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Development and study of waterproof breathable fabric using silicone oil and polyurethane binder

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Development and Study of Waterproof Breathable Fabric Using Silicone Oil and Polyurethane Binder

by

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ABSTRACT

The focus of this study is on determining the optimum combination of hydrophilic and hydrophobic components in coating material to obtain high breathability and waterproof properties. Polyurethane binder and silicone oil were used in eight different combinations to coat the fabric along with one sample with 100% polyurethane binder for control. A knife-over-roll coating machine was used to coat the fabric. The coated samples were tested by using the Sweating Guarded Hot Plate method for breathability and the spray test and contact angle method for waterproof properties. Results obtained from the tests showed that fabric coated with an 80%-20% and 85%-15% polyurethane-silicone oil combination displayed best performance in terms of waterproof and breathable properties. The research also concludes that with a decrease in percentage of silicone in the material, there is an increase in breathability as well as waterproof properties of fabric, and best performance is achieved when its percentage is between 20 and 25%.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1: INTRODUCTION

The onset of the 21st century has marked great developments in technology and science. However, these developments have come with a price, one of which is aggravated global warming, leading to sudden climatic changes. In order to survive and be productive in such conditions, there is a need for appropriate apparel and work gear for people specifically working in outdoor environments. Waterproof breathable fabrics are engineered with the aim of protecting the wearer from weather conditions like wind, snow, and rain, as well as preventing excessive loss of body heat (Holmes, 2000).

Waterproof breathable fabrics are one of the harsh weather fabrics that protect the wearer without hampering their efficiency. Garments made from such fabrics keep water from entering and wetting the body but allow the passage of air and moisture. The passage of water vapor from the garment makes it breathable and hence comfortable. Comfortability is one of the most essential attributes that a garment should possess (Krishnan, 1991). It helps in maintaining and improving the efficiency of the wearer. Various techniques can be used to produce waterproof breathable fabrics.

One of the different methods of achieving waterproof breathable fabrics is application of solid coating on the substrate. These coatings work on the principle of adsorption and diffusion and desorption of water vapour (Roey, 1992). These coatings are developed by incorporation of hydrophilic agents in them. However, there are some disadvantages to using hydrophilic coatings; for example, for water vapour to begin transmission, a certain amount of vapour build-up is required (Painter, 1996). The incorporation of hydrophobic agents along with hydrophilic agents helps in the balance of the components and leads to better waterproof breathable properties along with other performance properties.

However, the use of both hydrophilic and hydrophobic components in the same mixture can generate unstable coating that might separate and deteriorate after application (Lomax, 1990). The incorporation of hydrophilic groups in the coating can also lead to reduction in water resistant properties of the substrate (Jassal, Khungar, Bajaj, & Sinha, 2004). It thus becomes important to optimize the combination of hydrophilic and hydrophobic agents to derive highest performance.

Problem Statement

This study will provide an assessment of the effects of variation in the amount of silicone oil and polyurethane binder on waterproof breathable properties of the fabric.

Purpose of Study

This research will determine the effect of the amount of resin application on waterproof breathable properties of the fabric. The following specific objectives emerge from the goal of this study:

1. Development of formulations with different combinations of silicone oil and polyurethane binder for coating polyester-cotton fabric.
2. Development of waterproof breathable fabric by application of all of the combinations of resin and binder mixtures.
3. Testing of coated and control fabric for effectiveness of its waterproof properties using goniometer and spray tests.
4. Testing of coated and control fabric for effectiveness of its breathable properties using the sweating plate method.
5. Determination of optimal combination of silicone oil and polyurethane binder to achieve highest waterproof and breathable properties.

Justification and Significance

Breathable fabrics find applications in different market segments from regular apparel and special high performance apparel to technical textiles (Mukhopadhyay & Midha, 2008). Different end products require different specifications and properties.

Waterproof properties can be achieved using different methods like high density tight weaving, microporous coating or lamination, and solid coating or lamination. However, use of solid polymer coatings has some advantages. For example, due to the continuous solid layer on the structure, there are no pores on the surface, which prevents the contamination and provides better water resistance (Lomax, 1991).

To achieve the required specifications and properties like high water vapour transmission, high water resistance, greater strength, improved flexibility, and better durability, it is necessary to use an optimized combination of hydrophobic and hydrophilic components in the coating (Holmes, 2000).

This study will focus on establishing an optimum combination of polyurethane (hydrophilic) and silicone (hydrophobic) components to achieve the highest waterproof and moisture transfer properties.

Hypothesis

Higher amounts of silicone oil in the mixture will give better waterproof properties but lower breathability.

CHAPTER 2: LITERATURE REVIEW

Introduction

Clothing forms an integral part of human history. It has been estimated that humans began wearing clothes at least 83,000 years ago and perhaps as early as 170,000 years ago (Toups, Kitchen, Light, & Reed, 2011). It became mandatory for humans to cover their body for protection from environment as they began moving long distances in colder climate. (Scott, 2005). Hence, since the beginning, one of the basic functions of clothing is protection from various elements. Protective clothing is used today for various purposes like fire, heat and cold, chemical, mechanical, electrical, biological, and radiation protection (Zhou, Reddy, & Yang, 2005).

Even though clothing is used for various purposes, one key function is still protection against foul weather like wind, rain, and snow. The first 100% waterproof coat was introduced by Charles Macintosh in 1823. The raincoat provided complete protection against rain; however, it used to be stiff and smelled heavily of rubber (The Return of Mac: Reinvention of Mackintosh, 2007). It lacked the property of comfort in many ways.

Comfort is defined as “A state of physical ease and freedom from pain or constraint” (Oxford dictionaries, 2014). Clothing comfort can be divided into three main categories: tactile comfort, thermal comfort, and aesthetic comfort (Yoon, Sawyer, & Buckley, 1984). However, it can also be categorised as mechanical and thermal comfort. Thermal comfort can be assessed by the air permeability of fabric as well as its permeabilty to water and heat. Mechanical comfort can be evaluated by its handle, rigidity, tensile properties, and smoothness (Behera & Hari, 2010)

Breathability of the fabrics is one of the factors which play a key role in comfort properties of clothing. The term “breathable” refers to the ability of fabrics to diffuse water vapour while preventing the penetration of water. Breathability is very important as it prevents the accumulation of water vapour or sweat near the body. Core body temperature required for the wellbeing of individuals is approximately 37 ^{o}C (Sen, 2008). Perspiration is produced when the body temperature exceeds the standard temperature of 37 ^{o}C. This temperature is balanced by secretion of sweat. It is important that the garments help in passage of sweat from body to atmosphere. This is because, if a person is in a cold climate performing high activity wearing non-breathable clothing, he may suffer from hypothermia, and if he is in a hot and humid climate, he may suffer from heat stress (Scott R. A., 2000).

Breathability and waterproofness are two contrasting abilities. Breathability allows the flow of air and water vapour from the one side of fabric to another, while waterproof abilities restrict the transfer of water from outside the fabric to inside, protecting the wearer from getting wet. It is therefore a challenge to develop fabrics that allow the transfer of water vapour, air, and perspiration from the inside of the fabric to the outside and simultaneously restrict the passage of water from the outside to the inside (Fan & Hunter, 2009).

This chapter discusses the various studies and research that have been done to address the challenge of developing waterproof breathable fabrics and clothing. The key points that this chapter will address are:

1. Methods of developing waterproof breathable fabrics
    - Types of waterproof breathable fabrics
    - Mechanism of moisture transmission from fabric to atmosphere
    - Advantages of coating over lamination
    - Methods of applications of coatings to develop waterproof breathable fabrics
2. Methods of evaluation of waterproof and breathable properties

3. Factors affecting properties of waterproof breathable fabrics

This literature study will form the basis of the main study and help to develop the problem statement for the study. It is important to review the earlier studies to devise the proper plan of study and methodology.

Methods of Developing Waterproof Breathable Fabrics

Waterproof fabrics and clothing have been on the market since they were introduced by Macintosh in form of raincoats, which were basically fabrics coated with crude rubber (Fan & Hunter, 2009). Waterproof clothing has gone through lot of changes since then, one of the latest changes being incorporation of breathability for giving the wearer a sense of comfort and flexibility. Waterproof breathable fabrics can be categorized into various types based on the method of their manufacturing.

The types of waterproof breathable fabrics, based on the methods of development, have been summarized into the following categories in a research study (Mukhopadhyay & Midha, 2008):

a. Tightly woven fabrics
b. Microporous membranes or coatings
c. Solid membranes or coatings
d. Combination microporous and solid coatings
e. Smart breathable fabrics
f. Incorporation of retro-reflective microbeads
g. Fabric based on biomimetics

a. Tightly woven fabrics

The first type of effective waterproof breathable fabric was developed from this method. The fabric produced is known as “Ventile.” Long staple, combed, and plied cotton yarns are woven using the Oxford weave (Lomax, 1985). This ensures that there are minimum pores in the fabric. When this fabric is inserted into water, the cotton fibers swell transversely and further reduce the pore size. Very high pressure of water is required to penetrate such fabric. The density of yarns is very high in such fabrics. Synthetic filament yarns can also be used in a similar way by using fibers that have inherent water repellent properties. However, they do not swell when inserted in water, and hence further coatings are required to obtain desirable results (Holmes, 2000).

b. Microporous membranes and coatings

Microporous membranes and coatings have pores with a diameter as small as 1 micron (Kannekens, 1994). These types of membranes and coatings are hydrophobic in nature. One example of microporous membrane is Polytetrafluoroethylene (PTFE). PTFE membranes are also widely known by their trade name Gore-Tex (Brzeziński, Malinowska, Nowak, Schmidt, Marcinkowska, & Kaleta, 2005). Application of the PTFE membrane on fabric leads to the creation of about 1.4 billion tiny holes per square centimeter of the fabric. These holes are smaller than raindrops but much larger than water vapour molecule (Holmes, 2000). Various methods of developing microporous coatings and membranes are (Mukhopadhyay & Midha, 2008):

- Wet coagulation
- Solvent extraction
- Melt blown technology

- Point bonding technology
- Radio frequency beam radiation

c. Solid membranes and coatings

Solid membranes and coatings are usually thin hydrophilic films with no pores or holes. They consist of modified polymers and diffuse moisture by molecular diffusion or by adsorption-diffusion-desorption process (Fan & Hunter, 2009). The solid membranes and coatings can be developed by combining hydrophobic and hydrophilic components to obtain better properties (Lomax, 1985). One of the researchers has suggested that hydrophilic coatings and membranes can be developed using a combination of hydrophilic and hydrophobic urethane components to obtain better properties while maintaining other physical properties (Krishnan, 1991).

