Association, 69*, 4-5. Retrieved from http://cdm16001.contentdm.oclc.org/cdm/ref/collection/p16001coll5/ id/13199.

Chinta, S. K. & Gujar, P. D. (2013). Significance of moisture management for high performance textile fabrics. *International Journal of Innovative Research in Science, Engineering and Technology, 2*(3), 814-819.

Clark, I. E. S. , Grainger, K. J. L., Agnew, J. L., & Driscoll, C. M. H. (2000). Clothing protection measurements. *Radiation Protection Dosimetry, 91*(1-3), 279-281.

Clothes Care Research Center (2007). *Topload or frontload*. Retrieved from http://www.fabricology.com/science/top-or-front.php.

Collier, B. J., Bide, M. J. & Tortora, P. G. (2009). *Understanding textiles* (7th ed.). Upper Saddle River, NJ: Prentice Hall, Inc.

Collier, B. J., & Epps, H. H. (1999). *Textile testing and analysis*. Upper Saddle River, NJ: Prentice Hall, Inc.

Cordell, H. K. (2008, Spring). The latest on trends in natura-based outdoor recreation. *Forest History Today, 14*(1), 4-10.

Cotton Incorporated. (2004). *Technical bulletin (TRI 3019) – Effects of Laundering Conditions on Colorfastness to Home Laundering.* Cary, NC: Cotton Incorporated.

Crews, P. C., Kachman, S., & Beyer, A. G. (1999). Influence on UVR transmission on undyed woven fabrics. *Textile Chemist and Colorist, 31*(6), 17-26.

Crews, P. C., & Zhou, Y. (2004). The effect of wetness on the UVR transmission of woven fabrics. *AATCC Review, 4*(8), 41-43.

Dai, L., & Zhang, Y. (2011). The influences of material and structure on the UV protection of summer fabrics. *Advanced Materials Research, 298*, 73-77. doi: 10.4028/www.scientific.net/AMR.298.

Davis, S., Capjack, L., Kerr, N., & Fedosejevs, R. (1997). Clothing as protection from ultraviolet radiation: Which fabric is most effective? *International Journal of Dermatology, 36*(5), 374-379. doi: 10.1046/j.1365-4362.1997.00046.x.

Das, B. R. (2010). UV Radiation Protective Clothing. *The Open Textile Journal, 3*, 14-21.

Değirmenci, Z., Kaynak, H. K., & Kireççi, A. (2010, Spring). *UV protection of naturally colored cotton woven and knitted fabrics in comparison to white and dyed fabrics*. Paper presented at the The Fiber Society International Conference, Bursa, Turkey.

Dickerson, D. K., Lane, E. F., & Rodriguez, D. F. (1999). *Naturally colored cotton: Resistance to changes in color and durability when refurbished with selected laundry aids*. Fresno, CA: California Agricultural Technology Institute, California State University.

Diffey, B. L. (1991). Solar ultraviolet radiation effects on biological systems. *Physics in Medicine and Biology, 36*(3): 299-328. doi: 10.1088/0031-9155/36/3/001.

Dubrovski, P. D., & Golob, D. (2009). Effects of woven fabric construction and color on ultraviolet protection. *Textile Research Journal, 79*(4), 351-359. doi: 10.1177 /0040517508090490.

Dutt, Y., Wang, X. D., Zhu, Y. G., & Li, Y. Y. (2004). Breeding for high yield and fibre quality in coloured cotton. *Plant Breeding, 123*(2), 145-151. doi: 10.1046/j.1439-0523.2003.00938.x.

Eckhardt, C., & Rohwer, H. (2000). UV protector for cotton fabrics. *Textile Chemist and Colorist, 32*(4), 21-23.

Eckhardt, C., & Osterwalder, U. (1998). Laundering clothes to be sun protective. In A. Cahn (Ed.), *American Society for Quality Control Conference Proceedings, Montreux, Switzerland* (pp. 317-322). Urbana, IL: AOCS Publishing.

Edlich, R. F., Cox, M. J., Becker, D. G., Horowitz, J. H., Nichter, L. S., Britt, L. D., et al. (2004). Revolutionary advances in sun-protective clothing – An essential step in eliminating skin cancer in our world. *Journal of Long-Term of Medical Implants, 14*(2), 95-105.

Elesini, U. S., Richards, A. F., & Rowe, T. (1996, June 12-14). *Characteristics of naturally-colored cottons.* Paper presented at the 30th International Symposium on Novelties in Textiles, Ljubljana.

Energy Star (2013). *About energy start.* Retrieved from http://www.energystar.gov/index.cfm?c= about.ab_index.

European Committee for Standardization (1999). *Textiles—solar UV-protective properties-methods of test for apparel fabrics*. PrEN 13758. CEN, Brussels.

Evenson, J., & Epps, H. H. (1999, November). *Effects of instrumental weathering on the color of naturally colored cotton*. Paper presented at the 56th Annual Meeting of International Textile and Apparel Association Annual Conference, Santa Fe, New Mexico.

Firgo, H., Suchomel, F., & Burrow, T. (2006). Tencel® high performance sportswear. *Lenzinger Berichte, 85,* 44-50.

Fitzpatrick, T. B. (1988). The validity and practicality of sun-reactive skin types I through VI. *Archives of Dermatology, 124*(6), 869-871. doi:10.1001/archderm.1988.01670060015008.

Gambichler, T., Hatch, K. L., Avermaete, A., Bader, A., Herde, M., Altmeyer, P., & Hoffmann, K. (2002). Ultraviolet protection factor of fabrics: Comparison of laboratory and field-based measurements. *Photodermatology, Photoimmunology & Photomedicine, 18*(3), 135-140. doi: 10.1034/j.1600-0781.2001.00739.x.

