Study of Abrasion on Performance of Lightweight Water Impermeable Coated Textiles

by

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Dedication

This work is dedicated to my parents, for their love, support, wisdom and guidance, and to Mac, for his inspiration at Schoolhouse Pond.
Biographical Sketch

The author was born in Goshen, NY on November 3rd, 1987. He attended the University of Rochester from 2006-2010, and graduated with a Bachelor of Science in 2010 after receiving a Dean's scholarship and the Mechanical Engineering Teaching Service Award. Post graduation he continued his studies at the University of Rochester in the fall of 2010 and began graduate work in the Mechanical Engineering department. He pursued his research in applied mechanics of materials under the direction of Professor Robert Clark. At the time of defense he lives in Somerville, MA where he works as an optomechanical engineer.
Abstract

The impact of abrasive wear on high-performance, lightweight coated textiles and their water impermeable properties was examined using a novel approach measuring the permeation rate with respect to pressure and wear. Using variations on the Seuter textile testing and Accelerotor textile abrasion systems, water permeation through various commercially available textiles was studied and characterized. Permeation mechanisms for several fabric weights and coatings were reported and described. The impact of fabric denier and confounding factors were found to be statistically significant; however, the various fabric coatings utilized were unable to be characterized as significant. Nonetheless, Scanning Electron Microscopy and direct testing analysis investigated phenomena related to the physical coating properties and material response.
A special thanks to Dr. Robert Clark for aid with funding for the development and completion of this research. Research funding was supplied from a start-up account through Dr. Clark.

I also wish to thank Dr. Paul Funkenbusch, R. Scott Russell, and the members of the Clark Research Group for their assistance and guidance with non-trivial matters.
# Table of Contents

1. Introduction .................................................................................................................. 1
   1.1 Motivation for research .................................................................................. 1
   1.2 Glossary of common textile terms .................................................................. 4

2. Literature review ........................................................................................................ 6

3. Experimental development and testing procedure .............................................. 9
   3.1 Hydrostatic head testing and apparatus design ........................................... 9
   3.2 Accelerorotor .............................................................................................. 18
   3.3 Fabric abrasion rig design .......................................................................... 19
   3.4 Experimental design .................................................................................. 22
   3.5 Data analysis ............................................................................................. 23

4. Test candidate description .................................................................................. 25

5. Results .................................................................................................................... 28
   5.1 Types of damage ....................................................................................... 28
   5.2 Impact of denier ........................................................................................ 32
      5.2.1 - 20D fabrics .................................................................................... 32
      5.2.2 - 30D fabrics .................................................................................... 34
      5.2.3 - 70D fabrics .................................................................................... 38
      5.2.4 - 200D fabrics .................................................................................. 39
      5.2.5 Statistical analysis of denier ............................................................... 41
   5.3 Impact of coating ....................................................................................... 45
      5.3.1 - Silicone coated fabrics ...................................................................... 45
      5.3.2 - PU coated fabrics ........................................................................... 47
      5.3.3 Statistical analysis of coating ............................................................. 49

6. Final conclusions ..................................................................................................... 51

Bibliography .................................................................................................................. 55

Appendix A - Complete permeation data ............................................................... 57
Appendix B - MATLAB data analysis code ............................................................. 62
# Index of Figures

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Hydrostatic testing platform</td>
<td>10</td>
</tr>
<tr>
<td>2</td>
<td>Top side view of sample mounting platform</td>
<td>15</td>
</tr>
<tr>
<td>3</td>
<td>Sample mounting platform</td>
<td>16</td>
</tr>
<tr>
<td>4</td>
<td>Example of permeation through fabric tester</td>
<td>16</td>
</tr>
<tr>
<td>5</td>
<td>LabVIEW control panel</td>
<td>17</td>
</tr>
<tr>
<td>6</td>
<td>PWM controlled fabric abrasion chamber</td>
<td>21</td>
</tr>
<tr>
<td>7</td>
<td>Ripstop SEM micrograph with indicated ripstop junction</td>
<td>26</td>
</tr>
<tr>
<td>8</td>
<td>Surface damage SEM micrograph, evenly distributed over surface</td>
<td>29</td>
</tr>
<tr>
<td>9</td>
<td>Ripstop damage SEM micrograph</td>
<td>31</td>
</tr>
<tr>
<td>10</td>
<td>20D Surface damage feature SEM micrograph</td>
<td>33</td>
</tr>
<tr>
<td>11</td>
<td>Permeation variation across five 30D samples with 240s abrasion</td>
<td>34</td>
</tr>
<tr>
<td>12</td>
<td>30D compound damage SEM micrograph</td>
<td>36</td>
</tr>
<tr>
<td>13</td>
<td>Coating compliance SEM micrograph</td>
<td>37</td>
</tr>
<tr>
<td>14</td>
<td>Comparison of 70D fabrics at peak extent of abrasion</td>
<td>39</td>
</tr>
<tr>
<td>15</td>
<td>200D unraveling SEM micrograph</td>
<td>41</td>
</tr>
<tr>
<td>16</td>
<td>Coating irregularity SEM micrograph</td>
<td>47</td>
</tr>
<tr>
<td>17</td>
<td>PU physical barrier SEM micrograph</td>
<td>49</td>
</tr>
<tr>
<td>18</td>
<td>Sample A permeation data</td>
<td>57</td>
</tr>
<tr>
<td>19</td>
<td>Sample B permeation data</td>
<td>57</td>
</tr>
<tr>
<td>20</td>
<td>Sample C permeation data</td>
<td>58</td>
</tr>
<tr>
<td>21</td>
<td>Sample D permeation data</td>
<td>58</td>
</tr>
<tr>
<td>22</td>
<td>Sample E permeation data</td>
<td>59</td>
</tr>
<tr>
<td>23</td>
<td>Sample F permeation data</td>
<td>59</td>
</tr>
<tr>
<td>24</td>
<td>Sample G permeation data</td>
<td>60</td>
</tr>
<tr>
<td>25</td>
<td>Sample H permeation data</td>
<td>60</td>
</tr>
<tr>
<td>26</td>
<td>Sample I permeation data</td>
<td>61</td>
</tr>
</tbody>
</table>
Index of Tables

Table 1 - Test candidate tablature ........................................................................................................... 27
Table 2 - ANOVA analysis for denier ........................................................................................................ 44
Table 3 - ANOVA analysis for coating .................................................................................................... 50
1. Introduction

1.1 Motivation for research

Coated textiles have provided protection from the elements for thousands of years, evolving from hides to modern synthetic fibers with advanced coatings and laminates. An entire spectrum of testing has been developed for the textile industry to define and quantify general material properties as well as application properties under unique performance criteria [1]. These testing methods include the relative water permeation properties of textiles.

A specific segment of testing procedures seeks to define both impermeable (waterproof) and semi-permeable (breathable) standards through a range of tests to define permeability resistance. However, several of the standard textile tests exhibit a lack of correlation between laboratory and practical considerations, particularly those for water permeability. Tests pertaining to water permeability from both the American Association of Textile Chemists and Colorists (AATCC) and ASTM International (ASTM) can be considered binary procedures [2]. That is, the ATTCC and ASTM testing is concluded as soon as sufficient hydrostatic forces are applied and the material begins to permeate. A novel method and apparatus for testing was developed to more accurately define material performance with respect to water permeation.

The disassociation between real-world applications and current standard laboratory tests is that many materials may be useful at water pressures higher
than where they first begin to permeate. For example, many fabrics may begin to permeate minute amounts of liquid however still be fully functional when viewed in the context of a larger environment or application. There are, however, no extended testing methods or data available for the performance of coated textiles past the point of permeation.