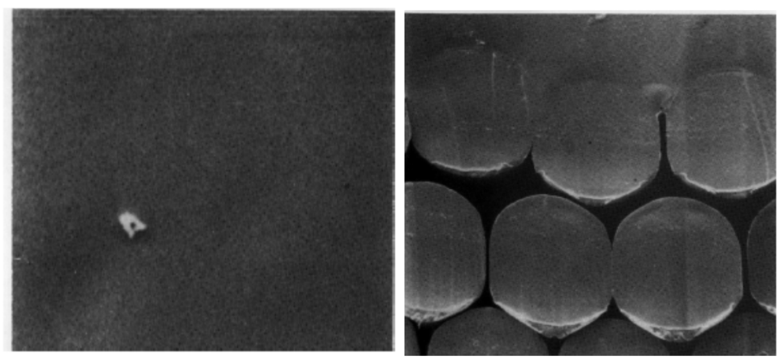

Figure 1. Left: Photograph of surface of coated hydrophilic fabric developed by Shirley Institute. Right: Cross-section of the fabric (Lomax, 1985).

One of the other methods of developing the waterproof breathable fabrics includes combining the microporous and hydrophilic membranes and coatings. In case of membranes, the microporous mesh or material is imbued with a hydrophilic material like polyurethane. In the case of coatings, hydrophilic finishes are applied over microporous films that have been attached to the fabric. This ensures enhanced waterproofing capacity while not hampering the breathability to a large extent (Roey, 1992).

In recent years, other techniques such as use of retroreflective microbeads, use of biomimetic phenomenon, and use of smart technology have been developed and practiced to obtain improved properties.

- Mechanism of moisture transmission from fabric to atmosphere:

Water vapour is transmitted through the fabric through the following various mechanisms (Das, Das, Kothari, Fanguiero, & Araujo, 2009):

1. Absorption, transmission, and desorption
2. Diffusion
3. Adsorption and transmission
4. Convection

In case of solid coatings, the water vapour transmission occurs due to chemical diffusion. The hydrophilic component in the material attracts the moisture and helps transfer it from higher relative humidity to lower humidity. The positively charged water molecule is attracted to negatively charged hydrophilic material. Weak bonds are formed, and due to this, water molecules are easily displaced until all the vapour is transmitted from the fabric into the atmosphere. Hydrophobic components in the coating help to resist penetration of larger water drops, thus maintaining the waterproof properties of fabric (Mukhopadhyay & Midha, 2008). The hydrophilic components form the amorphous regions of the coating. Swelling of these regions increases the vapour diffusion. However, if there is extensive swelling, it can lead to total dissolution and damage to the coating. The hydrophobic component helps in avoiding this by holding the polymer chains so that dissolution does not occur (Lomax, 1990).

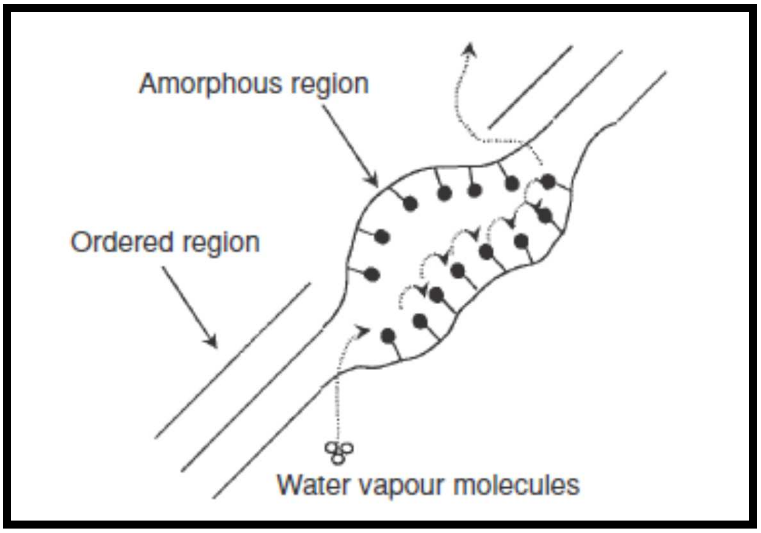

Figure 2. Mechanism of water vapour transmission (Holmes, 2000)

- Advantages of coating over lamination

As discussed in the section "Types of waterproof breathable fabrics," a fabric can be coated or laminated to obtain the desired properties. However, there are certain advantages to the use of coatings over the use of lamination.

Lamination, both hydrophilic and microporous, displays low adherence to the fabric surface as compared to coatings. The hydrophilic films also have lower moisture transmission ability (Krishnan, 1991). One other disadvantage of using the films is that they are more expensive and require experience to obtain accurate control over web tension (Kannekens, 1994). The waterproof breathable properties of the fabric can be altered by changing the number of layers of coating, thickness of the layer, and the type of coating. Coatings also impart better handle and drapability to the fabric, compared to the laminations (Kramar, 1998).

- Methods of applications of coatings to develop waterproof breathable fabrics:

There are many methods for application of coatings on fabrics. Proper method is selected based on availability of equipment, end use, cost, and efficiency.

The main types of coating methods are (Singha, 2012):

1. Direct coating
2. Transfer coating
3. Hot melt extrusion coating
4. Calendar coating
5. Rotary Screen coating
6. Foamed and crushed foam coating

1. Direct coating:

Direct coating consists of coating using the knife mechanism. The thickness of coating depends on the gap between the knife and the surface. There are various techniques in which this mechanism can be used (Hall, 2000) :

- Knife over roller
- Knife on air
- Knife over table
- Knife over rubber blanket

Direct coating is usually carried on tightly woven fabrics with smooth surfaces (Lomax, 1985).

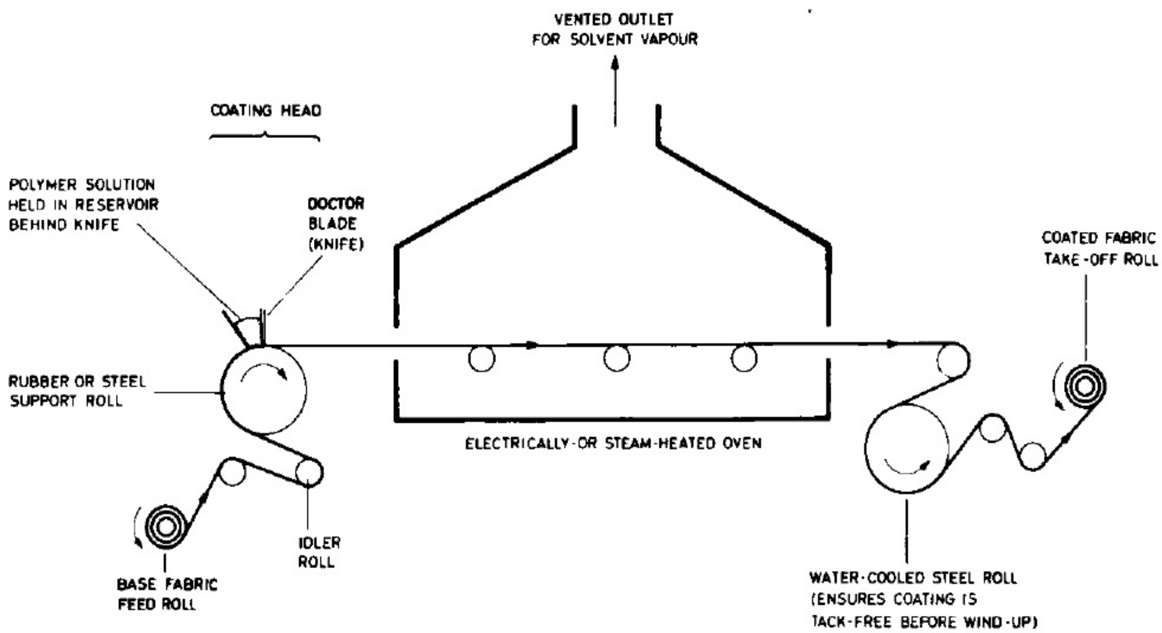

Figure 3. Direct Coating Method of Application (Lomax, 1985)

2. Transfer coating:

In this method, the resin is coated on a transfer paper, and then this paper is used to laminate the fabric. First, the release paper is knife coated, cured, and dried. Then another adhesive coating is applied on this paper. The paper is then bonded to the fabric, cured, and dried. At last the release paper is removed (Lomax, 1985).

3. Hot melt extrusion coating:

In this method, only thermoplastic polymers can be used. Polymer granules are fed between heated rollers. When heated, the granules melt and spread onto the substrate (Hall, 2000).

4. Calendar coating:

In this method, the coating films are created from polymer dough. The calendars evenly spread the dough over the fabric substrate using pressure. The calendars can be made up of a number of rollers (Singha, 2012).

5. **Rotary screen coating:**

In this method, a screen consisting of perforated holes is used. The polymers are spread across the center of the screen and then pressurized through the holes by a rotary blade (Hall, 2000).

6. **Foamed and crushed foam coating:**

Foam coating is used on substrates that cannot be directly coated due to non-smooth surfaces. This method also helps to maintain the handle and drape properties of fabric (Singha, 2012).

Evaluation of Waterproof Breathable Fabrics

The evaluation of the properties of waterproof breathable fabrics helps in understanding the role or effect of different parameters on the performance of the product as well as to establish relations between the parameters and change in properties. Various methods are present to evaluate waterproof and breathable properties of the fabrics. It is, however, also important to measure the mechanical properties of the waterproof fabric which is developed. Mechanical properties of fabrics are altered during processes like coating. When coating is done, there is longitudinal tension on yarns, which affects the position of both warp and weft (Sen, 2008).

- Evaluation of waterproof characteristics:

These are the different test methods which can measure the waterproof properties of the fabric:

1. Bundesmann rain tester (Holmes, 2000)
2. AATCC 22 – Spray test (Ozen, 2012)
3. AATCC 127 – Hydrostatic Pressure Test (Ozen, 2012)
4. Contact angle – Using drop method [Goniometer] (Wang, Li, Jiang, Fang, & Tian, 2007; Rowen & Gagliardi, 1947).