Gambichler, T., Laperre, J., & Hoffmann, K. (2006). The European standard for sun-protective clothing: EN 13758. *Journal of the European Academy of Dermatology and Venereology, 20*(2), 125-130. doi: 10.1111/j.1468-3083.2006.01401.x.

Genkov, D., & Atmažov, P. (1968). Permeability of ultraviolet and infrared rays through cotton and synthetic textiles. *Folia Medica, 10*(4), 227-280.

Gies, P. H., Roy, C. R., & Elliot, G. (1992). Ultraviolet radiation protection factors for personal protection in both occupational and recreational situation. *Radiation Protection in Australia, 10*(3), 59-66.

Gies, P. H., Roy, C. R., Elliot, G., & Wang, Z. (1994). Ultraviolet radiation factors for clothing, *Health Physics, 67*(2), 131-139.

Gies, P. H., Roy, C. R. McLenan, A., Differy, B. L., Pailthorpe, M. T., Driscoll, C., et al. (1997). UV protection by clothing: An intercomparison of measurement and methods. *Health Physics, 73*(3), 456-464.

Gies, P. H., Roy, C. R., McLennan, A., & Toomey, S. (1998). Clothing and protection against solar UVR: Current status. *Journal of the Home Economics Institute of Australia, 5*(2), Sunsmart Supplement S8-S11.

Gobeil, N. B., & Mueller, B. J. (1974). Evaluating colorfastness to perspiration: Lab tests vs. wear tests. *Textile Chemist & Colorist, 6*(11), 46-47.

Gokarneshan, N., & Jeyathy, B. (2009). Nano finishes for textiles using UV protection. *The Textile Magazine, 50*(9), 56-58.

Goyal, R. (2005). UV radiation and protection. *Colourage Annual, 52*(10), 81-87.

Grimes, M. A. (1933). The effect of sunlight and other factors on the strength and color of cotton fabric. *Texas Agricultural Experiment Station,* 474, 1-56.

Grant, W. B., Strange, R. C., & Garland, C. F. (2003). Sunshine is good medicine. The health benefits of ultraviolet-B induced vitamin D production. *Journal of Cosmetic Dermatology, 2*(2), 86-98. doi: 10.1111/j.1473-2130.2004.00041.x.

Guoping, B., & Slater, K. (1990). The progressive deterioration of textile materials. Part V: The effect of acid treatment on fabric tensile strength. *Journal of the Textile Institute, 81*(1), 59-68.

Haerri, H. P., Haenzi, D., Donze, J. J. (2001). Application of UV absorbers for sun protection. *Melliand International, 7*, 59-61.

Hatch, K. L. (1993). *Textile Science*. St. Paul, MN: West Publishing Company.

Hatch, K. L. (2005). Solar ultraviolet protective clothing: What's behind the label? *AATCC Review, 5*(8), 31-34.

Hatch, K. L., & Osterwalder, U. (2006). Garments as solar ultraviolet radiation screening materials. *Dermatologic Clinics, 24*(1), 85-100. doi:10.1016/j.det.2005.09.005.

Hawkins, W. L. (1984). *Polymer degradation and stabilization*. Berlin - Heidelberg, Germany: Springer-Verlag.

Hayden, C. G. J. (1997). Skin absorption of oxybenzone in humans. *Food and Chemical Toxicology, 35*(12), 1232.

Heckman, C. J., Chandler, R., Kloss, J. D., Benson, A., Rooney, D., Munshi, T., … Oslin, D. W. (2013). Minimal erythema dose (MED) testing. *Journal of Visualized Experiments, 75*. doi:10.3791/50175.

Herzog, B., Quass, K., Schmidt, E., Müller, S., & Luther, H. (2004). Physical properties of organic particulate UV absorbers used in sunscreens II. UV-attenuating efficiency as function of particle size. *Journal of Colloid and Interface Science, 276*(2), 354-363.

Hilfiker, R., Kaufmann,W., Reinert, G., & Schmidt, E. (1996). Improving sun protection factors of fabrics by applying UV-absorbers. *Textile Research Journal*, *66*(2), 61-70. doi:10.1177/004051759606600201

Hoffmann, K., Hoffmann, A., Hanke, D., Bohringer, B., Schindling, G., Schon, U., et al. (1998). Sun protection by optimally designed fabrics. *Der Hautarzt, 49*(1), 10-16.

Hoffmann, K., Kesners, P., Bader, A., Avermaete, A., Altmeyer, P., & Gambichler, T. (2001a). Repeatability of in vitro measurements of the ultraviolet protection factor (UPF) by spectrophotometry with automatic sampling. *Skin Research and Technology*, *7*(4), 223-226.

Hoffmann, K., Lapperre, J., Avermaete, A., Altmeyer, P., & Gambichler, T. (2001b). Defined UV protection by apparel textiles. *Archives of Dermatology, 137*(8), 1089-1094.

Howard, J. W., & McCord, F. A. (1960). Cotton quality study: IV: Resistance to weathering. *Textile Research Journal, 30*(2), 75-117. doi: 10.1177/004051756003000201.

Hua, S., Wang, X., Yuan, S., Shao, M., Zhao, X., Zhu, S., & Jiang, L. (2007). Characterization of pigmentation and cellulose synthesis in colored cotton fibers. *Crop Science Society of America, 47*(4), 1540–1546. doi: 10.2135/cropsci2006.12.0835.

Hustvedt, G., & Crews, P. C. (2005). The Ultraviolet Protection Factor of Naturally-pigmented Cotton. *The Journal of Cotton Science, 9*(1), 47-55.