Moreover, a connection between the impact of physical wear due to abrasion of materials and the permeation method had not been identified after a comprehensive literature search. It is proposed that specialized fabrics used for applications related to outdoor adventure sports are still useful past the point of their rejection from the AATCC and ASTM common water permeation testing procedures. The goal of this research was to provide a baseline characterization not only for the point of permeation but also to relate the analytical observations of textile damage to the point of permeation and beyond.

The primary motivation for the development of this research and the development it saw relates to the apparent need for applied research in regards to lightweight coated textiles, primarily under 60 g m\(^{-2}\). In the outdoor adventure sports industry, weight plays a key role in market acceptability. Materials and coatings have been developed and combined in order to minimize weights while still achieving the minimum head pressure required to meet the needs of those who depend on their gear for survival.
The most popular materials used in many adventure sports include silicone or polyurethane (‘PU’)-coated nylons; each with properties that include excellent coating adherence to a nylon substrate that remains flexible through a wide temperature range while still minimizing overall weight. These lightweight materials are not, however, water impermeable under all conditions and are susceptible to permeation through high pressures and/or after repeated exposure to abrasion. This research ultimately looks to quantify and describe the mechanical interactions between several common nylons with varying coatings, water pressures, and levels of abrasion.
1.2 Glossary of common textile terms

Several important common textile terms are used throughout the remainder of this work. As such, it is appropriate that the reader is informed and knowledgeable of their meaning prior to continuing with the text. Several of the following definitions are paraphrased from Fairchild's Dictionary of Textiles [2].

Textile - A broad classification of woven and knitted materials, generally not including laminates or non-woven materials.

Denier - A measurement of the weight, and corresponding thickness, of the monofilament yarn which is woven into finished textiles. Numerically equivalent to the number of grams per 9,000 meters of yarn. Typically abbreviated with an uppercase D, i.e. '200D'.

Fabric coating - Textiles which have been encapsulated with a liquid emulsion, typically with a hot knife edge system for lighter weight material. Coatings are generally defined as a surface coating on a single side or as an impregnation consisting of a complete filling of all textile interstices within the woven volume.

Calendared - Finishing process whereby fabric is rolled between cylinders under pressure to produce a glossy, smooth surface due to plastic deformation. Analogous to cold rolling in cold working of metals.
Warp - Component of woven textiles that run lengthwise in a fabric, parallel to the selvage edge. Warp yarns are woven first as the base of a textile and are typically made stronger than weft yarns.

Weft - Yarns that are woven perpendicular to the warp yarns, typically out of weaker material or at an equal or lower filament count to the warp yarn.
2. Literature review

Limited data for textile coating durability is available, or is proprietary and out of public or academic access. Much of the published literature that is applicable to this research is with respect to heavier silicone coatings, on the order of 60-150 g m\(^{-2}\), which are thick enough to form a completely impermeable silicone barrier and heavier than are typically used in the adventure sports industry [1]. These materials are commonly used with heavier 420 denier (further printed as '420D') fabrics for airbags, but these coatings are not focused on water impermeability but rather air porosity, as water impermeability can be obtained in a more straightforward fashion by using heavier solid membranes rather than coated textiles. Light (under 1 g m\(^{-2}\)) silicone coatings are commonly used to impart wrinkle resistance or lubricating properties but can also be used to develop water resistance [3]. Little published information exists for the durability of small denier (under 200D) textiles, regardless of coating.

An important consideration when applying water impermeable coatings to a textile material is the ability to retain the texture, properties, density and coloring of the base fabric [4]. In the case of a multi-filament yarn, silicone, polyurethane and PVC coatings typically mask the surface of a textile with a smooth, regular surface [5]. The high specific strength of nylon of approximately 40 gf tex\(^{-1}\) [6] and low glass transition temperatures combine to enable low cost manufacturing techniques [7]. These coated fabrics are generally quite robust
and provide excellent performance to cost and weight characteristics when compared to other commercially available options.

Silicone provides a logical textile coating material due to its relative chemical inertness and its long term stability at temperature [1]. Chemically, silicone is hydrophobic; defined as ‘a material which is not easily wetted, and resists the flow of water on its surface’ [8]. Much of the current research devoted to water impermeable textiles has focused on super-hydrophobic materials; coated membranes that exhibit very high contact angle and cause water droplets to become nearly spherical when placed on the surface of the material. These properties are unrelated to the head pressures the coatings are capable of resisting, but provide a useful baseline for coating chemistry and methods of analysis. Furthermore, super-hydrophobic materials have historically suffered from a lack of mechanical durability, and are not appropriate for applications of head pressure [5]. As such, these types of coatings have mainly been limited to research into contact angle.

In addition to silicone, polyurethane (PU) coatings have also been extensively researched and documented. PU coatings apply to textiles that completely fill the pores on fabric surfaces and relay on a solid barrier for water impermeability [8]. Polyurethane is a hydrophilic material; it attracts and wicks water through a permeable membrane without a solid barrier to prevent transport, largely due to a polarity difference. For water-impermeable breathable
fabrics, this solid barrier can have pores no larger than 3 µm, which provides sufficient pore size for water vapor to escape while still preventing the transmission of liquid water through the textile [9,10]. Newer GORE-TEX™ brand PTFE coated water-impermeable breathable membranes have pores no larger than 200 nanometers. With water vapor molecules approximately 30 nanometers in diameter, this enables the gaseous particles, which are several thousand times smaller than liquid water, to pass through the membrane while maintaining liquid water-impermeable properties through surface tension effects [11]. When used in clothing, this property allows a fabric to 'breathe', and requires care to ensure the pores are not clogged with contaminants. Coated fabrics, however, can be expected to have much smaller pores, as breathability is not an issue and a non-porous structure is advantageous for durability. One would expect these thin coatings to have a porous nature due to the molecular structure of the coating. However, the pores are so small that only a limited amount of liquid or gaseous water is expected to infiltrate through these intermolecular pores [10].
3. Experimental development and testing procedure

3.1 Hydrostatic head testing and apparatus design

In order to characterize the materials permeation rate, a new mechanism was derived from the Suter testing method. To properly observe the sample being tested for failure and for ergonomic reasons, the water column on the Suter tester is placed beneath the textile sample. Water pressure is then applied from the bottom of the tester to force water through the sample. This method, however, does not measure the rate of liquid being forced through the material. For the new testing design, the testing rig was inverted so that a column of water would be applied from above, with permeating water collected in a small receptacle underneath the membrane. This derivation to older testing specifications allowed for new pressure-dependent properties to be investigated.

The collecting receptacle was placed on top of a laboratory balance and connected via an RS-232 port to LabVIEW for data import and processing, thus enabling measurements of the rate of permeation. The balance used throughout the experiment was an Ohaus GT-410, with a 410 g maximum capacity and resolution of .001 grams. Prior to testing, the water collector was dried and the balance was tared and sealed off from room drafts and oscillations which could have skewed the collected results. Water used throughout all experimental testing was room temperature, distilled water. Testing was programmed to stop
once the balance reached 95% of its maximum derived capacity. Figure 1 shows a full view of the frame and testing platform for reference.