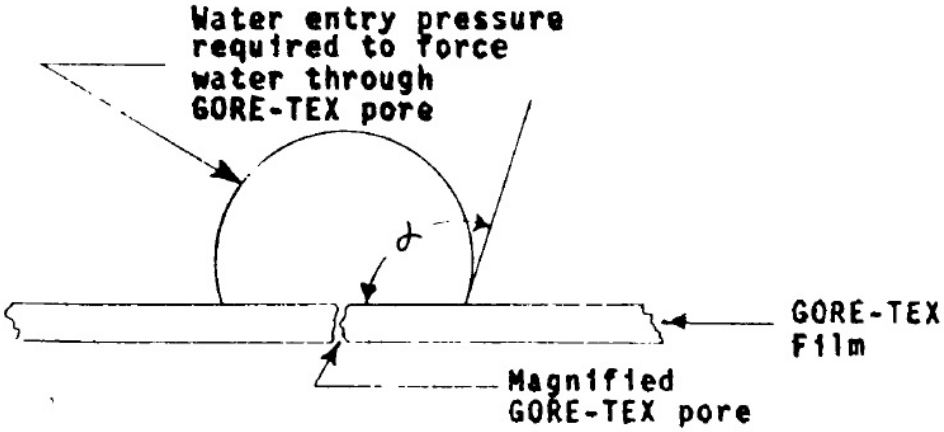

Figure 4. Schematic representation of water droplet on microporous membrane, α represents contact angle equaling 108° (Gohlke & Tanner, 1976).

- Evaluation of Breathable Properties:

These are the different test methods which can measure the waterproof properties of the fabric:

1. Evaporative dish method – ASTM E96-80 (Gretton, Brook, Dyson, & Harlock, 1997)
2. Guarded Sweating Hot Plate method – ASTM F1868 (Huang & Qian, 2008; Scott, 2000).

Evaluation of mechanical properties:

As discussed in the earlier section regarding comfort, it is important to test the mechanical properties of the fabric that has been coated or laminated to obtain waterproof breathable characteristics.

The different mechanical properties that can be measured are (Desai & Athawale, 1995):

1. Tensile strength
2. Elongation at break
3. Stiffness
4. Abrasion resistance

Factors Affecting Properties of Waterproof Breathable Fabrics

The waterproof breathable properties of a fabric depend not only on the type of mechanism used to develop them; they can also be affected by various factors like structure of yarn, type of fiber used, and moisture-modulus (Adler & Walsh, 1984).

In one of his studies, Lomax has reported that the construction of fabric and method of coating application has an effect on the breathable property of fabric. Direct coating is used on tighter weaves made of nylon or polyester filament yarns. Cotton-Polyester blends show higher amounts of moisture transmission than nylon and polyester, as the fibers under the coating also display hydrophilicity (Lomax, 1985). However, in a recent experiment performed by Ozen, it was found that regardless of fiber and weave type used, when the samples were treated with certain combination of microporous film and structure, all the samples portrayed similar behavior (Ozen, 2012).

- Importance of combining hydrophilic and hydrophobic components:

In case of coatings and laminations, it is important to use the optimized combination of hydrophilic and hydrophobic materials. Hydrophobic components tend to lower the breathability of fabrics, however, showing excellent waterproof properties. On the other hand, hydrophilic components increase the breathability but are water soluble and hence non-durable. Hence the combination of hydrophilic and hydrophobic components is used to obtain desired water vapour transmission and proper protection (Save, Jassal, & Aggarwal, 2005).

In one of the experiments performed by Wang and Yasuda, it was found that when the different fabric types were coated using hydrophilic and hydrophobic components, the fabrics with better wicking ability showed better water vapour flux (Wang & Yasuda, 1991). Inclusion of hydrophilic fibers in the fabric leads to quicker absorption of water vapour or sweat from near the body. In an experiment performed by Das et al., it was inferred that the use of certain proportions of viscose along with polyester led to quick absorption of sweat. However, as the proportion of viscose increased, the transmission of liquid vapour from fabric to atmosphere decreased and the fabric was clogged with liquid (Das, Das, Kothari, Fanguiero, & Araujo, 2009). Hence the proportion of hydrophilic component in the material should be optimum so that proper results are derived.

In research undertaken by Mukhopadhyay and Midha, it was stated that the most widely used polymers for breathable fabrics are polyurethanes, poly(tetrafluoroethylenes), acrylics, and polyamino acids. Amongst these, polyurethane polymer is the best because it displays higher toughness and flexibility and it can be developed according to specific end use (Mukhopadhyay & Midha, 2008).

Lomax has suggested that to obtain better characteristics, the combination of polyurethane and silicone rubber can be used. However, this mixture can become unstable and may separate out after prolonged use of the coated material, but it is still used for developing the waterproof fabrics (Lomax, 1990).

Summary

There are various methods that can be used to develop waterproof breathable fabrics. The selection of the proper method is highly important to get desired properties. With the help of this literature study, an appropriate methodology has been chosen for the experiment based on end use and availability of materials and equipment.

CHAPTER 3: METHODOLOGY

This chapter discusses the methodology applied in this research. The methodology was developed by referring to past studies and research. This chapter contains information regarding material, chemicals, application processes, and test methods used to obtain the results for the experiment.

Materials

The following material was used to conduct the experiment:

- Fabric design: Plain weave, lightweight fabric.
- Fabric composition: 55/45 polyester-cotton fabric.

  This combination of poly-cotton was used to minimize the effect of fiber type on the results.
- Fabric EPI = 59, PPI = 47.

Polyester-cotton blend is one of the most commonly used blends in regular-wear apparel. Cotton has natural moisture absorbency while polyester has inherent hydrophobic properties and usually cannot absorb moisture easily (Chaudhari, Chitmis, & Ramkrishnan). Hence the combination of both the fibers in almost equal proportion was used to obtain better results.

Chemicals

The following chemicals were used in preparation of coating material:

1. Polyurethane – Lubrizol Permax 200

   Viscosity of Lubrizol Permax 200 was 200 mm^2/s.

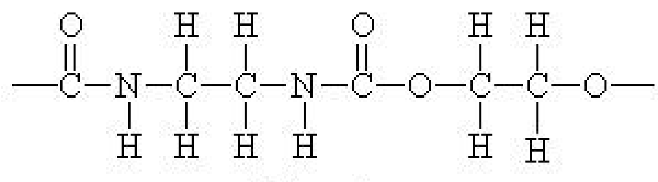

Figure 5. Structure of Polyurethane

2. Silicone oil – Wacker AK350

Viscosity of Wacker Silicone oil (AK350) was 350 mm^2/s.

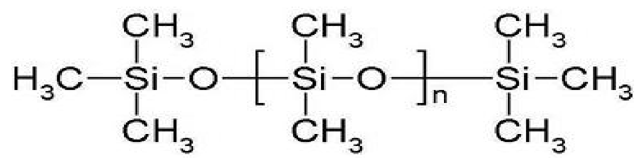

Figure 6. Structure of silicone oil

3. Surfactant – Triton X 100 (Non-Ionic)

The polyurethane resin forms the hydrophilic part of the composition while silicone oil acts as hydrophobic component. Triton-X, the non-ionic surfactant, helps in emulsifying the resin and silicone oil and avoids separation of the two components in the solution. It also acts as a wetting agent.

The components were used in varying percentages in the composition. In a research study carried out by Mukhopadhyay and Midha, various compositions of polymers were noted. The compositions contained the waterproof breathable component in the range of 15% to 45% (Mukhopadhyay & Midha, 2008). Hence, the below compositions were developed to derive the composition with optimum results. A total of 8 variations were selected based on both the previous studies and the probability of error that could occur.

Table 1 details the different compositions used.

Table 1

Composition of Chemicals in Coating Solution

Sample No.	PU (%)	Silicone (%)	Surfactant (%)
1	50	50	3% of Silicone
2	55	45	
3	60	40	
4	70	30	
5	75	25	
6	80	20	
7	85	15	
8	90	10	
9	100% PU - Control fabric		NA

The total amount of solution used for coating was 25 gm for each composition.

So for example, for a sample with 75-25 composition, the calculation was done as below:

Polyurethane = 75% of 25 = 18.75 gm.

Silicone = 25% of 25 = 6.25 gm.

Triton – X (Surfactant) = 3% of silicone = 3% of 6.25gm = 0.1875gm.

The solution was prepared by mixing polyurethane, silicone, and surfactant using high-speed electronic stirring. Speed of stirring was 1000 rpm.

Method of Application

Coating technology was used for the application of the resin to fabric. The type of coating was knife over roller coating, and the machine used was the Mathis Lab Coating Machine. In this method, a sample size of 15 in x 13.5 in was used. The fabric was stretched over a metal frame. All four sides of the frame had small pointed spikes; the fabric was fixed to these spikes on all sides. It was made sure that there were no wrinkles on the fabric surface.

Once the fabric was attached, the frame was mounted on the coating machine. The knife was then mounted on top of the fabric and placed in particular grooves such that consistent gaps were maintained between the fabric surface and the knife. Consistent pressure was applied to the knife by maintaining pressure on both sides of the grooves. The solution was then poured near the knife, and the knife was moved forward manually. The fabric was coated 4 times to obtain consistent thickness and even coating.

After the fabric was coated, the knife was removed carefully and immediately cleaned with ethyl alcohol to remove the resin residue. The coated fabric was then inserted into the curing oven inside the coating machine.

The following parameters were set for curing:

Sample size = 15 x 13 in

Curing temperature = 120^{o} C = 248 ^{o} F.

A curing temperature of 248 ^{o} F was selected based on the trial runs. At this particular temperature and dwell time, the sample was observed to be cured completely.

Dwell time = 5 min.

No. of coats = 4.

Fan speed = 2300 RPM.

Test Methods

Various kinds of tests were performed to judge the waterproof, breathable, and mechanical properties of the coated fabric.

1. Spray Test (AATCC – 22) :

   In this test, water was poured on the fabric in the form of a shower, and the water proofness of fabric was tested. A nozzle with two concentric rings of tiny holes was used to create the spray. The outer ring had a 21-mm diameter and contained 12 holes. The inner ring had a 10-mm diameter and contained 6 holes; there was a hole at the center of the rings as well. The diameter of all the holes was 0.86mm each.

A funnel with the nozzle attached to it was mounted on a stand. A plate was placed at a 45^{o} angle at the bottom of the stand at a 150-mm distance from the nozzle. The fabric was attached in an embroidery hoop of 6-in diameter, such that there were no wrinkles on it. 250 ml of distilled water was poured through the funnel in about 25-30 s. The fabric was then compared to the chart (AATCC method 22), and ratings were given accordingly.