IndexMundi (2014, July 2). *Cotton daily price.* Retrieved from http://www.indexmundi.com/commodities/?commodity=cotton.

Jahagirdar, C. J., Srivastava, Y., & Venkatakrishnan, S. (2000). Light fastness of coloured cotton germplasm of gossypium hirsutum L. *Journal of the Textile Association, 61*(1), 27-33.

Jevtic, A. P. (1990). The sun protective effect of clothing, including beachwear. *The Australasian Journal of Dermatology, 31*(1), 5-7.

Kadolph, S. J. (2007). *Quality Assurance for Textiles and Apparel* (2nd ed.). New York: Fairchild Publications.

Kadolph, S. J. (2010). *Textiles* (11th ed.). Upper Saddle River, NJ: Prentice-Hall, Inc.

Kantor, M., & Moore, M. A. (2004). Effects of laundering treatments on naturally colored cotton knit fabrics. *Undergraduate Research Journal for the Human Sciences, 3*. Retrieved from http://www.kon.org/urc/laundering_with_addition.html.

Kathirvelu, S., D'Souza, L., & Dhurai, B. (2009). UV protection finishing of textiles using ZnO nanoparticles. *Indian Journal of Fibre & Textile Research, 34*(3), 267-273.

Katz, D., Boone, N., & Vreeland, J. M. (1997). *Organically grown and naturally colored cotton: a global overview. Proceedings of the Beltwide Cotton Conferences,* 293-297.

Kim, J., Stone, J., Crews, P., Shelley, M., & Hatch, K. (2004). Improving knit fabric UPF using laundry consumer products: A comparison of results using two instruments. *Family and Consumer Sciences Research Journal, 33*(2), 141-158. doi: 10.1177/1077727X04269185.

Kimlin, M. G., Parisi, A., & Meldrum, L. R. (1999). Effect of stretch on the ultraviolet spectral transmission of one type of commonly used clothing. *Photodermatology, Photoimmunology & Photomedicine, 15*(5), 171-174.

Kingsburg, N. (2009). *Hybrid: the history and science of plant breeding*. Chicago:University of Chicago Press.

Klausing, S. L., Maloney, J., & Easter, E. P. (2012). Evaluating dimensional change in home laundry. *AATCC Review, 12*(6), 51-57.

Lee, B., Marlenga, B., & Meich, D. (1991). *Farmer caps and hats: Skin cancer prevention project*. Eau Claire, Wisconsin: Marshfield Clinic.

Liffrig, J. R. (2001). Phototrauma prevention, *Wilderness and Environmental Medicine, 12*(3), 195-200.

Little, A. H., & Parsons, H. L. (1967). The weathering of cotton, nylon, and terylene fabrics in the United Kingdom. *Journal of the Textile Institute, 58*(10), 449-462.

Lucas, J. (2001). Weathering and light stability testing. *Industrial Fabric Products Review, 77*(11), 56-59.

Lyle, D. S. (1977). *Performance of textiles*. New York: John Wiley & Sons, Inc.

Majumdar, A., Kothari, V. K., & Modal, A. K. (2010). Engineering of cotton fabrics for maximizing in vitro ultraviolet radiation protection. *Photodermatology, Photoimmunology & Photomedicine, 26*(6), 290-296.

Malik, S. K., & Arora, T. (2003). UV radiations: Problems and remedies. *Man Made Textiles in India, 46*(5), 164-169.

Mankodi, H., & Agarwal, B. (2011). Studies on nano – UV protective finish on apparel fabrics for health protection. *Research Journal of Textile & apparel, 15*(3), 11.

Marques, J. (2002). Fight the fade: Testing products for lightfastness & weatherability. *Textile: Canadian Textile Journal/Revue Canadienne du Textile, 119*(5), 18-20.

Mason, R. (2008). Fabrics for atopic dermatitis. *The Journal of Family Health Care, 18*(2), 63-65.

McSwiney, B. A. (1934). The Composition of Human Perspiration. *Proceeding of the Royal Society of Medicine, 27*(7), 839-848.

Menter, J. M., & Hatch, K. L. (2003). Clothing as solar radiation protection. *Current Problem in Dermatology, 31*, 50-63. doi: 10.1159/000072237.

Menzies, S. W., Lukin, P. B., Greenoak, G. E., Walker, P. J., Pailthorpe, M. T., Martin, J. M., … Georgouras, K. E. (1991). A comparative study of fabric protection against ultraviolet-induced erythema determined by spectrophotometric and human skin measurements. *Photodermatology, Photoimmunology & Photomedicine, 8*(4), 157-163.

Merkel, R. S. (1991). *Textile product serviceability*. New York: Macmillan Publishing Company.

Morris, M. A. (1966). Effect of weathering on cotton fabrics. *California Agricultural Experiment Station, Davis, CA, Bulletin 823*, 193-202.

Moon, R. L., & Pailthorpe, M. T. (1995). Effect of stretch and wetting on the UPF of elastane fabrics. *Australasian Textiles, 15*(5), 39-42.

Murthy, M. S. S. (2001). Never say dye: The story of coloured cotton. *Resonance, 6*(12), 29-35. doi: 10.1007/BF02913764.

Myers, D. (1999). Organic cotton: A more sustainable approach. In D. Myer, & S. Solton (Eds.), Organic cotton: from field to final product (pp.1-7). London: Intermediate Technology Publications Ltd.

Namiligöz, S. E., Çoban, S. & Bahtiyari, I. M. (2010). Comparison of moisture transport properties of the various woven fabrics. *Tekstil ve Konfeksiyon, 20*(2), 93-100.