Figure 1 - Hydrostatic testing platform
The fabric specimen and water for pressure testing were placed directly above the balance. As pressures of possibly more than 25 kPa were expected, designing a rig that would impart a greater than 2.5 meter water head was not ideal as it would not fit into available laboratory space. Instead, a much smaller head of liquid, no larger than 25 cm (300 mL), was used in combination with a computer controlled regulator that applied air pressure over the liquid. This allowed for the capacity to simulate a much larger pressure, up to 100 kPa, by using a ControlAir T900X E/P transducer. This pressure regulator is capable of producing pressures ranging from 0-15 psi (0-103 kPa), and is controllable via a 0-5 V input provided by a LabVIEW supplied PCI-breakout box. The regulator features a specified accuracy of +/- .1% and was supplied with clean, dry air from a house air pressure line at 250 kPa after being calibrated against a regulated tank.

The test materials were attached to the pressurized chamber with a system of gaskets and a three-point bolt/nut combination, which sandwiched the samples and allowed for rapid changing of the material and emptying of the liquid chamber after tests were completed. Liquid was stored in a 1 meter tall, 2.53 cm inner diameter clear acrylic chamber to enable monitoring of water levels and to facilitate the quick sourcing of permeation. The automated pressure system required three inputs into this chamber; one for regulator input above the liquid, one for filling the chamber with liquid and one for venting the chamber during filling. In order to prevent liquid from falling and impacting the fabric before
testing, an undersized internal disk was placed at the top of the chamber which caused the water to wick down the edges of the pipe rather than fall uninhibited and possibly permeate through the material due to its velocity.

The inversion of the test apparatus platform was not without incident, as several problems arose. A primary issue with proper data collection occurred when droplets of water formed on the underside of the fabric under test that were too small to break from surface tension and fall into the collector underneath. The various hydrophobic and hydrophilic coatings, coupled with the surface tension of the water, allowed droplets approximately 1 mm in diameter (with masses on the order of one microgram) to form and stay suspended without permeating to the collector. To solve the issue of this permeation not being recorded, a dwell time of 120 seconds was utilized at lower pressure testing to allow a steady stream of water to form, effectively mitigating any issues with stationary liquid collecting. Once drops were larger than 1-1.5 mm in diameter they typically dropped into the collection pan, given a long enough dwell period. Testing using various AATCC and ASTM standards would have stopped at the first formation of these drops, so this issue was unique to this specific type of test.

Various other solutions were considered to measure these infinitesimal permeations. Following an analysis of the orders of magnitude of mass needing to be measured, the other solutions were disregarded. Capturing these samples would have required a much more sensitive balance, which would have, in turn,
sharply limited the maximum capacity down to around 5 grams, the peak capacity of most commercially available scales with that resolution. This capacity was deemed unsuitable for testing as it would have drastically shortened the testing length window. In addition, the testing chamber would have needed a better seal from drafts and vibrations, possibly hampering efforts to reload the test material as well as requiring drying the balance between tests. Lastly, a higher capacity balance would be cost-prohibitive and would best be used for future research specifically trying to quantify low pressure permeation.

Given the longer dwell times to allow droplets to form and eventually fall, all small yet observable permeation rates were comfortably defined as steady state and not skewed by lengthening the dwell period. Shorter dwell periods as low as 15 seconds per pressure level were utilized to compensate for very high permeation rates and the maximum capacity of the balance. In fabrics which exhibited higher permeation rates, these rates remained remarkably stable throughout the entire range of pressures tested despite shorter testing times.

Mounting the material presented problems with respect to the original design intent. Water was prone to being forced through the interface between the test samples and the two hard gaskets originally implemented, shown from a top view in Figure 2. After investigating different designs, a flexible gasket system was chosen as the ideal solution. This system featured an AS568-010 5 cm diameter silicone O-ring above a 7.5 cm OD by 4.5 cm ID round neoprene
gasket. This large doughnut shaped gasket allowed the fabric samples to give
and deflect on the order of several millimeters when higher pressures (>15 kPa)
were applied, limiting yielding of the material purely due to pressure, and is
visible in Figure 3. The flexibility of this mounting scheme can be seen in Figure
4, where water is being forced through the material and the gasket is allowing a
small amount of sample compliance. The O-ring and neoprene gasket provide a
uniform and appropriately sized surface for leaks to saturate the fabric for
collection. The three point bolt/nut combination used with the 6.4 mm (0.25 in)
厚 acrylic plate had a tendency to bend the underside support when tensioned,
whereas a 6.4 mm (0.25 in) thick aluminum base plate successfully minimized
flexure of the mounting plate while loaded up against the gaskets as well as fully
eliminating leakage.

LabVIEW was used for the control aspects of the waterproof head testing,
with the LabVIEW VI control panel shown in Figure 5. A PCI-breakout box
provided voltage control of the regulator and in-line pressure sensor readings. An
RS-232 serial connection was used for real-time reading of the balance, with
data collected by LabVIEW at 1 Hz. Pressure applied to the test materials
included both the pressure of the actual water head as well as the regulator
pressure, and the correct air pressure was calculated based on the balance
output and initial water fill level, with a typical initial value of approximately 2 kPa.
Series of pressures and dwell points were programmed into LabVIEW to allow for
an automatic sweep through a programmed regimen. It was also possible to
independently control the pressures and dwell points in the event that additional control was required or a specific phenomenon was identified that warranted additional investigation. Data were exported as a tab-delimited .lvm file for import into MATLAB and Excel for post collection cleanup and analysis.

Figure 2 - Top side view of sample mounting platform
Figure 3 - Sample mounting platform

Figure 4 - Example of permeation through fabric tester
Figure 5 - LabVIEW control panel

(demonstrating active testing conditions)
3.2 Accelerator

Several methods were considered to test the mechanical durability of the coatings on the textile specimens. While numerous ASTM specifications for rotary and belt-driven abrasion systems exist, these methods have several key flaws. Principally, they generally only abrade one surface of the textile, while several of the test candidates are either coated on both sides or impregnated through the entire fabric. Additionally, given the small-denier nature of the materials, there was a concern that a method which relied solely on mechanical scrubbing of the surface might lead to wearing completely through the nylon substrate and lead to a compromised testing situation.

AATCC Test No. 93 [12] provided a method that appeared to solve many of the issues with the abrasive-only tests. Referred to as the 'Accelerator' abrasion system, this impact-induced method produces several types of wear as a result of its design and is ideal and well-characterized for woven fabric abrasion [6]. The Accelerator test consists of an elongated S-shaped impeller driven against a small sample of material around a chamber at high speeds; resulting damage to small-denier uncoated fabrics is primarily in the form of fiber breakage. Additionally, the test material is abraded by a sandpaper liner on the inside of the chamber as the samples are thrown outwards by the spinning impeller. There is also an abrasive effect from the fabric rubbing against itself while being propelled through the test chamber. For uncoated fabrics, using this testing design, loss of sample weight increased linearly with the square of
impeller rotation rate, the time of the test and finally with the sample weight [6]. With respect to experimental design, it was important to keep these factors in mind to best utilize the properties and properly control the test conditions. Video captured at 60 frames per second was evaluated to verify smooth, constant operation and engagement with the textile samples and to optimize rotor speeds.

### 3.3 Fabric abrasion rig design

Construction and use of the Accelerotor fabric testing device was derived from the AATCC test defining the major properties of the apparatus, as is shown in Figure 6. As per the AATCC specifications, a 12.7 cm (5 in) acrylic chamber was lined with 0.15 cm (.063 in) open cell foam to give the inside of the chamber more compliance during fabric impact on the inner wall. The inside diameter of the foam sleeve was lined with a continuous layer of 240 grit sandpaper which acted as an abrasive liner. The test chamber was finished with a gasket-sealed acrylic door for observation and mounted to a PVC frame, with an AC to DC brick attached to the back of the frame for motor power.