2. Contact Angle Test:

A goniometer was used to measure the contact angle between water droplet and fabric surface. The results were measured and recorded digitally. A clean syringe was filled with distilled water and mounted on the assembly that inserted pressure on the needle to release one water droplet at a time. This assembly helped in applying constant pressure in constant time to avoid any bias. The name of the machine and software was FTA 32. This was a video-based contact angle measuring system. The software was used to control and record the results. A fabric strip of about 1.5 to 2 in long and about 0.25 in wide was mounted below the needle assembly on a block that was positioned such that the drop fell exactly on the desired area of the fabric. Using the software, the syringe was "pushed" until it released the water droplet. This process was monitored on the computer screen. The software captured about 50 picture frames of the water dropping on the fabric. The picture in which the water droplet was most stable was selected for analysis. The software then calculated the contact angle in that particular instance by drawing an arc over the droplet. Five readings were taken on each fabric strip.

3. Comfort Test:

The comfort test was one of the most important tests in this experiment. It helped to determine the moisture and thermal resistance of the fabric. ASTM F1868-02 standard method was followed for this test (ASTM method F1868). The details of the machine are:

Make: MTNW incorporation

Serial No.: 223-21

Chamber: TPS Lunaire Climatic chamber

Chamber model: CEO 910-4

Fabric sample size required: 12 in x 12 in

This machine consists of a guarded sweating hot plate with pores and behaves like skin under dry and wet conditions. The plate is placed inside a chamber which maintains constant relative humidity (RH) and a constant temperature of 65% RH and 25°C. The sweating plate is maintained at body temperature 35 ± 5°C. Heat flows from the test plate to the sweating plate across through the fabric material and across to the test environment. This heat flow is measured in terms of thermal resistance values, that is, “clo” value, and also in terms of “m^2 Pa/W” units.

First the thermal resistance that is dry test was performed. Initially, the bare plate thermal resistance was recorded and then the sample was mounted on the test plate to record the results. The sensors were securely connected to the controller for proper result recording. The wind sensor had to be at a 7-mm distance from the fabric sample. The height of the sensor could be adjusted by raising or lowering the plenum.

After the dry test, a wet test was performed. Distilled water was stored in a resource tank and was supplied to the test area through a small pipe. The test plate was wetted by pushing water through all the holes in it by pressing the pump. Mylar paper was also wetted and mounted on the sweating plate. The Mylar paper was secured using rubber tube on all four sides and by applying painter's tape on it. Extra water was removed using a sponge. Water gradually seeped through the topmost plate to the Mylar paper, stimulating sweating phenomenon. Bare plate moisture resistance was first recorded. After that, fabric was mounted on top of the Mylar paper and secured using tape. The wind sensor was again adjusted to be at a distance of 7 mm from the fabric, and moisture resistance of the fabric is recorded in terms of Ret (m^2 Pa/W). During the whole process it was made sure that the RH and temperature were maintained at standard conditions.

4. Tensile Test:

The tensile strength test was performed to determine the breaking strength, or the amount of load a sample can withstand before breaking. This test was performed to review whether the coating and the coating process altered any of the mechanical or physical properties of the fabric. ASTM standard method D5035-95 method was used for this test. According to this test (ASTM method D5035), 4 samples each were cut in weft and warp directions from the fabric. The sample size was 9 in x 1 in. The sample was mounted in between the jaws, which were 6 in apart from one another. MTS software was used to control and record the results. The following are the machine and set-up details used:

Machine – MTS Tensile Tester

Principle – CRE (Constant Rate of Extension)

Software – MTS Test works

Distance between jaws – 6 in

Jaw speed – 12 in/min

Width – 1 in

The machine was calibrated at zero reading before beginning the test. With the help of the software, the machine was prompted to start the test. After the test was complete, the breaking force and elongation at break were recorded.

5. Stiffness Test:

The stiffness test was performed to check whether the samples gained undesirable rigidity after coating. A Taber Stiffness Tester was used to perform the test with ASTM standard method D 5342-97 (ASTM method D5342). Fabric samples of size 1.5 in x 2.75 in were used for the test. The stiffness tester had a dial, a pendulum, and a unit scale with markings in terms of angle. Initially the zero reading on the dial, unit scale, and pendulum were matched by adjusting the machine using screws at the bottom of the machine stand. The fabric was mounted between the clasps, carefully making sure that the clasps were at an equal distance from the center. The dial, unit scale, and pendulum were checked again for a zero reading.

The machine was turned on and the handle was rotated to the left side first until the 15-degree mark on the dial coincided with the zero reading on the unit scale. After that, the reading was taken at the mark where the pendulum pointed on the unit scale. After the left side reading was obtained, the handle was brought back to the center, and zero readings on all three components were adjusted to coincide. The handle was moved to the right, and readings were obtained in the same manner as for the left side.

All readings were measured in Taber stiffness units. Five readings each were taken for both left and right side for each sample.

6. Thickness Test:

The thickness test was performed to determine how many layers of thickness were added to the fabric due to coating. The thickness test also helped in measuring the evenness of the coating. If the thickness in one area is much greater than in another area of the coated material, it means that the coating is uneven and the other test results will be skewed. An electronic thickness tester, “Elektrophysik – MiniTest 600B” with standard 526 µm ± 1% plate, was used for this test. This tester had a display which showed the reading and a probe which had sensors. The probe was placed on the fabric sample and slightly pressed. The display then showed the reading in terms of “µm.” Ten readings were recorded on each fabric sample in different areas. It had to be made sure that the readings were taken in different areas of the fabric as it would eliminate bias and would help to determine if the thickness was uneven.

The results obtained from the testing performed are discussed in the next chapter.

CHAPTER 4: RESULTS AND DISSCUSSION

This chapter contains the results obtained from various tests performed to determine the optimum combination for waterproof breathable coating. Each result will be analyzed and discussed in detail to obtain the conclusion.

1. Thickness Test:

The thickness test was performed to evaluate whether an application of coating added undesirable thickness to the fabric.

Table 2

Thickness Readings

Sample No.	Composition (PU-Si %)	Average sample thickness (µm)	Average coating thickness (µm)	Standard Deviation
1	50-50	322.5	25.5	15.99
2	55-45	332	35	7.89
3	60-40	337	40	11.35
4	70-30	324	27	6.24
5	75-25	334	37	24.15
6	80-20	343.5	46.5	21.53
7	85-15	326.5	29.5	10.07
8	90-10	331	34	21.11
9	100% PU (Control)	334.5	37.5	16.06
10	Uncoated fabric	297	0	7.15

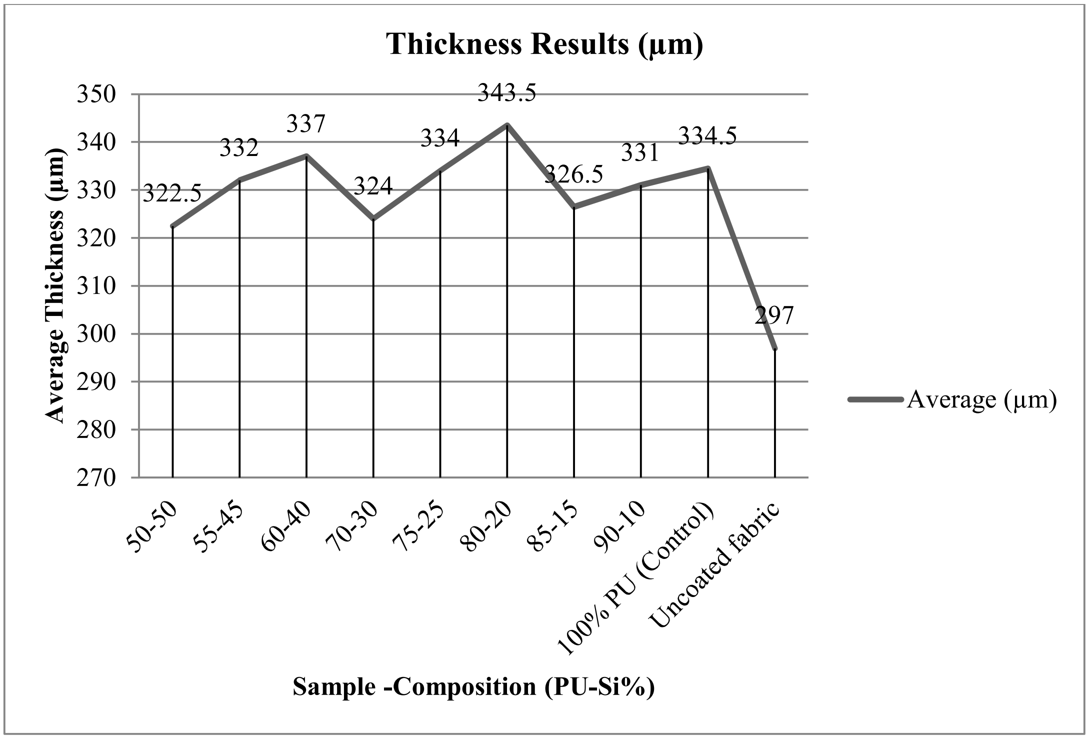

Figure 7. Graph showing thickness readings

In the case of the original fabric, the average thickness was calculated to be 297 µm. The sample composed of 50% PU and 50% silicone has the lowest average thickness, equaling 322.5 µm. The sample with 70-30% PU-Si and 85-15% PU-Si also has lower values of thickness as well as lower values of standard deviation. Lower values of standard deviation can be interpreted as less difference between the readings, which in this case means more evenness in the coating.

In the case of Sample 8, which has the lowest average thickness, only 25.5 µm thickness was added to the fabric due to coating. This is because it contains the highest amount of silicone oil, which is more fluid than the polyurethane resin. It was observed during preparation that the solution was difficult to emulsify due to the high amount of oil. The solution was unstable and had high fluidity. During coating, the solution seeped through the fabric rather than being deposited on the surface. Due to this, there was loss of the solution and hence the thickness was lower. In the case of Samples 70-30 and 85-15, it was observed that the emulsification was faster and more stable. The coating process was also efficient. These solutions were neither very viscous nor very fluid, and hence their application was smooth. It can be noted that the standard deviation in these two cases is lower than others, which also implies that both the samples had an even coating.

The maximum amount of thickness addition can be seen in the sample with 80-20% PU-Si, having 343.5 µm average thickness. However, the standard deviation in that case is very high, which implies uneven coating.

2. Spray Test:

The spray test determines the water resistance of the fabric. AATCC method 22 was used for the test.

Table 3 displays the results that were obtained.