New Generation of Horizontal-Axis Washing Machines on the Way. (1997). *Environmental Building News, 6*(4), 6-9.

Norton, J. E., Stone, R. L., Ofjord, O. A., & Hemphill, J. E. (1975). Predicting colorfastness to light in subtropical climates. *Textile Chemist & Colorist, 7*(8), 27-29.

Oda, H. (2011). Development of UV absorbers for sun protective fabrics. *Textile Research Journal*, *81*(20), 2139-2148. doi: 10.1177/0040517511416277.

Öktem, T., Gürel, A., & Akdemir, H. (2003). The Characteristic Attributes and Performance of Naturally Colored Cotton. *AATCC Review*, *3*(5), 24-27.

Oehlert, G. W. (2010). *A first course in design and analysis of experiments*. New York: Freeman.

Orzada, B. T., Moore, M. A., Collier, B. J., & Chen, J. Y. (2009). Effect of laundering on fabric drape, bending and shear. *International Journal of Clothing Science and Technology, 21*(1), 44-55.

Osterwalder, U., Schlenker, W., Rohwer, H., Martin, E., & Schuh, S. (2000). Facts and fiction on UV protection by clothing. *Radiation Protection Dosimetry, 91*(1-3), 255-260.

Pailthorpe, M. T. (1993). Textile parameters and sun protection factors. *Proceedings of the Textile and Sun Protection Mini-Conference, Australia,* 32-50.

Pailthorpe, M. T. (1994). Textiles and sun protection: The current situation. *Australasian Textiles, 14*(6), 54-66.

Pailthorpe, M. T. (1998). Apparel textiles and sun protection: A marketing opportunity or a quality control nightmare? *Mutation Research*, *422*(1), 175-183.

Parmar, M. S., Giri, C. C., Singh, M., & Chabbra, J. (2006). Development of UV and flame resistant fabric from natural coloured cotton. *Colourage, 53*(7), 57-60.

Parthasarathi, K., & Borkar, P. (2007). Antibacterial and UV protection finishes of textiles by metal and metal oxide nano particles – A review. *Colourage, 54*(7), 43-45.

Paul, R., Bautista, L., De la Varga, M., Botet, J. M., Casals, E., Puntes, V., & Marsal, F. (2010). Nano-cotton fabrics with high ultravioler protection. *Textile Research Journal,* 80(5), 454-462. doi: 10.1177/0040517509342316.

Perdue, G. R. (1966). *The technology of washing*. London: British Launderers' Research Association.

Perspiration Fastness Subcommittee. (1952). Investigations into fastness to perspiration. *Journal of the Society of Dyers and Colourists, 68*(10), 392-394. doi: 10.1111/j.1478-4408.1952.tb02738.x.

Phoenix Brands LLC. (2005). FAQs. Retrieved from http://www.sunguardsun-protection.com.

Picken, M. B. (2010). *The language of fashion: A dictionary and digest of fabric, sewing, and dress.* New York: Funk & Wagnalls.

Ramkumar, S. S., Purushothaman, A., Hake, K. D., & McAlister, D. D. (2007). Relationship between cotton varieties and moisture vapor transport of knitted fabrics. *Journal of Engineered Fibers and Fabrics, 2*(4), 10-18.

Ranby, B., & Rabek, J. F. (1975). *Photodegradation, photo-oxidation and photostabilization of polymers.* London: John Wiley & Sons Ltd.

Reinert, G., Fuso, F., Hilfiker, R., & Schmidt, E. (1997).UV-protecting properties of textile fabrics and their improvement. *Textile Chemist and Colorist, 29*(12), 36-43.

Reinert, G., Schmidt, E., & Hilfiker, R. (1994). Facts about the application of UV-absorbers on textiles. *Melliand Textilberiche, 75*(7/8), 606–614.

Roberts, R. (1999). Sunlight, UV, and accelerated weathering testing - tools for determining performance. *Industrial Textiles, 2*(3-4), 1-13.

Rohwer, H., & Eckhardt, C. (1998). Laundry additive for the sun protection of the skin. *Sonderdruck aus SOFW Journal, 124*, 1-4.

Rogers, H. W., Weinstock, M. A., Harris, A. R., Hinckley, M. R., Feldman, S. R., Fleischer, A. B., & Coldiron, B. M. (2010). Incidence estimate of nonmelanoma skin cancer in the United States, 2006. *Archives of Dermatology, 146*(3), 283-287.

Ross, E. S., Taube, K., & Greene, D. S. (1954). *Home washing machines - Operating characteristics and factors affecting performance* (Bulletin No. 1088). Washington, DC: U.S. Department of Agriculture.

Sales share of the leading 10 liquid laundry detergent brands of the United States in 2012 (2012). Retrieved from http://www.statista.com/statistics/251472/sales-share-of-the-leading-10-liquid-laundry-detergent-brands-of-the-us/

Saville, B. P. (1999). *Physical testing of textiles*. Cambridge, England: Woodhead Publishing Limited.

Sayre, R. M., & Hughes, S. (1993). Sun protective apparel: Advancements in sun protection. *Skin Cancer Journal, 8*(2/3), 41-47.

Schaumann, M., & Rohwer, H. (2003). UV absorbers for fabrics: Ciba chemists detail the benefits of adding Tinosorb FD and FR to laundry care products. *Household & Personal Products Industry, 36*(2), 59-61.

Schlag, M. T., & Ordonez, M. (2010). Comparison of the Effects of a Top-Loading and a Front-Loading Washing Machine on Cotton Fabric. *Proceedings of the Annual International Conference & Exhibition of AATCC,* 30-39.