Power was supplied by a 3600 RPM, 12 V DC motor to spin the impeller. The AATCC specification does not define an exact speed required, only a sample size dependent on fabric weight. The recommended rotor speed and time for testing are left to the discretion of the tester. For heavier materials, 3000 RPM is recommended in the test specification. However, with small-scale testing, this rotational speed was found to be overly rough to the lightweight materials due to
the edges of the impeller ripping through the small fibers of the samples. Small scale visual experiments showed that slower speeds induced what appeared to be surface and structural wear without simply tearing the fabric. With a PWM circuit installed to throttle down the motor to 1200 RPM with no load, satisfactory wear was achieved with the addition of increased torque output from the motor, resulting in a smooth, constant rotor rotation speed for all test samples. The PWM controller interfaced over USB allowing for fine tuning of the motor speed and behavior. Throughout testing, loading on the rotor caused by the rotor contacting the specimens at high speed led to a small decrease in rotational velocity. These decreases were deemed insignificant and random enough to be disregarded.

The impeller itself did not have an official specification. Several variations were available commercially, all ranging between 10.5 and 12 cm in diameter at their widest point. However, for this research, a custom-made 11 cm aluminum version was milled, carefully wet-sanded down to a smooth and uniform finish, and finally press-fit onto the motor shaft. The shape was held roughly consistent with that of commercially available rotors, with an elongated S-shape enabling the rotor to pull the fabric out from the back of the chamber.
Figure 6 - PWM controlled fabric abrasion chamber
3.4 Experimental design

Utilizing the two customized research rigs, a full factorial-designed experiment was prepared and carried out. Small 6 inch by 6 inch square test samples were taken from larger 1 meter long pieces of fabric; these samples were taken from central points in the fabric to avoid influence from the selvedge edge. Once cut, randomly selected fabric samples were placed unfolded in the Accelerotor and were abraded for 0, 1, 2, 4, and 8 minute intervals. After abrasion, the specimens were removed and placed into the hydrostatic testing rig, which was subsequently preloaded with 200 mL of water at room-temperature (20 degrees Celsius). Upon loading, the balance was tared and testing began. Utilizing the pressurized air system, pressures of 2.5 (hydrostatic head only), 5, 7.5, 12.5, 17.5, and 27.5 kPa were tested and permeation rates recorded. These test pressures were chosen to maximize the experimental power of the data collection at low pressures (under 7.5 kPa) as well as at pressures which would mimic extreme conditions in nature (up to 27.5 kPa). Pressures were swept through for up to two minutes for highly permeation resistant fabrics and as short as 15 seconds when a steady stream was clearly visible. To decrease the likelihood of excess water from higher pressure tests tainting lower pressure permeation data, pressures were not randomized but rather were run and captured in sequential order.

Designing and implementing a full factorial design enabled maximum statistical resolution of the experiment; a critical consideration as higher order
confounding could not be deemed inconsequential prior to testing. While increasing the experimental complexity required to complete an entire round of testing, this strategy led to high confidence intervals when analyzing the data post experiment. Given the number of treatment conditions and a suitable number of terms for error estimate, a full test replicate was deemed unnecessary.

3.5 Data analysis

For data cleanup and analysis, raw LVM files were imported into MATLAB. This process removed erroneous data from the balance readings and binned each data point into the appropriate pressure. The average permeation rate per pressure level for each sample was calculated, forming the basis for the material quantitative analysis. Throughout the range of testing, there was no evidence of a significant change in the permeation rate of the samples within each pressure dwelling. This enabled the analysis of the data with the assumption, through numerical confirmation, that the second derivative of the permeation rate was zero. This allowed each pressure bin to be analyzed and compared against other common factors. This phenomenon also indicates that there was little to no yielding of the textile samples during testing. Example code for data binning can be found in Appendix B.

JMP software, published by SAS, was utilized to perform an ANalysis Of VAriance (ANOVA) analysis to test for statistical significance of test factors. The collected data were analyzed linearly with respect to the permeation rate, and the
analysis was used to show the relative importance and statistical significance of each of the various factors.

For visual comparison and verification, data were graphed against the permeation rate with pressure as the dependent variable and each abrasion condition plotted as a contiguous series. Rates were graphed in µL s⁻¹ in a logarithmic scale, with a common range of 0-10000 µL s⁻¹ to facilitate comparison between all tested samples. Complete graphed permeation data is presented in Appendix A.
4. Test candidate description

Fabric samples were carefully chosen to present a well-rounded summary of current commercially available textiles with a focus on the aforementioned lighter weight samples.

Five samples featured a 30D base fabric with silicone coatings or impregnations which were chosen to provide a wide range of samples within a similar class of fabrics. These samples were labeled as Samples B, C, D, E and F and all have very different feels and behaviors. These samples also have different countries of origin and coating operations.

Two samples featuring a polyurethane coating, one each in 70D and 200D varieties, were also chosen for testing. A 70D silicone-coated sample with a very similar hand to that of the PU-coated sample, was tested for as direct a coating comparison as possible. Neither 30D PU-coated samples nor 200D silicone-coated samples were obtainable with 'commercial off the shelf' availability.

A final sample chosen, Sample A, offered an expansion of the test for denier, featuring a calendared 20D base fabric with a silicone coating.

As is common for many new high performance fabrics, several of the tested fabrics featured a ripstop grid pattern. The ripstop features incorporate a nominally larger weave spaced throughout the fabric which is intended to be stronger than the surrounding area, designed to prevent a rip or tear in the material from spreading once the rip propagates to the site of the thicker weave,
with a sample pattern shown in the center of Figure 7. Prior to testing in the Accelerotor system, it was not well understood if and/or how the ripstop patterns in these fabrics would have an impact on their waterproof qualities after wear.

Prior to abrasion, all of the fabrics featured an uninterrupted coating and held a column of water equal to a minimum pressure of 12.5 kPa without permeation, with the exception of the Sample A.

A summary of these samples is provided in Table 1 below.

Figure 7 - Ripstop SEM micrograph with indicated ripstop junction
Table 1 - Test candidate tablature

<table>
<thead>
<tr>
<th>Sample identification</th>
<th>Denier of fabric</th>
<th>Finished weight</th>
<th>Ripstop</th>
<th>Coating</th>
<th>Notes (See below)</th>
<th>No. of filaments per weave - warp x weft</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample A</td>
<td>20</td>
<td>33 g m⁻²</td>
<td>Yes</td>
<td>Silicone</td>
<td>1</td>
<td>14 x 10</td>
</tr>
<tr>
<td>Sample B</td>
<td>30</td>
<td>48 g m⁻²</td>
<td>Yes</td>
<td>Silicone</td>
<td>2</td>
<td>10 x 10</td>
</tr>
<tr>
<td>Sample C</td>
<td>30</td>
<td>46 g m⁻²</td>
<td>Yes</td>
<td>Silicone</td>
<td>3</td>
<td>12 x 9</td>
</tr>
<tr>
<td>Sample D</td>
<td>30</td>
<td>49 g m⁻²</td>
<td>Yes</td>
<td>Silicone</td>
<td>4</td>
<td>10 x 10</td>
</tr>
<tr>
<td>Sample E</td>
<td>30</td>
<td>45 g m⁻²</td>
<td>Yes</td>
<td>Silicone</td>
<td></td>
<td>10 x 6</td>
</tr>
<tr>
<td>Sample F</td>
<td>30</td>
<td>47 g m⁻²</td>
<td>Yes</td>
<td>Silicone</td>
<td>5</td>
<td>18 x 12</td>
</tr>
<tr>
<td>Sample G</td>
<td>70</td>
<td>64 g m⁻²</td>
<td>Yes</td>
<td>Silicone</td>
<td></td>
<td>12 x 10</td>
</tr>
<tr>
<td>Sample H</td>
<td>70</td>
<td>66 g m⁻²</td>
<td>No</td>
<td>PU</td>
<td></td>
<td>12 x 12</td>
</tr>
<tr>
<td>Sample I</td>
<td>200</td>
<td>94 g m⁻²</td>
<td>No</td>
<td>PU</td>
<td></td>
<td>16 x 16</td>
</tr>
</tbody>
</table>

Notes: 1) This material was calendared and the stiffest material of the 9 test specimens.