Table 3

Spray Test Readings

	Sample (According to composition)									
	50-50	55-45	60-40	70-30	75-25	80-20	85-15	90-10	(100% PU) control	Uncoated fabric
Rating	50	70	80	80	80	90	90	90	70	0
ISO	1	2	3	3	3	4	4	4	2	0

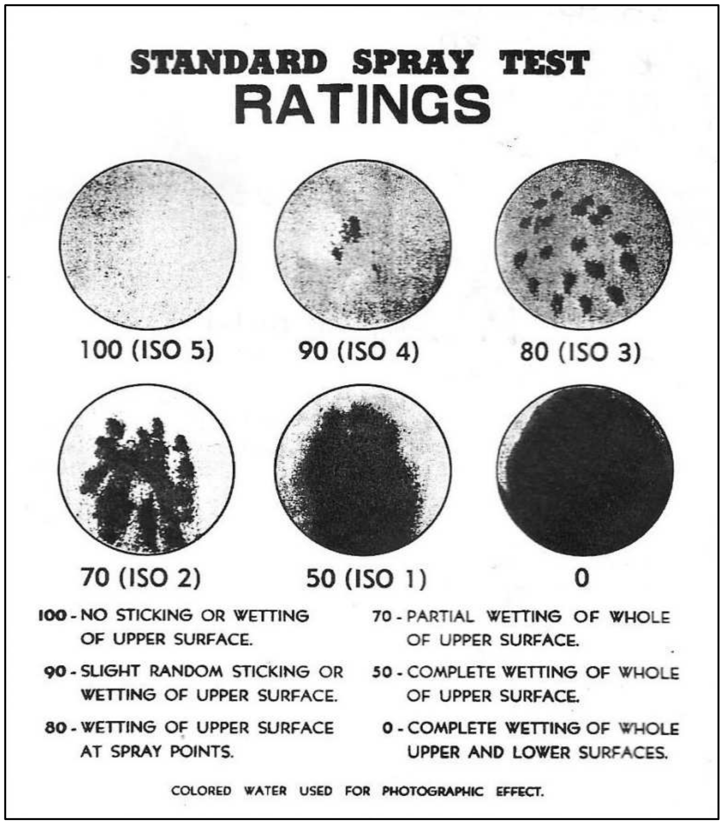

Figure 8. Spray Test rating chart – AATCC method 22 (AATCC standards)

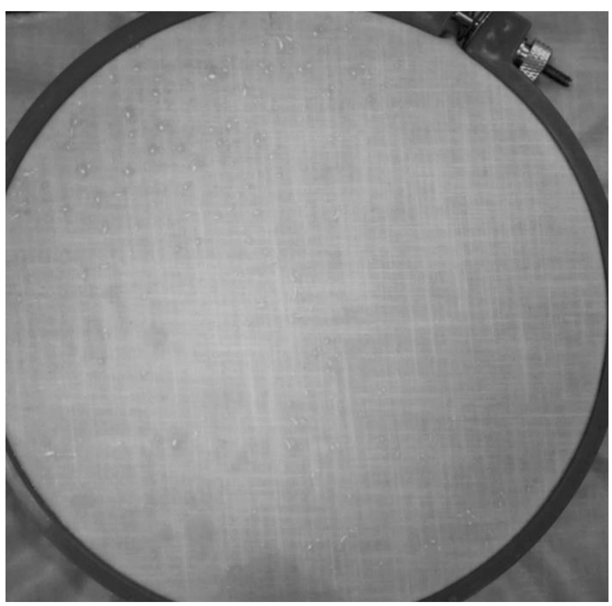

Figure 9. Sample 85-15 showing one of the highest spray test ratings. Water droplets can be seen on the fabric.

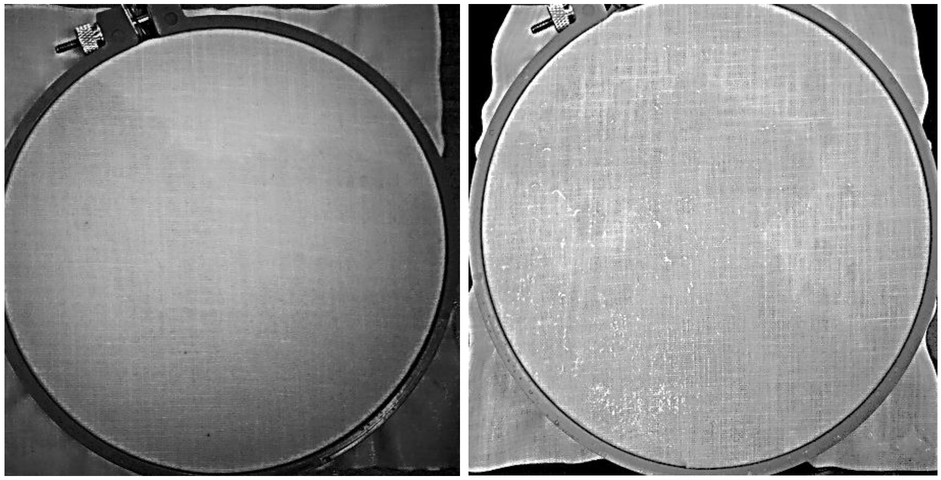

Figure 10. Samples showing low spray test ratings. Original uncoated fabric sample on left is completely wet on both surfaces while sample 50-50, on right has complete wetting on upper surface.

According to the rating chart, three samples—75-25, 80-20, and 85-15—have the highest rating. They have the "90" rating according to AATCC and "4" rating according to ISO. This rating implies that there was "slight random sticking or wetting of upper surface," according to the chart. It was observed that amongst these three samples, the sample with 85% PU and 15% Si showed maximum resistance to water and very slight wetting of the surface. It can be noted that as the amount of silicone was lowered, the water resistance was increased. However, when silicone was totally eliminated in the 100% PU sample, the rating was again lower and there was partial wetting of whole upper surface. The three samples with higher ratings consist of higher amounts of polyurethane, which was the hydrophilic component. This is observed because when the quantity of silicone increases in the mixture, the composition becomes unstable and will not show better properties. Hence, it can be seen that the sample with 50% PU and 50% silicone has the lowest spray test rating as it contains equal amounts of hydrophilic and hydrophobic materials.

3. Contact angle:

Contact angle measurement helps in deriving the wettability of the surface. The higher the angle between the surface and water, the higher the water resistance and the lower the wettability.

Table 4 shows the results for the contact angle test.

Table 4

Contact Angle Readings

Sample No.	Composition (PU-Si %)	Average (Lbf) - Warp	Standard deviation
1	50-50	96.9180	2.088793432
2	55-45	91.8250	10.48922199
3	60-40	82.2665	4.082834555
4	70-30	99.3965	3.961212188
5	75-25	75.4500	6.458006233
6	80-20	90.5170	4.127382282
7	85-15	95.9880	4.490128061
8	90-10	70.7880	5.194406415
9	100% PU (Control)	96.5955	5.714129899
10	Uncoated fabric	82.2665	4.127382282

It was observed that the samples 70-30, 80-20, and 85-15 showed the highest contact angle. The sample with 80% PU and 20% Si has an average contact angle of 93.59^{o} with the water droplet. The standard deviation in this case is 1.81, which is very low and implies that the data were accurate and not skewed. The sample with 85% PU and 15% Si also has high contact angle and low standard deviation. In one of the studies, the contact angle of a water drop on Gore-Tex fabric was given to be 108^{o} (Gohlke & Tanner, 1976). As compared to Gore-Tex, by using a polyurethane-silica combination, slightly lower contact angles were achieved. One of the reasons for this is that the fabric was lightweight and had slightly loose weave or structure. Use of tighter weave would lead to better water resistance but in turn reduce the breathability of the fabric.

Lower contact angle values were found in case of 50-50 and 55-45 samples. Similar to the lower spray test ratings, the lower contact angles in these samples means that their water repellency is lower.

It was observed in case of uncoated fabric that the drop of water would seep into the fabric in 5-10 seconds. Hence it was very difficult to measure the contact angle, and some of the readings were as low as 3^{o}, indicating complete wettability of the fabric. After the application of the coating there was very significant increase in the average contact angle of the fabric.