Sievenpiper, F. (1974). Colorfastness to perspiration and chemicals. *Textile Chemist & Colorist, 6*(10), 45-48.

Sinclair, S. A., & Diffey, B. L. (1997). Sun protection provided by ladies stockings. *British Journal of Dermatology, 136*(2), 239-241. doi: 10.1046/j.1365-2133.1997.d01-1177.x.

Slater, K. (1986). The progressive deterioration of textile materials. Part I: Characteristics of degradation. *Journal of the Textile Institute, 77*(2), 76-87.

Sleiman, M. (2011). Soiling of building envelope surfaces and its effect on solar reflectance. Part I: Analysis of roofing product databases. *Solar Energy Materials and Solar Cells, 95*(12), 3385-3399. Retrieved from: http://escholarship.org/uc/item/4n18r135.

Sliney, D. H., Benton, R. E., Cole, H. M., Epstein, S. G., & Morin, C. J. (1987). Transmission of potentially hazardous actinic ultraviolet radiation through fabrics. *Applied Industrial Hygiene, 12*(1), 36-44.

Smith, L. W. (1993). Sun Day Best Clothes (Hiking in Hot Weather). *Backpacker, 21*(126), 20-23.

Srinivasan, N., & Gatewood, B. M. (2000). Relationship of dye characteristics to UV protection provided by cotton fabric. *Textile Chemist and Colorists & American Dyestuff Reporter, 32*(4), 36-43.

Srivastava, M. (1992). Testing colorfastness to perspiration in certain fabrics. *Textile Trends, 35*(6), 37-39.

Standards Australia/Standards New Zealand (1996). *Sun p*rotective clothing: Evaluation and classification. AS/NZS 4399. Standards Australia, Sydney and Standards New Zealand, Wellington.

Stanford, D. G., Georgouras, K. E., & Pailthorpe, M. T. (1995a). Sun protection by a summer-weight garment: The effect of washing and wearing. *Medical Journal of Australia*, *162*(8), 422-425.

Stanford, D. G., Georgouras, K. E.,& Pailthorpe, M. T. (1995b). The effect of laundering on the sun protection afforded by a summer weight garment. *Journal of the European Academy of Dermatology and Venereology*, *5*(1), 28-30. doi: 10.1016/0926-9959(95)00053-G.

Stevens, J. M. (2009). *Applied Multivariate Statistics for the Social Sciences* (5th ed.). Mahwah, NJ: Lawrence Erlbaum Associates, Inc., Publishers.

Stone, R. L., Hardegree, G. L., Norton, J. E., & Smith, W. W. (1977). A weathering correlation study. *Textile Chemist and Colorist, 9*(7), 11-16.

Tamura, L. (2010, August 10). Designers sweat the details to let athletic clothes breathe. *The Washington Post*. Retrieved from http://www.washingtonpost.com/wp-dyn/content/article/2010/08/09/AR2010080904129.html.

The National Nanotechnolgy Initiative (2013). *What is Nanotechnology?* Retrieved from http://www.nano.gov/nanotech-101/what/definition.

The National Tanning Training Institute (2013). *Training for the professional operation of indoor tanning salons.* Retrieved from http://www.tanningtraining.com/btc/ ch6.html ?prodid=2.

The Soap and Detergent Association (SDA) (2008). *High efficiency washers and detergents: Working in harmony to save energy and water*. Retrieved from http://www.cleaning101.com/laundry/HE.pdf.

Thiry, M. C. (2002). Here comes the sun. *AATCC Review, 2*(6), 13-16.

Tomlinson, J. J., & Rizy, D. T. (1998). *Bern clothes washer study: Final report (National Technical Information Service)*. Springfield, VA: U.S. Department of Commerce. Retrieved from http://www.energystar.gov/ia/partners/manuf_res/bernstudy.pdf.

Tortora, P. G., & Johnson, I. (2014). *The Fairchild books dictionary of textiles* (8th ed.). New York: Fairchild Publication.

Truhan, Andrew P. (1991). Sun protection in childhood. *Clinical Pediatrics, 30*(12), 676-681.

Vass, C. C. N. (1931). Fastness of dyes to perspiration. *The Journal of the Society of Dyers and Colourists, 47*(1), 9-10.

Vigneshwaran, N., Kumar, S., Kathe, A. A., Varadarajan, P. V., & Prasad, V. (2006). Functional nano finishes for textiles. *Nanotechnology, 17*(20), 5087-5095.

Vreeland, J. M. J. (1999). The revival of colored cotton. *Scientific American, 280*(4), 90-96.

Waghmare, V. N., & Koranne, K. D. (1998). Coloured cotton: Present status, problems and future potentials. *The Indian journal of genetics & plant breeding, 58*(1), 1-15.

Wakelyn, P. J., & Gordon, M. B. (1995). Cotton, Naturally. *Textile Horizons, 15*(1), 36-38.

Wakelyn, P. J. & Chaudhry, M. R. (2007). Organic cotton. In S. Gordon & Y-L. Hsieh (Eds.), *Cotton: Science and technology* (pp. 130-175). Cambridge: Woodhead Publishing Limited.

Wall, M. J., & Frank, G. C. (1971). A study of the spectral distributions of sun-sky and xenon-arc radiation in relation to the degradation of some textile yarns: Part I: Yarn degradation. *Textile Research Journal, 41*(1), 32-38. doi: 10.1177/004051757104100107.

Wang, S. Q., Kopf, A. W., Marx, J., Bogdan, A., Polsky, D., & Bart, R. S. (2001). Reduction of ultraviolet transmission through cotton T-shirt fabrics with low ultraviolet protection by various laundering methods and dyeing: Clinical implications. *Journal of American Academy of Dermatology*, *44*(5), 767-774.