2) This material appeared to have the thickest silicone coating of the 30D samples.

3) This material appeared to have the lowest surface coefficient of friction from its coating of the 9 test specimens.

4) This material was the stiffest 30D sample tested.

5) This material had the softest hand of any materials tested - it draped over objects more smoothly than any of the 9 test specimens.
5. Results

5.1 Types of damage

By utilizing the Accelerotor, damage to the fabric was well distributed and showed no bias toward particular regions or quadrants on the textile samples. However, there was a bias toward particular types of feature damage. Three distinct kinds of abrasive damage offer the excellent characterization for damage assessment and can be applied to both the fabric and the coating in analysis with respect to sample damage. These damage profiles are likely common to the Accelerotor system as well as real-world damage and should thus correlate well for practical considerations. The profiles are summarized below and are subsequently used in discussion of the performance during hydrostatic head testing. Complete permeation data can be found in Appendix A, and specific data for comparison is included in each analysis section.

Surface damage

The first category of damage is the mechanical wearing of the coating and underlying material from the hard Accelerotor impeller. This surface degradation is unique in that it is relatively regular over the entire surface of the abraded material. Damage can be distinguished for both the warp and weft surfaces, and variations in the relative amounts of damage to each of these areas are evaluated for wear characterizations. For most of the fabric samples, with the exception of several of the 70D samples, the warp thread surfaces sustained a
significantly higher degree of damage due to their physical location of protruding and being exposed over the weft surfaces. This served to concentrate much of the surface damage on specific areas of the fabric surfaces, wearing at both the coating and the underlying textile material. This damage was almost exclusively located in small concentrated regions, possibly exacerbating permeation and failure, and is shown in Figure 8.

Figure 8 - Surface damage SEM micrograph, evenly distributed over surface
Ripstop damage

The second type of damage is a failure in the region around the ripstop threads. The warp and weft strands of each ripstop fabric weave have unique geometries and split into a more complex weave at an intersection of the warp and weft ripstop threads, shown undamaged in Figure 7 and after a light abrasion in Figure 9. This split leads to areas with sharper features and surfaces, analogous to a stress concentration factor, which correspondingly are less resilient to abrasion than the more regular fabric regions; thus leading to voids in the material for liquid to permeate through.

Impact damage

The final kind of damage seen in testing was larger gashes and holes caused by a tear in and subsequent opening of the entire weave of the material, on the order of magnitude from tens to thousands of microns. This damage is separate from the surface damage in that it is not regular over the entire surface, but rather a localized area of severe trauma and destruction. Given that this type of damage was not seen on all test samples, it is appropriate to suggest that the damage inflicted on these samples was from repeated strikes and not from a single sharp edge or impact during testing.
Figure 9 - Ripstop damage SEM micrograph

(Note gap in weave with relatively little damage to other portions of material)
5.2 Impact of denier

Two primary sets of experimental variables, denier and coating, were examined to determine their effect on the permeation of the woven coated textile samples.

Tests are sorted with respect to their denier, in order of increasing fabric weight. Experimental observations and theories are reported along with supporting data and micrographs where appropriate. The impact of denier was shown to be statistically significant for textile permeation, with both micrographs and abrasion theories supporting the statistical analysis of collected data.

5.2.1 - 20D fabrics

The method of degradation and abrasion through the range of deniers tested ranged widely. For Sample A, the lightest material with a 20D base fabric and silicone coating, the coating was not as much of a determining factor in the permeation as was the underlying fabric. Through the entire range of abrasion testing, the bulk of the material saw very little surface damage, which was surprising given the extreme lightweight nature and relative stiffness of the material. The lack of surface damage appears to be related to the fact that the fabric is compliant and shifts in response to surface abrasion and impact due to its low yarn weight.

The 20D fabric showed signs of some ripstop damage, but the main cause of damage was from impact, the third damage component listed in Section 5.1.
There were very large holes and crevices through the entire plane of the material. These defects measured on the order of hundreds of microns in width and stretched over the surface of the material for over a centimeter in locations as seen in Figure 10. These uniquely large and long holes can be most readily attributed to the extreme lightweight nature of the material and were clearly visible with the naked eye. This damage led to a permeation rate of two to ten times that of all other materials; which was not surprising given the relative extent of the damage.

Figure 10 - 20D Surface damage feature SEM micrograph
5.2.2 - 30D fabrics

For the 30D sample swatches, all three types of damage were imparted to the investigated samples. Surface damage was ubiquitous starting from the lower periods of abrasion, with the protruding warp surfaces taking the brunt of the impact and damage. However, given the five different manufacturers and sources of material, this is where the similarities end and individual test candidates must be scrutinized and examined for similarities and patterns. Figure 11 shows the variation in permeation for the five different fabrics, all with 240 second abrasion times on the 30D silicone coated samples.

![Permeation variation across five 30D samples with 240s abrasion](image)

Figure 11 - Permeation variation across five 30D samples with 240s abrasion
The Sample C test candidate showed the best permeation performance at the highest abrasive levels, and had very little impact damage. The samples exhibited only a slight gouging of the coating off of the warp surfaces and a few threads loosened within the weave from extended abrasion. This thread loosening phenomenon was more apparent at the point of the warp and weft ripstop junction, which was most likely caused by the smaller width and subsequent bunching of the weave threads. These effects were relatively small and lead to an asymptotic maximum permeation rate of 45 µL s⁻¹ at 120 seconds and 140 µL s⁻¹ at 480 seconds.

In contrast with the Sample C test candidates, the Sample D specimen showed surface damage similar in type although greater in magnitude with deeper gouges in the face material. Ripstop damage was present but was completely overshadowed by many large, deep fissures, some over 2000 µm in length and resulting in a complete unraveling of several 400 x 400 µm areas of fabric. This fabric had much higher permeation rates as compared to Sample C which was most likely due to the more widespread plastic surface damage and extensive breakage in large stretches of continuous damage characterized by the impact-damaged surface shown in Figure 12.
Although Sample B showed very little damage to the underlying nylon material, the damage to the coating was widespread. Much of the damage that was done in other samples to both the coating and nylon appeared to have been done solely to the coating in this sample, with much of the layer gouged or wiped into large piles, or off of the textile surface completely, illustrated in Figure 13. This left many of the underlying threads exposed, allowing water to permeate under low pressure through small channels and pockets in the coated surfaces. Even at pressures of 12.5 kPa, this material allowed significant rates of permeation when compared to the other 30D material samples.
The final two silicone-coated 30D samples illustrated noteworthy phenomena and permeation patterns. Sample F exhibited a moderate amount of permeation, on the order of 200 µL s\(^{-1}\) at 27.5 kPa after 240 seconds of abrasion, while Sample E's permeation rate peaked at 375 µL s\(^{-1}\) at the same abrasive time interval. These two materials both showed moderate amounts of surface damage, which accounted for the general increase in permeation from zero µL s\(^{-1}\) to the aforementioned rates.