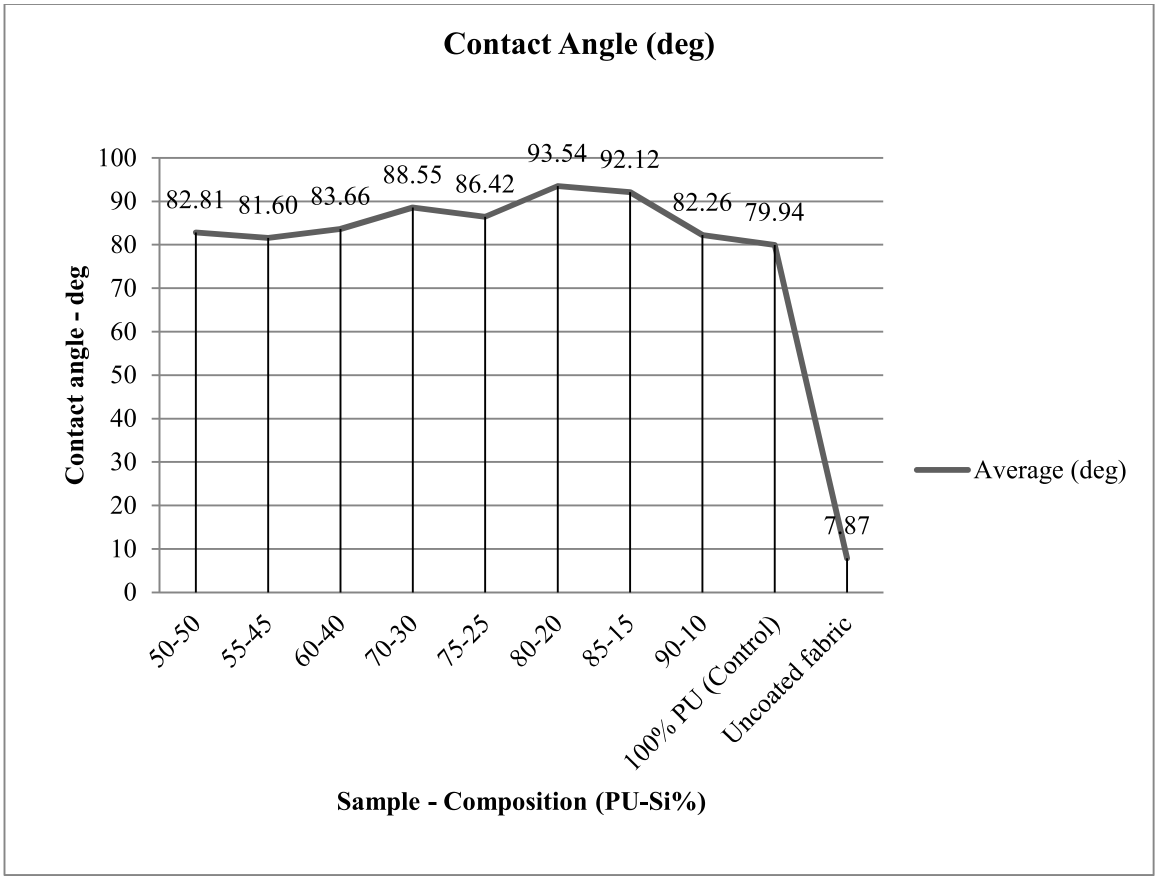

Figure 11. Graph showing contact angle readings

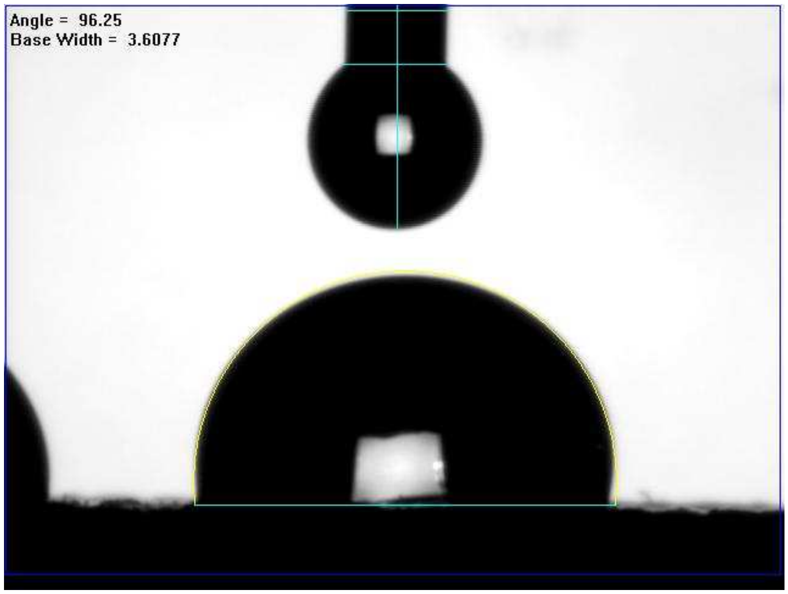

Figure 12. Contact angle reading for sample 85-15 showing one of the highest contact angles: 96.25°

Figure 12 shows the picture captured by FTA 32 software during the contact angle measurement test. The angle is measured by drawing an arc over the silhouette of the droplet.

Figure 13. Contact angle reading for original uncoated sample showing one of the lowest contact angles: 8.64º

Figure 13 shows the extremely small contact angle made by the water droplet and the fabric sample. This implies that the original fabric has no resistance to water.

4. Comfort Test

Comfort testing was performed in terms of thermal and moisture resistance of the fabric. The readings were measured in terms of "m^2Pa/W."

Table 5

Moisture Resistance Test Readings in Terms of Ret and Ref

Sample No.	Composition (PU-Si %)	Average Ret (m^2Pa/W)	Average Ref (Ret-Rebp) (m^2Pa/W)	Standard Deviation (Rebp-Ret)
1	50-50	9.0131	4.109141	2.416489
2	55-45	7.6275	2.971184	1.996928
3	60-40	8.5501	3.737923	0.133449
4	70-30	5.6847	0.872434	1.231911
5	75-25	6.1314	1.549717	0.353388
6	80-20	6.4597	1.577732	0.021974
7	85-15	5.7829	1.610135	3.612022
8	90-10	6.7737	1.961521	0.517002
9	100% PU (Control)	4.9495	-1.35219	0.180888
10	Uncoated fabric	5.2176	2.386931	0.065718

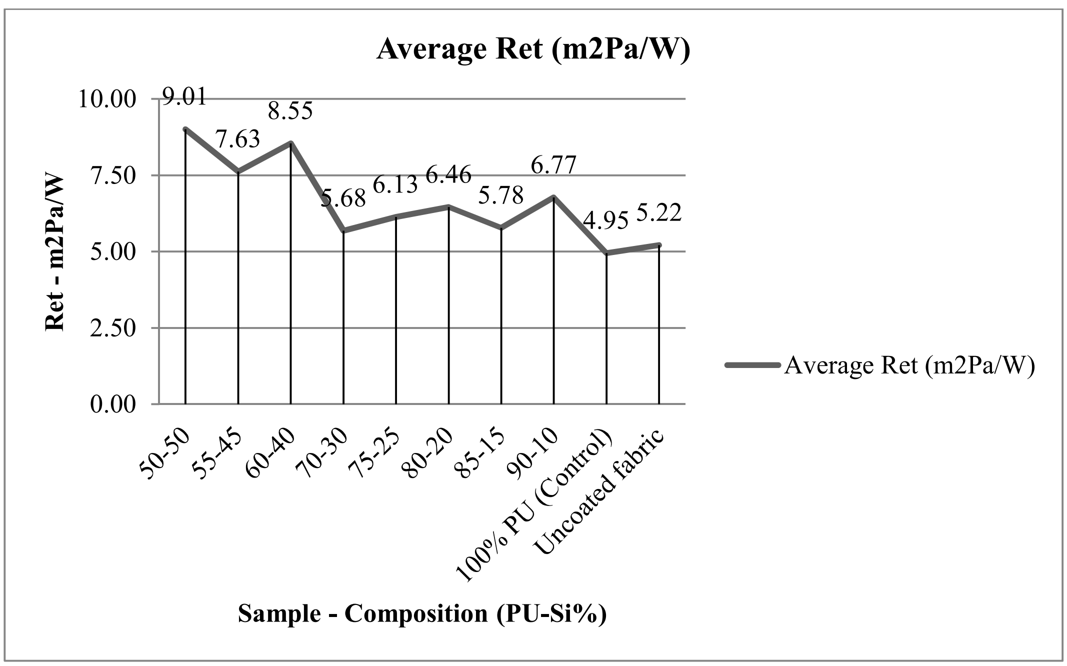

Figure 14. Graph showing Ret readings

The Ret values indicate the moisture resistance of the fabric, including the moisture resistance of the test plate. Ref can be calculated by subtracting the Ret value from the Rebp value. Lower values of Ret indicate lower moisture resistance, implying more breathability. The following classes have been developed to indicate the breathability rating of the fabrics (European Standards EN 343:2003):

- Class 1. Materials having Ret values greater than 40 m^2Pa/W are considered to be in Class 1 and are impermeable to moisture, that is, they provide no comfort to the wearer.
- Class 2. Materials having Ret values between 20 m^2Pa/W and 40 m^2Pa/W are considered to be in Class 2 and are moderately breathable and offer moderate comfort to wearer.
- Class 3. Materials having Ret values lower than 20 m^2Pa/W are considered to be in Class 3 and are extremely breathable. They provide maximum comfort to the wearer.

As compared to the above classification, all the readings fall under the Class 1 category, meaning that all of the samples are extremely breathable. The high average breathability can be seen in the sample coated with 70% PU and 30% Si. Slightly lower than the 70-30 sample, the sample with 85% PU and 15% Si also has higher breathability. The 100% PU fabric has the highest average breathability amongst all the samples. These breathability ratings indicate that samples containing about 15-30% silicone show maximum moisture permeability and are the best combinations of hydrophilic and hydrophobic components.

It can also be noted that the breathability of the coated fabric samples has not changed drastically from that of the uncoated or original fabric.

The thermal resistance of the fabrics is listed in Table 6.

Table 6

Thermal Resistance Readings of the Samples in Terms of Rcf and Rct

Sample No.	Composition (PU-Si %)	Average Rct (m^2Pa/W)	Average Rcf (Rct-Rcbp) (m2Pa/W)	Standard Deviation
1	50-50	0.0912	0.0407	0.0368
2	55-45	0.0841	0.0339	0.0252
3	60-40	0.0818	0.0332	0.0004
4	70-30	0.0717	0.0232	0.0034
5	75-25	0.0918	0.0439	0.0177
6	80-20	0.1261	0.0783	0.0128
7	85-15	0.0887	0.0422	0.0129
8	90-10	0.0679	0.0194	0.0097
9	100% PU (Control)	0.0831	0.0264	0.0048
10	Uncoated fabric	0.0675	0.0149	0.0003

These results show the thermal resistance of the fabric. A higher value of Rcf indicates higher resistance to heat flow through the fabric. It can be noted from the above results that there is no significant difference between the thermal resistance of the coated fabrics and uncoated fabrics. This indicates that the coating did not add any undesirable properties to the fabric.

5. Tensile Strength

The tensile strength test is performed to evaluate the mechanical properties of the fabric. During the coating process, the fabric might undergo changes in its physical properties due to tension and stretching. Sometimes the tensile strength of the fabric might get reduced due to the coating process. Hence this test ensures that no undesirable change has occurred in the strength of the fabric due to the coating process.

The tensile strength was performed in both the directions: warp and weft.

Below are the results for tensile strength test.

Table 7

Tensile Strength Readings – Warp Direction

Sample No.	Composition (PU-Si %)	Average (Lbf) - Warp	Standard deviation
1	50-50	96.9180	2.0888
2	55-45	91.8250	10.4892
3	60-40	82.2665	4.0828
4	70-30	99.3965	3.9612
5	75-25	75.4500	6.4580
6	80-20	90.5170	4.1274
7	85-15	95.9880	4.4901
8	90-10	70.7880	5.1944
9	100% PU (Control)	96.5955	5.7141
10	Uncoated fabric	82.2665	4.1274