Wang, X. D., Li, Y. Y. (2002). Study on characteristics of colored cotton fiber development. *Journal of Zhejiang University Agriculture and Life Sciences, 28*(3), 237-242.

Washers & dryers: Saving at a price. (2006). *Consumer Reports, 71*(3), 43-47.

Washers & dryers: Dirty laundry. (2007). *Consumer Reports, 72*(6), 42-45.

Washers & dryers: Costs are up, but you don’t have to get soaked. (2012). *Consumer Reports, 77*(8), 52-54.

Watkin, S. M. (1995). *Clothing: The portable environment*. Ames, Iowa: Iowa State University Press.

Watson, J. (1991). *Textiles and the environment* (Special report No. 2150). London: Business International Limited.

Welsh, C. & Diffey, B. L. (1981). The protection against solar actinic radiation afforded by common clothing fabrics. *Clinical and Experimental Dermatology, 6*(6), 577-582.

Williams, B. L., & Horridge, P. (1996). Effects of selected laundering and drycleaning pretreatments on the colors of naturally colored cotton. *Family and Consumer Sciences Research Journal, 25*(2), 137-158.

Wilson, P. (1976). *Household equipment: Selection & management*. Boston, MA: Houghton Mifflin.

Wilson, C. A., Gies, P. H., Niven, B. E., McLennan, A., & Bevin, N. K. (2008). The relationship between UV transmittance and color - Visual description and instrumental measurement. *Textile Research Journal, 78*(2), 128-137.

Wimberley, V. S., & Roper, L., L. (1997). Colorfastness of naturally pigmented cotton fabrics. *ARS Textrina, 28*, 175-192.

Wong, J. C., Cowling, I., & Parisi, A.V. (2000). *Reducing human exposure to solar ultraviolet radiation*. Retrieved from http://www.photobiology.com/v1/wong.

Wong, S. W., Chen-Yu, J., & Emmel, J. (2012). Comparison of the effect of traditional and front-loading high-efficiency washers and dryers on the performance of colorfastness and dimensional change. *Proceedings of International Textile and Apparel Association, 69*, 16-17. Retrieved from http://cdm16001.contentdm.oclc.org/cdm/ref/collection/p16001coll5/id/13199.

Xin, J. H., Daoud, W. A., & Kong, Y. Y. (2004). A new approach to UV-blocking treatment for cotton fabrics. *Textile Research Journal*, *74*(2), 97-100.

Yadav, A., Prasad, V., Kathe, A. A., Raj, S., Yadav, D., Sundaramoorthy, C., & Vigneshwara, N. (2006). Functional finishing in cotton fabrics using zinc oxide nanoparticles. *Bulletin of Material Science, 29*(6), 641-645.

Yam, E. L-Y., Kan, C-W., Lam, J. K-C., Ng, S-P., Hu, H., & Yuen, C-W. M. (2013). The relationship between ultraviolet protection factor and fibre content. *Journal of Textile Engineering, 59*(4), 83-86.

Yang, H., Zhu, S. & Pan, N. (2004). Studying the mechanisms of titanium dioxise as ultraviolet-blocking additive for films and fabrics by an improved scheme. *Journal of Applied Polymer Science, 92*(5), 3201-3210. doi: 10.1002/app.20327.

Yin, H., & Rogers, C. (1996). The characteristic performance of naturally colored cotton. *Proceedings of the Beltwide Cotton Conference*, 1335-1337.

Zhang, M., Song, X., Sun, X., Wang, Z., Zhao, Q., Li, Z., ... Xu, X. (2011). Patterns of color formation in different fibers during development of colored cotton (Gossypium hirsutum L.) cultivars. *Australian Journal of Crop Science, 5*(13), 1796-1800.

Zhang, Z., Thomas, B. W., Wong, C. F., & Fleming, R. A. (1997). Fast measurement of transmission of effective irradiance through clothing fabrics. *Health Physics, 72*(2), 256-260.

Zhou, Y., & Crews P. C. (1998). Effect of OBAs and repeated launderings on UVR transmission through fabrics. *Textile Chemist and Colorist, 30*(11), 19-24.

APPENDICES

APPENDIX A: Coding System for Whole Plot Treatment Groups

Weathering Exposure
S = Standard condition
F = Semi-tropical w/o water spray (Florida)
A = Semi-arid (Arizona)

Fabric Swatch Number	Repeat Group Number	Weathering Exposure Condition
1	2	F
2	1	A
3	3	S
4	1	S
5	3	A
6	1	F
7	2	A
8	2	S
9	3	F

APPENDIX B: Random Codes for Specimen Cutting Plans

Repeat Group #	Test Specimen #	Column #	Row #	Perspiration (P=with treatment) (N=w/o treatment)	Washing Action (T=traditional) (H=HE)	Replicate	Cut Plan
1	1	12	5	P	T	1	A
1	2	1	4	P	H	1	A
1	3	16	2	N	T	1	A
1	4	11	1	N	H	1	A
1	5	21	8	P	T	2	A
1	6	5	6	P	H	2	A
1	7	8	7	N	T	2	A
1	8	17	3	N	H	2	A
2	1	3	7	P	T	1	B
2	2	23	2	P	H	1	B
2	4	18	4	N	T	1	B
2	6	9	6	N	H	1	B
2	1	19	1	P	T	2	B
2	8	14	8	P	H	2	B
2	3	7	3	N	T	2	B
2	8	13	5	N	H	2	B
3	1	15	4	P	T	1	C
3	2	24	1	P	H	1	C
3	3	20	5	N	T	1	C
3	4	6	7	N	H	1	C
3	5	10	2	P	T	2	C
3	6	4	8	P	H	2	C
3	7	22	6	N	T	2	C
3	8	2	3	N	H	2	C

APPENDIX C: The Order of Weathering Exposure in Weathering Chamber

- The order list in Appendix C is organized by repeat group set, where the first repeat group will start first, followed by the second repeat group, and then the third repeat group.