However, both sets of material permeation rates increased dramatically once abraded for the maximum interval. Sample E exhibited a 2.5X increase whereas Sample F exhibited a 12.5X increase from a doubling of abrasion time.
There was no easily observable evidence for this with respect to impact damage, as was the case for the 20D samples. In comparison to the other 30D samples, Sample E and F had the softest hand and were the most flexible and supple. This likely led to the separation and eventual water permeation at pressures of 12.5 kPa and above, regardless of any apparent coating differences.

5.2.3 - 70D fabrics

The next class of materials tested was the 70D fabrics, in both silicone and polyurethane varieties, exhibited by samples G and H, respectively. Both fabrics showed very similar damage accumulation; each with small amounts of surface damage at 60 and 120 second abrasion intervals. Unlike all other samples that showed some kind of surface damage, there was little to no difference between the warp and weft surfaces; each had similar damage. The surface damage evident on both coating options displayed a randomly distributed set of longer scrapes and markings in the coating and upper portion of the underlying nylon. The silicone-coated sample showed more separation between individual threads than the polyurethane-coated sample.

For longer abrasion periods, both sets of samples showed very similar impact damage patterns of small yet significant holes approximately 20-30 µm, predominantly explained by having the underlying nylon cut and pulled from the weave. Again, the silicone version showed a greater degree of this impact
damage at the highest abrasion times, which can be correlated to the marginally higher permeation rate versus that of the PU-coated version. With very similar damage mechanisms, the permeation rates through the entire range of testing were analogous in form and shown in Figure 14, especially when comparing the shape of the permeation curves over the full range of pressures.

Figure 14 - Comparison of 70D fabrics at peak extent of abrasion

5.2.4 - 200D fabrics

For the heaviest samples (Sample I), the 200D material showed unique wear patterns. At the lowest abrasion level of 60 seconds, there was primarily surface damage, no ripstop damage (the 200D fabric has no integrated ripstop pattern), and little to no impact damage. At the higher periods of abrasion, there were increasing amounts of damage which can be characterized as a combination of both surface and impact types, which are exacerbated by the
larger denier of the material. The large 200D threads appear to have little self-healing action or ability to deflect the impact of the impeller, unlike many of the smaller denier materials tested whose damage features were relatively small as well.

As a result of this inability, many portions of the weave were separated from each other (with their coatings intact, see 200D coating results section), due to surface damage accumulating and eventually resulting in bird-nest areas of pulled threads, shown in Figure 15. Once these threads were exposed, they appeared to have been severed completely by the impeller, leading to even larger gaps in the surrounding areas. Like the 20D fabric, this material exhibited extensive permeation, shown in Figure 26 (Appendix A). This permeation occurred even at low pressures (7.5 kPa) once the initial surface coating was compromised and water was able to permeate through larger holes that had developed.
5.2.5 Statistical analysis of denier

Utilizing the power of the designed experiment, an ANOVA approach was used to examine the statistical significance of tested factors, with results shown in Table 2. Values shown in bold are significant to a 95% confidence interval ($p = 0.05$) [13]. With a large full factorial experiment, the power of the testing procedure can now be illustrated, as well as the true scale of importance denier has on the permeation rate. All three main effects - time, pressure and denier - are found to be significant with respect to the permeation rate. Abrasion time and
pressure factors are incontrovertible and were expected before testing. The impact of denier, as explained through visual observations and micrograph analysis, has now been shown to be statistically significant as well.

There is also shown to be statistical power to all three two factor interaction terms, crossing time, pressure and denier with one another, acting independently from the first order factors. These terms and their respective F values show that the higher order relations of the three terms cannot be ignored. Interactions between the pressure and denier (B x C) indicate a connection between how different weight fabrics react differently under changing pressures, most likely related to how they stretch under changing conditions. The abrasion time and pressure (A x B) interaction indicates that pores and longer damage times leads to more permeation as pressures increase, thereby allowing for larger deflections as the fabric matrix breaks down with abrasion. The final second order interaction between abrasion time and denier (A x C) indicates a nontrivial relationship between different yarn weights and their reactions to varying periods of abrasion. This figure was the weakest interaction of the three, and there may be confounding and undocumented interactions due to the different coatings imparting properties to the denier, particularly in the 30D samples.

The third order factor, A x B x C, was also suggested to be statistically significant. Care must be taken to looking into suggesting this factor is indeed
significant, based on the experimental procedure used. There may have been some experimental confounding due to each test 'scan' of pressure sweeps comprising a single abraded textile, as well as the overwhelming power of the impact of the denier and pressure terms independently.
Table 2 - ANOVA analysis for denier

<table>
<thead>
<tr>
<th>Source</th>
<th>DOF</th>
<th>SS (x 10^6)</th>
<th>MS (x 10^6)</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>A. Time</strong></td>
<td>1</td>
<td>2.33593028</td>
<td>2.33593028</td>
<td>8.85452263</td>
</tr>
<tr>
<td><strong>B. Pressure</strong></td>
<td>5</td>
<td>39.8668925</td>
<td>7.97337849</td>
<td>30.2237018</td>
</tr>
<tr>
<td><strong>A x B</strong></td>
<td>5</td>
<td>20.0461221</td>
<td>4.00922442</td>
<td>15.1972722</td>
</tr>
<tr>
<td><strong>C. Denier</strong></td>
<td>3</td>
<td>58.0170749</td>
<td>19.339025</td>
<td>73.3060553</td>
</tr>
<tr>
<td><strong>A x C</strong></td>
<td>3</td>
<td>2.32227521</td>
<td>0.774091735</td>
<td>2.93425401</td>
</tr>
<tr>
<td><strong>B x C</strong></td>
<td>15</td>
<td>44.8433611</td>
<td>2.98955741</td>
<td>11.3321463</td>
</tr>
<tr>
<td><strong>A x B x C</strong></td>
<td>15</td>
<td>28.0143894</td>
<td>1.86762596</td>
<td>7.07937924</td>
</tr>
<tr>
<td>Error</td>
<td>215</td>
<td>56.719603</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Total</td>
<td>262</td>
<td>235.685057</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

**Bold** = Significant at 95% confidence
5.3 Impact of coating

The second experimental variable examined, isolating fabric coating from fabric denier, did not have a statistically significant impact on fabric performance and permeation. Silicone and polyurethane coatings were thought to have imparted differing waterproof properties to their respective fabrics. While this turned out to be partially true, verification on the impact of their respective permeation rates could not be determined. The coating did help show evidence of the mechanism of permeation in combination with the denier of the material.

5.3.1 - Silicone coated fabrics

The silicone-coated fabrics had a wide range of permeation rates, and the significance of this coating type is problematic to determine with the current material samples. Some of this uncertainty comes from the manufacturers of these test materials as many of these producers use proprietary methods for coating their textiles. There appears to be several variations in the finished product after analyzing SEM micrographs, adding difficulty to confirm significance in the coating properties. Thickness of the coating on some samples was uneven, including Sample F as shown in Figure 16 which had a more uneven application of silicone than any other sample. The toughness and adherence of the coating also varied among samples, which is challenging to quantify and apply to statistical analysis for this research without having access to proprietary information about the coating and curing processes used.
The actual permeation action of the silicone coated fabrics were all very similar, with small beads of water forming mainly at the ripstop intersection points and randomly throughout the body of the fabric as abrasion time increased. The rate of permeation increased until hitting a 'saturation pressure' after which the increase in permeation rate was relatively linear with respect to pressure. For the silicone-coated fabrics, this saturation pressure was also fairly consistent between abrasion test times, accounting for only a variance in the subsequent rate of permeation. For the 20D samples and the two aforementioned silicone samples prone to high permeation rates at extended abrasion (Samples E and F), high pressure jets of water eventually formed the majority of the permeation at 27.5 kPa, generally located at the ripstop weave intersection points.
5.3.2 - PU coated fabrics

The polyurethane-coated materials impart their relative water impermeability by providing a solid, physical surface barrier through which water cannot penetrate, shown exposed in Figure 17. This feature was theorized to be responsible for the susceptibility to physical damage of the fabric by creating cracking and fissures through which water could permeate. However, evaluation of this theory in the two polyurethane-coated fabrics led to mixed conclusions.
For the 200D test samples, the large threads were separated which led to very large permeation rates in a unique fashion. The numerous pores and cracks in the large denier threads coated with hydrophilic polyurethane offered little resistance to permeation at any pressures after abrasion of any amount breaks down the coating. Due to the unbundling of the fabric, water did not form jets and higher-pressure streams, but rather formed a slow permeating wall of water that appeared to seep out of the entire area of the textile under test. This method of permeation fits well with the physical degradation of the material and the corresponding damage seen in SEM micrographs. This permeation pattern for the heaviest polyurethane-coated sample was very different than that in other test samples.