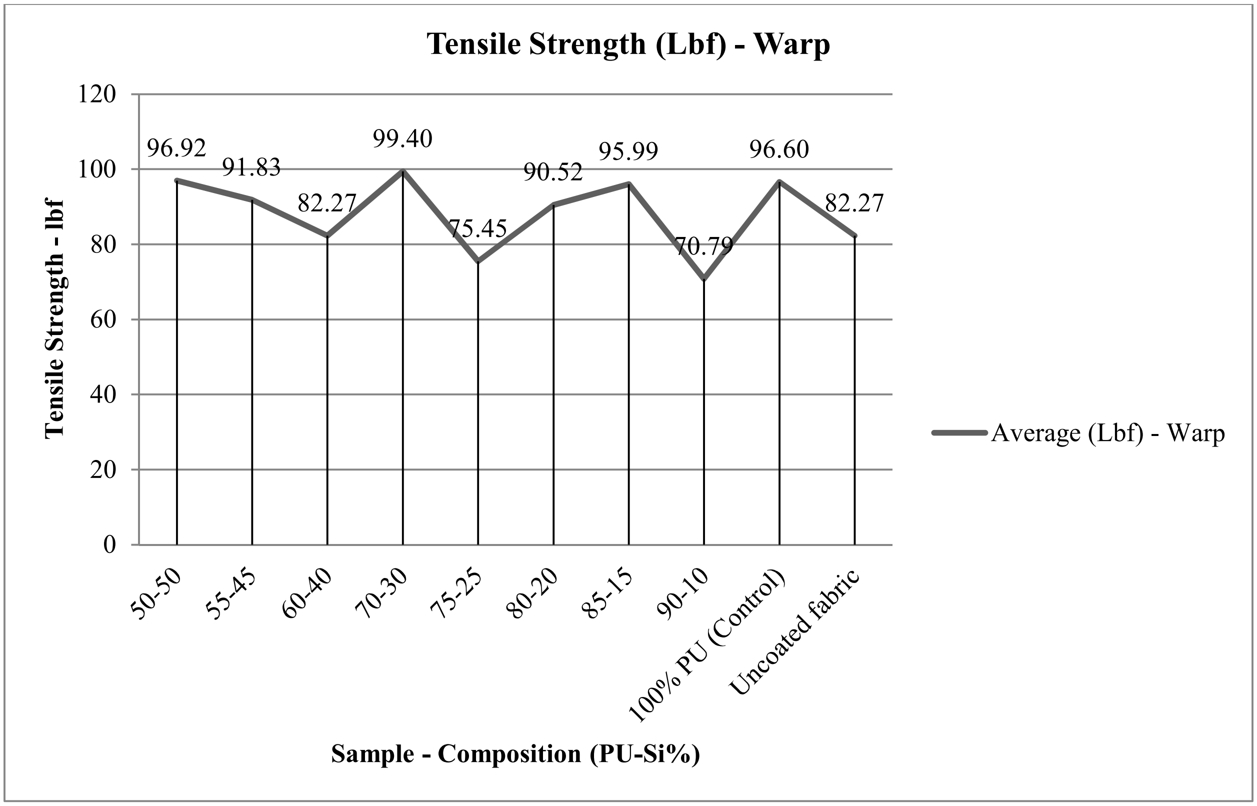

Figure 15. Graph showing Tensile Strength results for Warp direction

Table 8

Tensile Strength Readings – Weft Direction

Sample No.	Composition (PU-Si %)	Average (Lbf) - Weft	Standard deviation
1	50-50	33.8605	1.1512
2	55-45	54.9170	3.5179
3	60-40	65.6480	4.7468
4	70-30	60.3510	3.6671
5	75-25	60.0280	12.3447
6	80-20	43.7195	3.3969
7	85-15	45.2145	1.7466
8	90-10	56.0610	11.3399
9	100% PU (Control)	66.0635	4.8345
10	Uncoated fabric	58.9005	1.6879

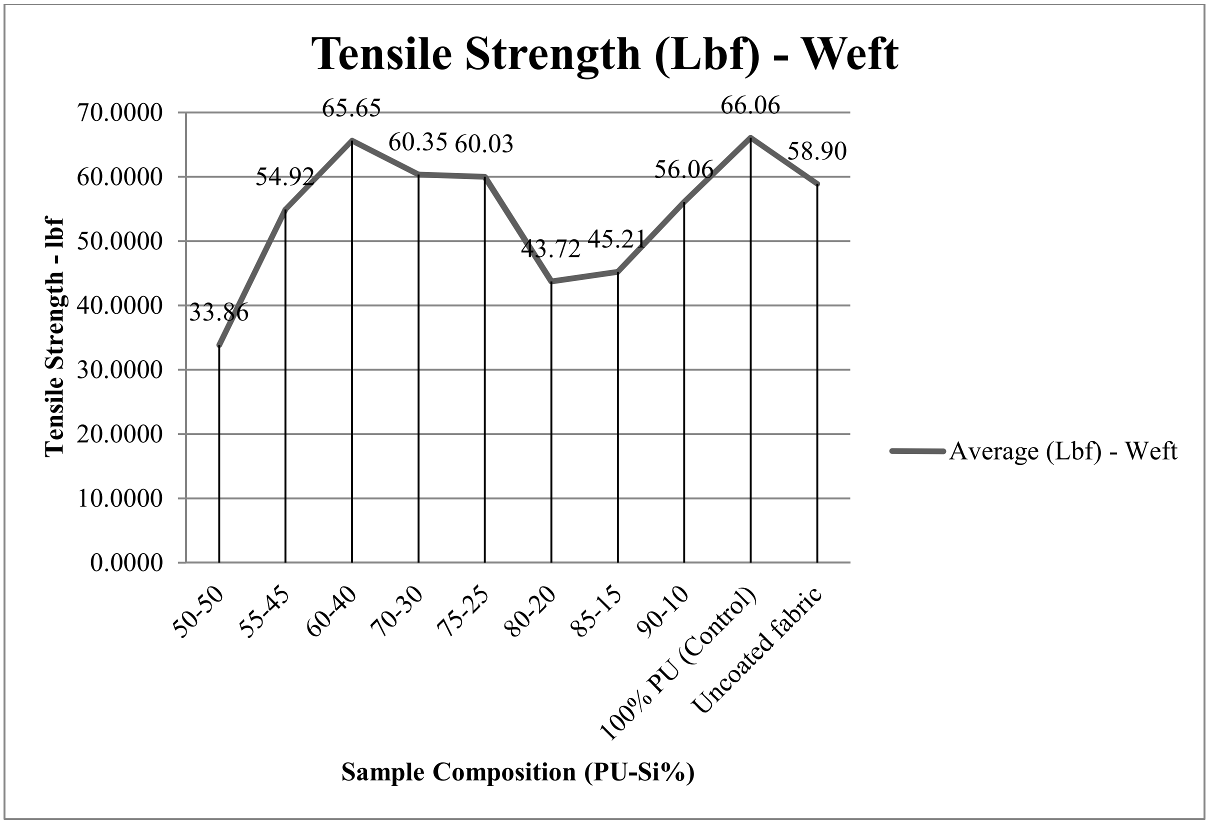

Figure 16. Graph showing Tensile Strength results for Weft direction

From the results it was observed that in most cases, the tensile strength increased in both directions after the coating was applied. The maximum increase in average tensile strength in warp direction was seen in the sample with a 70-30 composition. In weft direction, the maximum increase in average strength occurred in sample with a 60-40 composition.

The increase in thickness after coating can be one of the contributing factors in the increase of strength. However, it was also observed that there was loss in average strength in the case of samples 75-25 and 90-10, in the warp direction. Loss of strength in weft direction can be observed in the 50-50 sample as well as in 80-20 and 85-15.

6. Stiffness Test

Stiffness test results indicate any change in rigidity or flexibility of fabric. Sometimes due to deposition of coating on the material, the yarns might lose their flexibility, leading to stiffening of the fabric. Very stiff fabric can be uncomfortable and not fit for use. Table 9 shows the readings for stiffness in terms of Taber units.

Table 9

Readings for Stiffness Test

	Left side deflection		Right side deflection	
	Average	Std dev	Average	Std dev
75-25	0.10	0.0000	0.07	0.0577
80-20	0.07	0.0577	0.10	0.0000
85-15	0.03	0.0577	0.13	0.0577
90-10	0.10	0.0000	0.17	0.0577
70-30	0.07	0.0577	0.03	0.0577
60-40	0.03	0.0577	0.10	0.0000
55-45	0.07	0.0577	0.13	0.0577
50-50	0.17	0.0577	0.20	0.0000
control	0.43	0.0577	0.27	0.0577
fabric	0.10	0	0.10	0

It was observed that in most cases, the average stiffness after coating was the same as the average stiffness of the original fabric. This was because the coating thickness was not very significant. As the coating layer was thin, it did not add significant weight to the fabric samples. The lower values of stiffness indicate that the fabric is bendable and can be used in regular apparel. The highest increase in average stiffness was observed in the case of sample 50-50 in left direction as well as in the right direction. It was also observed that 100% PU-coated fabric had maximum increase in the average stiffness in both the directions. This can be associated to the thicker coating.

The results can be summarized by tabulating the average readings for all of the tests for the samples.

Table 10

Summary of Results

		Sample (PU-Si %)							
		50-50	55-45	60-40	70-30	75-25	80-20	85-15	90-10
Test									
Spray Test (AATCC rating)		50	70	80	80	80	90	90	90
Contact angle Test (Deg)		82.81	81.60	83.66	88.55	86.42	93.54	92.12	82.26
Comfort [Ref] (m^2Pa/W)		4.11	2.97	3.74	0.87	1.54	1.57	1.6	1.9
Tensile Test (lbf)	Warp	96.91	91.82	82.27	99.40	75.45	90.52	95.99	70.79
	Weft	33.86	54.92	65.65	60.35	60.02	43.72	45.21	56.06
Stiffness Test (Taber units)		0.085	0.085	0.08	0.135	0.05	0.065	0.1	0.185
Thickness Test (µm)		322.5	332	337	324	334	343.5	326.5	331

From the above table we can see that the samples 80-20 and 85-15 showed the highest readings for the spray test and the contact angle test. This indicates that they have high waterproof properties. The high percentage of polyurethane contributes to the higher hydrophilicity. Simultaneously, the moisture resistance values of the samples are low, which means they have higher breathability. This combination of high waterproofness and breathability is the most desirable combination to create waterproof clothing that can be used during performing activities in harsh weather conditions with comfort.

It can be seen from the table that as the percentage of silicone in the composition decreases, the waterproof characteristics increase, that is, the samples become more resistant to water. It can also be noted that resistance to moisture decreases with a decrease in percentage of silicone until its percentage is 25%, and then the resistance increases with further decreases in percentage.

CHAPTER 5: CONCLUSION

This experiment was carried out with the aim of developing waterproof, breathable fabric that displays the best possible characteristics. An optimum combination of hydrophobic and hydrophilic compound was developed to achieve these desired results. Different tests were performed to evaluate the performance. Based on these tests, it can be concluded that when the percentage of silicone oil increases, the waterproof properties of the fabric decrease and breathability also decreases.

We can compare the results to the hypothesis made in the Chapter 1.

Hypothesis: Higher amounts of silicone oil in the mixture will give better waterproof properties but lower breathability.

Conclusion: The first part of the hypothesis, "higher amounts of silicone oil in mixture will demonstrate higher water resistance," is rejected while the other part—the higher the amount of silicone oil in the mixture, the lower the breathability—is accepted.

Detailed conclusions can be drawn based upon the objectives set in the beginning of the study as follows:

- Objective 1: Development of formulations with different combinations of silicone oil and polyurethane binder for coating polyester-cotton fabric.