- The second column is "Treatment cycle." Each repeat group will go through 15 treatments cycles because there will be a total of 15 laundering cycles.

- The third column is "Types of Weathering Exposure." Because only one weathering chamber is available, and each repeat group contains two weathering exposure treatments, the test of one type of weathering (e.g., semi-tropical climate without water spray such as the climate in Florida) will be conducted first, and then the test of the other type of weathering (e.g., semi-arid such as the climate in Arizona) will follow. However, the order can be different. For example, the test of the semi-arid (Arizona) climate condition may become first and then semi-tropical (Florida) climate follows. Because these two weathering exposure treatments are acting like a pair for each repeat group, it is listed as "paired."

Order	**Repeat Group**	**Treatment Cycle**	**Types of Weathering Exposure**	
			Paired	
1	1	1	Florida	Arizona
2	2	1	Arizona	Florida
3	3	1	Florida	Arizona
4	1	2	Arizona	Florida
5	2	2	Florida	Arizona
6	3	2	Arizona	Florida
7	1	3	Arizona	Florida
8	2	3	Florida	Arizona
9	3	3	Florida	Arizona
10	1	4	Arizona	Florida
11	2	4	Florida	Arizona
12	3	4	Florida	Arizona
13	1	5	Arizona	Florida
14	2	5	Arizona	Florida
15	3	5	Arizona	Florida
16	1	6	Florida	Arizona
17	2	6	Florida	Arizona
18	3	6	Arizona	Florida
19	1	7	Arizona	Florida

20	2	7	Arizona	Florida
21	3	7	Florida	Arizona
22	1	8	Arizona	Florida
23	2	8	Arizona	Florida
24	3	8	Florida	Arizona
25	1	9	Arizona	Florida
26	2	9	Florida	Arizona
27	3	9	Florida	Arizona
28	1	10	Arizona	Florida
29	2	10	Florida	Arizona
30	3	10	Arizona	Florida
31	1	11	Florida	Arizona
32	2	11	Arizona	Florida
33	3	11	Florida	Arizona
34	1	12	Arizona	Florida
35	2	12	Florida	Arizona
36	3	12	Arizona	Florida
37	1	13	Arizona	Florida
38	2	13	Florida	Arizona
39	3	13	Florida	Arizona
40	1	14	Florida	Arizona
41	2	14	Arizona	Florida
42	3	14	Arizona	Florida
43	1	15	Arizona	Florida
44	2	15	Florida	Arizona
45	3	15	Florida	Arizona

APPENDIX D: The Order of Ballast Fabrics Taken from the Washer and Put into the Dryer

This appendix shows the random list of taking ballast fabrics from one of the washer to be dried together with the test specimens in the dryer.

The total number of laundering loads is 135 because each repeat group contains three different weathering exposure treatments, and there are 15 laundering cycles Therefore, there are 45 laundering loads for each repeat (3 weathering conditions x 15 laundering cycles = 45 laundering loads per repeat group). There are three repeat groups in this study. Therefore, the total number of laundering loads is 135 (45 laundering loads per repeat group x 3 repeats groups = 135 loads).

Laundering Load Number	Repeat Group	Types of Weathering Exposure	Treatment cycle	Types of Washer that Ballast Fabrics Taken from
1	1	Florida	1	Traditional
2	1	Standard conditioning	1	HE
3	1	Arizona	1	Traditional
4	2	Arizona	1	Traditional
5	2	Standard conditioning	1	HE
6	2	Florida	1	HE
7	3	Florida	1	Traditional
8	3	Standard conditioning	1	HE
9	3	Arizona	1	Traditional
10	1	Arizona	2	HE
11	1	Standard conditioning	2	Traditional
12	1	Florida	2	Traditional
13	2	Florida	2	Traditional
14	2	Standard conditioning	2	HE
15	2	Arizona	2	HE
16	3	Arizona	2	Traditional
17	3	Standard conditioning	2	Traditional
18	3	Florida	2	Traditional
19	1	Arizona	3	HE
20	1	Standard conditioning	3	HE

21	1	Florida	3	Traditional
22	2	Florida	3	HE
23	2	Standard conditioning	3	HE
24	2	Arizona	3	Traditional
25	3	Florida	3	HE
26	3	Standard conditioning	3	Traditional
27	3	Arizona	3	HE
28	1	Arizona	4	HE
29	1	Standard conditioning	4	Traditional
30	1	Florida	4	HE
31	2	Florida	4	HE
32	2	Standard conditioning	4	Traditional
33	2	Arizona	4	Traditional
34	3	Florida	4	HE
35	3	Standard conditioning	4	HE
36	3	Arizona	4	HE
37	1	Arizona	5	Traditional
38	1	Standard conditioning	5	Traditional
39	1	Florida	5	HE
40	2	Arizona	5	Traditional
41	2	Standard conditioning	5	HE
42	2	Florida	5	Traditional
43	3	Arizona	5	HE
44	3	Standard conditioning	5	Traditional
45	3	Florida	5	HE
46	1	Florida	6	HE
47	1	Standard conditioning	6	HE
48	1	Arizona	6	Traditional
49	2	Florida	6	Traditional
50	2	Standard conditioning	6	Traditional
51	2	Arizona	6	Traditional