The 70D polyurethane coating of Sample H exhibited very different performance that was comparable to the 70D silicone-coated sample. The coating on each fabric sustained similar amounts and types of damage, with both materials permeating on the order of 100 µL s\(^{-1}\) at the worst case, and exhibiting excellent performance at the 12.5 kPa mark with under 10 µL s\(^{-1}\) for all abrasive testing. The insignificant difference in the permeation rates and damage profile between these two materials further negated the theory that the coating itself is a key factor in the permeation rate. Instead, it appears that an interaction between the denier, coating and weave of the material controls the permeability with respect to abrasive damage.
5.3.3 Statistical analysis of coating

Again, ANOVA procedures were utilized to quantify the statistical significance of the unique terms, calculated in this instance for time, pressure and coating type. Shown in Table 3, the coating effects do not show a strong independent and statistically significant impact on the permeation rate. The time,
pressure, and time crossed with pressure (A x B) variables were, as in the denier based analysis, significant and independent.

A Tukey HSD (Honestly Significant Difference) test was also conducted in conjunction with the ANOVA analysis through JMP. This test seeks to identify treatment conditions which are significantly different from one another and can be binned as unique attributes. The analysis conducted using this tool was unable to yield a statistical identification of the different coatings, with the least square mean of each variable within a factor or two of one another. In comparison, the pressure terms were distinguishable from each other. Slight confounding exists between the lower pressure terms where permeation rates were lower, but separable and unique terms are identifiable at higher pressures.

Table 3 - ANOVA analysis for coating

<table>
<thead>
<tr>
<th>Source</th>
<th>DOF</th>
<th>SS (x 10^6)</th>
<th>MS (x 10^6)</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td>A. Time</td>
<td>1</td>
<td>3.214666</td>
<td>3.214666</td>
<td>4.1515</td>
</tr>
<tr>
<td>B. Pressure</td>
<td>5</td>
<td>12.261</td>
<td>2.4522</td>
<td>3.1669</td>
</tr>
<tr>
<td>A x B</td>
<td>5</td>
<td>6.907086</td>
<td>1.381417</td>
<td>1.784</td>
</tr>
<tr>
<td>C. Coating</td>
<td>1</td>
<td>1.893194</td>
<td>1.893194</td>
<td>2.4449</td>
</tr>
<tr>
<td>A x C</td>
<td>1</td>
<td>0.122802</td>
<td>0.122802</td>
<td>0.1586</td>
</tr>
<tr>
<td>B x C</td>
<td>5</td>
<td>1.430776</td>
<td>0.286155</td>
<td>0.3696</td>
</tr>
<tr>
<td>A x B x C</td>
<td>5</td>
<td>1.532004</td>
<td>0.306401</td>
<td>0.3957</td>
</tr>
<tr>
<td>Error</td>
<td>239</td>
<td>185.0656</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Total</td>
<td>262</td>
<td>235.6851</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
6. Final conclusions

This research investigated some principal questions and opened the door to several new avenues for future research. The primary goal of the research was to prove the significance of the impact of coating and denier on the relative water permeability of lightweight nylon fabrics.

1) As expected, abrasion time and variations in pressure were strongly correlated to fabric permeability after wear. Observations taken during permeation further contributed to the statistical analysis of data, and combined with micrograph analysis several permeation theories were developed.

2) Fabric denier was strongly associated with permeability. The denier, coupled with a subsequent micrograph analysis of the fabric weave and the fabric’s resistance to abrasion has been shown, along with confounding factors of time and pressure, to provide a critical element in determining the performance factors of the fabrics. Two types of damage, ripstop damage related to the weave of the material and impact damage, related to mechanical damage generated from the Accelerotor platform, were attributed chiefly to the denier. The concentrated abrasion that accompanied the Accelerotor derived surface damage appeared to lead to unbiased damage over the entire surface of the textile samples. This damage consisted of marring on the warp fibers in addition to the general wear and tear of direct hits of the blade and outer abrasive ring.
Conversely, the ripstop damage was far more localized and geographically centered on areas of unique geometry in the textiles.

3) The lack of statistically significant dependence on the hydrophobic silicone or hydrophilic polyurethane properties was not expected. The morphology of the coating was difficult to characterize, but clear trends from analyzing micrographs and the permeation data collected illustrated a trend of unique characteristics based on several factors aside from the fabric coating. The silicone fabrics tended to have sharp, well defined areas of permeation with the rate linearly increasing once a ‘saturation pressure’ was achieved. Conversely, the PU coated samples lacked these sharp permeation features and instead more evenly failed through a wide pressure range. It is unfortunately not possible to directly compare the two coating over a range of fabric deniers, e.g., 20D, 30D and 200D, given the fact that only 70D fabrics are commercially available with both silicone and polyurethane coatings.

4) The application method of the coating on the fabric and other proprietary factors unique to each commercial fabric mill also seemed to be important in determining how and when these fabrics permeate, however a characterization of these factors was not possible due to the proprietary nature of the processes.
With no single conclusive set of parameters to characterize these tested properties, trends and data collected from this research and unique testing equipment can be utilized for future testing using off the shelf equipment. To accomplish this, appropriate abrasion testing should be performed and analyzed to establish the wear properties of the coating and underlying fabric. From there, one can obtain a basic analysis of the waterproof properties from a Suter testing rig to determine the initial permeation. This data can be used and analyzed with the wear comparisons discussed in Section 5 to extrapolate the likely sources of water permeation without any specialized testing equipment.

These experiments suggest and establish data to define the variability in materials currently being commercially manufactured. Furthermore this testing provided a baseline for further testing and evaluation to understand the specific methods of water permeability failure. This research can ultimately be utilized in targeting new research and development funding in textile development. Specifically, technical fabrics can be analyzed with respect to specific wear criteria with greater accuracy in the lab and an enhanced correlation to real world characteristics.