  Conclusion: Eight different compositions consisting of polyurethane resin and silicone oil were used to obtain the waterproof breathable properties. The amount of silicone oil was varied from 10% to 50% of the total composition.
- Objective 2: Development of waterproof breathable fabric by application of all the combinations of resin and binder mixtures.

Conclusion: Various methods can be used to apply the coating on the fabric. During this experiment, the knife-over-roller coating method was used based on availability of machinery and efficiency of application.

- Objective 3: Testing of coated and control fabric for effectiveness of its waterproof properties using Goniometer and Spray test.

  Conclusion: Samples were tested to evaluate waterproof properties using AATCC method 22 for spray test and goniometer to measure the contact angle of water with fabric. Samples 80-20, 85-15, and 90-10 showed the highest spray test rating of 90. Sample 80-20 had the highest average contact angle of 93.56°.

- Objective 4: Testing of coated and control fabric for effectiveness of its breathable properties using Sweating plate method.

  Conclusion: Samples were tested to evaluate the breathability after coating. Sample 70-30 had the highest breathability amongst all samples.

- Objective 5: Determination of optimal combination of silicone oil and polyurethane binder to achieve the highest waterproof and breathable properties.

  Conclusion: The optimum combinations that yielded the best performance in terms of waterproof properties and breathability are samples with 80-20% PU-Si and 85-15% PU-Si. These combinations can be used to create active wear that can be worn in harsh conditions as well as for regular wear apparel.

Even though the samples could achieve high waterproof properties, they still could not achieve the highest waterproof ratings. One of the reasons behind this is the loose weave of the fabric. The lower thickness of the original fabric is also one of the attributes that might have led to lowering the waterproof capabilities. Hence, to obtain greater waterproofness, tighter weave and thicker fabric can be used in the future with the optimum composition of polyurethane and silicone oil.

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APPENDIX

Testing Results:

1. Thickness Test:

Sample (PU-Si %)	75-25	80-20	85-15	90-10	70-30	60-40	55-45	50-50	control	fabric
	900	855	855	830	855	875	870	855	855	820
	860	895	870	890	835	855	855	850	885	815
	875	885	855	830	855	860	855	835	850	810
	880	885	840	840	850	870	860	840	840	825
	850	850	850	870	855	860	845	830	870	825
	845	885	860	840	850	865	855	860	845	825
	825	865	840	860	850	885	860	825	855	825
	865	855	840	870	850	860	850	875	850	820
	825	890	860	860	855	845	870	850	885	830
	875	830	855	880	845	855	860	865	870	835
Average Thickness (µm)	860	869.5	852.5	857	850	863	858	848.5	860.5	823
Std dev	24.15	21.53	10.06	21.10	6.23	11.35	7.88	15.99	16.06	7.14

2. Tensile Strength Test

Sample (PU-Si %)	75-25	80-20	85-15	90-10	70-30	60-40	55-45	50-50	control	fabric
Warp 1	73.973	83.1	93.101	73.589	94.83	79.348	88.65	93.245	92.555	79.348
Warp 2	76.927	97.934	98.875	67.987	103.963	85.185	95	100.591	100.636	85.185
Average Strength (lbs)	75.45	90.517	95.988	70.788	99.3965	82.2665	91.825	96.918	96.5955	82.2665
Std Dev	2.088793	10.48922	4.082835	3.961212	6.458006	4.127382	4.490128	5.194406	5.71413	4.127382
Weft 1	60.842	41.232	48.571	53.468	69.08	63.246	53.682	41.879	69.482	57.707
Weft 2	59.214	46.207	41.858	58.654	51.622	68.05	56.152	25.842	62.645	60.094
Average	60.02	43.71	45.214	56.06	60.35	65.64	54.91	33.86	66.063	58.900

Sample (PU-Si %)	75-25	80-20	85-15	90-10	70-30	60-40	55-45	50-50	control	fabric
Strength (lbs)	8	95	5	1	1	8	7	05	5	5
Std Dev	1.151 17	3.517 856	4.7468 08	3.667 056	12.34 467	3.396 941	1.746 554	11.33 987	4.8344 89	1.6878 64

3. Stiffness Test :

Sample (PU -Si %)	75-25	80-20	85-15	90-10	70-30	60-40	55-45	50-50	control	fabric
Left	0.1	0	0	0.1	0	0	0	0.2	0.4	0.2
	0.1	0.1	0.1	0.1	0.1	0	0.1	0.1	0.4	0.2
	0.1	0.1	0	0.1	0.1	0.1	0.1	0.2	0.5	0.2
Average Stiffness (Taber units)	0.100 0	0.066 7	0.0333	0.100 0	0.066 7	0.033 3	0.066 7	0.166 7	0.4333	0.2000
Std Dev	0	0.057 7	0.0577	0	0.057 7	0.057 7	0.057 7	0.057 7	0.0577	0
Right	0	0.1	0.1	0.2	0	0.1	0.2	0.2	0.3	0.1
	0.1	0.1	0.2	0.1	0.1	0.1	0.1	0.2	0.2	0.1
	0.1	0.1	0.1	0.2	0	0.1	0.1	0.2	0.3	0.1
Average Stiffness (Taber units)	0.066 7	0.100 0	0.1333	0.166 7	0.033 3	0.100 0	0.133 3	0.200 0	0.2667	0.1000
Std Dev	0.057 7	0.000 0	0.0577	0.057 7	0.057 7	0.000 0	0.057 7	0.000 0	0.0577	0.0000

4. Spray Test:

Sample (PU - Si %)	50-50	55-45	60-40	70-30	75-25	80-20	85-15	90-10	control	fabric
Rating	50	70	80	80	80	90	90	90	70	0
ISO	1	2	3	3	3	4	4	4	2	0

5. Contact Angle Test:

Sample (PU - Si %)	75-25	80-20	85-15	90-10	70-30	60-40	55-45	50-50	control	fabric
	86.77	95.05	91.8	83.16	91.43	84.51	81.59	85.19	76.89	3.36
	84.63	91.38	96.25	80.9	87.01	82.76	80.42	82.89	79.55	8.04
	87.09	91.78	89.31	82.38	87.57	84.21	84.32	82.97	82.04	9.3
	85.74	94.43	89.99	81.35	86.52	86.37	82.52	82.59	80.55	10.1
	87.86	95.05	93.24	83.53	90.24	80.44	79.15	80.39	80.65	8.55
Average Contact Angle (Deg)	86.418	93.538	92.118	82.264	88.554	83.658	81.6	82.806	79.936	7.87
Std Dev	1.2561	1.8107	2.7769	1.1308	2.1565	2.2106	1.9773	1.7030	1.9196	2.6386

6. Comfort Test:

Sample (PU - Si %)		Rcbp	Rct	Rct -Rcbp	Rebp	Ret	Rebp-Ret
75-25	1	0.0450	0.1014	0.0564	4.0823	5.8819	1.7996
	2	0.0507	0.0821	0.0314	5.0810	6.3808	1.2998
	Average (m^2Pa/W)	0.0478	0.0918	0.0439	4.5817	6.1314	1.5497
	Std Dev	0.0040	0.0136	0.0177	0.7062	0.3528	0.3534
80-20	1	0.0485	0.1358	0.0873	5.7281	7.3214	1.5933
	2	0.0472	0.1165	0.0692	4.0359	5.5980	1.5622
	Average (m^2Pa/W)	0.0479	0.1261	0.0783	4.8820	6.4597	1.5777
	Std Dev	0.0009	0.0137	0.0128	1.1966	1.2186	0.0220
85-15	1	0.0505	0.1018	0.0513	6.2024	5.2584	-0.9439
	2	0.0424	0.0755	0.0331	2.1431	6.3073	4.1642
	Average (m^2Pa/W)	0.0464	0.0887	0.0422	4.1727	5.7829	1.6101
	Std Dev	0.0057	0.0186	0.0129	2.8703	0.7417	3.6120
90-10	1	0.0500	0.0626	0.0126	4.9903	6.5862	1.5959
	2	0.0470	0.0733	0.0262	4.6342	6.9613	2.3271
	Average (m^2Pa/W)	0.0485	0.0679	0.0194	4.8122	6.7737	1.9615
	Std Dev	0.0021	0.0075	0.0097	0.2518	0.2652	0.5170
70-30	1	0.0470	0.0678	0.0208	4.6342	4.6355	0.0013
	2	0.0500	0.0756	0.0255	4.9903	6.7338	1.7435
	Average (m^2Pa/W)	0.0485	0.0717	0.0232	4.8122	5.6847	0.8724
	Std Dev	0.0021	0.0055	0.0034	0.2518	1.4837	1.2319
60-40	1	0.0470	0.0800	0.0330	4.6342	8.2777	3.6436
	2	0.0500	0.0835	0.0335	4.9903	8.8226	3.8323
	Average (m^2Pa/W)	0.0485	0.0818	0.0332	4.8122	8.5501	3.7379
	Std Dev	0.0021	0.0025	0.0004	0.2518	0.3853	0.1334

Sample (PU - Si %)		Rcbp	Rct	Rct -Rcbp	Rebp	Ret	Rebp-Ret
55-45	1	0.0515	0.1032	0.0517	4.7347	6.2939	1.5591
	2	0.0490	0.0651	0.0161	4.5779	8.9611	4.3832
	Average (m^2Pa/W)	0.0502	0.0841	0.0339	4.6563	7.6275	2.9712
	Std Dev	0.0017	0.0269	0.0252	0.1109	1.8860	1.9969
50-50	1	0.0496	0.1163	0.0668	5.0732	7.4736	2.4004
	2	0.0515	0.0661	0.0147	4.7347	10.5526	5.8179
	Average (m^2Pa/W)	0.0505	0.0912	0.0407	4.9040	9.0131	4.1091
	Std Dev	0.0013	0.0355	0.0368	0.2393	2.1771	2.4165
Control	1	0.0511	0.0741	0.0230	6.6908	5.4665	-1.2243
	2	0.0623	0.0921	0.0298	5.9126	4.4325	-1.4801
	Average (m^2Pa/W)	0.0567	0.0831	0.0264	6.3017	4.9495	-1.3522
	Std Dev	0.0079	0.0127	0.0048	0.5503	0.7311	0.1809
Fabric	1	0.0485	0.0636	0.0151	2.7624	5.1028	2.3405
	2	0.0568	0.0715	0.0147	2.8990	5.3324	2.4334
	Average (m^2Pa/W)	0.0526	0.0675	0.0149	2.8307	5.2176	2.3869
	Std Dev	0.0058	0.0056	0.0003	0.0966	0.1623	0.0657