52	3	Arizona	6	HE
53	3	Standard conditioning	6	HE
54	3	Florida	6	Traditional
55	1	Arizona	7	Traditional
56	1	Standard conditioning	7	Traditional
57	1	Florida	7	HE
58	2	Arizona	7	Traditional
59	2	Standard conditioning	7	Traditional
60	2	Florida	7	Traditional
61	3	Florida	7	Traditional
62	3	Standard conditioning	7	Traditional
63	3	Arizona	7	HE
64	1	Arizona	8	HE
65	1	Standard conditioning	8	HE
66	1	Florida	8	Traditional
67	2	Arizona	8	Traditional
68	2	Standard conditioning	8	HE
69	2	Florida	8	Traditional
70	3	Florida	8	Traditional
71	3	Standard conditioning	8	HE
72	3	Arizona	8	Traditional
73	1	Arizona	9	Traditional
74	1	Standard conditioning	9	HE
75	1	Florida	9	Traditional
76	2	Florida	9	HE
77	2	Standard conditioning	9	Traditional
78	2	Arizona	9	Traditional
79	3	Florida	9	Traditional
80	3	Standard conditioning	9	HE
81	3	Arizona	9	HE
82	1	Arizona	10	HE

83	1	Standard conditioning	10	Traditional
84	1	Florida	10	Traditional
85	2	Florida	10	HE
86	2	Standard conditioning	10	Traditional
87	2	Arizona	10	HE
88	3	Arizona	10	Traditional
89	3	Standard conditioning	10	Traditional
90	3	Florida	10	HE
91	1	Florida	11	Traditional
92	1	Standard conditioning	11	HE
93	1	Arizona	11	HE
94	2	Arizona	11	Traditional
95	2	Standard conditioning	11	HE
96	2	Florida	11	HE
97	3	Florida	11	HE
98	3	Standard conditioning	11	Traditional
99	3	Arizona	11	HE
100	1	Arizona	12	HE
101	1	Standard conditioning	12	Traditional
102	1	Florida	12	HE
103	2	Florida	12	Traditional
104	2	Standard conditioning	12	Traditional
105	2	Arizona	12	HE
106	3	Arizona	12	Traditional
107	3	Standard conditioning	12	HE
108	3	Florida	12	HE
109	1	Arizona	13	Traditional
110	1	Standard conditioning	13	HE
111	1	Florida	13	Traditional
112	2	Florida	13	HE
113	2	Standard conditioning	13	Traditional

114	2	Arizona	13	HE
115	3	Florida	13	Traditional
116	3	Standard conditioning	13	HE
117	3	Arizona	13	HE
118	1	Florida	14	HE
119	1	Standard conditioning	14	Traditional
120	1	Arizona	14	Traditional
121	2	Arizona	14	HE
122	2	Standard conditioning	14	HE
123	2	Florida	14	HE
124	3	Arizona	14	Traditional
125	3	Standard conditioning	14	HE
126	3	Florida	14	HE
127	1	Arizona	15	Traditional
128	1	Standard conditioning	15	Traditional
129	1	Florida	15	HE
130	2	Florida	15	Traditional
131	2	Standard conditioning	15	HE
132	2	Arizona	15	HE
133	3	Florida	15	Traditional
134	3	Standard conditioning	15	Traditional
135	3	Arizona	15	HE

APPENDIX E: The Means for UPF values of the test specimen by Perspiration, Weathering Exposure, Washing Action of Automatic Home Clothes Washers, and Number of Laundering Cycles.

Perspiration	Weathering	Washing Action	Cycle															
			0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
No	Standard	Traditional	44.41	42.62	47.11	46.54	47.96	48.60	48.73	51.29	53.66	55.43	54.31	56.09	55.80	57.28	54.39	56.70
		HE	42.90	42.61	44.61	46.87	48.28	50.64	49.97	51.92	53.50	56.25	56.98	57.88	59.15	59.12	59.89	59.64
	Florida	Traditional	44.82	34.20	30.81	27.07	25.87	23.06	26.13	19.06	17.71	20.74	16.14	15.28	14.70	14.31	13.95	13.37
		HE	44.51	35.88	31.04	28.11	26.51	23.50	27.69	19.27	18.23	20.46	17.47	16.17	16.34	15.64	15.28	14.42
	Arizona	Traditional	45.33	35.11	32.56	30.74	29.26	26.68	28.81	23.63	22.07	22.03	21.48	19.71	19.54	17.92	18.19	17.56
		HE	43.91	35.60	32.27	29.51	29.21	28.08	29.69	24.94	22.18	22.50	22.06	20.78	20.53	19.33	18.96	18.53
Yes	Standard	Traditional	44.28	43.52	46.94	46.90	48.51	48.86	49.14	49.59	53.50	52.25	54.93	56.19	55.37	56.61	56.58	57.50
		HE	44.10	43.51	46.45	47.37	48.21	49.31	49.85	50.07	52.31	56.55	57.94	59.24	56.07	58.30	58.04	58.35
	Florida	Traditional	44.21	35.99	33.31	31.46	30.60	29.20	20.24	27.52	26.65	25.78	25.92	24.18	23.42	23.29	24.31	23.49
		HE	44.73	35.83	35.04	32.85	31.72	31.87	21.66	27.99	26.69	26.84	26.13	25.55	25.43	25.60	26.67	23.95
	Arizona	Traditional	45.88	35.79	35.22	32.37	31.82	30.94	25.83	27.56	26.69	26.81	26.78	24.50	24.70	23.60	24.10	23.37
		HE	44.98	36.38	34.81	32.87	31.66	31.31	24.96	28.82	27.76	27.83	27.74	26.59	26.19	25.54	25.66	25.56