Future research should focus on the most common denier commercially utilized for outdoor equipment by investigating exclusively 30 denier samples. Recommended techniques for additional investigations include the manufacturing of a small hot-knife coating operation utilizing greige fabrics from multiple
sources along with a uniformly applied silicone or polyurethane coating throughout all tests. This should eliminate much of the variation seen from different manufacturers and would enable honing in on any statistical significance for the coatings and any finer permeation mechanisms that may be in play. Fabrics heavier than 70D most likely share the same abrasive properties as the 200D fabric tested in this experiment; except in cases of extremely thick coatings, which are mechanically durable enough to resist wear, and therefore would be a different realm of research altogether.
Bibliography


Appendix A - Complete permeation data

Figure 18 - Sample A permeation data

Figure 19 - Sample B permeation data
Figure 20 - Sample C permeation data

Figure 21 - Sample D permeation data
Figure 22 - Sample E permeation data

Figure 23 - Sample F permeation data
Figure 24 - Sample G permeation data

Figure 25 - Sample H permeation data
Figure 26 - Sample I permeation data
Appendix B - MATLAB data analysis code

1 clear all
2 clc
3 cd('C:\Users\Brian\Desktop\FinalData')
4 files = dir('*.lvm');
5 w=1;
6 for iq=1:length(files);
7     cd('C:\Users\Brian\Desktop\FinalData')
8     dlmread(files(iq).name);
9     files(iq).name;
10    [X]=dlmread(files(iq).name);
11    % [X] = (ans)
12    % ans
13    %eval(['[X]= xlsread( '' files(iq).name ' .xls '')']);
14
15    % Eliminating zero rows caused by RS-232 scale timeout.
16    X(any(X==0,2),:)=[];
17    [M,N] = size(X);
18    [Mat] = zeros(M,4);
19
20    for i=1:M
21      for j=1:4
22        Mat(i,j) = X(i,j);
23    end
24    end
25
26    % Eliminating unwanted zero pressures at the end, from the 80th point to the
27    [Msize,Garbage]=size(Mat);
28    for i=80:Msize-5
29      if Mat(i+4,1) < (.2)*Mat(i,1)
30        Mat(i+4,:)=[];
31    end
32    end
33
34    [Msize,Garbage]=size(Mat);
35    % Rate of water permeation in mL/s for each dwell point.
36    for i=1:Msize-1
37      Mat(i,5)=abs(Mat(i+1,2)-Mat(i,2));
38    end
39
40    clear Temp0 Temp25 Temp50 Temp100 Temp150 Temp250
41    T0=1;T25=1;T50=1;T100=1;T150=1;T250=1;
42
43    Temp0=zeros(200,5);
44    Temp25=zeros(200,5);
45    Temp50=zeros(200,5);
46    Temp100=zeros(200,5);
47    Temp150=zeros(200,5);
48    Temp250=zeros(200,5);
49
50    % Binning Data WRT pressures
% Splitting up sorted data into sub-matrices Temp0-Temp400, corresponding to ln(pressure) relationships of 0, 2.5, 5, 10, 15, 25 kPa used during testing.

% S0, S25, S50... samples used for average rate calculations as this was still time used for permeation to occur.

for i=1:Msize
    if Mat(i,1) >= 0 & Mat(i,1) <= 1 & Mat(i,2); %0 kPa, water head
        Temp0(T0,:)=Mat(i,:);
        T0=T0+1;
        [N1,R1]=size(Temp0);
        S0=Temp0(1,4);
    elseif Mat(i,1) > 1.01 & Mat(i,1) <= 3.5; %2.5 kPa
        Temp25(T25,:)=Mat(i,:);
        T25=T25+1;
        [N2,R2]=size(Temp25);
        S25=Temp25(1,4);
    elseif Mat(i,1) > 3.51 & Mat(i,1) <= 6; %5 kPa
        Temp50(T50,:)=Mat(i,:);
        T50=T50+1;
        [N3,R3]=size(Temp50);
        S50=Temp50(1,4);
    elseif Mat(i,1) > 6.01 & Mat(i,1) <= 12; %10 kPa
        Temp100(T100,:)=Mat(i,:);
        T100=T100+1;
        [N4,R4]=size(Temp100);
        S100=Temp100(1,4);
    elseif Mat(i,1) > 12.01 & Mat(i,1) <= 18; %15 kPa
        Temp150(T150,:)=Mat(i,:);
        T150=T150+1;
        [N5,R5]=size(Temp150);
        S150=Temp150(1,4);
    elseif Mat(i,1) > 18.01 & Mat(i,1) <= 25; %25 kPa
        Temp250(T250,:)=Mat(i,:);
        T250=T250+1;
        [N6,R6]=size(Temp250);
        S250=Temp250(1,4);
    else
        end
        end
    end

% Eliminating zeros from Temp### Matrices

Temp0(any(Temp0==0,2),:)=[];
[S0,R1]=size(Temp0);
Temp25(any(Temp25==0,2),:)=[];
[S25,R2]=size(Temp25);
Temp50(any(Temp50==0,2),:)=[];
[S50,R3]=size(Temp50);
Temp100(any(Temp100==0,2),:)=[];
102 [S100,R4]=size(Temp100);
103 Temp150(any(Temp150==0,2),:)=[];
104 [S150,R5]=size(Temp150);
105 Temp250(any(Temp250==0,2),:)=[];
106 [S250,R6]=size(Temp250);
107
108 V=zeros(6,3);
109
110 % True average permeation rates through sample
111 V1true=sum(Temp0)/S0;
112 V2true=sum(Temp25)/S25;
113 V3true=sum(Temp50)/S50;
114 V4true=sum(Temp100)/S100;
115 V5true=sum(Temp150)/S150;
116 V6true=sum(Temp250)/S250;
117
118 % Taking average of each ln-based pressure cycle, forming average
rate
119 % matrix V (mL/s) based *solely* on removed samples. Need to
account for
120 % samples removed --> *** V#*TRUE* terms***
121 V1=mean(Temp0);
122 V(1,1)=V1(1,5); V(1,2)=V1true(1,5); V(1,3)=0. ;
123 V2=mean(Temp25);
124 V(2,1)=V2(1,5); V(2,2)=V2true(1,5); V(2,3)=2.5;
125 V3=mean(Temp50);
126 V(3,1)=V3(1,5); V(3,2)=V3true(1,5); V(3,3)=5;        
127 V4=mean(Temp100);
128 V(4,1)=V4(1,5); V(4,2)=V4true(1,5); V(4,3)=10;
129 V5=mean(Temp150);
130 V(5,1)=V5(1,5); V(5,2)=V5true(1,5); V(5,3)=15;
131 V6=mean(Temp250);
132 V(6,1)=V6(1,5); V(6,2)=V6true(1,5); V(6,3)=25;
133
134 % Sanity check to make sure all data points are being used under
pressure
135 % limit defined in final elseif statement above, otherwise states
how many
136 % data points are not within threshold
137 if N1+N2+N3+N4+N5+N6==size(Mat,1)
138   disp('Using all data points')
139 else disp('Not using all data')
140 NumVar=abs(N1+N2+N3+N4+N5+N6-size(Mat,1))
141 fprintf('%4.0f points not being used in average calc''s (%3.2f
percent of data from%4.0
142 % Outputting submatricies in first four matrix columns, average
data in
143 % 5th column in first 6 rows.
144 end
[T, Q] = size(Mat);
T = T - 1;
AnsOutput = zeros(T, 6);
for i = 1:T
  for j = 1:4
    AnsOutput(i, j) = Mat(i, j);
  end
end
for i = 1:6
  AnsOutput(i, 6) = V(i, 1);
  AnsOutput(i, 7) = V(i, 2);
  AnsOutput(i, 8) = V(i, 3);
end

% Exporting Data to xls file
% Pressure (psi), Mass of fluid (g), Water Head (psi), 0, Avg. Rate (mL/s), pressure in
xlswrite('TEST1.xls', AnsOutput);
cd('C:\Users\Brian\Desktop\FinalData1');
a = 'ans';
xlswrite(files(iq).name, AnsOutput);
for i = 1:6
  AnsOutput(i, j);
end
w = w + 1;
end
c = struct2cell(files)
xlswrite('AnsOrder.xls', c);